EUROPLEXUS

A Computer Program for the Finite Element Simulation of Fluid-Structure Systems under Transient Dynamic Loading

USER'S MANUAL

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1 GETTING STARTED

1.1 ABOUT EUROPLEXUS

EUROPLEXUS is a computer code being jointly developed since 1999 by CEA (CEN Saclay, DMT) and EC (JRC Ispra, SS&M) under a collaboration contract. It stems from CEA's CASTEM-PLEXUS (a program belonging to the CASTEM system) and the previous CEA-EC joint product PLEXIS-3C.

The code analyses 1-D, 2-D or 3-D domains composed of solids (continua, shells or beams) and fluids. Fluid-structure interaction is also taken into account.

The program uses an explicit algorithm (central-difference) for the discretization in time and therefore it is best adapted to rapid dynamic phenomena (fast transient dynamics) such as explosions, impacts, crashes etc. Geometric non linearity (large displacements, large rotations, large strains), and the non-linearity of materials (plasticity, viscoplasticity, etc) are fully taken into account.

The spatial discretization is mainly based on the Finite Element or Finite Volume method. Other formulations such as SPH (Smoothed Particle Hydrodynamics), Spectral ELements, Diffuse Elements etc. are also available or under development. Numerous element types and a comprehensive library of material types for solids, fluid and special media (e.g. impedances) are available.

Three main descriptions are available in the code: the Lagrangian description which is well suited for the structural domain, the Eulerian description useful for purely fluid problems, and the Arbitrary Lagrangian Eulerian (ALE) description which is typically used in fluid-structure interaction problems.

EUROPLEXUS is interfaced to various pre- and post-processing programs that enable the meshing of the studied domain (e.g. CEA's Cast3m) and the visualization of the results (e.g. Cast3m, ParaView or EUROPLEXUS itself).

Different types of licenses are available of EUROPLEXUS. A limited version of the code can be downloaded. For research and education these licenses are mainly for free. Details can be found on the web page of EUROPLEXUS (http://www-epx.cea.fr/). This User's manual is updated daily and can be downloaded from http://europlexus.jrc.ec.europa.eu/.

A large bibliography concerning EUROPLEXUS as well as its ancestors is provided at the end of the present manual (see Section BIB). Many of the cited documents are available to EUROPLEXUS developers in electronic form on the EUROPLEXUS Consortium web site (https://europlexus.jrc.ec.europa.eu/).

Video tutorials for beginners are provided as an easy and smart starting to us the code. The tutorials can be watched here: https://counterterrorism.ec.europa.eu/epx_tutorials/index.php .

1.2 Installation

1.2.1 License types

Different types of licenses are available of EUROPLEXUS. A limited version of the code can be downloaded for free. For research and education a full version can be obtained for free. Details can be found on the web page of EUROPLEXUS (http://www-epx.cea.fr/). This User's manual is updated daily (development version) and can be downloaded from http://europlexus.jrc.ec.europa.eu/.

1.2.2 Installation under Windows

The light and the ER version consists of a single zip file containing two main folders: bin - containing the executable and some additional libraries and tests with all the benchmarks and validation examples. In addition the redistributables for Intel Fortran are also included as a zip.

It is recommended to extract all the files. After doing so, the Fortran redistributables needs to be installed by unzipping and running the executable. In the bin folder, the serial as well as the parallel version is available. It is recommended to start with the serial one (europlexus_binary_seq_intel.exe).

EUROPLEXUS can be started from the console (cmd). The input file should be either located in the same folder or the path to the file must be given to the file. An exemplary command might be

europlexus_binary_seq_intel.exe input_file.epx

The MPI version is compiled against MS-MPI. Microsoft provides the MPI exe (https://www.microsoft.com/us/download/details.aspx?id=57467) Download and install msmpisetup.exe and msmpisdk.msi. The running of the MPI installation can be tested by typing mpiexec on the cmd. EUROPLEXUS might then be started by

mpiexec -n nnp europlexus_binary_MSMPI_intel.exe input_file.epx

where nnp are the number of processes that should be used.

1.2.3 Installation under Linux

to be written

1.2.4 Manual

The getting started manual is part of the EPX manual containing all information of the code. It is divided in main sections (GROUPS). In general an EPX input file can be created by following all groups and taking the needed commands.

A large bibliography concerning EUROPLEXUS as well as its ancestors is provided at the end of the present manual (see GBIBB). Many of the cited documents are available to EPX developers in electronic form on the EPX Consortium web site (https://europlexus.jrc.ec.europa.eu/).

1.2.5 Benchmarks

to be written

1.3 Data flow

The first step in learning an FE tool is to understand its particular data flow. Figure 1 presents a general description of the procedure how to perform an EPX calculation.

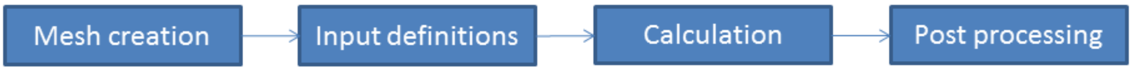


Figure 1: General data flow in EPX

The mesh creation concerns the creation of nodes and elements. The meshes were mainly stored in external files. The next step is to define materials, loadings and calculation parameters in an EPX input file. The calculation of the inputs is done normally via the command line tool. The result files can be then assessed by several post-processing tools. The detailed data flow is shown in 2.

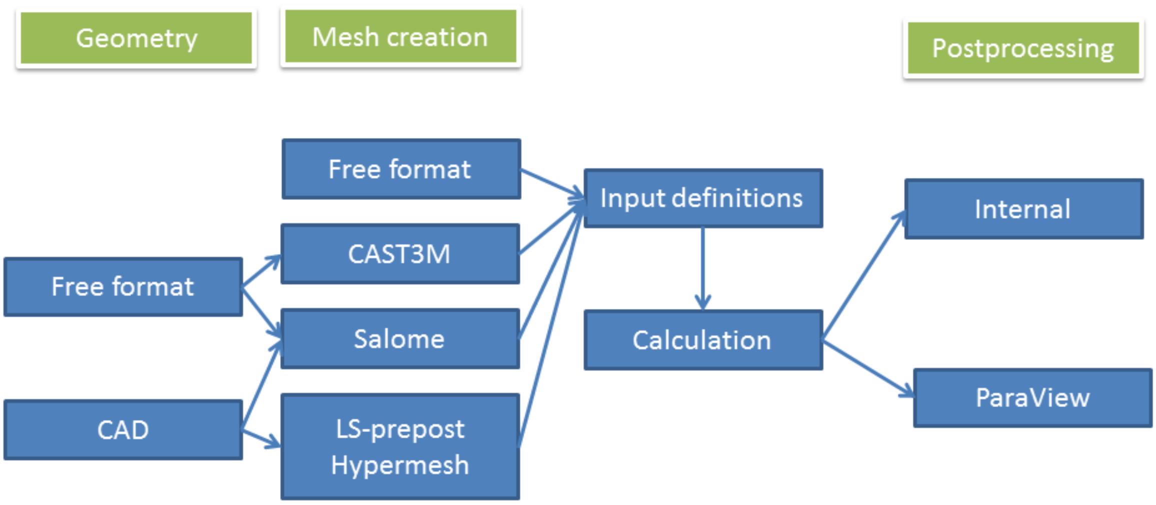


Figure 2: Detailed data flow in EPX

1.3.1 Files in EPX

extension	description	ref
epx	input file	GBINT_0018
k	Mesh file: k file format from ls_dyna	GBINT_0016
listing	Listing output	
log	Log file	GBH_0020

med	Mesh file: salome	GBINT_0016
msh	Mesh file: Cast3m	GBINT_0016
pvd	ParaView time step file	GBG_0070
std	Standard outputs (error messages)	
vtu	ParaView result file	GBG_0070

1.4 Mesh generation

One of the fundamental steps to perform a FE/FV calculation is to create the meshes. There are several possibilities in EUROPLEXUS to perform that task.

- **Free format**: nodes and elements are written in the EPX input file in a specific format. This is very effective for very small models but not feasible for bigger models. The advantage is that the mesh is included in the input file and not separated. It is therefore used for many benchmarks. There is no known FE mesher that can produce this mesh format. Further information about the format are given in GBB_0020.

- **k-file (LS-DYNA)**: This is a text file input where nodes, elements and sets of them are defined based on a given format. The advantage of that format is that it can be produced form different graphical mesh generators like LS-Prepost (freeware) or Hypermesh.

- **med (SALOME)**: Med files are files produced by the open source tool SALOME. With SALOME also full EPX inputs can be created.

- **CAST3M**: CAST3M is a FEM software from CEA that is freely available. It can produce msh files that can be used very efficiently in EUROPLEXUS. The meshes were created by defining points, lines, surfaces etc. in a script language. That is very powerful but also difficult to learn.

1.4.1 k-file (LS-DYNA)

The format of the input is described in the LS-DYNA manuals. It is very simple and can therefore also be written by scripts.

The following not exhaustive list of tools can create k-files:

- **LS-prepost**: Free graphical tool from LS-DYNA (http://www.lstc.com/lspp/). Some support to create FE meshes from CAD files.

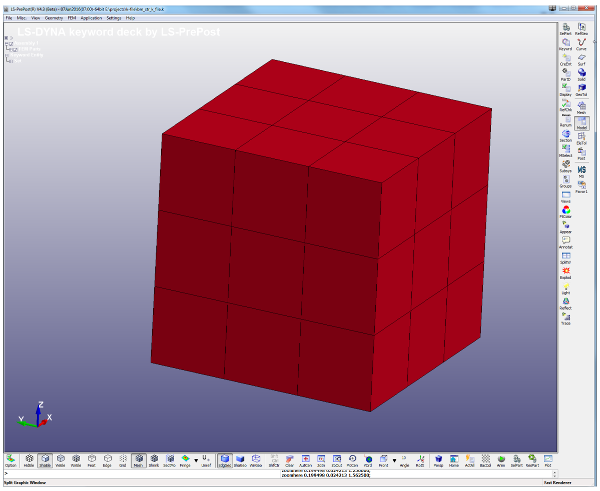


Figure 3: LS-Prepost mesh generation

- **HyperMesh**: Very big graphical tool from Altair (http://www.altairhyperworks.it/product/HyperMesh). Can efficiently be used for the conversion of CAD geometries to FE meshes.

- **ANSYS**

1.4.2 med (SALOME)

SALOME is an open-source software that provides a generic platform for Pre- and Post-Processing for numerical simulation. It is based on an open and flexible architecture made of reusable components. The software can be downloaded on the webpage: http://www.salome-platform.org/.

1.4.3 CAST3M

The CAST3M .msh-file format is the mesh file format with the widest support in EUROPLEXUS. Nevertheless, the mesh creation can only be done with the FE software tool CAST3M. This tool is quite powerful since the mesh generation can easily be parametrised and automatized. But it needs additional effort to be learned. For an introduction in the CAST3m methodology it is referred to the CST3M webpage (http://www-cast3m.cea.fr/)

1.5 EUROPLEXUS Inputs

1.5.1 First input sample

Let's start with an very easy EUROPLEXUS example. It is recommend to start with such a very easy calculation in order to test the installation.

```
1    impact0                                 !title of the problem
2    ECHO                                    !Output on the console
3    KFIL                                    !mesh file definition
4    TRID LAGR                               !3d structural calculation
5    GEOM Q4GS PART 1 TERM                   !element definition
6    COMP EPAI 2 LECT PART 1 TERM            !Thickness
8    MATE LINE RO 7800 YOUN 2.E11 NU 0.3     !Material definition: linear
9              LECT PART 1 TERM              !for part 1
10   LINK COUP                               !Links (coupled)
11        BLOQ 123 LECT NSET 1 NSET 2 TERM   !Boundaries
12   INIT VITE 3 -110 LECT PART 1 TERM       !Initial conditions
13   ECRI FICH PVTK TFRE 1.0E-3              !Output as ParaView
14                  VARI DEPL                !Output variable displacement
15   OPTI NOTE LOG 1                         !Log file written each step
16        CSTA 0.5                           !Stability step
17   CALC TINI 0.0 TFIN 100.E-3              !Start and end time of calculation
18   FIN
```

1. The first line contains the title of the calculation. It is important to give that title. Otherwise, the first input line will be taken as the title.

2. ECHO indicated that the output will be written on the command line and not only to the listing.

3. KFIL identifies that a k-file in LS-DYNA format will be read. The name of the file can be added after the command included in ' '. If the name is not given, the default will be chosen as the name of the epx input file with the extension .k.

4. TRID identifies a three-dimensional calculation and LAGR a purely structural one.

5. The elements that were read via the mesh file must be attached to element types. That is done with the command GEOM. A list of all element types is given in GBINT_0080. Some general elements are listed in xxx. The structure of the element type allocation is that first, the element type is given and second the elements are chosen. Here, the PART 1 from the k-file is taken. The keywords depend on the mesh file type used. Here a shell element of type Q4GS is chosen. The command must be closed with TERM as soon as all elements are defined.

6. Depending on the element type several additional definitions can be given with COMP. All available commands in this section are described in GBC_0010. Here, the thickness of 2 is set to all elements of PART 1 with the command EPAI. The classical structure of reading elements or nodes is to use LECT xxx TERM. This procedure is described more in detail in GBINT_0050.

7. This line contains the material definition. The complete list of all materials is collected on page GBC_0100. A linear material is defined.

8. Selection of the elements for the given material

9. The links (e.g. boundary conditions) are defined here with LINK (GBD_0010). A coupled approach (Lagrange Multiplier) is chosen (COUP).

10. Boundary conditions are given here with BLOQ (blockages). The number afterwards identifies that all three directions are blocked. The nodes concerned are again taken with LECT. Here two NSETs were chosen.

11. Initial conditions were given in that line as an initial velocity for PART 1. Initial conditions were described more in detail on page GBE_0040.

12. The outputs were defined with ECRI (see GBG_0010). FICH indicates that the outputs were written in a separate file and not in the listing. PVTK means the ParaView output files. As default these files were binary. ASCII files can be written by adding FORM. With TFRE, the frequency of the output steps is given (see GBINT_0057).

13. With VARI (in case of PVTK) the output fields can be defined (here displacement - DEPL).

14. Some options can be given with OPTI (GBH_0010). LOG 1 indicates that the log file is written per step. This should not be done in case of MPI calculations. NOTE DFEINS the output of the energy check.

15. CSTA the stability step. A value of 0.5 indicates that the calculated stability step will be multiplied by 0.5 for safety.

16. The calculation is started with CALC (GBI_0020). TINI (initial time) and TFIN (end time) must be given.

17. The input file must be closed with FIN.

1.5.2 Elements

Several elements are available for EUROPLEXUS. Its full list is given on GBINT_0080. It is very important to know the history behind the elements. These were created in the past either by JRC or CEA and its formulation in the back can be totally different. This means also that not all elements are available for all materials. A table with all possible material-element combinations is given in (GBC_0100) In this general introduction, the main elements for structural and fluid calculations were presented. Details about further elements (like SPH or diffuse elements) can be taken from the list.

The following structural elements are recommended. They vary depending their mechanical assumptions. Further details are given in the description of the elements.

1. Solid elements: CUBE/CUB8, PRIS, TETR. CUBE is a cubic element with reduced integration while

2. Beams: POUT for beams. The cross section information can be given with EPAI.

3. Triangular shells:T3GS, DST3, DKT3

4. Quadrilateral shells: Q4G4, Q4GS, Q4GR

5. Loading surface elements: CL3T, CL3D

6. Material points: PMAT, DEBR

Fluid calculations can be done by using finite elements or finite volumes. The accuracy of finite elements is not very high. Therefore, only finite volumes are recommended to use for fluid or fluid structure interaction calculations. The following finite volumes can be taken: CUVF, PRVF, TEVF, PYVF. Further information about fluid calculations by using finite volumes are given here:

1.5.3 Sandwich Elements

The code also allows to use layered elements for beams and in particular for shell elements. This means that the materials of the integration points through the thickness could be different. More information are given in GBINT_0110. As an example, the benchmark bm_str_lsgl01 could be used.

1.5.4 Materials

Several material laws are implemented in EUROPLEXUS. The full list of materials can be found on GBC_0100. Not all elements accept all material types. GBC_0100 shows also the possible material-element combinations.

The table below presents some materials that have a general use.

number	name	ref	law of behaviour
74	ABSE		
21	CLVF	7.9.34	Boundary conditions for finite volumes
109	DADC	7.7.20	Dynamic Anisotropic Damage Concrete
111	DPDC	7.7.21	dynamic plastic damage concrete
87	DPSF	7.7.51	Drucker Prager with softening and viscoplastic regularization
83	DRPR	7.7.61	Drucker Prager Ispra model
12	DRUC	7.7.6	Drucker-Prager
19	DYNA	7.7.9	dynamic Von Mises isotropic rate-dependent
17	FANT	7.7.39	phantom: ignore the associated elements
9	GAZP	7.8.4	perfect gas
118	GGAS	7.8.1	generic ideal gas material
116	GLIN	7.7.3	generic linear material
117	GPLA	7.7.4	generic plastic material
48	GVDW	7.8.28	Van Der Waals gas
40	GZPV	7.8.24	perfect gas for Van Leer
95	HYPE	7.7.64	hyperelastic material (Model of Mooney-Rivlin, Hart-Smith and Ogden)
4	ISOT	7.7.9	isotropic Von Mises
108	JCLM	7.7.75	Johnson-Cook with Damage Lemaitre-Chaboche for SPHC
50	JWL	7.8.21	explosion (Jones-Wilkins-Lee model)
66	JWLS	7.8.29	Explosion (Jones-Wilkins-Lee for solids)
72	LEM1	7.7.13	Von Mises isotropic coupled with damage (type Lemaitre)
1	LINE	7.7.1	linear elasticity
23	LIQU	7.8.14	incompressible (or quasi-) fluid
70	LMC2	7.7.15	Von Mises isotropic coupled with damage (Lemaitre) with strain-rate sensitivity
26	MASS	7.7.35	mass of a material point
85	MAZA	7.7.19	Mazars-linear elastic law with damage
2	PARF	7.7.9	perfectly plastic Von Mises
125	RIGI	7.7.77	Rigid material (for rigid bodies)

99	SLZA	7.7.66	Steinberg-Lund-Zerilli-Armstrong
35	VM23	7.7.47	Von Mises elasto-plastic radial return
2/4/5/19	VMIS	7.7.9	Von Mises materials
76	VMJC	7.7.57	Johnson-Cook
78	VMLP	7.7.58	Ludwig-Prandtl
79	VMLU	7.7.59	Ludwik
84	VMSF	7.7.50	Von Mises with softening and viscoplastic regularization
77	VMZA	7.7.60	Zerilli-Armstrong
120	VPJC	7.7.76	visco-plastic Johnson-Cook
67	ZALM	7.7.14	Zerilli-Armstrong with damage Lemaitre-Chaboche

1.5.5 Element erosion

Element erosion means that elements are deleted from the table of elements and were not treated any more. This is a particular procedure in explicit codes since the general energy balance is violated by eroding elements. There are several reasons why element erosion could be indicated:

1. The material has reached a failure mode (damage or other criteria)
2. The element became so distorted that it cannot be treated any more (CROI)
3. The time step size of the element is too small (CALC TFAI)
4. Parts of the model should be removed at a certain time (e.g. certain elements have to become "fantom", i.e. have to be eroded, at a chosen time GBH_0100), or due to further criteria (e.g. displacement-driven erosion, see GBC_0067 and GBC_0067b).
5. The user decides to erode some elements interactively at the current time reached by the calculation GBO_0010.

The objective in most of the cases is that the calculation is not stopped due to critical behaviour of material or elements.

In all cases, the keyword EROS (see GBA_0030) must be added in the beginning (before DIME and GEOM). This keyword is followed by CROI as soon as element erosion for distorted elements is needed. Erosion due to too small time steps sizes can be activated in the CALC PART by adding TFAI (see GBI_0020).

In case of failure erosion, the ratio between failed and total gauss point in an element can be given. This parameter must be written immediately after EROS. The global value for the material failure element erosion can be overwritten for parts of the elements by COMP EROS (see GBC_0069).

1.5.6 Fluid calculations

1.5.7 INTRODUCTION TO FLUID-STRUCTURE INTERACTION

EUROPLEXUS offers a rich variety of models for Fluid-Structure Interactions (FSI). The following is a short introduction to FSI and a tentative classification of the models available in the code, in order to guide the user in the choice of the most appropriate FSI models for the applications of interest. For a more detailed overview of the available FSI models see e.g. [303].

Fluid-structure interaction (FSI) phenomena play an important role in many areas, ranging from aeronautical and space applications, to civil and marine/offshore engineering and to the transport industry, to name just a few. The EUROPLEXUS development team has been involved for many years in the development of numerical methods for FSI modeling applied to safety studies—initially for the nuclear industry and more recently for conventional power plants (electrical machinery)—to civil engineering (vulnerability of buildings and other critical infrastructures to terrorist attacks) and to land mass transports (blast effects in railway stations, metro lines, rolling stock).

All these studies are characterized by the violent blast loading, resulting either from an accident or from an intentional attack, and by the very short time scale (fast transient dynamics). Strong pressure waves propagate in the fluid and load the surrounding structures, which typically undergo large deformations and in some cases reach complete failure and fragmentation.

For this class of problems, an explicit time marching algorithm is usually adopted, where the fluid is modelled as compressible and inviscid (Euler equations). An Arbitrary Lagrangian Eulerian (ALE) formulation is adopted for the fluid sub-domain, while the structure is Lagrangian.

Three different discretization approaches are available in the code for the fluid sub-domain: finite elements (FE), node-centred finite volumes (NCFV) and cell-centred finite volumes (CCFV):

- In the FE case, kinematic variables (such as the velocity v) are discretized at the element nodes, while state variables (such as the fluid pressure p) are discretized at Gauss points, typically located at the element centroid.
- In the NCFV case, a virtual FV (dual) mesh centred on fluid nodes is automatically built up starting from the FE-like (primal) mesh provided in input, and all variables are discretized at the nodes.
- In the CCFV case, the FV mesh looks similar to the FE case, but all variables are discretized at the volume centres. Note that in this case the 'nodes' carry no relevant information other than their position, used to compute the volume.

The coupling between the fluid (ALE) and the structure (Lagrangian) is realized by suitable FSI algorithms. Two broad classes of algorithms are available in the code. The first class uses a **strong** approach, based on constraints imposed on the (velocity of) fluid and structure nodes at the F-S interface. The second class uses a **weak** approach, based on direct application of fluid pressure forces to the structure. This terminology (strong/weak) is tentatively adopted here in an attempt to characterize the different nature of the two approaches, but it should not be confused with other uses of the same terms in the literature, in particular with weak (i.e. integral) forms in continuum mechanics. Traditionally, strong FSI algorithms are mainly used in FE, while weak FSI algorithms are mainly used in FV.

Yet another classification of FSI algorithms concerns the degree of deformation/damage that the structure can undergo (and thus the type of application). One class of **basic** algorithms is suitable for large motion and large deformation of structures, but only provided these do not fail. Another class of algorithms can go up to complete failure, and fragmentation, of the loaded structures. Finally, FSI algorithms can be classified in three types according to spatial discretization: (nodally) conforming, non-conforming, and embedded (or immersed). The first two types are mostly used in applications without structural failure (but there are exceptions), while embedded algorithms are the only ones capable of dealing with extreme loading cases where the structure fails and breaks up in pieces.

The following Table summarizes the architecture of a typical FSI model, consisting of a *detection* module and of an *enforcement* module. The various types of approaches (*basic / embedded* or *strong / weak*) are briefly summarized.

The following Table completes the classification of the available FSI models, by showing the type of spatial discretization (*conforming, non-conforming* or *embedded*), the name of the input directive (when applicable/needed), and the associated fluid discretization(s).

1.5.8 Restart

Table 3: A classification of FSI algorithms

FSI Algorithm	**FSI Detection**	**Basic**	No structural failure, moderate rotations.
		Embedded	Structure can fail, arbitrary rotations.
	FSI Enforcement	**Strong**	Constraints on F and S velocities are imposed, e.g. by Lagrange multipliers (implicit).
		Weak	Pressure forces are transmitted from the fluid to the structure; structure motion provides weak feedback on fluid (S = master / F = slave).

Table 4: The available FSI algorithms

	Detection Strategy	Spatial Discretization	Enforcement Strategy	Name / Command	Use with
FSI Algorithm	**Basic** (no structural failure)	**Conforming** F-S meshes	**Strong**	`FSA`	FE, NCFV
			Weak	Merge F-S nodes	CCFV
		Non-conforming F-S meshes	**Strong**	`FSA`	FE, NCFV
			Weak	Declare non-matching F-nodes	CCFV
	Embedded (structure can fail)	S-mesh is **immersed** in the F-mesh	**Strong**	`FLSR`	FE, NCFV
			Weak	`FLSW`	CCFV

1.5.9 Index of important commands

This is is an non exhaustive list of important commands that may be useful to understand the basic working of EUROPLEXUS. Additional lists are given for the materials GBC_0100 and elements GBINT_0080.

command	main group	description	ref
BLOQ	LINK	Boundary conditions	GBD_0030
CALC		Calculation definitions	GBI_0020
COMP		Geometric complements	GBC_0010
COUP	LINK	Treatment of the links as coupled (Langrange multipliers)	GBD_0010
CSTA	OPTI	Time step safety coefficient	GBH_0020
DECO	LINK	Treatment of the links as decoupled	GBD_0010
ECHO	—-	Output on the console	GBA_0020
ECRI		Output of the results	GBG_0010
EPAI	COMP	Thickness (e.g. of shell elements)	GBC_0040
GEOM		Mesh and grid motion	GBB_0010
KFIL	—-	mesh file definition (k-file)	GBA_0030
INIT		Initial conditions	GBE_0040
LAGR	—-	Structural calculation	GBA_0030
LINK		Links	GBD_0010

LOG	OPTI	Log file .log is created	GBH_0020
MATE		Material definition	GBC_0100
NOTE	OPTI	No energy check printed per each step	GBH_0020
OPTI		Definition of options	GBH_0010
PVTK	ECRI	Output as ParaView	GBG_0070
TFIN	CALC	End time of calculation	GBI_0020
TINI	CALC	Start time of calculation	GBI_0020
TRID	—-	3D calculation	GBA_0030

1. INT.70

1.6 Outputs/Post processing

1. Writing outputs in EPX in files
2. Internal postpro
3. Interactive work
4. ParaView

2 PREPARATION OF THE INPUT DATA

Rule 1:

All the data may be coded in FREE format (unless a fixed format is explicitly chosen by the user for specific data, e.g. the geometry). One or more blanks and/or an end of line act as a separator between data items.

Only columns 1 to 72 of each 'data card' are analysed. A data card is a record, i.e. a sequence of up to 72 characters terminated by a new line character.

Rule 2:

The data consist in a sequence of instructions or DIRECTIVES, (each one possibly including a number of OPTIONS and SUBOPTIONS) that can be specified using keywords.

Only the FIRST FOUR LETTERS ARE COMPULSORY for the coding of keywords, since these are unique in each situation. EUROPLEXUS ignores characters beyond the fourth one when decoding a keyword.

Rule 3:

Numeric values are coded with or without a decimal point:

Example:

```
12  24.  .3   1.3E-4   1E4  .5D+2   -.4E 00
```

Rule 4:

Comment 'cards' (records, in the sense defined above) can be freely interspersed with the data, except that the first record of a data file cannot be a comment (it is the problem title, see below).

A comment card begins with a dollar (`$`) or an asterisk (`*`) in column 1. Alternatively, it is possible to use an exclamation point (`!`) which may be placed at any position in the 'card' and not only in column 1.

Any characters that follow one of these special characters on an input card are ignored by EUROPLEXUS. By using an exclamation point, it is therefore possible to add comments on the same line as the data.

Note that the program does include in the input data echo comments written at the beginning of the output listing.

A semicolon is considered as the end of a card.

Example:

```
"TRID"  "ALE"      !  3D ALE computation
```

2.1 WRITING CONVENTIONS

Object:

To ensure that the necessary keywords, optional key-words as well as the numerical values to be entered show up clearly in the syntax of the instructions, the following conventions have been adopted.

Description of language conventions:

Keywords are enclosed in quotation marks: `"TRIDIM"`.

Anything not enclosed in quotation marks represents numerical values or something else to be described. Names representing character strings are enclosed in apostrophes:

```
< "SAUVE"  nb  ifreq  < "PROT"  'mykey'  > >
```

When a sequence is optional, it is enclosed in angle brackets: (`<...>`).

If there is a choice between several sequences among which ONE ONLY is compulsory, the sequences are enclosed between (`|[...]|`) symbols, each of them separated by semicolons (;). The list of sequences can be written on several lines, for example:

```
|[ "DEPL" ; "VITE" ; "ACCE" ]|

or

|[
   "DEPL" ;
   "VITE" ;
   "ACCE"
]|
```

If there is a choice between several sequences among which ONE AT MOST is compulsory, the sequences are enclosed between (`$[...]$`) symbols, each of them separated by semicolons (;). Again, the list of sequences can be written on several lines, for example:

```
$[  "ECHO" ; "NOEC" ]$

or

$[
   "ECHO" ;
   "NOEC"
]$
```

If a sequence can be repeated as many times as wanted, it is enclosed in parentheses: `(...)`.

If a sequence must be repeated, for example nf times, it is framed by: `nf*(...)`. The reading of nf must precede immediately the first sequence:

```
( "VMIS" "ISOT"  "RO" rho  "YOUNG" e  "NU" nu  ...
        ... "TRAC" nf*( sig eps ) /LECTURE/ )
```

In this case, the input data should contain an integer (`nf`), immediately followed by nf couples of values. For example, if nf=3, the sequence `nf*( sig eps)` could be written as:

```
3     0. 0.     1.E8 1.E-3     1.E9 1.E-1
```

In order to simplify the writing, a symbolic name is sometimes assigned to frequently used sequences, that are described only once and then referred to simply by their name enclosed in `/`, as in:

```
"MASSE" ( /LECDDL/   xm /LECTURE/  )
```

These named sequences are sometimes called procedures. It should be stressed that these names should not appear as such in an input data, but have to be replaced by the appropriate sequence of keywords and values. Named sequences should not be confused with keywords or directives. Their names therefore do not obey to the 4-character rule like keywords.

2.2 USE OF LITERAL VARIABLES

Object :

It is possible to replace any data (a number, a keyword or a text) by a literal variable.

The name of this variable must start by % (per cent), followed by at most 16 alphanumeric characters.

Before being used for the first time, a literal variable must be assigned a value.

In order to assign a value to a literal varaible, type its name followed by the equals sign (=) and then by the value, like in the Fortran programming language.

Example :

```
   . . .
  %diameter_1 = 0.0548      %diameter_2 = 0.2027
  %tube_1 = lig_ent         %tube_2 = lig_tot
   . . .
COMPLEMENT
    DIAMETRE DROIT %diameter_1  LECT %tube_1 TERM
    DIAMETRE DROIT %diameter_2  LECT %tube_2 TERM
   . . .
```

Comments :

It is possible to re-define a literal variable (i.e., change its 'contents'), at any place in the input data set.

The assignment sign '=' must lie on the same input line as the variable name in the input data set.

A literal variable represents JUST ONE data: in the previous example, `%tube_1` and `%tube_2` represent each one a single word, that is an object name.

Experimental feature: it is possible to define a real number variable through the evaluation of a mathematical expression. The variable must be written as a text, and the expression must begin and end with a double $ (the number of spaces is not important). The text defining the variable must not exceed 72 characters. The order of operations is: parentheses, power (ˆ), multiplication (*) and division (/), addition (+) and subtraction (-). If one wants to write a negative number located after an operator, it must be surrounded by the symbols [and]. Below, we give an example of the evaluation of the two ordinates of a point of abscissa 2, located on a circle of radius 2 and center (1, 1). One can use Fortran mathematical instrinsic functions as 'COS(...)', 'SIN(...)', 'EXP(...)', etc.

```
   . . .
  %c_x = 1.          %c_y = 1.
  %radius = 2        %one_half = 0.5
```

```
%y_1 = '$$ %c_y+(%radius^2-(2-%c_x)^2)^%one_half $$'
%y_2 = '$$ %c_y-(%radius^2-(2-%c_x)^2)^%one_half $$'
 . . .
```

2.3 PROCEDURE /LECTURE/

Object:

Procedure used to define a set of integers. Most of the time it is used to specify a list of nodes or of elements.

Syntax:

Explicit definition (direct list of values):

```
|   "LECT"  n1  n2  . . .  nk  "TERM"               |
```

Implicit definition (by using an increment `npas`):

```
|   "LECT"  ndeb  "PAS"  npas  nfin  "TERM"         |
```

Definition using the objects created by the mesh generator "GIBI":

```
|   "LECT"    (  'nomobjet'  )   "TERM"             |
```

Definition using the "permanent groups" created by the mesh generator "I-DEAS":

```
|   "LECT"    (  'nomgroup'  )   "TERM"             |
```

Definition using the selections created by the LS-DYNA k-file format":

```
|   "LECT"    (  'kfileselections'  )   "TERM"             |
```

All the elements or all the nodes are concerned (special keyword `TOUS`):

```
|   "LECT" "TOUS" "TERM"                            |
```

None of the elements or none of the nodes are concerned (special keyword `NONE`). This can be useful to avoid an error message in directives where the specification of elements or nodes is optional:

```
|   "LECT" "NONE" "TERM"                            |
```

Difference, intersection or symmetric difference between two sets (each set being defined by one of the above syntaxes):

```
|   "LECT" <first_set> "DIFF" <second_set> "TERM"  |
|   "LECT" <first_set> "INTR" <second_set> "TERM"  |
|   "LECT" <first_set> "SDIF" <second_set> "TERM"  |
```

'kfileselections':

The selection of entities from the LS-DYNA k-file can be done with the following commands

```
$[PART partnr; NSET nsetnr; SSHE sshell; SSOL ssolid; SBEA sbeam;
  NODE nodenr; ELEM elemnr]$
```

`partnr`

Elements from PART partnr (also the part name can be used with a maximum length of 32 characters).

`nsetnr`

Nodes from NSET number nsetnr.

`ssolid`

Solid elements from SET_SOLID number ssolid.

`sshell`

Shell elements from SET_SHELL number sshell.

`sbeam`

Beam elements from SET_BEAM number sbeam.

`elemnr`

Elements with the numbers elemnr. These are the numbers in the k-file and not the internal epx-numbers.

`nodenr`

Nodes with the numbers nodenr. These are the numbers in the k-file and not the internal epx-numbers.

Comments:

The explicit and implicit syntaxes can be linked together. For example, to obtain the integers 3, 5, 2, 4, 6, 8, 10, 14, 15, 18, 21, 24, write:

```
LECT 3 5 2 PAS 2 10 14 15 PAS 3 24 TERM
```

For the implicit syntax, the step `npas` can be negative.

In the case of GIBI objects, the procedure extracts, if necessary, the indexes of the nodes or of the elements that constitute the objects/groups defined by the user. The directive where the procedure `/LECTURE/` appears determines if the indexes indicate nodes or elements.

If the `DIFF`, `INTR` or `SDIF` keywords are used, they must be at the end of the directive, as shown in the examples below. In other words, first the basic set must be defined, followed by one of these three keywords and then by the definition of the second set.

From now on this procedure will be called `/LECTURE/` or `/LECT/`.

Remarks:

EUROPLEXUS systematically checks the coherence of the indexes taking into account the expected type (nodes or elements).

Once they have been read, the indexes are classified in ascending order (if this does not harm the concerned directive).

If GIBI object names are mixed up with EUROPLEXUS numbers, separate the sequences by the keyword `SUIT`.

I-DEAS permanent group names can be freely mixed up with EUROPLEXUS indexes.

The keywords `DIFF`, `INTR` and `SDIF` may only be used in `/LECT/`ures that return lists of elements or nodes *ordered* in growing sequence and *without repeated items.* These are the vast majority in the code.

In any case, the finale result of the `/LECT/ure` may not be the empty set. An error is issued in this case.

To indicate **all** the elements or all the nodes in the model, the advised syntax is, as indicated above: `LECT TOUS TERM`. Other (obsolete) forms of the same directive are also accepted sometimes, for example the short syntax `TOUS` (i.e. without the keyword `LECT`). These alternative syntaxes are still accepted for compatibility with old input files, but might become unsupported in the short future. Note that the full syntax (`LECT TOUS TERM`) is the only supported syntax for use in conjunction with operations introduced by the keywords `DIFF`, `INTR` or `SDIF`.

Examples:

```
LECT 3 5 2 4 6 8 10 14 15 18 21 24 TERM
LECT 3 5 2 PAS 2 10 14 15 PAS 3 24 TERM
LECT 3 5 10 PAS -2 2 14 15 PAS 3 24 TERM
LECT objet1 objet2 SUIT 25 27 TERM
LECT objet1 SUIT 25 27 SUIT objet2 TERM
LECT toto tata DIFF titi tutu TERM
LECT TOUS DIFF titi tutu TERM
LECT 1 PAS 3 25 INTR titi tutu TERM
LECT toto tata SDIF 1 5 PAS 2 28 TERM
```

Warning concerning the DIFF operator:

Pay attention in the use of the `DIFF` operator in `/LECT/`ures where a set of **nodes** is required. For example, the expression:

```
LECT coco DIFF caca TERM
```

used in a context where a set of nodes is expected, and when `coco` is an object composed of elements, is evaluated as follows:

- First, the nodes of all the elements belonging to the `coco` object are evaluated.
- Next, the nodes belonging to the object `caca` are evaluated. If `caca` contains only nodes, these are directly available. If `caca` contains only elements, then all the nodes belonging to such elements are evaluated.
- Finally, the nodes of the second set belonging also to the first set are removed from the first set.

Note that this might not be the result you want or expect. In particular, in the case that both `coco` and `caca` contain elements, the resulting set of nodes is different from (smaller than) the set of nodes belonging to the difference between the two element sets. If the latter is what you want, proceed as follows: first, define a named group of elements (say `edif`) containing the difference of the elements, by using the `COMP GROU` directive; then, use directly the name `edif` in the `/LECT/` expecting the nodes:

```
 COMP GROU 1 'edif' LECT coco DIFF caca TERM ! element group
 . . .
!LINK COUP BLOQ 1 LECT coco DIFF caca TERM   ! wrong !!!
 LINK COUP BLOQ 1 LECT edif TERM             ! ok : nodes of the
                                             ! element group
```

The following example may also help clarify the matter. Assume the following simple mesh:

```
4-------5-------6
|       |       |
|   1   |   2   |
|       |       |
1-------2-------3
```

and assume that the Cast3m object `mesh` contains elements 1 and 2, while the object `right` contains element 2.

Then, in a `/LECT/` directive looking for nodes (e.g. the following blockage directive), the expression:

```
LINK COUP ... BLOQ 1 LECT mesh DIFF right TERM
```

will return nodes 1 and 4 (but *not* nodes 2 and 5). This is because: first the nodes of `mesh` are extracted (nodes 1 to 6); then the nodes of `right` are extracted (nodes 2, 3, 5 and 6); and finally these are subtracted from the first set, thus leaving only nodes 1 and 4.

If one wants instead to select all the nodes of the difference between the element sets (i.e. nodes 1, 2, 4 and 5), one can proceed as follows:

```
COMP GROU 1 'edif' LECT mesh DIFF right TERM
  . . .
LINK COUP ... BLOQ 1 LECT edif TERM
```

The first directive builds up the element group containing the difference between the two element sets (difference between *elements*), which results into element 1. The second directive then extracts all the nodes of such element set, i.e. nodes 1, 2, 4 and 5.

2.4 PROCEDURE /PROGRESSION/

Object:

Procedure used to prescribe a group of real numbers. For example, it can be used to specify the values of the physical times at which the solution has to be printed or stored.

Syntax:

Explicit definition :

```
|   "PROG"  r1  r2  . . .  rk  "TERM"             |
```

Implicit definition :

```
|   "PROG"  rdeb  "PAS"  rpas  rfin  "TERM"       |
```

Comments:

The explicit and implicit syntaxes can be linked together. For example, to obtain the values 3., 5., 2., 4., 6., 8., 10., 14., 15., 18., 21., 24. write:

```
"PROG"  3. 5. 2. "PAS" 2. 10. 14. 15. "PAS" 3. 24. "TERM"
```

For the implicit syntax, the step rpas can be negative.

From now on this procedure will be called `/PROG/`.

Remark:

Once they have been read, the values are classified in ascending order (if this does not harm the instruction concerned).

2.5 PROCEDURE /CTIME/

Object:

Procedure used to choose time values in the form of equidistant values (in time steps or in time values) or user-defined values. Typically, this can be used to specify the times at which output operations such as printouts, storage of data for restart or post-processing, etc., should take place during a computation.

Syntax:

```
< "FREQ" ifreq  > < "TFRE" tfreq  >
< "NUPA" /LECT/ > < "TIME" /PROG/ >
```

`FREQ`

A fixed frequency in time steps is chosen.

`ifreq`

Value of the frequency in time steps, starting from step 0.

`TFRE`

A fixed frequency in time is chosen.

`tfreq`

Value of the frequency in time units, starting from the initial time.

`NUPA`

A series of time steps is specified by the user.

`/LECT/`

Definition of the series of time step numbers.

`TIME`

A series of time values is specified by the user.

`/PROG/`

Definition of the series of time values.

Comments:

The above optional forms of specifying time values can be freely combined. For example:

```
FREQ 10 NUPA LECT 10 15 35 TERM TFRE 1.E-3
TIME PROG 0.5E-3 PAS 1.E-3 3.5E-3 TERM
```

is a valid specification and prescribes that the concerned event (e.g., a printout) will take place each 10 steps, and at steps 15 and 35, and each 1.E-3 time units, and at time values of `0.5E-3, 1.5E-3, 2.5E-3 and 3.5E-3`.

If repeated values occur (such as in the above example for step number 10), they are automatically dealt with, i.e. only one event takes place for repeated values.

Note that if a time frequency is specified (keyword `TFRE`), the resulting time values take into account the **initial time** of the calculation declared in directive `CALC` by the `TINI` keyword. For example, if `TFRE 2.E-3` and `TINI 0.0`, then the corresponding event will take place at times 2.E-3, 4.E-3, 6.E-3 etc. But if `TFRE 2.E-3` and `TINI 1.0E-3`, then the corresponding event will take place at times 3.E-3, 5.E-3, 7.E-3 etc.

In a few instances, the keyword `"TEMPS"` can be used as an alias for `"NUPA"`. This keyword has been maintained for backwards compatibility, but should no longer be used in newly-written input data.

Warning

Be aware that values given in time units with the above `"TFRE"` and `"TIME"` keywords are rounded to the closest number of 'time normalization units', as described below in the directive `"OPTION"`, see page H.20. The default value of time normalization unit is 1 picosecond (1.D-12 s). If necessary, this can be changed by the `OPTI TION` option described on page H.20.

2.6 PROCEDURE /LCHP/

Object:

Procedure used to read a field of values ('champoint') generated by CASTEM2000.

Syntax:

```
"LCHP" nomobjet "TERM"
```

Reads a CASTEM2000 object called `nomobjet`, of the type 'champoint', previously stored in CASTEM2000 with the directive `"SAUV"`. The object is read and stored for successive use by other directives (see e.g. `"EPAI"`).

2.7 PROCEDURE /LECDDL/

Object:

It often occurs in a set of EUROPLEXUS input data that one has to define, for some nodes, the degrees of freedom according to which it is necessary to add a mass, prescribe the direction of a velocity, set a displacement to zero, and so on.

These degrees of freedom are identified by the numbers from 1 to 7 as described hereafter. See also the description of the available elements.

Meaning of the numbers:

AXISYMMETRIC CASE (see AXIS):

Solid elements:

- 1 : d.o.f. along R;
- 2 : d.o.f. along Z.

Shell elements:

- 1 : d.o.f. along R;
- 2 : d.o.f. along Z;
- 3 : rotation d.o.f.

TWO DIMENSIONAL CASES (see CPLA and DPLA):

Same as for the axisymmetric case (but with X and Y instead of R and Z).

THREE DIMENSIONAL CASE (see TRID):

Solid elements:

- 1 : d.o.f. along X;
- 2 : d.o.f. along Y;
- 3 : d.o.f. along Z.

Shell, beam and pipe elements:

- 1 : d.o.f. along X;
- 2 : d.o.f. along Y;
- 3 : d.o.f. along Z;
- 4 : d.o.f. of rotation around X;

- 5 : d.o.f. of rotation around Y;
- 6 : d.o.f. of rotation around Z;
- 7 : fluid d.o.f. in coupled 1-D (for pipes only).

Conventions:

The degrees of freedom are specified by the corresponding numbers, one immediately after the other, i.e. without blanks.

Examples:

```
346   ===>  d.o.f.  3, 4, and 6;
1426  ===>  d.o.f.  1, 4, 2, and 6.
```

The number of degrees of freedom described must correspond to the problem type (plane, axisymmetric, tridimensional) and to the element type.

In the following this procedure is called /LECDDL/.

2.8 MPI PARALLEL CALCULATIONS

Parallel calculations on distributed memory clusters yield the following requirements:

- Calculations must be launched through a working MPI library installed on the system (for questions about hardware or compatibility between EUROPLEXUS executable and MPI library, please contact CEA).
- Since data distribution is achieved through domain decomposition, subdomains must be used (see `STRUCTURE` and `INTERFACE` directives on page I.15). If these directives are ignored, subdomains and interfaces are automatically created using default parameters corresponding to the following input:

```
STRUCTURE AUTO ROB
INTERFACE LINK NOMU
```

One subdomain is attached to each thread of the parallel simulation. Data between subdomains are exchanged through MPI messages.

For details about parallel algorithms implemented in EUROPLEXUS, please consult:

- Parallel development plan for EUROPLEXUS [857]
- Progress report [865]
- Description and evaluation of the first available parallel version [871]

2.9 READING DATA FROM EXTERNAL FILES

For convenience, it is sometimes useful to read some (bulky) input data for EPX not from the normal input file (.EPX) but from an external file.

For example, consider the case where a complex set of initial conditions or of external loads must be specified, with thousands of input lines. Sometimes, such complex files can be produced by some external software, which has no relation to (and is not interfaced with) EPX.

In order not to clutter the (main) input file .EPX, the use may proceed as follows:

- In the .EPX file, in place of the (entire) main directive concerned (`INIT` or `CHAR` in this example), use the `INCLUDE` command, followed by the name of the file in quotes, i.e. for example: `INCLUDE 'init.txt'` or `INCLUDE 'char.txt'`.
- Make available the chosen `.txt` file, which should contain the text of the complete directive, followed by a line containing the keyword `RETURN`.

When EPX encounters the `INCLUDE` directive, it continues reading the input from the specified external file. When it encounters the `RETURN` keyword in the external file, it goes back to reading from the main input file, at the line immediately following the `INCLUDE` statement.

Comments:

At the moment, this mechanism can be used for all main directives of EPX, except the `GEOM` directive in a direct calculation and the `SORT` directive during post-processing of results with EPX (but work is ongoing for these directives).

The inclusion mechanism is not recursive, i.e. an included file cannot call another included file.

3 SPATIAL DISCRETIZATION (ELEMENT TYPES)

This Section gives a short description of all the "element" types available in EUROPLEXUS for the spatial discretization of the problem to be solved.

The code contains various formulations, including:

- Finite Elements, which may be used for both structural and fluid parts of the model;
- Finite Volumes, which are suited for the fluid parts;
- Spectral Elements, which can be used for the discretization of continuum-like solid parts which behave linearly (e.g. small-strain wave propagation);
- SPH particles, often used for high-speed impact problems;
- Diffuse Elements.

3.1 ELEMENT TYPES

Object:

We describe now the different elements available for a one-dimensional, two-dimensional (plane or axisymmetric), or three-dimensional problem, by specifying, for each problem type:

- the number associated to the element type (num.),
- the element name for EUROPLEXUS (Name),
- the element name for the CASTEM meshing (Gibi),
- the developer (JRC or CEA),
- the number of nodes (npt),
- the number of degrees of freedom per node (dof),
- the number of integration points where the stresses will be computed (ngp).

Specific information relative to each particular element type follows these tables.

Remark:

Stresses are computed at the integration points.

In the output (on the listing or on the result file) all the stresses for a given element and for each of its integration points will be printed. See chapter GBC_0010 as well.

3.1.1 1-D ELEMENTS

The various elements available in 1D are presented below.

num.	Name	Gibi	Dev	npt	dof	ngp	Remarks
22	TUBE	SEG2	CEA	2	1	1	fluid only (rigid tube)
23	TUYA	SEG2	CEA	2	7	2	tube coupled with FSI
24	CL1D	POI1	CEA	1	1	1	fluid boundary condition
25	BIFU	SUPE	CEA	1:9	7	1	bifurcation junction
26	CAVI	SUPE	CEA	1:9	1	1	cavity junction
31	CLTU	POI1	CEA	1	7	1	boundary condition with FSI
44	ED1D	SEG2	JRC	2	1	1	1D/2D-3D structural coupling
146	BREC	SEG2	CEA	2	7	1	pipeline rupture
147	TUVF	SEG2	CEA	2	1	1	rigid tube (1D vfcc)
148	TYVF	SEG2	CEA	2	7	1	tuvf coupled with FSI (1D vfcc)
149	BIVF	SEG2	CEA	2	1	1	bifurcation junction (1D vfcc) or pipeline rupture
150	CAVF	SEG2	CEA	1:9	1	1	cavity junction (1D vfcc)

For these elements (apart ED1D), the `"EULER"` option is mandatory (see page GBA_0030). Furthermore, the mesh nodes must have three coordinates. Thus, the directives for the type of problem treated by these elements will always be of the form:

```
"TRIDIM"  "EULER"
```

Note that, for the ED1D elements the `ED1D` is used to perform coupled 1-D/multi-d calculations, therefore the problem must be declared either `"AXIS"` or `"CPLA"` or `"DPLA"` or `"TRID"` and the `"EULE"` is not needed.

These elements are specified hereafter:

TUBE

This element allows to model the fluid contained within a fixed pipeline. It is assumed that fluid properties are the same in all points of a give cross-section of the pipe (one-dimensional calculation).

CL1D

This element allows to introduce the different boundary conditions or localised singularities, in a pipeline meshed by elements of type "TUBE".

CAVI

To assemble the different branches of a pipeline. The junction is done by a finite volume with an attached constitutive law, unlike in the case of a simple bifurcation.

BIFU

This element allows to simply specify the relationships between the inputs and outputs of different branches which are joined together. The conservation of mass flow rate and pressure is ensured.

TUYA

This element allows to treat the motions of pipelines in the presence of an internal flow. It results from the superposition of elements “TUBE” and “POUTRE”.

CLTU

Similarly to “CL1D”, this element further allows to introduce coupled boundary conditions of the fluid-structure type (e.g. a closed pipe end).

BREC

This element allows to model a pipeline rupture. Before the optional rupture instant, this element behaves like a bifurcation.

TUVF

This 1D finite volume element allows to model the fluid contained within a fixed pipeline. It is assumed that fluid properties are the same in all points of a give cross-section of the pipe (one-dimensional calculation).

TYVF

This 1D finite volume element allows to treat the motions of pipelines in the presence of an internal flow. It results from the superposition of elements “TUVF” and “POUTRE”.

BIVF

This 1D finite volume element allows to simply specify the relationships between the inputs and outputs of 2 branches which are joined together. The conservation of mass flow rate is ensured. This element allows to model a pipeline rupture too.

Warning:

The BIVF element can be used only with 2 branches of fixed pipeline at the moment (tuvf element).

CAVF

To assemble the different branches of a pipeline composed of 1D finite volume element. The junction is done by a finite volume with an attached constitutive law, unlike in the case of a simple bifurcation.

Warning:

The 1D finite volume element are under development and testing at CEA and EDF and should therefore be used with great care.

ED1D

A 2-node element used as an interface between a 1D structure and a multi-D structure.

This element can be used to couple a 2D or 3D model to a 1D model to be calculated by the EURDYN-1D code, developed at JRC Ispra (this “code” is now embedded within EUROPLEXUS, so that its usage is transparent to the EUROPLEXUS user). Of the two nodes, one is used to define the location of the interface (i.e. the point at which forces are transmitted between the two structures), while the other is only used to indicate the direction in space along which coupling is enforced.

This direction remains unchanged during deformation. The distance between the two nodes is therefore irrelevant. The 1D structure has to be separately modelled by EURDYN-1D, which is seen by EUROPLEXUS as a standard element module. A special set of input data for EURDYN-1D (ED1D “input deck”) has to be prepared. This must be included within the normal EUROPLEXUS input file, immediately after the CALCUL directive and before any additional EUROPLEXUS directives (see page I.23 and the EURDYN-1D manual listed in the References: ([33])).

The ED1D input deck must be immediately preceded by a line containing ”ED1D START” (capitals, starting in column 1, followed only by blanks if any) and be immediately followed by a line containing ”ED1D END” (capitals, starting in column 1, followed only by blanks if any).

The following (fixed) logical unit numbers are used by the EURDYN-1D module:

- 01 (formatted) used to copy the ED1D input deck, thus “extracting” it from the normal EUROPLEXUS input file. At run end it contains the list of 1D space plots storages;
- 04 (unformatted) used to store data for TPLOT (time plots);
- 33 (unformatted) used to store data for TPLOT (space plots);
- 34 (unformatted) used to store data for restart.

Note that units 33 and 34 are used by default to store data for TPLOT (space plots) and for a restart, respectively. They are both unformatted. These values, however, can be changed from the input.

Since EURDYN-1D is a specialised module, its usage can lead to important savings in the overall computation cost in large, complex multi-D problems when one or more portions of the structure can be conveniently represented by a 1D model.

In setting up a coupled 1-D/multi-D model, the following guidelines should be followed:

1. The multi-D part of the model is meshed as usual and an `ED1D` interface element is placed at each point of connection between the multi-D domain and the 1-D domain. An arbitrary number of such interface elements can be used in a calculation, according to user needs.

2. Each `ED1D` element must be so oriented that its first node coincides with the interface (attachment) point, while the second node only defines the orientation of the 1-D structure (i.e., of the interaction force) in multi-D space. The length of such elements is therefore irrelevant.

3. All 1-D parts of the model are represented in a single 1-D model, for which a separate input data set has to be provided.

4. When more than one 1-D part is present, each one of these will form a separate 'level' in the 1-D model (see the EURDYN-1D manual for the definition of level).

5. In setting up the 1-D model, the abscissa of each level should be oriented from the interface point toward the outside of the multi-D body. Thus, the interface node is always the first one (or the 'left' node, according to EDURDYN-1D conventions) of each level.

6. Each ED1D element should be assigned a different VM1D material (see page C.220) and the `"PT1D"` directive of this material should be used to assign the associated node index in the 1-D model.

Furthermore, note that a few directives, most notably saving for restart, are not available in coupled 1-D/multi-D computations.

Some care should also be taken in specifying the final times for the calculation and times for printouts and data storages. The following procedure is suggested in order to minimize potential problems:

- Assume that the initial and final physical times of interest for the calculations be `TI` and `TF`, respectively.
- Then, in the 1-D input file choose a final time (see EURDYN-1D input manual) `FINTIM` larger than `TF`, say:

```
FINTIM = TF + (TF - TI) * K
```

with : $0.01 < K < 0.1$

- Choose a final printout time:

```
TPRINT(NPRINT) = TF
```

If the final 1-D results should appear on the listing, and choose a final space plots storage time:

```
TSTOR(NSSTOR) = TF
```

If space plots in the final 1-D configuration are desired.

- In the multi-D input file (EUROPLEXUS), choose in the CALCUL directive a final time `TEND` larger than `TF`, but smaller than the 1-D value (`FINTIM`) specified above:

```
TF < TEND < FINTIM
```

- Choose printout and storage times as appropriate, by including the value `TF` if desired.

In this way, the coupled calculation will be stopped at the end by the multi-D part of the code at time `TEND`, and the printouts and storages at `TF` should be correctly produced for both the 1-D and the multi-D models.

The only drawback of this method is that the 'space plots summary' table in the 1-D listing is not produced at the end of the run because the 1-D calculation is stopped before its declared final time is actually reached. However, this is not a real problem, since the 1-D space plots file is nevertheless correctly generated.

3.1.2 2-D ELEMENTS

The various elements available in 2D are presented below.

num.	Name	Gibi	Dev	npt	dof	ngp	Remarks
1	COQU	SEG2	CEA	2	3	2	thin shell
2	TRIA	TRI3	CEA	3	2	1	triangle
3	BARR	SEG2	CEA	2	2	1	bar (membrane only)
4	PONC	POI1	CEA	1	2	1	circular bar(axisym.)
5	MEMB	SEG2	CEA	2	2	1	'virole' in membrane (axisym.)
7	CL2D	SEG2	CEA	2	2	1	boundary conditions
8	CAR1	QUA4	CEA	4	2	1	quadrangle with 1 Gauss pt.
9	CAR4	QUA4	CEA	4	2	4	quadrangle with 4 Gauss pt.
10	COQC	SEG2	CEA	2	3	1	thin shell with shear
15	FS2D	RAC2	CEA	4	2	1	F.S. coupling
28	PMAT2D	POI1	CEA	1	2	1	material point
38	Q92	QUA8	JRC	9	2	4	9-node quadrilateral
39	Q93	QUA8	JRC	9	2	9	9-node quadrilateral
42	CL23	SEG3	JRC	3	2	2	3-node b.c.s
43	ED01	SEG2	JRC	2	3	10	beam/conical-shell
45	TVL1	TRI3	CEA	3	2	1	Van Leer triangle
46	CVL1	QUA4	CEA	4	2	1	Van Leer quadrangle
49	Q92A	QUA8	JRC	9	2	4	Q92 on symmetry axis
52	FLU1	QUA4	JRC	4	2	1	fluid quadrilateral
54	PFEM2D	POI1	JRC	1	2	1	particle finite element
56	ED41	SEG2	JRC	4	3	10	old version of ED01
58	ADQ4	QUA4	JRC	4	2	1	advection-diffusion quadrilateral
64	FL23	TRI3	JRC	3	2	1	fluid triangle
65	FL24	QUA4	JRC	4	2	1	fluid quadrilateral
70	CL22	SEG2	JRC	2	2	2	2-node b.c.s
71	Q41	QUA4	JRC	4	2	1	ALE structural quadrilateral
72	Q42	QUA4	JRC	4	2	4	ALE structural quadrilateral
73	Q41N	QUA4	JRC	4	2	1	ALE structural quadrilateral
74	Q42N	QUA4	JRC	4	2	4	ALE structural quadrilateral
75	Q41L	QUA4	JRC	4	2	1	Lagr. structural quadrilateral
76	Q42L	QUA4	JRC	4	2	4	Lagr. structural quadrilateral
77	Q95	QUA8	JRC	9	2	4	test version of Q92
97	MC23	TRI3	JRC	3	2	1	finite volume fluid triangle
98	MC24	QUA4	JRC	4	2	1	finite volume fluid quadrilateral
100	Q42G	QUA4	JRC	4	2	4	ALE structural quadrilateral
105	MS24	QUA4	JRC	4	2	1	spectral "macro" quadrilateral
106	S24	QUA4	JRC	4	2	1	spectral "micro" quadrilateral
109	FUN2	SEG2	JRC	2	2	1	cable element
114	BSHT2D	SEG2	CEA	2	2	-	bushing with translational dof
118	MAP2	—-	CEA	3	2	-	Point on solid edge
121	MAP5	—-	CEA	3	2	-	Point on 2D shell
124	INT4	—-	CEA	4	2	2	quadrilateral interface element
131	T3VF	TRI3	CEA	3	2	1	triangle finite volume
132	Q4VF	QUA4	CEA	4	2	1	quadrangle finite volume
140	DEBR2D	POI1	JRC	1	2	-	debris particle
41	TUBM2D	SUPE	CEA	1*	2*	1	connection 2D-1D
163	TBM22D	SUPE	JRC	1*	2*	1	connection 2D-2D

The specifications for these elements are given hereafter:

COQU

Reference element for all calculations with 2D thin shells.

TRIA

This element can equally well represent solids or fluids. However, if the mesh is not very regular, it may give rise to fluctuations in the distribution of masses, especially near the axis of revolution.

The element has 4 components of stress (SIG) and strain (EPST) (when used for solids), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

BARR

This element is intended for the modeling of steel reinforcement in concrete structures, or of bars that work only in traction-compression.

PONC

This element should only be used to model circular steel reinforcement in axisymmetric concrete structures.

MEMB

This element is similar to COQU, but has a purely membrane behaviour.

CL2D

This element allows to specify a condition of absorbing medium or an impedance.

CAR1

This element is especially used to represent fluids. However, due to its under-integration, it is strongly advised to add some anti-hourglass numerical damping, unless the boundary conditions themselves prevent the appearance of hourglass motions.

The element has 4 components of stress (SIG) and strain (EPST) (when used for solids), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.

- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

CAR4

This element is recommended for elastoplastic solids.
The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

COQC

Simpler than `"COQUE"`, it also enables to evaluate the shear, if this is not too large.

FS2D

Incompressible fluid elements which ensure the transmission of forces.

The first face (1-2) is in the fluid, the other (3-4) in the solid. To ensure a proper fluid-structure connection, it is useful that the sides 2-3 and 1-4 be as short as possible, possibly of zero length. In this last case, only the forces normal to faces 1-2 and 3-4 will be transmitted.

These elements are defined in the mesh but they work only through the directive `"LIAISON"`. It is therefore possible to "activate" or "deactivate" this particular connection depending on the problem to be treated, by modifying the `"LIAISON"` directive during a `"REPRISE"` (see page SR.40).

PMAT

This element is particularly aimed at modeling rigid projectiles, in connection with the directive `"IMPACT"`. It can also be used to specify added masses.

TVL1

This element has been developed for Van Leer fluids.

CVL1

Similarly to TVL1, this element has been developed for Van Leer fluids.

BSHT

The availability of the bushing element family allows to define generalized stiffness and damping between two nodes. The implemented model provides in 2D the element BSHT, with only translation degrees of freedom. All the characteristics of the bushing element are defined using "JOINT PROPERTIES" material type.

MAP2

This element is used in order to glue one slave node to a master side. The slave node should be on the side. 2 kinematic constraints are introduced in order to impose the translation dof of the slave node. These elements are defined in the topology but they work only through the directive `"LIAISON"`.

MAP5

This element is used in order to glue one slave node to a master shell side. The slave node should be on the side. 2 kinematic constraints are introduced in order to impose the translation dof of the slave node and a kinematic constraint is added on the rotational dof of the slave node. These elements are defined in the topology but they work only through the directive `"LIAISON"`.

INT4

The INT4 element is a quadrilateral pure displacement interface element (sometimes called *cohesive element*) dedicated to the modeling of interlayers, separating "standard" structural elements. In the particular case of a composite model, this element can be considered as representing a homogeneous resin layer ensuring the interlaminar stress transfer between adjacent plies. This approach is most often referred to as "mesoscopic" laminate modeling.

T3VF

2D triangle finite volume element. The finite volume is defined as cell centred. Several options for the calculation can be chosen with OPTI VFCC.

Q4VF

2D quadrangle finite volume element. The finite volume is defined as cell centred. Several options for the calculation can be chosen with OPTI VFCC.

Q92

This element can be used for precise modelling of continua. It can undergo arbitrarily large deformations. Since it is underintegrated, it is locking-free, but it may occasionally suffer from mechanisms if boundary conditions are too loose. In such cases, use of the Q93 element (which, however, is more expensive) is recommended.

The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.

- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

Q93

This is the fully-integrated version of the Q92 element. Its use is only recommended in plane cases, when mechanisms might occur.

The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

CL23

This element is mainly used to specify uniform pressure conditions acting on the boundaries of quadratic elements of type Q92, Q93 or Q92A.

ED01

This element is integrated through the thickness (5 points at each of 2 longitudinal stations) and offers accurate modelling in highly nonlinear cases (spreading of plasticity through the thickness). The effect of arbitrarily large membrane strains over the element thickness is taken into account, unless option `"EDSS"` is used (see `"OPTION"`).

The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, $\tau_{xy} = 0$, $\sigma_z \approx 0$ and ϵ_x, $\epsilon_y = 0$, $\gamma_{xy} = 0$, ϵ_z.
- In an axisymmetric calculation (AXIS): σ_x, σ_θ, $\tau_{xy} = 0$, $\sigma_z \approx 0$ and ϵ_x, ϵ_θ, $\gamma_{xy} = 0$, ϵ_z.
- In a plane stress calculation (CPLA), which means uniaxial stress here, so that the element represents a beam in the xz-plane: σ_x, $\sigma_y \approx 0$, $\tau_{xy} = 0$, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, $\gamma_{xy} = 0$, ϵ_z.

Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

Q92A

This element should (only) be used in place of Q92 in axisymmetric problems, for those elements that have one side along the axis of symmetry (y-axis). It does not suffer from mechanisms.

The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.

FLU1

This element offers a specialised treatment which is thought to be particularly effective for fluids, in conjunction with the A.L.E. formulation. An implicit phase for the calculation of pressure is introduced during time integration. The element can be degenerated to represent a triangle by simply repeating one of the nodes in the description of topology.

PFEM

This element is used to represent a 2D (or 3D) continuum (usually a fluid) by means of the Particle Finite Element method (PFEM).

ED41

A 4-node version of the ED01 element that facilitates fluid-structure interaction for certain problems. Two nodes are used at each extremity of the element in order to define the element thickness. However, these are really one physical node since displacements, velocities etc. are coincident.

In the element numbering, the first two nodes must define an 'external side' of the element. In other words, they must not be along the element thickness.

The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, $\tau_{xy} = 0$, $\sigma_z \approx 0$ and ϵ_x, $\epsilon_y = 0$, $\gamma_{xy} = 0$, ϵ_z.
- In an axisymmetric calculation (AXIS): σ_x, σ_θ, $\tau_{xy} = 0$, $\sigma_z \approx 0$ and ϵ_x, ϵ_θ, $\gamma_{xy} = 0$, ϵ_z.
- In a plane stress calculation (CPLA), which means uniaxial stress here, so that the element represents a beam in the xz-plane: σ_x, $\sigma_y \approx 0$, $\tau_{xy} = 0$, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, $\gamma_{xy} = 0$, ϵ_z.

ADQ4

4-node quadrilateral for advection-diffusion problems.

This element is used to model advection-diffusion problems in incompressible fluids with heat transfer, according to JRC's models.

FL23

3-node triangle for compressible fluids. This is an alternative to the degeneratable FLU1 quadrilateral.

FL24

4-node quadrilateral for compressible fluids. This is an alternative to the degeneratable FLU1 quadrilateral.

CL22

2-node boundary condition. This is recommended for use with 2-D Ispra models. This element automatically recognizes the element to which it is attached, and uses the most appropriate pressure discretization.

Q41

4-node quadrilateral for structural ALE calculations with reduced integration.
The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

Q42

4-node quadrilateral for structural ALE calculations with full integration.
The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

Q41N

4-node quadrilateral for structural ALE calculations with reduced integration. Uses Godunov algorithm.
The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

Q42N

4-node quadrilateral for structural ALE calculations with full integration. Uses Godunov algorithm. This element doesn't work well in some test cases, so it is advisable to use Q42G instead.
The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

Q41L

4-node quadrilateral for Lagrangian calculations with reduced integration.
The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

Q42L

4-node quadrilateral for Lagrangian calculations with full integration.
The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

Q95

9-node isoparametric quadrilateral with curved sides. This is a special version of the Q9 element under test, that should avoid mechanisms.
Its use is not recommended for the moment.
The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

MC23

3-node finite volume triangle for multicomponent flows.

MC24

4-node finite volume quadrilateral for multicomponent flows.

Q42G

4-node quadrilateral for structural ALE calculations with full integration. Uses Godunov algorithm.
The element has 4 components of stress (SIG) and strain (EPST), organized as follows.

- In a plane strain calculation (DPLA): σ_x, σ_y, τ_{xy}, σ_z and ϵ_x, ϵ_y, γ_{xy}, $\epsilon_z = 0$.
- In an axisymmetric calculation (AXIS): σ_x, σ_y, τ_{xy}, σ_θ and ϵ_x, ϵ_y, γ_{xy}, ϵ_θ.
- In a plane stress calculation (CPLA): σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$ and ϵ_x, ϵ_y, γ_{xy}, ϵ_z.

MS24

4-node quadrilateral MACRO spectral element.

The integration points coincide with the Gauss-Lobatto-Legendre points and are determined by specifying the MICRO spectral elements S24.

S24

4-node quadrilateral MICRO spectral element This element is used only to specify 'internal' nodes of an MS24.

FUN2

2-node cable element.

This is a specialized element for the representation of cables in 2D space, in conjunction with the FUNE material (it resists only in traction, not in compression). When used with the VM23 material, it represents a bar (which resists both in traction and in compression). The element is large-strain.

The element has 4 components of stress (SIG), organized as follows: σ_x, $\sigma_y \approx 0$, $\tau_{xy} = 0$, $\sigma_z \approx 0$. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, $\gamma_{xy} = 0$, ϵ_z.

DEBR

1-node debris particle element.

This is a specialized element for the representation of flying debris, as e.g. resulting from an explosion or an impact, by means of spherical particles. It may be used both in 2D and in 3D.

TUBM

Connection 2D-1D.

TBM2

Connection 2D-2D for VFCCs.

3.1.3 3-D ELEMENTS

The various elements available in 3D are presented below.

num.	Name	Gibi	Dev	npt	dof	ngp	Remarks
57	ADC8	CUB8	JRC	8	3	1	advection-diffusion brick
32	APPU	POI1	CEA	1	6	1	support
130	ASHB	—-	CEA	8	3	5	assumed strain thick shell
79	BILL	POI1	CEA	1	3	1	particle element (NABOR and SPH)
19	BR3D	SEG2	CEA	2	3	1	bar
115	BSHR	—-	CEA	2	6	–	bushing with trans. and rot. dof
114	BSHT	—-	CEA	2	3	–	bushing with translational dof
144	C272	CU27	JRC	27	3	8	27-node cube
145	C273	CU27	JRC	27	3	27	27-node cube
155	C81L	CUB8	JRC	8	3	1	8-node cube
156	C82L	CUB8	JRC	8	3	8	8-node cube
62	CL32	QUA4	JRC	4	6	4	b.c.s for CQD4
63	CL33	QUA9	JRC	9	6	9	b.c.s for CQD9
18	CL3D	QUA4	CEA	4	3	1	bound. cond. (4-node face)
78	CL3I	TRI3	JRC	3	3	1	3-node b.c.s
99	CL3Q	QUA4	JRC	4	3	1	4-node b.c.s
29	CL3T	TRI3	CEA	3	3	1	bound. cond. (3-node face)
151	CL92	QUA9	JRC	9	3	4	9-node (3D) b.c. for C272
152	CL93	QUA9	JRC	9	3	9	9-node (3D) b.c. for C273
95	CLD3	TRI3	JRC	3	6	3	b.c.s for CQD3
96	CLD6	TRI6	JRC	6	6	4	b.c.s for CQD6
47	CMC3	TRI3	CEA	3	6	2	multilayer shell
12	COQ3	TRI3	CEA	3	6	1	triangular thin shell
14	COQ4	QUA4	CEA	4	6	4	quadrangular thin shell
40	COQI	TRI3	JRC	3	6	15	triangular shell (small strain)
93	CQD3	TRI3	JRC	3	6	15	degenerated shell (Hughes-Liu)
91	CQD4	QUA4	JRC	4	6	20	degenerated shell (Hughes-Liu)
94	CQD6	TRI6	JRC	6	6	20	degenerated shell (Hughes-Liu)
92	CQD9	QUA9	JRC	9	6	45	degenerated shell (Hughes-Liu)
13	CUB6	CUB8	CEA	8	3	6	brick with 6 Gauss pt
30	CUB8	CUB8	CEA	8	3	8	brick with 8 Gauss pt
6	CUBB	CUB8	EDF	8	3	8	brick based on B-bar method
11	CUBE	CUB8	CEA	8	3	1	brick with 1 Gauss pt
133	CUVF	CUB8	CEA	8	3	1	cube finite volume
81	CUVL	CUB8	CEA	8	3	1	Van Leer cube
140	DEBR	POI1	JRC	1	3	-	debris particle
84	DKT3	TRI3	CEA	3	6	15	shell (Mindlin)
83	DST3	TRI3	CEA	3	6	15	shell (Discrete Shear Triangle)
80	ELDI	POI1	EDF	1	6	1	discrete element
66	FL34	TET4	JRC	4	3	1	fluid tetrahedron
67	FL35	PYR5	JRC	5	3	1	fluid pyramid
68	FL36	PRI6	JRC	6	3	1	fluid prism
69	FL38	CUB8	JRC	8	3	1	fluid hexahedron
53	FLU3	CUB8	JRC	8	3	1	fluid brick
16	FS3D	RAC3	CEA	8	3	1	F.S. connection (4-node face)
48	FS3T	PRI6	CEA	6	3	1	F.S. connection (3-node face)
110	FUN3	SEG2	JRC	2	3	1	cable element

153	LIGR	SUPE	CEA	2*	6	-	mechanism (articulated systems)
125	INT6	—-	CEA	6	3	1	triangular prism interface element
126	INT8	—-	CEA	8	3	4	hexahedron interface element
119	MAP3	—-	CEA	4	3	–	point on a triangular facet
120	MAP4	—-	CEA	5	3	–	point on a quadrangular facet
122	MAP6	—-	CEA	4	6	–	point on a triangular shell facet
123	MAP7	—-	CEA	5	6	–	point on a quadrangular shell facet
101	MC34	TET4	JRC	4	3	1	finite volume tetrahedron
102	MC35	PYR5	JRC	5	3	1	finite volume pyramid
103	MC36	PRI6	JRC	6	3	1	finite volume prism
104	MC38	CUB8	JRC	8	3	1	finite volume hexahedron
33	MECA	SEG2	CEA	2	6	1	mechanism (articulated systems)
128	MOY4	—-	CEA	4	3	–	node to element mean connector
129	MOY5	—-	CEA	5	3	–	node to element mean connector
107	MS38	CUB8	JRC	8	3	1	spectral ”macro” quadrilateral
54	PFEM	POI1	JRC	1	3	1	particle finite element
28	PMAT	POI1	CEA	1	3	1	material point
17	POUT	SEG2	CEA	2	6	2	Euler beam
20	PR6	PRI6	CEA	6	3	6	prism with 6 Gauss pt
27	PRIS	PRI6	CEA	6	3	1	prism with 1 Gauss pt
134	PRVF	PRI6	CEA	6	3	1	prism finite volume
82	PRVL	PRI6	CEA	6	3	1	Van Leer prism
136	PYVF	PYR4	CEA	5	3	1	pyramid finite volume
138	Q4MC	QUA4	CEA	4	6	-	multilayered quadrangular shell
90	Q4G4	QUA4	CEA	4	6	4	shell (Batoz)
111	Q4GR	QUA4	CEA	4	6	5	idem Q4G4 (simplified : 1 pt)
112	Q4GS	QUA4	CEA	4	6	20	idem Q4G4 (simplified : 4 pts)
35	QPPS	QUA4	CEA	4	6	5	similar to Q4GR
113	RL3D	SEG2	EDF	2	3	1	two-node spring
143	RL6D	SEG2	EDF	2	6	1	beam element with 12x12 matrix
165	CB40	SEG2	EDF	2	3	1	nonlinear spring with contact
166	CORA	POI1	EDF	1	6	-	6-dof corps with damping
108	S38	CUB8	JRC	8	3	1	spectral ”micro” quadrilateral
117	SH3D	—-	CEA	3	6	–	node to shell connector
127	SH3V	—-	CEA	8	3	4	node to element connector
85	SHB8	CUB8	CEA	8	3	5	thick shell
89	SPHC	POI1	CEA	1	6	1	particle element (thick shell)
139	T3MC	TRI3	CEA	4	6	-	multilayered triangular shell
51	T3GS	TRI3	EDF	3	6	5	shell (Reissner-Mindlin)
21	TETR	TET4	CEA	4	3	1	tetrahedron with 1 Gauss pt
135	TEVF	TET4	CEA	4	3	1	tetrahedron finite volume
41	TUBM	SUPE	CEA	1*	3*	1	connection 3D-1D or 2D-1D
163	TBM2	SUPE	JRC	1*	3*	1	connection 3D-3D
116	TUYM	SUPE	CEA	1*	3*	1	connection 3D-1D

The specifications for these elements are given hereafter:

CUBB

Solid element for elasto-plastic computations. This element developed at EDF ([974]) is free from volumetric locking and does not exhibit hourglassing. When the material becomes quasi-incompressible, one should decrease CSTAB coefficient to maintain the calculation stable.

CUBE

This element is used especially with fluid materials. However, because of its under-integration, ”hourglassing” phenomena may appear, if they are not prevented by the boundary conditions. Such phenomena may be contrasted by using the HOURG option (anti-hourglass artificial viscosity).

The element has 6 components of stress (SIG), organized as follows (for solid materials): σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, ϵ_z, γ_{xy}, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

COQ3

This element must be used with care. In order to obtain good results make sure to use a symmetric mesh (ex: British flag).

CUB6

Solid element for elasto-plastic computations. This element should be used with caution, because being underintegrated it may lead to hourglassing. Use preferentially CUBB or CUB8 elements.

The element has 6 components of stress (SIG), organized as follows: σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, ϵ_z, γ_{xy}, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

COQ4

This element is recommended for computations on 3-D shells if the deformations are small. In reality, this element is composed of 4 triangular COQ3 plates which are superimposed and symmetrized.

FS3D

Same remarks as for FS2D.

POUT

This Euler beam element enables the modelling of complex profile beams submitted to a tension or bending stress. The default stability time step for this element is quite conservative (optimized for tubes?). Larger or even much larger values for different cross sections may be obtained by using the option `DTBE` (see H 20).

CL3D

Same remarks as for CL2D.

BR3D

This element is mainly used to model concrete rebars or any other beam submitted to a simple tension.

PR6

As it is the case of CUB8, this element is recommended for elasto-plastic computations.

The element has 6 components of stress (SIG), organized as follows: σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, ϵ_z, γ_{xy}, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

TETR

This element may be used for fluids or for elasto-plastic computations.

The element has 6 components of stress (SIG), organized as follows (for solid materials): σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, ϵ_z, γ_{xy}, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

PRIS

This prismatic element is especially used for fluids (see CUBE).

The element has 6 components of stress (SIG), organized as follows (for solid materials): σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, ϵ_z, γ_{xy}, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

PMAT

Primarily, this element enables the modelling of rigid missiles in connection with the keyword `"IMPACT"`; but it also enables the introduction of added masses.

CL3T

Same remarks as for CL2D.

CUB8

Solid element recommended for elasto-plastic computations (no hourglassing phenomena).

The element has 6 components of stress (SIG), organized as follows: σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, ϵ_z, γ_{xy}, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

APPU

This element has one node and six degrees of freedom. It allows to use constitutive equations of type non-linear support in a chosen direction. See also page C2.108.

MECA

This element has two nodes with six degrees of freedom. It allows to use constitutive equations for mechanisms (articulations, etc.).

TUBM

Connection 3D-1D. Consult the corresponding ‘liaison’ (connection).

TBM2

Connection 3D-3D for VFCCs.

TUYM

Connection 3D-1D for moving meshes (ALE). Consult the corresponding ‘liaison’ (connection).

CMC3

This element is used for the modelling of an eccentric layer in relation to the average plane defined by its 3 nodes. The layer is associated with an orthotropic behaviour in the given plane. Several CMC3 elements are supported by the same nodes, but they are differently eccentric; they represent a multilayer structure.

The geometric and mechanical characteristics of the element (eccentricity, orthotropy associated to a local system) can be defined either when CASTEM2000 generates the mesh (see option CASTEM page A.30) or directly by EUROPLEXUS (see page C.95) in a normal mesh generated by COCO or GIBI.

The local reference of the element is as follows: the first axis is formed by side 1-2, the second is such that the 3rd node lies in the half-plane (Y>0).

FS3T

Same remarks as for FS2D.

T3GS

3-node thick shell (Reissner-Mindlin) element with 1 integration point in the plane. It has the same local frame as COQ3. This element developed at EDF ([960]).

It is a predecessor of the Q4G family, uses the same approach for representing the shear strain and is thus the best suited among T3 shell elements to be combined with Q4G shell elements.

The element has 8 components of stress (SIG), organized as follows: σ_x^m, σ_y^m, τ_{xy}^m, σ_x^b, σ_y^b, τ_{xy}^b, τ_{xz}, τ_{yz}, where the first three components are the membrane contributions, the second three components are the bending contributions and the last two components are the transverse shear contributions (note that the order in which these last two components are given is opposite to what is usually found in 3D continuum elements, for example). The total strains (EPST) follow the same organization: ϵ_x^m, ϵ_y^m, γ_{xy}^m, ϵ_x^b, ϵ_y^b, γ_{xy}^b, γ_{xz}, γ_{yz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

BILL

This element is primarily aimed at the modeling of fluids or structures by using the method of particles and forces.

ELDI

This point-like element has one node with six degrees of freedom. The element is developed at EDF ([965]) to model fragmentation of concrete structures. The discrete element mesh is generated by using a particular geometric padding technique (Jerier 2010) implemented into SpherePadder tool (free software under GNU GPL v2 license) and integrated as a plug-in into SMESH mesher of SALOME plate-form. The DE mesh is available in MED format only. Interactions between these elements allow to model cohesive nature of materials or contact.

CUVL

Specific element (hexahedron) for Van Leer fluids in 3D.

PRVL

Specific element (prism) for Van Leer fluids in 3D.

DST3

3-node shell element (Discrete Shear Triangle).

It is a thick shell element (Mindlin). Same local frame as COQ3.

The element has 8 components of stress (SIG), organized as follows: σ_x^m, σ_y^m, τ_{xy}^m, σ_x^b, σ_y^b, τ_{xy}^b, τ_{xz}, τ_{yz}, where the first three components are the membrane contributions, the second three components are the bending contributions and the last two components are the transverse shear contributions (note that the order in which these last two components are given is opposite to what is usually found in 3D continuum elements, for example). The total strains (EPST) follow the same organization: ϵ_x^m, ϵ_y^m, γ_{xy}^m, ϵ_x^b, ϵ_y^b, γ_{xy}^b, γ_{xz}, γ_{yz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

DKT3

3-node shell element (Discrete Kirchhoff Triangle). It is a thick shell element (Mindlin). It has the same local frame as COQ3.

The element has 6 components of stress (SIG), organized as follows: σ_x^m, σ_y^m, τ_{xy}^m, σ_x^b, σ_y^b, τ_{xy}^b, where the first three components are the membrane contributions and the second three components are the bending contributions. The total strains (EPST) follow the same organization: ϵ_x^m, ϵ_y^m, γ_{xy}^m, ϵ_x^b, ϵ_y^b, γ_{xy}^b. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

SHB8

8-node thick shell element obtained starting from the 8-node brick. The 2 faces of this element are formed by the nodes: 1, 2, 3, 4 for the first face and 5, 6, 7, 8 for the second face.

SPHC

This thick shell (Mindlin-Reissner) particle element has one node with five degrees of freedom: 3 translations and 2 rotations.

Q4G4

4-node shell element (Batoz), with 4 integration points in the plane and 5 integration points through the thickness for plasticity.

There are 8 stress components: sigm-x, sigm-y, sigm-xy, sigf-x, sigf-y, sigf-xy, tau-xz, tau-yz.

It is a thick shell element with 4 nodes (BATOZ formulation) which accounts for the non-coplanarity of the four nodes. It is a complete but expensive version of Batoz's element.

A local frame is defined at each Gauss point: the first vector is tangent to the line (csi=cst.) in the sense from node 1 to node 2, the second vector is the vector product of the first by the vector tangent to the line (eta=cst.) in the sense from node 1 to node 4. The frame is completed so as to be right-handed.

Q4GR

4-node shell element (BATOZ) with 1 integration point in the plane and 5 integration points through the thickness for plasticity.

It is a simplified version of Q4G4 with a single integration point in the plane. An incomplete anti-hourglass stiffness (only in rotation) is implemented; an adjusting coefficient for anti-hourglass can be set using the following syntax:

```
"OPTI" "HGQ4" hgq4ro
```

The default value of hgq4ro is 0.018.

The element has 10 components of stress (SIG), organized as follows: σ_x^m, σ_y^m, τ_{xy}^m, σ_x^b, σ_y^b, τ_{xy}^b, τ_{xz}, τ_{yz}, σ_h^1, σ_h^2, where the first three components are the membrane contributions, the second three components are the bending contributions, the next two components are the transverse shear contributions (note that the order in which these last two components are given is opposite to what is usually found in 3D continuum elements, for example) and the last two components are anti-hourglassing (pseudo-)stresses. The total strains (EPST) follow the same organization: ϵ_x^m, ϵ_y^m, γ_{xy}^m, ϵ_x^b, ϵ_y^b, γ_{xy}^b, γ_{xz}, γ_{yz}, ϵ_h^1, ϵ_h^2. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

QPPS

This element is similar to Q4GR.

The element has 10 components of stress (SIG), organized as follows: σ_x^m, σ_y^m, τ_{xy}^m, σ_x^b, σ_y^b, τ_{xy}^b, τ_{xz}, τ_{yz}, σ_h^1, σ_h^2, where the first three components are the membrane contributions, the second three components are the bending contributions, the next two components are the transverse shear contributions (note that the order in which these last two components are given is opposite to what is usually found in 3D continuum elements, for example) and the last two components are anti-hourglassing (pseudo-)stresses. The total strains (EPST) follow the same organization: ϵ_x^m, ϵ_y^m, γ_{xy}^m, ϵ_x^b, ϵ_y^b, γ_{xy}^b, γ_{xz}, γ_{yz}, ϵ_h^1, ϵ_h^2. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

Q4GS

4-node shell element (Batoz), with 4 integration points in the plane and 5 integration points through the thickness for plasticity.

It is a simplified version of Q4G4 with 4 integration points in the plane.

The element has 8 components of stress (SIG), organized as follows: σ_x^m, σ_y^m, τ_{xy}^m, σ_x^b, σ_y^b, τ_{xy}^b, τ_{xz}, τ_{yz}, where the first three components are the membrane contributions, the second three components are the bending contributions and the last two components are the transverse shear contributions (note that the order in which these last two components are given is opposite to what is usually found in 3D continuum elements, for example). The total strains (EPST) follow the same organization: ϵ_x^m, ϵ_y^m, γ_{xy}^m, ϵ_x^b, ϵ_y^b, γ_{xy}^b, γ_{xz}, γ_{yz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

RL3D

Two-node nonlinear spring element to model paraseismic supports ([975]). This element has no mass and can have a zero length when using RESG material.

RL6D

A beam element with an linear elastic behavior defined by a 12x12 symmetric stiffness matrix. This element can be used with KTRL and RE6G materials only. This element has no mass and can have a zero length when using RE6G material.

CB40

A nonlinear spring with elastic-plastic behavior in compression and unilateral contact in tension (inspired by COMBIN40 element from Ansys). This element can be used with EPCO material only.

CORA

A rigid 6-dof corps allowing to add a ponctual mass and inertia and apply a mass proportional daming defined through the CAMO material.

BSHT and BSHR

The availability of the bushing element family allows to define generalized stiffness and damping between two nodes. The implemented model provides a first type of element, BSHT, with only translation degrees of freedom (available both in 2D and in 3D), and a second type, BSHR, with rotational degrees of freedom too.

All the characteristics of the bushing element are defined using "JOINT PROPERTIES" material type.

SH3D

This element is used to connect a slave node to a master edge of shell. Three kinematic constraints are introduced on the translational and rotational degrees of freedom of the slave node. The displacements and rotations of the slave node are linearly interpolated between the two master nodes. These elements are defined in the topology but they work only through the "LIAISON" directive.

SH3V

This element is used to connect a slave node to a master edge of element. It is the same as for the SH3D element except that there is no constraint on rotations. These elements are defined in the topology but they work only through the "LIAISON" directive.

MAP3 and MAP4

This element is used in order to glue one slave node to a master face. The master face is triangular in the case of the MAP3 and quadrangular in the case of the MAP4. 3 kinematic constraints are introduced in order to impose the translation dof of the slave node. These elements can be used in order to glue 2 volumic meshes. These elements are defined in the topology but they work only through the "LIAISON" directive.

MAP6 and MAP7

This element is used in order to glue one slave node to a master shell face. The master face is triangular in the case of the MAP6 and quadrangular in the case of the MAP7. 3 kinematic constraints are introduced in order to impose the translation dof of the slave node and 3 kinematic constraints are added on the rotational dof. These elements can be used in order to glue 2 shell meshes. These elements are defined in the topology but they work only through the "LIAISON" directive.

INT6 and INT8

The INT6 (triangular prism) and INT8 (hexahedron) elements are pure displacement interface elements (also called *cohesive elements*) dedicated to the modeling of interlayers, separating "standard" structural elements. In the particular case of a composite model, these elements can be considered as representing a homogeneous resin layer ensuring the interlaminar stress transfer between adjacent plies. This approach is most often referred to as "mesoscopic" laminate modeling.

ASHB

8-node thick shell element obtained starting from the 8-node brick. This element is identical as SHB8 but follows the assumed strain formulation. The 2 faces of this element are formed by the nodes: 1, 2, 3, 4 for the first face and 5, 6, 7, 8 for the second face.

Q4MC

4-node multilayered shell element which is a generalization of the Q4GS element. This element is also multi-material. The number of Gauss point in the thickness depends on the number of plies. The user has to define the total number of Gauss points in the thickness using the parameter NGPZ in COMP (resp. SAND).

T3MC

3-node multilayered shell element which is a generalization of the DST3 element. This element is also multi-material. The number of Gauss point in the thickness depends on the number of plies. The user has to define the total number of Gauss points in the thickness using the parameter NGPZ in COMP (resp. SAND).

The element has 8 components of stress (SIG), organized as follows: σ_x^m, σ_y^m, τ_{xy}^m, σ_x^b, σ_y^b, τ_{xy}^b, τ_{xz}, τ_{yz}, where the first three components are the membrane contributions, the second three components are the bending contributions and the last two components are the transverse shear contributions (note that the order in which these last two components are given is opposite to what is usually found in 3D continuum elements, for example). The total strains (EPST) follow the same organization: ϵ_x^m, ϵ_y^m, γ_{xy}^m, ϵ_x^b, ϵ_y^b, γ_{xy}^b, γ_{xz}, γ_{yz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

CUVF

3D cubic finite volume element. The finite volume is defined as cell centred. Several options for the calculation can be chosen with OPTI VFCC.

PRVF

3D prism finite volume element. The finite volume is defined as cell centred. Several options for the calculation can be chosen with OPTI VFCC.

TEVF

3D tetrahedral finite volume element. The finite volume is defined as cell centred. Several options for the calculation can be chosen with OPTI VFCC.

PYVF

3D pyramid finite volume element. The finite volume is defined as cell centred. Several options for the calculation can be chosen with OPTI VFCC.

LIGR

This element has several nodes with six degrees of freedom. The first node belongs to a shell and the following ones belong to a beam. It allows to use constitutive equations for following two mechanisms :

- ARTI TGGR
- ARTI CRGR

COQI

3 node triangular plate element.

This element can be used to model 3D plates or shells (by plane facet approximation). It is integrated through the thickness. The element can undergo large displacements and large rotations as a whole (rigid body), thanks to a co-rotational formulation, but is limited to small strains. In particular membrane strains should remain small (maximum a few %).

The element has 4 components of stress (SIG), organized as follows: σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, γ_{xy}, ϵ_z. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

FLU3

8 node specialised element for compressible fluids.

The same remarks apply as for FLU1 in 2D. The element can be degenerated to represent a prism (6 nodes), a pyramid (4 nodes), or a tetrahedron (4 nodes) by suitable repetition of node numbers in the topology.

PFEM

This element is used to represent a 2D (or 3D) continuum (usually a fluid) by means of the Particle Finite Element method (PFEM).

ADC8

8 node brick for advection-diffusion problems.

This element is used to solve advection-diffusion problems in incompressible fluids with heat transfer according to JRC models.

CL32

4-node boundary condition for the CQD4.

These elements must be attached directly to the CQD4, i.e., they share the same nodes.

CL33

9-node boundary condition for the CQD9.

These elements must be attached directly to the CQD9, i.e., they share the same nodes.

FL34

4-node tetrahedron for compressible fluids. Is an alternative to the degeneratable FLU3 hexahedron.

FL35

5-node pyramid for compressible fluids. Is an alternative to the degeneratable FLU3 hexahedron.

FL36

6-node prism for compressible fluids. Is an alternative to the degeneratable FLU3 hexahedron.

FL38

8-node hexahedron for compressible fluids. Is an alternative to the degeneratable FLU3 hexahedron.

CL3I

Boundary conditions of 3 nodes.

Recommended for use with COQI triangular shell elements and in general with all 3D Ispra models. This element automatically recognizes the element to which it is attached and uses the most appropriate pressure discretization.

CQD4

4-node quadrilateral degenerated shell element (Hughes-Liu).

The element has 6 components of stress (SIG), organized as follows: σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, γ_{xy}, ϵ_z, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

CQD9

9-node quadrilateral degenerated shell element (Hughes-Liu).

The element has 6 components of stress (SIG), organized as follows: σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, γ_{xy}, ϵ_z, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

CQD3

3-node triangular degenerated shell element (Hughes-Liu).

Similar to CQD4 but with a triangular shape.

The element has 6 components of stress (SIG), organized as follows: σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, γ_{xy}, ϵ_z, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

CQD6

6-node triangular degenerated shell element (Hughes-Liu).

Similar to CQD9 but with a triangular shape.

The element has 6 components of stress (SIG), organized as follows: σ_x, σ_y, τ_{xy}, $\sigma_z \approx 0$, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, γ_{xy}, ϵ_z, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

CLD3

3-node boundary condition element for CQD3.

CLD6

6-node boundary condition element for CQD6.

CL3Q

Boundary conditions of 4 nodes.

Recommended for use with 3D Ispra models. This element automatically recognizes the element to which it is attached and uses the most appropriate pressure discretization.

MC34

Finite-volumes: 4-node tetrahedron for multicomponent flows. This element is part of the models developed by the CESI team (formerly at ENEL, Milano) in collaboration with JRC. For more information on this element, see reference [135].

MC35

Finite-volumes: 5-node pyramid for multicomponent flows. This element is part of the models developed by the CESI team (formerly at ENEL, Milano) in collaboration with JRC. For more information on this element, see reference [135].

MC36

Finite-volumes: 6-node prism for multicomponent flows. This element is part of the models developed by the CESI team (formerly at ENEL, Milano) in collaboration with JRC. For more information on this element, see reference [135].

MC38

Finite-volumes: 8-node hexahedron for multicomponent flows. This element is part of the models developed by the CESI team (formerly at ENEL, Milano) in collaboration with JRC. For more information on this element, see reference [135].

MS38

Finite-volumes: 8-node hexahedral MACRO spectral element. This element is part of the models developed by the CESI team (formerly at ENEL, Milano) in collaboration with JRC.

The integration points coincide with the Gauss-Lobatto-Legendre points and are determined by specifying the MICRO spectral elements S38.

S38

8-node hexahedral MICRO spectral element.

This element is used only to specify 'internal' nodes of an MS38.

FUN3

This is a specialized element for the representation of cables in 3D space, in conjunction with the FUNE material (it resists only in traction, not in compression). When used with the VM23 material, it represents a bar (which resists both in traction and in compression). The element is large-strain.

The element has 4 components of stress (SIG), organized as follows: σ_x, $\sigma_y \approx 0$, $\tau_{xy} = 0$, $\sigma_z \approx 0$. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, $\gamma_{xy} = 0$, ϵ_z.

DEBR

1-node debris particle element.

This is a specialized element for the representation of flying debris, as e.g. resulting from an explosion or an impact, by means of spherical particles. It may be used both in 2D and in 3D.

C272

This element can be used for precise modelling of continua. It can undergo arbitrarily large deformations. Since it is underintegrated, it is locking-free, but it may occasionally suffer from mechanisms if boundary conditions are too loose. In such cases, use of the C273 element (which, however, is more expensive) is recommended.

The element has 6 components of stress (SIG), organized as follows: σ_x, σ_y, τ_{xy}, σ_z, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, γ_{xy}, ϵ_z, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

C273

This is the fully-integrated version of the C272 element. Its use is only recommended when mechanisms might occur.

The element has 6 components of stress (SIG), organized as follows: σ_x, σ_y, τ_{xy}, σ_z, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, γ_{xy}, ϵ_z, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

CL92

9-node boundary condition element for C272.

CL93

9-node boundary condition element for C273.

C81L

8-node hexahedron with reduced spatial integration (1 Gauss Point). This element can be used for precise modelling of continua. It can undergo arbitrarily large deformations. Since it is underintegrated, it is locking-free, but it may suffer from mechanisms. In such cases, use of the C82L element (which, however, is more expensive) is recommended.

The element has 6 components of stress (SIG), organized as follows: σ_x, σ_y, τ_{xy}, σ_z, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, γ_{xy}, ϵ_z, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

C82L

This is the fully-integrated version (8 Gauss Points) of the C81L element. Its use is recommended when mechanisms might occur.

The element has 6 components of stress (SIG), organized as follows: σ_x, σ_y, τ_{xy}, σ_z, τ_{yz}, τ_{xz}. The total strains (EPST) follow the same organization: ϵ_x, ϵ_y, γ_{xy}, ϵ_z, γ_{yz}, γ_{xz}. Note that, as concerns the shear strains, the engineering values γ and not the tensor values ϵ are used, with $\gamma_{ij} = 2\epsilon_{ij}$.

3.2 SANDWICH (MULTI-LAYER) ELEMENTS

Some shell elements developed at Ispra may be defined as a sandwich (an assembly) composed of several layers, each one having its own material. The usual hypothesis that fibers (straight lines across the thickness of an undeformed shell) remain straight during deformation is retained. The fiber may or may not be/remain normal to some 'mean' or 'reference' shell surface depending on the theory (Kirchhoff or Mindlin) assumed, i.e. on the fact that transverse shear strains are taken into account or not. As a consequence of fibers remaining straight, the deformation assumes a simple pattern through the thickness. In sandwich elements the state of stress may be discontinuous at layer interfaces because the different materials have in general different properties. No detachment (delamination) of the various layers is modelled at present.

These models are useful e.g. for representing reinforced concrete structures, or other composite materials (sandwich structures).

For the moment, this feature is available for elements of type ED01 in 2D and elements of type COQI, CQD3, CQD4, CQD6, CQD9, T3MC, Q4MC, Q4GS, Q4GR, QPPS, T3GS, DKT3 in 3D.

In order to use these models, see the `SAND` directives in the Geometry (page C.45) and in the Materials (page C.1110) Sections of the manual.

3.2.1 LOCATION AND NUMBER OF THE INTEGRATION POINTS

When using sandwich elements, the number of layers and of integration points through the thickness in each layer is specified by the user and may therefore vary from test case to test case. In order to facilitate the use of these elements, the following rule has been chosen:

> **For sandwich elements, the numbering of the integration points proceeds along each fiber (through the thickness) first, and from the lower to the upper part of the fiber**

The lower and upper element surfaces are defined by element numbering and the right-hand rule, as usual in EUROPLEXUS. The above numbering scheme is called 'fiber-first', as opposed to 'lamina-first' numbering schemes.

As an example, consider an element with two fibers, i.e. two integration stations in the element's plane (sometimes called lamina) and 5 integration points through the thickness. Then, the points numbered 1 to 5 belong to the first fiber, while points 6 to 10 belong to the second fiber. Furthermore, points 1 and 6 are the bottom ones, 3 and 8 the middle ones and 5 and 10 the top ones, and so on.

For ease of reference, the precise numbering schemes for elements susceptible of being multi-layered is given below.

ED01 element

The numbering scheme is fiber-first (i.e. identical) for both the old (until August 1995) and the new (homogeneous or multilayered) element.

COQI element

The unlayered element used until August 1995 an unusual numbering rule where the outer integration points were numbered first, then the intermediate points and finally a (single) point in the mean surface (see the Technical Note: "A Triangular Plate Element for the Nonlinear Dynamic Analysis of Thin 3D Structural Components", reference [87]). The element had 13 points altogether.

The new numbering rule is fiber-first, and is the same for both the unlayered and the layered element. For the unlayered element, 3 fibers of 5 points each (15 points altogether) are assumed, while in the multilayer element the fibers are still 3 but the number of points through the thickness may vary.

CQDx elements

In the versions before August 1995, (unlayered element) a 'lamina-first' numbering rule was assumed. Along each lamina, points were numbered along the η direction first, then along the ξ direction (these directions as well as the lower and upper faces of the elements are uniquely defined by the numbering of the element nodes). The number of points through the thickness was chosen by the user.

In the current version, for both the homogeneous and the multilayer elements, integration points are numbered fiber-first and of course the number of points through the thickness is still variable.

Q4MC and T3MC elements

Those element are a generalization of the Q4GS and DST3 elements. The number of total Gauss point through the thickness must be defined with the NPGZ parameter in the dimensioning section.

4 GROUP A—PROBLEM TYPE AND DIMENSIONING

Object:

The keywords of this group enable the definition of the problem, and the dimensioning (memory allocation) of the computation.

Comments:

These keywords are described in detail in the following pages.

4.1 TITLE AND PRELIMINARY INFORMATION

4.1.1 TITLE

The title, composed of a maximum of 72 characters, is the first card of the data set and is compulsory.

The contents of this data card is printed at the top of each page edited by EUROPLEXUS together with the date of the run.

4.1.2 INPUT DATA ECHO AND INPUT CHECK UP

Object:

These keywords are used to obtain an echo on the terminal or console window of the input data being precessed and to check up the syntactical correctness and the coherence of the data.

Syntax:

```
< $[ "ECHO" ; "NOEC" ]$ >
```

Comments:

The ”ECHO” optional keyword produces an echo on the screen or terminal of the input file directives as they are being processed. If the input file is very long, this may be annoying. By default no echo is produced. See also the option OPTI ECHO, Page H.50, which may be used at any point of the input file after the dimensioning.

The ”NOEC” optional keyword disables the echo on the screen or terminal of the input file directives as they are being processed. By default no echo is produced. See also the option OPTI NOEC, Page H.50, which may be used at any point of the input file after the dimensioning.

4.2 INTERACTIVE (FOREGROUND) EXECUTION

Object:

The `CONV` directive can be used to execute EUROPLEXUS **interactively**, i.e. in the foreground (as opposed to the default **batch** or background execution). In this execution mode, the user pilots the advancement of the computation, and the results at selected time instants can be either visualized on graphic screens of various types (**on-screen** rendering), or be stored in graphic files of various types (**off-screen** rendering), including animation files.

Syntax:

```
< "CONV"   $[ "TEKT" ; "WIN" ; "PS" ; "MIF" ]$ >
```

`TEKT`

Tektronix 4014 screen (PLOT-10 graphics language).

`WIN`

MS-Windows graphics (QuickWin or OpenGL). Note that OpenGL may be supported also on non-Windows platforms, e.g. on Linux.

`PS`

PostScript (but see also the TRAC PS interactive command).

`MIF`

FrameMaker MIF (but see also the TRAC MIF interactive command).

Comments:

When interactive execution is chosen, EUROPLEXUS reads the input data-set as usual, performs step 0 to initialise the computation, then prompts the user for commands from the keyboard with the phrase: `COMMANDE ?`.

The user can then issue various commands and subcommands **typically from the keyboard** in order to pilot the computation. For example, he can ask the program to perform a certain number of steps, then to pause again for further commands. Each time the calculation is paused, the current computational model can be visualized (e.g. by means of the built-in OpenGL-based visualization module) and information concerning the computation (time step, CPU time, etc.) can be printed. Furthermore, the current time step can be varied by the user.

As an alternative to typing commands by hand from the keyboard, such commands may be included in the regular EUROPLEXUS input file by enclosing them into a special directive `PLAY` ... `ENDPLAY` as described in Section 13.6 (Page I.24) and in Section 14.7 (Page ED.140).

All EUROPLEXUS interactive commands are described in detail in Section 15 (Group O).

4.3 FILE MANAGEMENT

This Section gives some information about the management of files related to the EUROPLEXUS program.

4.3.1 DEFAULT FILE NAMES

The code tries whenever possible to use default values both for the file names that it needs during the calculation, and for the associated logical unit numbers.

The idea is that logical unit numbers (a concept specific only to FORTRAN) are irrelevant for the user and should be totally transparent to him or her. What *does* matter for users is file *names*.

In many cases the code helps users by providing default values for such names (the behaviour may depend on the platform, though, see below). Of course, users are free to choose file names (and even unit numbers) if for any reason they find such defaults inconvenient.

Default names under MS-Windows

Under the MS-Windows platform default file names are built automatically by the code by using the base name of the (main) input file used in the run.

For example, suppose that the main input file is called `test01.epx` and resides on a directory `D:\Work`. The user may launch the program for example by opening a console window on the directory `D:\Work` (i.e., such that `D:\Work` is the current directory) and by typing a command such as:

```
epx_bench -l test01
```

The actual command may vary depending on the implementation.

The code interprets the name passed on the command line (after removing any options such as the `-l` above) as the name of the main input file. It removes the extension `.epx` from this name, if present, and uses the resulting string as the base name for default file names. Thus, the user may give a full file name, complete with its path, if preferred.

Suppose now that for run `test01` the user needs to read a CASTEM 2000 mesh and wants to produce results for ALICE TEMPS and CASTEM 2000.

The first task may be accomplished by the CAST directive (see page A.30). If the mesh file is formatted, and the global (main) mesh object is called `model`, this directive may take any of the following forms:

1. `CAST FORM ‘test01.msh’ model`

2. `CAST FORM 9 model`

3. `CAST FORM model`

In the first form, the file name containing the mesh is given explicitly. The code associates this name to the default unit number, which for CASTEM mesh reading is number 9.

In the second form, the unit number is given explicitly. The code uses the given number as unit number and opens a file without specifying its name. This results in different behaviour depending on the platform. Under MS-Windows, a file `fort.9` is opened.

In the third form neither the name nor the unit number are specified. The code uses the default file name (`test01.msh` in this case) and the default unit number (9).

It is clear that, whenever possible, the third form is preferable. This requires, however, that the mesh file name matches the main input file name (and is on the same directory).

When either of these conditions is impractical, the first form should be used by preference (name chosen by the user, unit number chosen by default by the code).

The second syntax is obsolete and should be avoided in new inputs.

The task of producing results files may be accomplished similarly, by the ECRI directive (see page G.70). For example, for the ALICE TEMPS output, this directive may take any of the following forms:

```
1.   ECRI FICH ALIC TEMP 'test01.alt' /CTIME/ . . .

2.   ECRI FICH ALIC TEMP 11 /CTIME/ . . .

3.   ECRI FICH ALIC TEMP /CTIME/ . . .
```

Default names under Unix

Under the Unix platform(s), the same concepts apply as seen above.

Let us assume for example that the main input file is called `test01.epx` and resides on a directory `/u/user/My_dir`. The user may run the program starting from his work directory (`My_dir`) by the command:

```
europlexus test01.epx
```

The mesh file will be sought in this directory under the name `test01.msh`. If some other input files are required, they will also be sought in this directory, under the same name but a different extension. The same rule applies to output files, in particular to the listing file.

However, for reasons related to efficient exploitation of disk space, output files may of course be directed to special directories. It is therefore recommended to contact your system administrator to learn about local disk space policies.

Alternatives under MS-Windows

Under the MS-Windows platform, there exist other ways of launching the program, alternative to the one (command line) assumed in the above example.

For example, a user might double click on the EUROPLEXUS executable or on an icon (shortcut) to this executable, or on the input file `test01.epx` (provided file association is used), etc.

Whenever a file name is not directly available (like in the first two alternative methods listed above), the program prompts interactively the user for such a name. The behaviour is thereafter identical to the case of command-line execution.

Comments:

Currently, default file names are available for the following directives:

- Reading a CASTEM 2000 or GIBI mesh, `GIBI` and `CAST` keywords (see page A.30);

- Writing result files, `ECRI FICH` keywords (see page G.70);
- Reading a results file (post-treatment by EUROPLEXUS), keyword `RESU` (see page ED.10).
- Reading a modal basis file in a multi-domain computation (see `STRU` directive on page I.15).

4.3.2 EXPLICIT FILE OPENING

Object :

This directive allows to open a file directly from the input data, by specifying its logical unit number and its name.

It may be used whenever either the user wants to override a file choice made by default by the code (example: a very long calculation requires its results file to be written to a remote disk, due to space problems), or to force opening of a unit that is otherwise not opened by the code.

Note, however, that including this directive in input files generally renders them not portable across different platforms or even different machines belonging to the same platform. In fact, absolute (full) file names are usually required.

For this reason, it is preferable to use the short file name syntax (or even the default name syntax) described in the previous sections whenever possible.

Syntax

```
 1. Open a generic file:
  "OPNF"  < "FORMAT" >  nfic  'nomfic' ;

 2. Open an XDR file in read or write mode:
  "OPNF"  $ WXDR ; RXDR $  nfic  'nomfic' ;

 3. Create a results directory:
  "OPNF"  $ "PATH"; "DRST" ; "DPRV" $  $ 'nomdir' ; "PWDO" $
```

`FORMAT`

Specify that a formatted file is required. By default, the file is unformatted.

`WXDR`

Specify that a writeable XDR file is required. For the output ”K2000” file for example.

`RXDR`

Specify that a readable XDR file is required. For the input mesh file for example.

`nfic`

Logical unit number of the file.

`'nomfic'`

File name.

`PATH, DRST, DPRV`

Any of these keywords (which are aliases) specifies that the following name is that of a directory to be created for the storage of calculation results. This allows, among other uses, to un-clutter the currect directory where the calculation is performed, for those type of outputs that produce many results files (typically ALIC split format and ParaView).

`'nomdir'`

Results directory name.

`PWD0`

The directory will be the current directory.

Comments :

It is forbidden to open explicitly the logical unit numbers 0, 5, 6 and 7, that are reserved in most operating systems. Other unit numbers reserved by EUROPLEXUS are 15, 16 and from 91 onwards.

The way of coding the file name depends upon the operating system:

- Under Unix, the full name must be given, for example: `/u/user/ssrep/fich.sortplex`.
- Under MS-Windows the full path name is recommended, like under Unix. For example: `D:\Users\Epx\myfile.abc`.

For other operating systems, please contact your system administrator.

Results sub-directory

To unclutter the current directory from results files, a typical usage would be as follows. Suppose we are running a test named `mytest.epx` in a certain directory. The test produces split ALIC files and PVTK files. We want to place all these results files (which are potentially very numerous) in a sub-directory called `mytest.res` of the current directory, rather than directly in the current directory. To this end, the input would be the following:

```
MYTEST
  . . .
OPNF PATH 'mytest.res' ! Redundant if sub-directory exists, but safe
  . . .
ECRI . . .
  FICH SPLI ALIC 'mytest.res\mytest.ali' ...
  FICH PVTK 'mytest.res\mytest.pvd' ...
```

The above `OPNF` command is only necessary if the sub-directory `mytest.res` does not exist yet, and it will create it. Otherwise, the command would do nothing and it can be omitted (but leaving it is no harm).

The presence of back-slash characters as separators in the path names indicates that we are under Windows. At the end of the run, in the sub-directory `mytest.res` one will find the `.ali` files, the `.pvd` file and the `.vtu` files:

```
mytest.res\mytest_0000.ali
mytest.res\mytest_0001.ali
  . . .
mytest.res\mytest.pvd
mytest.res\mytest.0001.0001.vtu
mytest.res\mytest.0001.0002.vtu
  . . .
```

The ParaView results can be visualized by directly opening with ParaView the `.pvd` file from the sub-directory where it resides.

4.3.3 EXPLICIT OUTPUT DIRECTORY DEFINITION

Object :

This directive allows to define a directory for output files.
Like for EXPLICIT FILE OPENING, the rules for the name of the given directory may vary from one platform to another.

Syntax

```
"OPNF"  "DRST"  |[ 'nomdir' ; "PWDO" ]|
```

`DRST`

Following by the name of directory used for named result files (ALICE, ALICE TEMPS, K2000, INP, VTK-PARAVIEW, ...). Alias : DPRV or PATH.

`'nomdir'`

Name of directory used for result files.

`PWDO`

Directory name is the current directory.

Comments :

In the case of an UNIX system, the defined directory is an absolute path. In the case of a WINDOWS system, the directory is given as a relative path.

In both cases, if given directory does not exist, it is created.

4.4 TYPE OF MESH, PROBLEM AND LISTING

Object:

1/ To define the mesh type that will be used:

- Mesh in free format.
- Mesh generated by GIBI or CAST3M (uses objects).
- Mesh generated by I-DEAS Version 6 or Master Series (uses so-called "permanent groups").
- Mesh described in a MED file
- Mesh generated LS-PrePost (free pre-processor of LS-Dyna)

2/ To define the general type of computation:

- Axisymmetric, 2-D, 3-D, 1-D, etc.
- Lagrangian or Eulerian or A.L.E. formulation.
- Presence of mechanical rezoning for ALE computations.

3/ To define some general options about the form of printed results (useful to reduce the size of the output listing in extremely large test cases)

Syntax:

```
$[
    $[ "GIBI" ; "CASTEM" ]$ <$[ "FORM" ; "XDR" ; "BINA" ]$>
                              <$[ ndis ; 'file_name' ]$>  'nomobjet' ;
    "IDEA" <$[ ndidea ; 'file_name' ]$> < "REWR" > < "MAPP" > ;
    "MEDL" 'file_name' ;
    "LECM";
    "KFIL" 'file_name' ;
]$

|[ "DPLA"  ;  "CPLA"  ;  "AXIS" <"HOLE" hole> ;  "TRID"  ]|

< $[ "LAGR" ; "EULE" ; "ALE" ]$ >

< "NAVIER" >   < "HOMO" nhtube >
< "MBETON"     nssc     >
< "FRQR"       nfrqr    >  < "SPCO" sphcon >
< "LAGC"  >
< "MBACON"  < "POST" > >
< "SAUVEGARDE" ... >    < "REPRISE" ... >

< "ADDF" < "NAVS" > < "TEMP" >  < "TURB" > >
```

```
    < "MECA" >
    < "MEDE" <"NEPX"> <"ONEF"> >
    < "EROS" <ldam>  <CROI>  <LIMI>       >
    < "RISK" < "PROB" |[ "FERR" ; "YETP" ]| >
             < "LUNG" |[ "BAKE" ; "LEES" ]| >
             < "SPLI" > >

    < "SCLM" ... >
    < "BMPI" >
    < "ADAP" "MLVL" rlvl < ( 'nomelm' rlel ) > >
    < "CFVN" >
```

`GIBI`

Mesh generated by GIBI (GIBI objects will be read to define the mesh) and stored with the 'SORT' directive (see Comments below).

`CASTEM`

Mesh and other characteristics (geometrical, material, champoints) generated by CASTEM2000 and stored with the 'SAUV' directive (see Comments below).

`FORM`

The CAST3M generated data are to be read in formatted (ASCII) mode (this is the default).

`XDR`

The CAST3M generated data are to be read in XDR mode.

`BINA`

The CAST3M generated data are to be read in binary mode.

`ndis`

Number of the logical unit of the mesh file.

`'file_name'`

Complete path localising the mesh file, under Unix operating systems. If both this and the unit number ndis are omitted, the code chooses a name and a unit number by default (see page GBA_0027).

`'nomobjet'`

Name of the whole (main) object meshed by GIBI.

`IDEA`

Mesh generated by I-DEAS. At the moment, only formatted IDEAS files are allowed in input.

`ndidea`

Number of the logical unit of the mesh file.

`'file_name'`

Complete path localising the mesh file, under Unix operating systems. If both this and the unit number ndis are omitted, the code chooses a name and a unit number by default (see page GBA_0027).

`REWR`

Write a new I-DEAS file with re-ordered numbering (no holes), see details below.

`MAPP`

Stop run after re-writing the new I-DEAS file with re-ordered numbering, see below for details.

`MEDL`

Mesh described in a MED file.

`LECM`

Allow an automatic deletion of double nodes or double elements in a MED "LECT" procedure. !!! It should be notice that this procedure will perform a new ordination of readen elements or nodes. It is not compatible with the "RACCORD BIFU" method. !!!

`'file_name'`

Full path of the med file (this file contains the mesh). The key word OPEN followed by a unit number is not available to open a MED file.

`KFIL`

Mesh described in a LS-DYNA k-file.

`'file_name'`

Full path of the k-file file (this file contains the mesh).

`AXIS`

Axisymmetric computation.

`HOLE`

Optionally, for axisymmetric cases a central 'hole' may be specified by this keyword: in this case the given hole radius is automatically added to the mesh radial coordinates given in input (this is a shorthand alternative to providing a mesh with the actual hole in it).

`DPLA`

Two-dimensional plane strain computation.

`CPLA`

Two-dimensional plane stress computation.

`TRID`

Three-dimensional computation.

`LAGR`

Computation with the Lagrangian formulation (default). All nodes are Lagrangian. The GRIL directive is not required.

`EULE`

Computation with the Eulerian formulation. All nodes are Eulerian. The GRIL directive is not required.

`ALE`

Computation with the A.L.E. formulation. The GRIL directive may be used to specify the motion of nodes (see GBINT_0018).

`NAVIER`

One-dimensional uncoupled calculation (fixed pipelines), with incompressible or nearly incompressible fluids. The calculation may only be done in Eulerian. Therefore, it is mandatory to specify also the directive "EUL E".

`nhtube`

Maximum number of tubes per unit cell (homogenised material).

`nssc`

Number of layers for the CMC3 element with the BETO material. By default, there is just one layer per element. This number must be between 1 and 20.

`FRQR nfrqr`

Frequency of searching neighbour nodes. By default = 1. This option, valid only for calculations with the NABOR or SPH methods, allows the user to considerably reduce the calculation time.

`SPCO sphcon`

Maximum number of retained structure faces in contact with the same SPH particle. By default it is 1, meaning that only the first contacting face is treated (the penetrated face which is closest to the particle). The value of `sphcon` must be less than or equal to the value of parameter NBCPOS, which is hard coded in MPEF3D (currently NBCPOS = 6).

`LAGC`

This keyword specifies that the contact forces due to impact and sliding will be computed implicitly by the Lagrange multipliers method. This enables the coupling with the permanent connections (relations, boundary conditions, etc.)

`MBACON`

This keyword specifies that the characteristics of multi-layer homogenised elements will be read from a BACON file (see page GBC_0165).

`POST`

This option of MBACON indicates that the rupture criteria will be evaluated in the multi-layer elements during the direct calculation. During post-treatment, this option allows to compute the maximum deformations (upper and lower "skin"), and also the deformations along the directions of strain gauges.

`SAUV`

The directives for saving and restart are described in Section "SR" (see page GBSR_0010 and following).

`ADDF`

Advection-diffusion computation. The Eulerian description is used, therefore the "EULE" keyword is compulsory in this case. See description on page GBA_0031.

`NAVS`

Solution of Navier-Stokes equations (for fluid velocities) has to be performed in the advection-diffusion computation. See description on page GBA_0031.

`TEMP`

Solution of the temperature equation has to be performed in the advection-diffusion computation. See description on page GBA_0031.

`TURB`

Solution of the turbulence equations (k, eps) has to be performed in the advection-diffusion computation (this option is still under development).

`MECA`

ALE computation with mechanical rezoning model.

`MEDE`

to create a med file.

`NEPX`

By default, if the input mesh is a MED file, the output MED file uses the MED mesh numbering. The NEPX option forces the output MED file to use the EPX numbering that is different. See description on page GBG_0070.

`ONEF`

By default, for a EPX field (CONT, ECRO, EPST), one MED field is created by mesh type and by material. This option allows to creates an single MED field by EPX field.

`EROS`

This keyword activates the "erosion" algorithm of the code. The algorithm has the following characteristics:
1- Those elements whose erosion criterion (mainly number of failed Gauss points where failure is triggered by damage, principal strain, minimum pressure, ...) is beyond a certain level are considered as eroded and are ignored during the rest of the calculation. Erosion can activated in general for all structural elements. The failure criterion of one Gauss point can be defined via a global command in COMP (page GBC_0069), or in some materials.

Erosion can also be defined using displacement erosion (see GBC_0067) or using a minimum time step size of an element (see page GBI_0020).
2- In the case of a calculation with contact by sliding surfaces in 3D (see page GBD_0180), the contact surfaces are updated by eliminating the eroded elements.
3- The list of the eroded elements is stored in the results file. This allows to remove them from the visualization (if so desired) during the post-treatment.
4- The erosion can also be activated for a part of the elements (see page GBC_0069).
5- Obsolete are the keywords `FAIL` and `GHOS`.

`ldam`

Optional parameter indicating the number of failed Gauss points that cause erosion of the element, in proportion to the total number of Gauss points of an element. It should lie between 0 and 1. The default value is 1. Negative values indicate no erosion will taken into account for material erosion. The value 1.0 indicates that an element is eroded when *all* its Gauss points have failed. The value 0.5 indicates that an element is eroded whenever approximately half of its Gauss points have failed. The special value 0.0 may be used to indicate that an element is eroded when any one of its Gauss points fails. This value is global and is used (as a default) for all elements in the current calculation. However, specific material types (see e.g. `LEM1`) may contain parameters that allow to override this value. In this way the user may set different values of the erosion threshold in different parts of the model (e.g. low values or even 0.0 for very brittle materials such as glass, and high values for ductile materials such as metals).

`CROI`

This option allows the erosion of crossed elements (negative Jacobian matrix/negative volume). The calculation is not stopped in such case.

`LIMI`

Special limitation for the element erosion: 2D: only elements, which have not 3 nodes connected to already failed elements can fail. This avoids large zone with eroded elements.

`RISK`

This keyword activates the calculation of risk analysis related to explosive events. Note that to perform this type of analysis, it is mandatory to use standard measurement units. In particular, the pressures must be expressed in Pa. This is because the model internally uses some non-dimensionless constants. Furthermore the model assumes that the atmospheric pressure has the standard value of 1.D5 Pa, i.e. 1 bar. The risk estimation is performed according to the two references listed below. In order to compute the total probability from the probit functions, two different approaches can be chosen using the keyword `PROB`. A very conservative probability function from Yet-Pole can be activated with `YETP`. The more realistic probability function of Ferradás can be chosen with `FERR` (this is the default in case no `PROB` is defined). Two different formulations for risk of lung haemorrhage can be activated using the keyword `LUNG`. The default is equation (7, Baker, `BAKE`) from Ferradas paper. Equation (9, Lees, `LEES`) doesn't consider the impulse and is conservative. Note that thre optional sub-directives `PROB` ... and `LUNG` ... must be redefined in case of results reading from an Alice file. This allows to perform a calculation, say, with the default values (i.e. by specifying only the `RISK` directive, possibly followed by `SPLI` if so desired), and then to do several post-processing of the results each time computing (and visualizing) the risk by using a different set of sub-options (e.g. once by using the Ferradas probits and another time using the Yet-Pole probits), without having to run again the main calculation (which may be very time-consuming). Therefore, be aware that in calculations with risk it is mandatory to re-define the entire `RISK` directive before the `RESU` directive (which typically reads the results from an Alice file).

`SPLI`

The risk of death is split into three contributions: i) risk of head impact; ii) risk of body impact and iii) risk of lung haemorrhage. The resulting risk can only be visualized starting from a `PVTK` results file.

`SCLM`

This keyword introduces options related to memory distribution in MPI calculations, see details on Page GBA_0037.

`BMPI`

The simulation will only be executed using a parallel MPI version of EUROPLEXUS. Any sequential version running the case will produce a clean stop just after the keyword is read, declaring any qualification as valid.

`ADAP MLVL`

[MPI Only] Automatic dimensioning for ADAPTIVITY: `rlvl` is an estimated average refinement level for all the adaptable elements of the mesh (floating point value)). It is used to compute the size of the extension zones in replacement of the DIME ADAP directive. Specific values can also be entered for given element types through the `rlel` floating point parameter associated to one element name `'nomelm'`.

`CFVN`

Create the central Finite Volume nodes in Cell-Centred Finite Volume meshes.

References

The “probit” functions for risk estimation are taken from:

- E. González Ferradás, F. Díaz Alonso, M. Doval Miñarro, A. Miñana Aznar, J. Ruiz Gimeno and J.F. Sánchez Pérez: *Consequence analysis by means of characteristic curves to determine the damage to humans from bursting spherical vessels.* Process safety and environmental protection **86** (2008), 121–129.

- I. Yet-Pole, Cheng Te-Lung: *The development of a 3D risk analysis method.* Journal of hazardous materials **153** (2008), 600–608.

Comments:

The CASTEM directive is meant to read data produced by CAST3M and saved by the directive ”SAUV”. It will read also objects of type ’champoint’ explicitly stored, together with the mesh, by CAST3M.

On the other hand, the GIBI directive is meant to read only mesh objects (maillage) produced by CAST3M and saved by the directive ”SORT”. No champoints may be stored by CAST3M with this directive, therefore they may not be transmitted to EUROPLEXUS.

The syntax in CAST3M is:

(SORT)

Assume we have an object 'mymesh' of type 'maillage' to write on the file 'myfile.msh' on the current directory. Then :

```
 . . .
OPTI SORT 'myfile.msh' ;
SORT mymesh ;
 . . .
```

(SAUV)

Assume we have an object 'mymesh' of type 'maillage' and an object 'mychampnt' of type 'champoin' to write on the file 'myfile.msh' on the current directory. Then :

(formatted mode)

```
 . . .
OPTI SAUV FORM 'myfile.msh' ;
SAUV FORM mymesh mychampnt ;
```

or:

(XDR mode)

```
 . . .
OPTI SAUV  'myfile.msh' ;
SAUV  mymesh mychampnt ;
```

or:

(binary mode)

```
 . . .
OPTI SAUV BINA 'myfile.msh' ;
SAUV BINA mymesh mychampnt ;
```

Note that, if the data have been produced by CAST3M in formatted mode, then the keyword FORM may optionally be used in the EUROPLEXUS directive, for clarity, but it is not necessary, since this is the default reading mode for this directive.

On the other hand, if the data have been produced by CASTEM in "XDR" (rep. "BINA") mode, then the keyword XDR (resp. BINA) is mandatory in the EUROPLEXUS directive.

Note also, the XDR mode is the default mode for CAST3M output "SAUVER" file.

In the case of the "GIBI" directive, the mesh file is always formatted.

If neither the keyword "GIBI" nor "CASTEM" appear, the program assumes that the mesh is directly given in the main input file under the form of a list of coordinate values, and as many lists of node index (topology) values as there are element zones. This format is also known as the 'COCO' type format.

This form allows also to use meshes issued from mesh generators other than CASTEM-GIBI or even, in case for example the mesh is quite simple, to enter this data directly, or to generate them by an independent software. For more information, consult the 'GEOM' directive.

The type of problem directive must be specified and contain at least one keyword (at least 2 for non-Lagrangian cases), for example:

```
"AXIS"
```

or

```
"TRID"  "ALE"
```

The various options are mutually incompatible.

I-DEAS mesh

When the IDEA directive is used, the program reads the mesh from an I-DEAS 'universal file'. This file may contain other information besides the mesh, but the extra information is ignored.

The program interprets the following information: 1) nodal coordinates (dataset 781 or 2411) ; 2) element topology (dataset 780 or 2412); 3) permanent groups (dataset 752 or 2429 or 2430). Permanent groups are identified by a name, which can then be used in the EUROPLEXUS input file (like in the case of CASTEM mesh) to identify the corresponding list of nodes or elements.

Note that normally I-DEAS universal files do not have consecutive node or element numbers, while EUROPLEXUS requires consecutive numbering (and starting from 1). In order to solve this problem, use the optional `REWR` directive: the code reads the universal file (use extension '.unv'), re-orders the mesh numbering and writes the result in a new universal file (same name but with the characters 'new' appended). Nodes are re-ordered simply by eliminating 'holes' in the numbering. For the elements, however, a subdivision into homogeneous 'blocks' of the same element type, material and physical properties (geometrical complements) is performed. A summary of the resulting blocks is printed on the listing.

Elements are re-ordered subdividing them into homogeneous ‘blocks’ of the same element type, material and physical properties (geometrical complements). This permits the mapping of the I-DEAS element library onto the EUROPLEXUS one, for the relation between I-DEAS and EUROPLEXUS element libraries is not unique. The ordering criterion followed by the procedure is: [material property number] - [element type number] - [physical property number]; as an example, if some elements have to be declared as the last ones (i.e. CLxx elements when present), they must be associated to the highest material number in the I-DEAS mesh.

A list of the resulting blocks is printed on the listing, containing the number of elements, the element type in I-DEAS mesh and a list of possible choices for the corresponding EUROPLEXUS element type; these informations are useful in order to set up the declaration of the geometry in the EUROPLEXUS input file (see 5.3).

The `MAPP` optional directive may be used in order to stop the code right after writing the re-ordered universal file.

Example 1: EUROPLEXUS input file:

```
$------------------------------------
Example of use of IDEAS universal file: 1. file re-writing
IDEA 'myfile.unv' REWR MAPP
DIME TERM
FIN
```

This input reads in universal file ‘myfile.unv’, re-orders the mesh and produces a new universal file ‘myfile.unvnew’.

It is important to note that in order to post-process the EUROPLEXUS results with I-DEAS, use should be made of the reordered universal file (myfile.unvnew in the above example).

Example 2: EUROPLEXUS input file:

```
$------------------------------------
Example of use of IDEAS universal file: 2. actual computation
IDEA 'myfile.unvnew'
DIME
...
(problem definition, using 'permanent group' names)
FIN
```

In this second example, the geometry is read from the re-ordered universal file, and in any successive input directive the names of permanent groups may be used to define element or node lists. The syntax is the same as with CAST3M objects.

MED mesh

When the MEDL directive is used, the program reads the mesh from a MED file. This file may contain other information besides the mesh. If the file comes from EPX or Code_Aster, displacements, velocities, strains, stresses and internal variables could be read and used for the initialization. (See description on page GBE_0180). Other extra informations are ignored.

From the elements families and from the nodes families the program reconstructs the elements groups and the nodes groups. Groups are identified by a name, which can then be used in the EUROPLEXUS input file (like in the case of CASTEM mesh) to identify the corresponding list of nodes or elements. The elements groups described in a MED file are homogeneous 'blocks' of the same geometric support.

Note that the MED elements numbers are not necessarily the EUROPLEXUS elements numbers.

A summary of the resulting blocks is printed on the listing.

Warning

For an axisymmetric computation, the program considers a sector of ONE RADIAN. Therefore, all the forces, added masses, etc. must be defined correspondingly.

This has to be taken into account in particular when defining the mass associated to a material point: the "true" mass shall be divided by 2π.

Example:

If the whole force is F_{tot}, the force to be introduced in EUROPLEXUS is:

$$F_{\text{plex}} = \frac{F_{\text{tot}}}{2\pi}.$$

4.4.1 MODELING OF ADVECTION-DIFFUSION PHENOMENA

EUROPLEXUS includes a module for the modeling of advection-diffusion phenomena. This module stems from the TRAFLU-2D and TRAFLU-3D codes developed at JRC Ispra in the late eighties [53, 54].

The module is activated by using elements of type ADQ4 (in 2D) or ADC8 (in 3D), the ADFM material, specific generalised "loads" (see page F.320) and initial conditions (see page E.85), and specific options (see page H.70). Here is a synthetic description of these models, borrowed from [54].

The model uses a quasi-explicit finite element algorithm for the solution of the basic equations describing combined conductive and convective transfer of heat in a liquid. The presence of enclosing solid (rigid) structures is accounted for.

The governing equations in the fluid region are the incompressible Navier-Stokes equations and the thermal energy equation. These equations are treated in an Eulerian frame of reference and they are expressed in terms of primitive variables: velocity, pressure and temperature.

The flow is assumed to be laminar and the fluid Newtonian and incompressible within the Boussinesq approximation. Either the velocity components or the total surface stress are specified as boundary conditions for the Navier-Stokes equations.

The governing equation in the solid is the transient heat conduction equation. Boundary conditions are of prescribed temperature, imposed normal heat flux and heat transfer by convection or radiation.

Spatial discretization is achieved by means of four-node quadrilateral elements in 2D (ADQ4) or eight-node hexahedral elements in 3D (ADC8) with multi-linear velocity and temperature fields. The pressure is assumed uniform over each fluid element.

A fractional step method is employed for time integration of the Navier-Stokes and thermal energy equations. This consists of three distinct steps dealing, respectively, with the advective terms, the viscous/diffusion terms and the pressure/incompressibility terms.

A second-order explicit Taylor-Galerkin method is used in the advection step, where the mass matrix is retained in its consistent form to improve phase accuracy.

A first-order explicit Euler method is used in the viscous-diffusion phase. Here the mass matrix is put into diagonal form.

Finally, a first-order implicit method is used in the pressure phase for the momentum equations. The pressure field itself is obtained as solution of a linear algebraic system arising from the discrete form of the incompressibility condition.

4.4.2 TYPE OF OUTPUT LISTING

Object:

To define the type of printed output listing. If nothing is specified, in extremely large model computations the standard listing could be very large. Therefore, it may be useful to selectively reduce the printed information via the following directives.

Syntax:

```
< $ "LIST"

    | "COOR" ; "ELEM" ; "GIBI" ; "GRIL" ; "EPAI" ; "NORM" ; "NONE" |

    "TERM" $ >
```

`COOR`

the initial nodal coordinates will be printed on the output listing; furthermore, the principal directions of inertia of COQI element nodes will also be printed

`ELEM`

the mesh topology (element nodes) will be printed on the output listing

`GIBI`

the composition of CASTEM2000 objects will be printed on the output listing

`GRIL`

the characteristics of ALE grid motion will be printed on the output listing

`EPAI`

the initial element thicknesses will be printed on the output listing

`NORM`

the FSA and FSR normals will be printed on the output listing

`NONE`

none of the above quantities will be printed on the output listing

Remarks

By default, i.e. in the absence of the `LIST` directive, all the above quantities are printed out in the normal way. When the `LIST` directive is encountered, all the above printouts are inhibited, i.e. the effect is the same as with `LIST NONE`. Any of the keywords `COOR` ... `NORM` may then be used to re-activate the printing of selected quantities. In this case, however, printing of sequences of integer numbers occurs in a "compact" way, in the sense that any sequence of four or more **consecutive** numbers n_1, n_2, ..., n_n is listed simply as 'n_1 to n_n'. In many cases this allows important savings in the quantity of output data.

For example, the directive:

```
LIST NONE ELEM EPAI TERM
```

would print only the mesh topology and element thicknesses.

To obtain the most compact listing, use `LIST NONE TERM`.

Another way of obtaining a compact listing is the option `OPTI NOPR`, see Page H.50. However, that directive does not allow selective printout.

4.5 MPI GLOBAL OPTIONS

Object:

Optional global options to set for MPI calculations:

- `SCLM` toggles aggressive memory distribution, coming with restrictions upon output and qualification options (**still under strong development**),
- `BMPI` prevents current dataset to be run without MPI.

Syntax:

```
< "SCLM" <"DTUN"> <"PMET"> <"ROB" <"REGU"> <"CART"> <"CINI">
        <"WFIL" <ndwfil>> <"DACT" /LECDDL/> <"DPRE" ipre>
        <"IOPT" iopt> >

< "BMPI">
```

`DTUN`

Multiple time scales treatment (one per subdomain) is deactivated. Every subdomain has the same time scale (see comment below).

`PMET`

ParMetis library is used to perform domain decomposition.

`ROB`

Recursive Orthogonal Bisection algorithm is used to perform domain decomposition (see comment below).

`REGU`

Activates a regularizaing step for ROB domain decomposition to avoid quasi-orphans (i.e. elements sharing a majority of their faces with elements from another subdomain). The purpose is to optimize interfaces and to provide robustness for geometric operations associated with mesh adaptivity.

`CART`

MPI only. Activates an optimization step improving the splitting of elements located on located on a plane orthogonal to the actual cutting direction during ROB decomposition. Concerned grid cells must then be selectively chosen using the directive "OPTI DOMD CART" after the GEOM directive and before the MATE directive.

`CINI`

Automatic domain decomposition with ROB after a restart is performed using initial coordinates instead of current coordinates.

`WFIL`

Use of an element weight file for automatic domain decomposition (see comment below).

`ndwfil`

Number of the logical unit of the weight file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is .wgt.

`DACT`

Selection of active directions (from 1 to 2 in 2D, from 1 to 3 in 3D) for automatic domain decomposition using ROB.

`ipre`

Number of the first cutting direction for automatic domain decomposition using ROB (see comment below).

`iopt`

Level of memory optimization (see comment below).

`BMPI`

When present, the current dataset can only be run using MPI.

Comments:

Keywords to be used with `SCLM` option are very close to the ones dedicated to the `STRUCTURE` directive with automatic domain decomposition activated (keyword `AUTO`, see page I.15). Indeed, to provide an optimized memory distribution, the domain decomposition has to be defined and performed before the global data structure is built and initialized, which is not the case when using the `STRUCTURE` directive just before launching the calculation. Only automatic domain decomposition can be defined this way. See comments on page I.15 for a complete description of keywords `DTUN`, `PMET`, `ROB`, `CINI`, `WFIL`, `DACT`, `DPRE`.

When activating memory optimization for MPI calculations with `SCLM` option, **the `STRUCTURE` directive must not be used**, since domain decomposition has already been defined.

`IOPT` keyword is used to define the level of memory optimization: the more aggressive the optimization is, the more restrictions upon output and qualification there are.

- Level 0: all centralized outputs are forbidden (`ECRI` directive), except listing printouts, `ALICE` and `ALICE TEMPS` files (without time splitting), distributed `PVTK` files (`MPI` keyword) and `MED` files.
- Level 1: same as level 0, plus immediate qualification `QUAL` directive just after `CALCUL` directive also forbidden.

TIP: The right way to deal with restrictions imposed by `SCLM` option is to write an ALICE file during the parallel calculation within a series of time-steps of interest and then to generate the desired output files and perform the desired qualifications from this file.

4.6 DIMENSIONING

Object:

Allocation of memory for the problem variables.

Syntax:

```
"DIMENSION"
```

Comments:

The dimensioning of variables data is specified by keywords, which enable the user to reserve for a given problem only the memory that will be really necessary to perform the computation. All the dimensions are maximum values, their value by default is 0 (unless a different value is specified in the description).

On the following pages, the keywords have been classified according to the data they affect. Actually, they can be provided in any order. These keywords together form the directive "DIMENSION".

4.6.1 DIMENSIONS RELATIVE TO GROUP B (GEOMETRY)

These dimensions concern the geometry (elements) and, in ALE computations, the motion of grid nodes.

Overview:

The overall syntax is as follows:

```
< NPOI np   >  < NDDL   nd >
< "typ1" n1 "typ2" n2 ...  >

< ADAP NPOI np <NIND ni> <NVFI nvfi> <NTHR nthr> <NPIN npin>
       "typ1" n1 "typ2" n2 ... ENDA >

< DECO NPOI np ENDD >

< NALE nale >  < NBLE nble >

< NGPZ mxngpz >

< ME1D me1d >
```

NODES

Syntax:

```
< "NPOI" np  >  < "NDDL" nd >
```

np

Maximum number of mesh points. This parameter **is not necessary**, except some special cases. (Cf. comment below).

nd

Total number of degrees of freedom. This parameter **is not necessary**, except some special cases. (Cf. comment below).

Comments:

Normally EUROPLEXUS detects automatically the exact number of nodes (and the number of degrees of freedom), the exact number of each element types required, from the input file or from the associated mesh file. Therefore, the directives `NPOI`, `NDDL` and `TYPi` are usually not necessary.
These directives are needed only in special cases, whereby EUROPLEXUS has to create additional nodes (not specified in the input nor in the associated mesh file) after the reading of the geometry: for example a pipeline circuit with a bifurcation, a rigid body, or in case of remeshing.

NUMBER OF ELEMENTS

Object:

The number of the different elements that will be used in the problem is specified (if necessary).

Syntax:

```
| "typ1" n1 "typ2" n2 .....  |
```

`typi`

name of an element type (see page INT.80).

`ni`

maximum total number of corresponding elements.

Comments:

Normally EUROPLEXUS detects automatically the exact number of each element type required, from the input file or from the associated mesh file. Therefore, theses directives are usually not necessary. These directives are needed only in special cases, whereby EUROPLEXUS has to create additional elements (not specified in the input nor in the associated mesh file) after the reading of the geometry: for example a pipeline circuit with a bifurcation, a rigid body, in case of remeshing, or in case of flying debris.

The various elements are described on page INT 80.

Warning :

If you use 1-D elements (except ED1D), the directives:

```
"TRID"  "EULE"
```

are mandatory in the definition of the problem type (page A.30).

ADAPTIVITY (Adaptive Mesh Refinement)

Purpose:

This optional sub-directive allows to set the dimensions for the automatic mesh refinement during a computation, as required e.g. in adaptivity. The directive syntax is similar to that described in the previous pages for the “base” mesh. The user must define the maximum number of nodes, of degrees of freedom, and of elements (for each element type which can be refined) that are allowed to be “created” during the transient calculation. This is referred to as the “extension” zone as opposed to the “base” zone containing the base (normal) mesh. The optional directive must be terminated by the keyword `ENDA`.

Syntax:

```
< ADAP
      NPOI np <NIND ni> <NVFI nvfi> <NTHR nthr> <NPIN npin>
      "typ1" n1 "typ2" n2 ...
  ENDA >
```

`np`

Maximum number of mesh points in the extension zone.

`ni`

Total number of error indicator variable types used in the adaptive calculation. For example, if one wants to use both displacement and velocity as indicators, then it must be `NIND 2`. By default (i.e. if this keyword is omitted) only one error indicator variable is allowed. This quantity is used only in adaptive calculations with the error indicator.

`nvfi`

Maximum number of cell-centred finite volume (VFCC) interfaces in the extension zone. This quantity is used only in adaptive calculations with VFCC fluids.

`nthr`

Total number of threshold indicator variable types used in the adaptive calculation. For example, if one wants to use both displacement and velocity as indicators, then it must be `NTHR 2`. By default (i.e. if this keyword is omitted) only one threshold indicator variable is allowed. This quantity is used only in adaptive calculations with the threshold indicator.

`npin`

Maximum number of parent (0-level) pinballs in the extension zone. Such pinballs are automatically created during the mesh refinement process if the element being split has an attached (parent) pinball (and this recursively).

`n1, n2 ...`

Total number of elements of type ”typ1”, ”typ2” etc. in the extension zone. For the names of the element types see pages INT.80, INT.90 and INT.100.

Comments:

The number of degrees of freedom in the extension memory zone (i.e. the dofs relative to the adaptive nodes) is automatically computed by the code as the number of nodes in the extension zone (`np`) multiplied by the space dimension (2D or 3D). This implies of course that only elements whose nodes do not have any rotational dofs can be used in adaptivity, for the moment.

DECOHESION (Automatic Separation of the Elements)

Purpose:

This optional sub-directive allows to set the maximum number of created nodes during a computation as required for this numerical method (Automatic Separation of the Elements). Automatic separation of the elements is only available for CUB8 elements affected by the BOIS (wood) material. More explanations can be found in [928]. The optional directive must be terminated by the keyword `ENDD`.

Syntax:

```
< DECO
       NPOI np
  ENDD >
```

`np`

Maximum number of created nodes during a computation.

Comments:

For the moment this method (Automatic Separation of the Elements) is only available for CUB8 elements affected by the BOIS (wood) material.

GRID MOTION (A.L.E.)

Syntax:

```
< "NALE" nal  >  < "NBLE" nbl  >
```

`nale`

Maximum number of ALE nodes subjected to manual (i.e., non-automatic) rezoning. To be used only in ALE computations. The nodes are specified by the `GRIL` directive. By default (i.e., if not specified) the code assumes `nale` = 1 for ALE calculations.

`nble`

Maximum number of ALE nodes subjected to automatic rezoning. To be used only in ALE computations. The nodes are specified by the `GRIL` directive. By default (i.e., if not specified) the code assumes `nble` = 1, for ALE calculations.

SPACE INTEGRATION FOR SHELL AND BEAM ELEMENTS

Syntax:

```
< "NGPZ" mxngpz  >
```

`mxngpz`

Maximum number of Gauss Points through the thickness for shell, plate or beam elements which are integrated through the thickness. This value overrides the default value set in INICO1 for each of these element types. This value is global and affects *all* the concerned element types. To set the “true” number of integration points through the thickness for each element (possibly a different value for each element), see the `COMP` directive (Geometrical Complements) on page C.42.

MEMORY FOR ED1D CALCULATIONS

Syntax:

```
< "ME1D" mead  >
```

`me1d`

Length of memory table (in REAL*4) for the ED1D calculations, in case of a coupled 1-D/multi-D calculation. The 1-D part is computed by the EURDYN-1D code, now embedded in EUROPLEXUS (see Page I.23). The default value of `me1d` is $50,000$.

4.6.2 DIMENSIONS RELATIVE TO GROUP C (MATERIALS)

Object :

Dimensions relative to the materials used.

Syntax :

```
< "LMAS" lmas >
< "ECRO" lecr >
< "PYRO" mxpyro >
```

`lmas`

Size of the consistent mass matrix.

`lecr`

Maximum length of the vector of parameters associated to materials (ECR). This parameter **is not necessary**, except some special cases. (Cf. comment below).

`mxpyro`

Maximum number of distinct oil pyrolisis bubbles (material `FLUT ... PYRO`, see page C.530). This material is part of the models developed by the CESI team (formerly at ENEL, Milano) in collaboration with JRC.

Comments :

Normally EUROPLEXUS detects automatically the exact length of the ECR vector associated to materials, from the input file. Therefore, the directive `ECRO` is usually not necessary. This directive is needed only in special cases, whereby EUROPLEXUS has to create additional elements (not specified in the input nor in the associated mesh file) after the reading of the geometry: for example a pipeline circuit with a bifurcation, a rigid body, or in case of remeshing.

It is compulsory to enter the size of the consistent mass matrix, when the computation includes the material ”MHOM”.

4.6.3 DIMENSIONS RELATIVE TO GROUP D (CONNECTIONS)

Object:

Dimensions relative to the couplings.

Syntax:

```
< "MXLI" maxlie >        < "LNOD" maxnod>    < "LCOF" maxcof >
< "GLIS" nslid nemax >   < "JONC" njonc >
< "NPEF" nmpef    "NPTS" nomax >             < "SOLI" nsol >
< "MECA" nmeca >
< "FSSA" mxfssa >      < "FSSL" mxfssl >      < "FSSF" mxfssf >
< "NBJE" nbjeux >
< "VCON" mxvcon >
```

`maxlie`

Total number of connections in the 'LIAISONS'. This parameter **is not necessary**, except some special cases. (see comment below).

`maxnod`

Total number of nodes involved in the 'LIAISONS'. This parameter **is not necessary**, except some special cases. (see comment below).

`maxcof`

Total number of coefficients used in the 'LIAISONS'. This parameter **is not necessary**, except some special cases. (see comment below).

`nslid`

Number of couples of sliding lines.

`nemax`

Total number of nodes defining these lines (master AND slave).

`njonc`

Maximum number of nodes involved in each junction of type "TUBM" or "TUYM" (including the 1D node) and in each junction of type "TBM2" (considering both sides of the junction). That is, in each junction of type "TUBM" or "TUYM" compute the number of nodes on the 3D part of the junction, and add 1 (for the node on the 1D part of the junction). Then, for each junction of type "TBM2" compute the total number of nodes on the two sides of the junction. Finally, take the max of the above results over all junctions.

`nmpef`

Number of "particle-structure" couples.

`nomax`

Total number of nodes defining these "particle-structure" couples.

`nsol`

Number of rigid solids.

`nmeca`

Total number of mechanisms.

`mxfssa`

Maximum number of nodes or element side couples subjected to fluid-structure sliding of the ALE type according to JRC's model (see directive "FSS" "ALE").

`mxfssl`

Maximum number of nodes or element side couples subjected to fluid-structure sliding of the Lagrangian type according to JRC's model (see directive "FSS" "LAGR").

.

`mxfssf`

Maximum number of nodes or element side couples subjected to fluid-structure sliding of the fixed type according to JRC's model (see directive "FSS" "FIXE").

`nbjeux`

Number of couples of nodes to which an impact with gap is associated.

`mxvcon`

Maximum total number of parameters used to define bilateral constraints (CONT SPHE, CYLI, CONE, TORE) with variable coefficients (OPTI CONT VARI). Each sphere requires 3 parameters, each cylinder or cone requires 6 parameters, and each torus requires 9 parameters).

Comment:

Normally EUROPLEXUS detects automatically the exact number of LIAISONS parameters required, from the input file. Therefore, the directives `MXLI`, `LNOD`, `LCOF`, ... **are usually not necessary**. These directives are needed only in special cases, whereby EUROPLEXUS has to create additional nodes or additional elements.

4.6.4 DIMENSIONS RELATIVE TO GROUP G (PRINTOUTS)

Object:

Dimensions relative to printout and storage keywords.

Syntax:

```
< "MTTI" mttime >   < "MNTI" mntime >
< "NFRO" nfront >   < "NPFR" npfron >
< "NEPE" nepedi >
```

`mttime`

Maximum number of times for which the printing/storage of the results is requested.

`mntime`

Maximum number of time steps for which the printing/storage of the results is requested.

`nfront`

Number of borders ('frontiere') for which the calculation of resultants is requested.

`npfron`

Total number of nodes involved (by putting all borders together).

`nepedi`

Length of the memory reserved for the vector NEPEDI which is constructed in subroutine edit1. The code normally computes this automatically.

4.6.5 DIMENSIONS RELATIVE TO GROUP I (CALCULATION)

Object:

Dimensions relative to the calculation run.

Syntax:

```
< "TTHI" mtthis >
```

`mtthis`

Maximum number of time values for which the solution has to be computed, in case of "PAS UTIL" option and "CALC" ... "HIST" (the time marching is imposed by the user).

4.6.6 DIMENSIONS RELATIVE TO ADVECTION-DIFFUSION

Object:

Dimensions relative to advection-diffusion problems as declared by keyword "ADDF" above in this section.

Syntax:

```
< "ELSN" mxelsn   "BWDT" mxbwdt   "TPOI" mxtpoi
  "ELGR" mxelgr   "CVEL" mxcvel   "GRPS" mxgrps >
```

`mxelsn`

Maximum number of elements surrounding (i.e., connected to) any given node.

`mxbwdt`

Maximum bandwidth of pressure matrix (for direct solution) or maximum number of elements surrounding an element (for iterative solution).

`mxtpoi`

Maximum number of time points for prescribed time-dependent 'charges' in advection-diffusion problems (temperatures, heat flux, heat generation, heat convection, heat radiation, external pressure, velocities).

`mxelgr`

Maximum number of elements in each group with prescribed time-dependent 'charges'.

`mxcvel`

Maximum number of nodes with constrained velocities.

`mxgrps`

Maximum number of groups with prescribed time-dependent 'charges'.

4.6.7 END OF DIMENSIONING

Syntax:

```
"TERM"
```

Comments:

The word "TERM" marks the end of the dimension, it must appear.

5 GROUP B—MESH AND GRID MOTION

Object:

The following directives enable to define the mesh.

Syntax:

- Mesh generated by COCO or in free format:

```
"GEOM" <optional mesh manipulation commands> ... "TERM"
       ... COCO data or free format data ...
```

- Mesh generated by GIBI:

```
"GEOM" <optional mesh manipulation commands>
       ("nomelm" ('nomobjet') ) "TERM"
```

- Mesh generated by I-DEAS:

```
"GEOM" <optional mesh manipulation commands>
       (... zone declaration list ...) "TERM"
```

- Mesh generated by LS-DYNA (k-file) (see GBB_0055):

```
"GEOM" <optional mesh manipulation commands>
       ("nomelm" ('nomobjet') ) "TERM"
```

Comments:

These directives are described in detail on the following pages.

The `GEOM` directive accepts some simple optional mesh manipulation commands that can be used to scale, shift, etc. the mesh read from an external mesh generator before starting the transient calculation. These commands affect only the nodal coordinates, but not the mesh connectivity. They are described below on page GBB_0015.

5.1 OPTIONAL MESH MANIPULATION COMMANDS

Object:

To manipulate the mesh coordinates read from an external mesh generator before starting the transient calculation. For example, the mesh can be scaled, translated, centred, etc. Note that these commands only affect the (initial) nodal coordinates, they do not affect the elements (i.e. the connectivity).

Syntax:

```
< SCAL $[ FACT fc ;
          FACX fx ; FACY fy ; <FACZ fz> ]$ >
< SHIF $[ CENT ;
          SHIX sx SHIY sy <SHIZ sz> ]$ >
```

`SCAL`

Scale the coordinates of the mesh to be subsequently read in input either isotropically (i.e. by the same factor `fc` along all axes), or anisotropically.

`fc`

Isotropic scaling factor.

`fx`

Scaling factor along the x direction (by default 1.0).

`fy`

Scaling factor along the y direction (by default 1.0).

`fz`

Scaling factor along the z direction (by default 1.0).

`SHIF`

Shift the coordinates of the mesh to be subsequently read in input either in such a way that it is centered around the origin, or by specified amounts in each spatial direction.

`CENT`

Shift the coordinates of the mesh to be read in input in such a way that it is centered around the origin.

`sx`

Shift along the x direction (by default 0.0).

`sy`

Shift along the y direction (by default 0.0).

`sz`

Shift along the z direction (by default 0.0).

Comments:

The above commands, in particular the scaling commands, can be useful e.g. in case the geometry has been produced by an external mesh generator in some non-standard units. For example, assume the mesh has been generated in millimetres rather than metres. To convert to metres use the command `GEOM SCAL FACT 0.001 ...`

Note that the mesh manipulation occurs immediately after reading the nodal coordinates, so that the coordinates printed on the listing are the corrected ones, not the ones read from the input file.

Note that in case of simultaneous mesh scaling and shifting, the scaling occurs first, then the shifting is applied. Therefore, the shift amounts should be given in the corrected (scaled) mesh units, not in the original mesh units.

5.2 MESH IN COCO-LIKE OR IN FREE FORMAT

5.2.1 GEOMETRY

Object:

To read the mesh (i.e. the nodal coordinates and the elements connectivity) either in “free” format or in a fixed (COCO-like) format.

In the first case, the mesh data are read directly from the input file.

In the second case, the (fixed) format used for the mesh data must be specified and then the mesh data can either be read directly from the main input file, or from an external file whose unit number (`nl` in the following) is specified by the user. This second possibility can be handy e.g. to un-clutter the main input file in case of large mesh data, or to read a (formatted) mesh data set produced by an exotic mesh generator for which no direct EPX interface exists.

Syntax:

```
"GEOM"  $[        < "LIBR" >   < "POLA" >      ;
          < nl > < '(format1)'  '(format2)' > ]$

"POIN"  npoin
```

`LIBR`

The file describing the geometry will be read in free format.

`POLA`

Nodes are specified by their polar coordinates (by default Cartesian coordinates). In 2D, first enter the radius (R), then the angle (θ) in degrees for each node. In 3D, the third coordinate is interpreted as the elevation Z, thus the coordinate system is cylindrical. The corresponding Cartesian coordinates are computed according to: $x = R\cos(\theta)$, $y = R\sin(\theta)$ and $z = Z$ (3D only).

`nl`

Logical number of input unit (file) from which the geometry will be read. By default, nl=5 (15 at JRC). If it is omitted, then the core will read the mesh data directly from the (main) input file.

`format1`

Reading format of nodal coordinates. By default format1=6E12.5.

`format2`

Reading format of the numbers of the nodes composing the elements (i.e. the elements connectivity). By default format2=18I4.

`npoin`

Exact number of mesh nodes.

Comments:

If nothing is specified after the word "GEOM", the file describing the geometry is assumed to be in COCO format, it is read from logical unit 5 (15 at JRC) with the formats: format1 and format2.

If the formats are modified, they must be enclosed in parentheses AND in apostrophes.

Example:

```
"GEOM"  '(5E20.12)' '(16I5)'  "POIN" 123
```

The option "LIBR" is particularly useful for a simple mesh when the user himself prepares the coordinates and the topology.

In the case of polar coordinates, EUROPLEXUS transforms them into Cartesian coordinates for the following computations. If outputs in polar coordinates are desired, see keyword "OPTION".

The number of nodes npoin must not be greater than the number declared for the dimension (page A.40).

In order to read the mesh data from an external file, specify the `nl` unit number (an integer value) just after the `GEOM` keyword. This is treated as a file without a name. In Fortran, the actual (default) name of the file may vary depending upon the platform. For example, under Windows by choosing unit number 9, the code will try to open a file called `fort.9` for reading and will attempt reading the mesh data from this file. It is the responsibility of the User (or of the code-launching procedure) to make such a file available on the current directory. Under Windows, for example, unit 9 is the unit normally devoted to the `.msh` file, in case of mesh produced by Cast3m. Therefore the launching procedure automatically creates a `fort.9` file by copying the `.msh` file (if this exists). So the simplest way to read the mesh from an external file under Windows is to use the value 9 for `nl` (`GEOM 9 ...`) and to put the formatted mesh data in a file called `<base>.msh` where `<base>` is the base name of the main input file. See also the practical examples below.

5.2.2 ELEMENT ZONES

Object:

Each of the following keywords defines a zone of elements of the given type, that are sequentially numbered.

Syntax:

```
| "typ1" n1 "typ2" n2 ... |

  "TERM"

...   COCO data set with its title
        (title is optional if free format, see "LIBR")  ...
```

`typi`

Name of an element type (see page I.80).

`ni`

Number of elements in the zone

`TERM`

Marks the end of the directive GEOMETRY.

Comments:

The various elements are described on page INT.80.

The number of the elements announced for a zone must correspond exactly to the elements defined in the COCO data set.

The same type of element can occupy several zones.

The number of zones must be less than or equal to the one given during the dimensioning (p. A.40).

In the COCO data set, the topology of the elements must be read by zones, and these zones are arranged in the order of their definition in the directive "GEOM".

The word "TERM" is compulsory to indicate the end of the keyword GEOMETRY.

The title appearing before the coordinates of the points is not compulsory when reading in FREE format (see "LIBR").

In order to become acquainted with the keyword "GEOM" the user may have a look at the examples on pages EX 10 and on the following ones.

Warning

There is a mandatory logical order for the 1-D elements (except ED1D). These elements are to be subdivided in 3 groups, which are respectively:

- 1st group: TUBE and TUYA,
- 2nd group: CL1D and CLTU,
- 3rd group: CAVI and BIFU.

Further information allowing to completely define the properties of "CAVI" and "BIFU" elements are given by the "RACCORD" sub-directive of the "COMPLEMENT" directive (GBC_0080).

The elements of type "BIFU" cause the automatic generation of connections between the concerned d.o.f.s. It is therefore mandatory to list them again in the "LIAISON" directive: see this directive.

The junction elements "CAVI" and "BIFU" must possess the same materials as the neighbour elements of which they ensure the continuity.

5.2.3 EXAMPLE: MESH FROM FORMATTED EXTERNAL FILE

Hereafter a simple example is given of how to read the mesh data with a fixed (COCO-like) format. In a first case, we will read the data directly from the (main) input file. Then we will show how to read the data from an auxiliary file, so that the (main) input file is more compact and legible.

Here is the complete input file with formatted mesh read directly from the main input file (test00.epx):

```
TEST00 - MESH READ FROM THE MAIN INPUT FILE WITH FIXED FORMAT
LAGR AXIS
GEOM '(2E22.15)' '(7I10)' POIN 18
     Q92 1 Q93 1 ED01 2 TERM
The following is the mesh data in fixed format
 1.000000000000000E+00 0.000000000000000E+00
 1.500000000000000E+00 0.000000000000000E+00
 2.000000000000000E+00 0.000000000000000E+00
 2.500000000000000E+00 0.000000000000000E+00
 3.000000000000000E+00 0.000000000000000E+00
 1.000000000000000E+00 0.500000000000000E+00
 1.500000000000000E+00 0.500000000000000E+00
 2.000000000000000E+00 0.500000000000000E+00
 2.500000000000000E+00 0.500000000000000E+00
 3.000000000000000E+00 0.500000000000000E+00
 1.000000000000000E+00 1.000000000000000E+00
 1.500000000000000E+00 1.000000000000000E+00
 2.000000000000000E+00 1.000000000000000E+00
 2.500000000000000E+00 1.000000000000000E+00
 3.000000000000000E+00 1.000000000000000E+00
 0.000000000000000E+00 0.000000000000000E+00
 1.000000000000000E+00 1.000000000000000E+00
 1.000000000000000E+00 2.000000000000000E+00
         1         2         3         8        13        12        11
         6         7
         3         4         5        10        15        14        13
         8         9
        16        17        17        18
* Mesh data is finished, we continue reading the (main) input data
COMP EPAI 1. LECT 1 PAS 1 4 TERM
MATE VM23 RO 8000. YOUN 1.D11 NU 0.3 ELAS 2.D8
          TRAC 3 2.D8 2.D-3 3.D8 1. 3.1D8 2.
          LECT 1 2 TERM
     VM23 RO 4000. YOUN 2.D11 NU 0.2 ELAS 4.D8
          TRAC 2 4.D8 2.D-3 6.D8 1.
          LECT 3 4 TERM
LINK COUP
     BLOQ 12 LECT 5 PAS 5 15 TERM
     BLOQ 123 LECT 16 TERM
INIT VITE 2 300 LECT 6 PAS 1 9 TERM
     VITE 1 -200 LECT 6 PAS 1 8 TERM
```

```
     VITE 2 -100 LECT 17 TERM
     VITE 1 200 LECT 18 TERM
ECRI DEPL VITE ACCE FINT FEXT FLIA FDEC CONT ECRO FREQ 100
     FICH ALIC FREQ 1
OPTI PAS UTIL NOTE LOG 1
CALCUL TINI 0. TEND 0.001D0 PASF 1.D-5
FIN
```

The data are read directly from the main input file because no unit number (`nl`) is specified after the `GEOM` keyword. Instead of using the default reading formats we choose a format 2E22.15 for the nodal coordinates and a format 7I10 for the connectivity.

Note that a comment line (reading "The following is the mesh data in fixed format") must be put before the actual mesh data.

The mesh data start with the nodal coordinates. Two values (in 2D cases) or three values (in 3D cases) must be specified for each node, and this for the exact number of nodes (`POIN`) chosen by the user. Coordinates are read as a single block of data using the user-specified format.

Then, the element connectivity has to be specified, i.e. the nodes of each element. These data are read element zone by element zone, since each element type may have a different number of nodes. The element zones correspond to the declaration of the element types given by the user (`Q92 1 Q93 1 ED01 2`, i.e. three zones in the example).

In this example, the first zone has a single Q92 element, which has 9 nodes. This takes two lines of input to specify, since we have chosen to put only seven values per line. The second zone has one Q93 element and is similar to the first one. The third and last zone contains two ED01 elements, each with two nodes. Only one line (4 values) of input is needed for this.

Now we show how to modify the previous example in order to read the mesh data from an external input file.

The main input file (test01.epx) reads:

```
TEST01 - MESH READ FROM AN AUXILIARY INPUT FILE WITH FIXED FORMAT
LAGR AXIS
GEOM 9 '(2E22.15)' '(7I10)' POIN 18
     Q92 1 Q93 1 ED01 2 TERM
* Mesh data is finished, we continue reading the (main) input data
COMP EPAI 1. LECT 1 PAS 1 4 TERM
MATE VM23 RO 8000. YOUN 1.D11 NU 0.3 ELAS 2.D8
          TRAC 3 2.D8 2.D-3 3.D8 1. 3.1D8 2.
          LECT 1 2 TERM
     VM23 RO 4000. YOUN 2.D11 NU 0.2 ELAS 4.D8
          TRAC 2 4.D8 2.D-3 6.D8 1.
          LECT 3 4 TERM
LINK COUP
     BLOQ 12 LECT 5 PAS 5 15 TERM
     BLOQ 123 LECT 16 TERM
INIT VITE 2 300 LECT 6 PAS 1 9 TERM
     VITE 1 -200 LECT 6 PAS 1 8 TERM
```

```
     VITE 2 -100 LECT 17 TERM
     VITE 1 200 LECT 18 TERM
ECRI DEPL VITE ACCE FINT FEXT FLIA FDEC CONT ECRO FREQ 100
     FICH ALIC FREQ 1
OPTI PAS UTIL NOTE LOG 1
CALCUL TINI 0. TEND 0.001D0 PASF 1.D-5
FIN
```

We have chosen 9 as the unit number for the external file from which the mesh data will be read (`GEOM 9 ...`). Under Windows, this unit is automatically connected to the file `.msh` corresponding to the main input file, i.e. the launching procedure copies the `.msh` file onto a local file called `fort.9`, from which the mesh data will be read. If a different unit number is chosen, say 34, it is the responsibility of the user to provide a file `fort.34` containing the mesh data in the current directory.

The mesh file (test01.msh) reads:

```
The following is the mesh data in fixed format
 1.000000000000000E+00 0.000000000000000E+00
 1.500000000000000E+00 0.000000000000000E+00
 2.000000000000000E+00 0.000000000000000E+00
 2.500000000000000E+00 0.000000000000000E+00
 3.000000000000000E+00 0.000000000000000E+00
 1.000000000000000E+00 0.500000000000000E+00
 1.500000000000000E+00 0.500000000000000E+00
 2.000000000000000E+00 0.500000000000000E+00
 2.500000000000000E+00 0.500000000000000E+00
 3.000000000000000E+00 0.500000000000000E+00
 1.000000000000000E+00 1.000000000000000E+00
 1.500000000000000E+00 1.000000000000000E+00
 2.000000000000000E+00 1.000000000000000E+00
 2.500000000000000E+00 1.000000000000000E+00
 3.000000000000000E+00 1.000000000000000E+00
 0.000000000000000E+00 0.000000000000000E+00
 1.000000000000000E+00 1.000000000000000E+00
 1.000000000000000E+00 2.000000000000000E+00
         1         2         3         8        13        12        11
         6         7
         3         4         5        10        15        14        13
         8         9
        16        17        17        18
```

5.3 MESH IN CASTEM FORMAT

Object:

To define the objects associated to each element type.

Syntax:

```
"GEOM"  (  "nomelm"  (  'nomobjet'  )  )  "TERM"
```

`nomelm`

Name defining the type of element to be taken from the list of available elements.

`'nomobjet'`

Name of the GIBI object(s)

`TERM`

End of the directive "GEOM"

Comments:

The names of the available elements may be found on page GBINT_0080, the same keywords are used as in the case of COCO or free-format data (see the chapter ELEMENT ZONES).

The names of the elements cannot be used for other purposes. This explains why the names of the GIBI objects cannot begin with the same first four letters as the name of an element.

Several objects may be associated to a certain type of element. In order to obtain, on the GIBI drawings, the same node and element numbers as on EUROPLEXUS, write in GIBI:

```
"TRAC" ('objet1' "ET" 'objet2' "ET" 'objet3') ...;
```

in the same order as for the instruction "GEOM" of the EUROPLEXUS program.

There is a zone each time a name of an element is specified. Do not forget to sufficiently dimension the number of zones (page A.40).

Warning

The elements with variable number of nodes such as "CAVI" and "BIFU" may be simply generated by GIBI by means of so-called super-elements:

```
my_junction = 'MANU' 'SUPE' pt1 pt2 ... ptn ;
```

It is also possible to use topologically equivalent elements:

```
my_junct_1 = 'MANU' 'POI1' pt1 ;
my_junct_2 = 'MANU' 'SEG2' pt1 pt2 ;
my_junct_3 = 'MANU' 'TRI3' pt1 pt2 pt3 ;
my_junct_4 = 'MANU' 'QUA4' pt1 pt2 pt3 pt4 ;
my_junct_5 = 'MANU' 'PYR5' pt1 pt2 pt3 pt4 pt5 ;
   etc...
```

However, in order to generate a K2000 file correct for post-treatment, it is necessary that such objects be formed by one single element.

The elements of type "BIFU" cause the automatic generation of connections between the concerned d.o.f.s. It is therefore mandatory to list them again in the "LIAISON" directive: see this directive.

5.3.1 Superposed elements in a Cast3m mesh (color problem)

A problem may arise with meshes generated by Cast3m containing **superposed elements**, for example a structure made of 3D shells to which a layer of CLxx elements is attached in order to apply an external pressure. In this case, each structural element has the same nodes as the corresponding CLxx element.

EPX treats superposed elements correctly (i.e., in the way that is probably expected by the user) only if the two elements have **different colors**. If the color is the same, the two superposed elements are accepted (without error messages) and are made part of the EPX mesh. However, they are eliminated from the Cast3m object names, and therefore these objects contain the wrong elements (the structural objects end up containing the CLxx elements). The problem seems to occur only when the CLxx object is a complex one (i.e. if it has sub-objects), that is when there is more than one pressure sub-object.

To avoid the problem the following simple rule may be used: to generate CLxx elements (say object `pres`) in Cast3m, starting from a set of existing (shell-like) structural elements (say object `stru`), use the following syntax:

```
pres = stru COUL ROUG;
```

where it is assumed that the `stru` object either has no color or has a color different from `ROUG`. This ensures that the `pres` and `stru` objects have different colors and will be correctly read in by EPX.

The frequently used alternative syntax:

```
pres = stru PLUS (0 0 0);
ELIM tol (pres ET stru);
```

is strongly discouraged (although as said it seems to work when `stru` is a single object, without sub-objects).

5.4 MESH IN I-DEAS FORMAT

Object:

To read the coordinates of the nodes and the topology of the elements from an I-DEAS universal file. The elements are declared through a list of keywords defining zones of elements of the given type, that are sequentially numbered.

Due to the fact that the I-DEAS format is quite different depending on its version special attention must be given in order to check if the mesh is read in a right way.

Syntax:

```
"GEOM" | "typ1" n1 "typ2" n2 ... | "TERM"

(same as "Mesh by means of GIBI or CASTEM")
```

Comments:

Even when reading from an I-DEAS mesh, the topology of the elements has to be read by zones, as defined in the directive `GEOM`. The user has to be sure that the list of zones declared is consistent with the data contained in the I-DEAS universal file used. In order to make this easy, a first run using the `REWR` option (see Page A.30) can be carried out; the informations to be set into the `GEOM` list can be obtained from the table printed on the listing file.

The word `TERM` is compulsory to indicate the end of the keyword `GEOM`.

5.5 MESH IN LS-DYNA FORMAT (K-FILE)

Object:

To read the coordinates of the nodes and the topology of the elements from an LS-DYNA k-file. The elements can be defined in the k-file by using the PART command. No materials or element type must be assigned to the PART in the k-file. The elements are simply defined by a list and can be grouped by node lists. The k-file can be created by using the free LS-PREPOST software.

Syntax:

```
"GEOM" | "typ1" PART n1 "typ2" PART n2 "typ3" SSOL n3
         "typ4" SSHE n4 "typ5" SBEA n5
         "typ6" SOL8 SHE4 SHE3 BEAM MASS ... | "TERM"
```

`n1, n2`

Elements taken from PART n1, n2 (also the part name can be used with a maximum length of 4 characters)

`n3, n4, n5`

Elements taken from element set n3 (also the set name can be used with a maximum length of 4 characters)

`SOL8 SHE4 SHE3 BEAM MASS`

All elements of that geometric form

In the same way, the geometry objects (PART, SSOL, SSHE, SBEA, NSET, NODE, ELEM) can be addressed later on e.g. for the material or the boundary conditions (see also GBINT_0050).

Comments:

The following k-file keywords are interpreted:

- CONSTRAINED_SPOTWELD = CONSTRAINED_SPOTWELD_ID = CONSTRAINED_NODAL_RIG
- ELEMENT_SOLID
- ELEMENT_SHELL
- ELEMENT_BEAM
- ELEMENT_MASS
- INCLUDE
- MAT_ELASTIC
- NODE

- PARAMETER
- PART
- SECTION_SHELL = SECTION_SHELL_TITLE
- SET_NODE = SET_NODE_LIST = SET_NODE_LIST_TITLE
- SET_SOLID = SET_SOLID_TITLE = SET_SOLID_LIST
- SET_SHELL = SET_SHELL_TITLE = SET_SHELL_LIST
- SET_BEAM = SET_BEAM_TITLE = SET_BEAM_LIST
- SET_PART = SET_PART_TITLE = SET_PART_LIST

The word `TERM` is compulsory to indicate the end of the keyword `GEOM`.

The names of the available elements may be found on GBINT_0080.

5.6 GRID MOTION IN AN A.L.E. COMPUTATION

Object:

These keywords enable the user to impose the motion of the mesh under the Arbitrary Lagrangian Eulerian (ALE) formulation. Therefore, this directive can only be used in an ALE computation (see keyword "ALE" on page A.30).

Attention!

If you use any "RACCORDS" 1D ("CAVI" and "BIFU"), the "GRIL" directive must be placed **after** the directive "COMPLEMENT" (see GBC_0010).

Syntax:

```
"GRILLE"  <  "LAGRANGE"   /LECTURE/      >
          <  "EULE"       /LECTURE/      >
          <  "FS"         /LECTURE/      >
          <  "BFIXE"      /LECTURE/      >
          <  "GRFS"       /LECTURE/      >

          <  "SUIVRE"  ... >
          <  "LIGNE"   ... >
          <  "CONTOUR" ... >
          <  "PLAN"    ... >
          <  "TETR"    ... >
          <  "HEXA"    ... >
          <  "PRIS"    ... >
          <  "PYRA"    ... >
          <  "SLIP"    ... >
          <  "AUTO"    ... >
          <  "MEAN"    ... >
          <  "DIRE"    ... >
          <  "QUAD"    ... >
          <  "SPEC"    ... >
          <  "MECA"    ... >
          <  "ELAS"    ... >
          <  "HYPE"    ... >
          <  "GLOB"    ... >
```

`LAGRANGE`

The following nodes are Lagrangian: the mesh is fixed to material particles.

`EULE`

List of nodes explicitly declared Eulerian, they are fixed in space but they correspond to different material particles at different times, in general.

`FS`

The user has to mention all the elements of the fluid-structure type in contact with ALE continuum (fluid) elements. In this case, the keyword "SUIVRE", to ensure the continuity of the mesh, is redundant: the keyword "FS" will do it automatically.

`"BFIXE"`

The following nodes will be considered as fixed (purely Eulerian). This directive allows thus to specify all the fixed nodes that will serve as base points for manual rezoning options to be entered successively.

`"GRFS"`

The following elements must be of the CLxx type and their nodes must be geometrically coincident with structural nodes belonging to shell elements. During the calculation, the fluid nodes will be piloted by the corresponding structural nodes like if the "SUIVRE" directive would have been specified. These elements must always be associated to the "IMPE" "GRFS" material.

Comments:

If the motion of a node is not specified, then it is supposed to be Eulerian (fixed mesh).

Several options may be set for the fine-tuning of the automatic rezoning algorithms. For more information, please see the OPTI REZO directive in GBH_0150.

For the directive GLOB see section GBB_0136.

Warning:

Do not repeat the fluid-structure couplings in the instruction "LIAISON" (except in very specific cases: perforated plates described on GBC_0330).

Do not forget to dimension sufficiently: "NALE" described on GBC_0040 (number of A.L.E. or Eulerian nodes).

The order in which the different directives appear (LAGRANGE, BFIXE, FS, SUIVRE, CONTOUR...) is important: EUROPLEXUS follows the same order during the remeshing operations.

The following rule holds:

1) A node that has to be used as base (master) point for the motion of other points must have a defined motion, else it will be considered as fixed.

2) When a point is already used as base point, its motion may no longer be re-defined.

The order of instructions use more often is:

1) First, the LAGRANGIAN nodes are defined;

2) Then, one passes to a first manual rezoning directive among (SUIVRE, LIGNE, ...) by respecting the following rule: a node may be used as base point only if its motion is already defined previously.

The points defined by this directive may then be used as base points for the following directives.

Restrictions for 1-D problems:

In the presence of bifurcations or cavities (elements "BIFU" and "CAVI"), their junctions must be defined BEFORE specifying grid motions. For further details see the directive "COMPLEMENT", sub-directive "RACCORD".

It is useless to define a grid motion for elements "TUYA". In fact, they result from the assembly of an element of type "POUT" and one of type "TUBE", and the "grid" for the internal fluid is nothing but the set of nodes that define the tube walls. EUROPLEXUS automatically ensures their motion.

5.6.1 AUXILIARY FILE

Object :

This directive allows to read the grid remeshing data from an auxiliary file.

Syntax :

```
"GRILLE"     < "FICHIER"   'nom.fic'  >
```

In certain cases these data may be bulky. Then it is advisable to store them on an auxiliary file in order to shorten the main data file. The auxiliary file is activated by means of the directive "FICHIER", followed by the name (complete under Unix) of the file. Then, in the main data file remains only the keyword "GRILLE", followed by "FICHIER".

The auxiliary file (in free format) will contain all grid rezoning data, except the "GRILLE" keyword. In order to return to reading from the main input file, the auxiliary file must terminate by the keyword "RETOUR".

5.6.2 "SUIVRE"

Object:

To force one or more A.L.E. mesh nodes to follow the motion of a "base" node.

Syntax:

```
"SUIVRE"    "BASE"   /LECTURE/
            "LIST"   /LECTURE/
```

`BASE /LECTURE/`

Number of the "base" node to be followed.

`LIST /LECTURE/`

Numbers of the A.L.E. nodes with an imposed motion.

Comments:

The particle which is present at the node is changing all the time. This instruction is therefore very different from imposing a node to be Lagrangian.

Warning:

Please read the rule for defining the base points, page B.60.

5.6.3 "LIGNE"

Object:

To impose the motion of several nodes so that they remain aligned between two "base" nodes . The initial subdivision is maintained: the segments remain in the same relation.

Syntax:

```
    "LIGNE"      "BASE"   /LECTURE/
                 "LIST"   /LECTURE/
```

`"BASE" /LECTURE/`

Numbers of the 2 base nodes which will impose the motion.

`"LIST" /LECTURE/`

Numbers of A.L.E. nodes lying between the two proceeding points and following the motion. The list can safely include also the two base nodes: if present, they are automatically discarded from the list.

Comments:

It is possible to have roughly aligned points, but if the basic points are very distant from each other, the computation tends to realign the points (and vice versa).

Warning:

Please read the rule for defining the base points, page B.60.

5.6.4 "PLAN"

Object:

To impose a homeomorphic motion to several nodes of the grid describing a triangle or a quadrangle. This command is available both in 2D and in 3D. In the 3D case, all slave points should lie at least approximately on the plane defined by the triangle or quadrangle.

Syntax:

```
    "PLAN"      "BASE"   /LECTURE/
                "LIST"   /LECTURE/
```

`"BASE" /LECTURE/`

Numbers of the base points composing a triangle (3 points) or a quadrangle (4 points).

`"LIST" /LECTURE/`

Numbers of A.L.E. points submitted to homeomorphic motion. These nodes must be located inside the basic triangle or quadrangle, or on their boundaries. The list can safely include also the base nodes: if present, they are automatically discarded from the list.

Comments:

It is strongly recommended to use quadrangles. Triangles are only useful if the initial mesh already has a triangular shape.

Warning:

Please read the rule for defining the base points, page B.60.

5.6.5 "TETR"

Object:

To impose a homeomorphic motion to several nodes of the grid describing a tetrahedron. This command is available only in 3D.

Syntax:

```
    "TETR"      "BASE"   /LECTURE/
                "LIST"   /LECTURE/
```

`"BASE" /LECTURE/`

Numbers of the 4 (usually Lagrangian) base points defining the tetrahedron. These points should not be coplanar.

`"LIST" /LECTURE/`

Numbers of A.L.E. points submitted to homeomorphic motion. These nodes must be located inside the basic tetrahedron or along its boundaries. The list can safely include also the base nodes: if present, they are automatically discarded from the list.

Warning:

Please read the rule for defining the base points, page B.60.

5.6.6 "HEXA"

Object:

To impose a homeomorphic motion to several nodes of the grid describing a hexahedron. This command is available only in 3D.

Syntax:

```
"HEXA"      "BASE"   /LECTURE/
            "LIST"   /LECTURE/
```

`"BASE" /LECTURE/`

Numbers of the 8 (usually Lagrangian) base points defining the hexahedron.

`"LIST" /LECTURE/`

Numbers of A.L.E. points submitted to homeomorphic motion. These nodes must be located inside the basic hexahedron or along its boundaries. The list can safely include also the base nodes: if present, they are automatically discarded from the list.

Warning:

Please read the rule for defining the base points, page B.60.

5.6.7 "PRIS"

Object:

To impose a homeomorphic motion to several nodes of the grid describing a prism. This command is available only in 3D.

Syntax:

```
    "PRIS"      "BASE"   /LECTURE/
                "LIST"   /LECTURE/
```

`"BASE" /LECTURE/`

Numbers of the 6 (usually Lagrangian) base points defining the tetrahedron.

`"LIST" /LECTURE/`

Numbers of A.L.E. points submitted to homeomorphic motion. These nodes must be located inside the basic prism or along its boundaries. The list can safely include also the base nodes: if present, they are automatically discarded from the list.

Warning:

Please read the rule for defining the base points, page B.60.

5.6.8 "PYRA"

Object:

To impose a homeomorphic motion to several nodes of the grid describing a pyramid. This command is available only in 3D.

Syntax:

```
    "PYRA"      "BASE"   /LECTURE/
                "LIST"   /LECTURE/
```

`"BASE" /LECTURE/`

Numbers of the 6 (usually Lagrangian) base points defining the pyramid.

`"LIST" /LECTURE/`

Numbers of A.L.E. points submitted to homeomorphic motion. These nodes must be located inside the basic pyramid or along its boundaries. The list can safely include also the base nodes: if present, they are automatically discarded from the list.

Warning:

Please read the rule for defining the base points, page B.60.

5.6.9 "CONTOUR"

Object:

To impose a homeomorphic motion to the grid nodes inside a given bounded area.

Syntax:

```
"CONT"  <"NORM" "NX" nx "NY" ny <"NZ" nz> <"ORDB">>
                                           "BASE" /LECTURE/
                                           "LIST" /LECTURE/
```

`"NORM"`

Introduces the optional definition of the normal direction. This is the direction along which the contour will be deformed. For example, in case of impact on a circular pipe, the contour is initially a circle but later on is squeezed to an ellipsis or even a concave shape. In this case the normal direction coincides with the direction of the impact.

`"NX"`

Component of the normal along x.

`"NY"`

Component of the normal along y.

`"NZ"`

Component of the normal along z (3D only).

`"ORDB"`

Let the code try to order the base nodes given (in random order) in the following `BASE` sub-directive.

`"BASE" /LECTURE/`

Numbers of the base nodes defining the boundary. If no normal is specified, these can be given in any order. However, if a normal is specified, the nodes are assumed to be listed in the order they occur along the contour (starting from any node on the contour). If an odered list is not available, by specifying the optional `ORDB` keyword, the code itself tries to order the base nodes. Note, however, that the ordering can only succeed if the base nodes lie approximately on a plane and form a **convex** contour.

`"LIST" /LECTURE/`

Numbers of the ALE nodes submitted to the homeomorphic motion (in any order). In principle these nodes should be located inside the bounded area, they may not be on the contour. However, the list can safely include also the base nodes (on the contour): if present, they are automatically discarded from the list.

Comments:

It is recommended to use the facilities offered in GIBI by the keywords "CONTOUR" and "ENVELOPPE".

For ease of use, EUROPLEXUS accepts that among the points defined by "LIST" there be also the base points. These points will be then removed by a special treatment within the code.

Otherwise, one can also separate the internal points from those on the contour, as shown in the following example.

Given an object "LIQ", the user wants to distinguish its internal nodes (ALE) from the nodes defining the outline of the surface (Lagrangian).

```
In GIBI:

  TLIQ = LIQ changer POI1   ;
  CLIQ = contour LIQ        ;
  CLIQ = CLIQ changer POI1  ;
  ILIQ = TLIQ differ  CLIQ  ;

In EUROPLEXUS:

  CONTOUR BASE LECTURE CLIQ TERM
          LIST LECTURE ILIQ TERM
```

This directive should be relatively robust for translation and rigid rotation of the contour. It should perform well also for moderate deformation of the contour itself, provided the contour is initially convex (ideally, similar to a circle).

If the contour is (or becomes, due to deformation) concave, then the algorithm does not perform well in general. In this case, if the direction of the (predominant) deformation of the contour is known *a priori*, it is advised to specify it via the optional `NORM` keyword.

Recall, however, that in this case the list of base nodes (on the contour) **should normally** be given in the order they occur along the contour (starting from an arbitrary node). If an ordered list of the nodes is not available, you can try giving them in random order and specifying the optional `ORDB` keyword.

5.6.10 "SLIP"

Object:

Define 2D curves consisting of nodes that are allowed to slip tangentially to the curve itself. This only applies to ALE models in structures or fluids.

Syntax:

```
    "SLIP"    |[ "NORM" /LECTURE/  ;
                 "EQUI" /LECTURE/ ]|
```

`"SLIP"`

The following nodes belong to a curve (in 2D) that is Lagrangian in the normal direction but ALE in the tangential direction. Examples are free surfaces in fluids, free boundaries in solids treated by the ALE method for structures, or interfaces between different materials that should not be mixed. Sliding in the tangential direction can be of two types: a) no sliding (only normal motion) or b) slide tangentially so as to keep nodes nearly equidistant.

`"NORM" /LECTURE/`

The specified nodes will only move along the normal direction to the curve.

`"EQUI" /LECTURE/`

The specified nodes will move both along the normal and along the tangential direction, so as to remain nearly equidistant from each other.

Comments

The nodes have to be listed in /LECTURE/ in the order in which they appear along the curve, and by leaving the body on the left side (for free surfaces).

Each list must include an initial and a final node, not subject to the imposed "SLIP" motion, whose positions are used to evaluate the normal direction for each triple of nodes. Therefore, each /LECTURE/ must contain at least three numbers.

Restrictions

The algorithms implemented here are only valid for "nearly straight" curves, in the sense that the angle between successive segments of the curve (element sides) must be close to 180 degrees. If this is not the case, then the mesh should be refined locally.

5.6.11 "AUTO"

Object:

Use Giuliani's (automatic) rezoning algorithm to determine the motion of the nodes specified next.

Syntax:

```
"AUTO"    |[ "AUTRES"              ;
             "NOEUDS" /LECTURE/ ]|
```

`"AUTRES"`

All the 'remaining' A.L.E. nodes (i.e. those which have not been forced by a 'manual' command such as `SUIVRE`, `LIGNE`, ...) will be automatically rezoned.

`"NOEUDS" /LECTURE/`

Allows to list explicitly the nodes which have to be automatically rezoned.

Comments:

Use of the automatic rezoning technique is encouraged when tackling a new problem or in cases when the node pattern and the deformation process cannot be described by simple laws such as those provided by the 'manual' rezoning commands. However, compatibility is ensured so that manual commands can still be used in conjunction with the automatic option in case some nodes (usually few) are not properly treated by the automatic technique.

The algorithm starts by estimating node by node, and on the basis of purely geometric criteria, the best grid velocity W that would bring to an optimal rezoning in just one step.
Then, this velocity is projected onto the fluid velocity V at the node concerned: this in order to take automatically into account possible boundary conditions imposed at the node.
Finally, the resulting module is limited in order to avoid too high remeshing velocities. This limitation is done by a coefficient γ_0, i.e :

$$-\gamma_0 V < W < (1+\gamma_0) V$$

The coefficient γ_0 may be defined by the option `OPTI REZO GAMO`, see page H.150. This parameter does not have a large influence on remeshing, but in any case with small values of γ_0 one should get a slightly more effective remeshing. Suggested values are between 0.1 and 0.8, the default is 0.2.

Note that `GAMO` is a global parameter, and hence it is the same for the whole mesh. Consequently, it is recommended to "help" the remeshing algorithm, in case of need, by the manual remeshing directives such as `SUIVRE`, `LIGNE`, etc.

Note that ALE nodes lying on fluid-structure sliding lines of the ALE type (see directive `FSS ALE`) have to be declared as automatically rezoned. The program then automatically applies the correct sliding conditions.

The list of nodes can be given either explicitly, by a `/LECTURE/`, introduced by keyword `NOEU`, or implicitly, by keyword `AUTR`. In the latter case, the nodes considered are all nodes that have not been assigned any rezoning method up to the current point in the input file. The `GAMO` parameter should be specified in the `OPTI` directive, since it applies not only to Giuliani's but also to the other automatic remeshing methods (in fact, it is used in the mesh velocity restriction algorithm).

Several options may be set for the fine-tuning of the automatic rezoning algorithms. For more information, please see the `OPTI REZO` directive in Section 12.

Warning:

To date, the automatic rezoning facility is only implemented in 2D for nodes belonging to elements of type TRIA, CAR1, CAR4, FLU1, FL23, FL24, Q41, Q41N, Q42, Q42N, TRIA, CVL1, TVL1, MC23, MC24. In 3D, it is implemented for nodes belonging to elements of type FLU3, FL34, FL35, FL36, FL38, TETR, PRIS, CUBE.

5.6.12 "MEAN"

Object:

Use the mean algorithm to determine the motion of the nodes specified next. This rezoning method is available for all ALE element types.

Syntax:

```
    "MEAN"    $[ "NOEU" /LECTURE/  ;
                 "AUTR"           ]$
```

"NOEU"

The following (ALE) nodes will be rezoned by the "mean position" algorithm. The position of each node will tend to become the mean of the position of neighbour nodes. For a generic node I, neighbour nodes are those connected to it in the mesh by a straight (two-noded) element side.

"AUTR"

All other 'remaining' ALE nodes, i.e. those that have not been forced to move by a 'manual' command such as "SUIVRE", "LIGNE", etc., will be rezoned by the "MEAN" algorithm.

Comments:

Several options may be set for the fine-tuning of the automatic rezoning algorithms. For more information, please see the OPTI REZO directive in Section 12.

5.6.13 "DIRE"

Object:

Use the direct algorithm to determine the motion of the nodes specified next. Note, however, that this algorithm is experimental and is currently implemented only for 2D quadrilateral ALE finite elements and finite volumes.

Syntax:

```
"DIRE"    $[ "NOEU" /LECTURE/  ;
             "AUTR"           ]$
```

`"NOEU"`

The following (ALE) nodes will be rezoned by the "direct" algorithm.

`"AUTR"`

All other 'remaining' ALE nodes, i.e. those that have not been forced to move by a 'manual' command such as "SUIVRE", "LIGNE", etc., will be rezoned by the "DIRE" algorithm.

Comments:

Several options may be set for the fine-tuning of the automatic rezoning algorithms. For more information, please see the OPTI REZO directive in Section 12.

Warning

This algorithm is experimental and is currently implemented only for 2D quadrilateral ALE finite elements and finite volumes.

5.6.14 "QUAD"

Object:

Use the specific quadrilateral algorithm to determine the motion of the nodes specified next. Note, however, that this algorithm is experimental and is currently implemented only for 2D quadrilateral ALE finite elements and finite volumes.

Syntax:

```
"QUAD"    $[ "NOEU" /LECTURE/  ;
             "AUTR"            ]$
```

`"NOEU"`

The following (ALE) nodes will be rezoned by the "quadrilateral" algorithm.

`"AUTR"`

All other 'remaining' ALE nodes, i.e. those that have not been forced to move by a 'manual' command such as "SUIVRE", "LIGNE", etc., will be rezoned by the "QUAD" algorithm.

Comments:

Several options may be set for the fine-tuning of the automatic rezoning algorithms. For more information, please see the OPTI REZO directive in Section 12.

Warning

This algorithm is experimental and is currently implemented only for 2D quadrilateral ALE finite elements and finite volumes.

5.6.15 "SPEC"

Object:

Use the element-specific algorithm to determine the motion of the nodes specified next. Note, however, that this algorithm is experimental and is currently implemented only for 2D quadrilateral and triangular ALE finite elements and finite volumes.

Syntax:

```
"SPEC"    $[ "NOEU" /LECTURE/  ;
             "AUTR"            ]$
```

"NOEU"

The following (ALE) nodes will be rezoned by the "specific" algorithm.

"AUTR"

All other 'remaining' ALE nodes, i.e. those that have not been forced to move by a 'manual' command such as "SUIVRE", "LIGNE", etc., will be rezoned by the "SPEC" algorithm.

Comments:

Several options may be set for the fine-tuning of the automatic rezoning algorithms. For more information, please see the OPTI REZO directive in Section 12.

Warning

This algorithm is experimental and is currently implemented only for 2D quadrilateral and triangular ALE finite elements and finite volumes.

5.6.16 "MECA"

Object:

Use the mechanical algorithm to determine the motion of the nodes specified next.

Syntax:

```
"MECA"    $[ "NOEU" /LECTURE/  ;
             "AUTR"            ]$
```

`"NOEU"`

The following (ALE) nodes will be rezoned by the "mechanical" algorithm.

`"AUTR"`

All other 'remaining' ALE nodes, i.e. those that have not been forced to move by a 'manual' command such as "SUIVRE", "LIGNE", etc., will be rezoned by the "MECA" algorithm.

Comments:

Several options may be set for the fine-tuning of the automatic rezoning algorithms. For more information, please see the OPTI REZO directive in Section 12.

Warning

This algorithm is experimental and is currently implemented only for 2D quadrilateral ALE finite elements and finite vol- umes. Finally, in order to use this model the problem type keyword MECA must be specified in the initial part of the input file (see Section 4.2).

5.6.17 "ELAS"

Object:

Affects a fictitious elastic material to grid elements to control the motion of the ALE nodes.

Syntax:

```
"ELAS"  "RO" ro "YOUNG" young "NU" nu "DAMP" damp /LECTURE/
```

`"ro"`

Fictitious material's density.

`"young"`

Fictitious material's Young modulus.

`"nu"`

Fictitious material's Poisson ratio.

`"damp"`

Inertial damping.

`/LECT/`

List of the fluid *elements* concerned.

Comments:

At the moment, this type of rezoning is available for the following element types: TRIA, CAR1, TETR, PRIS, CUBE, T3VF, Q4VF, TEVF, PRVF, CUVF, FL23, FL24, FL34, FL36, FL38. Note that the model is not yet available for the pyramid elements (FL35 for example).

Be aware that a critical time step is computed for the explicit elastic rezoning problem to remain stable. A soft fictitious material should be used so that this time step is not smaller than the "physical" critical time step.

An large inertial damping coefficient (i.e. from 1.E3 to 1.E4) should be used to prevent vibrating oscillations of the deformed grid.

Do not forget to set option OPTI REZO LIAI (see Page H.150, Section 12.16), so that nodes subjected to kinematic links are rezoned accordingly.

5.6.18 “GLOB”

Object:

Option which gives the possibility to link a fluid grid to a structure

Syntax:

```
"GLOB"  "DACT"  /LECDDL/ "STRU" /LECTURE/
          /LECTURE/
```

`"DACT"`

Activation of the dlls to be linked

`/LECDDL/`

Reading procedure of the degrees of freedom concerned.

`"STRU"`

`/LECT/`

List of the structure *elements* concerned.

`/LECT/`

List of the fluid *elements* concerned.

Comments:

Multiphasic law is not available with this option

5.6.19 "HYPE"

Object:

Affects a fictitious hyperelastic material to grid elements to control the motion of the ALE nodes and allow large grid deformation. Material model is either Mooney-Rivlin constitutive law (see page 7.7.79 for details) or Ogden constitutive law (see page 7.7.80), the latter being the default.

Syntax:

```
"HYPE"  < "RO" ro >  < "BULK" bulk > < "SCOF" coef >
        < "MOON" < "C1" c1 > < "C2" c2 > >
        < "OGDE" < "AL1"al1 > < "AL2" al2 > < "MU1" mu1 > < "MU2" mu2 > >
        < "DAMP" damp >
        /LECTURE/
```

"ro"

Fictitious material's density.

"bulk"

Fictitious material's bulk modulus.

"coef"

Scaling coefficient of bulk modulus.

"MOON"

Selection of Mooney-Rivlin material model for fictitious material.

"c1"

Mooney-Rivlin coefficient C1.

"c2"

Mooney-Rivlin coefficient C2.

"OGDE"

Selection of Ogden material model for fictitious material.

"al1"

Ogden coefficient AL1.

"al2"

Ogden coefficient AL2.

"mu1"

Ogden coefficient MU1.

`"mu2"`

Ogden coefficient MU2.

`"damp"`

Inertial damping.

`/LECT/`

List of the fluid *elements* concerned.

Comments:

Ogden material model is the default. Default values are provided for `ro`, `bulk`, `c1`, `c2`, `al1`, `al2`, `mu1` and `mu2`, parameters. They are taken from the tests `bm_str_moon.epx` and `bm_str_ogde.epx` from the non-regression base. The coefficient introduced with `"SCOF"` keyword allows to simply scale the bulk modulus (including the default value) of the material without entering an all new set of parameters.

At the moment, this type of rezoning is available for the following element types: TRIA, CAR1, TETR, PRIS, CUBE, T3VF, Q4VF, TEVF, PRVF, CUVF, FL23, FL24, FL34, FL36, FL38. Note that the model is not yet available for the pyramid elements (FL35 for example).

Be aware that a critical time step is computed for the explicit hyperelastic rezoning problem to remain stable. A soft fictitious material should be used so that this time step is not smaller than the "physical" critical time step.

An large inertial damping coefficient (i.e. from 1.E3 to 1.E4) should be used to prevent vibrating oscillations of the deformed grid.

Do not forget to set option OPTI REZO LIAI (see Page H.150, Section 12.16), so that nodes subjected to kinematic links are rezoned accordingly.

5.6.20 USER'S ROUTINE "COOGRI"

Object:

This routine can be written by the user and exploited in order to specify the motion of fluid nodes when using the ALE description. Its use should be only needed in exceptional cases, because normally the automatic and manual rezoning directives are perfectly appropriate.

Since this routine is called last by routine NVCOOR any motion specified in it will overwrite any other motion, either automatic or by means of manual rezoning directives, specified by the user.

Normally, the routine does nothing.

The listing of the sample routine is included hereafter.

```
      SUBROUTINE COOGRI(V,WG,posp,mvgril)
C---------------------------------------------------------------
C     ---  ROUTINE UTILISATEUR ( vitesses DE LA GRILLE )
C---------------------------------------------------------------
c v     : fluid velocities
c wg    : mesh grid velocities
c posp  : pointer in both v and wg
C MVGRIL(I,1)
c             -1=LAGRANGIAN
c              0=EULERIAN
C              1=A.L.E.,AUTOMATICALLY REZONED (JRC);
C              2=A.L.E.,MANUALLY REZONED (CEA),
c              3=A.L.E, rezoned by FSS ALE (ALE sliding JRC)
c              4=A.L.E, "MEAN" rezoned (JRC)
C MVGRIL(I,2)   NODAL INDEXES IN THE FOLLOWING ORDER :
C               - FIRST LAGRANGIAN NODES (GROWING ORDER)
C               - THEN NON-LAGRANGIAN BASE NODES (USED AS MASTER
C                 NODES FOR MOTION OF SLAVE A.L.E. NODES)
C               - FINALLY ALL OTHER NODES
C MVGRIL(I,3)   IAD (ADDRESS IN <NBALE> AND <CBALE>) IF MVGRIL(I,1)=2
c              -1  IF NODE IS SUBJECT TO "LIAISON" AND MVGRIL(I,1)=1
C              0   IN ALL OTHER CASES
C---------------------------------------------------------------
c
      implicit none
      include 'CONTRO.INC'
C
      double precision V(*), WG(*)
      integer posp, mvgril
C
      dimension posp(*), mvgril(*)
c
c Insert hereafter the user's definition of the appropriate
c grid velocities:
```

```
c
C
      RETURN
      END
```

5.7 MESH REFINEMENT FOR WAVEFRONT TRACKING

Object:

This directive enables the user to impose the refinement of the computational mesh grid to follow the propagation of one or more prescribed wave fronts. It should be used in conjunction with mesh adaptivity dimensioning directive `ADAP`, see page A.62. However, note that this directive is incompatible with "true" adaptivity (piloted by an error indicator) which is activated by the `ADAP` directive of page B.210.

Note that this model does not represent a true implementation of adaptivity, since the mesh refinement and de-refinement is entirely piloted by the user with the present directive. However, it may be useful to check the mesh refinement and de-refinement processes in simple test cases, where the propagation of wave fronts is known a priori.

For a true implementation of adaptivity (piloted by an error indicator) see the `ADAP` directive on page B.210.

Syntax:

```
WAVE  nwav * ($ SPHE ; PLAN ; CYLI $
               X x Y y <Z z> <NX nx NY ny <NZ nz>>
               T0 t0 <T1 t1>
               $ C c ; D d $ <FONC nufo>
               MAXL m H1 h1 H2 h2
               < OBJE /LECT/ >)
```

`WAVE`

Prescribe one or more wave fronts to be tracked.

`nwav`

Number of wave fronts to be defined.

`SPHE`

The wave being defined is a spherical wave.

`PLAN`

The wave being defined is a plane wave.

`CYLI`

The wave being defined is a cylindrical wave.

`x`

X-coordinate of the wave source point.

`y`

Y-coordinate of the wave source point.

`z`

Z-coordinate of the wave source point (0 by default).

`nx`

X-component of the normal vector to the plane (for `PLAN` waves). X-component of the cylinder axis vector (for `CYLI` waves). Note that the vector need not be normalized to unit length.

`ny`

Y-component of the normal vector to the plane (for `PLAN` waves). Y-component of the cylinder axis vector (for `CYLI` waves).

`nz`

Z-component of the normal vector to the plane (for `PLAN` waves). Z-component of the cylinder axis vector (for `CYLI` waves). This is 0 by default.

`t0`

Time instant at which wave propagation starts from the corresponding source point.

`t1`

Time instant at which wave propagation terminates. The mesh is completely un-refined (thus returning to the base mesh) at times greater than this value.

`c`

Propagation speed of the wavefront. For spherical waves, propagation is assumed isotropic in all space directions.

`d`

Propagation displacement of the wavefront. For spherical waves, propagation is assumed isotropic in all space directions.

`nufo`

Nuber of the function describing the variation in time of the propagation speed (if `C` is given) or of the propagation displacement (if `D` is given). If omitted, the propagation speed or displacement is considered constant in time. Note that the function **must** be defined over the entire time interval of the calculation, i.e. between the initial time `TINI` and the final time `TEND` as defined in the `CALC` directive detailed on Page I.20.

`m`

Maximum level of mesh refinement at the wave front.

`h1`

Thickness of maximum refined mesh layer normally to the wave front.

`h2`

Thickness of refined mesh layer normally to the wave front. Refinement passes from level `m` to level 0 (no refinement) linearly when passing from a distance `h1` to a distance `h2` from the wave front.

`OBJE /LECT/`

Optionally specify to which object the WAVE applies, i.e. which are the (base) elements that should be refined / unrefined by the present WAVE. By default (`OBJE` not specified), a WAVE operates on all adaptable elements in the mesh. Note that, if specified, `OBJE` must be given after all other parameters of the WAVE.

Update of February 8, 2022

Note that a revision of the `WAVE` directive has been performed on February 8, 2022. This has involved ameliorations in the way that `WAVE` produces a graded mesh. The mesh grading is more uniform and more consistent than with the previous (original) version of the `WAVE` model. Moreover, some optimizations have been introduced that make the `WAVE` model more CPU-efficient, especially if one specifies the optional `OBJE` keyword.

Note that these changes might produce some (small) differences with respect to the previous version in the results of old tests using the `WAVE` directive.

Using stationary waves

A possible use of the `WAVE` directive is to refine the mesh *statically*, typically within a spherical region (`SPHE` keyword). This effect can be obtained by specifying a zero velocity (`C`) for the wave. The `X`, `Y` and `Z` define the center of the refined sphere, while `H1` and `H2` are the **radii** (not the diameters) of the refinement zone, since they represent the thickness of the wavefront (which in this case remains always at the origin point of the wave since there is no propagation).

Optionally, the stationary refinement can be applied only over a time window by specifying `T0` and `T1`.

If one wants to refine locally without a uniformly graded mesh then one should specify `H1` equal to `H2`. Optionally, the `ADAP RCON` option may be activated to obtain a minimal grading.

Combination with other types of adaptivity

The `WAVE` directive (stationary or not) can be combined with other forms of adapativity (notably `THRS` and/or FSI-driven adaptivity), by applying the `WAVE`(-s) only to a given region of the mesh, which in this case **must** be specified via `OBJE`.

Note that the region(s) subjected to `WAVE`(s) must be **disjoint** from the region(s) affected by other types of adaptivity. However, the code cannot check for this requirement, so it is left to the user's responsibility.

5.8 ADAPTIVITY

Object:

This directive enables the user to impose the refinement or un-refinement of the computational mesh grid (**adaptivity**) in accordance to some chosen **error indicator**. The error indicator can be:

- a “classical” error indicator quantity, or
- a point cloud-based indicator, or
- a threshold-based indicator.

The directive should be used in conjunction with mesh adaptivity dimensioning directive `ADAP`, see GBA_0062.

This directive enables automatic mesh refinement and un-refinement based on some criteria chosen by the user. However, note that at the moment this directive is incompatible both with the wave front tracking directive `WAVE` GBB_0200 and with the FSI-related adaptivity directives associated with the `FLSR` and `FLSW` directives, see GBD_0143 and GBD_0555, respectively. Compatible elements for the use of Finite Volumes are detailed in comments.

In contrast to the `WAVE` directive (GBB_0200), the present model represents a “true” implementation of adaptivity.

Syntax:

```
ADAP  < UPDT /CTIME/ >
      ( INDI |[ DEPL ; VITE ; ACCE ;
                PRES ; DENS ; CONT icon ; ECRO iecr ]|
        < TYPE |[ CURV ; GRAD ]| >
        STRA $[ PERR perr ; PELE pele ALFA alfa ; PEMA pema ]$
        CERR ( cerr /LECTURE/ ) )

      ( THRS |[ PRES ; DENS ; PEPS ; FAIL ;
                CONT icon ; ECRO iecr; EPST icon ]|
             |[ TMIN tmin TMAX tmax ; LEVL ]|
             MAXL maxl
             <CRIT crit>
             <UNSP ; NOUN>
             /LECTURE/ )

     $[ PCLD ( |[ INDI NIND nind MAXL maxi ELEM /LECTURE/ ;
                 THRS MAXL maxt ELEM /LECTURE/ ;
                 FSI  FLUI /LECTURE/
                      STRU /LECTURE/
                      MAXL maxf RADI radf ;
```

```
GAP  MAST /LECTURE/
     SLAV /LECTURE/
     MAXL maxg RADI radg
EDGE MAST /LECTURE/
     SLAV /LECTURE/
     MAXL maxe RADI rade
VOFI FLUI /LECTURE/
     CLIM clim
     MAXL maxv RADI radv ]| ) ]$
```

`ADAP`

Activates true adaptivity according to the error indicator(s) chosen next.

Directives related to classical error indicators

`UPDT`

MPI Only - Introduces an update frequency for the mesh adaptation to save computation time.

`INDI`

Introduces the variable(s) used as "classical" error indicator(s). Note that exactly `ni` variables must be specified next, where `ni` is the number given in the dimensioning (`NIND ni`), see page A.62. If the keyword `NIND` has been omitted in the dimensioning, then by default `ni = 1`.

`DEPL`

Use nodal displacement (norm) as error indicator.

`VITE`

Use nodal velocity (norm) as error indicator.

`ACCE`

Use nodal acceleration (norm) as error indicator.

`PRES`

Use (fluid) element pressure as error indicator. Only `GRAD` type of indicator can be used in this case.

`DENS`

Use (fluid) element density as error indicator. Only `GRAD` type of indicator can be used in this case.

`CONT icon`

Use element stress component `icon` as error indicator. Only `GRAD` type of indicator can be used in this case.

`ECRO iecr`

Use element hardening component `iecr` as error indicator. Only `GRAD` type of indicator can be used in this case.

`TYPE`

Introduces the types of error indicator(s). Note that exactly `ni` variables must be specified next, where `ni` is the number given in the dimensioning (`NIND ni`), see page GBA_0062. The types must be entered in the same order as the indicator variables, i.e. the first type corresponds to the first indicator variable, and so on. If the keyword `NIND` has been omitted in the dimensioning, then by default `ni = 1`. If the `TYPE` sub-directive is omitted, all indicators are assumed to be of the curvature type.

`CURV`

Error indicator is of curvature type, i.e. the curvature of the indicator variable is used to compute the error indicator. This type of error indicator can be used only for the node-based indicator variables listed above (i.e. only for `DEPL`, `VITE` or `ACCE`).

`GRAD`

Error indicator is of gradient type, i.e. the gradient of the indicator variable is used to compute the error indicator. This type of error indicator can be used for all indicator variables listed above.

`STRA`

Introduces the strategy used for the error indicator. At the moment, two strategies are available: prescribing the error or prescribing (approximately) the number of used elements.

`PERR perr`

Introduces the prescribed error `perr` ($\tilde{e}$). This is then used to compute the prescribed element size $\tilde{h}_k$, see formula below.

`PELE pele`

Introduces the prescribed number of adaptive elements `pele` ($\tilde{n}$).

`ALFA alfa`

Coefficient α used in the formula to estimate the predicted number of elements in memory (see below). This is an empirical value. The suggested value is 4 for 2D calculations.

`PEMA pema`

Introduces the prescribed number of adaptive elements `pema` ($\tilde{n}$). This version of the command is suited for use in conjunction with the `OPTI ADAP MAXL` option, see GBH_0180. In fact when this option is specified, the `PELE` strategy respects very badly the prescribed number of elements. Note that the `PEMA` strategy requires additional calculations with respect to `PELE` and is therefore more expensive. Note also that the `PEMA` strategy makes no use of the `ALFA` coefficient.

`CERR cerr`

Introduces the choice of the constant C (`cerr`) appearing in the expression of the error indicator (see below). The value may vary from element to element (e.g., due to different element types). Each (parent) element in the adaptive mesh must receive a value. Descendent elements inherit the value from their own parent element.

`/LECTURE/ (CERR keyword)`

List of the elements to which the value `cerr` is assigned.

Directives related to point-cloud indicators

`PCLD`

Introduce point cloud-based indicators.

`INDI`

Base the point-cloud indicator upon one of the "classical" adaptivity indicators that have been listed above.

`NIND nind`

Rank `nind` of the concerned indicator in the `INDI` list of original adaptivity indicators specified above.

`MAXL maxi`

Maximum refinement level `maxi` for this indicator as a PCLD indicator.

`ELEM /LECTURE/`

List of the elements concerned by this PCLD indicator.

`THRS`

Base the point-cloud indicator upon the threshold indicator that has to be defined above.

`MAXL maxt`

Maximum refinement level `maxi` for this indicator as a PCLD indicator.

`ELEM /LECTURE/`

List of the elements concerned by this PCLD indicator.

`FSI`

Base the point-cloud indicator upon Fluid-Structure Interaction.

`FLUI /LECTURE/`

List of the fluid elements concerned by this PCLD indicator.

`STRU /LECTURE/`

List of the structure elements defining the points of the cloud.

`MAXL maxf`

Maximum refinement level for this PCLD indicator.

`RADI radf`

Influence radius associated with the structure.

`GAP`

Base the point-cloud indicator upon contact (gap).

`MAST /LECTURE/`

List of the elements defining the point cloud.

`SLAV /LECTURE/`

List of the slave elements concerned by this PCLD indicator.

`MAXL maxg`

Maximum refinement level for this PCLD indicator.

`RADI radg`

Influence radius associated with the master elements.

`EDGE`

Base the point-cloud indicator upon distance from a free shell edge (3D only).

`MAST /LECTURE/`

List of the shell elements defining the point cloud.

`SLAV /LECTURE/`

List of the slave elements concerned by this PCLD indicator.

`MAXL maxg`

Maximum refinement level for this PCLD indicator.

`RADI radg`

Influence radius associated with the free edges of the master elements.

`VOFIRE`

Base the point-cloud indicator upon VOFIRE anti-dissipation fo physical interface tracking.

`FLUI /LECTURE/`

List of the concerned fluid elements..

`CLIM clim`

Minimum concentration for any fluid component to identify an interface cell. One cloud point is placed at the centroid of each interface cell.

`MAXL maxv`

Maximum refinement level for this PCLD indicator.

`RADI radv`

Influence radius associated with the interface cells.

Directives related to threshold-based indicators

`THRS`

Introduce threshold-based indicators.

`PRES`

Use element pressure as threshold-based indicator.

`DENS`

Use element density as threshold-based indicator.

`PEPS`

Use element principle strain as threshold-based indicator.

`CONT icon`

Use element stress component `icon` as threshold-based indicator.

`EPST icon`

Use element strain component `icon` as threshold-based indicator.

`ECRO iecr`

Use element hardening component `iecr` as threshold-based indicator.

`TMIN min`

Introduces the minimum threshold value `tmin` above which the mesh starts to be refined.

`TMAX max`

Introduces the maximum threshold value `tmax` at which the mesh refinement reaches the maximum level (specified below).

`LEVL`

Maximum and minimum values of are calculated automatically by scanning the entire zone and using the maximum and minimum value of that zone.

`MAXL maxl`

Maximum level of mesh refinement, which is reached at the value `tmax` of the threshold specified above.

`CRIT crit`

Optional criterion to be used to compute the monitored quantity's representative value over an element. By default (or by specifying `CRIT 0`) the average value of the monitored quantity over all Gauss points of the element is taken. Alternatively, 1 means taking the maximum value of all the Gauss points of the element, 2 means the minimum value, 3 means the maximum *absolute* value. Note that alternative criteria (other than the default one based on the average) are *not* available at the moment for monitored quantities of type `PEPS` and `FAIL`. Therefore, the value of `crit` is ignored in these two cases.

`UNSP`

Keyword in order to enable unsplitting procedures for the elements concerned.

`NOUN`

Keyword in order to disable unsplitting procedures for the elements concerned. This is the default, so this keyword should be redundant.

`/LECTURE/`

List of the elements concerned by this type of mesh adaptation.

Comments for classical indicators:

For a **curvature-based indicator**, the expression used to compute the error indicator is:

$$|e| \approx Ch^2 \max(|k_1|, |k_2|)$$

where C is the constant `cerr` given in input for the current element, h is the local mesh size (i.e. the characteristic length of the element under consideration), k_1 and k_2 are the principal curvatures of the variable chosen as error indicator on a patch composed by the element itself and by all its direct neighbors.

For a **gradient-based indicator**, the expression used to compute the error indicator is:

$$|e| \approx Ch||G||$$

where C is the constant `cerr` given in input for the current element, h is the local mesh size (i.e. the characteristic length of the element under consideration), $||G||$ is the norm of the gradient of the variable chosen as error indicator on a patch composed by the element itself and by all its direct neighbors.

The expression used to compute the prescribed element size $\tilde{h}_k$ is:

$$\tilde{h}_k = \sqrt{\frac{\tilde{e}}{e_k}} h_k, \quad k = 1, \ldots, N$$

where N is the current number of active elements in the mesh, and e_k in the estimated error in the k-th element.

The expression used to estimate the number of elements $\tilde{n}$ in memory is:

$$\tilde{n} \approx \frac{\alpha}{\tilde{e}} \sum_{k=1}^{N} e_k$$

This formula is actually used to compute $\tilde{e}$:

$$\tilde{e} \approx \frac{\alpha}{\tilde{n}} \sum_{k=1}^{N} e_k$$

and then the above formula gives $\tilde{h}_k$.

Comments for PCLD indicators:

The PCLD subdirective introduces particular indicators designed to be combined with one another.

They are mainly based on simple distance relations between the centroids of slave elements and some master points attached to chosen elements, defining a cloud of points. The minimum distance between a slave centroid and any point of the cloud (which can be seen as the projection of the point onto the cloud) defines the refinement level of the slave element, according to the ratio between this distance and the given radius. The given maximum refinement level is applied to the elements closest to the cloud, and then decreasingly for farther elements.

To be combined with other PCLD indicators, original adaptivity indicators must be slightly reformulated. This is the goal of the PCLD INDI sub-option.

Comments for threshold-based indicators:

The mesh refinement level varies linearly between 1 and `maxl` as the monitored value passes from `tmin` to `tmax`.

By default, threshold-based indicators cause splitting but never cause un-splitting of a mesh. This is because such indicators are typically associated with irreversible quantities, such as damage or plastification in structures. In order to activate possible un-splitting with threshold-based indicators, the optional keyword `UNSP` should be specified.

Comments for the use of Finite Volumes:

Compatible fluid elements for Finite Volumes and AMR are indicated in the table below.

Element	INDI	THRS	PCLD (FSI)
Q4VF	✓	✓	✓
T3VF	×	✓	×
CUVF	✓	✓	✓
PRVF	×	✓	×
TEVF	×	✓	×
PYVF	×	×	×
CL2D	✓	✓	×
CL3D	✓	✓	×
CL3T	×	✓	×

6 GROUP C—GEOMETRIC COMPLEMENTS

Object:

These directives enable the user to complete the geometry.

Syntax:

```
"COMPLEMENT"
```

Comments:

These directives are described in detail on the following pages.

The keyword "COMPLEMENT" and the associated data are compulsory only if required by the elements (shells, beams and 1-D elements) or if the user enters added masses.

Do not forget the corresponding dimensioning (page A.70).

6.1 AUXILIARY FILE

Object :

This directive allows to read complementary data from an auxiliary file.

Syntax :

```
< "FICHIER"   'nom.fic'  >
```

In certain cases the data may be bulky. It is then advisable to store the data on an auxiliary file in order to shorten the main input data file. The auxiliary file is activated by the keyword "FICHIER" that precedes the full name of the file (under Unix). Then, only the keyword "COMPLEMENT" preceding the keyword "FICHIER" remains in the main input file.

The auxiliary file (in free format) will contain the whole set of geometry complement data, with the exception of the keyword "COMPLEMENT" itself. To resume reading from the main input data file, the auxiliary file must be terminated by the keyword "RETOUR".

6.2 FS-Core GEOMETRIC COMPLEMENTS

Object:

This directive allows to enter geometric complements for structures (and possibly fluids in the future) in FS-Core application.

FSCORE STRUCTURE describes a Fuel Assembly by means of rod network characteristics and global properties of the associated equivalent Timoshenko beam.

Syntax:

```
"FSCORE" ( "STRU" "RDIA"   rdia
                  "RNUM"   inum
                  "WIDTH"  rwth
                  "PITCH"  rptc
                  "IROT"   rirt
                  /LECTURE/  )
```

`rdia`

Diameter of rods within Fuel Assembly.

`inum`

Number of rods within Fuel Assembly.

`rwth`

Width of Fuel Assembly.

`rptc`

Pitch of a the rod network within Fuel Assembly.

`rirt`

Rotational inertia of the Fuel Assembly seen as an equivalent beam.

`LECTURE`

List of the FSBM concerned elements.

6.3 ADDED MASSES

Object:

This instruction enables the user to define the masses which are added to certain nodes, along certain degrees of freedom.

Syntax:

```
< "MASS" ( /LECDDL/  xm  /LECTURE/ ) >
```

`LECDDL`

List of the degrees of freedom concerned.

`xm`

Value of the added mass.

`LECTURE`

List of the nodes concerned.

Comments:

1/ Several added masses may be defined without repeating the key-word "MASS".

Example:

```
"MASS"  /LECDDL/  xm1  /LECTURE/
        /LECDDL/  xm2  /LECTURE/
        . . .
```

2/ Use:

```
"MASS"  1342  xm  "SUIT" 1 2 3 "TERM"
```

The degrees of freedom 1,3,4,2 of the nodes 1,2,3 are modified by the mass xm (this mass is added to the initial one).

In axisymmetric cases, do not forget to divide the "true" mass by 2π.

Remark:

Material points ("PMAT" elements) may be used too, in order to enter added masses (see page C.200).

6.4 Automatic mass distribution : MAPM

Object:

The automatic mass distribution "MAPM" is a method that allows the user to complete the mass of an EUROPLEXUS model giving the spatial definition of the total mass. It should be notice that that mass can be only added and not removed.

In the data set, the user defines a spatial masses repartition of a model given the value of each mass and its respective coordinates. For each added mass, four words must be written in the data set: the first one is "MASS" and allows to define the mass value and the three others ("POSX", "POSY" and "POSZ") allow to define its x, y, z position.

Syntax:

```
<  "MAPM"
   "MASS" m "POSX" x "POSY" y  "POSZ" z
   /LECTURE/ >
```

`m`

mass of the current point

`x`

X coordinate of the current point

`y`

Y coordinate of the current point

`z`

Z coordinate of the current point

`/LECTURE/`

List of concerned nodes.

Comments:

Several masses may be defined without repeating the key-word "MAPM".

Example:

```
"MAPM"  "MASS" m1  "POSX" x1 "POSY" y1  "POSZ" z1
        "MASS" m2  "POSX" x2 "POSY" y2  "POSZ" z2
        . . .
```

6.5 THICKNESS OR SECTION

Object:

1/ Thickness:

By means of this directive the user specifies the thickness of two- and three-dimensional shells. A thickness must also be specified for elements of types Q92, Q93, Q92A, ED01, ED41, COQI, Q41, Q41N, Q42, Q42N, Q41L, Q42L, Q95, CQD4, CQD9, CQD3, CQD6, FUN2, FUN3. The directive is mandatory if the mesh contains any of these elements.
In case of FUN3 element, the thickness means the cross section of the element.

2/ Section:

This directive is similar to the preceding one, but it is only applied to beams and bars.

Syntax:

```
< |[ "EPAI"  (  ep   /LECTURE/  )          ;
     "EPAI"  (  "CQDX" /LCHP/ /LECTURE/  )  ]| >
```

`Or:`

```
<  "SECT"  (  ep   /LECTURE/  )  >
```

`ep`

Thickness or section.

`LECTURE`

List of the elements concerned.

Comments:

Various thicknesses can be defined for different elements without repeating the key-word "EPAI". It is the same for "SECT".

Example:

```
"EPAI"  ep1  /LECTURE/
        ep2  /LECTURE/
        ep3  /LECTURE/
```

A special syntax is foreseen to define the thickness of degenerated shell elements CQDx. For these elements, the thickness should be defined at the nodes. The most accurate way of doing this is to prepare a 'champoint' object with CASTEM2000 and store it together with the mesh in the CASTEM2000 file (see directive "SAUV' in CASTEM2000). This file is then read by EUROPLEXUS using the directive "CASTEM (see page A.30) and can then be referred to from other directives.

The keyword "CQDX" introduces this kind of syntax: the reference to the CASTEM2000 champoint object is read by the /LCHP/ procedure (see page INT.57) and the associated geometrical support (object of type 'maillage' containing the shell elements) is indicated by the following /LECT/. Note that /LCHP/ and /LECT/ must be given in this order.

A simpler, but not as precise, way of specifying the thicknesses of these shells is to assign a single value to each element by the standard "EPAI" directive, without using the CASTEM2000 objects for this purpose. In this case, the program itself estimates values for the thicknesses (and fiber orientations) at each node based on the values of the surrounding elements.

6.6 GEOMETRICAL PARAMETERS FOR SHELL ELEMENTS

Object:

This directive allows to choose some geometrical parameters for shell, plate and beam elements. For example, the type of spatial integration through the thickness or in the lamina directions, for certain types of shell/plate elements.

Syntax:

```
<"NGPZ" ngpz  /LECT/ > <"INTE" typl /LECT/>
<"ALPH" alpha /LECT/ > <"BETA" beta /LECT/>
<"SK"   sk    /LECT/ > <"REFE" refe /LECT/>
```

`ngpz`

Number of gauss points in the thickness for shell, plate or beam elements. This value must not exceed the maximum value specified in the dimensioning (see `DIME ... NGPZ` on page A.66). The default value for the CQDx elements is 3.

`typl`

Type of lamina integration for 3D degenerated shell elements (CQD3, CQD4, CQD6, CQD9), `SELE` means selective reduced, `REDU` means reduced, `FULL` means full, `SELM` means selectively reduced with 'mean tau' procedure and `FULM` means full with 'mean tau' procedure; the default is reduced.

`alpha`

Participation to bending (only for some shell elements). Default is 2/3. This parameter is only used by elements which adopt a global model: elements integrated through the thickness ignore the value of this parameter.

`beta`

Participation to membrane (only for some shell elements). Default is 1. This parameter is only used by elements which adopt a global model: elements integrated through the thickness ignore the value of this parameter.

`sk`

Shear correction factor for 3D degenerated shell elements (CQD3, CQD4, CQD6, CQD9), default value is 5/6.

`refe`

Location of the reference surface. refe = -1, 0, +1 indicates that the surface is located at the bottom, middle, and top surface of the shell, respectively. The shell element is moved in the positive direction of the element normal.

`/LECT/`

List of the concerned elements.

Comments:

The number of gauss points through the thickness for a sandwich element is defined by `COMP SAND NGPZ`, see Page C.45. Therefore, an additional `COMP NGPZ` for the *same* element should be avoided.

The 'mean tau' procedure may be applied to CQD3, CQD4, CQD6, CQD9 degenerated shell elements. However, it simply sets the transverse shear values to a mean value, not to a linearly variable pattern. This is likely to be too simplistic for the 9-node element CQD9 (and also for the 6-node CQD6).

The parameter `alpha` is used to modify the bending coefficient for the global shell models. The program will use the following criterion:

```
sig* = SQRT (sigm ** 2 + (alph * sigf) ** 2)
```

In this formula, `sig*`, `sigm` and `sigf` represent the Von Mises equivalent stress, the membrane stress and the bending stress, respectively. By default, $\alpha = 0.666$ (i.e. 2/3) . Of course, this parameter only makes sense for shell elements that use a global model (i.e. which are **not** integrated through the thickness).

Each of the above directives may be repeated as needed to associate appropriate values of the parameters to each concerned element.

6.7 EXCENTRICITY FOR SHELL ELEMENTS

Object:

This (optional) directive allows to specify excentricity for thick shell elements.

Syntax:

```
<"EXCE" exce  /LECT/ >
```

`exce`

Distance between the shell mean surface and the reference surface used in the calculation. The default value is 0 (no excentricity).

`/LECT/`

List of the elements concerned.

Comments:

For the moment, this feature concerns only T3GS and Q4GS shells [969].

6.8 SANDWICHES AND LAYERS

Object:

To define sandwiches, each composed of several layers, for use with some types of shell elements. Each `SAND` directive defines a new sandwich composed of several layers and associates it with a group of elements.

Syntax:

```
( "SAND"   nl "FRAC" nl*fracl "NGPZ" nl*ngpzl  /LECTURE/  )
```

`nl`

Number of layers in the sandwich, which is associated with each of the elements given in the following `/LECT/`.

`fracl`

Thickness fraction of each layer: this is the ratio of the layer thickness to the total thickness of the element.

`ngpzl`

Number of integration points through the thickness in each layer.

`LECTURE`

Elements concerned.

Comments:

For the moment, only the elements of type ED01, COQI, CQD3, CQD4, CQD6 and CQD9 may be chosen to be multi-layered sandwiches.

The directive `SAND` may be repeated as necessary (by repeating each time also the `SAND` keyword itself) in order to define all the geometrical information related to sandwiches. There may e.g. be a sandwich (and therefore elements) with, say, 3 layers, and another (other elements) with, say, 5 layers, in the same calculation.

Each sandwich stores all the geometrical information related to the layered structure. However, elements within the same sandwich may be made of different materials (or material combinations in the various layers).

Remember to assign a material to each layer, see page C.750.

The total number of integration points through the thickness of each element is defined by the sum of the `ngpzl` values over the layers of its sandwich. This value should not exceed the maximum value available for each element type. The value can be uncreased by using `DIME ... NGPZ`.

The number of Gauss points through the thickness for each layer is defined by `ngpzl`. Therefore, an additional `COMP NGPZ` for the *same* elements should be avoided.

The set of sandwiches defined in the `SAND` directive(s) is stored in an array. Each layer receives an index corresponding to its definition order within the corresponding sandwich. This index is then used in order to assign a material (see page C.1110) or a set of orthotropy directions (see page C.97) to each layer.

For example, suppose that we define two sandwiches, the first with 3 layers and the second with 5 layers. The layers of the first sandwich will be identified by indexes 1 to 3 while those of the second sandwich by indexes 1 to 5. These are the indexes to be used in successive directives to assign materials and/or orthotropy characteristics to each layer within the corresponding sandwich (i.e., within the associated element).

6.9 GEOMETRY OF BEAMS

Object:

Description of the characteristics of beam elements.

There are four possible shapes:

- arbitrary section `QUEL`;

- rectangular section `RECT`;

- circular section `CIRC`;

- annular section (pipe) `TUYA`.

Moreover, in the case of pipes, it is possible to enter a curvature in order to model the elbows.

References:

For an example of use of the various cross sections see e.g. reference [738]. For an example of use of annular sections see also reference [802]. The description of the beam element is given in [478]. Finally, reference [807] gives an overview of pipelines.

Syntax:

```
"GEOP" |[ "QUEL"  "VX" vx  "VY" vy   "VZ" vz  "AIRE" aire
                  "IY" iy  "IZ" iz   "HY" hy  "HZ" hz
                < "J" j >  "R" r  < "EXCE" ex > < "MDIA" mdia > ;

         "RECT"  "VX" vx  "VY" vy   "VZ" vz  "AY" ay
              "AZ" az   < "GAUC" gauch >  < "J" j >
            < "EXCE" ex > < "MDIA" mdia >                  ;

         "CIRC"  "VX" vx  "VY" vy  "VZ" vz  "DEXT" diam
            < "EXCE" ex > < "MDIA" mdia >                  ;

         "TUYA"  "VX" vx  "VY" vy  "VZ" vz  "DEXT" diam
              "EP" ep  <"COUR" co >  < "RAYC" rayco >
            < "SFY" sfy   "SFZ" sfz   "SFT" sft >
            < "EXCE" ex > < "MDIA" mdia >                  ; ]|

   < "VMIS"  "APRS" aprs  "AMMB" ammb  "ATRS" atrs  "AFLX" aflx >

    /LECTURE/
```

`vx vy vz`

Global coordinates `X`, `Y`, `Z` of a vector `v` defining the local system (`oxyz`), see comments below.

`aire`

Area of the cross section of the beam.

`iy iz`

Bending inertias around the local axes `y` and `z`.

`hy`

Distance along `y` used to estimate an “equivalent bending stress” around the local axis `z`.

`hz`

Distance along `z` used to estimate an “equivalent bending stress” around the local axis `y`.

`j`

Torsional inertia, if different from `iy` + `iz`.

`r`

Distance used to estimate an “equivalent torsional stress”.

`ex`

Excentricity along `y` (optional).

`mdia`

Type of the mass matrix diagonalization (optional).

`ay az`

Length of the sides for a rectangular beam section (along `y` and `z`, respectively)

`diam`

External diameter for a beam with a circular section or for a pipe.

`ep`

Thickness of the pipe making up the beam.

`co`

Curvature of the elbows. It is the inverse of the curvature radius. In the case of a straight pipe: `co` = `0.0` This curvature radius stays constant during a calculation.

`rayco`

Curvature radius for the elbows. It is infinite for straight pipes.

`sfy sfz sft`

Coefficients of “surflexion” of the elbow: in the elbow plane (`sfy`), out of the plane (`sfz`) and in torsion (`sft`). The moment of inertia corresponding to the straight pipe is divided respectively by `sfy` (or `sfz` or `sft`) in order to account for the increased flexibility of the elbows (see also the comments below).

`gauch`

Coefficient of “gauchissement” for the cross-section, allowing to compute the torsional inertia starting from $J_o = I_y + I_z$ by means of a multiplicative coefficient: $J_p = \texttt{gauch} * J_o$.

`VMIS`

This keyword states that the weighting coefficients that allow to compute the Von Mises criterion starting from the different “equivalent stresses” are given by the user.

`aprs`

Weighting coefficient in the Von Mises criterion for the internal pressure of pipes.

`ammb`

Weighting coefficient in the Von Mises criterion for the membrane stress (normal stress).

`atrs`

Weighting coefficient in the Von Mises criterion for the equivalent torsional stress.

`aflx`

Weighting coefficient in the Von Mises criterion for the equivalent bending stress.

`LECTURE`

List of the elements concerned.

Comments:

A local reference system `oxyz` is attached to each beam element. The origin `o` of the system is in node 1 of the element. The second node (node 2) of the element then defines the longitudinal direction of the beam, which is assumed to correspond to the local `x` axis.

Then, to complete the definition of the local reference frame, another direction corresponding to the local `y` axis must be specified. This is done by giving a vector `v` (by means of its global components `vX`, `vY` and `vZ`), which is located in the `oxy` plane and completely defines this plane. Thus, the `v` vector may **not** coincide with `x`. The length of the `v` vector is irrelevant (but of course it may not be zero).

The `y` vector is then computed as the vector normal to `x` and lying in the plane defined by `x` and `v`. Finally, the `z` vector is computed as the vector normal to `x` and `y`.

Several types of mass matrix diagonalization are available and can be chosen by users thanks to the `mdia` parameter. The differences concern only the rotational terms in the lumped mass matrix of the beam element. The four different choices are:

- `mdia`=0 (default) corresponds to the diagonal term: $\rho S l \left(\frac{l^2}{105} + \frac{I}{S}\right)$ with $I = \frac{I_y + I_z}{2}$ initially proposed by M. Lepareux [807, 478]
- `mdia`=1 corresponds to the diagonal term: $\rho S l \frac{l^2}{105}$ initially proposed by M. Ruznievski [478]
- `mdia`=2 corresponds to the diagonal term: $\rho S l \left(\frac{l^2}{24} + \frac{1}{2}\frac{\tilde{I}}{S}\right)$ with $\tilde{I} = \max\left(I_y, I_z\right)$ initially proposed by T. Belytschko and W.L. Mindle (Flexural wave propagation behavior of lumped mass approximations. Computers & Structures, 1980 12(6), 805-812.)
- `mdia`=3 corresponds to the diagonal term: $\rho S l \frac{l^2}{24}$ initially proposed by S.W. Key and Z.E. Beisinger (The transient dynamic analysis of thin shells by the finite element method. In Proc. of the third conference on matrix methods in structural mechanics. 1971)

with ρ the material density of the beam, S its cross-section area and l the length of the beam element. The condition stability used for the computation of the critical time step is also adpated from the mass matrix diagonalization (see also option `DTBE` in GBH_0020). Note that only the flexural critical time step depends on the rotational diagonal term of the lumped mass matrix. For the option `mdia`=0, the flexural time step is given by the CEA's formula expressed in [807]. For the three other options, the flexural time step is obtained through the resolution of the eigenvalue problem [989].

In the case of an elbow, the vector `v` must be in the elbow plane and directed to the inner side of the elbow, however it is not compulsory that `v` is radial (directed exactly towards the "center" of the elbow). Bending around the `y` axis is therefore outside the elbow plane, while bending around the `z` axis is in the plane of the elbow.

In case of arbitrary cross section, the equivalent stress corresponding to the moment around `y` (respectively `z`) is computed for a distance h_z from the axis (respectively h_y) according to the following formula:

$$\sigma_y = M_y \frac{h_z}{I_y}$$

In the other cases, the formula is identical but the distance h becomes:

- for a rectangle: the corresponding half-side,
- for a cylinder or a tube: the external radius.

In the case of torsion, it is again the same formula, and the h distance is then:

- for an arbitrary cross-section: the `r` parameter,
- for a rectangle: the semi-diagonal,
- for a cylinder or a tube: the external radius.

In the case of a rectangular cross-section, it is possible to give either a "gauchissement" coefficient allowing to compute the torsional inertia starting from the inertia terms `iy` and `iz`, or to give directly the torsional inertia `j`.

For a square cross section this "gauchissement" coefficient has the value 0.844.

The bending inertias are modified in the case of elbows in order to account for the flexibility produced by the curvature as :

$$I_{coude} = I_{droit}/k$$

where k is `sfy`, `sfz` or `sft`.

ATTENTION: these coefficients are associated with the parameters of the von Mises criterion. A modification of the default values of `sfy`, `sfz` and `sft` imposes a different set of input values for `aprs`, `ammb`, `atrs` and `aflx`.

By default, these coefficients are computed as follows, according to RCCMR 3644.31: *i)* it is assumed that there is no change for the torsion (`sft` $= 1$). *ii)* it is also assumed that the flexibility is the same in the plane

$$\texttt{sfy} = \texttt{sfz} = k$$

.

The coefficient k is a function of the elbow parameter λ, defined as follows: $k = 1.65/\lambda$. By definition, the elbow parameter λ is of the form :

$$\lambda = e\,R_c/{R_m}^2$$

where e is the thickness and R_m the mean radius of the tube, and R_c the curvature radius of the elbow. In practice, EUROPLEXUS computes and prints the inverse of this value, that vanishes for a straight tube.

The used Von Mises criterion σ^* is of the form : $\sigma^* = \sqrt{\alpha_p\, P^2 + \alpha_n\, {\sigma_n}^2 + \alpha_t\, {\sigma_t}^2 + \alpha_f\, {\sigma_f}^2}$

In this formula, coefficients α_p, α_n, α_t and α_f are respectively the parameters `aprs`, `ammb`, `atrs` and `aflx` defined above. By default, these coefficients assume the following values (which are those for a pipeline): $\alpha_p = 0.75$, $\alpha_n = 1$, $\alpha_t = 3$ and $\alpha_f = \pi^2/16$.
In the case of elbows, the coefficients α_t and α_f are modified. The default values are: $\alpha_t = 0.75$ and $\alpha_f = (\gamma\,\pi/4)^2$.

The coefficient γ has the expression: $\gamma = \max(1; \frac{8}{9}\lambda^{-2/3})$

Important: please consult also GBG_0025 for the printout of the results.

6.10 DIAMETERS

Object :

Diameters of pipeline branches meshed either by one-dimensional (1D) elements "TUBE", "TUYA", "CL1D", "CLTU", "TUVF", "TYVF", or by 2D/3D continuum CCFV elements "Q4VF" / "CUVF" (but limited to single-layer discretizations, i.e. a single row of such elements).

The branches made of elements "CL1D" and "CLTU" are always cylindrical, while those made of the other element types ("TUBE", "TUYA", "TUVF", "TYVF", "Q4VF" or "CUVF") may be either cylindrical (constant diameter) or conical (linearly varying diameter).

A branch can be either straight or moderately curved.

2D/3D continuum CCFV elements cannot be mixed up with other types of elements (1D) in the same branch (DIAM declaration). A branch formed by 2D/3D continuum CCFV elements is expected to be a single row of such elements, all connected one with the other from the inlet towards the outlet of the branch (without holes). The element numbers can be given in any order, and the code internally reconstructs the ordered sequence of elements starting from the inlet (which must be specified in this case via the ORIG directive even for a cylindrical branch).

A cylindrical branch (which may be either straight or moderately curved) can be specified by two alternative directives: the "DROI" directive is simpler and applies only to 1D branches. The "CYLI" directive requires the specification of the inlet of the branch ("ORIG") and applies only to 2D/3D continuum branches.

Syntax:

```
"DIAM" $[ "ELAS" ;
          "ELAT" "EPAI" epai "YOUN" youn "NU" nu ]$
          |[ "DROI" d /LECT1/ ;
             "CYLI" "D1" d1 "ORIG" /LECT2/ "LIST" /LECT3/ ;
             "CONE" "D1" d1 "D2" d2 "ORIG" /LECT4/ "LIST" /LECT5/ ]|
```

`"ELAS"`

This optional keyword activates an elastic correction of the speed of sound in the fluid of the pipe elements listed in the followed /LECT/ sequence. By default, the fluid vena section is rigid. For information about this correction see reference [956]. This keyword is ignored if applied to 2D/3D continuum branches.

`"ELAT"`

This optional keyword activates an elastic correction of the speed of sound in the fluid of the pipe elements listed in the followed /LECT/ sequence. When specified, this keyword must be associated with the keywords ”EPAI”, ”YOUN” and ”NU” defining the Allievi correction (characteristics of an equivalent pipe structure). By default, the fluid vena section is rigid. For information about this correction see reference [970]. This keyword is ignored if applied to 2D/3D continuum branches.

`"EPAI" epai`

Pipe thickness (optional keyword associated with ”ELAT” keyword) This keyword is ignored if applied to 2D/3D continuum branches.

`"YOUN" youn`

Young modulus (optional keyword associated with ”ELAT” keyword) This keyword is ignored if applied to 2D/3D continuum branches.

`"NU" nu`

Poisson coefficient (optional keyword associated with ”ELAT” keyword) This keyword is ignored if applied to 2D/3D continuum branches.

`"DROI" d`

Specifies the diameter d of a cylindrical branch. This form of the directive must be used (instead of CYLI) when the elements specified in the following /LECT1/ are 1D pipe elements, and not 2D/3D CCFV continuum elements.

`/LECT1/`

List of the elements of the cylindrical branch.

`"CYLI"`

Introduces the characteristics of a cylindrical branch. This form of the directive must be used (instead of DROI) when the elements specified in the following /LECT3/ are 2D/3D CCFV continuum elements, and not 1D pipe elements.

`"D1" d1`

Diameter of the 2D/3D cylindrical branch.

`"ORIG" /LECT2/`

The /LECT2/ specifies the origin nodes of the cylindrical branch, which define the first extremity, i.e. the inlet, of the branch. These are the nodes of the face located on the inlet of the branch. There must be two such nodes in 2D, four in 3D.

`"LIST" /LECT3/`

The /LECT3/ lists the elements forming the cylindrical branch.

`"CONE"`

Introduces the characteristics of a conical branch.

`"D1" d1`

Inlet diameter, corresponding to node(s) ”ORIG” specified in the following.

`"D2" d2`

Outlet diameter.

`"ORIG" /LECT4/`

The /LECT4/ specifies the origin node(s), i.e. the node(s) on the inlet, where the diameter is d1. If the branch is composed of 1D elements, there must be only one node in the /LECT4/ while, if the branch is composed of 2D or 3D elements there must be 2 or 4 nodes, respectively, in the /LECT4/.

`"LIST" /LECT5/`

The /LECT5/ lists the elements forming the conical branch.

Comments :

If the branch is cylindrical: d1 = d2. If the branch is conical, d1 is different from d2.

If a conical branch is composed of several elements, EUROPLEXUS automatically computes the inlet and outlet diameters of each element forming the branch.

If some friction (material PAROI) is associated to the fluid material, only cones with a vertex angle α less than 20 degrees are allowed. In this case, EUROPLEXUS computes the friction correction factor C_{frot}, according to the formulas of Idel'cik (diagram 5.2), where R is the ratio of the areas at the inlet and outlet of the cone ($R < 1$), and λ the loss coefficient for a cylindrical tube:

$$C_{\mathrm{frot}} = \frac{\lambda}{8\,\sin(\alpha)}\,(1 - R^2)$$

According to Idel'cik, the loss coefficients are then, C_{div} for a divergent pipe and C_{conv} for a convergent pipe (diagrams 3.7 and 5.2) :

$$C_{\mathrm{div}} = C_{\mathrm{frot}} \; + \; 3.2\tan(\alpha)^{\frac{5}{4}}\,(1 - R)^2$$

$$C_{\mathrm{conv}} = C_{\mathrm{frot}} \; + \; 0.45\,(1 - R)$$

6.11 NAMED ELEMENT GROUPS

Object:

To define a (new) set of named groups of elements. Note that the GROU directive may be repeated as needed within the COMP directive. The set of groups defined is *added* to any pre-existing named groups of elements.

Syntax:

```
( "GROU"  ngro * ('nom_grou' |[ /LECT/ ; STFL FLUI ; STFL CLXS ; DEBR ]| )
                                        <conditions>
                                        <"CENT" cx cy cz>
                                        <"SHRI" sh>
                                        <"SHFT" sx sy sz>)
```

ngro

Total number of groups that will be defined.

nom_grou

Name associated with the group, enclosed in quotes.

/LECT/

List of the concerned elements.

STFL FLUI

Instead of the explicit elements list /LECT/, all structured fluid elements (defined using STFL command, see page C.68) are taken. Of course, if present this command must be specified *after* the definition of the structured fluid mesh.

STFL CLXS

Instead of the explicit elements list /LECT/, all CLxS elements attached to structured fluid elements (defined using STFL CLxx command, see page C.68) are taken. Of course, if present this command must be specified *after* the definition of the structured fluid mesh.

DEBR

Instead of the explicit elements list /LECT/, all DEBR elements are taken. Of course, if present this command must be specified *after* the definition of the debris particles.

<conditions>

An optional set of conditions that allow to restrict the chosen elements to a subset of the list specified in the preceding /LECT/. See below for the syntax of conditional statements.

CENT

Introduces the optional definition of a centerpoint for the group, of coordinates `cx`, `cy`, `cz`, to be used in graphical rendering. In particular, this point is used for shrinking operations (see `SHRI` below). If omitted, the code computes it automatically as the (unweighted) average of the center points of the elements belonging to the group.

`SHRI`

Introduces the optional definition of a shrinkage factor for the group, of value `sh`, to be used in graphical rendering. If omitted, a factor 1.0 is assumed.

`SHFT`

Introduces the optional definition of a shift vector for the group, of components `sx`, `sy`, `sz`, to be used in graphical rendering. If omitted, zero shift is assumed.

Comments:

Object names are not case-sensitive: they are converted internally to upper-case before being used.

After their definition, group names may be used to specify in input directives lists of elements (or of the associated nodes), in exactly the same way as GIBI object names are, within a `/LECT/` directive. The set of nodes 'associated' with a group of elements is the union of all nodes belonging to the elements in the group.

GIBI object names, or universal format groups or I-DEAS groups have the precedence over the present element groups, in case they are present (and in case of homonimy).

Note that, if element groups are to be passed to the OpenGL-based visualization module, they should preferably be disjoint, i.e. such that each element belongs to (at most) one group. This would ensure independence of rendering from the order in which group selection/unselection operations are performed. However, the code does not enforce this requirement, so that the graphical results are under full control (and responsibility) of the user.

The optional center, shrink and shift definitions may be used e.g. to obtain special graphical rendering effects such as an "exploded" view of a geometrical model. Be aware that the code applies shrinkage by the chosen factor around the centerpoint first, then followed by the chosen shift, if any.

Conditional statements

Various types of conditions may be imposed. The first one compares the position of the element's barycenter to a given value. Another one selects the (single) element whose barycenter is nearest to a given node or point. Other directives allow to identify all elements within a certain geometric shape (a box, a sphere, a cylinder, a cone). The next one allows to build up the complement (symmetric difference) of the chosen object with respect to a second object. The last directive allows to extract the elements that share either all nodes or at least one node with a second object.

```
(COND | $ XB ; YB ; ZB $   $ LT ; GT $  val                             |
      | NEAR $ NODE /LECT/ ; POIN x y <z> $                             |
      | BOX  <X0 x0> <Y0 y0> <Z0 z0> DX dx DY dy <DZ dz>                |
      | SPHE <XC xc> <YC yc> <ZC zc>  R  r                              |
      | CYLI <X1 x1> <Y1 y1> <Z1 z1> <X2 x2> <Y2 y2> <Z2 z2>  R  r      |
      | CONE <X1 x1> <Y1 y1> <Z1 z1> <X2 x2> <Y2 y2> <Z2 z2>  R1 r1 R2 r2 |
      | COMP /LECT/                                                     |
      | APPU $ STRI ; LARG $ /LECT/                                     |)
```

`COND`

Introduces a condition. This keyword may be repeated as many times as necessary to specify multiple conditions, which are applied in sequence.

`XB`

X-coordinate of the element's barycenter.

`YB`

Y-coordinate of the element's barycenter.

`ZB`

Z-coordinate of the element's barycenter.

`LT`

Less than operator.

`GT`

Greater than operator.

`val`

Value.

`NEAR`

Selects the (single) element whose centroid is nearest to a given node or point. If there is more than one element at the minimum distance, then only the first one found is retained.

`NODE`

Specify the node by the following `/LECT`.

`POIN`

Specify the point by its coordinates `x`, `y` and `z`. The last coordinate is needed only in 3D calculations.

`BOX`

Introduces the definition of a "box", (a quadrilateral in 2D or a parallelepiped in 3D) with the sides aligned with the global axes.

`x0, y0, z0`

Coordinates of the 'origin' of the box.

`dx, dy, dz`

Lengths of the box sides.

`SPHE`

Introduces the definition of a sphere (in 3D, or a circle in 2D).

`xc, yc, zc`

Coordinates of the centre of the sphere (or of the circle).

`r`

Radius of the sphere or of the circle.

`CYLI`

Introduces the definition of a cylinder (3D only). The cylinder is defined by the two extremities of its axis (P1, P2) and its radius.

`x1, y1, z1`

Coordinates of the first extremity P1 of the cylinder axis.

`x2, y2, z2`

Coordinates of the second extremity P2 of the cylinder axis.

`r`

Radius of the cylinder.

`CONE`

Introduces the definition of a (truncated) cone (3D only). The cone is defined by the two extremities of its axis (P1, P2) and its radii.

`x1, y1, z1`

Coordinates of the first extremity P1 of the cone axis.

`x2, y2, z2`

Coordinates of the second extremity P2 of the cone axis.

`r1`

Radius of the cone at the first extremity.

`r2`

Radius of the cone at the second extremity.

`COMP`

Introduces a second object to be used for the symmetric difference (complement) operation.

`/LECT/`

List of the concerned elements.

`APPU`

Extract the elements that share nodes with an object to be defined next. This command is inspired by Cast3m's *appuyé* operator.

`STRI`

An elements is extracted if it shares *all* his nodes with the object defined next.

`LARG`

An elements is extracted if it shares *at least one* of his nodes with the object defined next.

`/LECT/`

Defines the second object, whose nodes are considered for the previously defined elements extraction.

Comments:

If any of the above coordinates (`x0`, `y0` etc.) is omitted, it is assumed to be 0.

Example:

Suppose that we want to select all the elements of a 2D object `ob1` that lie in the first quadrant. The syntax would be:

```
COMP ... GROU 1 'firqua' LECT ob1 TERM
                         COND XB GT 0
                         COND YB GT 0
```

The group is from now on accessible under the name `firqua`.

Suppose then that we want to do the same thing as in the previous example, but also get access to the parts of `ob1` in the other three quadrants, under the name `others`. The syntax would be:

```
COMP ... GROU 2 'firqua' LECT ob1 TERM
                         COND XB GT 0
                         COND YB GT 0
                'others' LECT ob1 TERM
                         COND COMP LECT firqua TERM
```

Note that the `firqua` object becomes available immediately after its definition, and may therefore be used in the definition of the `others` group.

6.12 NAMED NODE GROUPS

Object:

To define a (new) set of named groups of nodes. Note that the `NGRO` directive may be repeated as needed within the `COMP` directive. The set of groups defined is *added* to any pre-existing named groups of nodes.

Syntax:

```
( "NGRO"  nngr * ('nom_grou' /LECT/ <conditions>) )
```

`nngr`

Total number of node groups that will be defined.

`nom_grou`

Name associated with the group, enclosed in quotes.

`/LECT/`

List of the concerned nodes, except in the particular case of the `ENVE` condition (see `<conditions>` below), where this is the list of concerned *elements*.

`<conditions>`

An optional set of conditions that allow to restrict the chosen nodes to a subset of the list specified in the preceding /LECT/. See below for the syntax of conditional statements.

Comments:

Object names are not case-sensitive: they are converted internally to upper-case before being used.

After their definition, group names may be used to specify in input directives lists of nodes (or of the associated elements), in exactly the same way as GIBI object names are, within a `/LECT/` directive. An element is considered 'associated' with a group of nodes if and only if all its nodes belong to the group.

GIBI object names, or universal format groups or I-DEAS groups have the precedence over the present node groups, in case they are present (and of homonimy). Moreover, named groups of elements (see page C.61) also have the precedence over the present node groups, in case they are present (and of homonimy).

Note that, if node groups are to be passed to the OpenGL-based visualization module, they should preferably be disjoint, i.e. such that each node belongs to (at most) one group. This would ensure independence of rendering from the order in which group selection/unselection operations are performed. However, the code does not enforce this requirement, so that the graphical results are under full control (and responsibility) of the user.

Conditional statements

Various types of conditions may be imposed. The first one compares the node position to a given value. Other directives allow to identify all nodes within a certain geometric shape (a box, a sphere, a cylinder, a cone). Other directives allow to order a set of nodes according to their position along a straight line (`LINE`) or along a curve (`CURV`). The next one allows to build up the complement (symmetric difference) of the chosen object with respect to a second object. Finally, a directive allows to extract all the nodes located on the envelope (in 3D) or the contour (in 2D) of the object (set of elements) strictly insisting on the set of nodes subjected to the condition (an element is strictly insisting on a set of nodes if all nodes of the element belong to the set).

```
(COND | $ X ; Y ; Z $   $ LT ; GT $  val                                   |
      | NEAR $ NODE /LECT/ ; POIN x y <z> $                                |
      | BOX  <X0 x0> <Y0 y0> <Z0 z0> DX dx DY dy <DZ dz>                   |
      | SPHE <XC xc> <YC yc> <ZC zc>  R  r                                 |
      | CYLI <X1 x1> <Y1 y1> <Z1 z1> <X2 x2> <Y2 y2> <Z2 z2>  R  r         |
      | CONE <X1 x1> <Y1 y1> <Z1 z1> <X2 x2> <Y2 y2> <Z2 z2>  R1 r1 R2 r2 |
      | LINE X1 x1 Y1 y1 <Z1 z1> X2 x2 Y2 y2 <Z2 z2> TOL tol <DIST d>      |
      | CURV $ X1 x1 Y1 y1 <Z1 z1> ; NOD1 /LECT/ $                         |
      |      <DX dx DY dy <DZ dz>> <CLOS>                                  |
      | COMP /LECT/                                                        |
      | ENVE <LOCA>                                                        |)
```

`COND`

Introduces a condition. This keyword may be repeated as many times as necessary to specify multiple conditions, which are applied in sequence.

`X`

X-coordinate of the node.

`Y`

Y-coordinate of the node.

`Z`

Z-coordinate of the node.

`LT`

Less than operator.

`GT`

Greater than operator.

`val`

Value.

`NEAR`

Selects the (single) node nearest to a given node or point. If there is more than one node at the minimum distance, then only the first one found is retained.

`NODE`

Specify the node by the following `/LECT`. This node is of course excluded from the search of the nearest node to it.

`POIN`

Specify the point by its coordinates `x`, `y` and `z`. The last coordinate is needed only in 3D calculations.

`BOX`

Introduces the definition of a “box”, (a quadrilateral in 2D or a parallelepiped in 3D) with the sides aligned with the global axes.

`x0, y0, z0`

Coordinates of the ‘origin’ of the box.

`dx, dy, dz`

Lengths of the box sides.

`SPHE`

Introduces the definition of a sphere (in 3D, or a circle in 2D).

`xc, yc, zc`

Coordinates of the centre of the sphere (or of the circle).

`r`

Radius of the sphere or of the circle.

`CYLI`

Introduces the definition of a cylinder (3D only). The cylinder is defined by the two extremities of its axis (P_1, P_2) and its radius.

`x1, y1, z1`

Coordinates of the first extremity P_1 of the cylinder axis.

`x2, y2, z2`

Coordinates of the second extremity P_2 of the cylinder axis.

`r`

Radius of the cylinder.

`CONE`

Introduces the definition of a (truncated) cone (3D only). The cone is defined by the two extremities of its axis (P_1, P_2) and its radii.

`x1, y1, z1`

Coordinates of the first extremity P_1 of the cone axis.

`x2, y2, z2`

Coordinates of the second extremity P_2 of the cone axis.

`r1`

Radius of the cone at the first extremity.

`r2`

Radius of the cone at the second extremity.

`LINE`

Introduces the definition of a straight line. The line is defined by the two extremities (P_1, P_2), a relative tolerance ϵ (TOL) and an optional relative spacing δ (DIST) between the nodes to be retained. The nodes which fall on the line are extracted, listed in the order in which they occur passing from P_1 to P_2 (included).

In 3D space, the line passing through 2 points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ has the following parametric equations:

$$\begin{aligned} x &= x_1 + dx\,t, \quad dx = x_2 - x_1 \\ y &= y_1 + dy\,t, \quad dy = y_2 - y_1 \\ z &= z_1 + dz\,t, \quad dz = z_2 - z_1 \end{aligned}$$

From each equation a value for t can be defined:

$$\begin{aligned} t_x &= \frac{x - x_1}{dx} \\ t_y &= \frac{y - y_1}{dy} \\ t_z &= \frac{z - z_1}{dz} \end{aligned}$$

These 3 quantities are calculated for each point of the geometrical object to which the LINE condition is being applied and, if the 3 following conditions are satisfied, then the point is retained.

- t_x, t_y, t_z are equal or at least their difference (in absolute value) is smaller than or equal to the defined tolerance ϵ (for the point to lie on the line defined by P_1, P_2).
- The common value of t_x, t_y, t_z is between $(0 - \epsilon)$ and $(1 + \epsilon)$ (for the point to lie between P_1 and P_2, extremities included).
- If δ is not zero, then the value of t divided by δ (DIST) should be in the vicinity of an integer number (the length of the vicinity is defined by the input tolerance ϵ).

`x1 y1 z1`

Coordinates of the first extremity P_1 of the line.

`x2 y2 z2`

Coordinates of the second extremity P_2 of the line.

`tol`

Tolerance (relative) ϵ for searching the nodes on the line. The absolute tolerance τ is equal to the relative tolerance multiplied by the distance L between P_1 and P_2: $\tau = L\epsilon$.

`d`

Parametric (relative) distance δ between two consecutive nodes retained on the line. If omitted, all nodes on the line are retained. If specified, then the relative distance between two consecutive retained nodes will be greater or equal to δ (and so possibly some nodes on the line will be skipped). The absolute distance d is equal to the relative distance multiplied by the distance L between P_1 and P_2: $d = L\delta$.

`CURV`

The nodes are listed in the order in which they occur along the minimum-distance curve starting at one of them. The first node of the resulting ordered set is either the node closest to a given position in space (x_1, y_1, z_1) or and explicitly chosen node N_1. The next node is the closest one to the previous one, and so on, until *all* the selected nodes have been used. Note that this behaviour is different from the `LINE` directive, where only those selected nodes which are actually on the line specified (within the given tolerance) are retained. Optionally, the curve can be closed (`CLOS`), by repeating the first node at the end of the ordered set. Finally, the optional `DX`, `DY`, `DZ` sub-directive allows to specify the preferential direction of search for the *second* node in cases where there migh be an ambiguity. This can be useful if there are two or more nodes at the same distance (within a small tolerance) from the first node. Then, amomg the candidates we choose the one whose position vector with respet to the first node forms the largest dot (scalar) product with the given direction. An example of use of the `DX`, `DY`, `DZ` and `CLOS` optional keywords is as follows. Consider a series of nodes equi-spaced along a circle. We want to constract the curvilinear abscissa along the entire circle, starting at one node. There are two nodes at substantially the same distance to the chosen first node (a *left* one and a *right* one, so to say). The `DX`, `DY`, `DZ` keywords allow to choose whether to move along the circle in one sense or in the other. The `CLOS` keyword allows to obtain a curvilinear abscissa of the same length as the (discretized) circumference, instead of the circumference minus one sub-division.

`x1 y1 z1`

Coordinates of the first extremity P_1 of the curve. The first node in the ordered set is the node, among the previously selected ones, that is closest to P_1.

`NOD1 /LECT/`

Allows to explicitly choose the first node in the ordered set (N_1). Note that N_1 must be among the previously selected nodes.

`dx dy dz`

Preferential direction for the search of the *second* node of the ordered set, in case there are two or more selected nodes that are (approximately) equi-distant from the first node.

`CLOS`

Close the curve, i.e. close the ordered set. The index of the first node is added (repeated) to the end of the ordered set.

`COMP`

Introduces a second object to be used for the symmetric difference (complement) operation.

`/LECT/`

List of the concerned nodes.

`ENVE`

Extract all the nodes located on the envelope (in 3D) or the contour (in 2D) of the object (set of elements) *strictly insisting* on the set of nodes subjected to the condition. An element is *strictly* insisting on a set of nodes if *all* nodes of the element belong to the set. By default, the *global* envelope/contour is considered. That is, a node is on the envelope/contour of the object if it belongs to an external face of an element of the object, i.e. to a face that has no neighbour *in the whole mesh*. This behaviour may be modified by the `LOCA` keyword, see below. Attention: CLxx elements are NOT considered as valid neighbours for the search of envelope/contour.

`LOCA`

The *local* envelope/contour is considered. That is, a node is on the envelope/contour of the object if either it belongs to an external face of an element of the object i.e. to a face that has no neighbour *in the whole mesh*, or it has a neighbour but this neighbour is not part of the elements of the object. Attention: CLxx elements are NOT considered as valid neighbours for the search of envelope/contour. Clearly, if the object to which the `ENVE` condition is being applied is the set of all nodes in the mesh (`tous`), then specifying or not the `LOCA` keyword has no effect on the result.

Comments:

If any of the above coordinates (`x0`, `y0` etc.) is omitted, it is assumed to be 0.

Example:

Suppose that we want to select all the nodes of a 2D object `ob1` that lie (strictly) within the first quadrant. The syntax would be:

```
COMP ... NGRO 1 'firqua' LECT ob1 TERM
                         COND X GT 0
                         COND Y GT 0
```

The group is from now on accessible under the name `firqua`.

Suppose then that we want to do the same thing as in the previous example, but also get access to the nodes of `ob1` in the other three quadrants, under the name `others`. The syntax would be:

```
COMP ... NGRO 2 'firqua' LECT ob1 TERM
                         COND X GT 0
                         COND Y GT 0
                'others' LECT ob1 TERM
                         COND COMP LECT firqua TERM
```

Note that the `firqua` object becomes available immediately after its definition, and may therefore be used in the definition of the `others` group.

6.13 ELEMENT COLORS

Object:

To define or re-define (e.g. in the case of a mesh generated by Cast3m) the colors of elements, for visualization purposes.

Syntax:

```
"COUL" (nom_coul /LECT/)
```

`nom_coul`

Name of the color (**not** enclosed in quotes). The valid names are those of Cast3m, i.e. `bleu`, `roug`, `rose`, `vert`, `turq`, `jaun`, `blan` or `noir`, plus the following nine gray levels: `gr10` (almost black), `gr20`, `gr30`, `gr40`, `gr50`, `gr60`, `gr70`, `gr80` and `gr90` (almost white). Elements not assigned a color have a default color.

`/LECT/`

List of the concerned elements.

Comments:

Repeat as many times as necessary to define all the desired colors.

This directive is particularly useful in conjunction with the definition of element groups (see `GROU`) to assign colors to groups of elements.

If there are several colors to be defined, be sure **not** to repeat the keyword `COUL`, but only the color name `nom_coul` followed by the corresponding `/LECT/`. In fact, each time the keyword `COUL` is encountered, all colors defined so far are reset to the default color (black). For example:

```
COUL roug LECT explosive TERM
     vert LECT structure TERM
```

is correct, while:

```
COUL roug LECT explosive TERM
COUL vert LECT structure TERM
```

would be wrong (the `explosive` object would appear black and not red).

6.14 RTM COMPOSITE MATERIALS

Object:

This directive allows to define values to used by a composite material made by a RTM process ie. the CRTM material (page C264).

Syntax:

```
"RTMVF"   vf      /LECTURE/

"RTMRCT"  rct     /LECTURE/

"RTMANGL" angle   /LECTURE/
```

`vf`

Value of the volumic fraction

`rct`

Value of the ratio between warp and weft

`angle`

Value of the angle between warp and weft directions.

`LECTURE`

List of the elements concerned.

6.15 PFEM METHOD

Object:

Warning: the present model is under development at JRC and not all the directives described below are available yet!

This directive sets some parameters used by the PFEM method.

Syntax:

```
PFEM  H h ALPHA alpha
```

`h`

Expected distance between nodes in the Bowyer-Watson triangulation.

`alpha`

Alpha coefficient for the Alpha-shape method to determine the contour of the triangulation.

6.16 FLYING DEBRIS MODEL

Object:

This directive allows to model flying debris resulting from an explosion or an impact. Each piece of debris is modeled by a particle, optionally embedded in the surrounding fluid and optionally subjected to the gravity force. This latter force, if present, must be specified via the `CHAR CONS GRAV` directive, see page F.30.

The fluid surrounding the debris particles may be modeled either as a uniform field with constant properties (velocity, density), or as an evolving fluid field, discretized by Finite Elements or Finite Volumes, or even as a combination of the two (e.g., FE fluid field near the explosive source, uniform field far away).

The drag pressure acting on a particle is:

$$\underline{p}_D = -C_D \frac{1}{2} \rho_f ||\underline{w}||^2 \frac{\underline{w}}{||\underline{w}||}$$

where C_D is the particle's drag coefficient (see below), ρ_f is the fluid's density and $\underline{w}$ is the particle's velocity $\underline{v}$ relative to the fluid velocity $\underline{v}_f$: $\underline{w} = \underline{v} - \underline{v}_f$.

Then, the drag force F_D exerted by the fluid on the particle is computed by multiplying the drag pressure by the exposed area A of the particle:

$$F_D = p_D A = p_D \pi \frac{d^2}{4}$$

where $A = \frac{\pi}{4} d^2$ is the particle's cross-section, with d the diameter of the particle (assumed to be spherical).

One may also activate a feed-back mechanism whereby the drag forces generated by the fluid on the particles are applied (with the minus sign) to the fluid itself. This is currently the default when the fluid is discretized by FE (but not by VFCC). Note, however, that in general it is preferable to deactivate the feedback mechanism (see option `NOFB` below), since it perturbs the fluid flow, while the drag formula (whose coefficient C_D is determined experimentally) assumes an unperturbed fluid flow. In other words, in order to compute the relative velocity $\underline{w}$ to be introduced in the formula, the fluid velocity should be taken at a certain distance from the particle, where the effect of the particle is not felt. Furthermore, note that at the moment feedback forces are only applied (by default, i.e. without the `NOFB` option) when the fluid is discretized by Finite Elements (FE). They cannot be applied (with or without `NOFB`) to a fluid discretized by Cell-Centred Finite Volumes (VFCC).

The debris particles may either be active from the very beginning of the calculated transient (thus assuming that they result from a fragmentation process that occurred at a previous time), or they may be associated with certain finite elements representing a structure, and be activated automatically by the code only when the element undergoes complete failure.

In any case, since particles are represented by the specialized `DEBR` elements, and since the topology is basically constant in time in EUROPLEXUS, **all particles must be declared** (and thus they are present in the model) **from the beginning of the calculation**. However, some of them may be already active at the initial time, some not.

The model includes the optional treatment of the impact of debris particles against the surrounding structure. This is accomplished by the pinball method.

Syntax:

```
DEBR ![ <ROF rof>
      <VFX vfx> <VFY vfy> <VFZ vfz>
      <FLUI /LECT/ <DGRI> $[ HGRI hgri ; NMAX nmax ; DELE dele ]$ >
      < $ FBAC ; NOFB $ > ]!
      (PART particle_description)
      (FILL fill_description)
```

`rof`

Density of the (default) uniform fluid field in which the particles are embedded. This value is 0.0 by default, meaning that by default the particles move in vacuum (if they are not coupled with a discretized fluid domain by the `FLUI` keyword). Note that the drag force acting on a particle depends on the density but also on the drag coefficient (`DRAG`, see below). By setting `DRAG` to 0, the drag force vanishes even though the density is not zero.

`vfx, vfy, vfz`

Components of the velocity of the surrounding uniform fluid field. These values are 0.0 by default.

`FLUI`

Introduces the `/LECT/` of the discretized fluid domain with which the particles motion should be coupled. When a particle traverses this domain, the (local) fluid velocity and density are automatically computed by the code, instead of using the constant user-given values `rof`, `vfx`, `vfy`, `vfz` described above. A fast search algorithm based on a grid of cells (as in bucket sorting) is used to compute the fluid element (if any) encompassing each debris particle.

`DGRI`

Dump out the initial grid of cells used for fast searching on the listing. For brevity, the print is done only the first time that the grid is computed, that is, when some active debris are created.

`HGRI`

Specifies the size of the grid cell. Each cell has the same size in all spatial directions and is aligned with the global axes. Note that the size of this grid is related to the size of the **fluid** elements specified in `FLUI`, not of the structural elements producing the flying debris.

`NMAX`

Specifies the maximum number of cells along one of the global axes.

`DELE`

Specifies the size of the grid cell as a multiple of the diameter of the largest coupled **fluid** element. Element "diameters" are computed only along each global spatial direction and the maximum is taken. For example, by setting `DELE 4` the size of the cell is four times the diameter of the largest coupled fluid element. By default, i.e. if neither `HGRI`, nor `NMAX`, nor `DELE` are specified, the code takes `DELE 3` (this value is probably too large, a value of 1.1 or so should be more appropriate in most cases).

`FBAC`

Activate the feed-back mechanism whereby the drag forces generated by the fluid on the debris particle are also applied (with the minus sign) to the fluid itself. This is the default, although in many cases it is preferable to deactivate the feedback mechanism, since it perturbs the fluid flow while the drag formula assumes an unperturbed fluid flow (the fluid velocity should be taken at a certain distance from the debris particle, where the effect of the debris particle is not felt). Furthermore, note that at the moment feedback forces can only be applied when the fluid is discretized by Finite Elements (FE), not by Cell-Centred Finite Volumes (VFCC).

`NOFB`

Deactivate the feed-back mechanism whereby the drag forces generated by the fluid on the debris particle are also applied (with the minus sign) to the fluid itself. If the fluid is modelled by VFCC, activating or not the feedback mechanism has no influence on the solution because the feedback is not available for this type of fluid discretization.

`PART`

Introduces the description of a single particle, see details below. Such particles are active from the very beginning of the calculation. This directive may be repeated any number of times.

`FILL`

Fill by particles a single finite element or a finite element mesh. Such particles may either be active from the very beginning of the calculation, or be activated upon failure of the associated element(s). See below for the details of this directive. This directive may be repeated any number of times.

Dimensioning for the flying debris:

Dimensioning for the flying debris cannot be made fully automatic, because of the `FILL` command which generates a variable number of particles depending upon which finite element type it is applied to and upon how many such elements will actually fail.

The number given in the dimensioning is the maximum number of debris particles that can be generated in the calculation. If the number given is not sufficient, the code will issue a warning message but the calculation will be continued (without generating any more debris particles). At the end of the run, the code will print out the exact number of particles needed (should the calculation be repeated).

The following two-step procedure is suggested:

- Prepare an input file containing the `COMP DEBR ...` directive and a tentative dimensioning for the debris. Run the calculation. If the given dimension is insufficient, the code will print a warning message and it will continue the calculation as explained above. At the end of the run, the code will print the total number of `DEBR` needed, say `n_debr`.
- Add to the input file the directive `DIME DEBR n_debr TERM`. Next time the calculation should run smoothly. If the printed `n_debr` is less than or equal to the number given, of course it is not necessary to re-run the calculation (but you may want to adjust the dimension at the exact value anyway, should you need to re-run the test case for any reason).

Dimensioning in case of domain decomposition (MPI):

In case of a calculation with domain decomposition (MPI), the dimensioning for the flying debris can assume two forms:

- If one gives `DIME DEBR n_debr` with `n_debr` > 0, then the code will assume this size of the debris *on each processor* (so that the maximum total number of debris will be `n_debr` times the number of processors `n_proc`).
- If one gives `DIME DEBR n_debr` with `n_debr` < 0, the code will assume this size of the debris *in total* (so that the maximum number of debris on each processor will be `n_debr` divided by the number of processors `n_proc`).

Comments:

Debris particles may be subjected to the gravity force. This latter force, if present, must be specified via the `CHAR CONS GRAV` directive, see page F.30.

The total number of particles described by the `PART` and `FILL` sub-directives must be less than or equal to the number of elements of type `DEBR` that has been reserved in the dimensioning of the problem.

Describing a single particle

Object:

To describe a single particle of debris. The particle is already active at the beginning of the transient calculation. Therefore, it results from the fragmentation of a structure which has occurred at a previous time.

Syntax:

```
PART  <X x> <Y y> <Z z>   <VX vx> <VY vy> <VZ vz>
      RO ro  D d  DRAG drag
      <COUP> <IMPA> <TRAJ> <RISK> <ERIM>
```

`x, y, z`

Coordinates of the particle at the initial time. These values are 0.0 by default.

`vx, vy, vz`

Velocity components of the particle at the initial time. These values are 0.0 by default.

`ro`

Density of the particle.

`d`

Diameter of the particle.

`drag`

Drag coefficient of the particle. This is a number usually between 0.3 and 1.1 for a sphere. In the supersonic region the value is almost constant and close to 1.0, while it drops rapidly in the transonic region.

`COUP`

Couple the particle's motion with the surrounding fluid domain defined by the `FLUI` directive above. Note that this keyword is mandatory if one wants to activate risk evaluation (see the `RISK` keyword below).

`IMPA`

Treat the impact of the particle against surrounding structures (by the pinball method). One (parent) pinball is embedded in the particle, of diameter equal to that of the particle. Pinballs for the potentially impacted structures must be defined separately by the `PINB` directive, see page D.480.

`TRAJ`

Save the particle's trajectory, e.g. for visualization purposes. By default, the particle trajectory will consist of 100 points equispaced in time between the initial and final times of the calculation, but the number of points can be set by the `OPTI DEBR NTRA` option (see page H.45). Beware that, by default, the trajectory data are **not** stored in the ALIC results file. Therefore, visualization of the particles trajectory can only be done during the main calculation. In order to draw the trajectories when reading back results `RESU` from an ALIC file, one must activate the `OPTI DEBR STTR` option (see page H.45), which stores the trajectory data on the ALIC file (beware that the size of the file may increase considerably if there are many particles and many points per trajectory).

`RISK`

The risk of death due to the impact of the current flying debris particle on the human body is calculated. This keyword is only accepted if the `RISK` keyword has been specified in the problem type definition (see Page A.30). Furthermore note that, in order to actually compute the risk, the keyword `COUP` must also be specified as explained above. The debris-related risk calculation is based on the Lewis model and requires the presence of a (discretized) fluid domain. In fact, the risk is evaluated in each fluid element (or volume) as this is traversed by the flying debris particles.

`ERIM`

Activates the erosion of the debris after an impact by pinball contact.

Filling an element or a mesh by particles

Object:

To fill by debris particles an element or a mesh. Particles are automatically generated uniformly within the volume of the element or mesh (element by element). The particles inherit the density of the parent element's material when they are generated.

The particles may either: 1) be already active at the beginning of the transient calculation (in this case they result from the fragmentation of a structure which has occurred at a previous time), or 2) be activated automatically by the code when the associated element(s) undergo complete failure.

In case 1) above, the associated element or mesh is defined at the geometric level only as a geometric support for the particles generation. This element or mesh bf must be associated with a `FANT` material so as to exclude it from the transient computation. Assign to the `FANT` material the desired density, which will be inherited by the generated particles.

In case 2) above, the associated element or mesh must be assigned a structural material with a failure model (thus **not** the `FANT` material). When the element(s) fail, the associated particles are suddenly activated while at the same time the element is deactivated, so it no longer contributes to the model.

Syntax:

```
FILL  $<VX vx> <VY vy> <VZ vz> ; <VR vr <CX cx> <CY cy> <CZ cz>>$
      PLEV plev DRAG drag <AFLY afly>
      <COUP> <IMPA> <TRAJ> <RISK <MACR <RMAC rmac>>>
      <ERIM>
      OBJE /LECT/
```

`vx, vy, vz`

Components of the velocity of the particles at the initial time. This value is 0.0 by default.

`vr`

Radial velocity of the particles at the initial time. This value is 0.0 by default.

`cx, cy, cz`

Coordinates of the particles centroid with respect to which the radial velocity is expressed. By default this is the centroid of the geometrical object defined by the `/LECT/` directive given below.

`plev`

Level of hierarchic subdivision of the parent element(s) along each spatial direction in order to generate the particles. The particles' diameter is automatically determined so as to conserve the element's total volume. For example, a level of 3 means that $2^3 = 8$ subdivisions along each spatial direction to generate the particles. A 2D quadrilateral element would in this case be filled by $8 \cdot 8 = 64$ particles.

`drag`

Drag coefficient of the particles. This is a number usually between 0.3 and 1.1 for a sphere. In the supersonic region the value is almost constant and close to 1.0, while it drops rapidly in the transonic region.

`afly`

The drag forces and the `AIRB` forces depend on the area of the spherical particle, which can be different from the "true" debris cross section. For each shell element and beam element a minimum and a maximum area are estimated. By using the keyword `AFLY` the minimum (`afly` = 0.0) or the maximum (`afly` = 1.0) value is used. Values of `afly` between 0.0 and 1.0 interpolate linearly between these two values. The default value is 0.5. For solid elements, the cross section of the spherical particle is used and so `afly` is ignored.

`COUP`

Couple the particles' motion with the surrounding fluid domain defined by the `FLUI` directive above. Note that this keyword is mandatory if one wants to activate risk evaluation (see the `RISK` keyword below).

`IMPA`

Treat the impact of the particles against surrounding structures (by the pinball method). One (parent) pinball is embedded in each particle, of diameter equal to that of the particle. Pinballs for the potentially impacted structures must be defined separately by the `PINB` directive, see page D.480.

`TRAJ`

Save the particle's trajectories, e.g. for visualization purposes. By default, the particle trajectory will consist of 100 points equispaced in time between the initial and final times of the calculation, but the number of points can be set by the `OPTI DEBR NTRA` option (see page H.45). Beware that, by default, the trajectory data are **not** stored in the ALIC results file. Therefore, visualization of the particles trajectory can only be done during the main calculation. In order to draw the trajectories when reading back results `RESU` from an ALIC file, one must activate the `OPTI DEBR STTR` option (see page H.45), which stores the trajectory data on the ALIC file (beware that the size of the file may increase considerably if there are many particles and many points per trajectory).

`RISK`

The risk of death due to the impact of the active flying debris particles on the human body is calculated. This keyword is only accepted if the `RISK` keyword has been specified in the problem type definition (see Page A.30). Furthermore note that, in order to actually compute the risk, the keyword `COUP` must also be specified as explained above. The debris-related risk calculation is based on the Lewis model and it is applied to the active debris particles which are produced after the erosion of an element. The risk calculation requires the presence of a (discretized) fluid domain. In fact, the risk is evaluated in each fluid element (or volume) as this is traversed by the flying debris particles.

`MACR`

This keyword adds to the risk calculation described above (related to the flying debris particles produced **after** erosion of an element) also the calculation of the risk related to the impact of macro fragments (i.e., **before** the erosion of an element). To estimate such risk, "spurious" (inactive) particles ("markers") are attached to the elements (one particle per element) from the very beginning of the calculation (i.e., as long as the elements do not fail). In a recently proposed strategy which, however, has *not* been implemented yet, the risk estimation would take into account not only the mass of the current particle (current element) but also the mass of the surrounding (unfailed) elements, up to a certain influence radius that can be specified by the user (`RMAC`, see below). If an element fails and is eroded, the corresponding marker particle is suppressed and a suitable number of debris particles are activated (for which the impact risk is then computed normally).

`RMAC`

Attention: this keyword is silently accepted by the code but the corresponding model has *not* being implemented yet, so the keyword has *no effect*. Introduces the influence radius (`rmac`) for the evaluation of the impact risk of macro fragments. If a marker impacts (penetrates through) a fluid element, the risk is estimated by using the mass of all (unfailed) elements connected with the current one within a distance equal to `rmac`. By specifying `RMAC 0` an infinite radius of influence is taken. This means that the total mass of the macro fragment is considered in the impact.

`ERIM`

Activates the erosion of the debris after an impact by pinball contact.

`OBJE`

Introduces the list of the elements to be filled.

`/LECT/`

List of the elements to be filled.

Comments:

The initial velocity of each group of particles defined by the `FILL` directive described above may be defined in two ways:

- Either it is assumed as uniform for all particles: in this case specify the necessary Cartesian components `vx`, `vy` and `vz`;
- Or, it is assumed to be oriented radially from a point: in this case specify the velocity modulus `vr`. By default, the assumed point is the centroid of the geometric object being filled. However, the user may specify a different point by giving `cx`, `cy` and `cz`.

Correction of the drag formula (June 2019)

The formula of the drag force used in the initial implementation of the flying debris model was:

$$\underline{F}_D = -C_D \rho_f A ||\underline{w}||^2 \frac{\underline{w}}{||\underline{w}||}$$

that is, the factor 1/2 was originally *not* included. A correcton was introduced in June 2019 where the factor 1/2 was added (also for uniformity with the `DRAG` model described on Page D.630) and at the same time the optional keywords `FBAC` and `NOFB` were implemented.

In order to exactly reproduce with the new code version results once obtained with a version of EPX older than June 2019, it is sufficient to multiply by 2.0 the value of the drag coefficient C_D given in the input (`DRAG` keyword). Thus, for example, if the old input used `DRAG 1.0`, replace it by `DRAG 2.0`.

6.17 DISPLACEMENT EROSION

Object:

This directive allows to define an erosion (failure) criterion, which uses a maximum displacement of a given node.

The model can be used for calculations of laminated windows. The criterion of the complete erosion of a laminated window can be set to 30% of the span.

The model can be combined with any other erosion criterion.

Syntax:

```
FAIL  ( DISP disp NODE /LECT/ OBJE /LECT/ )
      ( AUTO rati DIRE disp /LECT/ )
```

`disp`

Displacement of the node given by the keyword `NODE`, which results in an erosion (failure) of the elements given by the keyword `OBJE`.

`node`

Node used for the displacement criterion. The following `/LECT/` must contain just one node index.

`OBJE`

Introduces the `/LECT/` of the elements which are eroded, if the criterion is reached.

`AUTO`

The keyword `AUTO` introduces an automatic development of the nodes used for the displacement criterion and the element which should eroded. The elements given by `/LECT/` are separated to several subsets, the node near the barycentre is used for the criterion, the full subset is used for the elements which could be eroded.

`rati`

Ratio of the minimum span which should be used for the displacement criterion.

`dire`

The maximum span is defined in this direction.

Remarks:

The set of keywords `DISP` ... `OBJE` may be repeated as many times as needed to define all the desired displacement-based erosion criteria.

6.18 DISPLACEMENT-DRIVEN EROSION

Object:

This directive allows to define an erosion (failure) criterion, which uses the displacement of an element's centroid.

Syntax:

```
DERO ( DISP disp /LECT/ )
```

`disp`

Displacement (norm), which results in erosion (failure) of the elements given by the following `/LECT/`.

`/LECT/`

List of the (base) elements which are eroded, if the criterion is reached.

Remarks:

In case of adaptivity, each descendant inherits the displacement erosion criterion from its base ancestor.

The `DISP ... /LECT/` sub-directive can be repeated as many times as needed to define the displacement-driven erosion criteria for all concerned elements.

6.19 STRUCTURED FLUID GRID MODEL

Object:

This directive allows to define a structured, Eulerian fluid grid consisting of either Finite Elements (FE) or of Cell Centred Finite Volumes (VFCC) that is added to the mesh specified in the `GEOM` directive. The grid has the form of a rectangular parallelepiped, is aligned along the global axes, and has a uniform spacing in each of the three global directions.

Using a structured fluid grid may substantially speed up the numerical calculations because many operations (especially those related to searching) can be highly optimized. In particular, this model is useful in conjunction with the `FLSR` model for fluid-structure interaction, see page D.143, in the case of fluid FE, or with the `FLSW` model, see page D.555, in the case of fluid VFCC.

If FE are chosen for the fluid, special fluid elements of type FL2S (in 2D) or FL3S (in 3D) are automatically built up and used to discretize the structured grid. The former is a simplified version of FL24 while the latter is a simplified version of FL38. Alternatively, one may activate use of CEA's finite elements CAR1 and CL2D (in 2D), CUBE and CL3D (in 3D), by the CEA optyional keyword (see below).

If VFCC are chosen for the fluid, fluid volumes of type Q4VF (in 2D) or CUVF (in 3D) are automatically built up and used to discretize the structured grid.

All nodes of the structured fluid grid (which are also generated automatically) must be declared Eulerian in the `GRIL` directive, see page B.60. Note that nodes not mentioned in the `GRIL` directive are indeed considered Eulerian.

This directive may only be used in ALE or purely Eulerian calculations.

In addition to the fluid elements (or volumes), special boundary condition elements of type CL2S (in 2D) or CL3S (in 3D) (for the FE fluid case) or of type CL2D (in 2D) or CL3D (in 3D) (for the fluid VFCC case) may be optionally generated along the appropriate faces of the fluid domain (see `CLij` input directives below). These may be used, for example, to specify absorbing boundary conditions.

Syntax:

```
STFL <VFCC> <CEA>
            X0 x0 Y0 y0 <Z0 z0>
            LX lx LY ly <LZ lz>
            NX nx NY ny <NZ nz>
            <CLX1> <CLX2> <CLY1> <CLY2> <CLZ1> <CLZ2>
```

`STFL`

Introduces the parameters for the generation of a structure fluid mesh.

`VFCC`

Use VFCCs for the structure fluid mesh. If this optional keyword is not specified, by default the structured mesh will be made of fluid FE.

`CEA`

Use CEA's fluid finite elements instead of JRC's fluid finite elements: that is, use CAR1 and CL2D (in 2D), CUBE and CL3D (in 3D). This optional keyword has only effect if FE are selected, i.e. if the previous optional keyword `VFCC` is *not* specified.

`x0, y0, z0`

Coordinates of the origin of the structured fluid grid. The z-coordinate `z0` is only needed in 3D calculations.

`lx, ly, lz`

Total lengths of the sides of the structured fluid grid. The z-length `lz` is only needed in 3D calculations.

`nx, ny, nz`

Number of cells of the structured fluid grid in each direction. The z-number of cells `nz` is only needed in 3D calculations. Cells have a uniform length in each direction.

`CLX1`

Automatically generate CL2S/CL2D elements (CL3S/CL3D in 3D) along the face of the fluid domain of equation $x = x_0$.

`CLX2`

Automatically generate CL2S/CL2D elements (CL3S/CL3D in 3D) along the face of the fluid domain of equation $x = x_0 + l_x$.

`CLY1`

Automatically generate CL2S/CL2D elements (CL3S/CL3D in 3D) along the face of the fluid domain of equation $y = y_0$.

`CLY2`

Automatically generate CL2S/CL2D elements (CL3S/CL3D in 3D) along the face of the fluid domain of equation $y = y_0 + l_y$.

`CLZ1`

Useful only in 3D. Automatically generate CL3S/CL3D elements along the face of the fluid domain of equation $z = z_0$.

`CLZ2`

Useful only in 3D. Automatically generate CL3S/CL3D elements along the face of the fluid domain of equation $z = z_0 + l_z$.

Comments:

Each cell (element) of the grid is a rectangle (rectangular parallelepiped in 3D) with sides of length l_x/n_x, l_y/n_y (and l_z/n_z in 3D).

Nodes and elements in the grid are numbered progressively starting from the chosen origin (x_0, y_0, z_0), first along the global X-direction, then along the Y-direction (in 3D, finally along the Z-direction).

Once the additional elements and nodes have been generated by the `STFL` directive, they are considered like any other elements and nodes, in particular as concerns the rest of the input file and the post-processing.

Appropriate materials must be assigned, in the usual way, to all the automatically generated elements. For example, a low-pressure gas to all fluid elements except those in a bubble zone, representing an explosion, in which a high-pressure gas is assigned. In order to identify the concerned elements, use may be made e.g. of directives for the definition of element groups, see page C.61. A special command to choose the STFL elements is provided, see `STFL FLUI` or `STFL CLXS` on page C.61.

In the frequent case of absorbing boundaries of the fluid domain, the concerned CL2S/CL2D or CL3S/CL3D elements must be identified in order to assign an adequate impedance material to them. The rule for automatic numbering of the generated elements is as follows: first, all fluid elements are generated (their number may be computed as specified above). Next, any specified CL2S/CL2D or CL3S/CL3D elements are generated, in the following order: `CLX1`, `CLX2`, `CLY1`, `CLY2`, `CLZ1`, `CLZ2`.

Appropriate boundary conditions may also be specified (e.g. via `LINK`) at the boundary nodes (e.g. to block a certain face of the fluid domain).

The `STFL` directive requires no dimensioning since the code is able to determine the number of necessary nodes and elements automatically.

The directive is also compatible with fluid mesh adaptivity (`ADAP`). For example, the user may activate FSI-driven fluid mesh adaptivity via the `FLSR` or `FLSW` directives by specifying as fluid domain a domain generated by `STFL`. See pages D.143 and D.555, respectively, for more information.

6.20 AUTOMATIC GENERATION OF SPECTRAL MICRO MESH

Object:

This directive allows to automatically generate a Spectral Element (SE) "micro" mesh starting from an SE "macro" mesh and a given degree (N) of the interpolation polynomial. The degree of the polynomial is the same for all spectral elements, and along each of the spatial directions.

The "macro" spectral element mesh is composed of either MS24 4-node quadrilateral elements (in 2D) or of MS38 8-node hexahedral elements (in 3D), and must have been specified in the previous GEOM directive. The generated micro SE mesh will be composed of S24 4-node quadrilaterals in 2D or of S38 8-node hexahedra in 3D.

Syntax:

```
SPEC GMIC NSPE nspe
```

`GMIC`

Introduces the automatic generation of micro SE elements according to the parameters given in the following.

`nspe`

Degree N of the interpolation polynomial for the SE mesh.

Comments:

Each macro SE generates exactly N^2 micro SE in 2D or N^3 micro SE in 3D.

The number of micro SE nodes generated is roughly (by excess) $(N+1)^2$ in 2D or $(N+1)^3$ in 3D, for each macro SE. The exact number of generated nodes is difficult to determine *a priori* because it depends upon the connectivity of the macro SE mesh (coincident nodes of adjacent micro SE and coincident nodes of micro and macro SE are eliminated). After the calculation of the exact number of nodes (and elements) required, the code prints out this information in case the user wants to keep the memory to a minimum (by giving minimum dimensioning commands).

The generated micro SE are available in an automatically created element group named `_S24` if the calculation is 2D, or `_S38` if the calculation is 3D.

Note that, like for other directives which change the mesh topology (by adding new elements and new nodes), the dimensioning related to geometrical data cannot be fully automatic. The user *must* in this case dimension the total number of nodes, the total number of degrees of freedom and the total number of micro SE generated elements (S24 in 2D or S38 in 3D), like in the following example:

```
. . .
DIME NPOI 9 NDDL 18 S24 4 TERM
. . .
GEOM . . .
COMP SPEC GMIC NSPE 2
. . .
```

6.21 ELEMENT-SPECIFIC EROSION

Object:

This directive allows to define an erosion criterion for a specific subset only of the elements. A global definition of the erosion criterion is given in the definition of the problem (see directive `EROS <ldam>` on GBA_0030)). The global value given there can be overridden for one or more subsets of the elements by using the present directive.

Syntax:

```
EROS  $[ eros ; NOER ]$ /LECT/
```

`eros`

Erosion criterion for the elements given by `/LECT/`. If no erosion limit is needed for a set of elements the keyword `NOER` can be taken. Negative erosion limit indicates also no erosions for the elements.

Remarks:

The set of keywords `EROS` ... `/LECT/` may be repeated as many times as needed to define all the desired element-based erosion criteria.

6.22 MESH ORIENTATION

Object:

To orient or re-orient those elements of the mesh for which a specific orientation is important. Typically, these are 3D shell elements without a topological thickness. Normally, proper orientation should be done in the mesh generator, but the present directive may be useful to correct any problems in case one uses a mesh whose generator is not available.

This sub-directive should be used only in emergency cases, e.g. when the mesh used in a calculation (especially flat 3D shell elements) has the wrong orientation and comes from a mesh generator that is not available. This command has the last word on the orientation of the elements, since it comes after the automatic re-orientation which is done in the SENS routine (called from the geometry reading routine). The user is therefore fully responsible of the use of this command.

Syntax:

```
"ORIE"   < "OBJE" /LEC1/ $[ "POIN" x y z ; "NODE" /LECN/ ]$ >
         < "INVE" /LEC2/ >
```

`OBJE`

The elements in object `/LEC1/` have to be oriented so that their outwards normal direction points towards a certain point or node in space, to be specified next. By “pointing” we intend here simply that the scalar product of the unit normal with the line joining the element’s center to the given point or node should be positive.

`POIN`

Introduces the coordinates of the point.

`x y z`

Coordinates of the point. Note that three coordinates should always be given even in 2D cases (but the `ORIE` directive is only useful in 3D cases anyway).

`NODE`

Introduces the index of the node.

`/LECN/`

One node index or the name of an object with just one node (e.g. a Cast3m point name if the mesh has been produced by Cast3m).

`INVE`

The orientation of elements in object `/LEC2/` has to be inverted without any checking.

Comments:

Only some element types admit re-orienting: typically, these are 3-node or 4-node “thin” elements in 3D, such as shell, membrane or CLxx elements.

Note that the `ORIE` sub-directive may be repeated any number of times, if needed. For example, this may be useful to re-orient a randomly oriented closed surface so that it points outwards. Use a first `ORIE` sub-directive to orient the all the surface elements consistently towards an internal point (e.g. its barycenter). Then, use a second `ORIE` sub-directive to invert the orientation:

```
COMP ... ORIE OBJE LECT toto TERM POIN x y z
         ORIE INVE LECT toto TERM
```

6.23 AUTOMATICALLY GENERATED SPH PARTICLES

Object:

To generate automatically SPH particles within user-defined volumes.

Syntax:

```
"GBIL"  ngen * (RBIL r <RESE rese>
(INSI | BOX  <X0 x0> <Y0 y0> <Z0 z0> DX dx DY dy <DZ dz>                 |
      | SPHE <XC xc> <YC yc> <ZC zc>  R  r                               |
      | CYLI <X1 x1> <Y1 y1> <Z1 z1> <X2 x2> <Y2 y2> <Z2 z2>  R  r       |
      | CONE <X1 x1> <Y1 y1> <Z1 z1> <X2 x2> <Y2 y2> <Z2 z2>  R1 r1 R2 r2 |
      | MESH /LECT/                                                      |)
(OUTS | BOX  <X0 x0> <Y0 y0> <Z0 z0> DX dx DY dy <DZ dz>                 |
      | SPHE <XC xc> <YC yc> <ZC zc>  R  r                               |
      | CYLI <X1 x1> <Y1 y1> <Z1 z1> <X2 x2> <Y2 y2> <Z2 z2>  R  r       |
      | CONE <X1 x1> <Y1 y1> <Z1 z1> <X2 x2> <Y2 y2> <Z2 z2>  R1 r1 R2 r2 |
      | MESH /LECT/                                                      |))
```

`ngen`

Total number of groups of SPH particles that will be generated.

`r`

Radius for the particles of this group.

`rese`

Type of spheres packing: 0 means compact hexagonal (default), 1 means compact cubic (to be implemented), 2 means trivial (non-compact) cubic (normally to be used only for tests and debugging).

`INSI`

Introduces an “inside” condition: all particles “within” a certain geometrical shape are to be generated. This keyword can be repeated as many times as necessary to specify multiple conditions, which are applied in sequence. As a result, all the particles “inside” the union of the specified geometrical shapes will be generated.

`OUTS`

Introduces an “outside” condition: from all particles in the set generated by the previously specified `INSI` condition(s), only those “external” to a certain geometrical shape are to be retained. This keyword can be repeated as many times as necessary to specify multiple conditions, which are applied in sequence. As a result, only the particles “outside” the union of the specified geometrical shapes will be retained.

`BOX`

Introduces the definition of a “box”, (a quadrilateral in 2D or a parallelepiped in 3D) with the sides aligned with the global axes.

`x0, y0, z0`

Coordinates of the ‘origin’ of the box.

`dx, dy, dz`

Lengths of the box sides.

`SPHE`

Introduces the definition of a sphere (in 3D, or a circle in 2D).

`xc, yc, zc`

Coordinates of the centre of the sphere (or of the circle).

`r`

Radius of the sphere or of the circle.

`CYLI`

Introduces the definition of a cylinder (3D only). The cylinder is defined by the two extremities of its axis (P1, P2) and its radius.

`x1, y1, z1`

Coordinates of the first extremity P1 of the cylinder axis.

`x2, y2, z2`

Coordinates of the second extremity P2 of the cylinder axis.

`r`

Radius of the cylinder.

`CONE`

Introduces the definition of a (truncated) cone (3D only). The cone is defined by the two extremities of its axis (P1, P2) and its radii.

`x1, y1, z1`

Coordinates of the first extremity P1 of the cone axis.

`x2, y2, z2`

Coordinates of the second extremity P2 of the cone axis.

`r1`

Radius of the cone at the first extremity.

`r2`

Radius of the cone at the second extremity.

`MESH /LECT/`

Introduces the definition of an arbitrary volume, represented by a mesh whose elements are specified in the following `/LECT/`. This mesh must have been defined in the `GEOM` directive and may be composed of elements of Cast3m shape CUB8, PRI6, TET4 and PYR5. Since these elements are probably useless for the calculation (they only serve to define the volume), they should be assigned the `FANT` material.

Comments:

If any of the above coordinates (`x0`, `y0` etc.) is omitted, it is assumed to be 0.

Example:

Suppose that we want to generate SPH particles within a cylinder representing a pipe full of fluid. Then the syntax would be simply:

```
GBIL 1 RBIL 0.001
       INSI CYLI X0 0 Y0 0 Z0 0 X1 0 Y1 0 Z1 10 R 0.1
```

The group of particles is from now on accessible under the name `_gbil001`.

Suppose then that the pipe of the previous example is submerged in the sea. To generate also the particles in a prismatic sea region around the pipe, the syntax would be:

```
GBIL 2 RBIL 0.001
       INSI CYLI X0 0 Y0 0 Z0 0 X1 0 Y1 0 Z1 10 R 0.1
       RBIL 0.001
       INSI BOX  X0 -1 Y0 -1 Z0 0 DX 2 DY 2 DZ 10
       OUTS CYLI X0 0 Y0 0 Z0 0 X1 0 Y1 0 Z1 10 R 0.1
```

The two group of particles are from now on accessible under the names `_gbil001` and `_gbil002`, respectively.

The presence of the (mandatory) `RBIL` keyword starts a new group of particles. Each group must contain at least one `INSI` condition. All `INSI` conditions must be specified before the `OUTS` conditions (if any).

6.24 WATER TABLES

Object :

These directives create tables containing the physical properties of water, according to one of the following textbooks:

1) Directive "TEAU" : Properties of water and steam in SI - units

(E.Schmidt Springer Verlag, Berlin 1979)

or

2) Directive "TH2O" (letter O) : NBS/NRC Steam Tables 1984

(Extended tables)

Syntax :

```
$[ "TEAU" ; "TH2O" ]$   "TMIN"  tmin  "TMAX"  tmax
                        "PMIN"  pmin  "PMAX"  pmax
                        "UNIL"  cl    "UNIM"  cm
                        "DBTE"  nbte  "DSAT"  nsat   "DHTE" nhte
                      < "DPHY"  nhy >

For the tests:
        < "DESS" >  < "PERF" >   < "TEST" ( "CAS" ... ) "FINT" >

With :
        "CAS"  num    "P1" p1 $ "T1" t1 ; "X1" x1 $
                   $  "P2" p2 $ "T2" t2 ; "X2" x2 $  $
                   $  "DVS" dvs     "DH"  dh         $
```

`tmin`

Minimum temperature in the tables (this must be lower than the saturation temperature corresponding to `pmin`).

`tmax`

Maximum temperature in the tables (this must be higher than the saturation temperature corresponding to `pmax`, in the case of a sub-critical domain, or to 374 degrees Celsius in the case of a hyper-critical domain).

`pmin`

Minimum pressure in the tables.

`pmax`

Maximum pressure in the tables.

`cl`

Conversion factor of the length units adopted, towards metres.

`cm`

Conversion factor of the mass units adopted, towards kilograms.

`nbte`

Number of intervals into which the low-temperature domain. is subdivided.

`nhte`

Number of intervals into which the high-temperature domain. is subdivided.

`nsat`

Number of intervals into which the pressure in the saturation curve is subdivided.

`nhy`

Number of intervals into which the pressure in the hypercritic domain is subdivided.

For the tests:

`"DESS"`

Allows to draw a cross-section of the tables in the plane (temperature, pressure).

`"PERF"`

Allows to output on a file (logical unit 7) the tables of water properties.

`"TEST"`

This keyword provides a trace of the work performed by the algorithm that searches the thermodynamic parameters of the one-phase or two-phase water, by giving an initial and a final state.

`"FINT"`

End of the sequence opened by keyword `TEST`.

`"CAS" nbr`

Number of the treated case. `nbr` is a simple identification number.

`p1,t1 or p1,x1`

Initial state of the water. If this state is two-phase, it is sufficient to specify `p1` and `x1`. Attention: temperatures are expressed in degrees Celsius, pressures in bar and concentrations are per unit mass.

`p2,t2 or p2,x2`

Final state of the water. If this state is two-phase, it is sufficient to specify `p2` and `x2`. Attention: temperatures are expressed in degrees Celsius, pressures in bar and concentrations are per unit mass.

`dvs,dh`

Instead of `p2` and `t2` (or `p2` and `x2`), it is possible to specify the variation of specific volume (in m^3/kg) and the variation of specific enthalpy (`dh`) in J/kg.

Warning :

If one intends just to run a test without a real EUROPLEXUS transient calculation, it is preferable to put the keyword "FIN" immediately after the directive "COMPLEMENT". This test is recommended, because it allows to verify the initial conditions (pressure, temperature, void fraction) and to check the composition of the tables.

Comments :

A portion of the saturation curve must be included in the Pressure-Temperature domain chosen.

The `nbte` temperature intervals start from the minimum water temperature to the saturation temperature (for the minimum pressure). It is the same for the `nhte` intervals between the saturation temperature and the maximum temperature, for the maximum pressure.

The `nsat` pressure intervals lie between minimum pressure and maximum pressure, if this is in the sub-critic domain ; else, they go from the minimum pressure to the critical pressure.

In the case of a maximum pressure above 221 bars (hypercritic domain), a further parameter is needed : the number `nhy` of intervals between the critical pressure and the maximum pressure.

For low temperatures ("DBTE"), the subdivision is linear in the temperature. Along the saturation curve ("DSAT"), the subdivision is initially linear in the temperature, then linear in the pressure, in order to obtain a regular subdivision along this curve. Beyond the critical point ("DHTE" and "DPHY"), the subdivison is logarithmic in temperature and in pressure.

When the "TEAU" directive is used, the pressure must be between 0.0062 bar and 1000 bar, and the temperature between 0 and 800 degrees Celsius.

If the extended tables are used (directive "TH2O"), the pressure must be between 0.0062 bar and 30000 bar, and the temperature between 0 and 2000 degrees Celsius.

If the user enters his data in the SI unit system, it is `cl`=`cm`=1. Otherwise, `cl` or `cm` represent the value of the SI unit expressed in the user's unit. For example, if the lengths are in mm, then `cl`=1000.

6.25 HELIUM TABLES

Object :

These directives create tables containing the physical properties of helium, according to CEA/IRF/DPC (1985).

Syntax :

```
"THEL"     "UNIL"  cl    "UNIM"  cm

For the tests:
          < "TEST" <"DETA" > ( "CAS" ... ) "FINT" >

With :
        "CAS"  num    "P1" p1 $ "T1" t1 ; "X1" x1 $
                   $  "P2" p2 $ "T2" t2 ; "X2" x2 $  $
                   $  "DVS" dvs     "DH"  dh         $
```

`cl`

Conversion factor of the length units adopted, towards metres.

`cm`

Conversion factor of the mass units adopted, towards kilograms.

For the tests:

`"TEST"`

This keyword provides a trace of the work performed by the algorithm that searches the thermodynamic parameters of the one-phase or two-phase helium, by giving an initial and a final state.

`"FINT"`

End of the sequence opened by keyword `TEST`.

`"CAS" nbr`

Number of the treated case. `nbr` is a simple identification number.

`p1,t1 or p1,x1`

Initial state of helium. If this state is two-phase, it is sufficient to specify `p1` and `x1`. Attention: temperatures are expressed in degrees Kelvin, pressures in bar and concentrations are per unit mass.

`p2,t2 or p2,x2`

Final state of helium. If this state is two-phase, it is sufficient to specify `p2` and `x2`. Attention: temperatures are expressed in degrees Kelvin, pressures in bar and concentrations are per unit mass.

`dvs,dh`

Instead of `p2` and `t2` (or `p2` and `x2`), it is possible to specify the variation of specific volume (in m^3/kg) and the variation of specific enthalpy (`dh`) in J/kg.

Warning :

If one intends just to run a test without a real EUROPLEXUS transient calculation, it is preferable to put the keyword "FIN" immediately after the directive "COMPLEMENT". This test is recommended, because it allows to verify the initial conditions (pressure, temperature, void fraction).

Comments :

The pressure must be above 0.042 bar, and the temperature above 2.1 Kelvin.

The critical point of helium is at 2.27 bars and 5.19 Kelvin. Beyond these values there is only one phase.

Only the gas and the liquid are considered. In the case of high pressures and very low temperatures, the latter must be higher tan the melting temperature: solid → liquid.

Unlike the water tables (page C.74), the thermodynamic parameters of helium are directly calculated starting from the interpolation polynomials. Therefore, calculations may at times become very time-consuming.

If the user enters his data in the SI unit system, it is `cl`=`cm`=1. Otherwise, `cl` or `cm` represent the value of the SI unit expressed in the user's unit. For example, if the lengths are in mm, then `cl`=1000.

6.26 PIPE JUNCTIONS

Object :

Join together different branches of a pipeline.

Syntax:

```
"RACC" |[ "BIFU" ;
          "CAVI" ;
          "BREC" ;
          "BIVF" ;
          "CAVF" ]|

       $[      n1 ... nk                             ;
         "LECT" racname "TERM" "LECT" P1 ....PK "TERM"  ]$

      ....   "DSOR" d1...dk < "VOLU" volu "DX" dx "AUTO">
```

`n1 ... nk`

Numbers of the nodes connected by the junction (the order is irrelevant).

`racname`

LECTURE of the name of the junction element in GIBI.

`P1....PK`

LECTURE of the names of the connected points as given in GIBI.

`d1 ... dk`

Internal diameters of the pipelines joined together (the order must correspond to that of the node numbers or names given above).

`volu`

Volume of the junction: mandatory for a cavity, useless for a bifurcation or a pipeline rupture.

`dx`

Mean mesh size of elements surrounding a bifurcation. Volume is then computed as $V = 1/k \sum_i^k d_i^2 \Delta x$

`AUTO`

The volume of the bifurcation is computed automatically from the mean volume of neighbor elements. AUTO is on by default, if no volume or dx is specified. If AUTO is set, VOLU and DX are not considered.

Warning:

If the MASS directive is used (added masses, also in COMPLEMENTS section), every RACC directive must be specified before the MASS keywords, else it raises an error.

Comments:

One may distinguish two cases:

"BIFU" or "BREC" : bifurcation with a small volume (acoustic continuity)

"CAVI" : cavity with a large volume (with a law describing its behaviour)

In the case of a bifurcation or a pipeline rupture, EUROPLEXUS re-computes a fictitious volume, which corresponds to the sphere having the same area as the sum of the areas of the branches that arrive at the bifurcation. When the mesh size is much smaller than the pipe diameters this fictitious volume can set the bifurcation as some kind of tank and cause unwanted reflection waves. In order to avoid that, it is recommended to put the "AUTO" keyword.

The exact number of junction elements must be specified in the "GEOM" directive (see page B.30), and the order of junctions is the same as in the "GEOM" directive if GIBI is not used.

Example:

```
"GEOM"   . . .  "CAVI"  2  "BIFU"  1   "BREC"  1  "TERM"
```

corresponds to:

```
"CAVI" ....   )   2 cavities
"CAVI" ....   )
"BIFU" .........  1 bifurcation
"BREC" .........  1 pipeline rupture
```

If GIBI is used, the number of junction elements specified may be larger than the exact number, and the order is not compulsory, because the name of each junction is specified in the directive.

Example:

```
"GEOM"  ...  "CAVI" cav_one "CAVI" cav_two "BIFU" my_bif "BREC" my_bre ..."TERM"
```

corresponds to (in the RACC directive) :

```
"CAVI"  "LECT" cav_one "TERM" "LECT" P1       "TERM" ....
"CAVI"  "LECT" cav_two "TERM" "LECT" P2 P3    "TERM" ....
"BIFU"  "LECT" my_bif  "TERM" "LECT" P4 P5 P6 "TERM" ....
"BREC"  "LECT" my_bre  "TERM" "LECT" P7 P8    "TERM" ....
```

6.27 TUBM (3D-1D JUNCTION)

Object:

To connect, by means of a "TUBM" element, a pipeline meshed in 1-D with a fluid meshed in 3-D.

Syntax:

```
"RACC" ( "TUBM" /LECTURE/  "NTUB" /LECTURE/  "DTUB" dtub  ...
                           "FACE" /LECTURE/               ...
                         < "COEF" coef > < "AUTO" >          )
```

`"TUBM" /LECTURE/`

The /LECTURE/ procedure allows to specify the name of the GIBI object associated with the junction element. The object must contain a single element. In case of a mesh in the MED format, the name of the junction element must follow a specific rule, see comments below.

`"NTUB" /LECTURE/`

The /LECTURE/ procedure allows to specify the name of the GIBI object or MED group associated with the 1D node of the tube.

`dtub`

Internal diameter of the connected tube.

`"FACE" /LECTURE/`

The /LECTURE/ procedure allows to specify the name of the GIBI object or MED group associated with nodes of the 3D face. The object **must** be composed of surface elements (typically CL3D), which are used to identify the 3D part of the junction. These CL3D elements should *not* be assigned any material, since EPX automatically assigns them a `FANT` material.

`"COEF" coef`

This coefficient allows to take into account of possible symmetries in the 3D mesh. The area of the face meshed in 3D is multiplied by `coef` in order to find out the same area as that of a non-symmetrised face. By default, i.e. if the `COEF` keyword is not used, the code takes `coef` = 1.0.

`AUTO`

This optional keyword forces the calculation of the coefficient `coef` as the ratio between the area of the pipe cross section (STUBE) and the area of the 3D side of the junction (SBASE). Note that this overrides the value of `coef` that has been possibly specified as well.

Comments :

These elements are created by CASTEM, by means of the following syntax:

```
mon_tubm = MANU SUPERELEMENT (p_tube ET s_face) ;
```

where `p_tube` is the object corresponding to the 1D point, and `s_face` the object corresponding to the nodes of the 3D face. All nodes of the 3D face must be coplanar.

In case of a mesh in the MED format, in which the `SUPERELEMENT` structure does not exist, the required procedure is the following:

- In the mesh, MED groups corresponding to the 1D point and the faces of the 3D face must be based on the same name, e.g. `"raccord"`, to which the suffixes `"_n"` and `"_s"` must respectively be added.
- The name of the junction element to be used is then `"splm_raccord"`. It is automatically created when a TUBM element is declared.

"TUBM" connects the fluid of the continuum elements (3D) with the fluid of a "TUBE" element (continuity of the mass flow rate). The velocities of nodes belonging to the 3D face are all equal and normal to the face itself.

The type of elements whose face(s) participate in forming the 3D face is irrelevant: therefore it is possible to use cubes, prisms or even tetrahedrons for the mesh.

A material must be associated to the "TUBM" element, although this has no behaviour law.

Warning:

It is mandatory to specify in the dimensioning the parameter "JONC", in order to reserve the space indispensable for the relations associated to the junction (see page A.80).

If the fluid is meshed by Finite Elements (velocities defined at nodes), do not forget to mention "TUBM" also in the "LIAISON" directive (page D.200).

If the fluid is meshed by Cell-Centred Finite Volumes (velocities defined at the element centroids), the "TUBM" liaison is not necessary.

6.28 TBM2 (2D-2D OR 3D-3D JUNCTION)

Object:

To connect, by means of a TBM2 element, two fluid meshes discretized by Cell-Centred Finite Volumes. Exactly one `RACC TBM2` directive must be specified for each element of type TBM2 present in the model. In 2D calculations, the elements (finite volumes) used in the two meshes to be joined can be either Q4VF or T3VF. In 3D calculations, the elements used can be CUVF, PRVF, PYVF or TEVF. Typically, but not necessarily, one of the objects consists of a single row of elements.

To identify the junction geometrically, CLxx elements are attached to all the CCFV element faces located on either side of the junction.

This junction is symmetric, that is, there is no conceptual difference between the two sides of the junction (unlike in the case of the `TUBM` or `TUYM` junction where one of the sides is continuum and the other one is a pipeline). Therefore, the two sides are simply denoted “First” and “Second” side of the junction and are arbitrarily chosen by the user. Swapping the two sides in the definition has no effect on the results.

A geometrical condition must be satisfied on each TBM2 junction, namely that each side of the junction stays on a straight line in 2D (on a plane in 3D) and that the lines (planes in 3D) on either side of the junction are parallel. The code checks this and raises an error if the rule is not satisfied.

Syntax:

```
"RACC" ( "TBM2" /LECTURE/  "FAC1" /LECTURE/ ...
                           "FAC2" /LECTURE/ ... )
```

`"TBM2" /LECTURE/`

The /LECTURE/ procedure allows to specify the name of the GIBI object associated with the junction element. The object must contain a single ”TBM2” element. If the mesh is given in free format, then the /LECTURE/ directly specifies the index of the ”TBM2” element of the junction.

`"FAC1" /LECTURE/`

The /LECTURE/ procedure allows to specify the name of a GIBI object composed of surface elements (CLxx), which is used to identify the first side of the junction. If the mesh is given in free format, then the /LECTURE/ specifies the indexes of the CLxx elements on the first side of the junction.

`"FAC2" /LECTURE/`

The /LECTURE/ procedure allows to specify the name of a GIBI object composed of surface elements (CLxx), which is used to identify the second side of the junction. If the mesh is given in free format, then the /LECTURE/ specifies the indexes of the CLxx elements on the second side of the junction.

Comments :

The CLxx elements used to define the two sides of the junction must *not* be assigned any material, since EPX automatically assigns them a `FANT` material. Also, no material must be associated to the "TBM2" element, since this has no behaviour law (EPX automatically assigns it a `FANT` material).

It is mandatory to specify in the dimensioning the parameter "JONC", in order to reserve the space indispensable in NUMN for the connectivity of the junction elements (see page A.80). The number to be specified is the maximum number of nodes in a "TBM2" junction (including both the first and the second side of the junction).

Since, unlike "TUBM" or "TUYM", the "TBM2" junction element can only be used with Cell-Centred Finite Volumes (velocities defined at the element centroids), imposing a specific ("TBM2") liaison is not necessary.

Note that, unlike TUBM junctions (1D-3D or 1D-2D), the present TBM2 junction (2D-2D) does *not* make use of an (optional) weighting coefficient α (`COEF`). This is because the model uses weighted average states on either side of the junction instead of cumulated fluxes. Even in case of symmetrizations the coefficient is not necessary because there is no 1D part (which cannot be symmetrized) in a "TBM2" junction.

6.29 TUYM (3D-1D JUNCTION)

Object:

To connect, by means of a "TUYM" element, a pipeline meshed ("TUYA" element) in 1-D with a fluid meshed in 3-D for moving meshes (A.L.E computation).

Syntax:

```
"RACC" ( "TUYM" /LECTURE/  "NTUB" /LECTURE/  "DTUB" dtub  ...
                           "FACE" /LECTURE/               ...
                         < "COEF" coef > < "AUTO" >          )
```

`"TUYM" /LECTURE/`

The /LECTURE/ procedure allows to specify the name of the GIBI object associated with the junction element. The object must contain a single element. In case of a mesh in the MED format, the name of the junction element must follow a specific rule, see comments below.

`"NTUB" /LECTURE/`

The /LECTURE/ procedure allows to specify the name of the GIBI object or MED group associated with the 1D node of the tube ("TUYA" element).

`dtub`

Internal diameter of the connected tube ("TUYA" element).

`"FACE" /LECTURE/`

The /LECTURE/ procedure allows to specify the name of the GIBI object or MED group associated with nodes of the 3D face. The object **must** be composed of surface elements (typically CL3D), which are used to identify the 3D part of the junction. These CL3D elements should *not* be assigned any material, since EPX automatically assigns them a `FANT` material.

`"COEF" coef`

This coefficient allows to take into account of possible symmetries in the 3D mesh. The area of the face meshed in 3D is multiplied by `coef` in order to find out the same area as that of a non-symmetrised face. By default, i.e. if the `COEF` keyword is not used, the code takes `coef` = 1.0.

`AUTO`

This optional keyword forces the calculation of the coefficient `coef` as the ratio between the area of the pipe cross section (STUBE) and the area of the 3D side of the junction (SBASE). Note that this overrides the value of `coef` that has been possibly specified as well.

Comments :

These elements are created by CASTEM, by means of the following syntax:

```
mon_tuym = MANU SUPERELEMENT (p_tuya ET s_face) ;
```

where `p_tuya` is the object corresponding to the 1D point, and `s_face` the object corresponding to the nodes of the 3D face. All nodes of the 3D face must be coplanar.

In case of a mesh in the MED format, in which the `SUPERELEMENT` structure does not exist, the required procedure is the following :

- In the mesh, MED groups corresponding to the 1D point and the faces of the 3D face must be based on the same name, e.g. `"raccord"`, to which the suffixes `"_n"` and `"_s"` must respectively be added.
- The name of the junction element to be used is then `"splm_raccord"`. It is automatically created when a TUYM element is declared.

"TUYM" connects the fluid of the continuum elements (3D) with the fluid of a "TUYA" element (continuity of the mass flow rate). The velocities of nodes belonging to the 3D face are all equal and normal to the face itself.

The type of elements whose face(s) participate in forming the 3D face is irrelevant: therefore it is possible to use cubes, prisms or even tetrahedrons for the mesh.

A material must be associated to the "TUYM" element, although this has no behaviour law.

Warning:

It is mandatory to specify in the dimensioning the parameter "JONC", in order to reserve the space indispensable for the relations associated to the junction (see page A.80).

If the fluid is meshed by Finite Elements (velocities defined at nodes), do not forget to mention "TUYM" also in the "LIAISON" directive (page D.200).
If the fluid is meshed by Cell-Centred Finite Volumes (velocities defined at the element centroids), the "TUYM" liaison is not necessary.

6.30 CORRESPONDENCE BETWEEN NODES

Object:

The purpose of this directive is to define a one-to-one correspondence between couples of nodes. This user-defined correspondence may be useful in various situations, in which the code needs to find a one-to-one correspondence between nodes in the mesh and the automatic determination of such a correspondence is impossible. For example, this might happen under exceptional circumstances in the following cases:

- In the search for structural (Lagrangian) nodes correspondent to fluid nodes in the `FSA` fluid-structure interaction directive, see page D.450.
- In the search for structural nodes corresponding to fluid nodes in the model for perforated plates `IMPE PPLT`, see page C.760.
- In the search for structural nodes corresponding to fluid nodes in the model for rupture disks `IMPE RUDI`, see page C.770.
- In the search for structural nodes corresponding to fluid nodes in the model for rupture disks for the MC formulation, `IMPE RDMC`, see page C.790.

In such cases, the code tries to automatically determine the structural (or other Lagrangian) node "corresponding" to a certain fluid node. This node is defined as the Lagrangian node having the same initial coordinates as the fluid node under consideration, within a certain small tolerance (that may be changed via the `OPTI TOLC`, page H.40). If there is no such node or if more than one candidate node is found (e.g. because there are several superposed structures in the mesh), then the automatic search would fail. In this case, the user may assume control by explicitly specifying the corresponding Lagrangian node to each "ambiguous" fluid node.

It is advised to use this directive only in case of necessity. First, an input without this directive should be prepared. Then, in case the code produces some error messages related to the impossibility of automatically determining the node correspondence, the present directive may be added to resolve the identified conflicts.

Syntax:

```
"CNOD"   "NODF"  /LECT1/     "NODS"   /LECT2/
```

`/LECT1/`

List of first nodes of each node couple. Typically, these are fluid nodes.

`/LECT2/`

List of second nodes of each node couple. These nodes must be Lagrangian. Typically, these are structure nodes, but Lagrangian fluid nodes are also accepted.

Comments:

The order in which nodes are listed in `/LECT1` or `/LECT2` is retained. To the i-th node of `/LECT1` corresponds the i-th node of `/LECT2`. The number of nodes in `/LECT1` and `/LECT2` must be the same.

Note that the directive `CNOD` may be specified only once in each calculation (i.e. it should not be repeated). In other words, all correspondent nodes should be specified in just one `/LECT1/` and `/LECT2/`.

In case of problems with the `FSA` directive, please note that another way of resolving node conflicts, alternative to the present `CNOD` directive, is the `STRU` sub-directive of `FSA`, see page D.450, which is more practical in case there is a large number of conflicting nodes.

6.31 SPH SHELL ELEMENT (SPHC)

Object :

This instruction introduces characteristics for the SPH shell elements (SPHC) which allow discretizing shell structures with a single layer of particles.

Syntax:

```
"CSPH"   "RAYO" rbille   "EPAI" ep
         "ORX" orx  "ORY" ory  "ORZ" orz
       < "LINE" cl >   < "QUAD" cq >
       < "RLIM" rlim > < "RESEAU" ires >
       < "VOIS" nvoi >
       ( "STRP" istrp /LECT/ )
```

`rbille`

Radius of the SPH shell particles.

`ep`

Thickness of the shell particles.

`orx, ory, orz`

x,y,z co-ordinates of a point used to orient normals of the SPH shell particles.

`cl`

Linear damping coefficient.

`cq`

Quadratic damping coefficient.

`rlim`

Multiplicative coefficient for the search radius.

`ires`

Type of particles lattice (1: cubic, 0: hexagonal).

`nvoi`

Number of neighbouring particles sought.

`istrp`

Type of stress points (1: free, 2: clamped) read in the following `/LECTURE/` sequence (see comment below).

Comments :

For the quadratic damping, it is advised to take cq=4.

To damp out the high-frequency oscillations it is advisable to use a value of cl between 0.1 and 0.5.

At least one set of stress points must be entered. Several sets can be entered by repeating the STRP keyword.

Two types of particle lattice are possible: for ires = 1 a cubic lattice is adopted; in the case ires = 0 (default value), a compact hexagonal lattice is adopted.

The number of sought neighbouring particles is by default 12. This number may not be changed for the PEF algorithm. Its modification is accepted only for the SPH method.

For a given particle, the search considers the neighbours whose center is within a distance of rlim*rbille from its center. By default, rlim=1.3.

6.32 DISCRETE ELEMENT MODEL (ELDI)

Object :

This instruction is mandatory in the input file when using discrete elements (ELDI). It allows printing out to the output listing the value of the radius of each discrete element and to impose the correct masses of different parts of the discrete element model (element density will be corrected).

This directive is used to define a bridging (recovering) zone allowing to couple a set of discrete elements (ELDI) with a 3D finite element model (meshed with the CUB8 elements only) or a shell model (Q4GS elements only).

Syntax:

```
"CELDI"  < "IMPR" >
         < "MASS" nval
                  nval*(val /LECTURE/ ) >
         < "ARMA"  /LECTURE/  >
         < "LTM"   nbse  nbse*(beta plas /LECTURE/)  >

           "TYPL"  nbtypl*(|[ "COHE" <"IMPR"> <"COEF" val>    /LECTURE/ ;
                              "BIMA" <"IMPR">
                                          "MAT1" <"COEF" val> /LECTURE/
                                          "MAT2" <"COEF" val> /LECTURE/ ;
                              "CONT" <"IMPR"> <"COEF" val>    /LECTURE/ ]| )

         < "CSTE"   coef  >
         < "EDEF" nbcoup
                  nbcoup*("NCOU"  ncouches
                         "ELDI"  /LECTURE/
                         "FRON"  /LECTURE/ ) >
         < "CBOX" xmin xmax ymin ymax zmin zmax >
```

"IMPR"

This optional keyword allows printing out in the output listing the value of the radius of each discrete element.

"MASSE"

This optional keyword enables the user to impose the masses of discrete elements lists.

nval

Number of imposed masses.

val

Value of the imposed mass.

`"ARMA"`

Indicates the presence of steel reinforcement modeled with aligned steel discrete elements. Caculates the main direction of the reinforcement used for steel-concrete interaction.

`LECTURE`

List of the discrete elements concerned.

`"LTM"`

Indicates the presence of bending properties (rotation stiffnesses for discrete elements).

`nbse`

Number of sequences with different bending properties.

`beta`

Coefficient used to calculate the bending stiffness: Kr=beta*EI/R.

`plas`

Coefficient used to calculate the plastic torque: Mp=plas*sigma*I/R. In elastic calculations, one should use plas=0 (no test on Mp) or put plas>>1 to guarantee Mp is very high.

`"TYPL"`

This keyword defines different types of links (interactions) between discrete elements (ELDI) within one or several sets of particles. Links may be of two kinds : cohesive links and contacts. The interaction forces between the discrete elements are then computed with respect to the types of material used.

`nbtypl`

Number of sequences beginning from one of the following words : "COHE" or "BIMA" or "CONT".

`"COHE"`

This keyword initializes the search of cohesive interactions within a set of discrete elements.

`<"COEF" val>`

Interaction range. The default value of the interaction range *val* is 1.

`"BIMA"`

This keyword initializes the search of cohesive interactions between two sets of discrete elements (permanent contact of two materials).

`"MAT1" <"COEF" val>`

This keyword allows to define the first set of discrete elements and its interaction range *val*. The default value is 1.

`"MAT2" <"COEF" val>`

This keyword allows to define the second set of discrete elements and its interaction range *val*. The default value is 1.

`"CONT"`

This keyword initializes the search of contact interactions inside one or several sets of discrete elements specified in /LECTURE/. In this case, the value of the interaction range is 1.

`<"IMPR">`

This optional keyword allows to print out in the output listing the result of the interactions search.

`"CSTE"`

This optional keyword enables the user to define the security coefficient of the time step.

`coef`

Security coefficient (by default 0.1) : dt=coef*dtcrit

`nbcoup`

Number of combined finite/discrete zones to connect.

`"NCOU"`

Number of finite element range defining the combined finite/discrete element zone.

`"ELDI" /LECTURE/`

List of the discrete elements concerned to research in the combined finite/discrete element zone.

`"FRON" /LECTURE/`

List of nodes forming the border of the finite elements mesh in the bridging finite/discrete element zone.

`"CBOX"`

Allows defining a box restraining search for DE contacts. Six reals must be given: xmin,xmax,ymin,ymax,zmin,zmax.

Comments :

To guarantee the masses of different parts of the discrete element model are correct, each discrete element should belong to one group only.

To identify the interacting neighbors, a grid subdivision method is used.

An interaction between elements a and b of radius R^a and R^b respectively, is defined within an interaction range *val* and does not necessarily imply that two elements are in contact (for cohesive interactions). Then, these elements will interact if,

$val * (R^a + R^b) > or = D^{a,b}$

where $D^{a,b}$ is the distance between the centroids of element a and b and where val is the interaction range. val is mandatory and must be $> or = 1$.

6.33 MULTILAYER ELEMENT CMC3

Object:

The characteristics of CMC3 elements are described when they have not been defined by CASTEM2000.

Syntax:

```
"CORTHO"   "EPAISSEUR"  ep     "EXCENTREMENT"   ex
        $[  "ANGLE"      angle       ;
            "VECTEUR"    vx  vy  vz  ]$           /LECTURE/
```

`ep`

Thickness of the element.

`ex`

Element eccentricity with respect to the plane defined by the 3 nodes of the mesh.

`angle`

Angle (in degrees) formed by the first side of the element and the first axis of the orthotropic system.

`vx,vy,vz`

The 3 components in the global frame of the vector that defines the first orthotropy direction.

`LECTURE`

List of the elements concerned.

Comments:

The sign of the excentricity is defined by the orientation of the normal. This depends on the numbering of the nodes of the CMC3 element (see Maxwell's cork-screw rule).

The first side of the element is the one formed by the first 2 nodes.

6.34 ORTHOTROPY

Object:

Description of the orthothropy directions for continuum elements in 2D and 3D. There are several alternative ways of defining the directions, as shown below. Some are suited only for 2D situations, others only for 3D situations. The fiber-related data for anisotropic hyperelastic materials (see keyword `AXEF` below) can be specified both in 2D and in 3D.

Syntax:

```
"MORTHO" ( $[ $["ALPH" angle1 ; "THET" angle2]$                    ;
              "AXE1" e11 e12 e13  "AXE2" e21 e22 e23               ;
              "AXEF" NFIB nfib*(f1 f2 f3 <$["KSTR" kstr ; "FA" fa]$>) ;
              "COCY" "POIN" $[/LEC1/ ; xx yy zz]$ "VECT" v1 v2 v3     ;
              "V1LC" v1x v2x v3x "V2LC" v2x v2y v2z                 ]$
              /LECT/ )
```

`ALPH angle1`

2D only. Angle (in degrees) formed by the Ox axis (in 2D plane cases) or the Or axis (in axisymmetric) and the first axis of the orthotropy reference frame.

`THET angle2`

2D only. Angle (in degrees) formed by the first side of the element and the first axis of the orthotropy reference frame (in 2D plane or axisymmetric). The first side of the element is the segment connecting the first two nodes declared for the element in the GEOM directive.

`AXE1 e11, e12, e13`

3D only. First vector defining the orthotropy plane of the material.

`AXE2 e21, e22, e23`

3D only. Second vector defining the orthotropy plane of the material.

`AXEF`

Introduces the optional fiber data.

`NFIB nfib`

Number of fibers in each element.

`f1 f2 f3`

2D or 3D. Definition of a fiber direction for use with anisotropic hyperelastic materials. The three values define a vector oriented along the fiber, not necessarily unitary (it is normalized internally). Note that `f3` should also be given (as 0) in 2D cases, but it is ignored.

`KSTR kstr`

2D or 3D. Structure parameter describing a π-periodic distribution of fibers in a matrix of isotropic hyperelastic material. The lower limit is 0, which represents regions with perfecly aligned fibers (transverse isotropy). The upper limit is 1/3 which describes regions with randomly oriented fibers (i.e., isotropy). The default value of `kstr` is 0, meaning that the material is transversely isotropic. If a negative value is specified, the value 0 is retained. If a value greater than 1/3 is specified, the value 1/3 is retained.

`FA fa`

2D or 3D. Fractional anisotropy parameter. Normalized measure of the degree of diffusion anisotropy. It should be between 0 and 1. The default value of `fa` is 0. If a negative value is specified, the value 0 is retained. If a value greater than 1 is specified, the value 1 is retained.

`COCY`

3D only. This directive allows to define a "cylindrical" type of orthotropy, that may be used for example by the BOIS (wood) material. The first axis of orthotropy is parallel to the vector defined by the `VECT` directive described above. The second axis of orthotropy (perpendicular to the first one) lies on the plane formed by a straight line passing through the `POINT` defined below and parallel to `VECT`, and the barycenter of the element.

`POIN`

This directive allows to define a point which is either a node of the mesh (option `/LEC1/`), or a geometric point defined by its three coordinates (`xx yy zz`).

`VECT v1 v2 v3`

First vector defining the orthotropy reference frame of the `COCY` directive.

`V1LC v1x, v1y, v1z`

3D only. First vector defining the orthotropy plane of the material in the local reference frame of the element.

`V2LC v2x, v2y, v2z`

3D only. Second vector defining the orthotropy plane of the material in the local reference frame of the element.

`/LECT/`

List of the elements concerned.

Comments:

One can define several orthotropy directions by repeating each time the keyword `MORT`. It is also possible to repeat it starting from different items.

The `ALPH` or `THET` keywords are used in 2D, the `AXE1` ... `AXE2`, `COCY` and `V1LC` ... `V2LC` directives are used in 3D.

The vectors V1(`e11,e12,e13 or v1x,v1y,v1z`) and V2(`e21,e22,e23 or v2x,v2y,v2z`) are not necessarily unit vectors, and V2 is not necessarily normal to V1.

If the `AXEF` directive is used to specify a fiber direction, but neither `KSTR` nor `FA` are given, then the code assumes `KSTR` equal to 0, i.e. trnsversely isotropic material.

Starting from these input data, EUROPLEXUS computes and stores the values in the local reference frames relatives to each element. These local values will be utilised during the transient calculation. For this reason, the calculation remains valid also for large rotations.

6.35 ORTHOTROPY FOR 3D SHELLS

Object:

Description of the orthotropy characteristics for 3D (layered) shell elements using JRC's "sandwiches" and "layers" model (see `SAND` and `LAYE` keywords).

The directive defines the orthotropy characteristics related to the following **material types**: `HILL` (3), `ORTS` (46), `ORPE` (55), `COMM` (88), `GLRC` (92), and to the following **element types**: `QPPS` (35), `COQI` (40), `T3GS` (51), `DST3` (83), `DKT3` (84), `CQD4` (91), `CQD9` (92), `CQD3` (93), `CQD6` (94), `Q4GR` (111), `Q4GS` (112), `Q4MC` (138), `T3MC` (139).

The othotropy characteristics are stored in the ECR() table of each GP of each concerned element. If the element has layers (`LAYE` directive) then the characteristics may vary from layer to layer. Here is how the characteristics are stored, for each material type:

```
HILL (3)  ! ECR(8) = ANGLE
ORTS (46) ! ECR(3) = ANGLE
ORPE (55) ! ECR(21) = ANGLE
COMM (88) ! ECR(6:8) = VX, VY, VZ
GLRC (92) ! ECR(11:13) = VX, VY, VZ
```

Note that the `GLRC` material may *not* be associated with a layer because this is a global material model.

For historical reasons, two alternative *input syntaxes* can be used:

1. `ORTS vx vy vz /LECT/ <LAYE /LECT_LAY/>`: This syntax specifies directly `vx`, `vy`, `vz` i.e. a vector whose projection on the lamina (local) reference of the (shell) element is the first orthotropy direction of the material which is sufficient to define the orthotropy for shell elements. This syntax applies directly to elements (or element layers) using the `COMM` or `GLRC` material, since such materials require the values of `VX`, `VY`, `VZ`. For elements (or element layers) using the `HILL`, `ORTS` or `ORPE` material the `vx`, `vy`, `vz` are converted internally to an angle, (by projecting the vector onto the shell's lamina plane), which is then stored in the ECR() table.

2. `ORTS $ ANGL angl ; AXE1 a1x a1y a1z ; CIRC cx cy cz $ /LECT/ <LAYE /LECT_LAY/>`: This syntax specifies either an angle `angl`, a vector `a1x`, `a1y`, `a1z` or a (central) point `cx`, `cy`, `cz`.

   - `ANGL`: The `angl` parameter is the angle between the first axis of the shell's lamina (local) reference frame and the first orthotropy direction of the material (also lying on the lamina plane). The angle is then stored in the ECR() table, if the material is `HILL`, `ORTS` or `ORPE`. For the other two materials (`COMM` or `GLRC`) an error message is currently raised because these materials require a vector (vx, vy, vz) and not an angle. (This might be corrected in a future release by computing the vector internally from the given angle.)
   - `AXE1`: The vector `a1x`, `a1y`, `a1z` has the same meaning as the `vx`, `vy`, `vz` in the first syntax. Therefore, if the material is `COMM` or `GLRC`, the values `a1x`, `a1y`, `a1z` are stored directly in the ECR() table. For the other materials (`HILL`, `ORTS` or `ORPE`), the vector defined by `ax1`, `ax2` and `ax3` is converted internally to an angle (by projecting the vector onto the shell's lamina plane), which is then stored in the ECR() table.
   - `CIRC`: `cx`, `cy`, `cz` define a center point. For each element, the first orthotropic direction is the projection of the vector [center point/element gravity center]. It allows to treat circular geometry.

Syntax:

```
"ORTS" |[ vx vy vz                                ;
          $[ "ANGL" alpha ;  "AXE1" a1x a1y a1z ]$
       ]|
       /LECT/   < "LAYE" /LECT_LAY/>
```

`vx vy vz`

Components, in the global reference frame, of a vector whose projection on the lamina (local) coordinate system of the 3D shell element indicates the orthotropy direction (one such direction is sufficient, for shell elements).

`ANGL alpha`

Angle between the first direction of the shell element and the first direction of the orthotropic frame (in radians). It can only be used with Q4GS, Q4GR, Q4MC, DKT3, DST3 or T3MC elements associated either with `HILL` or with `ORTS` material.

`AXE1 a1x a1y a1z`

Components, in the global reference frame, of a vector whose projection on the lamina (local) coordinate system of the 3D shell element indicates the orthotropy direction (one such direction is sufficient, for shell elements). It can only be used with Q4GS, Q4GR, Q4MC, DKT3, DST3 or T3MC elements associated either with `HILL` or with `ORTS` material

`/LECT/`

Concerned elements.

`/LECT_LAY/`

Concerned layers. Layers are identified by their indexes, as described in the `SAND` directive on page C.45.

Comments:

Note that the directive `COMP ORTS` must be specified *after* the definition of the material characteristics (`MATE` directive). If other quantities (e.g. thickness, etc.) are to be specified via the `COMP` directive, then *two* `COMP` directives should be used: the first one, immediately after the `GEOM` directive, and the second one (`COMP ORTS`) immediately after the `MATE` directive.

6.36 PARTICLE ELEMENT (BILLE)

Object :

Description of the characteristics of the BILLE element (particle element).

Syntax:

```
 "CBILLE"   "RAYON"  rbille    < "LINEAIRE"   cl    >    ...
      ... < "QUADRATIQUE" cq > < "RESEAU"     ires  >    ...
      ... < "VOISIN"      nvoi >
      ... < "RLIM"        rlim >
```

`rbille`

Radius of the particles.

`cl`

Linear damping coefficient.

`cq`

Quadratic damping coefficient.

`ires`

Type of particles lattice.

`nvoi`

Number of neighbouring particles sought.

`rlim`

Multiplicative coefficient for the search radius.

Comments :

For the quadratic damping, it is advised to take cq=4.

To damp out the high-frequency oscillations it is advisable to use a value of cl between 0.1 and 0.5.

Two types of particle lattice are possible: for ires = 1 a cubic lattice is adopted; in the case ires = 0 (default value), a compact hexagonal lattice is adopted.

The number of sought neighbouring particles is by default 12. This number may not be changed for the PEF algorithm. Its modification is accepted only for the SPH method.

For a given particle, the search considers the neighbours whose center is within a distance of rlim*Diameter from its center. By default, rlim=1.3.

6.37 RIGID BODIES (JRC Implementation)

Object :

To define one or more rigid (non-deformable) bodies. The geometrical characteristics of each rigid body are specified here. The material characteristics (basically, the density) are specified by assigning to each rigid body a `RIGI` (rigid) material, see Page C.295.

Syntax:

```
RIGI nrigi * ( <MASS mass <MTOT mtot> >
               <BARY bary <GX gx GY gy <GZ gz>> >
               <INER iner <JXX jxx JYY jyy JZZ jzz
                           JYZ jyz JXZ jxz JXY jxy> >
               /LECT/ )
```

`nrigi`

Total number of rigid bodies. Each rigid body is geometrically defined by a set of elements.

`MASS`

Optional specification of the method that should be used to compute the total mass of the body. The value **0** means using the **nodal masses** as computed by EPX using standard procedures. This method should *not* be used if there are any hybrid nodes, i.e. nodes on an interface between a rigid part and a deformable part of the model. The value **1** (default) means using the **element masses** as computed by EPX using standard procedures. The value **2** means decomposing each element into **simplexes** (triangles or tetrahedrons) and then using analytical formulas over each simplex in order to assemble the total mass of the whole body. The value **3** means that the **user** specifies the total mass by the following `MTOT` keyword. In this latter case the value of the `RIGI` material density is not used, but it must be specified anyway for input completeness, see Page C.295.

`BARY`

Optional specification of the method that should be used to compute the center of gravity (barycenter) of the body. The value **0** means using the **nodal masses**, located at the rigid nodes composing the body. This method should *not* be used if there are any hybrid nodes, i.e. nodes on an interface between a rigid part and a deformable part of the model. The value **1** (default) means using the **element masses**, located at the centroids of the rigid elements composing the body. An element's centroid is computed as the (non-weighted) arithmetic average of the element's nodal positions. In general, this is only an approximation of the real center of gravity (barycenter) of the element. The value **2** means decomposing each element into **simplexes** (triangles or tetrahedrons) and then using analytical formulas over each simplex in order to compute the barycenter of the whole body. The value **3** means that the **user** specifies the coordinates of the barycenter, by the following `GX`, `GY` and `GZ` (3D only) keywords. In this latter case the value of the `RIGI` material density is not used, but it must be specified anyway for input completeness, see Page C.295.

`INER`

Optional specification of the method that should be used to compute the tensor of inertia of the body with respect to three mutually perpendicular axes parallel to the global axes and passing through the barycenter of the body. The value **0** means using the **nodal masses**, located at the rigid nodes composing the body. This method should *not* be used if there are any hybrid nodes, i.e. nodes on an interface between a rigid part and a deformable part of the model. The value **1** (default) means using the **element masses**, located at the centroids of the rigid elements composing the body. An element's centroid is computed as the (non-weighted) arithmetic average of the element's nodal positions. In general, this is only an approximation of the real center of gravity (barycenter) of the element. The value **2** means decomposing each element into **simplexes** (triangles or tetrahedrons) and then using analytical formulas over each simplex in order to assemble the inertia tensor of the whole body. The value **3** means that the **user** specifies the tensor of inertia by the following `JXX`, `JXY`, `JZZ`, `JYZ`, `JXZ` and `JXY` keywords. In this latter case the value of the `RIGI` material density is not used, but it must be specified anyway for input completeness, see Page C.295.

`/LECT/`

List of the elements defining the rigid body.

Comments :

The elements belonging to a rigid body *must* be assigned a rigid (`RIGI`) material, which is used to define the density of the rigid body and thus to compute the mass, the barycenter and the inertia moments of the body (unless they are specified by the user).

Only elements belonging to a rigid body `RIGI` can be assigned a rigid material `RIGI`.

A named elements group `_RIGI<nnn>` is automatically created for each rigid body. The `<nnn>` is the rigid body index (`001`, `002`, ..., `nrigi`) in the order of definition of the rigid bodies. Each group contains only one element and only one node: the "lumped" element and the "lumped" node that represent the rigid body *as a whole*. These names can be used to apply external loads, boundary conditions, etc., to a rigid body *as a whole*.

7 GROUP C1—MATERIALS

Object:

This instruction enables the user to enter the properties of various materials.

Syntax:

```
"MATE"   (  < "LOI" numldc >  . . .  )
```

`LOI`

This keyword announces that a number will be assigned to the constitutive law whose definition follows.

`numldc`

Number of the constitutive law.

Comments:

The word "MATE" is compulsory and may only be used once, at the beginning of the data sequence relative to the instruction MATERIALS.

The numbers introduced by the "LOI" directive may be in arbitrary order, and some numbers may be missing. This is very useful in the case of multiple materials: one can add or move material data in the input file without changing the number of the corresponding material law (see `"MULT"`, page C.380).

If the "LOI" directive is absent, the number automatically attributed to the law by EUROPLEXUS is the index of the material in the order its constitutive law is listed in the input data.

Do not forget the corresponding dimensioning (GBA_0070).

7.1 LIST OF MATERIALS

The material models are (in alphabetical order):

number	name	ref	law of behaviour
74	ABSE		
53	ADCJ	7.8.25	hypothetical core disruptive accident with law of type JWL for the bubble
34	ADCR	7.8.19	containment accident (fast neutrons)
47	ADFM	7.8.32	advection-diffusion fluid
71	APPU	7.5	Material for elements of type PPUI
32	ASSE		motor asservissement (meca)
11	BETO	7.7.16	concrete (NAHAS model)
57	BILL	7.8.26	LIBRE (user's free particle material), or FLUIDE (isothermal fluid particle: c = cte)
29	BL3S	7.7.71	reinforced concrete for discrete elements
133	BLKO	7.7.81	Blatz-Ko hyperelastic material
20	BLMT	7.7.17	DYNAR LMT Concrete
75	BOIS	7.7.31	wood for shock adsorbing (only compression)
121	BPEL	7.7.17	model for prestressing cable-concrete friction
114	BREC	7.8.12	data for pipeline break
59	BUBB	7.8.38	Balloon model for air blast simulations
89	CAMC	7.7.53	Modified Cam-clay material
8	CAVI		isothermal fluid with cavitation
68	CDEM	7.8.39	Discrete Equation Method for Combustion
64	CHAN	7.7.26	Multi-layer with the CHANG-CHANG criterion
51	CHOC	7.8.22	Shock waves, Rankine-Hugoniot equation
21	CLVF	7.9.34	Boundary conditions for finite volumes
90	CLAY	7.7.54	Modified Cam-clay material (backward fully implicit algorithm, viscoplastic regularization)
88	COMM	7.7.52	Composite material (linear orthotropic), Ispra implementation
113	CREB		
58	CRIT	7.7.22	damage criteria calculation : PY (damage of type P/Y), DUCTile (ductile damage)
100	CRTM	7.7.67	Composite manufactured by RTM process
109	DADC	7.7.20	Dynamic Anisotropic Damage Concrete
62	DCMS	7.7.78	Damage in coarsely meshed shells
110	DEMS	7.8.40	Discrete Equation Method for Two Phase Stiffened Gases
38	DONE	7.7.49	viscoplastic material
111	DPDC	7.7.21	dynamic plastic damage concrete
87	DPSF	7.7.51	Drucker Prager with softening and viscoplastic regularization
83	DRPR	7.7.61	Drucker Prager Ispra model
12	DRUC	7.7.6	Drucker-Prager
19	DYNA	7.7.9	dynamic Von Mises isotropic rate-dependent
22	EAU	7.8.9	two-phase water (liquid + vapour)
115	ENGR	7.7.24	elastic gradient damage material
147	EPCO	7.7.7	elastic-plastic material with contact for CB40
105	EOBT	7.7.23	anisotropic damage of concrete
49	EXVL	7.8.20	hydrogen explosion Van Leer
17	FANT	7.7.39	phantom: ignore the associated elements

27	FLFA	7.8.15	rigid tube bundles
86	FLMP	7.8.35	Fluid multi-phase
7	FLUI	7.8.2	isothermal fluid (c = cte)
36	FLUT	7.8.30	fluid, to be specified by the user
93	FOAM	7.7.62	Aluminium foam (for crash simulations)
80	FUNE	7.7.56	specialized cable material (no compression resistance)
9	GAZP	7.8.4	perfect gas
118	GGAS	7.8.1	generic ideal gas material
44	GLAS	7.7.70	glass with strain-rate effect
116	GLIN	7.7.3	generic linear material
92	GLRC	7.7.63	Plasticity with kinematic softening for orthotropic shells. Global plastic criterion.
52	GPDI	7.8.23	diffusive perfect gas Van Leer
117	GPLA	7.7.4	generic plastic material
48	GVDW	7.8.28	Van Der Waals gas
40	GZPV	7.8.24	perfect gas for Van Leer
28	HELI	7.8.10	helium
3	HILL	7.7.69	Isotropic plasticity associated with a HILL criterion and with a orthotropic elastic behaviour
95	HYPE	7.7.64	hyperelastic material (Model of Mooney-Rivlin, Hart-Smith and Ogden)
16	IMPE	7.9	impedance
43	IMPV	7.9.21	impedance Van Leer
4	ISOT	7.7.9	isotropic Von Mises
108	JCLM	7.7.75	Johnson-Cook with Damage Lemaitre-Chaboche for SPHC
91	JPRP	7.12	for bushing elements
50	JWL	7.8.21	explosion (Jones-Wilkins-Lee model)
66	JWLS	7.8.29	Explosion (Jones-Wilkins-Lee for solids)
144	KTRL	7.7.9	Linear elastic behavior (12x12 matrix) for RL6D elements
72	LEM1	7.7.13	Von Mises isotropic coupled with damage (type Lemaitre)
13	LIBR	7.7.40	free (material defined by the user)
1	LINE	7.7.1	linear elasticity
23	LIQU	7.8.14	incompressible (or quasi-) fluid
70	LMC2	7.7.15	Von Mises isotropic coupled with damage (Lemaitre) with strain-rate sensitivity
63	LSGL	7.7.72	laminated security glass material
148	MAMO	7.7.36	mass with damping for a material point
149	CAMO	7.7.37	damped material for cora 6-dof element
26	MASS	7.7.35	mass of a material point
85	MAZA	7.7.19	Mazars-linear elastic law with damage
82	MCFF	7.8.34	multicomponent fluid material (far-field)
81	MCGP	7.8.33	multicomponent fluid material (perfect gas)
60	MCOU	7.7.25	Linear multi-layer homogenised through the thickness
45	MECA	7.10	mechanism associated to articulated systems
126	MFRONT	7.7.55	MFront constutive models
33	MHOM	7.8.16	homogenization
97	MINT	7.7.65	Material for interface element
130	MOON	7.7.79	Mooney-Rivlin hyperelastic material
31	MOTE		motor force or couple (meca)
25	MULT	7.8.13	multiple materials (coupled monodim.)
10	NAH2	7.8.7	sodium-water reaction

18	ODMS	7.7.30	nonlinear damage with orthotropy (ODM)
131	OGDE	7.7.80	Ogden hyperelastic material
132	ORSR	7.7.32	Rate dependent linear elastic orthotropic with local reference frame
134	OPFM	7.7.33	Onera Progressive Failure Model (Composite materials)
139	ORFM	7.7.34	Onera Rate dependent Failure Model (Composite materials)
42	ORTE	7.7.29	linear damage with orthotropy
41	ORTH	7.7.27	linear orthotropic in user system
46	ORTS	7.7.28	linear elastic orthotropic with local reference frame
2	PARF	7.7.9	perfectly plastic Von Mises
56	PARO	7.8.11	friction and heat exchange for pipeline walls
96	PBED		particle bed
6	POST		post-rupture (beton)
69	PRGL	7.8.27	Porous jelly for the particles
39	PUFF	7.8.17	equation of state of type "PUFF"
123	RESG	7.7.4	Material for RL3D spring element in the global reference frame
61	RESL	7.7.1	Material for RL3D spring element in the local reference frame
151	RE6G	7.7.37	Material for RL6D spring element in the global reference frame
125	RIGI	7.7.77	Rigid material (for rigid bodies)
54	RSEA	7.9.13	reaction sodium-water with three constituents
103	SG2P		
112	SGBN		
104	SGMP		
107	SLIN	7.7.74	Linear Damage for SPHC
99	SLZA	7.7.66	Steinberg-Lund-Zerilli-Armstrong
106	SMAZ	7.7.73	Mazars Damage for SPHC
24	SOUR	7.8.6	imposed pressure in a continuum element
30	STGN	7.7.11	Steinberg - Guinan
102	STIF		
94	SUPP	7.6	support
101	TAIT		
5	TETA	7.7.9	Von Mises dependent upon temperature
98	TVMC	7.7.68	elastoplastic short fibres with damage
37	VM1D	7.7.48	material for elements of type "ED1D"
35	VM23	7.7.47	Von Mises elasto-plastic radial return
2/4/5/19	VMIS	7.7.9	Von Mises materials
124	VMGR	7.7.12	Von Mises orthotropic reinforcement grid model
76	VMJC	7.7.57	Johnson-Cook
78	VMLP	7.7.58	Ludwig-Prandtl
79	VMLU	7.7.59	Ludwik
84	VMSF	7.7.50	Von Mises with softening and viscoplastic regularization
77	VMZA	7.7.60	Zerilli-Armstrong
120	VPJC	7.7.76	visco-plastic Johnson-Cook
67	ZALM	7.7.14	Zerilli-Armstrong with damage Lemaitre-Chaboche

The "FANT" material may be allocated to any element, with the effect of 'eliminating' it from the mesh, as far as mechanical resistance is concerned.

The different elements may use the following materials (defined by their numbers):

7.2 AVAILABLE MATERIALS FOR ELEMENT TYPES

```
====================================

NO. | ELEMENT | AVAILABLE MATERIALS
----|---------|---------------------------
  1 |  COQU   | LINE PARF ISOT TETA DYNA ORTH
  2 |  TRIA   | LINE PARF ISOT TETA POST FLUI CAVI GAZP NAH2 BETO
    |         | DRUC DYNA EAU  LIQU SOUR MULT FLFA STGN ADCR VM23
    |         | PUFF ORTH JWL  CHOC ADCJ RSEA CRIT BUBB JWLS ZALM
    |         | LMC2 LEM1 BOIS VMJC VMZA VMLP VMLU DRPR VMSF DPSF
    |         | CAMC CLAY SGMP ENGR VPJC
  3 |  BARR   | LINE PARF ISOT DYNA
  4 |  PONC   | LINE PARF ISOT
  5 |  MEMB   | LINE
  6 |  CUBB   | LINE PARF ISOT
  7 |  CL2D   | IMPE CLVF IMPV
  8 |  CAR1   | LINE PARF ISOT TETA POST FLUI CAVI GAZP NAH2 BETO
    |         | DRUC DYNA EAU  LIQU SOUR MULT FLFA STGN ADCR VM23
    |         | DONE PUFF ORTH JWL  CHOC ADCJ RSEA CRIT BUBB JWLS
    |         | ZALM LMC2 LEM1 BOIS VMJC VMZA VMLP VMLU DRPR VMSF
    |         | DPSF CAMC CLAY SGMP VPJC
  9 |  CAR4   | LINE PARF ISOT TETA POST FLUI CAVI GAZP BETO DRUC
    |         | DYNA EAU  MULT FLFA STGN VM23 DONE PUFF ORTH GLAS
    |         | CHOC ADCJ CRIT BUBB LSGL ZALM LMC2 LEM1 BOIS VMJC
    |         | VMZA VMLP VMLU DRPR VMSF DPSF CAMC CLAY HYPE ENGR
    |         | VPJC
 10 |  COQC   | LINE PARF ISOT ORTH
 11 |  CUBE   | LINE ISOT TETA FLUI GAZP NAH2 DRUC DESM DYNA BLMT
    |         | EAU  LIQU SOUR MULT FLFA STGN ADCR VM23 PUFF ORTH
    |         | ORTE GLAS ORTS JWL  CHOC ADCJ RSEA ORPE CRIT BUBB
    |         | LSGL JWLS ZALM LMC2 LEM1 BOIS VMJC VMZA VMLP VMLU
    |         | DRPR VMSF MAZA DPSF CAMC CLAY FOAM HYPE PBED TVMC
    |         | SLZA CRTM SGMP EOBT DADC DPDC BDBM VPJC ORTP ORSR
    |         | OPFM ORFM
 12 |  COQ3   | LINE ISOT TETA DYNA MCOU CHAN
 13 |  CUB6   | LINE ISOT TETA FLUI GAZP DRUC DYNA BLMT MULT STGN
    |         | VM23 PUFF ORTH ORTE GLAS ORTS CHOC ORPE CRIT LSGL
    |         | BOIS VMJC DRPR VMSF DPSF CAMC CLAY FOAM HYPE SLZA
    |         | CRTM VPJC ORSR
 14 |  COQ4   | LINE ISOT TETA DYNA MCOU CHAN
 15 |  FS2D   |
 16 |  FS3D   |
 17 |  POUT   | LINE ISOT DYNA
 18 |  CL3D   | IMPE CLVF
 19 |  BR3D   | LINE PARF ISOT DYNA
 20 |  PR6    | LINE HILL ISOT TETA FLUI GAZP BETO DRUC DESM DYNA
```

```
   |        | BLMT MULT VM23 PUFF ORTH ORTE ORTS ORPE CRIT ZALM
   |        | LMC2 LEM1 BOIS VMJC DRPR VMSF MAZA DPSF CAMC CLAY
   |        | FOAM HYPE SLZA CRTM EOBT DADC VPJC DPDC ORSR OPFM
   |        | ORFM
21 |  TETR  | LINE HILL ISOT TETA FLUI GAZP NAH2 DRUC DESM DYNA
   |        | BLMT EAU  LIQU SOUR MULT FLFA ADCR VM23 PUFF ORTH
   |        | ORTE ORTS JWL  CHOC ADCJ RSEA ORPE CRIT BUBB JWLS
   |        | ZALM BOIS VMJC DRPR VMSF MAZA DPSF CAMC CLAY FOAM
   |        | HYPE SLZA CRTM SGMP EOBT DADC ENGR VPJC DPDC
22 |  TUBE  | FLUI GAZP NAH2 EAU  LIQU SOUR MULT HELI ADCR GVDW
   |        | JWL  RSEA PARO JWLS
23 |  TUYA  | LINE ISOT FLUI GAZP NAH2 EAU  LIQU SOUR MULT HELI
   |        | ADCR GVDW RSEA PARO
24 |  CL1D  | IMPE CLVF
25 |  BIFU  | FLUI GAZP NAH2 EAU  LIQU SOUR ADCR GVDW RSEA
26 |  CAVI  | FLUI GAZP NAH2 EAU  LIQU SOUR MULT ADCR GVDW RSEA
   |        | PARO
27 |  PRIS  | LINE HILL ISOT TETA FLUI GAZP NAH2 DRUC DESM DYNA
   |        | BLMT EAU  SOUR MULT FLFA ADCR VM23 PUFF ORTH ORTE
   |        | ORTS JWL  CHOC ADCJ RSEA ORPE CRIT BUBB JWLS ZALM
   |        | LMC2 LEM1 BOIS VMJC DRPR VMSF DPSF CAMC CLAY FOAM
   |        | HYPE CRTM SGMP EOBT VPJC DPDC
28 |  PMAT  | LINE MASS MAMO
29 |  CL3T  | IMPE CLVF
30 |  CUB8  | LINE HILL ISOT TETA FLUI GAZP DRUC DESM ODMS DYNA
   |        | BLMT MULT STGN VM23 PUFF ORTH ORTE GLAS ORTS CHOC
   |        | ORPE CRIT LSGL ZALM LMC2 LEM1 BOIS VMJC VMZA VMLP
   |        | VMLU DRPR VMSF MAZA DPSF CAMC CLAY FOAM HYPE SLZA
   |        | CRTM EOBT DADC DPDC ENGR BDBM VPJC ORTP ORSR OPFM
   |        | ORFM
31 |  CLTU  | IMPE CLVF
32 |  APPU  | APPU SUPP
33 |  MECA  | MOTE ASSE MECA ABSE
34 |  QAX1  | FLUI GAZP BUBB
35 |  QPPS  | LINE ISOT DYNA VM23 DONE GLAS MCOU LSGL CHAN LEM1
   |        | VMJC VMZA VMLP VMLU VMSF DPSF GLRC SLZA VPJC
36 |  FHQ2  | MHOM
37 |  FHT2  | MHOM
38 |  Q92   | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU DRPR VMSF
   |        | DPSF CAMC CLAY VPJC
39 |  Q93   | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU DRPR VMSF
   |        | DPSF CAMC CLAY VPJC
40 |  COQI  | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU VMSF DPSF
   |        | COMM VPJC
41 |  TUBM  | FLUI GAZP NAH2 EAU  LIQU ADCR GVDW RSEA GAZD TAIT
   |        | STIF SG2P SGMP SGBN
42 |  CL23  | IMPE
43 |  ED01  | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU VMSF DPSF
   |        | VPJC
44 |  ED1D  | VM1D
45 |  TVL1  | GZPV GVDW EXVL GPDI
```

```
 46 |  CVL1   | GZPV GVDW EXVL GPDI
 47 |  CMC3   | LINE ISOT BETO ORTH
 48 |  FS3T   |
 49 |  Q92A   | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU DRPR VMSF
    |         | DPSF CAMC CLAY VPJC
 50 |  CL3L   |
 51 |  T3GS   | LINE ISOT TETA DYNA VM23 DONE GLAS LSGL LEM1 VMJC
    |         | VMZA VMLP VMLU VMSF DPSF GLRC VPJC
 52 |  FLU1   | FLUT BUBB
 53 |  FLU3   | FLUT BUBB
 54 |  PFEM   | FLUI
 55 |  FL2S   | FLUT BUBB FLMP
 56 |  ED41   | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU VMSF DPSF
    |         | VPJC
 57 |  ADC8   | ADFM
 58 |  ADQ4   | ADFM
 59 |  FL3S   | FLUT BUBB FLMP
 60 |  CL2S   | IMPE FLUT
 61 |  CL3S   | IMPE FLUT
 62 |  CL32   | IMPE
 63 |  CL33   | IMPE
 64 |  FL23   | FLUT BUBB FLMP
 65 |  FL24   | FLUT BUBB FLMP
 66 |  FL34   | FLUT BUBB FLMP
 67 |  FL35   | FLUT BUBB FLMP
 68 |  FL36   | FLUT BUBB FLMP
 69 |  FL38   | FLUT BUBB FLMP
 70 |  CL22   | IMPE FLUT IMPV MCFF
 71 |  Q41    | VM23 DONE LSGL VMSF DPSF
 72 |  Q42    | VM23 DONE LSGL VMSF DPSF
 73 |  Q41N   | VM23 DONE LSGL VMSF DPSF
 74 |  Q42N   | VM23 DONE LSGL VMSF DPSF
 75 |  Q41L   | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU DRPR VMSF
    |         | DPSF CAMC CLAY VPJC
 76 |  Q42L   | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU DRPR VMSF
    |         | DPSF CAMC CLAY VPJC
 77 |  Q95    | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU DRPR VMSF
    |         | DPSF CAMC CLAY VPJC
 78 |  CL3I   | IMPE FLUT MCFF
 79 |  BILL   | LINE ISOT PUFF BILL PRGL MAZA
 80 |  ELDI   | BL3S
 81 |  CUVL   | GZPV GVDW EXVL GPDI
 82 |  PRVL   | GZPV GVDW EXVL GPDI
 83 |  DST3   | LINE HILL ISOT TETA DYNA VM23 DONE GLAS ORTS MCOU
    |         | LSGL CHAN LEM1 VMJC VMZA VMLP VMLU VMSF DPSF HYPE
    |         | SLZA VPJC
 84 |  DKT3   | LINE ISOT DYNA VM23 DONE GLAS MCOU LSGL CHAN LEM1
    |         | VMJC VMZA VMLP VMLU VMSF DPSF GLRC SLZA VPJC
 85 |  SHB8   | LINE ISOT DYNA ZALM LMC2 LEM1 SLZA
 86 |  XCUB   | LINE PARF ISOT ODMS ORTE VMJC VMSF
 87 |  XCAR   | LINE PARF ISOT VMJC VMSF
```

```
 88 |  PROT   | LINE ISOT
 89 |  SPHC   | LINE ISOT LEM1 SMAZ SLIN JCLM
 90 |  Q4G4   | LINE ISOT
 91 |  CQD4   | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU VMSF DPSF
    |         | COMM VPJC
 92 |  CQD9   | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU VMSF DPSF
    |         | COMM VPJC
 93 |  CQD3   | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU VMSF DPSF
    |         | COMM VPJC
 94 |  CQD6   | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU VMSF DPSF
    |         | COMM VPJC
 95 |  CLD3   | IMPE
 96 |  CLD6   | IMPE
 97 |  MC23   | MCGP
 98 |  MC24   | MCGP
 99 |  CL3Q   | IMPE FLUT MCFF
100 |  Q42G   | VM23 DONE
101 |  MC34   | MCGP
102 |  MC35   | MCGP
103 |  MC36   | MCGP
104 |  MC38   | MCGP
105 |  MS24   | LINE
106 |  S24    | LINE
107 |  MS38   | LINE
108 |  S38    | LINE
109 |  FUN2   | VM23 DONE VMJC VMZA VMLP VMLU FUNE VPJC
110 |  FUN3   | VM23 DONE VMJC VMZA VMLP VMLU FUNE VPJC
111 |  Q4GR   | LINE HILL ISOT TETA DYNA VM23 DONE GLAS MCOU LSGL
    |         | CHAN LEM1 VMJC VMZA VMLP VMLU VMSF DPSF GLRC SLZA
    |         | VPJC VMGR DPDC
112 |  Q4GS   | LINE HILL ISOT TETA DYNA VM23 DONE GLAS ORTS MCOU
    |         | LSGL CHAN LEM1 VMJC VMZA VMLP VMLU VMSF DPSF GLRC
    |         | HYPE SLZA VPJC VMGR
113 |  RL3D   | RESL RESG
114 |  BSHT   | JPRP
115 |  BSHR   | JPRP
116 |  TUYM   | FLUI GAZP NAH2 EAU  LIQU ADCR GVDW RSEA GAZD TAIT
    |         | STIF SG2P SGMP SGBN
117 |  SH3D   | JPRP
118 |  MAP2   |
119 |  MAP3   |
120 |  MAP4   |
121 |  MAP5   |
122 |  MAP6   |
123 |  MAP7   |
124 |  INT4   | LINE MINT
125 |  INT6   | LINE MINT
126 |  INT8   | LINE MINT
127 |  SH3V   |
128 |  MOY4   |
129 |  MOY5   |
```

```
130 |  ASHB    | LINE ISOT DYNA ZALM LMC2 LEM1 SLZA
131 |  T3VF    | FLUI GAZP EAU  ADCR GVDW JWL  ADCJ BUBB JWLS CDEM
    |          | GAZD TAIT STIF SG2P SGMP DEMS SGBN CREB
132 |  Q4VF    | FLUI GAZP EAU  ADCR GVDW JWL  ADCJ BUBB JWLS CDEM
    |          | GAZD TAIT STIF SG2P SGMP DEMS SGBN CREB
133 |  CUVF    | FLUI GAZP EAU  ADCR GVDW JWL  ADCJ BUBB JWLS CDEM
    |          | GAZD TAIT STIF SG2P SGMP DEMS SGBN CREB
134 |  PRVF    | FLUI GAZP EAU  ADCR GVDW JWL  ADCJ BUBB JWLS CDEM
    |          | GAZD TAIT STIF SG2P SGMP DEMS SGBN CREB
135 |  TEVF    | FLUI GAZP EAU  ADCR GVDW JWL  ADCJ BUBB JWLS CDEM
    |          | GAZD TAIT STIF SG2P SGMP DEMS SGBN CREB
136 |  PYVF    | FLUI GAZP EAU  ADCR GVDW JWL  ADCJ BUBB JWLS CDEM
    |          | GAZD TAIT STIF SG2P SGMP DEMS SGBN CREB
137 |  COQ2    | LINE ISOT TETA
138 |  Q4MC    | LINE HILL ISOT DYNA ORTS ORPE
139 |  T3MC    | LINE HILL ISOT DYNA VM23 ORTS ORPE LSGL VPJC
140 |  DEBR    |
141 |  INS6    |
142 |  INS8    |
143 |  RL6D    | KTRL RE6G
144 |  C272    | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU DRPR VMSF
    |          | DPSF CAMC CLAY VPJC
145 |  C273    | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU DRPR VMSF
    |          | DPSF CAMC CLAY VPJC
146 |  BREC    | EAU  MULT BREC
147 |  TUVF    | FLUI GAZP EAU  MULT ADCR GVDW JWL  ADCJ PARO JWLS
    |          | GAZD TAIT STIF SG2P SGMP SGBN
148 |  TYVF    | LINE ISOT FLUI GAZP EAU  MULT ADCR GVDW JWL  ADCJ
    |          | PARO JWLS GAZD TAIT STIF SG2P SGMP SGBN
149 |  BIVF    | FLUI GAZP EAU  ADCR GVDW JWL  ADCJ JWLS GAZD TAIT
    |          | STIF SG2P SGMP SGBN BREC
150 |  CAVF    | FLUI GAZP EAU  MULT ADCR GVDW JWL  ADCJ JWLS GAZD
    |          | TAIT STIF SG2P SGMP SGBN
151 |  CL92    | IMPE
152 |  CL93    | IMPE
153 |  LIGR    | MECA
154 |  RNFR    | BPEL
155 |  C81L    | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU DRPR VMSF
    |          | DPSF CAMC CLAY VPJC
156 |  C82L    | VM23 DONE GLAS LSGL VMJC VMZA VMLP VMLU DRPR VMSF
    |          | DPSF CAMC CLAY VPJC
165 |  CB40    | EPCO
166 |  CORA    | CAMO

 AVAILABLE ELEMENTS FOR EACH MATERIAL
 ====================================

 E AFTER MATERIAL INDICATES ERODIBLE.

NO. | MATERIAL| AVAILABLE ELEMENTS
----|---------|----------------------------
```

```
  1 |  LINE E | COQU TRIA BARR PONC MEMB CUBB CAR1 CAR4 COQC CUBE
    |         | COQ3 CUB6 COQ4 POUT BR3D PR6  TETR TUYA PRIS PMAT
    |         | CUB8 QPPS CMC3 T3GS BILL DST3 DKT3 SHB8 XCUB XCAR
    |         | PROT SPHC Q4G4 MS24 S24  MS38 S38  Q4GR Q4GS INT4
    |         | INT6 INT8 ASHB COQ2 Q4MC T3MC P3ZT TYVF
  2 |  PARF E | COQU TRIA BARR PONC CUBB CAR1 CAR4 COQC BR3D XCUB
    |         | XCAR
  3 |  HILL   | PR6  TETR PRIS CUB8 DST3 Q4GR Q4GS Q4MC T3MC P3ZT
  4 |  ISOT E | COQU TRIA BARR PONC CUBB CAR1 CAR4 COQC CUBE COQ3
    |         | CUB6 COQ4 POUT BR3D PR6  TETR TUYA PRIS CUB8 QPPS
    |         | CMC3 T3GS BILL DST3 DKT3 SHB8 XCUB XCAR PROT SPHC
    |         | Q4G4 Q4GR Q4GS ASHB COQ2 Q4MC T3MC P3ZT TYVF
  5 |  TETA E | COQU TRIA CAR1 CAR4 CUBE COQ3 CUB6 COQ4 PR6  TETR
    |         | PRIS CUB8 T3GS DST3 Q4GR Q4GS COQ2
  6 |  POST   | TRIA CAR1 CAR4
  7 |  FLUI   | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR TUBE TUYA BIFU
    |         | CAVI PRIS CUB8 QAX1 TUBM PFEM TUYM T3VF Q4VF CUVF
    |         | PRVF TEVF PYVF TUVF TYVF BIVF CAVF
  8 |  CAVI   | TRIA CAR1 CAR4
  9 |  GAZP   | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR TUBE TUYA BIFU
    |         | CAVI PRIS CUB8 QAX1 TUBM TUYM T3VF Q4VF CUVF PRVF
    |         | TEVF PYVF TUVF TYVF BIVF CAVF
 10 |  NAH2   | TRIA CAR1 CUBE TETR TUBE TUYA BIFU CAVI PRIS TUBM
    |         | TUYM
 11 |  BETO E | TRIA CAR1 CAR4 PR6  CMC3
 12 |  DRUC E | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8
 14 |  IFS    |
 15 |  DESM   | CUBE PR6  TETR PRIS CUB8
 16 |  IMPE   | CL2D CL3D CL1D CL3T CLTU CL23 CL2S CL3S CL32 CL33
    |         | CL22 CL3I CLD3 CLD6 CL3Q CL92 CL93
 18 |  ODMS   | CUB8 XCUB
 19 |  DYNA E | COQU TRIA BARR CAR1 CAR4 CUBE COQ3 CUB6 COQ4 POUT
    |         | BR3D PR6  TETR PRIS CUB8 QPPS T3GS DST3 DKT3 SHB8
    |         | Q4GR Q4GS ASHB Q4MC T3MC P3ZT
 20 |  BLMT   | CUBE CUB6 PR6  TETR PRIS CUB8
 21 |  CLVF   | CL2D CL3D CL1D CL3T CLTU
 22 |  EAU    | TRIA CAR1 CAR4 CUBE TETR TUBE TUYA BIFU CAVI PRIS
    |         | TUBM TUYM T3VF Q4VF CUVF PRVF TEVF PYVF BREC TUVF
    |         | TYVF BIVF CAVF
 23 |  LIQU   | TRIA CAR1 CUBE TETR TUBE TUYA BIFU CAVI TUBM TUYM
 24 |  SOUR   | TRIA CAR1 CUBE TETR TUBE TUYA BIFU CAVI PRIS
 25 |  MULT   | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR TUBE TUYA CAVI
    |         | PRIS CUB8 BREC TUVF TYVF CAVF
 26 |  MASS   | PMAT
 27 |  FLFA   | TRIA CAR1 CAR4 CUBE TETR PRIS
 28 |  HELI   | TUBE TUYA
 29 |  BL3S   | ELDI
 30 |  STGN   | TRIA CAR1 CAR4 CUBE CUB6 CUB8
 31 |  MOTE   | MECA
 32 |  ASSE   | MECA
 33 |  MHOM   | FHQ2 FHT2
```

```
34 | ADCR   | TRIA CAR1 CUBE TETR TUBE TUYA BIFU CAVI PRIS TUBM
   |        | TUYM T3VF Q4VF CUVF PRVF TEVF PYVF TUVF TYVF BIVF
   |        | CAVF
35 | VM23 E | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8 QPPS
   |        | Q92  Q93  COQI ED01 Q92A T3GS ED41 Q41  Q42  Q41N
   |        | Q42N Q41L Q42L Q95  DST3 DKT3 CQD4 CQD9 CQD3 CQD6
   |        | Q42G FUN2 FUN3 Q4GR Q4GS T3MC C272 C273 C81L C82L
36 | FLUT   | FLU1 FLU3 FL2S FL3S CL2S CL3S FL23 FL24 FL34 FL35
   |        | FL36 FL38 CL22 CL3I CL3Q
37 | VM1D   | ED1D
38 | DONE   | CAR1 CAR4 QPPS Q92  Q93  COQI ED01 Q92A T3GS ED41
   |        | Q41  Q42  Q41N Q42N Q41L Q42L Q95  DST3 DKT3 CQD4
   |        | CQD9 CQD3 CQD6 Q42G FUN2 FUN3 Q4GR Q4GS C272 C273
   |        | C81L C82L
39 | PUFF   | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8 BILL
40 | GZPV   | TVL1 CVL1 CUVL PRVL
41 | ORTH   | COQU TRIA CAR1 CAR4 COQC CUBE CUB6 PR6  TETR PRIS
   |        | CUB8 CMC3
42 | ORTE   | CUBE CUB6 PR6  TETR PRIS CUB8 XCUB
43 | IMPV   | CL2D CL22
44 | GLAS E | CAR4 CUBE CUB6 CUB8 QPPS Q92  Q93  COQI ED01 Q92A
   |        | T3GS ED41 Q41L Q42L Q95  DST3 DKT3 CQD4 CQD9 CQD3
   |        | CQD6 Q4GR Q4GS C272 C273 C81L C82L
45 | MECA   | MECA LIGR
46 | ORTS   | CUBE CUB6 PR6  TETR PRIS CUB8 DST3 Q4GS Q4MC T3MC
   |        | P3ZT
47 | ADFM   | ADC8 ADQ4
48 | GVDW   | TUBE TUYA BIFU CAVI TUBM TVL1 CVL1 CUVL PRVL TUYM
   |        | T3VF Q4VF CUVF PRVF TEVF PYVF TUVF TYVF BIVF CAVF
49 | EXVL   | TVL1 CVL1 CUVL PRVL
50 | JWL    | TRIA CAR1 CUBE TETR TUBE PRIS T3VF Q4VF CUVF PRVF
   |        | TEVF PYVF TUVF TYVF BIVF CAVF
51 | CHOC   | TRIA CAR1 CAR4 CUBE CUB6 TETR PRIS CUB8
52 | GPDI   | TVL1 CVL1 CUVL PRVL
53 | ADCJ   | TRIA CAR1 CAR4 CUBE TETR PRIS T3VF Q4VF CUVF PRVF
   |        | TEVF PYVF TUVF TYVF BIVF CAVF
54 | RSEA   | TRIA CAR1 CUBE TETR TUBE TUYA BIFU CAVI PRIS TUBM
   |        | TUYM
55 | ORPE   | CUBE CUB6 PR6  TETR PRIS CUB8 Q4MC T3MC P3ZT
56 | PARO   | TUBE TUYA CAVI TUVF TYVF
57 | BILL   | BILL
58 | CRIT   | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8
59 | BUBB   | TRIA CAR1 CAR4 CUBE TETR PRIS QAX1 FLU1 FLU3 FL2S
   |        | FL3S FL23 FL24 FL34 FL35 FL36 FL38 T3VF Q4VF CUVF
   |        | PRVF TEVF PYVF
60 | MCOU   | COQ3 COQ4 QPPS DST3 DKT3 Q4GR Q4GS
61 | RESL   | RL3D
62 | PIEZ   | P3ZT
63 | LSGL   | CAR4 CUBE CUB6 CUB8 QPPS Q92  Q93  COQI ED01 Q92A
   |        | T3GS ED41 Q41  Q42  Q41N Q42N Q41L Q42L Q95  DST3
   |        | DKT3 CQD4 CQD9 CQD3 CQD6 Q4GR Q4GS T3MC C272 C273
```

```
   |         | C81L C82L
64 |  CHAN   | COQ3 COQ4 QPPS DST3 DKT3 Q4GR Q4GS
65 |  MORI   |
66 |  JWLS   | TRIA CAR1 CUBE TETR TUBE PRIS T3VF Q4VF CUVF PRVF
   |         | TEVF PYVF TUVF TYVF BIVF CAVF
67 |  ZALM E | TRIA CAR1 CAR4 CUBE PR6  TETR PRIS CUB8 SHB8 ASHB
68 |  CDEM   | T3VF Q4VF CUVF PRVF TEVF PYVF
69 |  PRGL   | BILL
70 |  LMC2   | TRIA CAR1 CAR4 CUBE PR6  PRIS CUB8 SHB8 ASHB
71 |  APPU   | APPU
72 |  LEM1 E | TRIA CAR1 CAR4 CUBE PR6  PRIS CUB8 QPPS T3GS DST3
   |         | DKT3 SHB8 SPHC Q4GR Q4GS ASHB
73 |  GAZD   | TUBM TUYM T3VF Q4VF CUVF PRVF TEVF PYVF TUVF TYVF
   |         | BIVF CAVF
74 |  ABSE   | MECA
75 |  BOIS E | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8
76 |  VMJC E | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8 QPPS
   |         | Q92  Q93  COQI ED01 Q92A T3GS ED41 Q41L Q42L Q95
   |         | DST3 DKT3 XCUB XCAR CQD4 CQD9 CQD3 CQD6 FUN2 FUN3
   |         | Q4GR Q4GS C272 C273 C81L C82L
77 |  VMZA E | TRIA CAR1 CAR4 CUBE CUB8 QPPS Q92  Q93  COQI ED01
   |         | Q92A T3GS ED41 Q41L Q42L Q95  DST3 DKT3 CQD4 CQD9
   |         | CQD3 CQD6 FUN2 FUN3 Q4GR Q4GS C272 C273 C81L C82L
78 |  VMLP E | TRIA CAR1 CAR4 CUBE CUB8 QPPS Q92  Q93  COQI ED01
   |         | Q92A T3GS ED41 Q41L Q42L Q95  DST3 DKT3 CQD4 CQD9
   |         | CQD3 CQD6 FUN2 FUN3 Q4GR Q4GS C272 C273 C81L C82L
79 |  VMLU E | TRIA CAR1 CAR4 CUBE CUB8 QPPS Q92  Q93  COQI ED01
   |         | Q92A T3GS ED41 Q41L Q42L Q95  DST3 DKT3 CQD4 CQD9
   |         | CQD3 CQD6 FUN2 FUN3 Q4GR Q4GS C272 C273 C81L C82L
80 |  FUNE   | FUN2 FUN3
81 |  MCGP   | MC23 MC24 MC34 MC35 MC36 MC38
82 |  MCFF E | CL22 CL3I CL3Q
83 |  DRPR E | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8 Q92
   |         | Q93  Q92A Q41L Q42L Q95  C272 C273 C81L C82L
84 |  VMSF E | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8 QPPS
   |         | Q92  Q93  COQI ED01 Q92A T3GS ED41 Q41  Q42  Q41N
   |         | Q42N Q41L Q42L Q95  DST3 DKT3 XCUB XCAR CQD4 CQD9
   |         | CQD3 CQD6 Q4GR Q4GS C272 C273 C81L C82L
85 |  MAZA   | CUBE PR6  TETR CUB8 BILL
86 |  FLMP   | FL2S FL3S FL23 FL24 FL34 FL35 FL36 FL38
87 |  DPSF E | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8 QPPS
   |         | Q92  Q93  COQI ED01 Q92A T3GS ED41 Q41  Q42  Q41N
   |         | Q42N Q41L Q42L Q95  DST3 DKT3 CQD4 CQD9 CQD3 CQD6
   |         | Q4GR Q4GS C272 C273 C81L C82L
88 |  COMM   | COQI CQD4 CQD9 CQD3 CQD6
89 |  CAMC   | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8 Q92
   |         | Q93  Q92A Q41L Q42L Q95  C272 C273 C81L C82L
90 |  CLAY   | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8 Q92
   |         | Q93  Q92A Q41L Q42L Q95  C272 C273 C81L C82L
91 |  JPRP   | BSHT BSHR SH3D
92 |  GLRC   | QPPS T3GS DKT3 Q4GR Q4GS
```

```
 93 |  FOAM E | CUBE CUB6 PR6  TETR PRIS CUB8
 94 |  SUPP   | APPU
 95 |  HYPE   | CAR4 CUBE CUB6 PR6  TETR PRIS CUB8 DST3 Q4GS
 96 |  PBED   | CUBE
 97 |  MINT   | INT4 INT6 INT8
 98 |  TVMC   | CUBE
 99 |  SLZA   | CUBE CUB6 PR6  TETR CUB8 QPPS DST3 DKT3 SHB8 Q4GR
    |         | Q4GS ASHB
100 |  CRTM   | CUBE CUB6 PR6  TETR PRIS CUB8
101 |  TAIT   | TUBM TUYM T3VF Q4VF CUVF PRVF TEVF PYVF TUVF TYVF
    |         | BIVF CAVF
102 |  STIF   | TUBM TUYM T3VF Q4VF CUVF PRVF TEVF PYVF TUVF TYVF
    |         | BIVF CAVF
103 |  SG2P   | TUBM TUYM T3VF Q4VF CUVF PRVF TEVF PYVF TUVF TYVF
    |         | BIVF CAVF
104 |  SGMP   | TRIA CAR1 CUBE TETR PRIS TUBM TUYM T3VF Q4VF CUVF
    |         | PRVF TEVF PYVF TUVF TYVF BIVF CAVF
105 |  EOBT   | CUBE PR6  TETR PRIS CUB8
106 |  SMAZ   | SPHC
107 |  SLIN   | SPHC
108 |  JCLM   | SPHC
109 |  DADC   | CUBE PR6  TETR CUB8
110 |  DEMS   | T3VF Q4VF CUVF PRVF TEVF PYVF
111 |  DPDC   | CUBB CUBE CUB8 PRIS PR6  TETR Q4GR
112 |  SGBN   | TUBM TUYM T3VF Q4VF CUVF PRVF TEVF PYVF TUVF TYVF
    |         | BIVF CAVF
113 |  CREB   | T3VF Q4VF CUVF PRVF TEVF PYVF
114 |  BREC   | BREC BIVF
115 |  ENGR   | TRIA CAR4 TETR CUB8
116 |  GLIN E |
117 |  GPLA   |
118 |  GGAS   |
119 |  BDBM   | CUBE CUB8
120 |  VPJC E | TRIA CAR1 CAR4 CUBE CUB6 PR6  TETR PRIS CUB8 QPPS
    |         | Q92  Q93  COQI ED01 Q92A T3GS ED41 Q41L Q42L Q95
    |         | DST3 DKT3 CQD4 CQD9 CQD3 CQD6 FUN2 FUN3 Q4GR Q4GS
    |         | T3MC C272 C273 C81L C82L
121 |  BPEL   | RNFR
122 |  ORTP   | CUBE CUB8
123 |  RESG   | RL3D
124 |  VMGR   | Q4GR Q4GS
132 |  ORSR   | CUBE CUB6 CUB8 PR6
134 |  OPFM   | CUBE CUB8 PR6
139 |  ORFM   | CUBE CUB8 PR6
147 |  EPCO   | CB40
```

To print out (on the log file!) an up-to-date version of the above element and material tables, just run EUROPLEXUS with any input data file by adding the option `OPTI DPEM` (see also page GBH_0090).

7.3 AUXILIARY FILE

Object:

This directive allows to read the material data from an auxiliary file.

Syntax:

```
"MATE"     < "FICHIER"   'nom.fic'  >
```

In certain cases the data may be bulky. It is then advised to store the data on an auxiliary file in order to shorten the main input data file. The auxiliary file is activated by means of the keyword "FICHIER", followed by the full name (under Unix) of the file. Therefore, only the words "MATE" "FICHIER" 'nom.fic' remain in the main input file.

The auxiliary file (in free format) will contain the whole set of material data, with the exception of the "MATE" keyword. To return to the main input data file, the auxiliary file must be terminated by the keyword "RETOUR".

7.4 LOCALISED DAMPING

Object:

This directive allows adding a localised damping on some d.o.f.s of some particular nodes.

Syntax:

```
"AMORTISSEMENT" ( /LECDDL/  "BETA" beta   "FREQ" freq   /LECTURE/ )
```

`/LECDDL/`

Concerned degrees of freedom.

`beta`

Reduced damping β.

`freq`

Frequency f of the global mode to be damped out.

`/LECTURE/`

List of the concerned nodes.

Comments:

The value $\beta = 1$ corresponds to the critical damping for the frequency f. All frequencies are damped. The components with a frequency lower than the cut-off frequency: $f_c = \beta f$ will be damped in a pseudo-periodic manner while those having higher frequencies will be damped in an aperiodic manner.

This damping is proportional to the mass M and to the particles velocity v, and may be used in order to damp out preferably the structures without influence on the internal fluid, for example.

One adds an external force F_{amort} of the form:

$$F_{\mathrm{amort}} = -2\beta\omega M v$$

where $\omega = 2\pi f$.

It is evident that the work of external forces will be modified by the damping forces.

This directive differs from the global damping directive (`OPTI AMOR ...`, see page H.30) mainly by the fact that here the region to which damping is applied may be specified by the user, while in the other case the damping applies to the whole model (but limitedly to some element types, see page H.30).

7.5 NON-LINEAR SUPPORTS : "APPU"

Object :

This directive allows to model non-linear supports of type spring or damper. It may be used only for the elements of type "APPUI" (material points with 6 d.o.f.s). The user gives the evolution curve of the force applied by the support as a function of its displacement (for the springs) or of its velocity (for the dampers). These supports work in translation or in rotation.

Syntax :

```
    "APPUI" |[ "RESS" ; "AMOR" ]|  |[ "TRAN" ; "ROTA" ]|
            "CMPX" cmpx     "CMPY" cmpy     "CMPZ" cmpz
            "COEF" coef     "NUFO" nufo    <"MASS" mass>
           <"INCR" incr>   <"DECX" decx>   <"DECY" decy>  /LECTURE/
```

`"RESS"`

The support is of type spring.

`"AMOR"`

The support is of type damper.

`"TRAN"`

The support works in translation.

`"ROTA"`

The support works in rotation.

`cmpx`

Component in X of the translation or rotation axis of the support.

`cmpy`

Component in Y of the translation or rotation axis of the support.

`cmpz`

Component in Z of the translation or rotation axis of the support.

`coef`

Multiplicative coefficient of the function.

`nufo`

Number of the function.

`mass`

Inertia of the support along its working direction.

`incr`

Increment of the velocity or displacement for the calculation of the local stiffness.

`decx`

Offset of the abscissas of the force/displacement or force/velocity curve.

`decy`

Offset of the ordinates of the force/displacement or force/velocity curve.

`/LECTURE/`

List of the concerned nodes.

Comments :

The user must define a vector corresponding to the rotation axis or translation axis of the support. This vector does not need to be normalised, just its direction matters. This direction defines the local reference frame of the support: it is the projection of the displacement (or of the velocity) of the concerned node onto this axis that allows to determine the reaction force.

An APPUI element may not work simultaneously as a spring AND as a damper, nor in translation AND in rotation. Therefore it will be sometimes necessary to define several APPUI elements, geometrically coincident, in order to correctly define the local stiffness.

The function defining the force generated by the support in response to displacement or velocity of its application point on the supported structure is of the form:

$$F = coef\, f(D) \qquad or \qquad F = coef\, f(V)$$

with f(D) or f(V) given by the user. Warning: these values have a sign. Do not forget to give the force with the opposite sign as the displacement (this is a reminder).

For the estimation of the stability step, it is necessary to know the local slope of the behaviour curve. To this end, the user must specify the keyword "INCR". The computation of the local stiffness will then be (by default, incr=1.E-4):

$$K = (F(D + incr) - F(D))/incr \qquad or \qquad C = (F(V + incr) - F(V))/incr$$

In the case that the structure is not in equilibrium for a zero displacement at the beginning of the calculation, the user may impose a translation of vector (decx, decy) of the behaviour curve. The computed force will then be (by default, decx and decy are zero):

$$F = (coef\, f(D + decx)) - decy$$

(in fact : $decy = coef\, f(decx)$)

Outputs :

The components of the ECR vector are:

ECR(1): Force (resp. moment) along X.

ECR(2): Force (resp. moment) along Y.

ECR(3): Force (resp. moment) along Z.

ECR(4): Current stiffness.

ECR(5): Current velocity (or angular velocity).

ECR(6): Total displacement (or rotation).

ECR(7): Applied force (or moment) to the node (reaction force).

7.6 NON-LINEAR SUPPORTS : "SUPP"

Object :

This directive allows to model a complex non-linear support, having arbitrary stiffness and damping values along the 6 dofs of the concerned node. It may only be used in conjunction with elements of type "APPUI" (material point with 6 dofs). The user gives the evolution curve of the reaction force generated by the support as a function of the displacement or of the velocity of the associated node.

Syntax :

```
"SUPP"  "MASS" m
         < |[ "KX" kx ; "KY" ky ; "KZ" kz ]|
             |[
                "NFKT" nufo1 ;
                "NFKX" nufokx "NFKY" nufoky "NFKZ" nufokz
             ]| >
         < |[ "AX" ax ; "AY" ay ; "AZ" az ]| "NFAT" nufo2 >
         <"IRX" irx>  <"IRY" iry>  <"IRZ" irz>
         < |[ "KRX" krx ; "KRY" kry ; "KRZ" krz ]| "NFKR" nufo3 >
         < |[ "ARX" arx ; "ARY" ary ; "ARZ" arz ]| "NFAR" nufo4 >
         /LECTURE/
```

`m`

Additional translational mass (optional).

`kx, ky, kz`

Translationl stiffnesses along the global axes.

`nufo1`

Index of the function associated with translational stiffnesses.

`nufokx, nufoky, nufokz`

Indexes of the functions associated with 3 translational stiffnesses.

`ax, ay, az`

Translationl dampings along the global axes.

`nufo2`

Index of the function associated with translational dampings.

`irx, iry, irz`

Additional rotational inertias along the global axes (optional).

`krx, kry, krz`

Rotational stiffnesses along the global axes.

`nufo3`

Index of the function associated with rotational stiffnesses.

`arx, ary, arz`

Rotational dampings along the global axes.

`nufo4`

Index of the function associated with rotational dampings.

`/LECTURE/`

List of the concerned nodes.

Comments :

The stiffnesses and the dampings are given along the global (fixed) axes of the problem. Each of the 4 associated functions applies to the 3 corresponding stiffnesses (or dampings). For translational stiffnesses one can prescribe three different functions.

If a key-word is missing, the corresponding value is zero, and the order in which the parameters are specified is irrelevant.

The reaction force generated by the support has the form (e.g., assuming translation along Ox):

$$F_x = k_x f_1(D_x) + a_x f_2(V_x)$$

If the displacement (or the velocity) is positive, the function f1 (or f2) must be negative in order to obtain a correct reaction.

Outputs :

The components of the ECR vector are:

ECR(1): Reaction of the support along X.

ECR(2): Reaction of the support along Y.

ECR(3): Reaction of the support along Z.

ECR(4): Reaction of the support along RX.

ECR(5): Reaction of the support along RY.

ECR(6): Reaction of the support along RZ.

7.7 SOLID MATERIALS

7.7.1 LINE: Linear elasticity

Object:

This option enables materials with a linear elastic behaviour to be used.

Syntax:

```
"LINE"  ![ "RO" rho  "YOUN" young  "NU" nu
          <"IREP" irep>
          <"VISC" visc "KRAY" kray "MRAY" mray "KSIL" ksil > ]!  /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`irep`

Indicator of the internal forces output frame for POUT element: 0 for the global frame (default), 1 for the local frame.

`visc`

Viscosity coefficient (decay factor), used only by spectral elements (MS24, MS38) and finite elements of the following types: TRIA, CAR1, CAR4, CUBE, CUB6, CUB8, TETR, PR6, PRIS.

`mray, kray`

Rayleigh's mass and stiffness proportional damping coefficients, used only by finite elements of the following types: POUT, TUYA, DKT3, T3GS, Q4GS. Default values: kray=0, mray=0. For information about Rayleigh's damping see reference [953]. Coefficient ksil allows imposing a maximum reduced damping coefficient for short beam elements (POUT element only).

`LECTURE`

List of the elements concerned.

Comments:

This option may be repeated as many times as necessary.

Outputs:

The components of the ECR table are as follows:

Solid elements:

ECR(1): pressure

ECR(2): Von Mises criterion

Shells:

ECR(1): Von Mises criterion (membrane)

ECR(2): Von Mises criterion (membrane + bending)

Bars (BARR, PONC, BR3D):

ECR(1): elastic strain

ECR(2): Von Mises criterion

Beams (3D):

ECR(1): Von Mises criterion (bending)

ECR(2): Von Mises criterion (membrane + bending + torsion)

Internal forces output for POUT elt (global for IREP 0, local for IREP 1):
ECR(3): FX in 1st node
ECR(4): FY in 1st node
ECR(5): FZ in 1st node
ECR(6): MX in 1st node
ECR(7): MY in 1st node
ECR(8): MZ in 1st node
ECR(9): FX in 2nd node
ECR(10): FY in 2nd node
ECR(11): FZ in 2nd node
ECR(12): MX in 2nd node
ECR(13): MY in 2nd node
ECR(14): MZ in 2nd node

7.7.2 RESL: Nonlinear spring in the local reference frame

Object:

This directive allows to model a complex non-linear two-node spring, having arbitrary stiffness and damping values along the 3 dofs of the two concerned nodes. It may only be used in conjunction with RL3D elements (two-node spring). Stiffness and damping are given along local axes. The first local axe (xloc) is defined by the direction of the element that why the element must have a non-zero length. Second (yloc) and third (zloc) axes are defined by the user. The user gives the evolution curve of the reaction force generated by the spring as a function of the displacement or of the velocity.

It is possible to activate this element at a given time.

Syntax:

```
"RESL"
         <|[ "KL" kl ; "KT1" kt1 ; "KT2" kt2 ]|
             |[
                "NFKT" nufo1 ;
                "NFKL" nufokl "NFKS" nufoks
             ]| >
         <|[ "AL" al ; "AT1" at1 ; "AT2" at2 ]|
             |[
                "NFAT" nufo2 ;
                "NFAL" nufoal "NFAS" nufoas
             ]| >
         <|[ "VX" vx ; "VY" vy ; "VZ" vz ]|>
         < "TACT" >
         /LECTURE/
```

`kl, kt1, kt2`

Translational stiffnesses along the local axes: xloc, yloc, zloc.

`nufo1`

Index of the function associated with translational stiffnesses.

`nufokl, nufoks`

Indexes of the functions associated with longitudinal and transverse stiffnesses.

`al, at1, at2`

Translational dampings along the local axes.

`nufo2`

Index of the function associated with translational dampings.

`nufoal, nufoas`

Indexes of the functions associated with longitudinal and transverse dampings.

`vx, vy, vz`

Coordinates of the vector v. Projection of v on the "orthogonal to xloc" plane gives yloc.

`tact`

Time of the spring activation.

`/LECTURE/`

List of the concerned elements.

Comments:

The stiffnesses and the dampings are given along the local axes of the problem in the initial configuration. If a single function is specified for stifnesses (dampings), it applies to the 3 corresponding stiffnesses (dampings).

If a key-word is missing, the corresponding value is put to zero. The order in which the parameters are specified is irrelevant.

The reaction force generated by the spring has the form (e.g., assuming translation along the xloc axis):

$$F_x = k_x f_1(D_x) + a_x f_2(V_x)$$

If the displacement (or the velocity) is positive, the function f1 (or f2) must be negative in order to obtain a correct reaction.

If TACT is specified, the element is inactive (no internal force produced) until this time. The function defining stiffness is then adjusted to account for the displacements gained at TACT time.

Outputs:

The components of the ECR vector are:

ECR(1): Force in the spring along xloc.

ECR(2): Force in the spring along yloc.

ECR(3): Force in the spring along zloc.

7.7.3 GENERIC LINEAR ELASTICITY

Object:

This option enables materials with a linear elastic behaviour to be used. It is an interface to convert the input to the appropriate material (LINE 7.7.1, VM23 7.7.47) for the elements used.

Syntax:

```
"GLIN"  ![ "RO" rho  "YOUN" young  "NU" nu ]!  /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`LECTURE`

List of the elements concerned.

Outputs:

The output variables are according to the material in which the generic material is converted.

7.7.4 GENERIC PLASTICITY

Object:

This option enables materials with a linear elastic behaviour to be used. It is an interface to convert the input to the appropriate material (VMIS ISOT 7.7.9, VM23 7.7.47) for the elements used.

Syntax:

```
    "GPLA"  ![ "RO" rho  "YOUN" young  "NU" nu ]!  "ELAS" sige ...
        ...        "TRAC"  npts*( sig  eps )    /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`sige`

Elastic limit.

`"TRAC"`

This key-word introduces the yield curve.

`npts`

Number of points (except the origin) defining the yield curve.

`sig`

Stress.

`eps`

Total strain (elastic + plastic)

`LECTURE`

List of the elements concerned.

Outputs:

The output variables are according to the material in which the generic material is converted.

7.7.5 RESG: Nonlinear spring in the global reference frame

Object:

This directive allows to model a complex non-linear two-node spring having arbitrary stiffness and damping values along the 3 dofs of the two concerned nodes. It may only be used in conjunction with RL3D elements (two-node spring). The user gives the evolution curve of the reaction force generated by the spring as a function of the displacement or of the velocity.

Syntax:

```
"RESG"
        <|[ "KX" kx ; "KY" ky ; "KZ" kz ]| "NFKT" nufo1>
        <|[ "AX" ax ; "AY" ay ; "AZ" az ]| "NFAT" nufo2>
        <"ACON" acon>
        <|[ "VX" vx ; "VY" vy ; "VZ" vz ]|>
        /LECTURE/
```

`kx, ky, kz`

Translational stiffnesses along the global axes.

`nufo1`

Index of the function associated with translational stiffnesses.

`ax, ay, az`

Translational dampings along the global axes.

`nufo2`

Index of the function associated with translational dampings.

`acon`

If set to 1 (0 by default), translational dampings will only be activated if

$$|F_{x,int}| = |k_x f_1(D_x)| > 1\mathrm{E}^{-16}$$

`vx, vy, vz`

Allows to override the definition of the normal vector of the spring (computed from its nodes positions) and to enter a user-defined normal vector. Useful when the two nodes of the spring are coincident. If not specified, original approach based on nodes positions is used.

`/LECTURE/`

List of the concerned elements.

Comments:

The stiffnesses and the dampings are given along the global (fixed) axes of the problem. Each of the 2 associated functions applies to the 3 corresponding stiffnesses (or dampings).

If a key-word is missing, the corresponding value is put to zero. The order in which the parameters are specified is irrelevant.

The reaction force generated by the spring has the form (e.g., assuming translation along Ox):

$$F_x = k_x f_1(D_x) + a_x f_2(V_x)$$

If the displacement (or the velocity) is positive, the function f1 (or f2) must be negative in order to obtain a correct reaction.

Outputs:

The components of the ECR vector are:

ECR(1): Force in the support along X.

ECR(2): Force in the support along Y.

ECR(3): Force in the support along Z.

7.7.6 DRUCKER-PRAGER

Object:

This option enables to specify materials with a perfect elasto-plastic behaviour (Drucker-Prager criterion).

Syntax:

```
"DRUC"  "RO"  rho  "YOUNG"  young  "POISSON"  nu  ...
  ...  "TRACTION"  sigt  "COMPRESSION"  sigc  ...
  ...  < "FRACTURE"   pf  >   /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`sigt`

Maximum stress under tension (without confinement).

`sigc`

Maximum stress under compression (without confinement).

`FRACTURE pf`

The material is fractured (does no longer resist tension) as soon as the criterion is reached for the first time. Then, the domain changes and the new D.P. criterion corresponds to vanishing cohesion whereas the slope is equivalent to the one in the previous case. The parameter 'pf' is compulsory and represents the maximum pressure of fracturing under compression. If the criterion is reached for the first time when the pressure is superior to pf, the domain does not change and the criterion is the same as initially.

`/LECTURE/`

Numbers of the elements concerned.

Comments:

The values of sigt, sigc and pf are absolute values.

If P defines the pressure (positive under tension) and SIG* the Von Mises criterion, the Drucker-Prager criterion is defined by:

```
Criterion = SIG* - cohe + P * pente   ( always <= 0 )
```

The 2 parameters : cohe and pente (slope), are calculated from sigt and sigc values, they are printed after the reading of the data. The parameter cohe (cohesion) corresponds to a maximum Von Mises under non-existant pressure. The slope is the straight line limiting the domain, in the coordinate system (P,SIG*).

In the space of the principal stresses the criterion determines a cone the axis of which is the straight line of equation: sig(1)= sig(2) = sig(3).

The maximum stresses: sigt and sigc correspond to the values observed during uniaxial tests without confinement. These two points enable the Drucker-Prager domain to be defined.

The value of the parameter "FRACTURE" enables the behaviour of concrete to be represented in a very simplified way. Two domains may be distinguished:

- Brittle rupture
- Ductile rupture (strong compressions)

Most often one may take pf = sigc/3. A great value for pf delay the fracturation.

Outputs:

The different components of the ECR table are as follows:

ECR(1): pressure

ECR(2): Von Mises

ECR(3): equivalent plastic strain

ECR(4): D.P. criterion (always <= 0)

ECR(5): cohesion (becomes non-existant in the case of brittle rupture)

7.7.7 TELA: Thermoelastic linear material

Object:

This directive allows modeling thermoelastic behavior of BR3D elements.

Syntax:

```
"TELA"  ![ "RO" rho  "YOUN" young  "NU" nu
           "ALPH" alph "DELT" delt  ]!  /LECTURE/
```

`rho`

Density of the material

`young`

Young's modulus

`nu`

Poisson's ratio

`alph`

Thermal expansion coefficient

`delt`

Temperature variation: delta T = T-T0

`LECTURE`

List of the elements concerned

Outputs:

The components of the ECR table are:

ECR(1): elastic strain

ECR(2): Von Mises criterion

7.7.8 EPCO: Nonlinear elastic-plastic spring with contact

Object:

This directive allows to model a complex non-linear two-node spring having an elastic-plastic response in compression and a unilateral contact behavior in tension. It uses force-displacement relationship. It may only be used in conjunction with CB40 element to represent a nonlinear stopper device.

Syntax:

```
"EPCO"
        <"GAP" gap>   <"TACT" tact>
        "FCOM" fcom
        "DIRE" vx vy vz
        /LECTURE/
```

`gap`

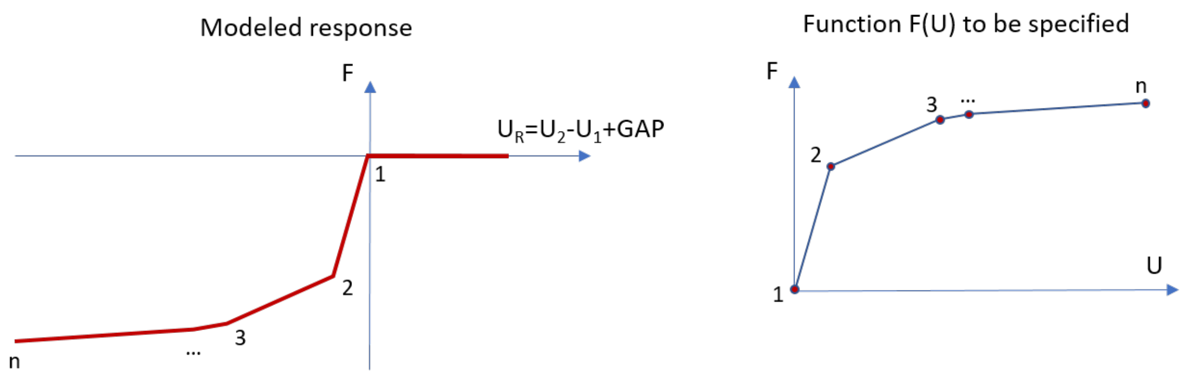
Initial gap (optional key-word, default value is 0).

`tact`

Activation time (optional key-word, default value is 0). For t less than tact, no reaction force is produced.

`fcom`

Number of the function defining the behavior in compression only. It is possible to give a 2-point function to model an elastic behavior. For elastic-plastic behavior one must define at least 3-point function. Positive values must be given as shown below:



`vx,vy,vz`

Components of the vector indicating the direction of the element (from node1 that must be fixed to node2 which is moving).

`/LECTURE/` List of the concerned elements.

Outputs:

The components of the ECR vector are:

ECR(1): Current elastic limit force.

ECR(2): Irreversible displacement cumulated.

ECR(3): Force in the element along the element direction.

ECR(4): FX component of the internal force.

ECR(5): FY component of the internal force.

ECR(6): FZ component of the internal force.

7.7.9 VMIS: Von Mises material

Object:

This sub-directive enables materials with an elasto-plastic behaviour to be used. There are four options:

- "VMIS" "PARF" : perfectly plastic Von Mises material;

- "VMIS" "ISOT" : isotropic Von Mises material;

- "VMIS" "DYNA" : isotropic Von Mises material depending on strain rate;

- "VMIS" "TETA" : isotropic Von Mises material depending on temperature.

Syntax:

```
"VMIS"
      $[
          "PARF" . . . ;
          "ISOT" . . .
          "DYNA" . . .
          "TETA" . . .
      ]$
```

Comments:

This sub-instruction may be repeated as many times as necessary with different options each time (if need be). The word "VMIS" cannot be separated from the option which follows.

PERFECTLY PLASTIC VON MISES

Object:

Perfectly plastic Von Mises material.

Syntax:

```
"VMIS"  "PARF"  "RO" rho  "YOUN" young  "NU" nu  "ELAS" sige   ...
         ...  /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`sige`

Elastic limit.

`ncrit`

`LECTURE`

List of the elements concerned.

Comments:

The law of behaviour is described by the following diagram of stresses and strains:

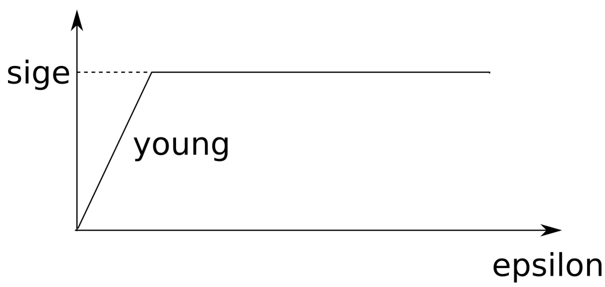


Figure 4: VMIS - stress-strain relation

Outputs:

The components of the ECR table are as follows:

Solid elements:

ECR(1): pressure
ECR(2): Von Mises criterion
ECR(3): plastic strain

Shells integrated through the thickness:

ECR(1): pressure
ECR(2): Von Mises criterion
ECR(3): plastic strain

Global model shells:

ECR(1): Von Mises criterion (membrane)
ECR(2): Von Mises criterion (membrane + bending)
ECR(3): plastic strain

Bars (BARR, PONC, BR3D):

ECR(1): elastic strain
ECR(2): Von Mises criterion
ECR(3): plastic strain

ISOTROPIC VON MISES

Object:

Isotropic Von Mises material.

Syntax:

```
    "VMIS" "ISOT" "RO" rho  "YOUN" young  "NU" nu  "ELAS" sige ...
              <"VISC" visc "KRAY" kray "MRAY" mray "KSIL" ksil > ]!  /LECTURE/
              <"IREP" irep>
              <FAIL fail LIMI limi>
        ...   "TRAC"  npts*( sig  eps )    /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`sige`

Elastic limit.

`mray, kray`

Rayleigh's mass and stiffness proportional damping coefficients, used only by finite elements of the following types: POUT. Default values: kray=0, mray=0. For information about Rayleigh's damping see reference [953]. Coefficient ksil allows imposing a maximum reduced damping coefficient for short beam elements (POUT element only).

`irep`

Indicator of the internal forces output frame for POUT element: 0 for the global frame (default), 1 for the local frame.

`FAIL`

Optional keyword: introduces an element failure model represented by a failure criterion and a by failure limit value. Two failure criteria only available for POUT and bar (BR3D, BARR, PONC) elements are:

fail = 1 for a criterion based upon Von Mises stress (membrane + bending + torsion),

fail = 2 for a criterion based upon plastic strain.

`limi`

Optional parameter, indicates the failure limit for the chosen criterion.

`"TRAC"`

This key-word introduces the yield curve.

`npts`

Number of points (except the origin) defining the yield curve.

`sig`

Stress.

`eps`

Total strain (elastic + plastic).

`/LECTURE/`

List of the elements concerned.

Comments:

1/ - The young parameter defines Young's modulus during an elastic phase.

2/ - The points (sig,eps) may have any position; however, concerning the first point, there must be a compatibility between the coordinates, Young's modulus and the elastic limit.

Outputs:

The components of the ECR table are as follows:

Solid elements

ECR(1): pressure
ECR(2): Von Mises criterion
ECR(3): plastic strain
ECR(7): new elastic limit

Shells integrated through the thickness:

ECR(1): pressure
ECR(2): Von Mises criterion
ECR(3): plastic strain
ECR(7): new elastic limit

Global model shells:

ECR(1): Von Mises criterion (membrane)
ECR(2): Von Mises criterion (membrane + bending)
ECR(3): plastic strain
ECR(7): new elastic limit

Beams (3D):

ECR(1): Von Mises criterion (bending)
ECR(2): Von Mises criterion (membrane + bending + torsion)
ECR(3): plastic strain
ECR(7): new elastic limit
ECR(10): failure flag (0=virgin Gauss Point, 1=failed Gauss Point)

Internal forces output for POUT elt (global for IREP 0, local for IREP 1):
ECR(11): FX in 1st node
ECR(12): FY in 1st node
ECR(13): FZ in 1st node
ECR(14): MX in 1st node
ECR(15): MY in 1st node
ECR(16): MZ in 1st node
ECR(17): FX in 2nd node
ECR(18): FY in 2nd node
ECR(19): FZ in 2nd node
ECR(20): MX in 2nd node
ECR(21): MY in 2nd node
ECR(22): MZ in 2nd node

Bars (BARR, PONC, BR3D):

ECR(1): elastic strain
ECR(2): Von Mises criterion
ECR(3): plastic strain
ECR(7): new elastic limit ECR(10): failure flag (0=virgin Gauss Point, 1=failed Gauss Point)

DYNAMIC VON MISES

Object:

Isotropic Von Mises material depending on strain rate.

Syntax:

```
"VMIS"  "DYNA"  "RO" rho  "YOUN" young  "NU" nu  <"EPMX" epmx> ...
   ...  "TRAC"  npts*( sig  eps )  ...

   ...   $[ "SYMO"  "D" d   "P" p             ;
            "ISPR" "VITE"  a  b  c  d  e  f    ;
            "LIBR"  num  "PARA"  /LECPARA/     :
            "ARMA" "ALFAY" alfay "ALFAU" alfau
            <"FAIL" nfail "LIMI" limi >        ]$   /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`epmx`

Optional parameter, allows the specification of a maximum strain rate, above which the law is saturated. The strain rate coefficient is then computed with this maximum value. It can be useful if the strain rate exceeds the validity range of the law and a conservative approach is desired.

`"TRAC"`

This key-word introduces the yield curve.

`npts`

Number of points (except the origin) defining the yield curve (in the case of the ARMA model only 3 points should be used : the yield point, the onset of hardening and the ultimate point before softening. Yield curve is defined analytically thanks to the assumption that it is a portion of parabola beginning at the onset of hardening and reaching a maximum at the ultimate point).

`sig`

Stress

`eps`

Total strain (elastic + plastic).

`"SYMO"`

Constitutive relation of Symonds and Cowper.

`d`

First coefficient of the Symonds and Cowper law.

`p`

Second coefficient of the Symonds and Cowper law.

`"VITE"`

This key-word introduces the parameters of the dynamic yield curve.

`a,b,c,d,e,f`

The 6 parameters of the dynamic yield curve.

`"LIBRE"`

Introduces the utilisation of a user's subroutine to compute the dynamic amplification coefficient.

`num`

Identification number of the free material.

`"PARA"`

Keyword that can be used to introduce a series of parameters for the free material. The number of parameters is arbitrary, because the /LECTURE/ procedure signals the termination of the list.

`"ARMA"`

This key-word introduces the parameters of the dynamic yield curve for steel reinforcing bars.

`alfay`

Coefficient to obtain the DIF for the yield stress.

`alfau`

Coefficient to obtain the DIF for the ultimate stress.

`FAIL`

Optional keyword: introduces an element failure model represented by a failure criterion and a by failure limit value. Two failure criteria only available for POUT and bar (BR3D, BARR) elements are:

fail = 1 for a criterion based upon Von Mises stress (membrane + bending + torsion),

fail = 2 for a criterion based upon plastic strain.

`limi`

Optional parameter, indicates the failure limit for the chosen criterion.

`/LECTURE/`

List of the elements concerned.

Comments:

For the Symonds and Cowper law, the dynamic traction curve is derived from the static one through a multiplicative coefficient which depends upon the strain rate (EPSP):

```
SIG(dyna) = SIG(stat) * ( 1 + ( EPSP / D ) ** (1/P) )
```

Indicatively, for the stainless steel 304 L, experimental results suggest: D = 100 s-1 and P = 10 (Forrestal and Sagartz 1978). For ordinary steel, it is usually assumed: D = 40 s-1 and P = 5 (Symonds 1965).

For titanium TI-50A, the values suggested are: D = 120 s-1 and P = 9 (Symonds et Chon 1974).

For aluminum alloys, some authors use D = 6500 s-1 and P = 4 (Symonds 1965).

In the case of the ISPRA law, the formulation is similar, but the multiplying coefficient depends upon the strain (EPS) as well as on the strain rate (EPSP):

```
SIG(dyna) = SIG(stat) * ( 1 + ( EPSP / K ) **M )
```

with the K and M coefficients of the form:

```
K = EXP( ( A + B * EPS ) / ( 1 + C * EPS ) )
M =      ( D + E * EPS ) / ( 1 + F * EPS )
```

Examples of data (source ISPRA-CADARACHE):

Material	a	b	c	d	e	f
Steel 304	5.82	168.76	9.62	0.242	2.263	12.77
Steel 316	6.388	86.215	6.457	0.233	0.0	0.0

For the ARMA model, the dynamic yield curve is obtained as follows:
The dynamic increase factor for the yield stress is given by:

```
SIG_Y(dyna) = SIG_Y(stat) * DIF_Y
DIF_Y = ( EPSP/ 10-4 ) ** ALFAY
```

The dynamic increase factor for the ultimate stress is given by:

```
SIG_U(dyna) = SIG_U(stat) * DIF_U
DIF_U = ( EPSP / 10-4 ) ** ALFAU
```

Then, the yield curve is defined analytically thanks to the assumption that it is a portion of parabola beginning at the onset of hardening and reaching a maximum at the ultimate point.

This model is suited for steel reinforcing bars, so it can be used only with bar and beam elements.

It is suggested in "Dynamic Increase Factors for Steel Reinforcing Bars, L. J. Malvar and J. E. Crawford, Twenty-Eighth DDESB Seminar, Orlando, Florida, USA, August 1998" that ALFAY and ALFAU can be estimated by the expressions:

```
ALFAY = 0.074 - ( 0.040 * fy / 414. )
ALFAU = 0.019 - ( 0.009 * fy / 414. )
```

where fy is the bar yield strength in MPa.

This formulation is valid for bars with yield stress between 290 and 710 MPa and for strain rates between 10^{-4} and 225 s^{-1}.

IMPORTANT POINT:

For all formulations, the strain rate EPSP is filtered with a first order low-pass filter:

```
dEPSP/dt=(EPSPC - EPSP)/tau
```

with EPSPC the current value of the strain rate and TAU the filter time constant:

```
TAU = 1 / ( 2 * pi * fc)
```

with fc the cutoff frequency of the filter.
By time integration, we obtains:

```
EPSP(n+1) = ( EPSP(n) + (DELTAT / TAU)*EPSPC(n+1) ) / ( 1 + (DELTAT / TAU) )
DELTAT = t(n+1) - t(n)
```

Furthermore, we supposed that:

```
BETA = DELTAT / TAU = Cte
```

and introduced FEPSP1:

```
FEPSP1 = BETA / (1 + BETA) = DELTAT / (DELTAT + TAU)
```

FEPSP1 is defined in OPTI FVIT.
Default value is 1, meaning TAU = 0, no filter is applied.
Advised value for FEPSP1 is 0.01.

Outputs:

The components of the ECR table are as follows:

Solid elements:

ECR (1): pressure
ECR (2): Von Mises criterion in dynamics
ECR (3): equivalent plastic strain
ECR (7): new elastic limit in statics
ECR (8): equivalent strain rate
ECR (9): total equivalent deformation
ECR(11): elastic limit in dynamics

Shells integrated through the thickness:

ECR (1): pressure
ECR (2): Von Mises criterion in dynamics
ECR (3): equivalent plastic strain
ECR (7): new elastic limit in statics
ECR (8): equivalent strain rate
ECR (9): total equivalent deformation
ECR(11): elastic limit in dynamics

Global model Shells:

ECR (1): Von Mises criterion (membrane)
ECR (2): global Von Mises criterion (membrane + bending)
ECR (3): equivalent plastic strain
ECR (7): new elastic limit
ECR (8): equivalent strain rate
ECR (9): total equivalent deformation
ECR(11): elastic limit in dynamics

Beams (3D) for ARMA only:

ECR(1): Von Mises criterion (bending)
ECR(2): Von Mises criterion (membrane + bending + torsion)
ECR(3): plastic strain
ECR(7): new elastic limit
ECR(10): failure flag (0=virgin Gauss Point, 1=failed Gauss Point)
ECR(11): elastic limit in dynamics

Bars (BARR, BR3D) for ARMA only:

ECR(1): elastic strain
ECR(2): Von Mises criterion
ECR(3): plastic strain
ECR(7): new elastic limit

ECR(10): failure flag (0=virgin Gauss Point, 1=failed Gauss Point)
ECR(11): elastic limit in dynamics

TEMPERATURE-DEPENDENT VON MISES

Object:

Von Mises isotropic material dependent upon the temperature.

Syntax:

```
"VMIS"  "TETA"  "RO" rho < "NU" nu >...
   ...  "NBCOURBE"  nc*( "TETA" ti "YOUNG" yg  <"NUT"> nut ...
   ...              "TRAC" npts*( sig eps ) ) /LECTURE/
```

`rho`

Density.

`nu`

Poisson coefficient. Only if NU does not depend on the temperature.

`nc`

Number of traction curves thet allow the interpolation as a function of temperature.

`ti`

Temperature associated with the following traction curve.

`yg`

Young's modulus.

`nut`

Poisson Poisson. If NU depend on temperature.

`"TRAC"`

Introduces the traction curve.

`npts`

Number of points (excluding the origin) which define the traction curve.

`sig`

Stress.

`eps`

Total strain (elastic + plastic).

`/LECTURE/`

List of the elements concerned.

Comments:

Each element is isothermal, i.e. its temperature remains constant during the whole calculation.

Depending upon temperature, the Young's modulus, the poisson coefficient and the traction curve are interpolated starting from the values associated to the known temperatures.

Note that it is possible to define either a temperature-dependant Poisson coefficient or not which can be sufficient in case of steels for example.

Outputs:

The components of the ECR table are as follows:

Continuum elements:

ECR(1) : pressure
ECR(2) : Von Mises criterion
ECR(3) : equivalent plastic strain

Shells integrated through the thickness:

ECR(1) : pressure
ECR(2) : Von Mises criterion
ECR(3) : equivalent plastic strain

Global model hells:

ECR(1) : Von Mises criterion (membrane)
ECR(2) : global Von Mises criterion (membrane + bending)
ECR(3) : equivalent plastic strain

7.7.10 KTRL: Linear beam behavior defined by a 12X12 symmetric stiffness matrix

Object:

This directive allows to model a linear elastic response of a beam defined by a 12x12 symmetric stiffness matrix. The coefficients of this matrix are given in the local reference frame of the beam element that must have a non-zero length. It may only be used in conjunction with RL6D elements.

Syntax:

```
"KTRL"
        <|[ "KVAL" kv ]|>
        <|[ "VX" vx ; "VY" vy ; "VZ" vz ]|>
        <|[ "MASP" mn ; "JTOR" jt ; "JFLY" jy ; "JFLZ" jz ]|>
        <|[ "KAMO" kamo ]|>
        /LECTURE/
```

`kv`

78 values of the upper triangle of the stiffness matrix, line by line:

EA/L	0	0	0	0	0	$-EA/L$	0	0	0	0	0
	$12EI_{zz}/L^3$	0	0	0	$6EI_{zz}/L^2$	0	$-12EI_{zz}/L^3$	0	0	0	$6EI_{zz}/L^2$
		$12EI_{yy}/L^3$	0	$-6EI_{yy}/L^2$	0	0	0	$-12EI_{yy}/L^3$	0	$-6EI_{yy}/L^2$	0
			GJ/L	0	0	0	0	0	$-GJ/L$	0	0
				$4EI_{yy}/L$	0	0	0	$6EI_{yy}/L^2$	0	$2EI_{yy}/L$	0
					$4EI_{zz}/L$	0	$-6EI_{zz}/L^2$	0	0	0	$2EI_{zz}/L$
						EA/L	0	0	0	0	0
							$12EI_{zz}/L^3$	0	0	0	$-6EI_{zz}/L^2$
								$12EI_{yy}/L^3$	0	$6EI_{yy}/L^2$	0
									GJ/L	0	0
										$4EI_{yy}/L$	0
											$4EI_{zz}/L$

`vx, vy, vz`

Coordinates of the vector v used as the second direction for the local reference frame

`mn`

Mass of the element

`jt, jy, jz`

Moments of inertia (J, Iyy, Izz) around x, y and z local axes

`kamo`

Damping coefficient for stiffness proportional damping

`/LECTURE/`

List of the concerned elements.

Comments:

The stiffnesses are given in a local reference frame whose first direction is defined by the element direction in the initial configuration. This direction is updated in the calculation to account for the element rotations.

Outputs:

The components of the ECR vector are:

ECR(1): Axial force Fx in the local frame

ECR(2): Shear force Fy in the local frame

ECR(3): Shear force Fz in the local frame

ECR(4): Torsional moment Mx in the local frame

ECR(5): Bending moment My in the local frame

ECR(6): Bending moment Mz in the local frame

7.7.11 STEINBERG-GUINAN

Object:

This is a Von Mises isotropic material whose Young's modulus and elastic limit are a function of hydrostatic pressure, temperature increase and strain rate.

Syntax:

```
"STGN"  "RO"  rhoz   "YOUN"  youngz  "NU"    nu      ...
   ...  "SIGE" sigez "SIGD"  sigd    "CHSP"  cv      ...
   ...  "TF"  tfus   "TINI"  tini    "B"      b      ...
   ...  "H" h        "BETA"  beta    "N"      n    /LECTURE/
```

`rhoz`

Density at the initial temperature.

`youngz`

Young's modulus at the initial temperature.

`nu`

Poisson coefficient (constant).

`sigez`

Static elastic limit at the initial temperature.

`sigd`

Dynamic elastic limit at the initial temperature.

`cv`

Specific heat capacity of the solid.

`tfus`

Melting temperature of the material.

`tini`

Initial temperature of the material.

`b,h,beta,n`

Coefficients of the STEINBERG and GUINAN law.

`/LECTURE/`

List of the elements concerned.

Comments:

The STEINBERG and GUINAN law uses the Young's modulus E, and an elastic limit Y, which vary according to the following expressions:

```
E = youngz * P1

Y = yield * P1
```

with:

```
P1 = 1 + b*P / K**(1/3) + h*dteta

yield  = MIN ( sigd , sigez*P2 )

P2 = ( 1+beta*EPSP )**n
```

where:

P is the hydrostatic pressure;

K is the compression ratio (ratio between the current density and the initial density);

EPSP is the total equivalent strain rate;

dteta is the temperature increase with respect to the initial temperature.

On the other hand, when the current temperature (teta = tini + dteta) exceeds the melting temperature of the material (tfus), it is assumed that the material is liquefied: the Young's modulus and the elastic limit are then taken as zero.

Outputs:

The various components of the ECR table are as follows:

ECR(1) : hydrostatic pressure

ECR(2) : Von Mises

ECR(3) : equivalent plastic strain

ECR(4) : temperature increase (dteta)

ECR(5) : current elastic limit

ECR(6) : current Young's modulus

ECR(7) : eauivalent plastic strain rate

7.7.12 VON MISES ORTHOTROPIC GRID MODEL

Object:

This orthotropic, perfect Von-Mises model allows to assign a grid behavior to a shell element. It is typically used to model steel reinforcement in concrete panels. The first orthotropic direction is declared in COMP ORTS directive.

Syntax:

```
"VMGR"  "RO" rho  "OM1" om1  "YG1" yg1 "SP1" sp1
                  "OM2" om2  "YG2" yg2 "SP2" sp2
   ...  /LECTURE/
```

`rho`

Density of the reinforcement material.

`om1`

Reinforcement ratio in the first orthotropic direction.

`yg1`

Young's modulus of the reinforcement material the first orthotropic direction.

`sp1`

Elastic limit of the reinforcement material in the first orthotropic direction.

`om2`

Reinforcement ratio in the second orthotropic direction.

`yg2`

Young's modulus of the reinforcement material in the second orthotropic direction.

`sp2`

Elastic limit of the reinforcement material in the second orthotropic direction.

`LECTURE`

List of the elements concerned.

Comments:

This law is available with or without layers (SANDWICH directive).

Outputs:

The components of the ECR table are as follows:

ECR(1): current plastic strain in the first orthotropic direction

ECR(2): current plastic strain in the second orthotropic direction

ECR(3): current grid stress in the first orthotropic direction (averaged shell stress divided by om1)

ECR(4): current grid stress in the second orthotropic direction (averaged shell stress divided by om2)

ECR(5): angle between local shell system and orthotropic system

IMPORTANT POINT:

With VMGR material, the stress CONT corresponds to an averaged stress over element width and layer thickness, while ECR(3-4) provide the actual stresses within reinforcement bars.

For this reason, to avoid confusion, it is strongly advised to specify a layer thickness fraction equal to the reinforcement ratio, so that the above quantities can coincide.

7.7.13 LEM1

Object :

This directive allows to describe the behaviour of an elasto-plastic material that may undergo some damage, according to the Lemaitre model. There is coupling between damage and plasticity, represented by the Von Mises criterion. The damage evolution rate is a function of the triaxiality ratio of stresses and of the equivalent plastic strain rate. A failure criterion is implicitly contained within the model: rupture occurs when the damage exceeds a critical value. Two optional parameters allow to introduce a limitation of the damage rate (thanks to the delayed damage model) in order to avoid the mesh dependency.

Syntax:

```
"LEM1"  "RO" rho "YOUN" young "NU" nu  "ELAS" sige ...
        "EPSD" epsd  "S0" s0  "DC" dc ...
        <"CSTA" csta "TAUC" tauc "NOCO" noco> ...
        "TRAC"  npts*( sig  eps )   /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's coefficient.

`sige`

Elastic limit.

`epsd`

Damage threshold (i.e. equivalent plastic strain, weighted by a function of stress triaxiality, within which damage vanishes).

`s0`

Parameter driving the damage evolution rate.

`dc`

Critical damage defining the failure criterion.

`csta`

Parameter of the delayed damage model

`tauc`

Characteristic time of the delayed damage model. (1/tauc) represents the maximum damage rate.

`noco`

Optional parameter indicating what to do when no convergence is reached in the material routine. The value 0 is the default and means that an error message is issued and the calculation is stopped. The value 1 indicates that the element (or more precisely, the element's current Gauss point) is made to fail (eroded). The value -1 indicates that subcycling is activated in an attempt to reach convergence, by subdividing the load step into smaller sub-cycles.

`"TRAC"`

Introduces the traction curve.

`npts`

Number of points (except the origin) defining the traction curve.

`sig`

Stress.

`eps`

Total strain (elastic + plastic).

`LECTURE`

List of concerned elements.

Comments:

A detailed description of the model can be found in the report DMT/98-026A, available on request.

Outputs:

The components of the ECR table are as follows for **Continuum elements**:

ECR(1) : pressure

ECR(2) : Von Mises criterion

ECR(3) : equivalent plastic strain

ECR(4) : plasticity multiplier

ECR(5) : damage

ECR(7) : new elastic limit

When the "erosion" algorithm is activated (see page A.30, Section 4.4, keyword `EROS`), an integration point is considered as failed if `damage >= dc`. It will be eroded concerning the rules for EROS.

7.7.14 ZALM

Object :

This directive allows to describe the behaviour of an Zirelli-Armstrong material that may undego some damage, according to the Lemaitre model. There is coupling between damage and plasticity, represented by the Von Mises criterion. The damage evolution rate is a function of the triaxiality ratio of stresses and of the equivalent plastic strain rate. A failure criterion is impicitly contained within the model: rupture occurs when the damage exceeds a critical value. Two optional parameters allow to introduce a limitation of the damage rate (thanks to the delayed damage model) in order to avoid the mesh dependency.

Syntax:

```
"ZALM"  "RO" rho "YOUN" young "NU" nu  "ELAS" sige ...
        "EPSD" epsd  "S0" s0  "DC" dc ...
        "ZAC0" zac0 "ZAC1" zac1 "ZAC2" zac2 "ZAC3" zac3 ...
        "ZAC4" zac4 "ZAC5" zac5 "ZAN" zan ...
        <"CSTA" csta "TAUC" tauc> ...
        "TRAC"  npts*( sig  eps )   /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's coefficient.

`sige`

Elastic limit.

`epsd`

Damage threshold (i.e. equivalent plastic strain, weighted by a function of stress triaxiality, within which damage vanishes).

`s0`

Parameter driving the damage evolution rate.

`dc`

Critical damage defining the rupture criterion.

`csta`

Parameter of the delayed damage model

`zac0`

Parameter of zerilli-armstrong model c0

`zac1`

Parameter of zerilli-armstrong model c1

`zac2`

Parameter of zerilli-armstrong model c2

`zac3`

Parameter of zerilli-armstrong model c3

`zac4`

Parameter of zerilli-armstrong model c4

`zac5`

Parameter of zerilli-armstrong model c5

`zan`

Parameter of zerilli-armstrong model n

`tauc`

Characteristic time of the delayed damage model. (1/tauc) represents the maximum damage rate.

`"TRAC"`

Introduces the traction curve.

`npts`

Number of points (except the origin) defining the traction curve.

`sig`

Stress.

`eps`

Total strain (elastic + plastic).

`LECTURE`

List of concerned elements.

Outputs:

The components ov the ECR table are as follows for **Continuum elements**:

ECR(1) : pressure

ECR(2) : Von Mises criterion

ECR(3) : equivalent plastic strain

ECR(4) : plasticity multiplier

ECR(5) : damage

ECR(7) : new elastic limit

When the "erosion" algorithm is activated (see page A.30, Section 4.4, keyword `FAIL`), an element is considered as failed if `damage >= dc`.

7.7.15 LMC2

Object:

This directive allows to describe the behaviour of an elasto-plastic material that may undergo some damage, according to the Lemaitre-Chaboche model. There is coupling between damage and plasticity, represented by the Von Mises criterion. The damage evolution rate is a function of the triaxiality ratio of stresses and of the equivalent plastic strain rate. A failure criterion is implicitly contained within the model: rupture occurs when the damage exceeds a critical value. Unlike model LEM1, the material properties may depend upon the strain rate. Two optional parameters allow to introduce a limitation of the damage rate (thanks to the delayed damage model) in order to avoid the mesh dependency

Syntax:

```
   "LMC2"  "RO" rho ...
           "YOUN" young < "FONC" nfyou ...
                 $[ "TABL" nptyou*( para vyou ) ; "ROUT" ; "DONE" ]$ > ...
           "NU" nu      < "FONC" nfnu  ...
                 $[ "TABL"  nptnu*( para vnu  ) ; "ROUT" ; "DONE" ]$ > ...
           "ELAS" sige  < "FONC" nfela ...
                 $[ "TABL" nptela*( para vela ) ; "ROUT" ; "DONE" ]$ > ...
           "EPSD" epsd  < "FONC" nfepd ...
                 $[ "TABL" nptepd*( para vepd ) ; "ROUT" ; "DONE" ]$ > ...
           "S0" s0      < "FONC" nfs0  ...
                 $[ "TABL"  npts0*( para vs0  ) ; "ROUT" ; "DONE" ]$ > ...
           "DC" dc      < "FONC" nfdc  ...
                 $[ "TABL"  nptdc*( para vdc  ) ; "ROUT" ; "DONE" ]$ > ...
           <"CSTA" csta "TAUC" tauc> ...

If the traction curve is given by a table:
           "TRAC" ctra "FTRA" nftra ...
                 $ "TABL" npt*( sig eps ) ; "ROUT" ; "DONE" $ ...

If the traction curve is given by an abaque:
           "TRAC" ctra "ATRA" natra $ "SET" npara ...
                  "NPTM" nptm*( "PARA" para "TABL" npt*( sig eps )); ...
                  "DONE" $ ...

          /LECTURE/
```

`rho`

Density.

`young`

Young's modulus if it is constant or multiplicative coefficient of Young's modulus if it is defined by a function.

`nfyou`

Number of the function defining the variation of the Young's modulus with the strain rate.

`nptyou`

Number of point defining the variation of the Young's modulus with the strain rate.

`para`

Parameter (here the strain rate).

`vyou`

Value of the Young's modulus corresponding to the parameter.

`nu`

Poisson's coefficient if it is constant or multiplicative coefficient of Poisson's coefficient if it is defined by a function.

`nfnu`

Number of the function defining the variation of the Poisson's coefficient with the strain rate.

`nptnu`

Number of point defining the variation of the Poisson's coefficient with the strain rate.

`vnu`

Value of the Poisson's coefficient corresponding to the parameter.

`sige`

Elastic limit if it is constant or multiplicative coefficient of the elastic limit if it is defined by a function.

`nfela`

Number of the function defining the variation of the elastic limit with the strain rate.

`nptela`

Number of point defining the variation of the elastic limit with the strain rate.

`vela`

Value of the elastic limit corresponding to the parameter.

`epsd`

Damage threshold (i.e. equivalent plastic strain, weighted by a function of traixiality rate of stresses, below which the damage is zero) if it is constant or multiplicative coefficient of the damage threshold if it is defined by a function.

`nfepd`

Number of the function defining the variation of the damage threshold with the strain rate.

`nptepd`

Number of point defining the variation of the damage threshold with the strain rate.

`vepd`

Value of the damage threshold corresponding to the parameter.

`s0`

Parameter driving the evolution rate of damage if it is constant or multiplicative coefficient of the parameter driving the evolution rate of damage if it is defined by a function.

`nfs0`

Number of the function defining the variation of the parameter driving the evolution rate of damage with the strain rate.

`npts0`

Number of point defining the variation of the parameter driving the evolution rate of damage with the strain rate.

`vs0`

Value of the dparameter driving the evolution rate of damage corresponding to the parameter.

`dc`

Critical damage defining the rupture criterion if it is constant or multiplicative coefficient of critical damage if it is defined by a function.

`nfdc`

Number of the function defining the variation of the critical damage with the strain rate.

`nptdc`

Number of point defining the variation of the critical damage with the strain rate.

`vdc`

Value of the critical damage corresponding to the parameter.

`csta`

Parameter of the delayed damage model

`tauc`

Characteristic time of the delayed damage model. (1/tauc) represents the maximum damage rate.

`"TRAC"`

Introduces the traction curve.

`ctra`

Multiplicative coefficient of the stress in the traction curve or curves.

`"FTRA"`

Introduces the single traction curve for all strain rates.

`nftra`

Number of the function defining the traction curve.

`npt`

Number of point (except the origin) defining the traction curve.
item[`sig`]

Stress. item[`eps`]

Strain (elastic+plastic).

`"ATRA"`

Introduces an abaque giving the traction curve for different strain rates.

`natra`

Number of the abaque defining the traction curves.

`npara`

Number of the set of parametrised functions that associate to each strain rate the corresponding traction curve.

`nptm`

Maximum number of point (except the origin) definig the traction curve amongst the set of parametrised functions.

`LECTURE`

List of the concerned elements.

Comments:

In the case of traction curve, parametrised or not, the origin is always omitted.

If both the Young's modulus and the traction curve are parametrised, the strain rate parameter should be identical.

Dans le cas de la courbe de traction parametree, il faudra fournir les vitesses de deformation de maniere croissante.

In the case of a component dependent upon strain rate, it is mandatory to give its value for a zero velocity (static case) and for a very large velocity.

A detailed description of the model may be found in the report DMT/98-036A, available on request.

Outputs:

The components of the ECR table are as follows for **Continuum elements** :

ECR(1) : pressure

ECR(2) : Von Mises criterion

ECR(3) : equivalent plastic strain

ECR(4) : plasticity multiplier

ECR(5) : damage

ECR(7) : new elastic limit

ECR(8) : strain rate

ECR(11): `= 1` critical damage reached, otherwise `< 1`

When the "erosion" algorithm is activated (see page A.30, Section 4.4, keyword `FAIL`), an element is considered as failed if `ECR(11) > 0.99`.

7.7.16 CONCRETE: Old version

Object:

This option is used to define materials such as concrete, soil, rock, etc.

Comments:

The law of behaviour used in this model is based on plasticity; it takes into account three modes of damaging the material:

1) Damage due to traction;

2) Damage due to shear;

3) Damage due to hydrostatic pressure.

A material of this type possesses 38 input parameters; however, only some of them are compulsory. Each parameter is entered into the input file by means of a key-word, these words can be entered in any order. Just remember that the data placed between angle brackets are not compulsory, for example: <"PREC" prec>.

The numerical values of the different parameter are entered in absolute value. Moreover the following conventions have been adopted for the outputs:

positive values: tension stresses;

negative values: compression stresses.

The option "BETON" can be repeated as many times as necessary.

Syntax:

The data can be classified in 4 groups.

- 1) Generic data

```
 "BETON"  "RO" rho  "YOUN" young  "NU" nu
             < "ALPH" alph >  < "PREC" prec >
```

`rho`

Density of the material.

`young`

Elasticity modulus.

`nu`

Poisson's ratio.

`alpha`

Coefficient of thermal expansion.

`prec`

Precision of the computation on the internal iterations.

- 2) Data concerning the damage due to traction:

This kind of damage occurs in 3 phases:

- a) elastic behaviour;
- b) cracked elastic behaviour;
- c) perfectly plastic behaviour.

```
          A           .           .
     sig  |<--- a --->.<--- b --->.<----- c -----
          |           .           .
      ltr |...........*           .
          |          * *          .
          |         *   *         .
          |        *     *        .
          |       *       *       .
          |      *         *      .
          |     *         * *     .
          |    *         *   *    .
          |   *         *     *   .
          |  *         *       *  .
          | *         *         * .
          |*         *           *.
        O .------------------------------------------>  eps
                                eptr
```

```
    < "BETA"  cisail >

  * initially isotropic material:
```

```
      "LTR"  ltr
      "EPTR" eptr

  * initially anisotropic material:

    < "IFIS" ifis >

    < "LT1"  lt1  >  < "LT2"  lt2  >  < "LT3"  lt3   >
    < "EPT1" ept1 >  < "EPT2" ept2 >  < "EPT3" ept3  >

    < "OUV1" ouv1 >  < "OUV2" ouv2 >  < "OUV3" ouv3  >

    < "ANGL" angle >  or  < "V1X" v1x    "V1Y" v1y    "V1Z" v1z >
                          < "V2X" v2x    "V2Y" v2y    "V2Z" v2z >
                          < "V3X" v3x    "V3Y" v3y    "V3Z" v3z >
```

`cisail`

Value of residual shear after cracking, in comparison with the initial status (value between 0 and 1).

`ltr`

Limit in traction in the case of an initially isotropic material.

`eptr`

Rupture strain in the case of an initially isotropic material.

`ifis`

Cracking index (0: no cracking, 1: one crack only, 2: two cracks, 3: three cracks).

`lt1, lt2, lt3`

Traction limits along the directions 1, 2 and 3 in the case of an initially anisotropic material.

`ept1, ept2, ept3`

Rupture strains along the directions 1, 2 and 3 in the case of an initially anisotropic material.

`ouv1, ouv2, ouv3`

Opening of the cracks along the directions 1, 2 and 3 in the case of an initially cracked material (deformations).

`angle`

Crack angle in the (X-Y) plane, in degrees, in the case of a plane stress analysis.

`v1x,v1y,v1z`

Components of the vector defining direction 1.

`v2x,v2y,v2z`

Components of the vector defining direction 2.

`v3x,v3y,v3z`

Components of the vector defining direction 3.

The model takes into account the anisotropy induced by the cracking.

The opening and closing of cracks is managed by the model.

For an axisymmetric or three-dimensional analysis, the user can enter different characteristics for the three directions.

In the case of an initially cracked material, one can input the opening of cracks by means of initial deformations along the cracked direction.

- 3) Data relative to shear damage:

Triaxial tests, carried out at different confinement levels, are necessary to determine the various parameters of the model. The results are then linearized and entered onto the diagram (sig1-sig3, eps1). The user may distinguish two different domains:

- a) brittle behaviour corresponding to the confinement levels, i.e. low sig3. This behaviour can be schematized by a decreasing branch and a negative work-hardening.
- b) ductile behaviour corresponding to the high confinement levels, i.e. high sig3. They can be schematized by a decrease in the elastic modulus and the appearance of irreversible strains and work-hardening.

Hence, the existence of a threshold stress of confinement, sig3, has been assumed. It corresponds to the border between the two domains: sig3 = PCT.

```
            A
  sig1-sig3 |
            |
    lcd-pcd |. . . . . . . . *--------------------
            |             *  .
            |          *     .
    lct-pct |. . . .*--------------------------
            |      *         .
            |     *          .
            |    *           .
        lcs | . *            .
            |  * *           .
            | *   *          .
            |*     *         .
          0 .---------------------------------------->  eps1
                   epcs      epcd
```

```
      "LCS" lcs   "EPCS" epcs

    < "LBIC" lbic >  or  < "LCT" lct   "PCT" pct >
                         < "LCD" lcd   "PCD"  pcd   "EPCD" epcd  >
```

`lcs`

Uniaxial compression limit.

`epcs`

Strain at rupture in uniaxial compression.

`lbic`

Limit in biaxial compression in the case of a plane stress analysis.

`lct`

Compression limit under a confinement pressure equal to the threshold confinement value (sig3).

`pct`

Threshold confinement pressure.

`lcd`

Compression limit under the pressure of ductile confinement.

`pcd`

Pressure of ductile confinement.

`epcd`

Strain corresponding to the beginning of the perfectly plastic behaviour in the ductile domain.

- 4) Data relative to damage due to hydrostatic pressure:

A test is carried out where the sample is submitted to a hydrostatic pressure. The results are then linearized and entered onto the diagram: (P, Dv/v)

```
           A
        P  |
           |                      *
           |                  *
           |              *
           |          *   pente
     lph   |. . .*. . . . . . . . . . .
           |    *
```

```
          |   *
          |  *
          | *
          |*
        O .---------------------------------------->   Dv/v
```

```
    "LPH" lph   "PENT" pente
```

`lph`

Limit under hydrostatic pressure.

`pente`

Slope of the plastic branch on the diagram.

Outputs:

The different components of the ECR table are as follows:

ECR(1): hydrostatic pressure

ECR(2): Von Mises criterion

ECR(3): equivalent plastic strain

ECR(4): crack angle in the (X-Y) plane (in degrees)

ECR(5): yield limit in traction along direction 1

ECR(6): yield limit in traction along direction 2

ECR(7): yield limit in traction along direction 3

ECR(8): crack opening in direction 1

ECR(9): crack opening in direction 2

ECR(10): crack opening in direction 3

ECR(11): X component of the vector defining direction 1

ECR(12): Y component of the vector defining direction 1

ECR(13): Z component of the vector defining direction 1

ECR(14): lambda(1) damage due to hydrostatic pressure

ECR(15): lambda(2) damage due to the steady ductile Drucker criterion

ECR(16): lambda(3) damage due to Von Mises criterion with hardening

ECR(17): lambda(4) damage due to the steady brittle Drucker criterion

ECR(18): lambda(5) damage due to the brittle Drucker criterion with hardening

ECR(19): index of the damage criterion (0: no shear, 1: ductile shear, 2: brittle shear, 3: both).

ECR(19): crack index (0: no crack, 1: one crack only, 2: two cracks, 3: three cracks).

Default values for an ordinary concrete:

All values are given in S.I. units.

- 1) Generic data:

```
RO      =     2.400E+03    Kg / m3
YOUN    =     37000E+06    Pa
NU      =     0.2100000
ALPH    =     1.200E-05
PREC    =     1.000E-03
```

- 2) Data for the traction damage:

```
BETA    =     0.1000000
LTR     =     4.440E+06    Pa
EPTR    =     3.600E-04
```

- 3) Data for shear damage:

```
LCS     =    44.400E+06    Pa
EPCS    =     1.200E-02
LBIC    =   111.000E+06    Pa
LCT     =   243.312E+06    Pa
PCT     =    71.040E+06    Pa
LCD     =   255.406E+06    Pa
PCD     =    79.920E+06    Pa
EPCD    =     6.000E-02
```

- 4) Data for the hydrostatic pressure damage:

```
LPH     =   134.887E+06    Pa
PENT    =  7088.120E+06    Pa
```

7.7.17 CONCRETE: DYNAR LMT (BLMT)

Object:

Isotropic visco-damage and viscoplastic concrete material.

References:

- Gatuingt F. and Pijaudier-Cabot G.,**Coupled damage and plasticity modelling in transient dynamic analysis of concrete**, *Int. J. Numer. Anal. Meth. Geomec., Vol 26, pp 1–24, 2002.*
- Gatuingt F., **"Modèle de comportement BETON DYNAR LMT".**Internal Report.

Syntax:

```
"BLMT"  "RO" rho  "YOUN" young  "NU" nu  "F0" f0
        "Q1" q1 "Q2" q2 "Q3" q3 "SGM0" sigM0 "XN" n
        "NVP" nvp "MVP" mvp "K" k "MDT" mDt "NDT" nDt
        "MDC" mDc "NDC" nDc "ED0" epsD0
        "AC" ac "BC" bc "AT" at "BT" bt   /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`f0`

Initial porosity of the concrete (0.3)

`q1`

Parameter of the modified Gurson plasticity criterion (0.5 to 2.)

`q2`

Parameter of the modified Gurson plasticity criterion (0.5 to 2.)

`q3`

Parameter of the modified Gurson plasticity criterion (0.5 to 2.)

`sigM0`

Resistance of the cement paste without pores (70 Mpa)

`n`

Exponent of the viscoplasticity threshold (15.)

`nvp`

Parameter of the Perzyna type viscoplasticity (1.5)

`mvp`

Parameter of the Perzyna type viscoplasticity (1.D-2)

`k`

Influence the porosity evolution (15 to 60)

`mDt`

Tension damage viscosity parameter (0.5D-4)

`nDt`

Tension damage viscosity parameter (5.)

`mDc`

Compression damage viscosity parameter (0.5D-3)

`nDc`

Compression damage viscosity parameter (20.)

`epsD0`

Strain tension threshold (1.D-04)

`ac`

Parameter for the compression (3000)

`bc`

Parameter for the compression (4.)

`at`

Parameter for the tension (20000)

`bt`

Parameter for the tension (1.6)

Comments:

1/ - BE CAREFUL the initial porosity influence the real young modulus
Km=YOUNG/(3*(1-2*NU))
Gm=YOUNG/(2*(1+NU))

2/ - Compressibily and shear moduli with porosity f (Mori-Tanaka)
Kporo=4*XKm*XGm*(1-f)/(4*XGm+3*XKm*f)
Gporo=XGm*(1-f)/(1+f*(6*XKm+12*XGm)/(9*XKm+8*XGm))

3/ - Plasticity criterion FNT:
F = 3*J2(SIG) / SGM**2 + 2Q1f cosh(Q2 I1 / 2SGM) - (1+(Q3 f)**2)

4/ - Plastic strain evolution:
EPSP = 1/(1-D)*(FNT/MVP)**NVP * dFNT/dSIG

5/ - Porosity evolution:
Df = K * f/(1-f) * (FNT/MVP)**NVP
f(t+dt) = f(t) + df

6/ - Damage threshold function in tension and compression:
FDi = (EPSE - ED0 - 1/Ai*(Di/(1-Di))**(1/Bi))

7/ - Damage evolution in tension and compression:
Di= (FDi/MDi)**NDi

Outputs:

The components of the ECR table are as follows:

ECR(1) : pressure
ECR(2) : Von Mises criterion
ECR(3) : Isotropic damage variable
ECR(4) : Material porosity
ECR(5) : xx plastic strain
ECR(6) : yy plastic strain
ECR(7) : zz plastic strain
ECR(8) : xy plastic strain
ECR(9) : yz plastic strain
ECR(10): zx plastic strain
ECR(11): Stress in the matrix without pores
ECR(12): Tension damage variable
ECR(13): Compression damage variable
ECR(14): Mazars threshold

7.7.18 BPEL: Model for prestressing cable-concrete friction

Object:

This material allows modelling friction between a prestressing cable and concrete according to BPEL rools (Prestressed Concrete with Borderlines). In French, BPEL stands for Beton Precontraint aux Etats Limites. This is a particular Coulomb-type friction law where the friction force threshold depends on tension in the cable. At each time step, the tension in a cable node is calculated first (mean tension between those in two cables elements using the considered node), then the friction force is calculated ans compared with a threshold.

Syntax:

```
"BPEL"  "FRLI" phil "FRCO" phic   /LECTURE/
```

`phil`

Friction coefficient for rectilinear motion,by unit length (1/m)

`phic`

Friction coefficient for curvilinear motion,by unit angle (1/rad)

`LECTURE`

List of the elements concerned.

Comments:

This material can be used with RNFR element (nonlinear frictional spring) only.

Outputs:

The components of the ECR table are as follows:

ECR(1): Tangential friction force.

ECR(2): Total relative tangential displacement between cable and concrete.

ECR(3): State indicator: 0 if sliding, 1 if adherence.

7.7.19 CONCRETE: MAZARS-LINEAR ELASTIC LAW WITH DAMAGE

Object:

Isotropic linear elastic with a modified Mazars damage for concrete and brittle rupture materials.

References:

1- Jacky MAZARS, "Application de la mécanique de l'endommagement au comportement non linéaire et à la rupture du béton de structure", Thèse de doctorat, Université Pierre et Marie Curie - Paris 6, 1984.

2- Yann CHUZEL-MARMOT, "Caractérisation expérimentale et simulation numérique d'impacts de glace à haute vitesse", Thèse de doctorat, Université MEGA de Lyon - INSA Lyon, 2009.

Syntax:

```
"MAZA" "RO"   rho  "YOUN" young  "NU"   nu   "EPSD" epsd
       "DCRI" dcri "AT"   at     "AC"   ac   "BT"   bt
     "BC"   bc   "LCAR" lcar   "CSTA" csta "DCOE" dcoe
     "VCRI" vcri "VIMP" vimp                          /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`epsd`

Initial strain threshold.

`dcri`

Critical value of damage (=1 per default).

`at`

Parameter of the tension law (asymptote of the curve stress-strain)

`ac`

Parameter of the compression law (asymptote of the curve stress-strain)

`bt`

Parameter of the tension law (shape of the curve stress-strain) `bc`

Parameter of the compression law (shape of the curve stress-strain)

`lcar`

Length parameter of the delay-damage

`csta`

Parameter of the delay-damage (=1 per default)

`dcoe`

Exponent of the sensitivity to the strain rate in tension ($=\frac{1}{3}$ per default)

`vcri`

Critical velocity in tension (=1 per default)

`vimp`

Velocity impact of the body (or strain rate if it's not an impact)

Comments:

You can deactivate the delay effect with a negative value for the parameter `lcar`.

You can also deactivate the damage (so you obtain a linear material) with a negative value for the parameter `epsd`.

Outputs:

The components of the ECR table are as follows:

ECR(1) : Pressure
ECR(2) : Von Mises criterion
ECR(3) : Equivalent deformation
ECR(4) : Global Damage
ECR(5) : Level "traction/compression"
ECR(6) : Strain rate
ECR(7) : Threshold damage
ECR(8) : Damage in traction
ECR(9) : Damage in compression
ECR(10): Factor of dynamic amplification in traction
ECR(11): Bc parameter eventually corrected

7.7.20 DADC: Dynamic Anisotropic Damage Concrete

Object:

Concrete material with induced anisotropic damage represented by one damage variable and modelling biaxial behaviour.

Reference:

Armand Leroux, *Modèle multiaxial d'endommagement anisotrope: Gestion numerique de la rupture et application à la ruine des structures en bèton armè sous impacts.* Thèse LaMSID-UMR EDF/CNRS/CEA (2012)[892]

Syntax:

```
"DADC"  "RO" rho      "YOUN" young    "NU" nu     "SIGT" sigyt
        "SIGC" sigyc <"SGBC" sigybc>  "ALPH" alpha
        "BETA" beta  "BT" bt    "DC" dc
        <"XINF" xinf>     <"BV" bv>     <"DTFI" dtfi>
        <"TCS" tcs>       /LECTURE/
```

`rho`

Density

`young`

Young's modulus

`nu`

Poisson's ratio

`sigyt`

Elastic limit for the tension

`sigyc`

Elastic limit for the compression in absolute value

`sigybc`

Elastic limit for the bi-compression in absolute value. Default value is taken from Kupfer diagram as $1.1 \cdot SIGC$.

`alpha`

Damage parameter ALPH. This parameter allows to modify peak values in tension and compression strengths.

`beta`

Damage parameter BETA. This parameter allows to modify the post-peak behaviour in compression and bi-compression `bt`

Parameter of the function b(Tx). It is used for Hillerborg regularization.

`dc`

Critical value of the damage for the numerical control of rupture. (0.9 to 1)

Optional parameters

`dinf`

Delay damage parameter (suggested value: 50000. s-1)

`bv`

Delay damage parameter (suggested value: 1.)

`dtfi`

Activating calculation of time step in the behaviour law with a value of first time step (recommended value, 1E-8 s.). The parameter is considered when the option "PAS AUTO" is used.

`tcs`

Formulation of the selected function b(Tx) (1: Formulation TCS1(default), 2: Formulation TCS2)

Outputs:

The components of the ECR table are as follows:

ECR(1) : pressure
ECR(2) : Von Mises criterion
ECR(3) : Damage Dxx
ECR(4) : Damage Dyy
ECR(5) : Damage Dzz
ECR(6) : Damage Dxy
ECR(7) : Damage Dyz
ECR(8) : Damage Dzx
ECR(9) : Rotation matrix for the eigenvector basis damage matrix (xx)
ECR(10): Rotation matrix for the eigenvector basis damage matrix (xy)
ECR(11): Rotation matrix for the eigenvector basis damage matrix (xz)
ECR(12): Rotation matrix for the eigenvector basis damage matrix (yx)
ECR(13): Rotation matrix for the eigenvector basis damage matrix (yy)
ECR(14): Rotation matrix for the eigenvector basis damage matrix (yz)
ECR(15): Rotation matrix for the eigenvector basis damage matrix (zx)
ECR(16): Rotation matrix for the eigenvector basis damage matrix (zy)
ECR(17): Rotation matrix for the eigenvector basis damage matrix (zz)
ECR(18): Critical state damage flag
ECR(19): Damage rate
ECR(20): Equivalent effective stress
ECR(21): 1st eigen value basis damage matrix
ECR(22): 2nd eigen value basis damage matrix

ECR(23): 3rd eigen value basis damage matrix
ECR(24): The biggest three eigen values basis damage matrix
ECR(25): Proposed time step
ECR(26): Filtered stress tensor after five time steps
ECR(27): Time step first flag
ECR(28): Estimation error flag (0=ok,1=error)
ECR(29): stress triaxiality
ECR(30): Component of filtered stress tensor (xx)
ECR(31): Component of filtered stress tensor (yy)
ECR(32): Component of filtered stress tensor (zz)
ECR(33): Component of filtered stress tensor (xy)
ECR(34): Component of filtered stress tensor (yz)
ECR(35): Component of filtered stress tensor (zx)
ECR(36): Number of times that the damage criterion (for the calculation of the time step in the behaviour law) is not respected
ECR(37): Largest components (absolute values) of the strain rate tensor

7.7.21 DPDC: Dynamic Plastic Damage Concrete

Object:

DPDC A three-invariant cap model with isotropic damage for concrete material. Perfect plasticity with isotropic hardening cap model, brittle and ductile damage, crack closing and strain rate effect.

The version 9 of DPDC can be used in shell elements, with layers or not. It is then possible to take transverse steel reinforcement into account, in an averaged fashion. To this aim, the transverse strain is computed from a fixed-point loop.

The version 10 of DPDC is an orthotropic brittle damage model coupled with plasticity. Plasticity and associated ductile damage are identical to the the previous versions but they act only on negative stresses (compression ones). The brittle damage is based on the Rankine criteria and can mimic up to 3 orthogonal cracks. A model of crack opening-closing and aggregate interlock is used to represent shear transfer across partially open cracks.

Reference:

Damage Plastic Model for Concrete Failure Under Impulsive Loadings, Daniel Guilbaud, XIII International Conference on Computational Plasticity - Fundamentals and Applications, COMPLAS XIII (2015), E. Oñate, D.R.J. Owen, D. Peric and M. Chiumenti (Eds)

Comments:

All values must be given in SI units.

Syntax:

```
"DPDC"  "RO" rho    "YOUN" young  "NU" nu    "FC" fc
        "DAGG" dagg
         <"GFT" gft       "GFC" gfc      "GFS" gfs>
         <"PWRC" pwrc>   <"PWRT" pwrt>
         <"B" b>         <"D" d>
         <"OVEC" overc>   <"OVET" overt>   <"SRAT" srate>
         <"R" r>         <"XO" xo>       <"W" w>
         <"D1" d1>       <"D2" d2>       <"PMOD" pmod>
         <"TXCA" txca "TXCT" txct "TXCL" txcl "TXCB" txcb>
         <"TXEA" txea "TXET" txet "TXEL" txel "TXEB" txeb>
         <"FTR"  ftr  "FBCR" fbcr "I1CR" i1cr "RJCR" rjcr>
         <"NC" nc "NOC" noc>     <"NT" nt "NOT" not>
         <"REPW" repow>   <"RECO" recov>
         <"PRED" pred>   <"COPP" copp>  <"EXCT" excent>
         <"LC" lc "DINF" dpinf>
         <"VERS" vers>
         <"EFVI">
         <"EFVN">
         <"EROD" <"ENDT" endt> <"ENDC" endc>
         <"DVOL" dvol> <"AVOL" avol> <"SSCC" sscc <"PPSH" ppsh>
         <"PCNF" pcnf> <"COEC" coec> <"CLCH" clch> <"CRUL" crul>>>
         <"REIN" <"ROST" rost> <"YGST" ygst> <"SIST" sist>>
          /LECTURE/
```

`rho`

Density

`youn`

Young's modulus

`nu`

Poisson's ratio

`fc`

Uniaxial compressive strength (Pa)

`dagg`

Maximum aggregate size (m)

`vers`

Version number (8 = old version intended to be replaced by version 9) (9 = new version). Version 9 is used by default.

Optional parameters

`gft`

Tensile fracture energy (default value: interpolated as a function of the maximum aggregate size) (J/m2)

`gfc`

Compressive fracture energy (default value: 200 gft) (J/m2)

`gfs`

Shear fracture energy (default value: gft) (J/m2)

`pwrc`

Shear-to-compression transition parameter (default value: 1.) (advised value: 3.3) (without unit)

`pwrt`

Shear-to-tension transition parameter (default value: 1.) (without unit)

`b`

Ductile shape softening parameter (default value: 100) (without unit)

`d`

Brittle shape softening parameter (default value: 0.1) (without unit)

`overc`

Maximum overstress allowed in compression (interpolated as a function of the material strength in compression) (Pa) `overt`

Maximum overstress allowed in tension (interpolated as a function of the material strength in compression) (Pa)

`srate`

Ratio of effective shear stress to tensile stress fluidity parameter (default value: 1.) (without unit)

`r`

Cap aspect ratio (default value: 5.) (advised value: 1.) (without unit)

`xo`

Cap initial location (interpolated as a function of the material strength in compression) (advised value: -10.E6) (Pa)

`w`

Maximum plastic volume compaction (default value: 0.05) (without unit)

`d1`

Linear shape parameter of the cap (default value: 2.5E-10 Pa^{-1})

`d2`

Quadratic shape parameter of the cap (default value: 3.49E-19 Pa^{-2})

parameters for meridians (for all versions until 7)

`txca`

TXC surface constant term (TXC: triaxial compression) (interpolated as a function of the material strength in compression) (Pa)

`txct`

TXC surface linear term (interpolated as a function of the material strength in compression) (without unit)

`txcl`

TXC surface nonlinear term (interpolated as a function of the material strength in compression) (Pa)

`txcb`

TXC surface exponent (interpolated as a function of the material strength in compression) (Pa^{-1})

`txea`

TXE surface constant term (TXE: triaxial extension) (interpolated as a function of the material strength in compression) (without unit)

`txet`

TXE surface linear term (interpolated as a function of the material strength in compression) (Pa^{-1})

`txel`

TXE surface nonlinear term (interpolated as a function of the material strength in compression) (without unit)

`txeb`

TXE surface exponent (interpolated as a function of the material strength in compression) (Pa^{-1})

parameters for meridians (for versions 8 and 9)

`ftr`

Ratio ft/fc with ft uniaxial tensile strength (default value: 0.1)

```
Be aware! ftr should be such that: 0.06 < ftr < 0.11
```

`fbcr`

Ratio fbc/fc with fbc biaxial compressive strength (default value: 1.16)

`i1cr`

Ratio i1/fc : horizontal coordinate of a point belonging to the compressive meridian (default value: -8.806)

`rjcr`

Ratio $\sqrt{J_2}/fc$: vertical coordinate of the same point (default value: 2.4985)

`pmod`

Modify moderate pressure softening parameter (default value: 0.) (without unit)

`nc`

Rate effects power for uniaxial compressive strength (default value: 0.78) (without unit)

`noc`

Rate effects parameter for uniaxial compressive strength (interpolated as a function of the material strength in compression). Default unit: $s^{-0.22}$. The unit depends on the value of nc

`nt`

Rate effects power for uniaxial tensile strength (default value: 0.48) (without unit)

`not`

Rate effects parameter for uniaxial tensile strength (interpolated as a function of the material strength in compression). Default unit: $s^{-0.52}$. The unit depends on the value of nt

`repow`

Power which increases fracture energy with rate effects (default value: 1.) (without unit)

`recov`

Option to recover stiffness in compression from tensile damage (default value: 0.) (without unit)

`pred`

Damage level for predamaged concrete (default value: 0.) (without unit)

`copp`

Coefficient for potential surface (default value: 1. associated plasticity)

`excent`

Constant excentricity (default value: excentricity function of J1)

`lc`

Caracteristic length for damage (m) (first parameter for EFVN option)

`dpinf`

Maximum rate of damage (1/s) (second parameter for EFVN option)

`EFVI`

Strain rate effect option (default value : strain rate effect excluded)

`EFVN`

Bounded damage rate effect option available with version 9 only

`EROD`

Mandatory keyword to introduce different failure criteria (damage, plastic strain). The keyword "EROS" must be added in the problem description of the data file to activate the "erosion" algorithm of the code. When one uses EROD, it is required to indicate at least one "erosion" criterion either devol or avol (version 9 only). When the two criterions are indicated, both are taken into account.

`endt`

Brittle damage threshold

`endc`

Ductile damage threshold

`dvol`

Volumetric strain threshold. The element gets eroded when the volumetric strain reaches 1+dvol.

`avol`

Optional keyword (version 9 only): Absolute volumetric strain threshold. The element gets eroded when the volumetric strain is lower than 1-avol. It is recommended to use dvol at the same time.

`sscc`

Optional keyword (version 9 only): Cutoff pure shear strain value - see comments for SSCC below.

`ppsh`

(for SSCC) Safety coefficient of the cutoff strain criterion (default value: 1.)

`pncf`

(for SSCC) Safety coefficient of the confinement criterion (default value: 0.75)

`coec`

(for SSCC) Coefficient of the confinement ratio relaxation (default value: 0.4)

`clch`

(for SSCC) Coefficient of the characteristic length (default value: 0.2)

`crul`

(for SSCC) Confinement ratio upper limit (default value: solved from $K_c = 0.75$ and FBCR)

`REIN`

Mandatory keyword to use DPDC with shell elements, layered or not. Triggers the use of the plane stress version of DPDC and supplies the following characteristics of the transverse steel reinforcement.

`rost`

Transverse reinforcement ratio (without unit)

`ygst`

Young modulus of the steel used (Pa)

`sist`

Yield stress of the steel used (Pa)

Outputs:

The components of the ECR table are as follows:

ECR(1) : Pressure
ECR(2) : Von Mises criterion
ECR(3) : Equivalent plastic strain
ECR(4) : Cube root of initial element volume (if version8)
ECR(5) : Lode angle
ECR(6) : Total variation of the isotropic hardening parameter
ECR(7) : Volumetric strain
ECR(8) : Plastic volumetric strain
ECR(9) : Ductile damage parameter

ECR(10): Brittle damage parameter
ECR(11): Ductile damage threshold
ECR(12): Brittle damage threshold
ECR(13): Current damage (not used in version 9)
ECR(14): Initial damage threshold in compression
ECR(15): Initial damage threshold in tension
ECR(16): filtered effective strain rate
ECR(17-22): Components of elastoplastic stress tensor
ECR(23-28): Components of viscoplastic stress tensor

ECR(29-34): Back stress if version 2. else:
ECR(29): Effective strain rate
ECR(30): Triaxiality
ECR(31): Static ductile damage threshold
ECR(32): Static brittle damage threshold

In addition, for shell elements:

ECR(57): Transverse steel plastic strain
ECR(58): True stress in the transverse reinforcing bars
→Please note that paraview outputs are limited to 40. An error could be raised by this limit. The option ECRC /LECT/ in paraview instructions allows to specify which components of the ECR vector are stored.

For SSCC erosion:

ECR(81): Characteristic length
ECR(82): Flag for shear criterion (0/1)
ECR(83): Largest calculated confinement
ECR(84): Pure shear strain content of an arbitrary strain state
ECR(85): Confinement ratio (0 if non-flagged element)

Specifications:

SSCC option:

Element erosion algorithm (available with EROD) based on shear and confinement. For more information on the formulas below, see '*Using the Abaqus CDP model in impact simulations*', Rakenteiden Mekaniikka (Fedoroff & Calonius - 2020) or '*Finite Element Analysis of Prestressed Concrete Slabs Under Impact Loading*', Aalto University (Özen - 2021). SSCC options are indicated in formulas with a non-italic font. An element is flagged (and keeps being flagged) when the criterion on pure shear strain is verified:

$$\epsilon_{psh} = \delta\sqrt{2}\epsilon_{oct}\frac{l_{ch}}{\mathrm{clch}} \geq \mathrm{sscc} \cdot \mathrm{ppsh}$$

In that case, the confinement criterion must be verified:

$$CR \leq \mathrm{pcnf} \cdot \mathrm{crul}$$

With,

$$CR^i = \frac{1}{\mathrm{fc}}(\mathrm{coec}\,\widetilde{\sigma_{cnf}}(t^i) + (1-\mathrm{coec})\max_{t\in[0,t^i]}\widetilde{\sigma_{cnf}})$$

When these two thresholds are crossed, the element is eroded.

DPDC V10

Comments:

All values must be given in SI units.

Syntax:

```
"DPDC"  "RO" rho     "YOUN" young   "NU" nu     "FC" fc
         <"GFT" gft>     <"GFC" gfc>
         <"D" d>         <"PMOD" pmod>
         <"R" r>         <"XO" xo>       <"W" w>
         <"D1" d1>       <"D2" d2>
         <"TXCA" txca "TXCT" txct "TXCL" txcl "TXCB" txcb>
         <"TXEA" txea "TXET" txet "TXEL" txel "TXEB" txeb>
         <"FTR"  ftr  "FBCR" fbcr "I1CR" i1cr "RJCR" rjcr>
         <"COPP" copp>  <"EXCT" excent>
         <"AMOR" amor>
         "KMIN" kmin "KMAX" kmax "KDEC" kdec
         |["FULL" full ; "GRAD" (... phik ...)]|
         "AGGD" aggd   "KVOL" kvol
         <"IMPR" impr>   <"ISOV" isov>
         "MSIG" msig "Rsig" rsig
         <"VERS" vers>
         <"EFVI">
         <"EROD" <"DVOL" dvol>>
          /LECTURE/
```

`rho`

Density

`youn`

Young's modulus

`nu`

Poisson's ratio

`fc`

Uniaxial compressive strength (Pa)

Optional parameters

`gft`

Tensile fracture energy per unit area (J/m2)

`gfc`

Compressive fracture energy per unit area (default value: 200 gft) (J/m2)

`d`

Brittle shape softening parameter (default value: 0.1) (without unit)

`pmod`

Modify moderate pressure softening parameter (default value: 0.) (without unit)

`r`

Cap aspect ratio (default value: 5.) (advised value: 1.) (without unit)

`xo`

Cap initial location (interpolated as a function of the material strength in compression) (advised value: -10.E6) (Pa)

`w`

Maximum plastic volume compaction (default value: 0.05) (without unit)

`d1`

Linear shape parameter of the cap (default value: 2.5E-10 Pa^{-1})

`d2`

Quadratic shape parameter of the cap (default value: 3.49E-19 Pa^{-2})

parameters for meridians (for all versions until 7)

`txca`

TXC surface constant term (TXC: triaxial compression) (interpolated as a function of the material strength in compression) (Pa)

`txct`

TXC surface linear term (interpolated as a function of the material strength in compression) (without unit)

`txcl`

TXC surface nonlinear term (interpolated as a function of the material strength in compression) (Pa)

`txcb`

TXC surface exponent (interpolated as a function of the material strength in compression) (Pa^{-1})

`txea`

TXE surface constant term (TXE: triaxial extension) (interpolated as a function of the material strength in compression) (without unit)

`txet`

TXE surface linear term (interpolated as a function of the material strength in compression) (Pa^{-1})

`txel`

TXE surface nonlinear term (interpolated as a function of the material strength in compression) (without unit)

`txeb`

TXE surface exponent (interpolated as a function of the material strength in compression) (Pa^{-1})

parameters for meridians (for versions 8 and 9)

`ftr`

Ratio ft/fc with ft uniaxial tensile strength (default value: 0.1)

```
Be aware! ftr should be such that: 0.06 < ftr < 0.11
```

`fbcr`

Ratio fbc/fc with fbc biaxial compressive strength (default value: 1.16)

`i1cr`

Ratio i1/fc : horizontal coordinate of a point belonging to the compressive meridian (default value: -8.806)

`rjcr`

Ratio $\sqrt{J_2}/fc$: vertical coordinate of the same point (default value: 2.4985)

`copp`

Coefficient for potential surface (default value: 1. associated plasticity)

`excent`

Constant excentricity (default value: excentricity function of J1)

`amor`

Damping coefficient

`kmin`

dmin=2.**kmin mimimum size (diameter in mm) of aggregates

`kmax`

dmax=2.**kmax maximum size (diameter in mm) of aggregates

`kdec`

To obtain the grain size distribution, each class of aggregate size is divided by 2**kdec

`full`

Exponent of a Fuller's curve used to obtain the grain size distribution (recommended value 0.45)

`phik`

A grading curve is used to obtain the grain size distribution. phik is the fraction of the quantity of grain size between di+1=2**(i+1) and di=2**i

`Be aware! kmax-kmin values of phik are needed`

`aggd`

Ratio of sliding displacement for which damage is complete to the radius of aggregate

`kvol`

Ratio of the volume of the aggregates to the total volume of concrete (typical values are between 0.7 and 0.8

`IMPR`

Impression of the grain size distribution (daggk, phik) on logic unit 7. Impression of tables: (tau, sign) versus (uslid,wfrac) and their dervatives on logic unit 7. Impression of tables: abrasion energy Eabr versus (uslid,wfrac) and its dervatives on logic unit 7.

`ISOV`

Impression of iso-values for abrasion energy Eabr on logic unit 7.

`msig`

Shear intercept to tensile strenght ratio for local damage surface (recommended value: 1.25)

`rsig`

Limiting friction ratio in which damage surface is based (recommanded value 0.8)

`vers`

Version number: 10. Version 9 is used by default.

`EFVI`

Strain rate effect option (default value : strain rate effect excluded)

`EROD`

Mandatory keyword to introduce different failure criteria (damage, plastic strain). The keyword "EROS" must be added in the problem description of the data file to activate the "erosion" algorithm of the code. When one uses EROD, it is required to indicate at least one "erosion" criterion. For the time being, only devol is allowed.

`dvol`

Volumetric strain threshold. The element gets eroded when the volumetric strain reaches 1+dvol.

Outputs:

The components of the ECR table are as follows:

ECR(1) : Pressure
ECR(2) : Von Mises criterion
ECR(3) : Equivalent plastic strain
ECR(4) : Cube root of initial element volume (if version8)
ECR(5) : Lode angle
ECR(6) : Total variation of the isotropic hardening parameter
ECR(7) : Volumetric strain
ECR(8) : Plastic volumetric strain
ECR(9-14): Components of elastoplastic stress tensor
ECR(15): Work done by compression in the plasticity range
ECR(16): Initial damage threshold in compression
ECR(17): Damage threshold in compression
ECR(18): Damage in compression
ECR(19-21): first stress eigen vector or normal to a plane of degradation
ECR(22-24): second stress eigen vector or normal to a plane of degradation

* for the first direction, in local
ECR(25): Initial brittle damage threshod Zeta0
ECR(26): Effective strain rate
ECR(27): Filtered effective strain rate
ECR(28): Brittle damage threshold Zeta
ECR(29): Number of the plane of degradation
ECR(30): Strain along the normal of the plane of degradation
ECR(31): Inelastic strain induced by contact along the normal of the pod
ECR(32): Abrasion energy threshold in the right direction
ECR(33): Abrasion energy threshold in the left direction
ECR(34): Angle of wear lanes
ECR(35): Brittle damage
ECR(36): Sign of sliding displacement

* for the other directions
ECR(37-48): same variables for the second direction
ECR(49-60): same variables for the third one

ECR(61): Component 21 of the sliding strain in the first pod
ECR(62): Componant 31 of the sliding strain in the first pod
ECR(63): Component 32 of the sliding strain in the second pod

ECR(64): Component 21 of the inelastic sliding strain in the first pod
ECR(65): Cpmponent 31 of the inelastic sliding strain in the first pod
ECR(66): Component 32 of the inelastic sliding strain in the second pod

ECR(67-72): Components of the fracture strain tensor

ECR(73): 0 if reduced integration is used for damaged element else 1 (for CUBM element only)
ECR(74): Triaxiality
ECR(75): Min of ECR(8)

7.7.22 DAMAGE

Object:

This option allows to associate to the materials VON MISES ISOTROPE and VON MISES PARFAIT different damage laws, and to request the calculation of several fracture criteria. Now, only one criterion (Tuler-Butcher) is available.

Syntax:

```
    "CRIT"  $[ "TULE" <"SIGL" sigl >  <"EPSL" epsl >  <"TAUL" taul >
                       "SIGS" sigs     "LAMB" lamb    <"KER"  ker  >  ]$
                       /LECTURE/
```

`"CRIT"`

Indicates that the calculation of different damage criteria is required.

`"TULE"`

The TULER-BUTCHER's criterion is selected.

`sigl`

Maximum principal stress criterion.

`epsl`

Maximum volumetric deformation criterion.

`taul`

Octahedral shear stress criterion.

`sigs`

First parameter of the Tuler-Butcher law.

`lamb`

Second parameter of the Tuler-Butcher law.

`ker`

Third parameter of the Tuler-Butcher law.

`LECTURE`

List of the concerned elements.

Comments:

The element types accepting these materials are: in 2D elements TRIA, CAR1 and CAR4 and in 3D elements CUBE, CUBE6, CUBE8, PRIS, TETR and PRI6.

Currently the damage model is only available in association with the materials Isotropic Von Mises, Steinberg-Guinan and dynamic Von Mises.

The isotropic Von Mises material must appear first in the input file, before the calculation of the damage criteria, if any, and one of the two damage laws, if necessary.

The Tuler-Butcher is given by the following expression where $\sigma_1, \sigma_2, \sigma_3$ representing the principal stresses:

$$\int_0^t (Max(\sigma_1, \sigma_2, \sigma_3) - \sigma_s)^\lambda \, dt \quad < \quad \texttt{ker}$$

The results stored in the ECR table (5 values) are, according to the material type:

Tuler-Butcher :

ECR(1) = Maximum principal stress
ECR(2) = Maximum principal deformation
ECR(3) = Octahedral shear stress
ECR(4) = Volume deformation
ECR(5) = Tuler-Butcher criterion

Exemple:

A criterion "LOI 3", is associated with the principal material "LOI 1".

The corresponding data will be for example:

```
LOI  1    VMIS ISOT RO 7800.  YOUN 74020E6  NU .3  ELAS 350E6
                    ENDO 3
               TRAC 4
                     350.E6         .472845E-2
                     476.26E6      7.2835E-2
                     518.51E6      15.700E-2
                     538.03E6      21.607E-2
                     550.24E6      26.083E-2
               LECT TOUS

LOI 3    CRIT TULE  SIGS 1E7 LAMB 1.0
               LECT TOUS
```

7.7.23 EOBT: Anisotropic damage of concrete (edf)

Object:

Concrete material with induced anisotropic damage.

Reference:

V. Godard, Modélisation de l'endommagement anisotrope du béton avec prise en compte de l'effet unilatéral : Application à la simulation numérique des enceintes de confinement, Thèse de l'Université Paris VI, 2005.

M. Bottoni, Loi de comportement ENDO_ORTH_BETON, Manuel de référence de Code_Aster, R7.01.09.

Syntax:

```
"EOBT"  "RO" rho   "YOUN" young   "NU" nu   "K0" k0
        "K1" k1   "K2" k2   "ECRB" ecrb    "ECRD" ecrd
        < "DC" dc >  < "DM" dm >   /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`k0`

Threshold in stress for the tension.

`k1`

Parameter for the threshold in stress in compression.

`k2`

Parameter for the threshold in stress in compression.

`ecrb`

Parameter driving the evolution of the loading surface while the damage tensor B is growing.

`ecrd`

Parameter driving the evolution of the loading surface while the damage scalar d is growing.

Optional parameters:

`dc`

Limit value for the eigenvalues of the damage tensor B and for the damage scalar d. When this limit is reached, the material is considered to be broken and damage can not grow anymore. The damage is set to dm. By default, dc is set to 0.999

`dm`

Imposed value for damage when it reaches its limit value. By default, dm is set to 0.999

Outputs:

The components of the ECR table are as follows:

ECR(1) : pressure
ECR(2) : Damage in compression D
ECR(3) : Damage Dxx
ECR(4) : Damage Dyy
ECR(5) : Damage Dzz
ECR(6) : Damage Dxy
ECR(7) : Damage Dyz
ECR(8) : Damage Dzx
ECR(9) : Rotation matrix for the eigenvector basis damage matrix (xx)
ECR(10): Rotation matrix for the eigenvector basis damage matrix (xy)
ECR(11): Rotation matrix for the eigenvector basis damage matrix (xz)
ECR(12): Rotation matrix for the eigenvector basis damage matrix (yx)
ECR(13): Rotation matrix for the eigenvector basis damage matrix (yy)
ECR(14): Rotation matrix for the eigenvector basis damage matrix (yz)
ECR(15): Rotation matrix for the eigenvector basis damage matrix (zx)
ECR(16): Rotation matrix for the eigenvector basis damage matrix (zy)
ECR(17): Rotation matrix for the eigenvector basis damage matrix (zz)
ECR(21): 1st eigen value of the damage tensor B
ECR(22): 2nd eigen value of the damage tensor B
ECR(23): 3rd eigen value of the damage tensor B

7.7.24 ENGR: Elastic gradient damage material

Object:

This section describes an elastic-damage material with gradient regularization. The development is still in progress and a more detailed presentation can be found in [981], [982].

This model can be used to predict crack initiation and propagation in a quasi-brittle medium (such as glass or concrete) under dynamic loading conditions. In particular, no plasticity is currently accounted for in this model. It can be seen as a variational approach to fracture in the sense of [Francfort and Marigo 1998, Revisiting brittle fracture as an energy minimization problem]. Crack nucleation, kinking, branching, coalescence or arrest can be automatically predicted through energy minimization. It is known that traditional approaches (with or without X-FEM numerical schemes) in fracture mechanics may fail in the case of crack initiation from a perfectly regular domain or complex crack topological changes. The variational approach can thus be considered as a unified and complete framework of fracture.

An additional scalar nodal field $0 \leq \alpha \leq 1$, called damage, is introduced to the model. This field depicts a continuous transition between the undamaged part $\alpha = 0$ and the crack $\alpha = 1$. Spurious mesh dependency observed in traditional damage mechanics is suppressed by gradient regularization $\nabla\alpha$. As a consequence, a material characteristic internal length ℓ naturally appears, which determines the size of the damage process zone. This parameter is linked to the maximal tensile stress σ_{m} that can be supported by the material.

Only two mandatory fracture-type material parameters need to be entered. One is the fracture toughness G_{c} defined as the energy needed to create a crack of unit area. Through Irwin's formula this quantity G_{c} can be related to the criterion in stress intensity factors K_{IC}. Another parameter is the internal length ℓ or equivalently the maximal tensile stress σ_{m}.

Two resolution methods are availables.

In the first one (called by default), the damage problem is solved with an implicit resolution method. From a computational point of view, we need to solve at every time step a bound-constrained (quadratic or convex) minimization problem for damage. For that reason, the parallel linear algebra library PETSc is used to manipulate the Hessian matrix and various vectors. For various options of PETSc used for this material `ENGR`, it is advised to refer to 12.23.

In the second one (called if "MOBI" parameter is given), the damage problem is solved with an explicit resolution method. This method is numericaly more efficient but results depend on the value of "MOBI" parameter. There isn't currently a formula to get the optimal value for "MOBI".

Syntax:

```
"ENGR"     "RO"   rho   "YOUN" young   "NU"   nu   "GC"   gc
        |[ "ELL"  ell ; "SIGM" sigm ]|
         < "LAW"  law   "TC"   tc      "AC"   ac   "MOBI" mob >  /LECTURE/
```

Mandatory parameters:

`rho`

Density ρ.

`young`

Young's modulus E.

`nu`

Poisson's ratio ν.

`gc`

Fracture toughness G_c.

ONE additional mandatory fracture parameter from two possibilities:

`ell`

Material characteristic (internal) length ℓ.

`sigm`

Maximal tensile stress σ_m.

Optional parameters:

`law`

Damage constitutive law describing local stiffness degradation due to damage $a(\alpha)$ and local damage dissipation evolution function $w(\alpha)$. 3 choices are currently implemented.

- Integer 1: this *default* damage law ensures a brittle material behavior by providing an elastic limit σ_c which equals to the maximal stress σ_m possibly entered by the user. The computational cost of this law is also smaller. *We recommend using this damage constitutive law.*

$$a(\alpha) = (1-\alpha)^2\,, \quad w(\alpha) = w_1\alpha$$

  where $w_1 = 3G_c/(8\ell)$.
- Integer 2: this damage law is widely used in phase-field modeling for fracture mechanics.

$$a(\alpha) = (1-\alpha)^2\,, \quad w(\alpha) = w_1\alpha^2$$

  where $w_1 = G_c/(2\ell)$.
- Integer 3: this damage law named `PB` depicts a *P*erfectly *B*rittle material. During a homogeneous traction test, the stress will immediately drops to zero when the elastic limit is reached.

$$a(\alpha) = (1-\alpha)^2\,, \quad w(\alpha) = w_1\big(1-(1-\alpha^2)\big)$$

  where $w_1 = G_c/(\pi\ell)$.

`tc`

This parameter determines the tension-compression asymmetry formulation. For brittle materials such as glass or concrete, the material can be easily damaged or cracked under tension. It is no longer the case under compression. Currently 6 formulations are available.

- Integer 1: by *default* we do not distinguish tension and compression in this gradient damage model. It means cracks may be developed in compressive zones. Use this formulation only if you are sure that material non-interpenetration will not occur.

- Integer 2: the formulation proposed in [Amor et al. 2009, Regularized formulation of the variational brittle fracture with unilateral contact: Numerical experiments] stipulates that under compression flagged by a negative strain trace $\operatorname{tr}\varepsilon < 0$, only deviatoric part of the elastic energy contributes to damage.
- Integer 3: this formulation is slightly different from the 2nd model and is proposed in [Zouari et al. 2012, Prise en compte de la différence traction/compression pour les lois d'endommagement. Tests sur les structures en béton]. This formulation prohibits damage evolution as long as the strain trace is negative $\operatorname{tr}\varepsilon < 0$.
- Integer 4: this formulation proposed in [Lancioni et al. 2009, The Variational Approach to Fracture Mechanics. A Practical Application to the French Panthéon in Paris] permits only deviatoric-type damage.
- Integer 5: [Miehe et al. 2010, A phase field model for rate-independent crack propagation] initially proposed this model. It uses the principal values of the strain tensor via eigen- decomposition and only positive ones contribute to damage. However this model presents a peculiar behavior under uniaxial compression, where homogeneous damage occurs accompanied by an increasing stress. For this reason, use the 6th model of [Freddi et al. 2010].
- Integer 6: this model is initially formulated by [Freddi et al. 2010, Regularized variational theories of fracture: A unified approach]. The problem with the [Miehe et al. 2010] model under compression is overcome. *We recommend using this formulation for all brittle materials.*

`ac`

This parameter can be used with the erosion mechanism to define a critical stiffness degradation. Its default value is 10^{-3}. If this value is reaches, the Gauss point will be considered as eroded.

`mob`

This parameter of "mobility", inverse of a viscosity, activates the explicit method to solve the problem of damage. This parameter affects the results, so it is necessary to provide an appropriate value. However, there is no method yet to determine this value. Work is ongoing on this subject.

Outputs:

No public ECR components are available for output.

7.7.25 LINEAR MULTI-LAYER

Object

This directive allows to define materials obtained by homogenisation through the thickness of different layers (or plies) each having a linear orthotropic behaviour.

Syntax:

```
    "MCOU"      |[    "BACON"     ibacon                      ;
                    "NBCOUCHE"  ...          /LECTURE/      ]|

   For the user data option (NBCOUCHE) :

     ... "NBCOUCHE"  nbcouche  "ZMIN"  zmin

        nbcouche times   :

        |  "ZMAX"  zmax   "TETA"  teta   "ROCO"  roco   "YG1"   yg1 |
        |  "YG2"   yg2    "NU12"  nu12   "G12"   g12                |
        | < "G13"  g13 >  < "G23"  g23 >  "TERM"                    |
```

`ibacon`

Logical unit number of the BACON file from which the characteristics of this material will be read. Using this option implies the necessity to introduce the keyword "MBACON" in part A of the input file (see page A.30) in order to dimension the arrays used by this model.

`NBCOUCHE`

The characteristics will be listed below.

`nbcouche`

Numbers of layers of the composite.

`zmin`

Minimum side of the first layer.

`zmax`

Maximum side of the current layer.

`teta`

Angle (in degrees) of the first vector of the orthotropy frame of the current layer with respect to the first side of the element.

`roco`

Density of the current layer.

`yg1`

Young's modulus along direction 1 of the current layer.

`yg2`

Young's modulus along direction 2 of the current layer.

`nu12`

Poisson's coefficient among directions 1-2.

`g12`

Shear modulus among directions 1-2.

`g13`

Shear modulus among directions 1-3.

`g23`

Shear modulus among directions 2-3.

`TERM`

Indicates that the data for layer i are terminated.

`LECTURE`

List of the concerned elements.

Comments:

When the BACON option is used, EUROPLEXUS reads the numbers of the elements associated with this material directly from the BACOn file: the /LECTURE/ procedure is redundant. Currently, one may read only one type of laminated material per calculation. On the other hand, EUROPLEXUS will write on the logical unit (ibacon+1):

```
1) the element number (1 value)
2) the angle (in degrees) between the first side and the
      first direction of the laminated (1 value)
3) the components of the symmetric matrices A, B and D
      ( A(1,1), A(2,1),A(2,2), A(3,1),A(3,2),A(3,3)...)
      (3x6= 18 values).
```

For the NBCOUCHE option, the various layers must be described in growing order of z. In particular, zmax(couche_i) = zmin(couche_i+1).

The value z=0 corresponds to the neutral fiber of the element. This material allows to take excentricity into account.

For the shells that consider transverse shears, i.e. DST3, Q4G4, Q4GR, Q4GS, it is necessary to give the values of G23 and G13.

Outputs:

The various components of the ECR table (values computed in the local reference of the shell element) are as follows:

Element COQ3:

ECR(1) : Von Mises on the lower face of the shell
ECR(2) : Von Mises on the upper face of the shell
ECR(3) : -d3w/dx3 at the integration point
ECR(4) : -d3w/dy3 at the integration point
ECR(5) : -d3w/dx2dy at the integration point
ECR(6) : -d3w/dxdy2 at the integration point

Elements DKT3 and DST3:

ECR(1) : Von Mises on the lower face of the shell
ECR(2) : Von Mises on the upper face of the shell
ECR(3) : d2beta_x/dx2 at the first integration point
ECR(4) : d2beta_x/dy2 at the first integration point
ECR(5) : d2beta_x/dxdy at the first integration point
ECR(6) : d2beta_y/dx2 at the first integration point
ECR(7) : d2beta_y/dy2 at the first integration point
ECR(8) : d2beta_y/dxdy at the first integration point

Recall that the table of deformations EPST is composed by the following parameters (computed at the integration point):

EPST(1) : du/dx (membrane deformation e_xx)
EPST(2) : dv/dy (membrane deformation e_yy)
EPST(3) : du/dy+dv/dx (membrane deformation 2*e_xy)
EPST(4) : dbeta_x/dx (=-d2w/dx2 if thin shell)
EPST(5) : dbeta_y/dy (=-d2w/dy2 if thin shell)
EPST(6) : dbeta_y/dx + dbeta_x/dy
EPST(7) : 2*epsi_xz (eventually)
EPST(8) : 2*epsi_yz (eventually)

Example:

We assume a composite formed by 6 layers regularly spaced on a thickness of 0.12 m. The corresponding data will be:

```
MCOUCH    NBCOUCHE  6       ZMIN -0.06
    ZMAX -0.04  TETA  5. ROCO 2.5E3  YG1 40E9 YG2 20E9
                NU12 0.2 G12 16.6666667E9 TERM
    ZMAX -0.02  TETA 36. ROCO 2.5E3  YG1 40E9 YG2 25E9
                NU12 0.2 G12 16.6666667E9 TERM
    ZMAX -0.00  TETA 48. ROCO 2.5E3  YG1 40E9 YG2 20E9
                NU12 0.2 G12 16.6666667E9 TERM
    ZMAX  0.02  TETA 135 ROCO 2.5E3  YG1 40E9 YG2 20E9
                NU12 0.2 G12 16.6666667E9 TERM
    ZMAX  0.04  TETA 33. ROCO 2.5E3  YG1 40E9 YG2 20E9
                NU12 0.2 G12 16.6666667E9 TERM
    ZMAX  0.06  TETA 15. ROCO 2.5E3  YG1 40E9 YG2 40E9
                NU12 0.2 G12 16.6666667E9 TERM
                                                       LECT 3  4 5 TERM
```

7.7.26 CHANG-CHANG MULTI-LAYER MODEL

Object:

This directive allows to define composite materials using the CHANG-CHANG criterion, as described in:

```
A Progressive Damage Model of Laminated Composites
  Containing Stress Concentrations
by F.-K. CHANG and K.-Y. CHANG
in  Journal of Composite Materials, Vol. 21, Sept. 1987.
```

Syntax:

```
"CHANG"     |[    "BACON"     ibacon                      ;
            $    "NBCOUCHE"  ...  PBASE ....  /LECTURE/      $

For the user data option (NBCOUCHE) :

 ... "NBCOUCHE"  nbcouche  "ZMIN"  zmin

    nbcouche times   :

    |  "ZMAX"  zmax   "TETA"  teta   "ROCO"  roco   "YG1"   yg1 |
    |  "YG2"   yg2    "NU12"  nu12   "G12"   g12                |
    |  "XT"    xt     "XC"    xc     "YT"    yt     "YC"    yc  |
    |  "SC"    sc     "A0"    a0     "BETA"  beta               |
    | "TERM"                                                    |

Once described the layers, one gives 2 points in order to
define a reference direction:

     "PBASE"   "LECTURE" nod1 nod2 "TERM"
```

`ibacon`

Logical unit number of the BACON file from which the characteristics of this material will be read. Using this option implies the necessity to introduce the keyword "MBACON" in part A of the input file (see page A.30) in order to dimension the arrays used by this model.

`NBCOUCHE`

The characteristics will be listed below in the main input file.

`nbcouche`

Number of layers in the composite.

`zmin`

Minimum side of the first layer.

`zmax`

Maximum side of the current layer.

`teta`

Angle (in degrees) of the first vector of the orthotropy frame of the current layer with respect to the reference direction.

`roco`

Density of the current layer.

`yg1`

Young's modulus along direction 1 of the current layer.

`yg2`

Young's modulus along direction 2 of the current layer.

`nu12`

Poisson's coefficient among directions 1-2.

`g12`

Shear modulus among directions 1-2.

`xt`

Traction limit along direction 1 of the orthotropy frame.

`xc`

Compression limit along direction 1 of the orthotropy frame.

`yt`

Traction limit along direction 2 of the orthotropy frame.

`yc`

Compression limit along direction 2 of the orthotropy frame.

`sc`

Shear limit 1-2 of the orthotropy frame.

`a0`

Critical area a0 of the CHANG-CHANG criterion.

`beta`

Weibull coefficient.

`TERM`

Indicates that the data for layer i are terminated.

`nod1,nod2`

Numbers of 2 nodes defining the reference direction.

`LECTURE`

List of the concerned elements.

Comments:

When the BACON option is used, EUROPLEXUS reads the numbers of the associated elements directly from the BACON file: the procedure /LECTURE/ is redundant. For this material, the number of laminas is unlimited. However, one should give the adequate numbers in the dimensioning section of the input file: see the key-words MATE and ECRO in the DIMENSIONS directive.

For the NBCOUCHE option, the various layers must be described along increasing order of z. In particular, zmax(couche_i) = zmin(couche_i+1).

The value z=0 corresponds to the neutral fiber of the element. This material allows to account for excentricity.

Outputs:

This constitutive law computes the damages appearing in each plie of the laminated structure. To this end, it is necessary to define the damage parameters in each layer. In each ply, the ECR table is dimensioned at 10, and the main parameters are:

DIMENSION ECR(10,NPLIS)

ECR(2,ipli) : Von Mises of the ply

ECR(3,ipli) : Rupture criterion of the matrix in traction

ECR(4,ipli) : Rupture criterion of the matrix in compression

ECR(5,ipli) : Rupture criterion of the fiber, or fiber-matrix delamination.

7.7.27 LINEAR ORTHOTROPY

Object:

The directive is used to enter materials with a linear orthotropic behaviour into a coordinate system defined by the user. The model is described in: Mécanique des Matériaux Solides (J-Lemaitre, L-Chaboche. Ed: Dunod, 1986).

Syntax:

```
"ORTH"  "RO"   rho    "YG1"  yg1    "YG2"   yg2  "YG3" yg3
        "NU12" nu12  "NU13" nu13   "NU23" nu23
        "G12"  g12   "G13"  g13    "G23" g23          /LECTURE/
```

`rho`

Density of the material.

`yg1`

Young's modulus along direction 1.

`yg2`

Young's modulus along direction 2.

`yg3`

Young's modulus along direction 3.

`nu12`

Poisson's ratio between directions 1 and 2.

`nu13`

Poisson's ratio between directions 1 and 3.

`nu23`

Poisson's ratio between directions 2 and 3.

`g12`

Shear modulus between directions 1 and 2.

`g13`

Shear modulus between directions 1 and 3.

`g23`

Shear modulus between directions 2 and 3.

`LECTURE`

List of the elements concerned.

Comments:

This option may be repeated as many times as necessary.

The associated coordinate system is defined by the option "CORTHO" (see page C1.95) for the multilayer element CMC3.

The associated coordinate system is defined by the option "MORTHO" (see page C1.96) for the continuum elements in 3D and in plane strain.

The associated coordinate system is defined by the directive "COMPLEMENT" (pages C1.95 and C1.96):

- "COMPLEMENT" "CORTHO" for the shells;

- "COMPLEMENT" "MORTHO" for the continuum elements 3D and 2D plane strain and axisymmetric.

Verify that this material is available for your elements, by means of the tables of page C.100.

Outputs:

The different components of the ECR table are as follows, for the CMC3 element:

ECR(1): Von mises criterion on the lower face of the multilayer element CMC3.

ECR(2): Vom mises criterion on the upper face of the multilayer element CMC3.

The different components of the ECR table are as follows, for the continuum elements:

ECR(1): pressure.

ECR(2): Vom mises criterion.

7.7.28 ORTS : LINEAR ORTHOTROPY (Local basis)

Object:

Attention: The description of the material is not showing all capabilities of the material. The material allows erosion and has several more input and output variables.

The directive is used to enter materials with a linear orthotropic behaviour into a coordinate system defined by the user. The model is described in: Mécanique des Matériaux Solides (J-Lemaitre, L-Chaboche. Ed: Dunod, 1986).

Stress and strain are expressed in the user coordinate system.

Syntax:

```
"ORTS"  "RO"  rho    "YG1"  yg1    "YG2"   yg2  "YG3" yg3
        "NU12" nu12  "NU13" nu13   "NU23" nu23
        "G12"  g12   "G13"  g13    "G23" g23
        <"XT1"  xt1   "XT2"  xt2    "XT3" xt3
        "XC1"  xc1   "XC2"  xc2    "XC3" xc3
        "RST1" rst1  "RST2" rst2   "RST3" rst3
        "CRIT" icrit>        /LECTURE/
```

`rho`

Density of the material.

`yg1`

Young's modulus along direction 1.

`yg2`

Young's modulus along direction 2.

`yg3`

Young's modulus along direction 3.

`nu12`

Poisson's ratio between directions 1 and 2.

`nu13`

Poisson's ratio between directions 1 and 3.

`nu23`

Poisson's ratio between directions 2 and 3.

`g12`

Shear modulus between directions 1 and 2.

`g13`

Shear modulus between directions 1 and 3.

`g23`

Shear modulus between directions 2 and 3.

`xt1`

Failure criterion for tension in x-direction.

`xt2`

Failure criterion for tension in y-direction.

`xt3`

Failure criterion for tension in z-direction.

`xc1`

Failure criterion for compression in x-direction.

`xc2`

Failure criterion for compression in y-direction.

`xc3`

Failure criterion for compression in z-direction.

`rst1`

Failure criterion for shear in xy-direction.

`rst2`

Failure criterion for shear in yz-direction.

`rst3`

Failure criterion for shear in xz-direction.

`icrit`

Erosion criteria type (e.g.: tsai-hill)

`LECTURE`

List of the elements concerned.

Comments:

This option may be repeated as many times as necessary.

The associated coordinate system is defined by the directive "COMP" (see GBC_0095 and GBC_0096):

- "COMP" "CORTHO" for the shells and the multilayer element CMC3;
- "COMP" "MORTHO" for the continuum elements in 3D and in 2D plane strain and axisymmetric.

Outputs:

The different components of the ECR table are as follows, for the CMC3 element:

ECR(1): Von Mises criterion on the lower face of the multilayer element CMC3.

ECR(2): Von Mises criterion on the upper face of the multilayer element CMC3.

The different components of the ECR table are as follows, for the continuum elements:

ECR(1): pressure.

ECR(2): Von Mises criterion.

7.7.29 ORTE : ELASTIC DAMAGE ORTHOTROPY (only in 3D)

Object:

The directive is used to enter materials with an orthotropic (local) behaviour into a coordinate system defined by the user, coupling with damage. There is coupling between damage (as material LEM1) and orthotropy (as material ORTS). There are 6 damages : $d_1, d_2, d_3, d_{12}, d_{13}, d_{23}$. Each damage evolution rate is a function of strain tensor. A failure criterion is implicitly contained within the model: rupture occurs when a damage exceeds a critical value.
Two parameters (for each damage) allow to introduce a limitation of the damage rate (thanks to the delayed damage effect) in order to avoid the mesh dependency.

$$D_{nc} = dc < \frac{\epsilon - ep}{s_0 - ep} >$$

$$\dot{d} = \frac{1}{to}\left(1 - e^{-a<D_{nc}-d>}\right)$$

References:

This material behavior has been studied in [992].

Syntax:

```
"ORTE"  "RO"    rho    "YG1"   yg1    "YG2"   yg2    "YG3"  yg3
        "NU12"  nu12   "NU13"  nu13   "NU23"  nu23
        "G12"   g12    "G13"   g13    "G23"   g23
        "EP1"   ep1    "EP2"   ep2    "EP3"   ep3
        "EP12"  ep12   "EP13"  ep13   "EP23"  ep23
        "S01"   s01    "S02"   s02    "S03"   s03
        "S012"  s012   "S013"  s013   "S023"  s023
        "DC1"   dc1    "DC2"   dc2    "DC3"   dc3
        "DC12"  dc12   "DC13"  dc13   "DC23"  dc23
        <"A1"   a1>    <"A2"   a2>    <"A3"   a3>
        <"A12"  a12>   <"A13"  a13>   <"A23"  a23>
        <"TO1"  to1>   <"TO2"  to2>   <"TO3"  to3>
        <"TO12" to12>  <"TO13" to13>  <"TO23" to23>
         /LECTURE/
```

`rho`

Density of the material.

`yg1`

Young's modulus along direction 1.

`yg2`

Young's modulus along direction 2.

`yg3`

Young's modulus along direction 3.

`nu12`

Poisson's ratio between directions 1 and 2.

`nu13`

Poisson's ratio between directions 1 and 3.

`nu23`

Poisson's ratio between directions 2 and 3.

`g12`

Shear modulus between directions 1 and 2.

`g13`

Shear modulus between directions 1 and 3.

`g23`

Shear modulus between directions 2 and 3.

`ep1`

Strain threshold for damage in direction 1.

`ep2`

Strain threshold for damage in direction 2.

`ep3`

Strain threshold for damage in direction 3.

`ep12`

Strain threshold for damage in direction 12.

`ep13`

Strain threshold for damage in direction 13.

`ep23`

Strain threshold for damage in direction 23.

`dc1`

Critical damage defining the rupture criterion, in direction 1.

`dc2`

Critical damage defining the rupture criterion, in direction 2.

`dc3`

Critical damage defining the rupture criterion, in direction 3.

`dc12`

Critical damage defining the rupture criterion, in direction 12.

`dc13`

Critical damage defining the rupture criterion, in direction 13.

`dc23`

Critical damage defining the rupture criterion, in direction 23.

`a1`

Parameter of the delayed damage model, for the direction 1.

`a2`

Parameter of the delayed damage model, for the direction 2.

`a3`

Parameter of the delayed damage model, for the direction 3.

`a12`

Parameter of the delayed damage model, for the direction 12.

`a13`

Parameter of the delayed damage model, for the direction 13.

`a23`

Parameter of the delayed damage model, for the direction 23.

`to1`

Characteristic time of the delayed damage model in direction 1. (1/to) represents the maximum damage rate.

`to2`

Characteristic time of the delayed damage model in direction 2. (1/to) represents the maximum damage rate.

`to3`

Characteristic time of the delayed damage model in direction 3. (1/to) represents the maximum damage rate.

`to12`

Characteristic time of the delayed damage model in direction 12. (1/to) represents the maximum damage rate.

`to13`

Characteristic time of the delayed damage model in direction 13. (1/to) represents the maximum damage rate.

`to23`

Characteristic time of the delayed damage model in direction 23. (1/to) represents the maximum damage rate.

`s01`

Critical strain for damage in direction 1.

`s02`

Critical strain for damage in direction 2.

`s03`

Critical strain for damage in direction 3.

`s012`

Critical strain for damage in direction 12.

`s013`

Critical strain for damage in direction 13.

`s023`

Critical strain for damage in direction 23.

`LECTURE`

List of the elements concerned.

Comments:

This option may be repeated as many times as necessary.

The associated coordinate system is defined by the directive "COMP" (see GBC_0095) and GBC_0096)):

- "COMP" "CORTHO" for the shells;
- "COMP" "MORTHO" for the continuum elements in 3D and in 2D plane strain and axisymmetric.

Outputs:

The different components of the ECR table are as follows, for the continuum elements:

ECR(1): Pressure ($1/3\sigma_{kk}$).

ECR(2): Von Mises criterion.

ECR(3:7) : Unused.

ECR(8) : d1 - damage in direction 1.

ECR(9) : d2 - damage in direction 2.

ECR(10): d3 - damage in direction 3.

ECR(11): d12 - damage in direction 12.

ECR(12): d13 - damage in direction 13.

ECR(13): d23 - damage in direction 23.

ECR(14): d1 - damage not corrected (before delay effect) in direction 1.

ECR(15): d2 - damage not corrected (before delay effect) in direction 2.

ECR(16): d3 - damage not corrected (before delay effect) in direction 3.

ECR(17): d12 - damage not corrected (before delay effect) in direction 12.

ECR(18): d13 - damage not corrected (before delay effect) in direction 13.

ECR(19): d23 - damage not corrected (before delay effect) in direction 23.

ECR(20): T - time.

7.7.30 ODMS : ONERA DAMAGE MODEL (only in 3D)

Object:

The directive is used to enter materials with an orthotropic (local) behaviour into a coordinate system defined by the user, coupling with damage. There is coupling between damage (as material LEM1) and orthotropy (as material ORTS). There are 3 matrix damages : d_1^m, d_2^m, d_3^m (direction 1, 2 and 3), and 4 fiber damages : $d_1^f, d_2^f, d_3^f, d_4^f$ (traction direction 1, compression direction 1, traction direction 2, compression direction 2). Each damage evolution rate is a function of strain tensor following the ONERA Damage Mechanics law.
This material behaviour is intended for braided and woven composite materials.

References:

The Onera damage model (ODM) is theorized in [990]. It's implementation in Europlexus is studied in [992].

Two parameters (for each damage) allow to introduce a limitation of the damage rate (thanks to the delayed damage effect) in order to avoid the mesh dependency.

$$\dot{d} = \frac{1}{tau}\left(1 - e^{-a<D_{nc}-d>}\right)$$

The constitutive law is :

$$C_{eff}^{-1} = S_{eff} = S_0 + \sum_{i=1}^{3} \eta_i d_i^m H_{0i}^m + \sum_{j=1}^{4} d_j^f H_{0j}^f = C_{matrix}^{-1} + \sum_{j=1}^{4} d_j^f H_{0j}^f$$

$$[\sigma] = C_{matrix}.[\epsilon] - C_{eff}.[\epsilon_{residual}]$$

where the matrix 6x6 S_0 and H_0^i are defined as:

Compliance S_0: $S_0(1,1) = 1/E_1^0$, $S_0(2,2) = 1/E_2^0$, $S_0(3,3) = 1/E_3^0$; $S_0(1,2) = -\nu_{12}/E_1^0$, $S_0(1,3) = -\nu_{13}/E_1^0$, $S_0(2,3) = -\nu_{23}/E_2^0$; $S_0(4,4) = 1/G_{12}^0$, $S_0(5,5) = 1/G_{23}^0$, $S_0(6,6) = 1/G_{13}^0$, and 0 otherwise.

Matrix damage effect tensors H_0^{m1}, H_0^{m2}, H_0^{m3}:
H_0^{m1}: $H_0^{m1}(1,1) = h_1^n/E_1^0$, $H_0^{m1}(4,4) = h_1^p/G_{12}^0$, $H_0^{m1}(6,6) = h_1^{pn}/G_{13}^0$, and 0 otherwise.
H_0^{m2}: $H_0^{m2}(2,2) = h_2^n/E_2^0$, $H_0^{m2}(4,4) = h_2^p/G_{12}^0$, $H_0^{m2}(5,5) = h_2^{pn}/G_{23}^0$, and 0 otherwise.
H_0^{m3}: $H_0^{m3}(3,3) = h_3^n/E_3^0$, $H_0^{m3}(5,5) = h_3^p/G_{23}^0$, $H_0^{m3}(6,6) = h_3^{pn}/G_{13}^0$, and 0 otherwise.

Fiber damage effect tensors H_0^{f1}, H_0^{f2}, H_0^{f3}, H_0^{f4}:
H_0^{fi}: $H_0^{fi}(1,1) = hf_1^i/E_1^0$, $H_0^{fi}(2,2) = hf_2^i/E_2^0$, $H_0^{fi}(3,3) = hf_3^i/E_3^0$, $H_0^{fi}(1,2) = H_0^{fi}(2,1) = hf_4^i.S_0(1,2)$, $H_0^{fi}(1,3) = H_0^{fi}(3,1) = hf_5^i.S_0(1,3)$, $H_0^{fi}(2,3) = H_0^{fi}(3,2) = hf_6^i.S_0(2,3)$, $H_0^{fi}(4,4) = hf_7^i/G_{12}^0$, $H_0^{fi}(5,5) = hf_8^i/G_{23}^0$, $H_0^{fi}(6,6) = hf_9^i/G_{13}^0$.

Then, the matrix thermodynamic forces y_i^n, y_i^t are computed in function of positive strain as following: $y_i^n = \frac{1}{2}C_{ii}^0.\epsilon_i^+.\epsilon_i^+$ for $i \in 1,2,3$ and $y_1^t = (b_1.C_{66}^0.\epsilon_{13}^+.\epsilon_{13}^+ + b_2.C_{44}^0.\epsilon_{12}^+.\epsilon_{12}^+)$, $y_2^t = (b_3.C_{55}^0.\epsilon_{23}^+.\epsilon_{23}^+ + b_4.C_{44}^0.\epsilon_{12}^+.\epsilon_{12}^+)$, $y_3^t = (b_5.C_{66}^0.\epsilon_{13}^+.\epsilon_{13}^+ + b_6.C_{55}^0.\epsilon_{23}^+.\epsilon_{23}^+)$.
The fiber thermodynamic forces y_f^i are computed in function of strain as following: $y_f^1 = \frac{1}{2}C_0(1,1).\epsilon_1^+.\epsilon_1^+$, $y_f^2 = \frac{1}{2}C_0(1,1).\epsilon_1^-.\epsilon_1^-$, $y_f^3 = \frac{1}{2}C_0(2,2).\epsilon_2^+.\epsilon_2^+$, $y_f^4 = \frac{1}{2}C_0(2,2).\epsilon_2^-.\epsilon_2^-$.

The damage law is the following :

$$d_i = max\left(g_i(y_i), d_i^0\right)$$

where

$$g_i = d_{ci}\left(1 - e^{-\left(\frac{<\sqrt{y_i}-\sqrt{y_{0i}}>}{\sqrt{y_{ci}}}\right)^{p_i}}\right)$$

and if : $\Delta\epsilon_i^f \leq \bar{\epsilon}_i$,

$$\eta_i = 1$$

if : $-\Delta\epsilon_i^f \leq \bar{\epsilon}_i \leq \Delta\epsilon_i^f$,

$$\eta_i = \frac{1}{2}\left(1 - cos\left(\frac{\Pi}{2}\frac{\bar{\epsilon}_i + \Delta\epsilon_i^f}{\Delta\epsilon_i^f}\right)\right)$$

if : $\bar{\epsilon}_i \leq -\Delta\epsilon_i^f$,

$$\eta_i = 0$$

where

$$\Delta\epsilon_i^f = (1 + a_{if}d_i^m)\Delta\epsilon_i^0$$

Syntax:

```
"ODMS"  "RO"    rho    "YG1"   yg1    "YG2"   yg2    "YG3"   yg3
        "NU12"  nu12   "NU13"  nu13   "NU23"  nu23   "G12"   g12
        "G13"   g13    "G23"   g23    "DCN1"  dcn1   "DCN2"  dcn2
        "DCN3"  dcn3   "DCT1"  dct1   "DCT2"  dct2   "DCT3"  dct3
        "YON1"  yon1   "YON2"  yon2   "YON3"  yon3   "YCN1"  ycn1
        "YCN2"  ycn2   "YCN3"  ycn3   "YOT1"  yot1   "YOT2"  yot2
        "YOT3"  yot3   "YCT1"  yct1   "YCT2"  yct2   "YCT3"  yct3
        "PN1"   pn1    "PN2"   pn2    "PN3"   pn3    "PT1"   pt1
        "PT2"   pt2    "PT3"   pt3    "HN1"   hn1    "HN2"   hn2
        "HN3"   hn3    "HP1"   hp1    "HP2"   hp2    "HP3"   hp3
        "HHP1"  hhp1   "HHP2"  hhp2   "HHP3"  hhp3   "XSI1"  xsi1
        "XSI2"  xsi2   "XSI3"  xsi3   "AIF1"  aif1   "AIF2"  aif2
        "AIF3"  aif3   "DEO1"  deo1   "DEO2"  deo2   "DEO3"  deo3
        "B1"    b1     "B2"    b2     "B3"    b3     "B4"    b4
        "B5"    b5     "B6"    b6     "TAU1"  tau1   "TAU2"  tau2
        "TAU3"  tau3   "A1"    a1     "A2"    a2     "A3"    a3
        "GHOS"  ghos   "LATE"  late
     <  "DCF1"  dcf1   "DCF2"  dcf2   "DCF3"  dcf3   "DCF4"  dcf4
        "YFO1"  yfo1   "YFO2"  yfo2   "YFO3"  yfo3   "YFO4"  yfo4
        "PF1"   pf1    "PF2"   pf2    "PF3"   pf3    "PF4"   pf4
        "HF11"  hf11   "HF21"  hf21   "HF31"  hf31   "HF41"  hf41
        "HF51"  hf51   "HF61"  hf61   "HF71"  hf71   "HF81"  hf81
        "HF91"  hf91   "HF12"  hf22   "HF32"  hf32   "HF42"  hf42
        "HF52"  hf52   "HF62"  hf62   "HF72"  hf72   "HF82"  hf82
        "HF92"  hf92   "HF13"  hf23   "HF33"  hf33   "HF43"  hf43
        "HF53"  hf53   "HF63"  hf63   "HF73"  hf73   "HF83"  hf83
        "HF93"  hf93   "HF14"  hf14   "HF34"  hf34   "HF44"  hf44
        "HF54"  hf54   "HF64"  hf64   "HF74"  hf74   "HF84"  hf84
        "HF94"  hf94   "HF24"  hf24   "AF1"   af1    "AF2"   af2
        "AF3"   af3    "AF4"   af4    "TOF1"  tof1   "TOF2"  tof2
        "TOF3"  tof3   "TOF4"  tof4   "RDC1"  rdc1   "RDC2"  rdc2
```

```
"RDC3"  rdc3  "RDC4"  rdc4  "EPS1"  eps1  "EPS2"  eps2
"EPS3"  eps3  "EPS4"  eps4   >
/LECTURE/
```

`rho`

Density of the material.

`yg1`

Young's modulus along direction 1.

`yg2`

Young's modulus along direction 2.

`yg3`

Young's modulus along direction 3.

`nu12`

Poisson's ratio between directions 1 and 2.

`nu13`

Poisson's ratio between directions 1 and 3.

`nu23`

Poisson's ratio between directions 2 and 3.

`g12`

Shear modulus between directions 1 and 2.

`g13`

Shear modulus between directions 1 and 3.

`g23`

Shear modulus between directions 2 and 3.

`dcn1`

Normal critical damage defining the rupture criterion, in direction 1.

`dcn2`

Normal critical damage defining the rupture criterion, in direction 2.

`dcn3`

Normal critical damage defining the rupture criterion, in direction 3.

`dct1`

Tangential critical damage defining the rupture criterion, in direction 1.

`dct2`

Tangential critical damage defining the rupture criterion, in direction 2.

`dct3`

Tangential critical damage defining the rupture criterion, in direction 3.

`yon1`

Normal damage threshold in direction 1.

`yon2`

Normal damage threshold in direction 2.

`yon3`

Normal damage threshold in direction 3.

`ycn1`

Critical normal damage threshold in direction 1.

`ycn2`

Critical normal damage threshold in direction 2.

`ycn3`

Critical normal damage threshold in direction 3.

`yot1`

Tangential damage threshold in direction 1.

`yot2`

Tangential damage threshold in direction 2.

`yot3`

Tangential damage threshold in direction 3.

`yct1`

Critical tangential damage threshold in direction 1.

`yct2`

Critical tangential damage threshold in direction 2.

`yct3`

Critical tangential damage threshold in direction 3.

`pn1`

Parameter in normal damage law for direction 1.

`pn2`

Parameter in normal damage law for direction 2.

`pn3`

Parameter in normal damage law for direction 3.

`pt1`

Parameter in tangential damage law for direction 1.

`pt2`

Parameter in tangential damage law for direction 2.

`pt3`

Parameter in tangential damage law for direction 3.

`hn1`

Parameter in damaged constitutive law for normal direction 1.

`hn2`

Parameter in damaged constitutive law for normal direction 2.

`hn3`

Parameter in damaged constitutive law for normal direction 3.

`hp1`

Parameter in damaged constitutive law for tangential direction 1.

`hp2`

Parameter in damaged constitutive law for tangential direction 2.

`hp3`

Parameter in damaged constitutive law for tangential direction 3.

`hhp1`

Parameter in damaged constitutive law for tangential direction 1.

`hhp2`

Parameter in damaged constitutive law for tangential direction 2.

`hhp3`

Parameter in damaged constitutive law for tangential direction 3.

`xsi1`

Parameter to take into account residual deformation.

`xsi2`

Parameter to take into account residual deformation.

`xsi3`

Parameter to take into account residual deformation.

`aif1`

Parameter to evaluate limit deformation for activation index 1 calculus.

`aif2`

Parameter to evaluate limit deformation for activation index 2 calculus.

`aif3`

Parameter to evaluate limit deformation for activation index 3 calculus.

`deo1`

Parameter to evaluate limit deformation for activation index 1 calculus.

`deo2`

Parameter to evaluate limit deformation for activation index 2 calculus.

`deo3`

Parameter to evaluate limit deformation for activation index 3 calculus.

`b1`

Parameter for thermodynamic forces calculus.

`b2`

Parameter for thermodynamic forces calculus.

`b3`

Parameter for thermodynamic forces calculus.

`b4`

Parameter for thermodynamic forces calculus.

`b5`

Parameter for thermodynamic forces calculus.

`b6`

Parameter for thermodynamic forces calculus.

`tau1`

Characteristic time of the delayed damage model in direction 1. (1/tau) represents the maximum damage rate.

`tau2`

Characteristic time of the delayed damage model in direction 2. (1/tau) represents the maximum damage rate.

`tau3`

Characteristic time of the delayed damage model in direction 3. (1/tau) represents the maximum damage rate.

`a1`

Parameter of the delayed damage model, for the direction 1.

`a2`

Parameter of the delayed damage model, for the direction 2.

`a3`

Parameter of the delayed damage model, for the direction 3.

`ghos`

Parameter driving the post damage evolution: case 0. : nothing special happens (default case is 0.); case 1. : if a fiber damage is almost critical (ratio rdc1, rdc2, rdc3 rdc4) at a Gauss point of the element, then the element becomes Ghost; case 2. : if a strain reaches its given limit value at a Gauss point of the element, then the element becomes Ghost; case 3. : if case 1 or case 2 is reached, then the element becomes Ghost; case 4. : if there is an almost critical damage at each Gauss points of the element, then the element becomes Ghost; case 5. : if there is a critical strain at each Gauss points of the element, then the element becomes Ghost; case 6. : if case 4 or case 5, then the element becomes Ghost.

`late`

Parameter driving the delay effect : case 0. : delay effect not active (default case is 0.) ; case 1. : delay effect is active in calculus, for the 3 matrix damages (and the 4 fiber damages).

`dcf1`

Normal critical damage defining the rupture criterion of fiber in tension, in direction 1.

`dcf2`

Normal critical damage defining the rupture criterion of fiber in compression, in direction 1.

`dcf3`

Normal critical damage defining the rupture criterion of fiber in tension, in direction 2.

`dcf4`

Normal critical damage defining the rupture criterion of fiber in compression, in direction 2.

`yfo1`

Damage threshold in tension, in direction 1.

`yfo2`

Damage threshold in compression, in direction 1.

`yfo3`

Damage threshold in tension, in direction 2.

`yfo4`

Damage threshold in compression, in direction 2.

`yfc1`

Critical damage threshold in tension, in direction 1.

`yfc2`

Critical damage threshold in compression, in direction 1.

`yfc3`

Critical damage threshold in tension, in direction 2.

`yfc4`

Critical damage threshold in compression, in direction 2.

`pf1`

Parameter in tangential fiber damage law for direction 1, in tension.

`pf2`

Parameter in tangential fiber damage law for direction 1, in compression.

`pf3`

Parameter in tangential fiber damage law for direction 2, in tension.

`pf4`

Parameter in tangential fiber damage law for direction 2, in compression.

`hf11`

Fiber parameter in damaged constitutive law for tensile direction 1.

`hf21`

Fiber parameter in damaged constitutive law for tensile direction 1.

`hf31`

Fiber parameter in damaged constitutive law for tensile direction 1.

`hf41`

Fiber parameter in damaged constitutive law for tensile direction 1.

`hf51`

Fiber parameter in damaged constitutive law for tensile direction 1.

`hf61`

Fiber parameter in damaged constitutive law for tensile direction 1.

`hf71`

Fiber parameter in damaged constitutive law for tensile direction 1.

`hf81`

Fiber parameter in damaged constitutive law for tensile direction 1.

`hf91`

Fiber parameter in damaged constitutive law for tensile direction 1.

`hf12`

Fiber parameter in damaged constitutive law for compressive direction 1.

`hf22`

Fiber parameter in damaged constitutive law for compressive direction 1.

`hf32`

Fiber parameter in damaged constitutive law for compressive direction 1.

`hf42`

Fiber parameter in damaged constitutive law for compressive direction 1.

`hf52`

Fiber parameter in damaged constitutive law for compressive direction 1.

`hf62`

Fiber parameter in damaged constitutive law for compressive direction 1.

`hf72`

Fiber parameter in damaged constitutive law for compressive direction 1.

`hf82`

Fiber parameter in damaged constitutive law for compressive direction 1.

`hf92`

Fiber parameter in damaged constitutive law for compressive direction 1.

`hf13`

Fiber parameter in damaged constitutive law for tensile direction 2.

`hf23`

Fiber parameter in damaged constitutive law for tensile direction 2.

`hf33`

Fiber parameter in damaged constitutive law for tensile direction 2.

`hf43`

Fiber parameter in damaged constitutive law for tensile direction 2.

`hf53`

Fiber parameter in damaged constitutive law for tensile direction 2.

`hf63`

Fiber parameter in damaged constitutive law for tensile direction 2.

`hf73`

Fiber parameter in damaged constitutive law for tensile direction 2.

`hf83`

Fiber parameter in damaged constitutive law for tensile direction 2.

`hf93`

Fiber parameter in damaged constitutive law for tensile direction 2.

`hf14`

Fiber parameter in damaged constitutive law for compressive direction 2.

`hf24`

Fiber parameter in damaged constitutive law for compressive direction 2.

`hf34`

Fiber parameter in damaged constitutive law for compressive direction 2.

`hf44`

Fiber parameter in damaged constitutive law for compressive direction 2.

`hf54`

Fiber parameter in damaged constitutive law for compressive direction 2.

`hf64`

Fiber parameter in damaged constitutive law for compressive direction 2.

`hf74`

Fiber parameter in damaged constitutive law for compressive direction 2.

`hf84`

Fiber parameter in damaged constitutive law for compressive direction 2.

`hf94`

Fiber parameter in damaged constitutive law for compressive direction 2.

`tof1`

Characteristic time of the delayed damage model in tensile direction 1. (1/tau) represents the maximum damage rate.

`tof2`

Characteristic time of the delayed damage model in compressive direction 1. (1/tau) represents the maximum damage rate.

`tof3`

Characteristic time of the delayed damage model in tensile direction 2. (1/tau) represents the maximum damage rate.

`tof4`

Characteristic time of the delayed damage model in compressive direction 2. (1/tau) represents the maximum damage rate.

`af1`

Parameter of the delayed damage model, for the tensile direction 1.

`af2`

Parameter of the delayed damage model, for the compressive direction 1.

`af3`

Parameter of the delayed damage model, for the tensile direction 2.

`af4`

Parameter of the delayed damage model, for the compressive direction 2.

`rdc1`

Fiber damage (tensile direction 1) ratio for which element becomes ghost.

`rdc2`

Fiber damage (compressive direction 1) ratio for which element becomes ghost.

`rdc3`

Fiber damage (tensile direction 2) ratio for which element becomes ghost.

`rdc4`

Fiber damage (compressive direction 2) ratio for which element becomes ghost.

`eps1`

Strain limit (tensile direction 1) for which element becomes ghost.

`eps2`

Strain limit (compressive direction 1) for which element becomes ghost.

`eps3`

Strain limit (tensile direction 2) for which element becomes ghost.

`eps4`

Strain limit (compressive direction 2) for which element becomes ghost.

`LECTURE`

List of the elements concerned.

Comments:

This option may be repeated as many times as necessary.

The associated coordinate system is defined by the directive "COMPLEMENT" (see pages C.95, section 6.33 and C.96, section 6.34):

- "COMPLEMENT" "CORTHO" for the shells;
- "COMPLEMENT" "MORTHO" for the continuum elements in 3D and in 2D plane strain and axisymmetric.

Verify that this material is available for your elements in the tables of page C.100, section 7.

Outputs:

The different components of the ECR table are as follows, for the continuum elements:

ECR(1): Pressure.

ECR(2): Von Mises criterion.

ECR(3): d1 - damage in direction 1.

ECR(4): d2 - damage in direction 2.

ECR(5): d3 - damage in direction 3.

ECR(6): eta1 - activation damage index in direction 1.

ECR(7): eta2 - activation damage index in direction 2.

ECR(8): eta3 - activation damage index in direction 3.

ECR(9): epsilon s 11 - residual deformation 11.

ECR(10): epsilon s 22 - residual deformation 22.

ECR(11): epsilon s 33 - residual deformation 33.

ECR(12): epsilon s 12 - residual deformation 12.

ECR(13): epsilon s 23 - residual deformation 23.

ECR(14): epsilon s 13 - residual deformation 13.

ECR(15): epsilon r 11 - residual deformation 11.

ECR(16): epsilon r 22 - residual deformation 22.

ECR(17): epsilon r 33 - residual deformation 33.

ECR(18): epsilon r 12 - residual deformation 12.

ECR(19): epsilon r 23 - residual deformation 23.

ECR(20): epsilon r 13 - residual deformation 13.

ECR(21) : df1t - fiber tensile damage in direction 1.

ECR(22) : df1c - fiber compressive damage in direction 1.

ECR(23): df2t - fiber tensile damage in direction 2.

ECR(24): df2c - fiber compressive damage in direction 2.

ECR(25): T - time.

7.7.31 WOOD

Object:

This directive allows to define the BOIS (wood) material, that is used for example for packaging and transportation as a shock absorber. Only the compressive behaviour of the material is considered, while the material response in traction is approximated as perfectly linear (or linear perfecly plastic) because of the lack of experimental data.

Syntax:

```
"BOIS"  "RO"  rho    "YG1"  yg1    "YG2"   yg2  "YG3" yg3
        "NU12" nu12  "NU13" nu13   "NU23" nu23
        "G12"  g12   "G13"  g13    "G23" g23
        "SY_1" sy1  "SY_2"  sy2   "SY_3"  sy3
        "ED_1" ed1  "ED_2"  ed2   "ED_3"  ed3
      < "TR_1" tr1  > < "TR_2" tr2  > < "TR_3" tr3  >
      < "COE1" coe1 > < "COE2" coe2 > < "COE3" coe3 >
      < "EDCV" edcv > < "DIRF" idir >
      < "CI23" ci23 > < "CI31" ci31 > < "CI12" ci12 >
      < $[ "RUPT" ; "DECO"]$
        < "CONT" |[ "TR1M" tr1m ; "TR2M" tr2m ; "TR3M" tr3m ;
                    "T23M" t23m ; "T31M" t31m ; "T12M" t12m ;
                    "CO1M" co1m ; "CO2M" co2m ; "CO3M" co3m ]|> ;
        < "DPLA" |[ "EP23" ep23 ; "EP31" ep31 ; "EP12" ep12 ]|> >

            /LECTURE/
```

`rho`

Density of the material.

`yg1`

Young's modulus along direction 1.

`yg2`

Young's modulus along direction 2.

`yg3`

Young's modulus along direction 3.

`nu12`

Poisson's ratio between directions 1 and 2.

`nu13`

Poisson's ratio between directions 1 and 3.

`nu23`

Poisson's ratio between directions 2 and 3.

`g12`

Shear modulus between directions 1 and 2.

`g13`

Shear modulus between directions 1 and 3.

`g23`

Shear modulus between directions 2 and 3.

`sy1`

Elastic limit in compression along the first orthotropy direction.

`sy2`

Elastic limit in compression along the second orthotropy direction.

`sy3`

Elastic limit in compression along the third orthotropy direction.

`ed1`

Limit deformation before reconsolidation along the first orthotropy direction.

`ed2`

Limit deformation before reconsolidation along the second orthotropy direction.

`ed3`

Limit deformation before reconsolidation along the third orthotropy direction.

`tr1`

Optional keyword : Limit elastic stress in traction along the first orthotropy direction. If omitted, an elastic behaviour is assumed along this direction.

`tr2`

Optional keyword : Limit elastic stress in traction along the second orthotropy direction. If omitted, an elastic behaviour is assumed along this direction.

`tr3`

Optional keyword : Limit elastic stress in traction along the third orthotropy direction. If omitted, an elastic behaviour is assumed along this direction.

`coe1`

Optional keyword : Scale factor between initial Young's modulus and Young's modulus after reconsolidation in direction 1.

`coe2`

Optional keyword : Scale factor between initial Young's modulus and Young's modulus after reconsolidation in direction 2.

`coe3`

Optional keyword : Scale factor between initial Young's modulus and Young's modulus after reconsolidation in direction 3.

`edcv`

Optional keyword : Threshold deformation in all directions starting convergence of the material towards a consolidated linear elastic material (see comment below).

`idir`

Optional keyword : Spatial direction of wood fibers, if not the first orthotropy direction (see comment below).

`ci23`

Optional keyword : Limit elastic shear stress in the (second orthotropy direction,third orthotropy direction) plane. If omitted, an elastic behaviour is assumed. Only available in 3D.

`ci31`

Optional keyword : Limit elastic shear stress in the (third orthotropy direction,first orthotropy direction) plane. If omitted, an elastic behaviour is assumed. Only available in 3D.

`ci12`

Optional keyword : Limit elastic shear stress in the (first orthotropy direction,second orthotropy direction) plane. If omitted, an elastic behaviour is assumed. Only available in 3D.

`RUPT`

Optional keyword : Introduces an element failure model represented by a failure criterion and by a failure limit value. Only available in 3D.

`DECO`

Optional keyword : Introduces an model of automatic separation of elements defined by a failure criterion and by a failure limit value. Only available in 3D. Only available for CUB8 element. More explanations can be found in [928].

`CONT`

Failure criterion based upon stress associated to RUPT keyword or DECO keyword (but not the both). Only available in 3D.

`DPLA`

Failure criterion based upon plastic strain associated to RUPT keyword or DECO keyword (but not the both). Only available in 3D.

`tr1m`

Optional keyword : Failure limit value for stress in traction along the first orthotropy direction.

`tr2m`

Optional keyword : Failure limit value for stress in traction along the second orthotropy direction.

`tr3m`

Optional keyword : Failure limit value for stress in traction along the third orthotropy direction.

`t23m`

Optional keyword : Failure limit value for shear stress in the (second orthotropy direction,third orthotropy direction) plane.

`t31m`

Optional keyword : Failure limit value for shear stress in the (third orthotropy direction,first orthotropy direction) plane.

`t12m`

Optional keyword : Failure limit value for shear stress in the (first orthotropy direction,second orthotropy direction) plane.

`co1m`

Failure limit value for stress in compression along the first orthotropy direction.

`co2m`

Optional keyword : Failure limit value for stress in compression along the second orthotropy direction.

`co3m`

Optional keyword : Failure limit value for stress in compression along the third orthotropy direction.

`ep23`

Optional keyword : Failure limit value for shear plastic strain in the (second orthotropy direction,third orthotropy direction) plane.

`ep31`

Optional keyword : Failure limit value for shear plastic strain in the (third orthotropy direction,first orthotropy direction) plane.

`ep12`

Optional keyword : Failure limit value for shear plastic strain in the (first orthotropy direction,second orthotropy direction) plane.

`LECTURE`

List of the elements concerned.

Comments:

This material model is taken from the thesis of P. François: “Plasticité du bois en compression multi-axiale : Application à l’absorption d’énergie mécanque”. Doctoral Thesis of the Bordeaux I University (October 1992).

The associated coordinate system is defined by the option `MORTHO` (see page C.96) for the continuum elements in 2D and 3D.

Verify that this material is available for your elements, by means of the tables of page C.100.

Compression instability may be encountered after reconsolidation, since the material becomes very stiff in the consolidated direction and is still very soft in the other directions. To overcome this problem, it may be considered that the orthotropy of the material is lost when reconsolidation is achieved, since the microstructure has been completely crushed and all the voids filled. This assumption is taken from the observations made in the PhD Thesis of C. Adalian: ”The behaviour of wood under multiaxial dynamic compression - Use for the modelling of crashes of containers”, PhD Thesis of Bordeaux I University (1998)

Such a behaviour is activated using `EDCV` keyword. The floating value associated to this keyword defines the level of deformation above which the process of convergence towards an elastic isotropic material is started. It should be less than the reconsolidation limit given in each orthotropy direction.

The convergence process is such that material characteristics of the element converge continuously towards the isotropic consolidated values, whatever the first direction is in which reconsolidation is achieved.

Isotropic elastic parameters of the consolidated materials are deduced from elastic parameters given in the wood fibers direction. If this direction is not the first orthotropy direction, it can be specified using `"DIRF"` keyword. Isotropic consolidated parameters are then obtained by the formulae (assuming the fibers direction is direction 1):

$$E_c = E_1.coe1$$

$$\nu_c = \frac{\nu_{12} + \nu_{13}}{2}$$

$$G_c = \frac{E_c}{2.(1+\nu)}$$

Outputs:

The different components of the ECR table are as follows, for the continuum elements:

ECR(1) : Pressure.

ECR(2) : Von mises criterion.

ECR(3) : Plastic strain along the first orthotropy direction.

ECR(4) : Plastic strain along the second orthotropy direction.

ECR(5) : Plastic strain along the third orthotropy direction.

ECR(6) : Principal stress along the first orthotropy direction.

ECR(7) : Principal stress along the second orthotropy direction.

ECR(8) : Principal stress along the third orthotropy direction.

ECR(9) : Total strain along the first orthotropy direction.

ECR(10): Total strain along the second orthotropy direction.

ECR(11): Total strain along the third orthotropy direction.

ECR(12): Flag for isotropic elastic converged material (0: not fully converged, 1: fully converged)

ECR(13): Convergence level in the first orthotropy direction.

ECR(14): Convergence level in the second orthotropy direction.

ECR(15): Convergence level in the third orthotropy direction.

ECR(16): Failure flag (0=virgin Gauss Point, 1=failed Gauss Point) (only in 3D).

ECR(17): Shear stress in the (second orthotropy direction,third orthotropy direction) plane (only in 3D).

ECR(18): Shear stress in the (third orthotropy direction,first orthotropy direction) plane (only in 3D).

ECR(19): Shear stress in the (first orthotropy direction,second orthotropy direction) plane (only in 3D).

ECR(20): Shear Plastic strain in the (second orthotropy direction,third orthotropy direction) plane (only in 3D).

ECR(21): Shear Plastic strain in the (third orthotropy direction,first orthotropy direction) plane (only in 3D).

ECR(22): Shear Plastic strain in the (first orthotropy direction,second orthotropy direction) plane (only in 3D).

ECR(23): Shear total strain in the (second orthotropy direction,third orthotropy direction) plane (only in 3D).

ECR(24): Shear total strain in the (third orthotropy direction,first orthotropy direction) plane (only in 3D).

ECR(25): Shear total strain in the (first orthotropy direction,second orthotropy direction) plane (only in 3D).

7.7.32 ORSR : RATE DEPENDENT LINEAR ORTHOTROPY (Local basis)

Object:

Attention: The description of the material is not showing all capabilities of the material. The material allows erosion and has several more input and output variables.

The directive is based on ORTS material law, with the possibility to define rate dependent material properties. 9 material properties can be made rate dependent: E_{11}, E_{22}, E_{33}, ν_{12}, ν_{13}, ν_{23}, G_{12}, G_{13}, G_{23}. The rate dependency is based on the following polynomial law:

$$X_{ij}(\dot{\varepsilon}) = \sum_{k=0}^{5} X_{ij}^{k}(log(\dot{\varepsilon}))^{k} \tag{1}$$

As for ORTS directive, stress and strain are expressed in the user coordinate system.

Syntax:

```
  "ORSR"  "RO"  rho    "YG10"  yg10  "YG11"  yg11
           "YG12"  yg12  "YG13"  yg13 "YG14"  yg14
           "YG15"  yg15  "YG20"  yg20 "YG21"  yg21
               "YG22"  yg22  "YG23"  yg23 "YG24"  yg24
               "YG25"  yg25  "YG30"  yg30 "YG31"  yg31
               "YG32"  yg32  "YG33"  yg33 "YG34"  yg34
               "YG35"  yg35  "N120"  n120 "N121"  n121
               "N122"  n122 "N123"  n123  "N124"  n124
               "N125"  n125 "N130"  n130  "N131"  n131
               "N132"  n132 "N133"  n133  "N134"  n134
               "N135"  n135 "N230"  n230  "N231"  n231
               "N232"  n232 "N233"  n233  "N234"  n234
"N235"  n235 "G120"  g120  "G121"  g121
               "G122"  g122  "G123"  g123 "G124"  g124
               "G125"  g125  "G130"  g130 "G131"  g131
               "G132"  g132  "G133"  g133 "G134"  g134
               "G135"  g135  "G230"  g230 "G231"  g231
               "G232"  g232  "G233"  g233 "G234"  g234
               "G235"  g235  "MINE"  MINE "MAXE"  MAXE
<"XT1"  xt1   "XT2"  xt2   "XT3" xt3
               "XC1"  xc1   "XC2"  xc2   "XC3" xc3
               "RST1" rst1  "RST2" rst2  "RST3" rst3
               "CRIT" icrit>  /LECTURE/
```

`rho`

Density of the material.

`yg10`

0th order coefficient for the rate dependency of the Young's modulus along direction 1. Without rate dependency, Young's modulus along direction 1.

`yg11`

1st order coefficient for the rate dependency of the Young's modulus along direction 1.

`yg12`

2nd order coefficient for the rate dependency of the Young's modulus along direction 1.

`yg13`

3rd order coefficient for the rate dependency of the Young's modulus along direction 1.

`yg14`

4th order coefficient for the rate dependency of the Young's modulus along direction 1.

`yg15`

5th order coefficient for the rate dependency of the Young's modulus along direction 1.

`yg20`

0th order coefficient for the rate dependency of the Young's modulus along direction 2. Without rate dependency, Young's modulus along direction 2.

`yg21`

1st order coefficient for the rate dependency of the Young's modulus along direction 2.

`yg22`

2nd order coefficient for the rate dependency of the Young's modulus along direction 2.

`yg23`

3rd order coefficient for the rate dependency of the Young's modulus along direction 2.

`yg24`

4th order coefficient for the rate dependency of the Young's modulus along direction 2.

`yg25`

5th order coefficient for the rate dependency of the Young's modulus along direction 2.

`yg30`

0th order coefficient for the rate dependency of the Young's modulus along direction 3. Without rate dependency, Young's modulus along direction 3.

`yg31`

1st order coefficient for the rate dependency of the Young's modulus along direction 3.

`yg32`

2nd order coefficient for the rate dependency of the Young's modulus along direction 3.

`yg33`

3rd order coefficient for the rate dependency of the Young's modulus along direction 3.

`yg34`

4th order coefficient for the rate dependency of the Young's modulus along direction 3.

`yg35`

5th order coefficient for the rate dependency of the Young's modulus along direction 3.

`n120`

0th order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2. Without rate dependency, Poisson's ratio between directions 1 and 2.

`n121`

1st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2.

`n122`

2nd order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2.

`n123`

3rd order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2.

`n124`

4st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2.

`n125`

5st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2.

`n130`

0th order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3. Without rate dependency, Poisson's ratio between directions 1 and 3.

`n131`

1st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3.

`n132`

2nd order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3.

`n133`

3rd order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3.

`n134`

4st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3.

`n135`

5st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3.

`n230`

0th order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3. Without rate dependency, Poisson's ratio between directions 2 and 3.

`n231`

1st order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3.

`n232`

2nd order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3.

`n233`

3rd order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3.

`n234`

4st order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3.

`n235`

5st order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3.

`g120`

0th order coefficient for the rate dependency of the shear modulus between directions 1 and 2. Without rate dependency, shear modulus between directions 1 and 2.

`g121`

1st order coefficient for the rate dependency of the shear modulus between directions 1 and 2.

`g122`

2nd order coefficient for the rate dependency of the shear modulus between directions 1 and 2.

`g123`

3rd order coefficient for the rate dependency of the shear modulus between directions 1 and 2.

`g124`

4th order coefficient for the rate dependency of the shear modulus between directions 1 and 2.

`g125`

5th order coefficient for the rate dependency of the shear modulus between directions 1 and 2.

`g130`

0th order coefficient for the rate dependency of the shear modulus between directions 1 and 3. Without rate dependency, shear modulus between directions 1 and 3.

`g131`

1st order coefficient for the rate dependency of the shear modulus between directions 1 and 3.

`g132`

2nd order coefficient for the rate dependency of the shear modulus between directions 1 and 3.

`g133`

3rd order coefficient for the rate dependency of the shear modulus between directions 1 and 3.

`g134`

4th order coefficient for the rate dependency of the shear modulus between directions 1 and 3.

`g135`

5th order coefficient for the rate dependency of the shear modulus between directions 1 and 3.

`g230`

0th order coefficient for the rate dependency of the shear modulus between directions 2 and 3. Without rate dependency, shear modulus between directions 2 and 3.

`g231`

1st order coefficient for the rate dependency of the shear modulus between directions 2 and 3.

`g232`

2nd order coefficient for the rate dependency of the shear modulus between directions 2 and 3.

`g233`

3rd order coefficient for the rate dependency of the shear modulus between directions 2 and 3.

`g234`

4th order coefficient for the rate dependency of the shear modulus between directions 2 and 3.

`g235`

5th order coefficient for the rate dependency of the shear modulus between directions 2 and 3.

`MINE`

Lower boundary of the strain rate interval used for the polynomial function identification.

`MAXE`

Upper boundary of the strain rate interval used for the polynomial function identification.

`xt1`

Failure criterion for tension in x-direction.

`xt2`

Failure criterion for tension in y-direction.

`xt3`

Failure criterion for tension in z-direction.

`xc1`

Failure criterion for compression in x-direction.

`xc2`

Failure criterion for compression in y-direction.

`xc3`

Failure criterion for compression in z-direction.

`rst1`

Failure criterion for shear in xy-direction.

`rst2`

Failure criterion for shear in yz-direction.

`rst3`

Failure criterion for shear in xz-direction.

`icrit`

Erosion criteria type (e.g.: tsai-hill)

`LECTURE`

List of the elements concerned.

Comments:

This option may be repeated as many times as necessary.

The associated coordinate system is defined by the directive "COMP" (see GBC_0095 and GBC_0096):

- "COMP" "CORTHO" for the shells and the multilayer element CMC3;
- "COMP" "MORTHO" for the continuum elements in 3D and in 2D plane strain and axisymmetric.

Outputs:

The different components of the ECR table are as follows, for the continuum elements:

ECR(1): pressure.

ECR(2): Von Mises criterion.

ECR(16): v1 - Strain rate in direction 1.

ECR(17): v2 - Strain rate in direction 2.

ECR(18): v3 - Strain rate in direction 3.

ECR(19): v4 - Strain rate for shear in 12-direction.

ECR(20): v5 - Strain rate for shear in 23-direction.

ECR(21): v6 - Strain rate for shear in 13-direction.

ECR(22): Apparent modulus in direction 1.

ECR(23): Apparent modulus in direction 2.

ECR(24): Apparent modulus in direction 3.

ECR(25): Apparent Poisson's ratio between directions 1 and 2.

ECR(26): Apparent Poisson's ratio between directions 1 and 3.

ECR(27): Apparent Poisson's ratio between directions 2 and 3.

ECR(28): Apparent shear modulus between directions 1 and 2.

ECR(29): Apparent shear modulus between directions 2 and 3.

ECR(30): Apparent shear modulus between directions 1 and 3.

7.7.33 OPFM : ONERA progressive failure model (Local basis)

Object:

The directive is based on an orthotropic (local) behaviour law developed at ONERA to describe the ply behaviour of laminate composite materials. First of all, a non linearity classically observed in fibre direction is considered as an elastic one. The Young Modulus in fibre direction $\tilde{E_{11}}$ can be described with the following equation:

$$\tilde{E_{11}} = \eta_1 E_{11}^t + (1-\eta_1)E_{11}^c \quad \text{with} \quad \eta_1 = \begin{cases} 1 & \text{if } \sigma_{11} \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

with E_{11}^t the Young Modulus in tension and E_{11}^c the Young Modulus in compression. These two parameters are assumed to evolve between the initial Young Modulus E_0 for $\sigma_{11} = 0$ and the asymptotic Young Modulus E_1^t for tension and E_1^c for compression:

$$E_{11}^t = E_1^t \frac{\sigma_{11} + E^t \varepsilon_0^t}{\sigma_{11} + (E^t + E_1^t)\varepsilon_0^t} \quad \text{with} \quad E^t = \frac{E_1^t E_0}{E_1^t - E_0} \tag{3}$$

$$E_{11}^c = E_1^c \frac{\sigma_{11} + E^c \varepsilon_0^c}{\sigma_{11} + (E^c + E_1^c)\varepsilon_0^c} \quad \text{with} \quad E^c = \frac{E_1^c E_0}{E_1^c - E_0} \tag{4}$$

with ε_0^t and ε_0^c the associated strains which are respectively obtained at $\sigma_{11} = 0$ with the asymptotic behaviour. The proposed behaviour law permits to describe hardening or softening behaviour. To identify E_0, the mean value of the longitudinal modulus in tension and in compression is used.

The ONERA model is considering two failure modes based on the Hashin's assumption: a fibre failure mode and an interfibre failure mode. These two failure modes are different in tension and in compression to take into account the differences observed in failure mechanisms between these two loadings.

As a first approximation, a maximum stress failure criterion is used in tension and in compression without coupling mechanisms. Consequently, the fibre failure mode is based on the following equations:

$$f_1^+ = \left(\frac{\sigma_{11}}{X_t}\right)^2 = 1 \tag{5}$$

$$f_1^- = \left(\frac{\sigma_{11}}{X_c}\right)^2 = 1 \tag{6}$$

where X_t is the longitudinal tensile strength and X_c is the longitudinal compressive strength.

Concerning the in plane interfibre failure, the criteria proposed in this study is based on the classical Hashin formulation of interfibre failure improved with a coupling term to better describe the strength of UD ply under combined shear and transverse loadings. The in plane interfibre failure mode is based on the following equations:

$$f_2^+ = \left(\frac{\sigma_{22}}{Y_t}\right)^2 + \left(\frac{\tau_{12}}{S_{12}(1-p_{21}\sigma_{22})}\right)^2 + \left(\frac{\tau_{23}}{S_{23}(1-p_{23}(\sigma_{22}+\sigma_{33}))}\right)^2 = 1 \tag{7}$$

$$f_2^- = \left(\frac{\sigma_{22}}{Y_c}\right)^2 + \left(\frac{\tau_{12}}{S_{12}(1-p_{21}\sigma_{22})}\right)^2 + \left(\frac{\tau_{23}}{S_{23}(1-p_{23}(\sigma_{22}+\sigma_{33}))}\right)^2 = 1 \tag{8}$$

The coupling parameters p_{21} and p_{23} are determined according to experimental consideration. Indeed, experimental results exhibit that a maximum apparent strength value is observed for a combined shear and transverse compression loading when $\sigma_{22} = Y_c/2$ [991]. Based on this assumption, $p_{21}^1 = 1/Y_c$ and $p_{23} = 1/Y_c$ are selected in order to increase the strength under compressive loading.

Similarly to the in-plane criterion, the out-of-plane plane interfibre failure criteria is based on the following equations:

$$f_3^+ = \left(\frac{\sigma_{33}}{Z_t}\right)^2 + \left(\frac{\tau_{13}}{S_{13}(1-p_{31}\sigma_{33})}\right)^2 + \left(\frac{\tau_{23}}{S_{23}(1-p_{32}(\sigma_{22}+\sigma_{33}))}\right)^2 = 1 \quad (9)$$

$$f_3^- = \left(\frac{\sigma_{33}}{Z_c}\right)^2 + \left(\frac{\tau_{13}}{S_{13}(1-p_{31}\sigma_{33})}\right)^2 + \left(\frac{\tau_{23}}{S_{23}(1-p_{32}(\sigma_{22}+\sigma_{33}))}\right)^2 = 1 \quad (10)$$

The coupling parameters p_{31} and p_{32} are determined with the same methodology that has been used for p_{21} and p_{23}, leading to $p_{31} = p_{32} = 1/Z_c$.

The previously described failure mechanisms will initiate a progressive degradation model. This model is based on continuum degradation models developed at ONERA. The degradation affects the effective ply properties of the homogeneous ply by increasing its effective elastic compliance $\tilde{S}$:

$$\tilde{S} = S^0 + d_1H_1 + d_2H_2 + d_3H_3 \quad (11)$$

with S^0 the initial elastic compliance, d_1H_1, d_2H_2 and d_3H_3 the tensor representing respectively the effect of fibre failure, in plane interfibre failure and out-of-plane interfibre failure on the ply compliance. For each degradation mode, the scalar variable d_i is linked to the kinetic of the degradation and the tensor variable H_i is linked to the effect of the degradation mode on the ply compliance. Regarding the different degradation kinetics, rather simple expression are used:

$$d_2 = \beta\left\langle\sqrt{f_2}-1\right\rangle^+ \quad \text{and} \quad \dot{d_2} \geq 0 \quad (12)$$

$$d_3 = \delta\left\langle\sqrt{f_3}-1\right\rangle^+ \quad \text{and} \quad \dot{d_3} \geq 0 \quad (13)$$

where $f_i = \eta_i f_i^+ + (1-\eta_1)f_i^-$ with $\eta_i = 1$ if $\sigma_{ii} \geq 0$ and $\eta_i = 0$ if $\sigma_{ii} < 0$.Based on these equations, the ply is broken and its mechanical properties are progressively degraded when the failure criterion is higher than one. To be in agreement with the Clausius Duhem principle, the degradation can only growth which ensure the thermodynamical consistency of the model. To describe the degradation kinetic, two parameters have to be identified: β and δ. The interfibre failure parameters β and δ are classically identified with a tensile test on a laminate. Regarding the fibre failure mechanism, the degradation kinetic is based on the limited damage rate and can be described with the following equations:

$$d_1 = max(g_i(f_1), d_{old}) \quad (14)$$

$$g_i(f_1) = d_{1s}\left(1-e^{\alpha_1(\sqrt(f_1)-1)^p}\right) \quad (15)$$

$$\dot{d_1} = \frac{1}{\tau_c}\left(1-e^{-a\langle d_{1s}-d_1\rangle}\right) \quad (16)$$

These equations are classically used with a different set of parameters between traction and compression.

For each degradation mode, the effect tensor H_i is different. These effect tensors describe the effects of a crack on the mesoscopic behaviour of the homogeneous failed ply. The unilateral nature of damage has to be taken into account by these tensors effects, which leads to different mathematical expression for tension and compression. The different effect tensors are described in the following equations:

$$H_1 = \begin{bmatrix} (\eta_1 h_{11}^+ + (1-\eta_1)h_{11}^-)S_{11}^0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & h_{44}^{FF}S_{44}^0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & h_{66}^{FF}S_{66}^0 \end{bmatrix} \quad with \quad \eta_1 = \begin{cases} 1 \text{ if } \sigma_{11} \geq 0 \\ 0 \text{ if } \sigma_{11} < 0 \end{cases} \tag{17}$$

$$H_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & (\eta_2 h_{22}^+ + (1-\eta_2)h_{22}^-)S_{22}^0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & h_{44}^{IFF2}S_{44}^0 & 0 & 0 \\ 0 & 0 & 0 & 0 & h_{55}^{IFF2}S_{55}^0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad with \quad \eta_2 = \begin{cases} 1 \text{ if } \sigma_{22} \geq 0 \\ 0 \text{ if } \sigma_{22} < 0 \end{cases} \tag{18}$$

$$H_3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (\eta_3 h_{33}^+ + (1-\eta_3)h_{33}^-)S_{33}^0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & h_{55}^{IFF3}S_{55}^0 & 0 \\ 0 & 0 & 0 & 0 & 0 & h_{66}^{IFF3}S_{66}^0 \end{bmatrix} \quad with \quad \eta_3 = \begin{cases} 1 \text{ if } \sigma_{33} \geq 0 \\ 0 \text{ if } \sigma_{33} < 0 \end{cases} \tag{19}$$

In these equation, the distinction between tension and compression is obtained with the coefficient η_i called activation index. When η_i is equal to 1, the crack is considered as opened. When η_i is equal to 0, the crack is considered as closed. No additional tests are required to determined the effect tensors. These tensors are identified with a micromechanical approach based on energy equivalence.

Syntax:

```
    "OPFM"  "RO"  rho   "YG1 "  YG1  "YG2 "  YG2
        "YG3 "  YG3  "NU12"  NU12 "NU13"  NU13
        "NU13"  NU13  "G12 "  G12 "G13 "  G13
"G23 "  G23  "E1T "  E1T "EP0T"  EP0T
"E1C "  E1C  "EP0C"  EP0C "XT  "  XT
"XC  "  XC  "YT  "  YT "YC  "  YC
"ZT  "  ZT  "ZC  "  ZC "SC12"  SC12
"SC13"  SC13 "SC23"  SC23  "H11T"  H11T
"H11C"  H11C "H44F"  H44F  "H22T"  H22T
"H22C"  H22C "H4I2"  H4I2  "H5I2"  H5I2
"H33T"  H33T "H33C"  H33C  "H5I3"  H5I3
"H6I3"  H6I3 "ALP2"  ALP2  "ALP3"  ALP3
"AL1T"  AL1T  "P1T "  P1T "D1TS"  D1TS
"A1T "  A1T  "T1T "  T1T "AL1C"  AL1C
"P1C "  P1C  "D1CS"  D1CS "A1C "  A1C
"T1C "  T1C  "PREC"  PREC "IMAX"  IMAX
/LECTURE/
```

`rho`

Density of the material.

`YG1`

Young's modulus along direction 1.

`YG2`

Young's modulus along direction 2.

`YG3`

Young's modulus along direction 3.

`NU12`

Poisson's ratio between directions 1 and 2.

`NU13`

Poisson's ratio between directions 1 and 3.

`NU23`

Poisson's ratio between directions 2 and 3.

`G12`

Shear modulus between directions 1 and 2.

`G13`

Shear modulus between directions 1 and 3.

`G23`

Shear modulus between directions 2 and 3.

`E1T`

Asymptotic Young's modulus along direction 1 in tension for the non linear elastic behaviour

`EP0T`

ε_0^t the associated strain which is obtained at $\sigma_{11} = 0$ with the asymptotical behaviour.

`E1C`

Asymptotic Young's modulus along direction 1 in compression for the non linear elastic behaviour

`EP0C`

ε_0^c the associated strain which is obtained at $\sigma_{11} = 0$ with the asymptotical behaviour.

`XT`

Failure criterion for tension in fibre direction.

`XC`

Failure criterion for compression in fibre direction.

`YT`

Failure criterion for tension in transverse direction.

`YC`

Failure criterion for compression in transverse direction.

`ZT`

Failure criterion for tension in out-of-plane direction.

`ZC`

Failure criterion for compression in out-of-plane direction.

`SC12`

Failure criterion for shear in 12-direction.

`SC13`

Failure criterion for shear in 13-direction.

`SC23`

Failure criterion for shear in 23-direction.

`H11T`

Coefficient h_{11}^{+} of the effet tensor for fibre failure.

`H11C`

Coefficient h_{11}^{-} of the effet tensor for fibre failure.

`H44F`

Coefficient h_{44}^{FF} of the effet tensor for fibre failure.

`H66F`

Coefficient h_{66}^{FF} of the effet tensor for fibre failure.

`H22T`

Coefficient h_{22}^{+} of the effet tensor for in-plane interfibre failure.

`H22C`

Coefficient h_{22}^{-} of the effet tensor for in-plane interfibre failure.

`H4I2`

Coefficient h_{44}^{IFF2} of the effet tensor for in-plane interfibre failure.

`H5I2`

Coefficient h_{55}^{IFF2} of the effet tensor for in-plane interfibre failure.

`H33T`

Coefficient h_{33}^{+} of the effet tensor for out-of-plane interfibre failure.

`H33C`

Coefficient h_{33}^{-} of the effet tensor for out-of-plane interfibre failure.

`H5I3`

Coefficient h_{55}^{IFF3} of the effet tensor for out-of-plane interfibre failure.

`H6I3`

Coefficient h_{66}^{IFF3} of the effet tensor for out-of-plane interfibre failure.

`ALP2`

Damage evolution laws parameter for in-plane interfibre failure.

`ALP3`

Damage evolution laws parameter for out-of-plane interfibre failure.

`AL1T`

Damage evolution laws parameter α_1 for fibre failure in tension.

`P1T`

Damage evolution laws parameter p for fibre failure in tension.

`D1TS`

Damage evolution laws parameter d_{1s} for fibre failure in tension.

`A1T`

Damage evolution laws parameter a for fibre failure in tension.

`T1T`

Damage evolution laws parameter τ_c for fibre failure in tension.

`AL1C`

Damage evolution laws parameter α_1 for fibre failure in compression.

`P1C`

Damage evolution laws parameter p for fibre failure in compression.

`D1CS`

Damage evolution laws parameter d_{1s} for fibre failure in compression.

`A1C`

Damage evolution laws parameter a for fibre failure in compression.

`T1C`

Damage evolution laws parameter τ_c for fibre failure in compression.

`PREC`

Precision of the local Newton-Raphson iterative scheme.

`IMAX`

Maximum number of iteration in the local Newton-Raphson iterative scheme.

`LECTURE`

List of the elements concerned.

Comments:

This option may be repeated as many times as necessary.

The associated coordinate system is defined by the directive "COMP" (see GBC_0095 and GBC_0096):

- "COMP" "CORTHO" for the shells and the multilayer element CMC3;
- "COMP" "MORTHO" for the continuum elements in 3D and in 2D plane strain and axisymmetric.

Outputs:

The different components of the ECR table are as follows, for the continuum elements:

ECR(1): η_1.

ECR(2): f1t.

ECR(3): d1t.

ECR(4): f1c.

ECR(5): d1c.

ECR(6): η_2.

ECR(7): f2.

ECR(8): d2.

ECR(9): η_3.

ECR(10): f3.

ECR(11): d3.

ECR(12): d1tE damage variable between 0 and 1

ECR(13): d1cE damage variable between 0 and 1

ECR(14): d2E damage variable between 0 and 1

ECR(15): d3E damage variable between 0 and 1

ECR(16:21): elastic strain.

ECR(22:27): sig in the material axis.

ECR(28:33): total strain.

ECR(34): number of iteration.

ECR(35): time

7.7.34 ORFM : ONERA Rate Dependant Failure Model (Local basis)

Object:

The directive is based on an orthotropic (local) behaviour law developed at ONERA to describe the rate dependent ply behaviour of laminate composite materials. This directive is an evolution of the OPFM behaviour law 7.7.33 which allows to define rate dependencies on some materials properties. The description of the OPFM behaviour law is detailled in the following paragraphs with a specific emphasis on the parameters that have been made rate dependent. For all these parameters, the rate dependency is introduced with 5th order polynomial functions, as shown in the following equation for an hypothetical variable $A(\dot{\varepsilon})$:

$$A(\dot{\varepsilon}) = \sum_{i=0}^{5} a^i \left(log(\dot{\varepsilon})\right)^i \tag{20}$$

First of all, a non linearity classically observed in fibre direction is considered as an elastic one. The Young Modulus in fibre direction $\tilde{E_{11}}$ can be described with the following equation:

$$\tilde{E_{11}} = \eta_1 E_{11}^t + (1-\eta_1) E_{11}^c \quad \text{with} \quad \eta_1 = \begin{cases} 1 & \text{if } \sigma_{11} \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{21}$$

with E_{11}^t the Young Modulus in tension and E_{11}^c the Young Modulus in compression. These two parameters are assumed to evolve between the initial Young Modulus E_0 for $\sigma_{11} = 0$ and the asymptotical Young Modulus E_1^t for tension and E_1^c for compression:

$$E_{11}^t = E_1^t \frac{\sigma_{11} + E^t \varepsilon_0^t}{\sigma_{11} + (E^t + E_1^t)\varepsilon_0^t} \quad \text{with} \quad E^t = \frac{E_1^t E_0}{E_1^t - E_0} \tag{22}$$

$$E_{11}^c = E_1^c \frac{\sigma_{11} + E^c \varepsilon_0^c}{\sigma_{11} + (E^c + E_1^c)\varepsilon_0^c} \quad \text{with} \quad E^c = \frac{E_1^c E_0}{E_1^c - E_0} \tag{23}$$

with ε_0^t and ε_0^c the associated strains which are respectively obtained at $\sigma_{11} = 0$ with the asymptotical behaviour. The proposed behaviour law permits to describe hardening or softening behaviour. To identify E_0, the mean value of the longitudinal modulus in tension and in compression is used. In this rate dependent law, E_0 can be defined as rate dependant. The other elastic parameters (E_{22}, E_{33}, G_{12}, G_{13}, G_{23}, ν_{12}, ν_{13} and ν_{23}) can all be defined as rate dependent.

The ONERA model is considering two failure modes based on the Hashin's assumption: a fibre failure mode and an interfibre failure mode. These two failure modes are different in tension and in compression to take into account the differences observed in failure mechanisms between these two loadings.

As a first approximation, a maximum stress failure criterion is used in tension and in compression without coupling mechanisms. Consequently, the fibre failure mode is based on the following equations:

$$f_1^+ = \left(\frac{\sigma_{11}}{X_t}\right)^2 = 1 \tag{24}$$

$$f_1^- = \left(\frac{\sigma_{11}}{X_c}\right)^2 = 1 \tag{25}$$

where X_t is the longitudinal tensile strength and X_c is the longitudinal compressive strength. These two parameters can be defined as rate dependent.

Concerning the in plane interfibre failure, the criteria proposed in this study is based on the classical Hashin formulation of interfibre failure improved with a coupling term to better describe the strength of UD ply under combined shear and transverse loadings. The in plane interfibre failure mode is based on the following equations:

$$f_2^+ = \left(\frac{\sigma_{22}}{Y_t}\right)^2 + \left(\frac{\tau_{12}}{S_{12}(1-p_{21}\sigma_{22})}\right)^2 + \left(\frac{\tau_{23}}{S_{23}(1-p_{23}(\sigma_{22}+\sigma_{33}))}\right)^2 = 1 \quad (26)$$

$$f_2^- = \left(\frac{\sigma_{22}}{Y_c}\right)^2 + \left(\frac{\tau_{12}}{S_{12}(1-p_{21}\sigma_{22})}\right)^2 + \left(\frac{\tau_{23}}{S_{23}(1-p_{23}(\sigma_{22}+\sigma_{33}))}\right)^2 = 1 \quad (27)$$

The different maximum stresses used in these equations (Y_t, Y_c, S_{12} and S_{23}) can be defined as rate dependent.

The coupling parameters p_{21} and p_{23} are determined according to experimental consideration. Indeed, experimental results exhibit that a maximum apparent strength value is observed for a combined shear and transverse compression loading when $\sigma_{22} = Y_c/2$ [991]. Based on this assumption, $p_{21}^1 = 1/Y_c$ and $p_{23} = 1/Y_c$ are selected in order to increase the strength under compressive loading.

Similarly to the in-plane criterion, the out-of-plane plane interfibre failure criteria is based on the following equations:

$$f_3^+ = \left(\frac{\sigma_{33}}{Z_t}\right)^2 + \left(\frac{\tau_{13}}{S_{13}(1-p_{31}\sigma_{33})}\right)^2 + \left(\frac{\tau_{23}}{S_{23}(1-p_{32}(\sigma_{22}+\sigma_{33}))}\right)^2 = 1 \quad (28)$$

$$f_3^- = \left(\frac{\sigma_{33}}{Z_c}\right)^2 + \left(\frac{\tau_{13}}{S_{13}(1-p_{31}\sigma_{33})}\right)^2 + \left(\frac{\tau_{23}}{S_{23}(1-p_{32}(\sigma_{22}+\sigma_{33}))}\right)^2 = 1 \quad (29)$$

The different maximum stresses used in these equations (Z_t, Z_c, S_{13} and S_{23}) can be defined as rate dependent.

The coupling parameters p_{31} and p_{32} are determined with the same methodology that has been used for p_{21} and p_{23}, leading to $p_{31} = p_{32} = 1/Z_c$.

The previously described failure mechanisms will initiate a progressive degradation model. This model is based on continuum degradation models developed at ONERA. The degradation affects the effective ply properties of the homogeneous ply by increasing its effective elastic compliance $\tilde{S}$:

$$\tilde{S} = S^0 + d_1 H_1 + d_2 H_2 + d_3 H_3 \quad (30)$$

with S^0 the initial elastic compliance, d_1H_1, d_2H_2 and d_3H_3 the tensor representing respectively the effect of fibre failure, in plane interfibre failure and out-of-plane interfibre failure on the ply compliance. For each degradation mode, the scalar variable d_i is linked to the kinetic of the degradation and the tensor variable H_i is linked to the effect of the degradation mode on the ply compliance. Regarding the different degradation kinetics, rather simple expression are used:

$$d_2 = \beta \left\langle \sqrt{f_2} - 1 \right\rangle^+ \quad \text{and} \quad \dot{d_2} \geq 0 \quad (31)$$

$$d_3 = \delta \left\langle \sqrt{f_3} - 1 \right\rangle^+ \quad \text{and} \quad \dot{d_3} \geq 0 \quad (32)$$

where $f_i = \eta_i f_i^+ + (1-\eta_1) f_i^-$ with $\eta_i = 1$ if $\sigma_{ii} \geq 0$ and $\eta_i = 0$ if $\sigma_{ii} < 0$.Based on these equations, the ply is broken and its mechanical properties are progressively degraded when the failure criterion is higher than one. To be in agreement with the Clausius Duhem principle, the degradation can only growth which ensure the thermodynamical consistency of the model. To describe the degradation kinetic, two parameters have to be identified: β and δ. The interfibre failure parameters β and δ are classically identified with a tensile test on a laminate. Regarding the fibre failure mechanism, the degradation kinetic is based on the limited damage rate and can be described with the following equations:

$$\begin{aligned} d_1 &= max(g_i(f_1), d_{old}) && (33) \\ g_i(f_1) &= d_{1s}\left(1 - e^{\alpha_1(\sqrt(f_1)-1)^p}\right) && (34) \\ \dot{d_1} &= \frac{1}{\tau_c}\left(1 - e^{-a\langle d_{1s}-d_1\rangle}\right) && (35) \end{aligned}$$

These equations are classically used with a different set of parameters between traction and compression.

For each degradation mode, the effect tensor H_i is different. These effect tensors describe the effects of a crack on the mesoscopic behaviour of the homogeneous failed ply. The unilateral nature of damage has to be taken into account by these tensors effects, which leads to different mathematical expression for tension and compression. The different effect tensors are described in the following equations:

$$H_1 = \begin{bmatrix} (\eta_1 h_{11}^+ + (1-\eta_1)h_{11}^-)S_{11}^0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & h_{44}^{FF}S_{44}^0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & h_{66}^{FF}S_{66}^0 \end{bmatrix} \quad with \quad \eta_1 = \begin{cases} 1 \text{ if } \sigma_{11} \geq 0 \\ 0 \text{ if } \sigma_{11} < 0 \end{cases} \tag{36}$$

$$H_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & (\eta_2 h_{22}^+ + (1-\eta_2)h_{22}^-)S_{22}^0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & h_{44}^{IFF2}S_{44}^0 & 0 & 0 \\ 0 & 0 & 0 & 0 & h_{55}^{IFF2}S_{55}^0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad with \quad \eta_2 = \begin{cases} 1 \text{ if } \sigma_{22} \geq 0 \\ 0 \text{ if } \sigma_{22} < 0 \end{cases} \tag{37}$$

$$H_3 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & (\eta_3 h_{33}^+ + (1-\eta_3)h_{33}^-)S_{33}^0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & h_{55}^{IFF3}S_{55}^0 & 0 \\ 0 & 0 & 0 & 0 & 0 & h_{66}^{IFF3}S_{66}^0 \end{bmatrix} \quad with \quad \eta_3 = \begin{cases} 1 \text{ if } \sigma_{33} \geq 0 \\ 0 \text{ if } \sigma_{33} < 0 \end{cases} \tag{38}$$

In these equation, the distinction between tension and compression is obtained with the coefficient η_i called activation index. When η_i is equal to 1, the crack is considered as opened. When η_i is equal to 0, the crack is considered as closed. No additional tests are required to determined the effect tensors. These tensors are identified with a micromechanical approach based on energy equivalence.

Residual thermal stresses related to the anisotropy of thermal dilation coefficient is considered in the material behaviour through a thermal strain tensor ε_{nl}, where α_{1th} and α_{1th} are the thermal dilation coefficient, T_{ess} the temperature difference to consider. These strains evolve as a smooth function of time t until a sufficient T_{ref} to avoid high frequencies in the solution, as given in the following equation:

$$\varepsilon_{nl} = \begin{bmatrix} \alpha_{1th} \\ \alpha_{2th} \\ \alpha_{2th} \\ 0 \\ 0 \\ 0 \end{bmatrix} T_{ess} \times \begin{cases} \frac{1}{2}\left(1+\sin\left(\pi\left(t/T_{REF}-0.5\right)\right)\right) \text{ for } t \le T_{REF} \\ 1.0 \text{ for } t > T_{REF} \end{cases} \tag{39}$$

If an instantaneous thermal strain is desired, user can still set $T_{ref} = 0.0$ and preserving non null α_{1th}, α_{1th} and T_{ess}.

A better method to account for the thermal residual stresses consists in initializing the stress tensor of each integration point with the equilibrium solution from an implicit simulation. Advantage rely in the stationarity of the obtained solution and the neglectable numerical cost to obtain it. The material law has been adapted to accurately take into account an initial stress at the first time step. Users can then define the stress state of each integration point thanks to the command “INIT CQST” at page E.160. These stresses have to be given in the material axis. If this solution is used, the thermal strains need to be null in the current material law as they are already accounted for in the stress state given through “INIT CQST”.

Syntax:

```
"ORFM"  "RO  "  rho  "YG1 " YG1  "YG2 "  YG2
        "YG3 "  YG3  "NU12" NU12 "NU13"  NU13
        "NU13"  NU13 "G12 " G12  "G13 "  G13
        "G23 "  G23  "E1T " E1T  "EPOT"  EPOT
        "E1C "  E1C  "EPOC" EPOC "XT  "  XT
        "XC  "  XC   "YT  " YT   "YC  "  YC
        "ZT  "  ZT   "ZC  " ZC   "SC12"  SC12
        "SC13"  SC13 "SC23" SC23 "H11T"  H11T
        "H11C"  H11C "H44F" H44F "H22T"  H22T
        "H22C"  H22C "H4I2" H4I2 "H5I2"  H5I2
        "H33T"  H33T "H33C" H33C "H5I3"  H5I3
        "H6I3"  H6I3 "ALP2" ALP2 "ALP3"  ALP3
        "AL1T"  AL1T "P1T " P1T  "D1TS"  D1TS
        "A1T "  A1T  "T1T " T1T  "AL1C"  AL1C
        "P1C "  P1C  "D1CS" D1CS "A1C "  A1C
        "T1C "  T1C  "PREC" PREC "IMAX"  IMAX
        "MINE"  MINE "MAXE" MAXE "YG11"  YG11
        "YG12"  YG12 "YG13" YG13 "YG14"  YG14
        "YG15"  YG15 "YG21" YG21 "YG22"  YG22
        "YG15"  YG15 "YG21" YG21 "YG22"  YG22
        "YG23"  YG23 "YG24" YG24 "YG25"  YG25
        "YG31"  YG31 "YG32" YG32 "YG33"  YG33
        "YG34"  YG34 "YG35" YG35 "N121"  N121
        "N122"  N122 "N123" N123 "N124"  N124
        "N125"  N125 "N131" N131 "N132"  N132
        "N133"  N133 "N134" N134 "N135"  N135
        "N231"  N231 "N232" N232 "N233"  N233
        "N234"  N234 "N235" N235 "G121"  G121
        "G122"  G122 "G123" G123 "G124"  G124
        "G125"  G125 "G131" G131 "G132"  G132
```

```
"G133"  G133 "G134" G134 "G135"  G135
"G231"  G231 "G232" G232 "G233"  G233
"G234"  G234 "G235" G235 "XT1 "  XT1
"XT2 "  XT2  "XT3 " XT3  "XT4 "  XT4
"XT5 "  XT5  "XC1 " XC1  "XC2 "  XC2
"XC3 "  XC3  "XC4 " XC4  "XC5 "  XC5
"YT1 "  YT1  "YT2 " YT2  "YT3 "  YT3
"YT4 "  YT4  "YT5 " YT5  "YC1 "  YC1
"YC2 "  YC2  "YC3 "  YC3 "YC4 "  YC4
"YC5 "  YC5  "ZT1 " ZT1  "ZT2 "  ZT2
"ZT3 "  ZT3  "ZT4 " ZT4  "ZT5 "  ZT5
"ZC1 "  ZC1  "ZC2 " ZC2  "ZC3 "  ZC3
"ZC4 "  ZC4  "ZC5 " ZC5  "S121"  S121
"S122"  S122 "S123" S123 "S124"  S124
"S125"  S125 "S131" S131 "S132"  S132
"S133"  S133 "S134" S134 "S135"  S135
"S231"  S231 "S232" S232 "S233"  S233
"S234"  S234 "S235" S235 "A1TH"  A1TH
"A2TH"  A2TH "TESS" TESS "TREF"  TREF
/LECTURE/
```

`rho`

Density of the material.

`YG1`

0th order coefficient for the rate dependency of the Young's modulus along direction 1. Without rate dependency, Young's modulus along direction 1.

`YG2`

0th order coefficient for the rate dependency of the Young's modulus along direction 2. Without rate dependency, Young's modulus along direction 2.

`YG3`

0th order coefficient for the rate dependency of the Young's modulus along direction 3. Without rate dependency, Young's modulus along direction 3.

`NU12`

0th order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2. Without rate dependency, Poisson's ratio between directions 1 and 2.

`NU13`

0th order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3. Without rate dependency, Poisson's ratio between directions 1 and 3.

`NU23`

0th order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3. Without rate dependency, Poisson's ratio between directions 2 and 3.

`G12`

0th order coefficient for the rate dependency of the shear modulus between directions 1 and 2. Without rate dependency, shear modulus between directions 1 and 2.

`G13`

0th order coefficient for the rate dependency of the shear modulus between directions 1 and 3. Without rate dependency, shear modulus between directions 1 and 3.

`G23`

0th order coefficient for the rate dependency of the shear modulus between directions 2 and 3. Without rate dependency, shear modulus between directions 2 and 3.

`E1T`

Asymptotic Young's modulus along direction 1 in tension for the non linear elastic behaviour

`EP0T`

ε_0^t the associated strain which is obtained at $\sigma_{11} = 0$ with the asymptotical behaviour.

`E1C`

Asymptotic Young's modulus along direction 1 in compression for the non linear elastic behaviour

`EP0C`

ε_0^c the associated strain which is obtained at $\sigma_{11} = 0$ with the asymptotical behaviour.

`XT`

0th order coefficient for the rate dependency of the maximum stress for tension in fibre direction. Without rate dependency, maximum stress for tension in fibre direction.

`XC`

0th order coefficient for the rate dependency of the maximum stress for compression in fibre direction. Without rate dependency, maximum stress for compression in fibre direction.

`YT`

0th order coefficient for the rate dependency of the maximum stress for tension in transverse (Y) direction. Without rate dependency, maximum stress for tension in transverse (Y) direction.

`YC`

0th order coefficient for the rate dependency of the maximum stress for compression in transverse (Y) direction. Without rate dependency, maximum stress for compression in transverse (Y) direction.

`ZT`

0th order coefficient for the rate dependency of the maximum stress for tension in out of plane (Z) direction. Without rate dependency, maximum stress for tension in out of plane (Z) direction.

`ZC`

0th order coefficient for the rate dependency of the maximum stress for compression in out of plane (Z) direction. Without rate dependency, maximum stress for compression in out of plane (Z) direction.

`SC12`

0th order coefficient for the rate dependency of the maximum stress for shear in 12-direction. Without rate dependency, maximum stress for shear in 12-direction.

`SC13`

0th order coefficient for the rate dependency of the maximum stress for shear in 13-direction. Without rate dependency, maximum stress for shear in 13-direction.

`SC23`

0th order coefficient for the rate dependency of the maximum stress for shear in 23-direction. Without rate dependency, maximum stress for shear in 23-direction.

`H11T`

Coefficient h_{11}^{+} of the effet tensor for fibre failure.

`H11C`

Coefficient h_{11}^{-} of the effet tensor for fibre failure.

`H44F`

Coefficient h_{44}^{FF} of the effet tensor for fibre failure.

`H66F`

Coefficient h_{66}^{FF} of the effet tensor for fibre failure.

`H22T`

Coefficient h_{22}^{+} of the effet tensor for in-plane interfibre failure.

`H22C`

Coefficient h_{22}^{-} of the effet tensor for in-plane interfibre failure.

`H4I2`

Coefficient h_{44}^{IFF2} of the effet tensor for in-plane interfibre failure.

`H5I2`

Coefficient h_{55}^{IFF2} of the effet tensor for in-plane interfibre failure.

`H33T`

Coefficient h_{33}^{+} of the effet tensor for out-of-plane interfibre failure.

`H33C`

Coefficient h_{33}^{-} of the effet tensor for out-of-plane interfibre failure.

`H5I3`

Coefficient h_{55}^{IFF3} of the effet tensor for out-of-plane interfibre failure.

`H6I3`

Coefficient h_{66}^{IFF3} of the effet tensor for out-of-plane interfibre failure.

`ALP2`

Damage evolution laws parameter for in-plane interfibre failure.

`ALP3`

Damage evolution laws parameter for out-of-plane interfibre failure.

`AL1T`

Damage evolution laws parameter α_1 for fibre failure in tension.

`P1T`

Damage evolution laws parameter p for fibre failure in tension.

`D1TS`

Damage evolution laws parameter d_{1s} for fibre failure in tension.

`A1T`

Damage evolution laws parameter a for fibre failure in tension.

`T1T`

Damage evolution laws parameter τ_c for fibre failure in tension.

`AL1C`

Damage evolution laws parameter α_1 for fibre failure in compression.

`P1C`

Damage evolution laws parameter p for fibre failure in compression.

`D1CS`

Damage evolution laws parameter d_{1s} for fibre failure in compression.

`A1C`

Damage evolution laws parameter a for fibre failure in compression.

`T1C`

Damage evolution laws parameter τ_c for fibre failure in compression.

`PREC`

Precision of the local Newton-Raphson iterative scheme.

`IMAX`

Maximum number of iteration in the local Newton-Raphson iterative scheme.

`MINE`

Lower boundary of the strain rate interval used for the polynomial function identification.

`MAXE`

Upper boundary of the strain rate interval used for the polynomial function identification.

`YG11`

1st order coefficient for the rate dependency of the Young's modulus along direction 1.

`YG12`

2nd order coefficient for the rate dependency of the Young's modulus along direction 1.

`YG13`

3rd order coefficient for the rate dependency of the Young's modulus along direction 1.

`YG14`

4th order coefficient for the rate dependency of the Young's modulus along direction 1.

`YG15`

5th order coefficient for the rate dependency of the Young's modulus along direction 1.

`YG21`

1st order coefficient for the rate dependency of the Young's modulus along direction 2.

`YG22`

2nd order coefficient for the rate dependency of the Young's modulus along direction 2.

`YG23`

3rd order coefficient for the rate dependency of the Young's modulus along direction 2.

`YG24`

4th order coefficient for the rate dependency of the Young's modulus along direction 2.

`YG25`

5th order coefficient for the rate dependency of the Young's modulus along direction 2.

`YG31`

1st order coefficient for the rate dependency of the Young's modulus along direction 3.

`YG32`

2nd order coefficient for the rate dependency of the Young's modulus along direction 3.

`YG33`

3rd order coefficient for the rate dependency of the Young's modulus along direction 3.

`YG34`

4th order coefficient for the rate dependency of the Young's modulus along direction 3.

`YG35`

5th order coefficient for the rate dependency of the Young's modulus along direction 3.

`N121`

1st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2.

`N122`

2nd order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2.

`N123`

3rd order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2.

`N124`

4st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2.

`N125`

5st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 2.

`N131`

1st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3.

`N132`

2nd order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3.

`N133`

3rd order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3.

`N134`

4st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3.

`N135`

5st order coefficient for the rate dependency of the Poisson's ratio between directions 1 and 3.

`N231`

1st order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3.

`N232`

2nd order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3.

`N233`

3rd order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3.

`N234`

4st order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3.

`N235`

5st order coefficient for the rate dependency of the Poisson's ratio between directions 2 and 3.

`G121`

1st order coefficient for the rate dependency of the shear modulus between directions 1 and 2.

`G122`

2nd order coefficient for the rate dependency of the shear modulus between directions 1 and 2.

`G123`

3rd order coefficient for the rate dependency of the shear modulus between directions 1 and 2.

`G124`

4th order coefficient for the rate dependency of the shear modulus between directions 1 and 2.

`G125`

5th order coefficient for the rate dependency of the shear modulus between directions 1 and 2.

`G131`

1st order coefficient for the rate dependency of the shear modulus between directions 1 and 3.

`G132`

2nd order coefficient for the rate dependency of the shear modulus between directions 1 and 3.

`G133`

3rd order coefficient for the rate dependency of the shear modulus between directions 1 and 3.

`G134`

4th order coefficient for the rate dependency of the shear modulus between directions 1 and 3.

`G135`

5th order coefficient for the rate dependency of the shear modulus between directions 1 and 3.

`G231`

1st order coefficient for the rate dependency of the shear modulus between directions 2 and 3.

`G232`

2nd order coefficient for the rate dependency of the shear modulus between directions 2 and 3.

`G233`

3rd order coefficient for the rate dependency of the shear modulus between directions 2 and 3.

`G234`

4th order coefficient for the rate dependency of the shear modulus between directions 2 and 3.

`G235`

5th order coefficient for the rate dependency of the shear modulus between directions 2 and 3.

`XT1`

1st order coefficient for the rate dependency of the maximum stress for tension in fibre direction.

`XT2`

2nd order coefficient for the rate dependency of the maximum stress for tension in fibre direction.

`XT3`

3rd order coefficient for the rate dependency of the maximum stress for tension in fibre direction.

`XT4`

4th order coefficient for the rate dependency of the maximum stress for tension in fibre direction.

`XT5`

5th order coefficient for the rate dependency of the maximum stress for tension in fibre direction.

`XC1`

1st order coefficient for the rate dependency of the maximum stress for compression in fibre direction.

`XC2`

2nd order coefficient for the rate dependency of the maximum stress for compression in fibre direction.

`XC3`

3rd order coefficient for the rate dependency of the maximum stress for compression in fibre direction.

`XC4`

4th order coefficient for the rate dependency of the maximum stress for compression in fibre direction.

`XC5`

5th order coefficient for the rate dependency of the maximum stress for compression in fibre direction.

`YT1`

1st order coefficient for the rate dependency of the maximum stress for tension in transverse (Y) direction.

`YT2`

2nd order coefficient for the rate dependency of the maximum stress for tension in transverse (Y) direction.

`YT3`

3rd order coefficient for the rate dependency of the maximum stress for tension in transverse (Y) direction.

`YT4`

4th order coefficient for the rate dependency of the maximum stress for tension in transverse (Y) direction.

`YT5`

5th order coefficient for the rate dependency of the maximum stress for tension in transverse (Y) direction.

`YC1`

1st order coefficient for the rate dependency of the maximum stress for compression in transverse (Y) direction.

YC2

2nd order coefficient for the rate dependency of the maximum stress for compression in transverse (Y) direction.

YC3

3rd order coefficient for the rate dependency of the maximum stress for compression in transverse (Y) direction.

YC4

4th order coefficient for the rate dependency of the maximum stress for compression in transverse (Y) direction.

YC5

5th order coefficient for the rate dependency of the maximum stress for compression in transverse (Y) direction.

ZT1

1st order coefficient for the rate dependency of the maximum stress for tension in out-of-plane (Z) direction.

ZT2

2nd order coefficient for the rate dependency of the maximum stress for tension in out-of-plane (Z) direction.

ZT3

3rd order coefficient for the rate dependency of the maximum stress for tension in out-of-plane (Z) direction.

ZT4

4th order coefficient for the rate dependency of the maximum stress for tension in out-of-plane (Z) direction.

ZT5

5th order coefficient for the rate dependency of the maximum stress for tension in out-of-plane (Z) direction.

ZC1

1st order coefficient for the rate dependency of the maximum stress for compression in out-of-plane (Z) direction.

ZC2

2nd order coefficient for the rate dependency of the maximum stress for compression in out-of-plane (Z) direction.

ZC3

3rd order coefficient for the rate dependency of the maximum stress for compression in out-of-plane (Z) direction.

`ZC4`

4th order coefficient for the rate dependency of the maximum stress for compression in out-of-plane (Z) direction.

`ZC5`

5th order coefficient for the rate dependency of the maximum stress for compression in out-of-plane (Z) direction.

`S121`

1st order coefficient for the rate dependency of the maximum stress for shear in 12-direction.

`S122`

2nd order coefficient for the rate dependency of the maximum stress for shear in 12-direction.

`S123`

3rd order coefficient for the rate dependency of the maximum stress for shear in 12-direction.

`S124`

4th order coefficient for the rate dependency of the maximum stress for shear in 12-direction.

`S125`

5th order coefficient for the rate dependency of the maximum stress for shear in 12-direction.

`S131`

1st order coefficient for the rate dependency of the maximum stress for shear in 13-direction.

`S132`

2nd order coefficient for the rate dependency of the maximum stress for shear in 13-direction.

`S133`

3rd order coefficient for the rate dependency of the maximum stress for shear in 13-direction.

`S134`

4th order coefficient for the rate dependency of the maximum stress for shear in 13-direction.

`S135`

5th order coefficient for the rate dependency of the maximum stress for shear in 13-direction.

`S231`

1st order coefficient for the rate dependency of the maximum stress for shear in 23-direction.

`S232`

2nd order coefficient for the rate dependency of the maximum stress for shear in 23-direction.

`S233`

3rd order coefficient for the rate dependency of the maximum stress for shear in 23-direction.

`S234`

4th order coefficient for the rate dependency of the maximum stress for shear in 23-direction.

`S235`

5th order coefficient for the rate dependency of the maximum stress for shear in 23-direction.

`A1TH`

Longitudinal thermal dilation coefficient (optional, default value = 0.0).

`A2TH`

Transverse thermal dilation coefficient (optional, default value = 0.0). Transverse isotropy hypothesis is assumed for the out of plane direction.

`TREF`

Time at which temporal evolution of the thermal strain stops, only activated if this parameter is greater than 0.0 (optional, default value = 0.0). If this parameters is set to 0 and “A1TH”, “A2TH” and “TESS” are non-null, thermal strain are instantaneously applied and high frequencies will be generated.

`TESS`

Temperature difference to consider for thermal strain computation (optional, default value = 0.0).

`LECTURE`

List of the elements concerned.

Comments:

This option may be repeated as many times as necessary.

The associated coordinate system is defined by the directive "COMP" (see GBC_0095 and GBC_0096):

- "COMP" "CORTHO" for the shells and the multilayer element CMC3;
- "COMP" "MORTHO" for the continuum elements in 3D and in 2D plane strain and axisymmetric.

Outputs:

The different components of the ECR table are as follows, for the continuum elements:

ECR(1): Time.

ECR(2): f1t.

ECR(3): d1t.

ECR(4): f1c.

ECR(5): d1c.

ECR(6): η_2.

ECR(7): f2.

ECR(8): d2.

ECR(9): η_3.

ECR(10): f3.

ECR(11): d3.

ECR(12): d1tE damage variable between 0 and 1

ECR(13): d1cE damage variable between 0 and 1

ECR(14): d2E damage variable between 0 and 1

ECR(15): d3E damage variable between 0 and 1

ECR(16:21): elastic strain (ε_{e11}, ε_{e22}, ε_{e33}, ε_{e12}, ε_{e23}, ε_{e13}).

ECR(22:27): sig in the material axis (σ_{11}, σ_{22}, σ_{33}, σ_{12}, σ_{23}, σ_{13}).

ECR(28:33): initial stress in the material axis, given with "INIT CQST" ($\sigma_{ini,11}$, $\sigma_{ini,22}$, $\sigma_{ini,33}$, $\sigma_{ini,12}$, $\sigma_{ini,23}$, $\sigma_{ini,13}$).

ECR(34): number of iteration.

ECR(35:40): Strain rate.

7.7.35 MASS

Object:

This directive enables the masses of the material points `PMAT` to be entered.

Optionally, the Young's modulus E and the Poisson's coefficient ν of the material may also be specified. These are used in order to determine the material's bulk modulus

$$\kappa = \frac{E}{3(1-2\nu)}$$

when the `PMAT` associated with the `MASS` material has a (*nodal*) pinball attached to it. In this case, it is allowed to specify a zero mass (i.e. a 0 value for `xm`) in order to avoid adding an extra mass to the structure if so desired.

Syntax:

```
"MASS" xm
     < "YOUN" youn> < "NU" nu >
       /LECTURE/
```

`xm`

Mass.

`youn`

Young's modulus. If not specified, it is assumed to be 0.

`nu`

Poisson's coefficient. If not specified, it is assumed to be 0.

`LECTURE`

Numbers of the elements concerned.

Comments:

If the node corresponding to the material point belongs also to another element, the added mass (`xm`) may be zero. This is very useful in the case of unilateral junctions or of added *nodal* pinballs for contact.

In this way, added masses may be entered too.

In axisymmetric, the real masses must be divided by 2π.

Outputs:

The different components of the ECR table are as follows:

ECR(1): integrated impulse from the origin

ECR(2): sum of the instantaneous reaction forces.

7.7.36 MAMO: Added ponctual mass with damping

Object:

This directive enables the material points PMAT to use masses that may be damped with mass proportional damping.

Syntax:

```
"MAMO" "MASS" xm < "BETA" beta> < "FROM" t1 > < "UPTO" t2 >
       /LECTURE/
```

xm

Mass.

beta

Damping coefficient. If not specified, it is assumed to be 0.

t1

Damping starting time. If not specified, it is assumed to be 0.

t2

Damping ending time. If not specified, it is assumed to be 1.D12.

LECTURE

List of the elements concerned.

Comments:

This damping produces a viscous force proportional to the mass m and the velocity v of the PMAT element:

$$f_{\mathrm{damp}} = -\beta m v$$

7.7.37 CAMO: Added ponctual mass-inertia with damping

Object:

This directive enables the ponctual 6-dof corps `CORA` to specify a mass/inertia characteristics and a mass proportional damping.

Syntax:

```
"CAMO" "MASS" xm  "IXX" ix  "IYY" iy  "IZZ" iz
       < "BETA" beta> < "FROM" t1 > < "UPTO" t2 >
       /LECTURE/
```

`xm`

Mass.

`ix`

Rotational inertia around the global X axis.

`iy`

Rotational inertia around the global Y axis.

`iz`

Rotational inertia around the global Z axis.

`beta`

Damping coefficient. If not specified, it is assumed to be 0.

`t1`

Damping starting time. If not specified, it is assumed to be 0.

`t2`

Damping ending time. If not specified, it is assumed to be 1.D12.

`LECTURE`

List of the elements concerned.

Comments:

This damping produces a 6-component viscous force proportional to the mass-inertia m and the velocity v of the `CORA` element:

$$f_{\mathrm{damp}} = -\beta m v$$

7.7.38 RE6G: Nonlinear spring in the global reference frame

Object:

This directive allows to model a complex non-linear two-node spring having arbitrary stiffness and damping values along the 6 dofs of the two concerned nodes. It may only be used in conjunction with RL6D elements (6 dofs two-node spring). The user gives the evolution curve of the reaction force generated by the spring as a function of the displacement or of the velocity.

Syntax:

```
"RE6G"
        <|[ "KX" kx ; "KY" ky ; "KZ" kz ]| "NFKT" nufo1>
        <|[ "AX" ax ; "AY" ay ; "AZ" az ]| "NFAT" nufo2>
        <|[ "KRX" krx ; "KRY" kry ; "KRZ" krz ]| "NFKR" nufo3>
        <|[ "ARX" arx ; "ARY" ary ; "ARZ" arz ]| "NFAR" nufo4>
        <"ACON" acon>
        <|[ "VX" vx ; "VY" vy ; "VZ" vz ]|>
        /LECTURE/
```

`kx, ky, kz`

Translational stiffnesses along the global axes.

`nufo1`

Index of the function associated with translational stiffnesses.

`ax, ay, az`

Translational dampings along the global axes.

`nufo2`

Index of the function associated with translational dampings.

`krx, kry, krz`

Rotational stiffnesses along the global axes.

`nufo3`

Index of the function associated with rotational stiffnesses.

`arx, ary, arz`

Rotational dampings along the global axes.

`nufo4`

Index of the function associated with rotational dampings.

`acon`

If set to 1 (0 by default), translational/rotational dampings will only be activated if

$$|F_{x,int}| = |k_x f_1(D_x)| > 1\mathrm{E}^{-16}$$

`vx, vy, vz`

Allows to override the definition of the normal vector of the spring (computed from its nodes positions) and to enter a user-defined normal vector. Useful when the two nodes of the spring are coincident. If not specified, original approach based on nodes positions is used.

`/LECTURE/`

List of the concerned elements.

Comments:

The stiffnesses and the dampings are given along the global (fixed) axes of the problem. Each of the 2 associated functions applies to the 3 corresponding stiffnesses (or dampings).

If a keyword is missing, the corresponding value is put to zero. The order in which the parameters are specified is irrelevant.

The reaction force generated by the spring has the form (e.g., assuming translation along Ox):

$$F_x = k_x f_1(D_x) + a_x f_2(V_x)$$

If the displacement (or the velocity) is positive, the function f1 (or f2) must be negative in order to obtain a correct reaction.

RL6D elements have zero mass so depending on the application, additionnal mass or inertia can be needed to obtain expected results (see `COMP MASS` or `CORA+CAMO` for example)

Outputs:

The components of the ECR vector are:

ECR(1): Force in the support along X.

ECR(2): Force in the support along Y.

ECR(3): Force in the support along Z.

ECR(4): Moment in the support along X.

ECR(5): Moment in the support along Y.

ECR(6): Moment in the support along Z.

7.7.39 FANT: Phantom material

Object:

This directive enables the elimination of elements in a mesh.

Syntax:

```
"FANT"  rho  /LECTURE/
```

`rho`

Density.

`LECTURE`

List of the elements concerned.

Comments:

The EUROPLEXUS program considers that all these elements do not exist.

However, the nodes are always present; as their masses may not be zero, it is necessary to give (very low) densities to ”FANT” elements.

7.7.40 FREE (USER'S MATERIAL)

Object:

The directive enables the user to enter his own constitutive laws.

Syntax:

```
        $  "STRU" ...  $
        $  "FLUI" ...  $
"LIBR"  $  "PMAT" ...  $    < "PARA"  a b c ... >  /LECTURE/
        $  "MECA" ...  $
        $  "CLIM" ...  $
```

`"STRU" ...`

Indicates that the free material is of type “STRUCTURE”.

`"FLUI" ...`

Indicates that the free material is of type “FLUIDE”.

`"PMAT" ...`

Indicates that the free material is of type “POINT MATERIEL”.

`"MECA" ...`

Indicates that the free material is of type “MECANISME”.

`"CLIM" ...`

Indicates that the free material is of type “CONDITION AUX LIMITES”.

`"PARA" ...`

Key-word used to introduce a series of additional parameters.

`LECTURE`

List of the elements concerned.

Comments:

The distinction between structure and fluid is due to the processing differences in A.L.E. In fact, there are transport terms for the fluid, whereas the structure is always Lagrangian.

Similarly, the cases of material points, mechanisms and boundary conditions are so peculiar that a dedicated syntax is provided.

These directives are described in detail on the following pages.

Remarks:

In the examples proposed in the following pages, there are some calls to utility routines that are available within EUROPLEXUS:

1. ERRMSS(STRING1,STRING2) :
   Subroutine named 'STRING1' generates the error message 'STRING2', increments the error counter and triggers the calculation stop. 'STRING1' and 'STRING2' are two character strings.

2. TILT :
   This subroutine without arguments triggers the calculation stop at the end of the current time step, and passes control to the next input directive in the input data set, which is normally either "SUIT" or "FIN", following the directive "CALCUL".

3. QUIDNE(LOOP,NUM,LON,VAL) :
   This subroutine extracts values relative to a node or to an element (of index "NUM"), and places them in the array "VAL".

   If the quantity to be extracted is a vector (e.g. a velocity), the length of the extracted vector is in "LON", and the array "VAL" must be dimensioned sufficiently (DIM(VAL) $\geq$ LON).

   Argument "LOOP" allows to select the values to be extracted.

   For a node :

   LOOP = 0 : Coordinates of node "NUM",
   LOOP = 1 : Displacements,
   LOOP = 2 : Velocities,
   LOOP = 5 : Nodal masses.

   For an element :

   LOOP = 21 : Stresses in element "NUM",
   LOOP = 22 : Total deformations,
   LOOP = 23 : Internal variables (ECR),
   LOOP = 24 : Internal energy.

7.7.41 FREE MATERIAL OF TYPE STRUCTURE

Object:

This directive introduces a user-defined constitutive behaviour of structural type ("STRUCTURE").

Syntax:

```
    "LIBR"  "STRU" num   "RO" rho   "YOUN" young   "NU" nu  ...
                ...   < "PARA" /LECPARA/ >  /LECTURE/
```

`"STRU" num`

Indicates that the free material of type "STRUCTURE" has the user-specified index `num`.

`"RO" rho`

Density. This value is mandatory in order to compute the element mass.

`"YOUN" young`

Young's modulus.

`"NU" nu`

Poisson's ratio.

`"PARA"...`

Key-word used to introduce a series of additional parameters.

`LECTURE`

List of the elements concerned.

Comments:

The number `num` enables several materials chosen by the user to be recognized. The three parameters `rho`, `young` and `nu` are compulsory.

The user specifies his material's parameters after the keyword "PARAM". When EUROPLEXUS finds the keyword "LECTURE", it considers that the list of parameters is terminated, whatever the number of values that have been read.

However, the total number of parameters for this material may not exceed 100, including the three mandatory values (`rho`, `young` and `nu`).

If there are no additional parameters besides the three mandatory ones, the keyword "PARAM" may be omitted.

The parameters are used within the subroutine "MSLIBR" that must be written by the user, compiled and linked with the code libraries to produce a special code executable before launching the run.

The elements that accept the free material of type "STRUCTURE" are the following:

2D : TRIA, CAR1, CAR4.

3D : CUBE, CUB6, CUB8, PRIS, PR6, TETR.

Be careful to respect the conventions chosen to rank the tensor components according to the 2-D plane, 2-D axisymmetric or 3-D cases. See page G.20 for further explanations.

The user can store for each element (and each integration point), the values he wants (up to 10) in the ECR table. For homogeneity with the other materials, the following data will be stored in the first two locations of the ECR table :

ECR(1) = Pressure

ECR(2) = Von Mises

The eight other locations are free.

Examples:

The following example, taken from the standard benchmark "bm_str_2d_libr", concerns the traction of an axisymmetric cylinder.

The material data are as follows:

```
MATERIAUX  LIBRE  STRUCTURE 901
                  RO 7800. YOUNG 210E9 NU 0.   TOUS
```

In this particular case there is just one material, identified by the user-supplied index 901. There are no additional parameters besides the three mandatory ones, and the Poisson coefficient is zero. All the elements in the mesh possess this material (keyword "TOUS").

Programming example relative to MSLIBR:

```
      SUBROUTINE MSLIBR(NLGEOM,NUM,TT,XMAT,SIG,DEPS,EDOT,RO,PI,
     &                  CSON,ECR,X,IEL,IDIM,NBN)
*
*     ------------------------------------------------------------------
*
*          materiau libre (structure)                m.lepareux 11.86
*
*     ------------------------------------------------------------------
```

```
*
*    entree :
*          num       = numero de reperage du materiau utilisateur
*          tt        = temps du calcul
*          xmat(1)   = masse volumique initiale
*          xmat(2)   = young
*          xmat(3)   = poisson
*          xmat(4: ) = autres parametres du materiau
*          sig       = contraintes au debut du pas
*          deps      = accroissement des deformations
*          edot      = vitesse de deformation
*          ro        = masse volumique courante
*          x         = coordonnees des nbn noeuds
*          iel       = numero de l'element
*          idim      = dimension (2=2d ou axis , 3=3d)
*    sortie :
!          nlgeom    = 0 (dans inico1.ff matal(13)=1)
*          pi        = contraintes a la fin du pas (a calculer)
*          cson      = vitesse du son (a calculer pour la stabilite)
*          ecr(1)    = pression                    (a calculer)
*          ecr(2)    = critere de von mises        (a calculer)
*          ecr(3:7)  = emplacements libres
*
*  attention !  le materiau 901 est utilise par le benchmark
*                              "bm_str_2d_libr.epx"
*
      IMPLICIT NONE
*
*---    variables globales :
      INTEGER, INTENT(IN)  :: NUM,IEL,NBN,IDIM
      INTEGER, INTENT(OUT)  :: NLGEOM
      REAL(8), INTENT(IN)  :: TT,XMAT(*),SIG(*),DEPS(*),EDOT(*),
     &                        RO,X(IDIM,NBN)
      REAL(8), INTENT(OUT) :: CSON,PI(*)
      REAL(8), INTENT(INOUT) :: ECR(*)
*
*---    variables locales :
      REAL(8) :: AMU,ALAMB,AUX,YOUNG,POISS,C1
*
*
*-----    on active les nonlinearites geometriques : nlgeom=0
      NLGEOM = 0
*
      SELECT CASE (NUM)
      CASE(901)
*-----     l'exemple qui suit concerne un mat. elastique (en 2d axis.)
        YOUNG=XMAT(2)
        POISS=XMAT(3)
*-         coefficients de lame :
        C1=YOUNG/(1.+POISS)
        AMU=0.5D0*C1
        ALAMB=C1*POISS/(1-2*POISS)
        AUX=ALAMB*(DEPS(1)+DEPS(2)+DEPS(4))
*-         nouveau tenseur des contraintes :
        PI(1) = SIG(1) + AUX + C1*DEPS(1)
        PI(2) = SIG(2) + AUX + C1*DEPS(2)
        PI(3) = SIG(3)      + AMU*DEPS(3)
        PI(4) = SIG(4) + AUX + C1*DEPS(4)
*-         pression :
        ECR(1)=(PI(1)+PI(2)+PI(4))/3.D0
*-         critere de von mises :
        ECR(2)=SQRT(PI(1)*(PI(1)-PI(2))+PI(2)*(PI(2)-PI(4))
     &             +PI(4)*(PI(4)-PI(1))+3*PI(3)*PI(3))
*-         vitesse du son (stabilite) :
        CSON=DSQRT(YOUNG/RO)
*
      CASE DEFAULT
        CALL ERRMSS('MSLIBR','ROUTINE UTILISATEUR NON PROGRAMMEE')
        STOP ' "MSLIBR" ABSENT'
      END SELECT
*
      END SUBROUTINE MSLIBR
```

7.7.42 FREE MATERIAL OF TYPE FLUID

Object:

This directive introduces a user-defined constitutive behaviour of fluid type ("FLUIDE").

Syntax:

```
"LIBR" "FLUI" num  "RO" rho  "PINI" pini  "PREF" pref  "EINT" ei ...
             ...   < "PARA"  /LECPARA/ >  /LECTURE/
```

`"FLUI" num`

Indicates that the free material of type "FLUIDE" has the user-specified index `num`.

`"RO" rho`

Density. This value is mandatory in order to compute the element mass.

`"PINI" pini`

Initial pressure.

`"PREF" pref`

Reference pressure.

`"EINT" ei`

Initial internal energy per unit mass.

`"PARA"...`

Key-word used to introduce a series of additional parameters.

`LECTURE`

List of the elements concerned.

Comments:

The number `num` enables several materials chosen by the user to be recognized. The four parameters `rho`, `pini`, `pref` and `ei` are compulsory.

The user specifies his material's parameters after the keyword "PARAM". When EUROPLEXUS finds the keyword "LECTURE", it considers that the list of parameters is terminated, whatever the number of values that have been read.

However, the total number of parameters for this material may not exceed 100, including the four mandatory values (`rho`, `pini`, `pref` and `ei`).

If there are no additional parameters besides the four mandatory ones, the keyword "PARAM" may be omitted.

The parameters are used within the subroutine "MFLIBR" that must be written by the user, compiled and linked with the code libraries to produce a special code executable before launching the run.

The elements that accept the free material of type "FLUIDE" are the following:

1D : TUBE, TUYA, CAVI.

2D : TRIA, CAR1.

3D : CUBE, PRIS, TETR.

Be careful to respect the conventions chosen to rank the tensor components according to the 2-D plane, 2-D axisymmetric or 3-D cases. See page G.20 for further explanations.

The user can store for each element (and each integration point), the values he wants (up to 10) in the ECR table. For homogeneity with the other materials, the following data will be stored in the first two locations of the ECR table :

ECR(1) = Pressure

ECR(2) = Density.

The eight other locations are free.

Examples:

The following example, taken from the standard benchmark "bm_flu_1d_libr", concerns a shock tube with a perfect gas.

The material data are as follows:

```
MATERIAUX

  LIBRE FLUIDE 903 RO 13. PINI 1e6 PREF 1e5 EINT 192.3077e3
                   PARAM  1.4  640.        LECT tub_1  TERM

  LIBRE FLUIDE 903 RO 1.3 PINI 1e5 PREF 1e5 EINT 192.3077e3
                   PARAM  1.4  640.        LECT tub_2  TERM
```

In this case there are two materials, whose user index is the same (903), but which have different initial conditions.

Note the value of the initial internal energy, which is mandatory because the behaviour of the perfect gas depends both on the density ρ and on the specific internal energy e:

$$P = (\gamma - 1)\rho e$$

These two variables ρ and e change during the transient, as a function of mass and energy transfer among the neighbouring elements. EUROPLEXUS computes these transfers automatically.

There are two additional parameters besides the four mandatory ones. These are respectively the ratio of specific heats (γ), and the apecific heat at constant volume (C_v), which allow to obtain the temperature (θ).

$$\theta = \frac{e}{C_v}$$

Programming example relative to MFLIBR:

```
      SUBROUTINE MFLIBR(NUM,TT,XMAT,SIG,DEPS,EDOT,RO,EINT,DSIG,CSON,
     &                  ECR,X,IEL,IDIM,NBN)
*
*     ---------------------------------------------------------------
*
*          materiau libre (fluide)                 m.lepareux 11.86
*
*     ---------------------------------------------------------------
*
*    entree :
*          num        = numero de reperage du materiau utilisateur
*          tt         = temps du calcul
*          sig        = contraintes au debut du pas
*          deps       = accroissement des deformations
*          edot       = vitesse de deformation
*          ro         = masse volumique courante
*          eint       = energie interne massique courante
*          x          = coordonnees des nbn noeuds
*          iel        = numero de l'element
*          idim       = dimension (2=2d ou axis , 3=3d)
*          nbn        = nombre de noeuds de l'element
*          xmat(1)    = masse volumique initiale
*          xmat(2)    = pression initiale
*          xmat(3)    = pression de reference
*          xmat(4)    = energie interne massique initiale
*          xmat(5:)   = parametres de l'utilisateur
*    sortie :
*          dsig       = increments de contraintes
*          cson       = vitesse du son (pour la stabilite)
*          ecr(1)     = pression
*          ecr(2)     = masse volumique
*          ecr(3:7)   = emplacements libres
*
*  attention !  le materiau 903 est utilise par le benchmark
*                              "bm_flu_1d_libr.epx"
*
      IMPLICIT NONE
*
*---   variables globales :
      INTEGER, INTENT(IN)  :: NUM,IEL,NBN,IDIM
      REAL(8), INTENT(IN)  :: TT,XMAT(*),SIG(*),DEPS(*),EDOT(*),RO,EINT,
     &                        X(IDIM,NBN)
      REAL(8), INTENT(OUT) :: DSIG(*),CSON
      REAL(8), INTENT(INOUT) :: ECR(*)
*
*---   variables locales :
      REAL(8) :: ROZR,PZER,PREF,PABS,PR,CV,GAMA,TRE
*
*
      SELECT CASE (NUM)
      CASE(903)
*--         cas d'un gaz parfait :
        PREF = XMAT(3)                       ! PRESSION DE REFERENCE
        GAMA = XMAT(5)                       ! GAMMA DU GAZ
        CV   = XMAT(6)                       ! CHALEUR MASSIQUE
        PABS = RO * (GAMA -1D0) * EINT       ! PRESSION ABSOLUE
        CSON = SQRT(GAMA*PABS/RO)            ! VITESSE DU SON
        PR   = PABS - PREF                   ! PRESSION RELATIVE
        TRE  = EINT/CV  - 273.15D0           ! TEMPERATURE
*--         increments de contrainte (1d)
        DSIG(1) = -PR -SIG(1)
*--         remplissage des "ecr" :
        ECR(1) = PABS
        ECR(2) = RO
        ECR(3) = CSON
```

```
        ECR(4) = TRE
*
      CASE DEFAULT
*----              routine use to write
        CALL ERRMSS('MFLIBR','ROUTINE UTILISATEUR NON PROGRAMMEE')
        STOP ' "MFLIBR" ABSENT'
      END SELECT
*
      END
```

7.7.43 FREE MATERIAL OF TYPE MATERIAL POINT

Object:

This directive introduces a user-defined constitutive behaviour of type material point ("POINT MATERIEL").

Syntax:

```
"LIBR" "PMAT" num  "MASS" m  < "PARA"  a b c ... >  /LECTURE/
```

"PMAT" num

Indicates that the free material of type "POINT MATERIEL" has the user-specified index `num`.

"MASS" m

Mass of the material point element.

"PARA"...

Key-word used to introduce a series of additional parameters.

LECTURE

List of the elements concerned.

Comments:

The number `num` enables several materials chosen by the user to be recognized. The single parameter "MASS" is mandatory.

The user specifies his material's parameters after the keyword "PARAM". When EUROPLEXUS finds the keyword "LECTURE", it considers that the list of parameters is terminated, whatever the number of values that have been read.

However, the total number of parameters for this material may not exceed 100, including the single mandatory value (`m`).

If there are no additional parameters besides the mandatory one, the keyword "PARAM" may be omitted.

The parameters are used within the subroutine "MPLIBR" that must be written by the user, compiled and linked with the code libraries to produce a special code executable before launching the run.

The only element that accepts the free material of type “POINT MATERIEL” is ”PMAT”, that is always 3-D.

Be careful to respect the conventions chosen to rank the tensor components according to the 3-D cases. See page G.20 for further explanations.

The user can store for each element (and each integration point), the values he wants (up to 10) in the ECR table. The ten locations are free.

Examples:

The following example, taken from the standard benchmark ”bm_str_terlun”, treats the case of two pointwise masses that attract each other according to the universal gravitation law.

The material data are as follows:

```
MATERIAUX

!--                                 cte G    nbr   pt_lune
LIBRE  PMAT 101  MASS 1.00    PARAM  1.14e4    1       2
                 LECT  terre TERM
!--                                 cte G    nbr   pt_terre
LIBRE  PMAT 101  MASS 0.0123  PARAM  1.14e4    1       2
                 LECT  lune  TERM
!                 param(1) = constante de gravitation
!                 param(2) = nbr de noeuds attires par cet element
!                 param(3) = liste des noeuds (ici un seul)
```

In this case there are two materials, whose user index is the same (101), but which have different parameters. Lines starting by a “!” are comments.

The used units are adapted to the treated problem. For masses, the reference is the earth mass, for lengths the earth radius and for times the day.

There are three additional parameters besides the mandatory one, that are respectively the gravity constant, the number of nodes subjected to gravity (here just one) and the index of the concerned node.

Programming example relative to MPLIBR:

```
      SUBROUTINE MPLIBR(NUM,T,PARAM,AMAS,ECR,X,U,F,V,DTSTAB)
*
*     ---------------------------------------------------------------
*
*          materiau libre pour les points mat.       m.lepareux 08-95
*
*     ---------------------------------------------------------------
*
*    entree :
*           num       : numero de reperage pour l'utilisateur
*           t         : temps
*           param     : tableau des parametres du mat. libre
```

```
*            amas      : masse de l'element
*            x         : coordonnees
*            u         : deplacements
*            v         : vitesses
*    sortie :
*            ecr       : tableau des parametres du materiau
*            f         : forces internes
*
*  attention !  le materiau 101 est utilise par le benchmark
*                               "bm_str_terlun.epx"
*
      IMPLICIT NONE
*
*---    variables globales :
      INTEGER, INTENT(IN)  :: NUM
      REAL(8), INTENT(IN)  :: T,PARAM(*),AMAS,X(3),U(3),V(3)
      REAL(8), INTENT(OUT) :: F(3)
      REAL(8), INTENT(INOUT) :: ECR(*),DTSTAB
*
*---    variables locales :
      INTEGER LON,NOD,NBR,II
      REAL(8) GG,FF,R(3),R2,R3,AMB,XB(3),AUX,EPSI,BM(3)
      REAL(8) CX,SS,ROL,V2,VV,COEF
*
*
      SELECT CASE (NUM)
      CASE (101)
!---     loi de gravitation universelle :
!--      (l'element affecte de ce materiau agit sur les noeuds designes)
!--          param(2+1:2+nbr)   ! numeros des noeuds designes
         GG    = PARAM(1)       ! CONSTANTE G DE GRAVITATION
         NBR   = PARAM(2)       ! NOMBRE DE NOEUDS SOUMIS A L'ATTRACTION
         DTSTAB = 1000.
         EPSI = 0.01
*
         F(:) = 0D0
         DO II=1,NBR
           NOD = PARAM( 2 + II )
           CALL QUIDNE( 0,NOD,LON,XB )   ! XB = POSITION DU NOEUD CIBLE
           CALL QUIDNE( 5,NOD,LON,BM )
           AMB = BM(1)                   ! MASSE DU NOEUD CIBLE
*
           R(:) = X(:) - XB(:)
           R2 = R(1) * R(1)  +  R(2) * R(2)  +  R(3) * R(3)
           R3 = R2 * SQRT(R2)
           FF = GG * AMAS * AMB / R3
           AUX = SQRT( R3 / ( GG * AMB )  )
           DTSTAB = MIN( DTSTAB , AUX * EPSI )
*
           F(:) = F(:) + R(:) * FF
         END DO
      CASE DEFAULT
         CALL ERRMSS('MPLIBR','NUMERO DE MATERIAU LIBRE INCONNU')
         STOP ' MPLIBR'
!
      END SELECT
*
      END
```

7.7.44 FREE MATERIAL OF TYPE MECHANISM

Object:

This directive introduces a user-defined constitutive behaviour of mechanism type ("MECANISME").

Syntax:

```
"LIBR" "MECA" num   < "PARA"  a b c ... >  /LECTURE/
```

`"MECA" num`

Indicates that the free material of type "MECANISME" has the user-specified index `num`.

`"PARA"...`

Key-word used to introduce a series of additional parameters.

`LECTURE`

List of the elements concerned.

Comments:

The number `num` enables several materials chosen by the user to be recognized. There are no mandatory parameters.

The user specifies his material's parameters after the keyword "PARAM". When EUROPLEXUS finds the keyword "LECTURE", it considers that the list of parameters is terminated, whatever the number of values that have been read.

However, the total number of parameters for this material may not exceed 100.

If there are no parameters the keyword "PARAM" may be omitted.

The parameters are used within the subroutine "MMLIBR" that must be written by the user, compiled and linked with the code libraries to produce a special code executable before launching the run.

The only element that accepts the free material of type "MECANISME" is "MECA", that is an element with two nodes and 6 degrees of freedom per node.

The main interest of this free material is to allow the user to specify arbitrary relations (in matricial form) between the displacements of the two nodes and the applied forces. For example, it is possible to enter a symmetric stiffness matrix in order to model a complicated support (78 values). However, it must be noted that the relations must be specified in (or converted to) the global reference frame, and that they stay constant during the whole transient calculation.

The user can store for each element (and each integration point), the values he wants (up to 10) in the ECR table. The ten locations are free.

Examples:

The following example, taken from the standard benchmark "bm_str_meca_lbr", treats the very simple case of springs in translation and rotation.

The 78 values are specified in the global reference frame, and the principal axex are parallel to the global ones. The translational stiffness is $K_T = 1E3$, and the rotational one is $K_R = 4E6$. The free material has the user-specified index 905.

The material data are as follows:

```
MATERIAUX

   LIBRE  MECA  905  PARAM
       1e3
       0.0  1e3
       0.0  0.0  1e3
       0.0  0.0  0.0  4e6
       0.0  0.0  0.0  0.0  4e6
       0.0  0.0  0.0  0.0  0.0  4e6
      -1e3  0.0  0.0  0.0  0.0  0.0  1e3
       0.0 -1e3  0.0  0.0  0.0  0.0  0.0  1e3
       0.0  0.0 -1e3  0.0  0.0  0.0  0.0  0.0  1e3
       0.0  0.0  0.0 -4e6  0.0  0.0  0.0  0.0  0.0  4e6
       0.0  0.0  0.0  0.0 -4e6  0.0  0.0  0.0  0.0  0.0  4e6
       0.0  0.0  0.0  0.0  0.0 -4e6  0.0  0.0  0.0  0.0  0.0  4e6
                LECT  L_meca TERM
```

Programming example relative to MMLIBR:

```
      SUBROUTINE MMLIBR(NUM,TT,NBPAR,XMAT,X,DU,F,XMA,V,DFX,
     &                  ECR,SIG,DEPS,PI,DWINT,IEL,DTSTAB)
*
*     ----------------------------------------------------------------
*
*             materiau libre mecanisme                m.lepareux 12-00
*
*     ----------------------------------------------------------------
*
*    entree :
*          num        = numero de reperage du materiau utilisateur
*          tt         = temps du calcul
*          nbpar      = nombre de parametres utilisateur
*          xmat(1: )  = parametres du materiau
*          x(1:3,1:2) = coordonnees des 2 noeuds
*          du(1:12)   = deplacements des 2 noeuds
*          xma(1:12)  = masses des 2 noeuds
*          v(1:12)    = vitesses des 2 noeuds
*          dfx(1:12)  = deplacements cumules des 2 noeuds
*          sig(1:6)   = forces internes au debut du pas
*                         en fait : sig = 0.5 * (f2 - f1)
```

```
*         deps(1:6)  = deplacement relatif : deps = (u2 - u1)
*         iel        = numero de l'element
*    sorties :
*         f(1:12)    = forces internes appliquees aux 2 noeuds
*         ecr(:)     = variables internes (emplacements libres)
*         pi(1:6)    = forces internes a la fin du pas
*         dwint      = travail des forces internes
*         dtstab     = pas de stabilite
*
*  attention !  le materiau 905 est utilise par le benchmark
*                              "bm_str_meca_lbr.epx"
*
      IMPLICIT NONE
*
*---   variables globales :
      INTEGER, INTENT(IN)    :: NUM,IEL,NBPAR
      REAL(8), INTENT(IN)    :: TT,XMAT(*),X(3,2),DU(12),XMA(12),
     &                          V(12),DFX(12),SIG(6),DEPS(6)
      REAL(8), INTENT(OUT)   :: F(12),PI(6),DWINT
      REAL(8), INTENT(INOUT) :: ECR(*),DTSTAB
*
*---   variables locales :
      INTEGER :: K,I,II
      REAL(8) :: R_K(12,12),RT(3),RR(3),DT(12)
*
*
      SELECT CASE (NUM)
      CASE(905)
        IF(NBPAR /= 78) THEN
          CALL ERRMSS('MMLIBR','IL FAUT 78 VALEURS')
          STOP ' MMLIBR'
        ENDIF
*
*--         construction de la matrice de raideur :
        II = 0
        DO K=1,12
          DO I=1,K
            II = II+1
            R_K(K,I) = XMAT(II)
            R_K(I,K) = R_K(K,I)
          END DO
        END DO
*
*--         calcul direct des forces internes :
        F(:) = 0D0
        DO K=1,12
          DO I=1,12
            F(K) = F(K) + R_K(K,I)*DFX(I)
          END DO
        END DO
*
*--          nouvelles forces internes (pour calculer wint)
        DO K=1,6
          PI(K) = 0.5D0 * (F(K+6) - F(K))
        END DO
*
*--          travail des forces internes (pendant le pas de temps)
        DWINT = 0D0
        DO K=1,6
          DWINT = DWINT + 0.5D0*(SIG(K)+PI(K))*DEPS(K)
        END DO
*
*--          ECR : variables internes (allongement)
        DO K=1,3
          RT(K) = DFX(K+6) - DFX(K)
          RR(K) = DFX(K+9) - DFX(K+3)
        END DO
        ECR(1) = SQRT(RT(1)*RT(1) + RT(2)*RT(2) + RT(3)*RT(3))
        ECR(2) = SQRT(RR(1)*RR(1) + RR(2)*RR(2) + RR(3)*RR(3))
*
*--          calcul du pas de stabilite :
        DTSTAB = 1000D0
        DO K=1,12
          DT(K) = SQRT(XMA(K)/R_K(K,K))
          DTSTAB = MIN(DTSTAB,2*DT(K))
        END DO
*
      CASE DEFAULT
        CALL ERRMSS('MMLIBR','ROUTINE UTILISATEUR NON PROGRAMMEE')
        STOP ' "MMLIBR" ABSENT'
      END SELECT
*
      END
```

7.7.45 FREE MATERIAL OF TYPE BOUNDARY CONDITIONS

Object:

This directive introduces a user-defined constitutive behaviour of the boundary condition type ("CONDITION AUX LIMITES"").

Syntax:

```
"LIBR" "CLIM" num  "PREF" pref  < "PARA"  a b c ... >  /LECTURE/
```

`"CLIM" num`

Indicates that the free material of type "CONDITION AUX LIMITES" has the user-specified index `num`.

`"PREF" pref`

Reference pressure.

`"PARA"...`

Key-word used to introduce a series of additional parameters.

`LECTURE`

List of the elements concerned.

Comments:

The number `num` enables several materials chosen by the user to be recognized. The only mandatory parameter is `pref`.

The user specifies his material's parameters after the keyword "PARAM". When EUROPLEXUS finds the keyword "LECTURE", it considers that the list of parameters is terminated, whatever the number of values that have been read.

However, the total number of parameters for this material may not exceed 100, including the single mandatory value `pref`.

If there are no additional parameters besides the mandatory one, the keyword "PARAM" may be omitted.

The parameters are used within the subroutine "CLIBRE" that must be written by the user, compiled and linked with the code libraries to produce a special code executable before launching the run.

The elements that accept the free material of type "CONDITION AUX LIMITES" are "CL1D" and "CLTU", which are respectively an element with one node and one dof and an element with one node and 7 dofs.

The main interest of this free material is to allow the user to specify boundary conditions applied to the 'fluid' degree of freedom of these elements, e.g. in order to model a special device mounted along a pipeline. In the case of "CLTU", only the 7-th dof is affected. The first 6 dofs concern the structure and are not affected.

The user can store for each element (and each integration point), the values he wants (up to 10) in the ECR table. For homogeneity with the other materials, the following data will be stored in the first two locations of the ECR table :

ECR(1) = DP : variation of pressure due to the device

ECR(2) = Density of the donor element

The eight other locations are free.

Examples:

The following example, taken from the standard benchmark "bm_cir_conteneur_eau", concerns the case of the brutal opening of a pressure container.

The container top is detached from the body and the opening (assumed circumferential) grows as the top moves away. The motion is parallel to the axis O_x. As a consequence of the detachment, the cross-section of the diaphragm across which the internal fluid passes is gradually increased, and the corresponding pressure drop is modified accordingly, as a function of the top distance.

The free material is identified by the index 906. Lines starting by a "!" are comments.

The material data are as follows:

```
MATERIAUX

      LIBRE  CLIM   906    PREF 10E5
             PARAM     1      25       22     0.1857
!--                  ptfond  ptcouv   eldon    diam
                      90e5     10e5    0.0       1.0
!--                  pamon     pext    tau      ksi idel'cik (sortie)
             LECT  esort TERM
!
!      materiau libre 906 (ouverture circonferentielle) :
!               param(1) = numero du premier point
!               param(2) = numero du second  point
!               param(3) = numero de l'element donneur
!               param(4) = diametre du tube
!               param(5) = pression amont initiale
```

```
!                param(6) = pression externe
!                param(7) = constante de temps pour l'ouverture
!                param(8) = perte de charge en sortie (idel'cik)
!
```

Programming example relative to CLIBRE:

```
      SUBROUTINE CLIBRE(NUNU,PREF,PARAM,AIRE,RHO,PAMON,VN,T,ECR,DP)
*
*     -----------------------------------------------------------------
*
*             materiau libre pour el. cl1d        m.lepareux 08-95
*
*     -----------------------------------------------------------------
*
*     attention !
*
*      le materiau nunu = 906 est utilise par "bm_cir_conteneur_eau.epx"
*
*    entree (ne pas les modifier) :
*             nunu      : numero de reperage pour l'utilisateur
*             pref      : pression de reference (obligatoire)
*             param     : tableau des parametres du mat. libre
*             aire      : section de la tuyauterie
*             rho       : masse volumique amont
*             pamon     : pression amont
*             vn        : vitesse du fluide dans la tuyauterie
*             t         : temps
*    sortie :
*             dp        : variation de pression due a l'appareil
*             ecr(1)    : affecte a dp
*             ecr(2)    : affecte a rho amont
*             ecr(3:9)  : selon utilisateur
*
*
*     les ecr libres permettent la sortie graphique
*     des grandeurs qui leur sont affectees
*
      IMPLICIT NONE
*
*--  variables globales :
      INTEGER, INTENT(IN)  :: NUNU
      REAL(8), INTENT(IN)  :: PREF,AIRE,RHO,PAMON,VN,T,PARAM(*)
      REAL(8), INTENT(OUT) :: ECR(*),DP
*
      REAL(8), PARAMETER :: ZERO=1D-6, RMIN=1D-3, RS2MIN=1.005D0
      INTEGER, PARAMETER :: LON1=7
*
*--  variables locales :
      INTEGER NP1,NP2,LON,NELDON,KAS
      REAL*8  DIAM,PZERO,PAVAL,TAU,PEXT,VAL1(LON1),VAL2(LON1),DIST,SECT,
     &        RAP,RS2,XKZ,PSEUIL,P0,XK,Q0,PP,ZMACH,
     &        DPE,DPK,ROVK,DPMAX,ROVN,XKSI,CSON
      LOGICAL OUVERT
!
!
      SELECT CASE (NUNU)

      CASE (906)
!---       diaphragme pour une ouverture progressive
        NP1    = NINT(PARAM(1))   ! NUMERO DU PREMIER POINT
        NP2    = NINT(PARAM(2))   ! NUMERO DU DEUXIEME POINT
        NELDON = NINT(PARAM(3))   ! NUMERO DE L'ELEMENT DONNEUR
        DIAM   = PARAM(4)         ! DIAMETRE DU TUBE
        PZERO  = PARAM(5)         ! PRESSION AMONT INITIALE
        PAVAL  = PARAM(6)         ! PRESSION EXTERNE
        TAU    = PARAM(7)         ! CONSTANTE DE TEMPS POUR L'OUVERTURE
        XKSI   = PARAM(8)         ! PERTE DE CHARGE EN SORTIE (IDEL'CIK)
!
        OUVERT = .TRUE.
!
!--        on va chercher les deplacements des 2 noeuds :
        CALL QUIDNE (1,NP1,LON,VAL1)
        CALL QUIDNE (1,NP2,LON,VAL2)
          IF(LON > LON1) STOP ' CLIBRE : DIM INSUFFISANTES'
        DIST = ABS( VAL2(1) + VAL1(1) )
        SECT = 3.1416 * DIAM * DIST
        RAP = SECT / AIRE
!
!--          le rapport des sections (rap) est limite a RMIN
!                              (cas des petites ouvertures) :
        IF( RAP .LT. RMIN ) THEN
          RAP = RMIN
          OUVERT = .FALSE.
        ENDIF
        RS2 = 1 / ( RAP*RAP )
!
!--          rs2 est limite a rs2min  (cas des grandes ouvertures) :
        IF(RS2 < RS2MIN) THEN
          RS2 = RS2MIN
```

```
          RAP = SQRT(1/RS2MIN)
        ENDIF
!
!--        perte de charge (idel'cik) :
        XK = RS2 * XKSI
!
!-----    si tau .ne. 0 la pression aval chute progressivement :
!           (a condition que pamon > paval)
!
        PSEUIL = PZERO - PAVAL
        IF(TAU.GT.ZERO .AND. PSEUIL.GT.ZERO*PZERO) THEN
          PEXT = PAVAL + PSEUIL*EXP( -T / TAU)
        ELSE
          PEXT = PAVAL
        ENDIF
!
        DPMAX = PAMON - PREF
        IF(OUVERT) THEN
          DPE = PEXT - PREF
          DPK =  0.5*XK * RHO * VN*VN
        ELSE
          DPE = PAMON - PREF
          DPK = 0
        ENDIF
        DP = DPE + DPK
        IF(DP > DPMAX) DP = DPMAX
!
        ECR(1) = DP + PREF
        ECR(2) = RHO
        ECR(3) = RHO*VN      ! PRODUIT RHO*VN (DEBIT MASSIQUE UNITAIRE)
        ECR(4) = PEXT        ! PRESSION DE SORTIE ( PEXT OU PCRIT )
        ECR(5) = DIST        ! DISTANCE ENTRE LES FRAGMENTS
        ECR(6) = XK          ! COEF. DE PERTE DE CHARGE
!
!-----   coefficient de stabilite ( xk * rho * vn ) :
        ROVK = ABS(ECR(6)*ECR(3))
!
!--   on arrete le calcul quand pamon < pext :
        IF( PAMON < PEXT )   CALL TILT
!
      CASE DEFAULT
        CALL ERRMSS('CLIBRE','ROUTINE UTILISATEUR NON PROGRAMMEE')
        STOP ' "CLIBRE" ABSENT'
      END SELECT
!
      RETURN
      END
```

7.7.46 FREE PARTICLE MATERIAL

Object:

This directive allows users to define their own constitutive laws for the particle elements (BILLE).

Syntax:

```
"BILLE  $  "LIBR" num  "RO" rho  $

        ...  < "FONC"  numfon >

        ...  < "PARA"  a b c ... >  /LECTURE/
```

`num`

Number of the material used for the particle elements.

`rho`

Density.

`numfon`

Number of the function used.

`"PARA" ...`

Introduces a series of complementary parameters.

`LECTURE`

List of the concerned elements.

Comments:

The number (num) allows to distinguish between several user-defined materials.

The rho parameter is mandatory.

The number (numfon) allows to identify the function used for the interaction.

The complementary parameters introduced by "PARA" may be as many as needed. EUROPLEXUS recognizes the end of the parameters when the "LECTURE" keyword is encountered.

The subroutine "MBLIBR", to be written by the user, computes the interaction forces between neighbouring particles of the "BILLE" element considered, starting from the quantities at the beginning of the step, which are known. Consult the following example for a list of the available variables.

The only element type accepting this material is "BILLE".

The user may store for each element the variables of his choice within the ECR table (up tp 7 values). However, for uniformity with the other materials, it is advised to use the first two slots as follows:

```
Fluid :                             Continuum structure:

  ECR(1) = Pressure                    ECR(1) = Pressure
  ECR(2) = Density                     ECR(2) = Von Mises
```

Example:

Two new materials of the fluid type are defined: a material of type acoustic fluid, and the other depending upon the distance between two neighbouring particles.

The corresponding data will be, for example:

```
"BILL" "LIBR" 1 "RO" 1000 "PARA" 1000   /LECTURE/

"BILL" "LIBR" 2 "RO"  800 "FONC" 1      /LECTURE/
```

Programming example for routine MBLIBR:

```
      SUBROUTINE MBLIBR(XMAT,DINI,DIST,A,B,C,NVOIS,NUMVOI,DVX,DVY,DVZ,
     * ROCOUR,IEL,INOE,INOEV,IPFONC,TABFON,T,DT1,FORCE,SIG,ECR)
C
C ----------------------------------------------------------------------
C
C                       MATERIAU "BILLE" "LIBRE"
C
C                                                       R.GALON 02/91
C ---------------------------------------------------------------------
C
C
C      ENTREE :
C      ------
C           XMAT(1)     =  MASSE VOLUMIQUE INITIALE
C           XMAT(2)     =  NUMERO DE REPERAGE DU MATERIAU UTILISATEUR
C           XMAT(3)     =  NUMERO DE LA FONCTION ASSOCIEE
C           XMAT(4:  )  =  AUTRES PARAMETRES DU MATERIAU
C           DINI        =  DIAMETRE INITIAL DE LA BILLE
C           DIST        =  DISTANCE SEPARANT LES 2 BILLES EN INTERACTION
C           A           =  COSINUS DIRECTEUR SUIVANT X DE LA LIAISON
C           B           =  COSINUS DIRECTEUR SUIVANT Y DE LA LIAISON
C           C           =  COSINUS DIRECTEUR SUIVANT Z DE LA LIAISON
C           NVOIS       =  NOMBRE DE BILLES VOISINES DE LA BILLE TRAITEE
C           NUMVOI      =  NUMVOI-IEME BILLE EN INTERACTION
C           DVX         =  VITESSE RELATIVE DES 2 BILLES DE LA LIAISON
C                          SUIVANT X
C           DVY         =  VITESSE RELATIVE DES 2 BILLES DE LA LIAISON
C                          SUIVANT Y
C           DVZ         =  VITESSE RELATIVE DES 2 BILLES DE LA LIAISON
C                          SUIVANT Z
C           ROCOUR      =  MASSE VOLUMIQUE ASSOCIEE A LA LIAISON
C           IEL         =  NUMERO DE L ELEMENT TRAITE
```

```
C          INOE        =  NUMERO DU NOEUD ASSOCIE A L ELEMENT IEL
C          INOEV       =  NUMERO DU NOEUD VOISIN DE LA BILLE
C          IPFONC      =  POINTE SUR LA TABLE DE FONCTION
C          TABFON      =  TABLE DE FONCTION ASSOCIEE AU MATERIAU
C          T           =  TEMPS DE CALCUL
C          DT1         =  INCREMENT DE TEMPS DE CALCUL
C
C
C      SORTIE :
C      ------
C          FORCE(1:3)  =  FORCES A APPLIQUER A LA BILLE TRAITEE
C          SIG(1:6)    =  CONTRAINTES A LA FIN DU PAS (FACULTATIF)
C          ECR(1:10)   =  EMPLACEMENTS LIBRES
C
C      REMARQUE : - DEUX BILLES SEPAREES DE PLUS DE 1.3 * DINI SONT
C      --------     SUPPOSEES NE PAS POUVOIR INTERAGIR ENTRE ELLES.
C
C                 - ON CUMULE TOUJOURS LES FORCES CAR ELLES PROVIENNENT
C                   DE L INTERACTION DE TOUTES LES BILLES VOISINES DE LA
C                   BILLE TRAITEE.
C
      IMPLICIT REAL*8(A-H,O-Z)
C
      DIMENSION XMAT(*),ECR(*),FORCE(*),TABFON(*),SIG(*),IPFONC(2,*)
C
C
      NUM = XMAT(2)
C
      IF(NUM.NE.1) GOTO 20
C
C --------- CAS D UN MATERIAU DE TYPE FLUIDE
C           ===============================
      RO = XMAT(1)
      CSON = XMAT(4)
C ------ POUR LA PREMIERE BILLE EN INTERACTION ON INITIALISE PAR EXEMPLE
C        LA MASSE VOLUMIQUE ET LA PRESSION MOYENNE DE L ELEMENT BILLE IEL
      IF(NUMVOI.EQ.1)THEN
            ECR(1)=0.
            ECR(2)=0.
            SIG(1)=0.
            SIG(2)=0.
            SIG(3)=0.
      ENDIF
C ------ DRO = VARIATION DE LA MASSE VOLUMIQUE
      DRO = ROCOUR - RO
      P = DRO * CSON * CSON
      DVOL = (ROCOUR/RO) -1.D0
      DP2 = DINI**3 / (DIST*(1.D0 + DVOL))
C
C ------ COEFICIENT DE PONDERATION POUR UN RESEAU HEXAGONAL DE BILLES
      COEF = SQRT(2.D0)/4.D0
C
C ------ COEFICIENT DE PONDERATION POUR UN RESEAU CUBIQUE DE BILLES
C     COEF = 1.D0
C ------ FORCE DANS LA DIRECTION DE LA LIAISON APPLIQUEE A LA BILLE
      FN = - DP2 * COEF * P
C ------ ON PROJETTE LA FORCE DANS LE REPERE GLOBAL
      FORCE(1) = FORCE(1) + A * FN
      FORCE(2) = FORCE(2) + B * FN
      FORCE(3) = FORCE(3) + C * FN
C ------ CONTAINTES DANS L ELEMENT (PRESSIONS)
C
      SIG(1) = SIG(1) + P/NVOIS
      SIG(2) = SIG(2) + P/NVOIS
      SIG(3) = SIG(3) + P/NVOIS
      SIG(4) = 0.
      SIG(5) = 0.
      SIG(6) = 0.
C ------ MASSE VOLUMIQUE MOYENNE
      ECR(1) = ECR(1) + ROCOUR/NVOIS
C ------ PRESSION MOYENNE
      ECR(2) = ECR(2) + P/NVOIS
      RETURN
C
C
 20   CONTINUE
C
C --------- FORCE DEFINIE PAR UNE FONCTION
C           =============================
C
C   REMARQUE : ON SUPPOSE ICI QUE LA FORCE AGISSANT SUR L ELEMENT BILLE
C              EST FONCTION UNIQUEMENT DE LA DISTANCE SEPARANT LES 2
C              BILLES EN INTERACTION (LA FONCTION EST DEFINIE PAR LA
C              DIRECTIVE "FONC".
C
      IFONC = XMAT(3)
C
C ------ FN EST LA FORCE CORRESPONDANT A UNE DISTANCE DIST SEPARANT LES
C        2 BILLES EN INTERACTION (ELLE EST APPLIQUEE A L ELEMENT IEL)
C
      CALL FFONCT(IFONC,DIST,FN,IPFONC,TABFON)
C
C ------ ON PROJETTE LA FORCE DANS LE REPERE GLOBAL
C
      FORCE(1) = FORCE(1) + A * FN
      FORCE(2) = FORCE(2) + B * FN
      FORCE(3) = FORCE(3) + C * FN
C
C ------ DISTANCE MOYENNE DANS ECR(1) PAR EXEMPLE OU TOUTE AUTRE VALEUR
```

```
C        QUE L ON DESIRE CONSERVER
C
      ECR(1) = ECR(1) + DIST/NVOIS
C
      RETURN
      END
```

7.7.47 VON MISES (ISPRA IMPLEMENTATION)

Object:

This option enables to choose the Von Mises material with the implementation developed at Ispra. Elasto-plasticity is implemented via a radial return algorithm. Only isotropic hardening is activated to date. There is no dependency on temperature nor on strain rate.

Syntax:

```
"VM23" ![ "RO" rho  "YOUN" young  "NU" nu  "ELAS" sige ...
         <"FAIL" $[ VMIS ; PEPS ; PRES ; PEPR ]$ "LIMI" limit>
         "TRAC" npts*(sig eps) ]!
         /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`sige`

Elastic limit.

`FAIL`

Optional keyword: introduces an element failure model, represented by a failure criterion and a by failure limit value. The available failure criteria are: `VMIS` for a criterion based upon Von Mises stress (isotropic criterion), `PEPS` for a criterion based upon the principal strain (see caveat below), `PRES` for a criterion based upon the hydrostatic stress, `PEPR` for a criterion based upon the principal strain if the hydrostatic stress is positive (traction): if the hydrostatic stress is negative (compression) there is no failure.

`limit`

Optional parameter, indicates the failure limit for the chosen criterion.

`"TRAC"`

This key-word announces the yield curve.

`npts`

Number of points (except the origin) defining the yield curve. By defining npts to 0 a linear material will be considered. The elastic limit will be neglected.

`sig`

Stress.

`eps`

Total strain (elastic + plastic).

`LECTURE`

List of the elements concerned.

Comments:

1/ - The young parameter defines Young's modulus during an elastic phase.

2/ - The points (sig, eps) may have any position; however, concerning the first point, there must be a compatibility between the coordinates, Young's modulus and the elastic limit.

3/ - The slope of the yield curve may not increase from one segment to the following one.

4/ - When using a failure criterion based upon the principal strains (`PEPS` or `PEPR`) be aware that the criterion is based upon the *cumulated* strains. These are usually a good approximation of the total strains for elements using a convected reference frame for the stresses and strains (such as e.g. plate, shell or bar elements). The approximation is likely to be very bad, instead, for continuum-like elements, at least when there are large rotations.

Outputs:

The components of the ECR table are as follows:

ECR(1): current hydrostatic pressure

ECR(2): current equivalent stress (Von Mises)

ECR(3): current equivalent plastic strain

ECR(4): current yield stress

ECR(5): sound speed

ECR(6): failure flag (0=virgin Gauss Point, 1=failed Gauss Point)

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.48 VM1D MATERIAL

Object:

This is the material to be used for the interface elements of type ED1D (see INT.80).

Syntax:

```
"VM1D"  "PT1D" pt1d /LECTURE/
```

`pt1d`

Associated node index in the 1-D model.

Comments:

Note that when several ED1D elements are present in a coupled 1-D/multi-D calculation, then each ED1D element must have a separate VM1D material, because the material is used to carry the information of the associated 1-D node to each one ED1D element (pt1d).

Outputs:

The components of the ECR table are as follows :

ECR(1) : unused

ECR(2) : unused

ECR(3) : unused

ECR(4) : unused

ECR(5) : unused

ECR(6) : unused

7.7.49 DONE MATERIAL

Object:

This is a viscoplastic material model mostly used to describe the sensitivity of commonly used stainless steels (e.g. AISI 304 and 316) to the rate of loading. It uses the theory of viscoplasticity based on total strain and overstress. To date, it is limited to small strains.

Syntax:

```
"DONE"  "RO" rho  "YOUN" young  "NU" nu  "ELAS" sige ...
  ...  "VIS1" vis1  "VIS2" vis2  "VIS3" vis3  ...
  ...  "VIS4" vis1  "VIS5" vis2  "VIS6" vis3  ...
  ...  "TRAC" npts*(sig eps) /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`sige`

Elastic limit.

`vis1,..,vis6`

Viscous coefficients.

`"TRAC"`

This key-word announces the yield curve (static).

`npts`

Number of points (except the origin) defining the static yield curve.

`sig`

Stress.

`eps`

Total strain (elastic + plastic).

`LECTURE`

List of the elements concerned.

Comments:

1/ - The young parameter defines Young's modulus during an elastic phase.

2/ - The points (sig, eps) may have any position; however, concerning the first point, there must be a compatibility between the coordinates, Young's modulus and the elastic limit.

3/ - The slope of the static yield curve may not increase from one segment to the following one.

Outputs:

The components of the ECR table are as follows:

ECR(1): current hydrostatic pressure

ECR(2): current equivalent stress (Von Mises)

ECR(3): current equivalent plastic strain

ECR(4): current yield stress

ECR(5): x-overstress

ECR(6): y-overstress

ECR(7): xy-overstress

ECR(8): z-overstress

ECR(9): previous time

ECR(10): yz-overstress

ECR(11): xz-overstress

Let P represent the point of intersection (in the equivalent stress - equivalent strain space) between the unloading path and the equilibrium stress-strain curve.

ECR(12): total x-strain at point P

ECR(13): total y-strain at point P

ECR(14): total z-strain at point P

ECR(15): total xy-strain at point P

ECR(16): total yz-strain at point P

ECR(17): total xz-strain at point P

ECR(18): equivalent total strain at point P

ECR(19): old equivalent total strain

ECR(20): EPSC (equivalent strain parameter)

EPSC is defined by the cyclic hardening law. It corresponds to the distance between point P and the new origin in the strain direction.

ECR(21): current cumulative value of number of crossings of the unloading path with the equilibrium stress-strain diagram

ECR(22): new x-stress at point P

ECR(23): new y-stress at point P

ECR(24): new xy-stress at point P

ECR(25): new z-stress at point P

ECR(26): new yz-stress at point P

ECR(27): new xz-stress at point P

ECR(28): new equivalent stress at point P

ECR(29): old equivalent stress

ECR(30): old equilibrium equivalent stress

ECR(31): old (Young's modulus * total strain)

ECR(32): sound speed

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.50 VON MISES WITH VISCOPLASTIC REGULARIZATION

Object:

This directive enables to choose an elastoplastic constitutive theory with Von Mises yield surface, associative flow rule, and isotropic hardening or softening, including a viscoplastic regularization. Elasto-plasticity is implemented via a radial return algorithm.

For more information about the theory, please refer to: J.C. Simo, J.G. Kennedy and S. Govindjee, "Non-Smooth Multisurface Plasticity and Viscoplasticity. Loading/Unloading Conditions and Numerical Algorithms", Int. J. Num. Meth. Eng., Vol 26, pp. 2161-2185 (1988).

Syntax:

```
"VMSF"  "RO" rho  "YOUN" young  "NU" nu  "ELAS" sige "ETA" eta
  ...  "TRAC" npts*(sig eps) /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`sige`

Elastic limit.

`eta`

Viscoplastic parameter (relaxation time).

`"TRAC"`

This key-word announces the yield curve.

`npts`

Number of points (except the origin) defining the yield curve.

`sig`

Stress.

`eps`

Total strain (elastic + plastic).

`LECTURE`

List of the elements concerned.

Comments:

1/ - The young parameter defines Young's modulus during an elastic phase.

2/ - The points (sig,eps) may have any position; however, concerning the first point, there must be a compatibility between the coordinates, Young's modulus and the elastic limit.

3/ - The slope of the yield curve may become negative in the softening part of the curve.

Outputs:

The components of the ECR table are as follows:

ECR(1): current hydrostatic pressure

ECR(2): current equivalent stress (Von Mises)

ECR(3): current equivalent plastic strain

ECR(4): current yield stress

ECR(5): x-stress before viscoplastic correction

ECR(6): y-stress before viscoplastic correction

ECR(7): xy-stress before viscoplastic correction

ECR(8): z-stress before viscoplastic correction

ECR(9): yz-stress before viscoplastic correction (3D only)

ECR(10): xz-stress before viscoplastic correction (3D only)

ECR(11): current time

ECR(12): sound speed

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.51 DRUCKER PRAGER WITH VISCOPLASTIC REGULARIZATION

Object

This directive enables to choose an elastoplastic constitutive theory with Drucker Prager yield surface, associative or non-associative flow rule, including hardening or softening, and a viscoplastic regularization.

This material is part of the models developed by the CESI team (formerly at ENEL, Milano) in collaboration with JRC.

The regularization technique is the same as the one implemented in the VMSF material, see: J.C. Simo, J.G. Kennedy and S. Govindjee, "Non-Smooth Multisurface Plasticity and Viscoplasticity. Loading/Unloading Conditions and Numerical Algorithms", Int. J. Num. Meth. Eng., Vol 26, pp. 2161-2185 (1988).

The model uses two parameters, alfa and c, related to the angle and the cohesion parameters of the classical Drucker Prager model. These two parameters are not constant in general, but depend on the plastic strain. Hardening and/or softening are thus possible.

References

More information on the formulation of this material model may be found in reference [120].

Syntax

```
"DPSF"  "RO" rho  "YOUN" young  "NU" nu
        "ALF1" alf1 "C1" c1 "BETA" beta "ETA" eta
        <"FAIL" $[ PEPS ; PEPR ]$ "LIMI" limit >
        "TRAA" npta*(alfa epsp)
        "TRAC" npts*(c    epsp) /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`alf1`

First value ("yield limit") of the TRAA curve for the alfa parameter, see below.

`c1`

First value (”yield limit”) of the TRAC curve for the c parameter, see below.

`beta`

Parameter indicating whether the model is associative or non associative. If the alfa parameter (given by the ”TRAA” directive below) does not depend upon the plastic strain, and beta=alf1, then an associative rule is taken. Otherwise, the law is non associative. E.g., beta=0 corresponds to return along a cylinder.

`eta`

Viscoplastic parameter (relaxation time).

`FAIL`

Optional keyword: introduces an element failure model, represented by a failure criterion and a by failure limit value. The available failure criteria are: `PEPS` for a criterion based upon the principal strain (see caveat below), `PEPR` for a criterion based upon the principal strain if the hydrostatic stress is positive (traction): if the hydrostatic stress is negative (compression) there is no failure.

`limit`

Optional parameter, indicates the failure limit for the chosen criterion.

`"TRAA"`

This key-word announces the curve defining the variation of the alfa parameter with the plastic strain.

`npta`

Number of points defining the curve.

`alfa`

Value of the alfa parameter.

`epsp`

Corresponding value of the plastic strain.

`"TRAC"`

This key-word announces the curve curve defining the variation of the c parameter with the plastic strain.

`npts`

Number of points defining the curve.

`c`

Value of the c parameter.

`epsp`

Corresponding value of the plastic strain.

`LECTURE`

List of the elements concerned.

Comments:

When using a failure criterion based upon the principal strains (`PEPS` or `PEPR`) be aware that the criterion is based upon the *cumulated* strains. These are usually a good approximation of the total strains for elements using a convected reference frame for the stresses and strains (such as e.g. plate, shell or bar elements). The approximation is likely to be very bad, instead, for continuum-like elements, at least when there are large rotations.

The parameter `ETA` can be effectively used to obtain a mesh size independence in case of static or quasi-static calculations. The parameter is very sensitive in case of dynamic simulations and must be set with care. It is recommended to set this parameter to 0 in case of fast dynamic simulations.

Outputs:

The components of the ECR table are as follows:

ECR(1): current hydrostatic pressure

ECR(2): current equivalent stress (Von Mises)

ECR(3): current equivalent plastic strain

ECR(4): cohesion

ECR(5): x-stress before viscoplastic correction

ECR(6): y-stress before viscoplastic correction

ECR(7): xy-stress before viscoplastic correction

ECR(8): z-stress before viscoplastic correction

ECR(9): yz-stress before viscoplastic correction (3D only)

ECR(10): xz-stress before viscoplastic correction (3D only)

ECR(11): current time

ECR(12): alfa

ECR(13): zone (sigma - tau plane)

ECR(14): yield (f=alfa*sigma+tau-cohe), >0 if plast

ECR(15): failure flag (0=virgin Gauss Point, 1=failed Gauss Point).

ECR(16): sound speed

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.52 COMPOSITE MATERIAL (LINEAR OTHOTROPIC) ISPRA IMPLEMENTATION

Object:

The option is used to enter materials with a linear orthotropic behaviour into a coordinate system defined by the user. The model is suitable to represent e.g. composite materials.

Syntax:

```
"COMM"  "RO"   rho    "YG1"  yg1    "YG2"   yg2  "YG3" yg3
        "NU12" nu12   "NU13" nu13   "NU23" nu23
        "G12"  g12    "G13"  g13    "G23" g23
        /LECTURE/
```

`rho`

Density of the material.

`yg1`

Young's modulus along direction 1.

`yg2`

Young's modulus along direction 2.

`yg3`

young's modulus along direction 3.

`nu12`

Poisson's ration between direction 1 and 2.

`nu 13`

Poisson's ration between direction 1 and 3.

`nu23`

Poisson's ratio between direction 2 and 3.

`g12`

Shear modulus between direction 1 and 2.

`g13`

Shear modulus between direction 1 and 3.

`g23`

Shear modulus between direction 2 and 3.

`LECTURE`

List of the elements concerned.

Comments:

This option may be repeated as many times as necessary.

The associated orthotropy directions are to be specified via the `COMP ORTS` directive (see page C.97).

Outputs:

The different components of the ECR table are as follows:

ECR(1) : current hydrostatic pressure (1/3(SX+SY+ST))

ECR(2) : current equivalent stress (von Mises)

ECR(3) : current equivalent plastic strain

ECR(4) : current yield stress

ECR(5): sound speed

ECR(6): angle alpha between lamina coordinate 1 and orthotropy direction 1

ECR(7): 10.

ECR(8): 10.

7.7.53 MODIFIED CAM-CLAY MATERIAL

Object

The directive is used to enter materials with a modified Cam-clay behaviour. The model is suitable to represent e.g. cohesive soil materials.

Although the model includes some treatment of the water possibly present in soils, the use of this feature is strongly discouraged because the modeling appears somewhat inconsistent in that case: for example, water motion within the soil is not treated, water pressure is not taken into account to compute internal forces, and finally the calculation of masses seems inconsistent. To model a dry soil, just leave out the keyword `ROW`: then the code assumes $\rho_w = 0$, the value given for ρ is the density of the (dry) soil alone, and the value given for z_f, if any, is irrelevant.

References

More information on the formulation of this material model may be found in reference [147].

Syntax

```
CAMC  RO ro |[ NU nu ; G g ]|
      M m     LAM lam   K k    E e   <ROW row>
      K0 k0   OCR ocr
      |[ ZF zf SLEV slev GRAV grav  ;  PRES pres ]|
      /LECT/
```

`ro`

Initial density ρ of the soil (including the water, if any: but see the comments above and below).

`nu`

Poisson's coefficient ν. If this value is given, then the shear modulus G may not be given and the calculation is done with constant Poisson's coefficient (G will vary accordingly).

`g`

Shear modulus G. If this value is given, then ν may not be given and the calculation is done with constant shear modulus (ν will vary accordingly).

`m`

Critical state parameter M. Corresponds to the CLAY model's M parameter. For the physical meaning, see the Remarks below.

`lam`

Isotropic consolidation modulus (λ).

`k`

Unloading-reloading modulus (κ).

`e`

Initial void ratio e, defined as: $e = V_{\mathrm{Voids}}/V_{\mathrm{Solid}}$.

`row`

Water density ρ_w. Use 0.0 for dry soils, or just leave out this keyword since the default value is 0.0. Note that in this case the value for ρ given above indicates the density of the (dry) soil alone.

`k0`

Coefficient of earth pressure at rest (K_0).

`ocr`

Overconsolidation ratio O_{cr}: ($O_{cr} = 1$ for normal-consolidated soil).

`zf`

Upper level of water, i.e. water surface "vertical" coordinate (y in 2D, z in 3D). Used to compute the in-situ (initial) stress and hardening state. This quantity is unused, and thus any value may be given, e.g. $z_f = 0$, if the user has specified $\rho_w = 0$ (dry soil).

`slev`

Upper level of soil, i.e. soil surface "vertical" coordinate (y in 2D, z in 3D). Used to compute the in-situ (initial) stress and hardening state.

`grav`

Acceleration of gravity along the "vertical" coordinate (y in 2D, z in 3D). Used to compute the in-situ (initial) stress and hardening state.

`pres`

Initial hydrostatic (uniform) pressure state. Note that here (but not for stresses SIG etc.) a positive value should be used to indicate an initial compression (negative stress).

`LECTURE`

List of the elements concerned.

Comments

This option may be repeated as many times as necessary.

This material model seems unable to start from initial stress-free conditions, so that in-situ (initial) stresses should always be specified.

The initial in-situ conditions (stresses and some of the ECR components) for elements using this material are computed by using the parameters (`zf`, `slev`, `grav`) or `pres`. One and only one of these two sets must be given. In the following discussion, the term “vertical” refers to the y-coordinate in 2D, to the z-coordinate in 3D calculations.

A) If `pres` (p) is specified, then the initial state is uniform hydrostatic stress ($-p$) all over the current `CAMC` material. This is typical, e.g., of simple one-element tests to check the behaviour of the constitutive law, or of simple laboratory experiments.

In this case, the code simply sets:

$$\sigma_1 = -p \quad , \quad \sigma_2 = -p \quad , \quad \sigma_3 = -p.$$

B) If (`zf`, `slev`, `grav`) are specified, then the initial conditions are computed as follows. The model assumes a horizontally stratified (homogeneous) soil, the lower part of which may contain water. The quantities z_f and s_{lev} are the vertical coordinates of the upper water and soil levels, respectively. Normally it should be $s_{\mathrm{lev}} > z_f$ so that the soil layer between z_f and s_{lev} is dry (no water) while the soil below that level is saturated by water.

For each element with the current CAMC material, the code computes the vertical coordinate of its centroid z_c. Then the vertical stress due to the soil weight (effective stress) is:

$$\sigma_v = -g(\rho - \rho_w)(s_{\mathrm{lev}} - z_c),$$

where ρ is the density of the wet soil (soil plus water), ρ_w is the density of the water. Thus, the difference between the two is the density of the (dry) soil. The vertical stress may not be positive:

$$\sigma_v = \mathrm{MIN}(\sigma_v, 0).$$

The horizontal stress is given by:

$$\sigma_h = K_0 \sigma_v,$$

where K_0 is the `k0` parameter specified above. Then, the code sets:

$$\sigma_1 = \sigma_h \quad , \quad \sigma_2 = \sigma_h \quad , \quad \sigma_3 = \sigma_v.$$

In addition to soil (effective) stresses, the water pressure (hydrostatic) is also evaluated:

$$p_w = -g\rho_w(z_f - z_c).$$

The water pressure may not be positive:

$$p_w = \mathrm{MIN}(p_w, 0).$$

This quantity is stored in ECR(7). Note, however, that the water pressure does *not* contribute to internal forces in the CAMC model: only the effective (soil) stresses are used.

Note also that if (`zf`, `slev`, `grav`) are specified one should also probably specify a “global” gravity term (equal to the value of g given above) by means e.g. of the `CHAR CONS GRAV` directive, in order to have (at least approximate) equilibrium in the initial configuration. In addition, suitable boundary conditions must also be prescribed along the envelope of the CAMC soil region.

Outputs

The different components of the ECR table are as follows:

ECR(1) : current hydrostatic pressure $\frac{1}{3}\mathrm{tr}(\sigma)$

ECR(2) : square root of the second invariant of the deviatoric stress tensor J_2' (i.e. square root of Von Mises equivalent stress)

ECR(3) : current void ratio

ECR(4) : hardening parameter P_c (isotropic consolidation pressure)

ECR(5): sound speed

ECR(6): water overpressure (u)

ECR(7): initial water pressure (p_0), $p = p_0 + u$ (p is the total water pressure)

ECR(8): volumetric strain ($\epsilon_V = \epsilon_x + \epsilon_y + \epsilon_z$)

ECR(9): deviatoric strain
$\epsilon_d = \sqrt{\frac{2}{3}[(\epsilon_x - \epsilon_y)^2 + (\epsilon_y - \epsilon_z)^2 + (\epsilon_y - \epsilon_z)^2] + (\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{xz}^2)}$

The components of the stress tensor are as follows:

SIG(1): σ_x

SIG(2): σ_y

SIG(3): σ_z

SIG(4): τ_{xy}

SIG(5): τ_{yz} (only 3D)

SIG(6): τ_{xz} (only 3D)

Remarks

Let M_1 be the ratio between the second invariant of the stress tensor J_2 and the first invariant of the stress tensor J_1 at critical state (i.e. for stress points which lie on the failure surface). This is the quantity which is usually available from tests.

Let M_2 be the ratio between the second invariant of the *deviatoric* stress tensor J_2' and the first invariant of the stress tensor J_1 at critical state.

The M parameter defined above in the input syntax corresponds to M_1. However, note that in the model description of the CAMC material the quantity $g(\theta)$ corresponds rather to M_2.

The following relation holds between the two quantities: $M_2 = M_1/\sqrt{3}$.

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements)

7.7.54 MODIFIED CAM-CLAY MATERIAL WITH VISCOPLASTIC REGULARIZATION

Object

The option is used to enter materials with a modified Cam-clay behaviour. The model is suitable to represent e.g. (dry) soil materials. The main differences with respect to the CAMC material are that:

- the CLAY model uses a fully implicit backward algorithm for the trial stress point to return onto the yield surface (similar to the radial return algorithm);
- the model includes an optional viscoplastic regularization;
- no attempt is made to take into account the possible presence of water (this feature is dubious in the `CAMC` material anyway).

Like for the `CAMC` material, the user may choose between a calculation with constant shear modulus and one with constant Poisson's coefficient.

References

More information on the formulation of this material model may be found in reference [123].

Syntax

```
CLAY  RO ro |[ NU nu ; G g ]|
      M m     LAM lam   K k   P0 p0
      K0 k0
      < BETA beta > < NUM num >
      |[ SLEV slev GRAV grav  ;  PRES pres ]|
      /LECT/
```

`ro`

Initial density ρ of the (dry) soil. Water content is not taken into account by this model.

`nu`

Poisson's coefficient ν. If this value is given, then G may not be given and the calculation is done with constant Poisson's coefficient (G will vary accordingly).

`g`

Shear modulus G. If this value is given, then ν may not be given and the calculation is done with constant shear modulus (ν will vary accordingly).

`m`

Critical state parameter M. Corresponds to the CAMC model's M parameter. For the physical meaning, see the Remarks below.

`lam`

First loading slope (λ). This is the slope of the normal consolidation line, divided by the reference volume V_λ. The normal consolidation line is defined in the plane $[V, \ln(P)]$, where V is the so-called specific volume ($V = 1 + e$, e being the void ratio i.e. the volune of the voids divided by volume of the solid). V_λ is the specific volume at unit pressure. P is the pressure.

`k`

Unloading-reloading slope κ. This is the slope of the unloading-reloading line, divided by the reference volume V_λ. The unloading-reloading line is defined in the plane $[V, \ln(P)]$, where V is the so-called specific volume ($V = 1 + e$, e being the void ratio i.e. the volune of the voids divided by volume of the solid). V_λ is the specific volume at unit pressure. P is the pressure.

`p0`

Initial value of the hardening parameter p_0.

`k0`

Coefficient of earth pressure at rest (K_0).

`beta`

Relaxation modulus β for the viscoplastic regularization. If $\beta = 0$, then no regularization is performed. By default, the code assumes $\beta = 0$.

`num`

Index (integer) n used by the initialization routine INICLA in order to set some initial properties of the soil (initial stresses and initial hardening parameters). By default, the program assumes $n = 0$.

`slev`

Upper level of soil, i.e. soil surface "vertical" coordinate (y in 2D, z in 3D). Used to compute the in-situ (initial) stress and hardening state.

`grav`

Acceleration of gravity along the "vertical" coordinate (y in 2D, z in 3D). Used to compute the in-situ (initial) stress and hardening state.

`pres`

Initial hydrostatic (uniform) pressure state. Note that here (but not for stresses SIG etc.) a positive value should be used to indicate an initial compression (negative stress).

`LECTURE`

List of the elements concerned.

Comments

This option may be repeated as many times as necessary.

The initial in-situ conditions (stresses and some of the ECR components) for elements using this material are computed by using the parameters (`slev`, `grav`) or `pres`. One and only one of these two sets must be given. In the following discussion, the term "vertical" refers to the y-coordinate in 2D, to the z-coordinate in 3D calculations.

A) If `pres` (p) is specified, then the initial state is uniform hydrostatic stress ($-p$) all over the current `CLAY` material. This is typical, e.g., of simple one-element tests to check the behaviour of the constitutive law, or of simple laboratory experiments.

In this case, the code simply sets:

$$\sigma_1 = -p \quad , \quad \sigma_2 = -p \quad , \quad \sigma_3 = -p.$$

B) If (`slev`, `grav`) are specified, then the initial conditions are computed as follows. The model assumes a horizontally stratified (homogeneous) soil in dry conditions, i.e. containing no water. The quantity $s_{\rm lev}$ is the vertical coordinate of the upper soil level.

For each element with the current CLAY material, the code computes the vertical coordinate of its centroid z_c. Then the vertical stress due to the soil weight (effective stress) is:

$$\sigma_v = -g\rho(s_{\rm lev} - z_c),$$

where ρ is the density of the (dry) soil. The vertical stress may not be positive:

$$\sigma_v = \mathrm{MIN}(\sigma_v, 0).$$

The horizontal stress is given by:

$$\sigma_h = K_0\sigma_v,$$

where K_0 is the `k0` parameter specified above. Then, the code sets:

$$\sigma_1 = \sigma_h \quad , \quad \sigma_2 = \sigma_h \quad , \quad \sigma_3 = \sigma_v.$$

Note that if (`slev`, `grav`) are specified one should also probably specify a "global" gravity term (equal to the value of g given above) by means e.g. of the `CHAR CONS GRAV` directive, in order to have (at least approximate) equilibrium in the initial configuration. In addition, suitable boundary conditions must also be prescribed along the envelope of the CLAY soil region.

Outputs

The different components of the ECR table are as follows:

ECR(1) : current hydrostatic pressure $\frac{1}{3}(\sigma_x + \sigma_y + \sigma_z)$

ECR(2) : current bulk modulus

ECR(3) : second invariant of the deviatoric cumulated strain

ECR(4) : hardening parameter p_0

ECR(5): sound speed

ECR(6): current value of the shear modulus G

ECR(7): current value of the Poisson's coefficient ν

The components of the stress tensor are as follows:

SIG(1): σ_x

SIG(2): σ_y

SIG(3): σ_z

SIG(4): τ_{xy}

SIG(5): τ_{yz} (only 3D)

SIG(6): τ_{xz} (only 3D)

Remarks

Let M_1 be the ratio between the second invariant of the stress tensor J_2 and the first invariant of the stress tensor J_1 at critical state (i.e. for stress points which lie on the failure surface). This is the quantity which is usually available from tests.

Let M_2 be the ratio between the second invariant of the *deviatoric* stress tensor J_2' and the first invariant of the stress tensor J_1 at critical state.

The M parameter defined above in the input syntax corresponds to M_1. However, note that in the model description of the CLAY material (*An Implementation of the Cam-Clay Elasto-Plastic Model Using a Backward Interpolation and Visco-Plastic Regularization*, Technical Note I.96.239) the quantity M corresponds rather to M_2.

The following relation holds between the two quantities: $M_2 = M_1/\sqrt{3}$.

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.55 MFRONT CONSTITUTIVE MODELS

Note: Before using this option, please make sure that your EPX version is supporting `MFront` behaviours. Besides, the user discretion is advised if you are not using the `MFront` generator provided by EPX.

Note: The following documentation assumes a basic knowledge about `MFront`.

Object:

This option enables the use of external constutive behaviours generated though the `MFront` library (saved as a `.so` under Unix, a `.dll` under Windows or a `.dylib` on MacOS). Assuming some requirements which are detailed later on, any behaviour can be handled for the finite elements compatible with `MFront`, i.e. the CUB8, CUB6, CUBE and TETR ones.

In case of inconsistencies, the user is to be notified by a embedded, dedicated `MFront` behaviour features parser.

References

To get more information about the `MFront` project, please refer to:

- the dedicated website: https://thelfer.github.io/tfel/web/index.html, or
- the GitHub repository: https://github.com/thelfer/tfel.git.

Syntax:

```
MFRONT
    'LibraryFilePath'
    'BehaviourLabel'
    DENS rho
    < nmatp * ( MATP 'MaterialPropertyEntryName' matp_value) >
    < nivar * ( IVAR 'InternalStateVariableEntryName' nisize * ( ivar_i ... ) ) >
    < nevar * ( EVAR 'ExternalStateVariableEntryName' nesize * ( evar_i ... ) ) >
    /LECT/
```

`LibraryFilePath`

Path towards the `MFront` library that is to be loaded.

`BehaviourLabel`

Behaviour label that is to be used (see the `MFront` `@Behaviour` macro).

`rho`

Initial material density.

`nmatp`

Number of material properties to be declared and initialized.

`MATP`

Keyword to trigger the delcaration of a material property (see the `MFront` `@MaterialProperty` macro).

`MaterialPropertyEntryName`

Material property entry name.

`matp_value`

Material property value.

`nivar`

Number of internal state variables to be initialized.

`IVAR`

Keyword to trigger a state variable initialization (see the `MFront` `@StateVariable` macro).

`InternalStateVariableEntryName`

State variable entry name.

`nisize`

State variable size (1 if scalar).

`ivar_i`

State variable initial values.

`nevar`

Number of external state variables to be initialized.

`EVAR`

Keyword to trigger an external state variable initialization (see the `MFront` `@ExternalStateVariable` macro).

`ExternalStateVariableEntryName`

External state variable entry name.

`nesize_value`

External state variable size (1 if scalar).

`evar_i`

State variable initial values.

Comments

To be compatible with an EPX calculation, an .mfront file has to get several requirements that will be checked:

- For 3D continuum elements, finite strain framework has to be activated. Moreover, the strain measure has to be specified and saved among state variables. This involves the declaration of a `@StrainMeasure` macro with a `save_strain:true` option.
- Two specific state variables with mandatory entry names has to be declared to handle speed of sound evaluation, namely a `MassDensity` and a `SpeedofSound` variable.

Initializing material properties declared in the .mfront file is **mandatory**. If not, EPX will throw an error.

Initializing internal/external state variables of the .mfront file is **optional**. If not, EPX will set them to zero.

Outputs

As any EPX material, EPST and SIGT variables will display strain and stress measure respectively. Concerning the ECRO variable, it will store all the declared internal state variables values, including those necessary to handle speed of sound computation. For each `MFront` material, **ECRO vector layout is to be found in the listing file**.

7.7.56 FUNE (SPECIALIZED CABLE MATERIAL)

Object:

This model represents an elastoplastic cable, with no resistance in compression, and should be used in conjunction with special cable elements FUN2 (in 2D) and FUN3 (in 3D). The material is elasto-plastic in traction.

Syntax:

```
"FUNE"  "RO" rho  "YOUN" young  "NU" nu  "ELAS" sige "ERUP" erup ...
    ...  "TRAC" npts*(sig eps) /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`sige`

Elastic limit.

`erup`

Rupture strain.

`"TRAC"`

This key-word announces the yield curve (in traction).

`npts`

Number of points (except the origin) defining the yield curve.

`sig`

Stress.

`eps`

Total strain (elastic + plastic).

`LECTURE`

List of the elements concerned.

Comments:

1/ - The young parameter defines Young's modulus during an elastic phase.

2/ - The points (sig,eps) may have any position; however, concerning the first point, there must be a compatibility between the coordinates, Young's modulus and the elastic limit.

3/ - The slope of the yield curve may not increase from one segment to the following one.

Outputs:

The components of the ECR table are as follows:

ECR(1): (free) (was total longitudinal strain of the cable element)

ECR(2): (free) (was total lateral strain of the cable element)

ECR(3): plastic longitudinal strain of the cable element

ECR(4): current yield stress in traction (0 if broken)

ECR(5): sound speed

Note that in order to post-process the total strains (which were formerly unappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.57 VMJC: Johnson-Cook model

Object:

In the Johnson-Cook model Elasto-plasticity is implemented via a radial return algorithm. Only isotropic hardening is activated to date and strain-rate dependency is included in the model. However, no temperature effects are included in the present implementation.

References

The implementation of this material model is described in reference [167].

The Johnson-Cook constitutive relation is given by:

$$\sigma_{\mathrm{eq}} = \left[A_1 + A_2 \left(\varepsilon^{\mathrm{p}}_{\mathrm{eq}}\right)^{\lambda_2}\right] \left[1 + \lambda_1 \ln\left(\frac{\dot{\varepsilon}^{\mathrm{p}}_{\mathrm{eq}}}{\dot{\varepsilon}^{\mathrm{p}}_{\mathrm{eq,ref}}}\right)\right] (1 - \theta^m) \tag{40}$$

where:

- A_1 is `COA1` (1st constant) in Europlexus
- A_2 is `COA2` (2nd constant) in Europlexus
- λ_1 is `CLB1` (3rd constant) in Europlexus
- λ_2 is `CLB2` (hardening parameter) in Europlexus
- $\dot{\varepsilon}^{\mathrm{p}}_{\mathrm{eq,ref}}$ is `SRRF` (reference strain rate) in Europlexus
- θ is the homologous temperature $\frac{T - T_{\mathrm{room}}}{T_{\mathrm{melting}} - T_{\mathrm{room}}}$ (currently not implemented in Europlexus)
- m is the homologous temperature exponent (currently not implemented in Europlexus)

The Johnson-Cook model is a simple empirical generalization of Ludwik's constitutive law (see `VMLU` on page C.253), represented by the first term of the above equation, trying to account for strain-rate effects (included in the second term of the equation) and for temperature effects (third and last term). The "reference" strain rate is the minimum plastic strain rate for which calibration of the model has been made.

In Johnson-Cook's model the Ludwik's law (first term) is multiplied by a function of the equivalent plastic strain rate. The form of this function is related to the often made experimental observation that the increase in flow stress is a logarithmic function of the strain rate.

The reference (or minimum) equivalent plastic strain rate $\dot{\varepsilon}^{\mathrm{p}}_{\mathrm{eq,ref}}$ is the value of equivalent plastic strain rate under which the material behaves in a "static" (i.e., strain-rate independent) way. In practice, in the code, when the equivalent plastic strain rate is below this value, only the static part of the model is considered. The parameters equivalent plastic strain rate and λ_1 are interconnected.

Syntax:

```
   "VMJC"  "RO" rho  "YOUN" young  "NU" nu "COA1" coa1
           "COA2" coa2 "CLB1" clb1 "CLB2" clb2 "SRRF" srrf
          <"FAIL" $[ "VMIS" "LIMI" limit ;
                     "DPLS" "LIMI" limit ;
                     "JOCO" "COD1" cod1 "COD2" cod2 "COD3" cod3 "COD4" cod4
                  ]$ >
     ...  /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus (elastic phase).

`nu`

Poisson's ratio.

`coa1`

1st constant (A_1) in the Johnson-Cook model.

`coa2`

2nd constant (A_2) in the Johnson-Cook model.

`clb1`

3rd constant (λ_1) in the Johnson-Cook model.

`clb2`

Hardening coefficient (λ_2) of the Johnson-Cook model.

`srrf`

Reference strain rate ($\dot{\varepsilon}^{\mathrm{p}}_{\mathrm{eq,ref}}$) of the Johnson-Cook model.

`FAIL`

Optional keyword: introduces an element failure model. The available failure criteria are: `VMIS` for a criterion based upon the equivalent Von-Mises stress, `DPLS` for a criterion based upon the equivalent plastic strain, `JOCO` for the so-called Johnson-Cook criterion based upon an equivalent plastic strain, depending on the strain rate and the triaxiality ratio. See comments below.

`limit`

Optional parameter, indicates the failure limit for the VMIS or PLAS criterion.

`cod1`

Optional parameter, 1st constant (D_1) in the Johnson-Cook failure criterion.

`cod2`

Optional parameter, 2nd constant (D_2) in the Johnson-Cook failure criterion.

`cod3`

Optional parameter, 3rd constant (D_3) in the Johnson-Cook failure criterion.

`cod4`

Optional parameter, 4th constant (D_4) in the Johnson-Cook failure criterion.

`LECTURE`

List of the elements concerned.

Comments:

The Johnson-Cook failure criterion is given by:

$$\varepsilon_{\mathrm{p}}^{\mathrm{f}} = \left[D_1 + D_2 \exp\left(D_3 \sigma^*\right)\right]\left[1 + D_4 \ln\left(\frac{\dot{\varepsilon}_{\mathrm{eq}}^{\mathrm{p}}}{\dot{\varepsilon}_{\mathrm{eq,ref}}^{\mathrm{p}}}\right)\right] \tag{41}$$

where:

- D_1 is `COD1` (1st constant) in Europlexus
- D_2 is `COD2` (2nd constant) in Europlexus
- D_3 is `COD3` (3rd constant) in Europlexus
- D_4 is `COD4` (4th constant) in Europlexus
- $\dot{\varepsilon}_{\mathrm{eq,ref}}^{\mathrm{p}}$ is `SRRF` (reference strain rate) in Europlexus
- $\sigma^* = \frac{p}{q}$ is the triaxiality ratio, where p is the hydrostatic pressure and q is the Von-Mises equivalent stress.

The damage parameter D triggers failure when it reaches 1. It is computed as:

$$D = \sum \frac{\Delta \varepsilon_{\mathrm{p}}}{\varepsilon_{\mathrm{p}}^{\mathrm{f}}} \tag{42}$$

Outputs:

The components of the ECR table are as follows:

ECR(1): current hydrostatic pressure
ECR(2): current equivalent stress (Von-Mises)
ECR(3): current equivalent plastic strain
ECR(4): current yield stress
ECR(5): sound speed
ECR(6): equivalent strain rate (Von-Mises)
ECR(7): failure flag (0=virgin Gauss Point, 1=failed Gauss Point)
ECR(8): damage parameter for the Johnson-Cook failure criterion

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.58 LUDWIG-PRANDTL MODEL

Object:

This directive enables to choose the Ludwig-Prandtl model, a purely elasto-plastic model implemented at Ispra. Elasto- plasticity is implemented via a radial return algorithm. Only isotropic hardening is activated to date. There is no dependency on temperature but strain rate effects are included.

References

The implementation of this material model is described in reference [167].

Syntax:

```
"VMLP"  "RO" rho  "YOUN" young  "NU" nu "COA1" coa1
        "COA2" coa2 "CLB1" clb1 "CLB2" clb2 "CLB3" clb3
        "CLB4" clb4
  ...  /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`coa1`

1st constant in the Ludwig-Prandtl model.

`coa2`

2nd constant in the Ludwig-Prandtl model.

`clb1`

3rd constant in the Ludwig-Prandtl model.

`clb2`

4th constant in the Ludwig-Prandtl model.

`clb3`

5th constant in the Ludwig-Prandtl model.

`clb4`

6th constant in the Ludwig-Prandtl model.

`LECTURE`

List of the elements concerned.

Comments:

1/ - The young parameter defines Young's modulus during an elastic phase.

2/ - The points (sig,eps) may have any position; however, concerning the first point, there must be a compatibility between the coordinates, Young's modulus and the elastic limit.

3/ - The slope of the yield curve may not increase from one segment to the following one.

Outputs:

The components of the ECR table are as follows:

ECR(1): current hydrostatic pressure
ECR(2): current equivalent stress (Von Mises)
ECR(3): current equivalent plastic strain
ECR(4): current yield stress
ECR(5): sound speed
ECR(6): equivalent strain rate (Von Mises)

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.59 LUDWIK MODEL

Object:

This directive enables to choose the Ludwik model, a purely elasto-plastic model implemented at Ispra. Elasto-plasticity is implemented via a radial return algorithm. Only isotropic hardening is activated to date. There is no dependency on temperature nor on strain rate.

References

The implementation of this material model is described in reference [167].

Syntax:

```
"VMLU"  "RO" rho  "YOUN" young  "NU" nu "ELAS" sige ...
        "COA2" coa2 "COEN" coen
  ...  /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`sige`

Elastic limit.

`coa2`

Plastic threshold value.

`coen`

Hardening coefficient.

`LECTURE`

List of the elements concerned.

Comments:

1/ - The young parameter defines Young's modulus during an elastic phase.

2/ - The points (sig,eps) may have any position; however, concerning the first point, there must be a compatibility between the coordinates, Young's modulus and the elastic limit.

3/ - The slope of the yield curve may not increase from one segment to the following one.

Outputs:

The components of the ECR table are as follows:

ECR(1): current hydrostatic pressure

ECR(2): current equivalent stress (Von Mises)

ECR(3): current equivalent plastic strain

ECR(4): current yield stress

ECR(5): sound speed

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.60 ZERILLI-ARMSTRONG MODEL

Object:

This directive enables to choose the Zerilli-Armstrong model with the implementation developed at Ispra. Elasto-plasticity is implemented via a radial return algorithm. Only isotropic hardening is activated to date and strain-rate dependency is included. However, no dependency on temperature exist in the present version of the model.

References

The implementation of this material model is described in reference [167].

Syntax:

```
"VMZA"  "RO" rho  "YOUN" young  "NU" nu  "COA1" coa1 ...
        "COA2" coa2 "COA3" coa3 "COA4" coa4 "CLB1" clb1
        "CLB2" clb2 "CLB3" clb3
  ...  /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`coa1`

1st coefficient of the Zerrilli-Armstrong model.

`coa2`

2nd coefficient of the Zerilli-Armstrong model.

`coa3`

3rd coefficient of the Zerilli-Armstrong model.

`coa4`

4th coefficient of the Zerilli-Armstrong model.

`clb1`

1st hardening coefficient of the Zerilli-Armstrong model.

`clb2`

2nd hardening coefficient of the Zerilli-Armstrong model.

`clb3`

3rd hardening coefficient of the Zerilli-Armstrong model.

`LECTURE`

List of the elements concerned.

Comments:

1/ - The young parameter defines Young's modulus during an elastic phase.

2/ - The points (sig,eps) may have any position; however, concerning the first point, there must be a compatibility between the coordinates, Young's modulus and the elastic limit.

3/ - The slope of the yield curve may not increase from one segment to the following one.

Outputs:

The components of the ECR table are as follows:

ECR(1): current hydrostatic pressure

ECR(2): current equivalent stress (Von Mises)

ECR(3): current equivalent plastic strain

ECR(4): current yield stress

ECR(5): sound speed

ECR(6): equivalent strain rate (Von Mises)

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.61 DRUCKER-PRAGER WITH HYDROSTATIC POST-FAILURE (JRC)

Object:

This directive enables to specify a Drucker-Prager material. The material behaves in a linear elastic way until failure is reached, and thereafter it behaves like a fluid (i.e. it resists only to compression). Failure occurs when the stress point in the J_1-$\sqrt{J_2'}$ space reaches the failure line (a straight line) of equation:

$$\sqrt{J_2'} = K - \alpha J_1$$

where $J_1 = \sigma_x + \sigma_y + \sigma_z$ is the first invariant of the stress tensor and J_2' is the second invariant of the deviatoric stress tensor:

$$J_2' = \frac{1}{3}(\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_x\sigma_z - \sigma_y\sigma_z) + \tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2$$

The constant K is the intersection of the failure line with the vertical axis and represents the failure stress of the material in pure shear (e.g. in torsion): it is also called cohesion.

The constant α is the slope of the failure line (tangent of the angle) and is also called the internal friction angle.

After failure is reached, the material behaves like a liquid: all tangential stresses are set to zero and the normal stresses are set to equal (hydrostatic) values if the material is under compression (negative volumetric strain), or to zero if the material is under traction (positive volumetric strain).

Due to its postulated after-failure behaviour, this material is not "erodable". That is, when failure is reached, even at all Gauss points of an element, the element is not removed from the calculation because it contributes to the solution with its post-failure (hydrostatic) behaviour. Of course, this only makes sense as long as the failed material remains confined (so that a hydrostatic pressure can build up in it).

References:

The material model is described in reference [13]. Note that although the material model had been originally denoted as a Mohr-Coulomb model, in reality it is a Drucker-Prager material. In fact, the yield surface corresponding to the expression given above (using J_2') is a cone with circular cross section (and not with hexagonal cross-section) in principle stress space.

Syntax:

```
"DRPR"  "RO" ro "YOUN" youn "NU" nu "COHE" cohe "FRIC" fric
        /LECTURE/
```

`ro`

Density.

`youn`

Young's modulus.

`nu`

Poisson's ratio.

`cohe`

Failure stress K in pure shear, e.g. in torsion (cohesion).

`fric`

Slope α of the failure line in the J_1-$\sqrt{J_2'}$ diagram (internal friction angle).

`/LECTURE/`

Numbers of the elements concerned.

Outputs:

The different components of the ECR table are as follows:

ECR(1): current J_1 invariant $(\sigma_1 + \sigma_2 + \sigma_3)$.
ECR(2): current $\sqrt{J_2'}$ invariant.
ECR(3): failure flag (0=not failed, 1=failed).
ECR(4): sound speed

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.62 FOAM: Aluminium foam

Object:

This option enables to specify an aluminium foam material and follows the Deshpande-Fleck model as implemented at NTNU, Trondheim (N).

References:

More information on the formulation of this material model may be found in the following references:

1. V.S. Deshpande and N.A. Fleck, Isotropic models for metallic foams, J. Mech. Phys. Solids 48 (2000), pp. 1253–1283.
2. A. Reyes, O. S. Hopperstad, T. Berstad, A. G. Hansen, M. Langseth, Constitutive modeling of aluminum foam including fracture and statistical variation of density, European Journal of Mechanics – A/Solids, Vol 22, pp 815–835, 2003.

The stresses are calculated by using the following equation:

$$\sigma = \sigma_p + \gamma \frac{e}{e_D} + \alpha_2 \ln\left(\frac{1}{1-(e/e_D)^\beta}\right)$$

The parameter e_D is taken from the recent foam density ρ_f and the density of the pure material ρ_{f0} by using this equation

$$e_D = 1 - \frac{\rho_f}{\rho_{f0}}$$

The parameter α defines the shape of the yield surface and can be calculated by using the plastic Poission's ratio ν_p:

$$\alpha^2 = \frac{9}{2} \frac{(1-2\nu_p)}{(1+\nu_p)}$$

The parameter γ is the initial hardening factor by reaching the plastic regime. The parameters α_2 and β can be taken by a best fit of the experimental curve.

Syntax:

```
FOAM  RO_F ro_f  YOUN youn  NU   nu    SIGP sigp  RO_0 ro_0
      ALFA alfa  GAMM gamm  ALF2 alf2  BETA beta <DERF derf>
      <EF ef> <SF sf> <RNUM rnum> <WC wc>
      /LECTURE/
```

`ro_f`

Initial density of the foam material, i.e. considering the voids.

`youn`

Young's modulus (initial).

`nu`

Poisson's coefficient (initial).

`sigp`

Yield stress.

`ro_0`

Initial density of the material, not considering the voids (pure material, ρ_{f0}).

`alfa`

Shape of the yield surface (see above).

`gamm`

Initial hardening factor by reaching the plastic regime.

`alf2`

Scale factor (material constant).

`beta`

Shape factor (material constant).

`derf`

Switch to choose the derivation of Fi in the model: 0 means numerical derivation, while 1 means normal derivation. The default is 1.

`efail`

Critical volumetric failure strain. A Gauss point fails if the volumetric strain exceeds `efail`. By default it is 0.0, meaning that the volumetric strain failure criterion is not active.

`sfail`

Critical failure stress. A Gauss point fails if the maximum principal stress exceeds `sfail` for a number of (consecutive) time steps greater than `rnum` (see next parameter). By default it is 0.0, meaning that the maximum principal stress failure criterion is not active.

`rnum`

Number of (consecutive) time steps with maximum principal stress exceeding `sfail` needed for a Gauss point to fail. By default it is ∞, meaning that the maximum principal stress failure criterion is not active.

`wc`

Critical failure energy (Cockcroft-Latham criterion). A Gauss point fails if the fracture energy exceeds `wc`. By default it is 0.0, meaning that the Cockcroft-Latham failure criterion is not active.

`/LECT/`

List of the concerned elements.

Outputs:

The components of the ECR table are as follows:

ECR(1): Equivalent plastic strain (ϵ_{eq})

ECR(2): Von Mises effective plastic strain (ϵ_e)

ECR(3): Volumetric strain (ϵ_m)

ECR(4): Equivalent stress (σ_{eq})

ECR(5): Von Mises effective stress (σ_e)

ECR(6): Mean stress (σ_m)

ECR(7): Isotropic hardening variable (R)

ECR(8): Iteration counter

ECR(9): (Y)

ECR(10): sound speed

ECR(11): first principal stress ($ps1$)

ECR(12): second principal stress ($ps2$)

ECR(13): third principal stress ($ps3$)

ECR(14): counter of the consecutive number of steps where `ps1 > sfail`

ECR(15): Cockcroft-Latham damage accumulation (W) when energy-based damage is activated and `ps1 > sfail`

ECR(16): "universal" damage parameter (D). May be used in combination with AMR?

ECR(17): Gauss point failure flag: 1 = virgin, 0 = failed.

7.7.63 GLRC: Reinforced concrete for shells

Object:

This material is designed to model reinforced concrete shells, possibly with prestressing and steel liner. It consists in a resultant variables constitutive law, using both plasticity (double JOHANSEN's criterion with a kinematic softening) and damage (to take into account concrete cracking). For information about this model see references [957], [958].

New syntax for non-linear GLRC material (elastoplastic with or without damage):

```
"GLRC" < "DAMA" > < "SHEA" >
       "RO"   rho
       "H"    thickness
       "EB"   yconcrete  "NUB"  pconcrete
       "NLIT" nblayer * ( |[ "NAPP" ("EA" ysteel  < "FY" tsteel >
                                     "OMX" ax       "OMY" ay
                                     "RX"  rx       "RY"  ry       ) ;
                              "PREC" ( "EA" ysteel  < "FY" tsteel >
                                      "OMX" ax       "OMY" ay
                                      "RX"  rx       "RY"  ry       ) ;
                              "LINR" ( "EA" ysteel  < "FY" tsteel >
                                      "OMLR" epliner "NULR" nuliner
                                      "RLR"  rliner                 ) ]| )
     < "OMT"  atrast       "EAT"  ytrast  >
     < "BT1"  shear1       "BT2"  shear2  >

     < "BTD1" sheard1      "BTD2" sheard2 >
     < "TSD"  tsheard >

     < "FT"   tconcrete  < "GAMM" gamma   >
       "QP1"  qslope1      "QP2"  qslope2 >

       "C1N1" pragmemb1x "C1N2" pragmemb1y "C1N3" pragmemb1xy
       "C2N1" pragmemb2x "C2N2" pragmemb2y "C2N3" pragmemb2xy
       "C1M1" pragbend1x "C1M2" pragbend1y "C1M3" pragbend1xy
       "C2M1" pragbend2x "C2M2" pragbend2y "C2M3" pragbend2xy

   $[    "FC"   cconcrete                   ;
     (  "MP1X"  < "FONC" >  plaslim1x
        "MP1Y"  < "FONC" >  plaslim1y
        "MP2X"  < "FONC" >  plaslim2x
        "MP2Y"  < "FONC" >  plaslim2y
      < "D1X"     "FONC"    dplaslim1x  >
      < "D1Y"     "FONC"    dplaslim1y  >
      < "D2X"     "FONC"    dplaslim2x  >
      < "D2Y"     "FONC"    dplaslim2y  >
      < "DD1X"    "FONC"    ddplaslim1x >
```

```
          < "DD1Y"    "FONC"    ddplaslim1y >
          < "DD2X"    "FONC"    ddplaslim2x >
          < "DD2Y"    "FONC"    ddplaslim2y > ) ]$

         < "PREX" nprecx  "PREY" nprecy  >

         < "KRAY" kray    "MRAY" mray    >

           /LECTURE/
```

`rho`

Density of the plate material (concrete and steel).

`thickness`

Thickness of the concrete (thickness of the plate).

`yconcrete`

Young's modulus of the concrete material.

`ypoisson`

Poisson's ratio of the concrete material.

`NAPP`

Keyword for the description of bending steel reinforcement (steel grid).

`PREC`

Keyword for the description of prestressing.

`LINR`

Keyword for the description of the steel liner.

`ysteel`

Young's modulus of the steel material.

`tsteel`

Yield stress of the steel. Used to calculate automatically the generalized Johansen criterion (when the `plaslim` functions are not specified).

`ax, ay`

Areas (per meter of plate) of the reinforcement layer in the x and y directions (m^2/m).

`rx, ry`

Nondimensional position of the layer in the x and y directions ($-1 \leq r \leq 1$).

`epliner`

Thickness of the liner.

`nuliner`

Poisson's ratio of the liner steel.

`rliner`

Nondimensional position of the liner ($-1 \leq rliner \leq 1$).

`shear`

Coefficients of the elastic shear matrix (for elements that take into account the transverse shear like Q4GR or Q4GS):

$$\begin{bmatrix} T_x \\ T_y \end{bmatrix} = \begin{bmatrix} \texttt{shear1} & 0 \\ 0 & \texttt{shear2} \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \end{bmatrix}$$

When the shear coefficients are not specified, they are calculated, for Q4GR and Q4GS elements, using the following expression:

$$T = k\frac{h}{2}(\frac{E_b}{1+\nu_b} + E_{aT}\omega_T)\gamma$$

with:

- h : shell thickness
- k : shear correcting coefficient usually set as 5/6 (Reissner theory)
- E_b : Young's modulus of concrete (`yconcrete`)
- ν_b : Poisson's ratio of concrete (`ypoisson`)
- E_{aT} : Young's modulus of transverse steel (`ytrast`)
- ω_T : Area of transverse steel (`atrast`)

If the keyword SHEA is specified then a nonlinear evolution of the shear force is taken into account ([972]). This nonlinear evolution can be compared to an elastoplastic constitutive law. Beyond a shear force defined by TSD, the shear force evolves according to a linear slope whose stiffness is defined through the keywords BTD1 and BTD2 and plate elements are then subjected to irreversible deformations.

When the values of the damaged shear coefficients `sheard1` and `sheard2` are not specified, they are calculated using the following expression:

$$\texttt{sheard1} = \texttt{sheard2} = k\frac{h}{2}(\frac{E_{aT}}{100}\omega_T)$$

`atrast`

Area (per square meter of plate) of the transverse reinforcement (m^2/m^2). Used to calculate the elastic shear coefficients when `shear` are not specified.

`ytrast`

Young's modulus of the steel material for transverse reinforcement. Used for the computation of the elastic shear coefficients when `shear` are not specified. Default value is the standard `ysteel` value.

`tconcrete`

Tensile strength of concrete (tensile stress). Must be positive. Used to calculate the bending cracking moment. Used only for damage.

`qslope1 qslope2`

Slopes quotient for positive and negative bending. The quotient is supposed to be the slope of the (curvature,moment) graph after cracking over the slope before cracking. Used only for damage.

$$Q_p = \frac{p_{eac}}{p_{ebc}}$$

with:

- Q_p : slope quotient `qslope` ($0 < Q_p \leq 1$)
- p_{ebc} : slope before cracking (elastic concrete)
- p_{eac} : slope after cracking (cracked concrete)

`gamma`

Damage computation parameter which characterizes the slope of the (curvature,moment) graph during cracking. gamma can be considered as the slope during cracking over the slope before cracking. If `gamma` > 0, the slope increases. If `gamma` < 0, the slope decreases and the stability is not warranted. In any case, we must have `gamma` $<$ `qslope1` and `gamma` $<$ `qslope2`. Default value is zero. Used only for damage.

$$\gamma = \frac{p_{edc}}{p_{ebc}}$$

with:

- γ : `gamma`
- p_{ebc} : slope before cracking (elastic concrete)
- p_{edc} : slope during cracking

`pragmemb, pragbend`

Prager coefficients corresponding to the matrices linking the plastic strain and curvature to the back membrane force and the backmoment.

$$n = CN_1 \epsilon_1^p + CN_2 \epsilon_2^p$$

$$m = CM_1 \kappa_1^p + CM_2 \kappa_2^p$$

with:

- $CN_1 = \begin{bmatrix} \texttt{pragmemb1x} & 0 & 0 \\ 0 & \texttt{pragmemb1y} & 0 \\ 0 & 0 & \texttt{pragmemb1xy} \end{bmatrix}$
- $CN_2 = \begin{bmatrix} \texttt{pragmemb2x} & 0 & 0 \\ 0 & \texttt{pragmemb2y} & 0 \\ 0 & 0 & \texttt{pragmemb2xy} \end{bmatrix}$
- $CM_1 = \begin{bmatrix} \texttt{pragbend1x} & 0 & 0 \\ 0 & \texttt{pragbend1y} & 0 \\ 0 & 0 & \texttt{pragbend1xy} \end{bmatrix}$
- $CM_2 = \begin{bmatrix} \texttt{pragbend2x} & 0 & 0 \\ 0 & \texttt{pragbend2y} & 0 \\ 0 & 0 & \texttt{pragbend2xy} \end{bmatrix}$

- ϵ_1^p and κ_1^p : plastic strain and curvature linked to the first criterion (`plaslim1`)
- ϵ_2^p and κ_2^p : plastic strain and curvature linked to the second criterion (`plaslim2`)

$$C = \frac{p_e p_p}{p_e - p_p}$$

with:

- C : Prager coefficient
- p_e : elastic slope (or slope after cracking, in case of bending)
- p_p : plastic slope

`cconcrete`

Compressive strength of concrete. Used to calculate automatically the generalized Johansen criterion (when the `plaslim` functions are not specified).

`plaslim`

Functions used in the generalized Johansen criterion. They describe the "beam" plastic limit moment depending on the membrane force. When they are not specified, they are automatically calculated and interpolated.

`plaslim1x plaslim2x`

Positive and negative plastic limit moments for a perfect bending in the x-direction (referring to the orthotropic axes of the shell element). If the directive "FONC" is used, `plaslim1x` or `plaslim2x` are integers referring to a function number (function of N_x). We should have usually `plaslim1x` > `plaslim2x`.

`plaslim1y plaslim2y`

Positive and negative plastic limit moments for a perfect bending in the y-direction (referring to the orthotropic axes of the shell element). If the directive "FONC" is used, `plaslim1y` or `plaslim2y` are integers referring to a function number (function of N_y). We should have usually `plaslim1y` > `plaslim2y`.

`dplaslim1x dplaslim2x dplaslim1y dplaslim2y`

Function number of the first derivative of `plaslim1x`, `plaslim2x`, `plaslim1y` and `plaslim2y` plastic limit functions. They are used when the membrane plasticity is taken into account and when they cannot be computed directly from the `plaslim1x`, `plaslim2x`, `plaslim1y` and `plaslim2y` functions.

`ddplaslim1x ddplaslim2x ddplaslim1y ddplaslim2y`

Function number of the second derivative of `plaslim1x`, `plaslim2x`, `plaslim1y` and `plaslim2y` plastic limit functions. They are used when the membrane plasticity is taken into account and when they cannot be computed directly from the `plaslim1x`, `plaslim2x`, `plaslim1y`, `plaslim2y` or `dplaslim1x`, `dplaslim2x`, `dplaslim1y`, `dplaslim2y` functions.

`nprecx, nprecy`

Prestressing force in the x and y directions (should be negative since it is normally a compression force).

`kray, mray`

Rayleigh's stiffness and mass proportional damping coefficients, used only by finite elements of the following types: DKT3, T3GS, Q4GS. Default values: kray=0, mray=0. For information about Rayleigh's damping see reference [953].

LECTURE

List of the elements concerned.

Syntax for perforation analysis (always used with the new syntax) :

```
"GLRC" < "DAMA" > "PERF" < "SHEA" >
       "RO"   rho
       "H"    thickness
       "EB"   yconcrete  "NUB"  pconcrete
       "NLIT" nblayer * ( |["NAPP" ( "EA" ysteel  < "FY" tsteel >
                                      "FS"  tsteelp
                                      "OMX" ax       "OMY" ay
                                      "RX"  rx       "RY"  ry       ) ;
                               "PREC" ( "EA" ysteel  < "FY" tsteel >
                                      "FS"  tsteelp
                                      "OMX" ax       "OMY" ay
                                      "RX"  rx       "RY"  ry       ) ;
                               "LINR" ( "EA" ysteel  < "FY" tsteel >
                                      "FS"  tsteelp
                                      "OMLR" epliner "NULR" nuliner
                                      "RLR"  rliner                 ) ]| )
       "OMT"  atrast    <  "EAT"  ytrast  >   "FST"  tsteelp_t
     < "BT1"  shear1       "BT2"  shear2  >

     < "BTD1" sheard1      "BTD2" sheard2 >
     < "TSD"  tsheard >

     < "FT"   tconcrete  < "GAMM" gamma   >
       "QP1"  qslope1      "QP2"  qslope2 >

       "FC"   cconcrete  "PHI"  friction   < "NUFC" eff_factor >
     < "NPER" nper >

       "C1N1" pragmemb1x "C1N2" pragmemb1y "C1N3" pragmemb1xy
       "C2N1" pragmemb2x "C2N2" pragmemb2y "C2N3" pragmemb2xy
       "C1M1" pragbend1x "C1M2" pragbend1y "C1M3" pragbend1xy
       "C2M1" pragbend2x "C2M2" pragbend2y "C2M3" pragbend2xy

   <   "MP1X"  < "FONC" >  plaslim1x
       "MP1Y"  < "FONC" >  plaslim1y
       "MP2X"  < "FONC" >  plaslim2x
       "MP2Y"  < "FONC" >  plaslim2y
     < "D1X"     "FONC"    dplaslim1x  >
     < "D1Y"     "FONC"    dplaslim1y  >
     < "D2X"     "FONC"    dplaslim2x  >
```

```
    < "D2Y"     "FONC"    dplaslim2y  >
    < "DD1X"    "FONC"    ddplaslim1x >
    < "DD1Y"    "FONC"    ddplaslim1y >
    < "DD2X"    "FONC"    ddplaslim2x >
    < "DD2Y"    "FONC"    ddplaslim2y >    >

    < "PREX" nprecx  "PREY" nprecy  >

    < "KRAY" kray    "MRAY" mray    >

      /LECTURE/
```

`cconcrete`

Compressive strength of concrete. Used to calculate automatically the generalized Johansen criterion (when the `plaslim` functions are not specified). Mandatory for perforation analysis.

`friction`

Friction angle of concrete (degrees). Mandatory for perforation analysis.

`tsteelp, tsteelp_t`

Limit stress of steel (for each layer and for transverse reinforcement). Mandatory for perforation analysis.

`eff_factor`

Effectiveness factor for concrete. When not specified, a default value is taken.

`nper`

Frequency of verification of the perforation criterion. Default value is 1 (every time step).

For information about the perforation criterion see references [955], [957].

Old syntax for the standard material (without damage):

```
"GLRC" "OLD"
       "RO" rho "BN11" memb11     "BN12" memb12
                "BN22" memb22     "BN33" memb33
                "BM11" bend11     "BM12" bend12
                "BM22" bend22     "BM33" bend22
              < "BC11" coup11 > < "BC12" coup12 >
              < "BC22" coup22 > < "BC33" coup22 >
              < "BT1"  shear1 > < "BT2"  shear2 >
              < "C1N1" pragmemb1x "C1N2" pragmemb1y "C1N3" pragmemb1xy >
              < "C2N1" pragmemb2x "C2N2" pragmemb2y "C2N3" pragmemb2xy >
                "C1M1" pragbend1x "C1M2" pragbend1y "C1M3" pragbend1xy
                "C2M1" pragbend2x "C2M2" pragbend2y "C2M3" pragbend2xy
                "MP1X"  < "FONC" >  plaslim1x
```

```
  "MP1Y"  < "FONC" >  plaslim1y
  "MP2X"  < "FONC" >  plaslim2x
  "MP2Y"  < "FONC" >  plaslim2y
< "D1X"     "FONC"    dplaslim1x >
< "D1Y"     "FONC"    dplaslim1y >
< "D2X"     "FONC"    dplaslim2x >
< "D2Y"     "FONC"    dplaslim2y >
< "DD1X"    "FONC"    ddplaslim1x >
< "DD1Y"    "FONC"    ddplaslim1y >
< "DD2X"    "FONC"    ddplaslim2x >
< "DD2Y"    "FONC"    ddplaslim2y >
  /LECTURE/
```

`rho`

Density of the material.

`memb, bend, coup`

Coefficients of the elastic matrix:

$$\begin{bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \\ M_{xx} \\ M_{yy} \\ M_{xy} \end{bmatrix} = \begin{bmatrix} \texttt{memb11} & \texttt{memb12} & 0 & \texttt{coup11} & \texttt{coup12} & 0 \\ \texttt{memb12} & \texttt{memb22} & 0 & \texttt{coup12} & \texttt{coup22} & 0 \\ 0 & 0 & \texttt{memb33} & 0 & 0 & \texttt{coup33} \\ \texttt{coup11} & \texttt{coup12} & 0 & \texttt{bend11} & \texttt{bend12} & 0 \\ \texttt{coup12} & \texttt{coup22} & 0 & \texttt{bend12} & \texttt{bend22} & 0 \\ 0 & 0 & \texttt{coup33} & 0 & 0 & \texttt{bend33} \end{bmatrix} \begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ 2\epsilon_{xy} \\ \kappa_{xx} - \kappa_{xx}^p \\ \kappa_{yy} - \kappa_{yy}^p \\ 2(\kappa_{xy} - \kappa_{xy}^p) \end{bmatrix}$$

When the coupling coefficients are not specified, they take the zero value.

`shear`

Coefficients of the elastic shear matrix (for elements that take into account the transverse shear like Q4GR or Q4GS):

$$\begin{bmatrix} T_x \\ T_y \end{bmatrix} = \begin{bmatrix} \texttt{shear1} & 0 \\ 0 & \texttt{shear2} \end{bmatrix} \begin{bmatrix} \gamma_x \\ \gamma_y \end{bmatrix}$$

When the shear coefficients are not specified, they take the zero value. Classical assumptions in elasticity give the following expression:

$$T = h\frac{kE}{2(1+\nu)}\gamma$$

with:

- h : shell thickness
- k : shear correcting coefficient usually set as 5/6 (Reissner theory)
- E : Young's modulus
- ν : Poisson's ratio

`pragmemb, pragbend`

Prager coefficients corresponding to the matrices linking the plastic strain and curvature to the back membrane force and the backmoment.

$$n = CN_1 \epsilon_1^p + CN_2 \epsilon_2^p$$

$$m = CM_1 \kappa_1^p + CM_2 \kappa_2^p$$

with:

- $CN_1 = \begin{bmatrix} \texttt{pragmemb1x} & 0 & 0 \\ 0 & \texttt{pragmemb1y} & 0 \\ 0 & 0 & \texttt{pragmemb1xy} \end{bmatrix}$
- $CN_2 = \begin{bmatrix} \texttt{pragmemb2x} & 0 & 0 \\ 0 & \texttt{pragmemb2y} & 0 \\ 0 & 0 & \texttt{pragmemb2xy} \end{bmatrix}$
- $CM_1 = \begin{bmatrix} \texttt{pragbend1x} & 0 & 0 \\ 0 & \texttt{pragbend1y} & 0 \\ 0 & 0 & \texttt{pragbend1xy} \end{bmatrix}$
- $CM_2 = \begin{bmatrix} \texttt{pragbend2x} & 0 & 0 \\ 0 & \texttt{pragbend2y} & 0 \\ 0 & 0 & \texttt{pragbend2xy} \end{bmatrix}$
- ϵ_1^p and κ_1^p : plastic strain and curvature linked to the first criterion (`plaslim1`)
- ϵ_2^p and κ_2^p : plastic strain and curvature linked to the second criterion (`plaslim2`)

The membrane Prager coefficients are not mandatory. If they are not specified by the user, the model takes into account only bending plasticity. Thus it has a non-normal plasticity flow if the plastic limits vary with the membrane force. This could lead to convergence problems. But if the membrane Prager coefficients are given, both membrane and bending plasticity are taken into account. The model is in fact regularized compared to the preceding one.

`plaslim1x plaslim2x`

Positive and negative plastic limit moments for a perfect bending in the x-direction (referring to the orthotropic axes of the shell element). If the directive "FONC" is used, `plaslim1x` or `plaslim2x` are integers referring to a function number (function of N_x). We should have usually `plaslim1x` > `plaslim2x`.

`plaslim1y plaslim2y`

Positive and negative plastic limit moments for a perfect bending in the y-direction (referring to the orthotropic axes of the shell element). If the directive "FONC" is used, `plaslim1y` or `plaslim2y` are integers referring to a function number (function of N_y). We should have usually `plaslim1y` > `plaslim2y`.

`dplaslim1x dplaslim2x dplaslim1y dplaslim2y`

Function number of the first derivative of `plaslim1x`, `plaslim2x`, `plaslim1y` and `plaslim2y` plastic limit functions. They are used when the membrane plasticity is taken into account and when they cannot be computed directly from the `plaslim1x`, `plaslim2x`, `plaslim1y` and `plaslim2y` functions.

`ddplaslim1x ddplaslim2x ddplaslim1y ddplaslim2y`

Function number of the second derivative of `plaslim1x`, `plaslim2x`, `plaslim1y` and `plaslim2y` plastic limit functions. They are used when the membrane plasticity is taken into account and when they cannot be computed directly from the `plaslim1x`, `plaslim2x`, `plaslim1y`, `plaslim2y` or `dplaslim1x`, `dplaslim2x`, `dplaslim1y`, `dplaslim2y` functions.

`LECTURE`

List of the elements concerned.

Old syntax for the material with damage (for cracking):

```
"GLRC" "OLD" "DAMA"
       "RO" rho "BN11" memb11     "BN12" memb12
                "BN22" memb22     "BN33" memb33
                "E"    young      "NU"   poisson
                "MF1"  cracklim1  "MF2"  cracklim2
                "QP1"  qslope1    "QP2"  qslope2
                "GAMM" gamma
              < "BT1"  shear1 > < "BT2"  shear2 >
              < "C1N1" pragmemb1x "C1N2" pragmemb1y "C1N3" pragmemb1xy >
              < "C2N1" pragmemb2x "C2N2" pragmemb2y "C2N3" pragmemb2xy >
                "C1M1" pragbend1x "C1M2" pragbend1y "C1M3" pragbend1xy
                "C2M1" pragbend2x "C2M2" pragbend2y "C2M3" pragbend2xy
                "MP1X"  < "FONC" >  plaslim1x
                "MP1Y"  < "FONC" >  plaslim1y
                "MP2X"  < "FONC" >  plaslim2x
                "MP2Y"  < "FONC" >  plaslim2y
              < "D1X"     "FONC"    dplaslim1x >
              < "D1Y"     "FONC"    dplaslim1y >
              < "D2X"     "FONC"    dplaslim2x >
              < "D2Y"     "FONC"    dplaslim2y >
              < "DD1X"    "FONC"    ddplaslim1x >
              < "DD1Y"    "FONC"    ddplaslim1y >
              < "DD2X"    "FONC"    ddplaslim2x >
              < "DD2Y"    "FONC"    ddplaslim2y >
                  /LECTURE/
```

`DAMA`

Enable the option which allows to take in account the concrete cracking by damage.

`rho, shear, pragmemb, pragbend, plaslim, dplaslim, ddplaslim`

Same parameters as those described for the standard GLRC material.

`memb`

Coefficients of the elastic matrix:

$$\begin{bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \end{bmatrix} = \begin{bmatrix} \texttt{memb11} & \texttt{memb12} & 0 \\ \texttt{memb12} & \texttt{memb22} & 0 \\ 0 & 0 & \texttt{memb33} \end{bmatrix} \begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ 2\epsilon_{xy} \end{bmatrix}$$

There is no elastic coupling between the bending and the membrane behaviour.

`young, poisson`

Homogenized elastic characteristics (Young's modulus and Poisson's ratio) for bending.

`cracklim1 cracklim2`

Positive and negative cracking limit moments.

`qslope1 qslope2`

Slopes quotient for positive and negative bending. The quotient is supposed to be the slope of the (curvature,moment) graph after cracking over the slope before cracking.

Comments:

All the limit plastic moments must be defined carefully. When they are declared as functions (using "FONC"), the domain defined as `plaslim1-plaslim2` > 0 must be a close convex domain: note particularly that the program tries to find two intersections of `plaslim1` and `plaslim2`.

When the limit plastic functions are not defined as polynomial (e.g. when "LSQU" is not used), the program requires prolongation of the functions: it is necessary to compute the elastic predictor which can be located outside the close convex elastic domain.

The first and second derivative of the limit plastic functions can be surely computed from the original limit plastic functions (i.e. without using the functions associated with the "D1", "D2", "DD1" and "DD2" directives) when these limit plastic functions are polynomials (see "LSQU" 9.1 to use table functions as polynomials).

After (and never before) the definition of the material characteristics ("MATE" directive), the orthotropy characteristics of the elements are mandatory. The syntax is:

```
"COMP"  "ORTS"   vx vy vz   /LECTURE/
```

See the "ORTS" directive for more details.

Outputs:

The components of the ECR table are as follows:

Plastic strain and curvature (ϵ^p and κ^p) in the orthotropic axes:

ECR(1): ϵ^p_x

ECR(2): ϵ^p_y

ECR(3): $2 \times \epsilon^p_{xy}$

ECR(4): κ^p_x

ECR(5): κ^p_y

ECR(6): $2 \times \kappa^p_{xy}$

Energy dissipated during plasticity:

ECR(7): plastic dissipation per Gauss point. The sum of ECR(7) on all Gauss points of the element gives the plastic dissipation in the element.

Damage parameters:

ECR(8): D_1/D_{1max} for positive bending

ECR(9): D_2/D_{2max} for negative bending

Energy dissipated during damage:

ECR(10): damage dissipation per Gauss point. The sum of ECR(10) on all Gauss points of the element gives the damage dissipation in the element.

Orthotropy caracteristics:

- Components, in the global reference frame, of the vector whose projection on the local coordinate system of the 3D shell element indicates the orthotropy direction (data following the "ORTS" directive).

  ECR(11): vx
  ECR(12): vy
  ECR(13): vz

- After the first time step, the orthotropy caracteristics are:

  ECR(11): angle defining the orthotropic axes referring to the local axes in the shell element plane.
  ECR(12): 10.
  ECR(13): 10.

Membrane force and moment minus back force and backmoment ($N - n$ and $M - m$) in the orthotropic axes:

ECR(14): $N_x - n_x$

ECR(15): $N_y - n_y$

ECR(16): $N_{xy} - n_{xy}$

ECR(17): $M_x - m_x$

ECR(18): $M_y - m_y$

ECR(19): $M_{xy} - m_{xy}$

Post-treatment parameters for the perforation criterion:

ECR(20): = 0 if the criterion is not reached
= 1 if the criterion is reached in bending mode
= 2 if the criterion is reached in shear mode

ECR(21): normalized value of the perforation criterion (> 0 if the criterion is reached)

ECR(22): nx (components of the vector which is

ECR(23): ny normal to the failure plan,

ECR(24): nz in the global reference frame)

7.7.64 HYPERELASTIC MATERIAL

Object:

This sub-directive enables materials with an hyperelastic behaviour to be used. Only two types of shell (Q4GS et DST3) and several solid elements (CUBE, TETR, etc.) can be used with this material. The following kinds of hyperelastic materials can be selected:

- Type 1: Mooney-Rivlin material, see also the new material MOON on page C.297.
- Type 2: Hart Smith material.
- Type 3: Ogden material (strongly *not* recommended, see below).
- Type 4: Ogden material (new formulation, still under development), see also the new OGDE material on page C.298.
- Type 5: Ogden-Storakers material (hyperelstic foam).

Note that a Blatz-Ko hyperelastic material model is also available, see the new BLKO material on page C.299.

For Type 1, the expression of the strain energy density corresponds to:

```
W = c1*(I1-3) + c2*(I2-3) + c3*(I1-3)**2 +
    c4*(I1-3)(I2-3) + c5*(I2-3)**2 +
    c6*(I1-3)**3 + c7*(I2-3)*(I1-3)**2 +
    c8*(I1-3)(I2-3)**2 + c9(I2-3)**3 +
    c10*(I1-3)**4 + c11*(I2-3)**2*(I1-3)**3 +
    c12*(I1-3)**2(I2-3) + c13*(I1-3)(I2-3) +
    K*(Log(I3))**2
```

For Type 2, the expression of the strain energy density corresponds to :

$$W = A\int C(I_1-3)^2 dI_1 + 3B\cdot\log(I_2) + K\cdot\log(I_3)^2 \tag{43}$$

Type 3, the Ogden material can be expressed with the following equation

$$W = \sum_{p=1}^{N} \frac{\mu_p}{\alpha_p}\left(\lambda_1^{\alpha_p} + \lambda_2^{\alpha_p} + \lambda_3^{\alpha_p} - 3\right) \tag{44}$$

with the principal stretch λ.

Type 4, the Ogden material (new formulation) can be expressed with the following equation

$$W = \sum_{p=1}^{N} \frac{\mu_p}{\alpha_p}\left(\lambda_1^{*\alpha_p} + \lambda_2^{*\alpha_p} + \lambda_3^{*\alpha_p} - 3\right) + K(J-1-\ln J) \tag{45}$$

with $\lambda^* = \lambda J^{-\frac{1}{3}}$. K is the bulk modulus, μ_p and α_p are the material parameters used for this expression.

Type 5, the Ogden-Storakers material can be expressed with the following equation

$$W = \sum_{p=1}^{N} \frac{\mu_p}{\alpha_p}\left(\lambda_1^{\alpha_p} + \lambda_2^{\alpha_p} + \lambda_3^{\alpha_p} - 3\right) + \sum_{p=1}^{N} \frac{\mu_p}{\alpha_p\beta_p}(J^{-\alpha_p\beta_p} - 1) \tag{46}$$

μ_p, α_p and β_p are the material parameters used for this expression.

The input parameters can be determined by the code if an experimental stress-strain curve is given, see the description below under Case **parameters identification**. A best-fit is done in this case in order to calculate them. The data must be provided in engineering strains from an 1-D experiment. The lateral deflection should not be limited by the experiment.

The Ogden formulation of Type 3 is not yet tested in detail. First tests show a shrinkage of the material under initially unloaded conditions. This is physically not possible. It is strongly recommended **not** to use this material type.

The material law uses total strains. These strains are sometimes not correct when large rotations occur.

Syntax:

Case 1 : TYPE = 1.

```
 "HYPE"
 "TYPE"     1
 "RO"       rho
 "C01"      c1
   .        .
   .        .
 "C014"     c14
 "BULK"     K
/LECTURE/
```

`rho`

Density.

`C01`

First coefficient of the potential

`C014`

14st coefficient of the potential

`K`

Compressibility coefficient, if 0.0 incompressible material is considered

`LECTURE`

List of the concerned elements.

Case 2 : TYPE = 2.

```
 "HYPE"
 "TYPE"     2
 "RO"       rho
 "C01"      c1
```

```
"CO2"      c2
"CO3"      c3
"BULK"     K
/LECTURE/
```

`rho`

Density.

`CO1`

First coefficient of the potential (=A)

`CO2`

Second coefficient of the potential (=B)

`CO3`

Third coefficient of the potential (=C)

`K`

Compressibility coefficient

`LECTURE`

List of the concerned elements.

Case 3 : TYPE = 3.

```
"HYPE"
"TYPE"     3
"RO"       rho
"CO1"      c1
"CO2"      c2
"CO3"      c3
"CO4"      c4
"CO5"      c5
"CO6"      c6
"CO7"      c7
"CO8"      c8
"CO9"      c9
"CO10"     c10
"CO11"     c11
"CO12"     c12
"BULK"     K
/LECTURE/
```

`rho`

Density

`CO1,CO2,CO3,CO4`

Alpha coefficients of the potential (α_p)

`CO5,CO6,CO7,CO8`

Mu coefficients of the potential (mu_p)

`CO9,CO10,CO11,CO12`

(1/D) coefficient of the potential (compressible contribution)

`LECTURE`

List of the concerned elements.

Case 4 : TYPE = 4.

```
"HYPE"
"TYPE"     4
"RO"       rho
"CO1"      c1
"CO2"      c2
"CO3"      c3
"CO4"      c4
"CO5"      c5
"CO6"      c6
"CO7"      c7
"CO8"      c8
"BULK"     K
/LECTURE/
```

`rho`

Density

`CO1,CO2,CO3,CO4`

Alpha coefficients of the potential (α_p)

`CO5,CO6,CO7,CO8`

Mu coefficients of the potential (μ_p)

`LECTURE`

List of the concerned elements.

Case 5 : TYPE = 5.

```
"HYPE"
"TYPE"     5
"RO"       rho
"CO1"      c1
"CO2"      c2
"CO3"      c3
"CO4"      c4
"CO5"      c5
```

```
"C06"      c6
"C07"      c7
"C08"      c8
"C09"      c9
"C010"     c10
"C011"     c11
"C012"     c12
/LECTURE/
```

`rho`

Density

`C01,C02,C03,C04`

Alpha coefficients of the potential (α_p)

`C05,C06,C07,C08`

Mu coefficients of the potential (μ_p)

`C09,C010,C011,C012`

Beta coefficients of the potential (β_p)

`LECTURE`

List of the concerned elements.

Case parameters identification : TYPE = 1, 3, 4 or 5.

This case is recognized by the presennce of the `PCAL` keyword in the input data, as shown below.

```
"HYPE"
"TYPE"   [1|3|4|5]
<"BULK"  k>
<"NU"    nu>
"PCAL"   npar
"TRAC"   npts * (strain stress)
```

`k`

Compressibility coefficient (*not* used for Type 5).

`nu`

Poisson's ratio (*only* used for Type 5).

`npar`

Number of parameters that should be calculated (i.e. between 1 and 4).

`npts`

Number of (strain, stress) couples of values given.

The type and the number of elements is irrelevant since only the material is called. (However, note that at least one element must be defined in order to run the code.) Four different models are possible: for the Mooney-Rivlin material a two-parameter model is included (CO1 and CO2); for the Ogden material a six-parameter model is included neglecting the influence of the D parameter and for the Ogden New model a six parameter model is included.

Note that as soon as the code encounters the `TRAC` keyword in the above syntax it reads the traction curve, then performs the parameters calibration *and stops*. Therefore, any parameters given **after** the `TRAC` subdirective **are simply ignored**. This means that if values should be set for the optional keywors `BULK` or `NU`, they must be entered *before* and *not after* the `TRAC` subdirective, as indicated in the syntax above.

For this reason, the usual `/LECT/` at the end of the material directive is *not* included in the syntax (since it would not be interpreted anyway).

Range of validity

Note that the range of validity of the hyperelastic material models is as follows:

- Neo-Hookean: $\epsilon < 30\%$ (1 parameter). This corresponds to a Mooney-Rivlin material with only the first parameter defined.
- Mooney-Rivlin: $\epsilon < 100\%$ for 2 or 3 parameters, $\epsilon < 200\%$ for 4 to 9 parameters.
- Ogden new: $\epsilon < 700\%$ for third order.

Outputs:

The components of the ECR table are as follows:

ECR(1): Pressure

ECR(2): Von Mises Stress

ECR(3): Normal transverse strain (shell elements) or tangential stiffness (solid elements)

ECR(4): Updated thickness (shell elements)

ECR(5): Initial thickness (shell elements) or initial volume (solid elements)

ECR(6): Energy potential

ECR(7): Maximum time step for the element

7.7.65 MINT: MATERIAL FOR INTERFACE ELEMENT

Object:

This directive allows to choose the material applied to interface elements. Thus, it can only be used with interface elements `INT4` (2D quadrilateral), `INT6` (3D triangular prism) and `INT8` (3D hexahedron). The combination of such elements and material `MINT` forms a cohesive zone model, suitable to solve problems like delamination and debonding.

Only `TYPE 2` material is functional. Three damage laws could be chosen with material `TYPE 2`: exponential, linear or Cachan interface meso-model.

- To select the exponential law, parameters `CO1` to `CO7` are required.
- To select the linear law, parameters `CO1` to `CO8` are required.
- To select the Cachan interface meso-model law, parameters `CO1` to `CO9` (`CO8` is optional) are required.
- Parameters `CO10` to `CO13` are optional in any case.

References:

For the Cachan interface damage meso-model:

- Allix O. and Ladevèze P., *Interlaminar interface modelling for the prediction of delamination.* Composite Structures 22, 1992.
- Lévêque D., *Analyse de la tenue au délaminage des composites stratifiés : identification d'un modèle d'interface interlaminaire.* PhD thesis, ENS Cachan LMT, 1998.

The implementation of material `TYPE 2` is explained in [945].

Syntax:

```
"MINT" "TYPE" 2
        "CO1" co1 "CO2" co2 "CO3" co3
        "CO4" co4 "CO5" co5 "CO6" co6
        "CO7" co7 "CO8" co8 "CO9" co9
        "CO10" co10 "CO11" co11 "CO12" co12
        "CO13" co13
        /LECTURE/
```

`co1`

Young's modulus along direction 3.

`co2`

Shear modulus between direction 1 and 3.

`co3`

Shear modulus between direction 2 and 3.

`co4`

Critical energy release rate in mode 1.

`co5`

Critical energy release rate in mode 2.

`co6`

Critical energy release rate in mode 3.

`co7`

Power coefficient to couple the thermodynamic forces of the three modes (default value = 1.0).

`co8`

Thermodynamical force threshold for damage. Required for the linear damage law. Optional for the Cachan interface meso-model.

`co9`

Exponent n for damage evolution law of Cachan interface meso-model.

`co10`

Delay effect : parameter τ (optional).

`co11`

Delay effect : parameter a (optional).

`co12`

Maximum damage (optional, default value = 1.0).

`co13`

Initial damage (optional, default value = 0.0).

`LECTURE`

List of the concerned elements.

Comments:

When damage reaches the maximum damage value `co12`, element stiffness becomes null. Erosion algorithm is activated with `EROS` keyword (see page A.30,Section 4.4). Without erosion, the damaged elements are still able to avoid bulk elements interpenetration due to damage deactivation in compression.

Prescribing an initial damage with `co13` is usefull to create some pre-cracks and avoid bulk element penetration along the calculation without employing contact algorithm. Values greater than 0.0 will automatically be set equal to 1.0.

Outputs:

The components of the ECR table are as follows:

ecr(1): Damage

ecr(2): Equivalent thermodynamic force

ecr(3): Time

ecr(4): Current mixity, -1 without damage

ecr(5): Dissipated energy

ecr(6): Previous step displacement jump in direction 3

ecr(7): Previous step displacement jump in direction 13

ecr(8): Previous step displacement jump in direction 23

7.7.66 THE SL-ZA MODEL

Object:

This directive enables to choose the SLZA model which is an extension of both STEINBERG LUND and ZERILLI ARMSTRONG models. This model uses an expression for the internal stress that comes from the ZA model and an expression of the effective stress that comes from SL model.

Syntax:

```
"SLZA" "RO" rho   "YOUN" young   "NU" nu    "SIGE" sige
       "YA" ya    "YMAX" ymax    "YP" yp    "ER"   er
       "N"  n     "C1"   c1      "UK" uk    "CP"   cp
       "TM" tm    "T0"   t0      "BETA" beta
       /LECTURE/
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`sige`

Elastic limit at ambient temperature.

`ya`

Coeffiecient of the CEA SL-ZA model.

`ymax`

Coefficient of the CEA SL-ZA model.

`yp`

Coefficient of the CEA SL-ZA model.

`er`

Coefficient of the CEA SL-ZA model.

`n`

Coefficient of the CEA SL-ZA model.

`c1`

Coefficient of the CEA SL-ZA model.

`uk`

Coefficient of the CEA SL-ZA model.

`cp`

Heat capacity per unit mass of the solid.

`tm`

Melting temperature of the solid.

`t0`

Initial temperature of the solid.

`beta`

Taylor and Quiney coefficient.

`LECTURE`

List of the elements concerned.

Comments:

The expression of the elastic limit is given by:

$y_d = (y_a + (y_{\max} - y_a)((1 - \exp(-e_p/e_r))^n)) + y_p(1 - \sqrt{kt/2u_k}\log(c_1/\dot{e}))$

where k is the Boltzmann constant and $\dot{e}$ is the strain rate.

Outputs:

The components of the ECR table are as follows:

ecr(1) : Hydrostatic pressure
ecr(2) : Von mises stress
ecr(3) : Equivalent plastic strain
ecr(4) = Increment of temperature
ecr(5) = Elastic limit
ecr(6) = Total strain at the last timestep
ecr(7) = Time of the last call of the element
ecr(8) = Equivalent strain rate

7.7.67 RTM composite material

Object:

This directive allows to chose a composite material made by a RTM process. The behavior is orthotropic and the 9 independant coefficents can defined by using abaques of 3 or 4 parameters. These parameters are the volumic fraction, the angle between warp and weft directions and the warp and weft ratio. The 4th parameter is the temperature which can be optionnal.

Syntax:

```
"CRTM"
   "RO" rho
   "NTEM" ntem  "NVF" nvf  "NANG"  nang  "NRCT" nrct
   "PTEM" ptem  "PVF" pvf  "PANG"  pang  "PRCT" prct
      "E11" ne11
        PAR1 val-par1-1   PAR2 val-par2-1     PAR3 val-par3-1
            TABLE nval-par4
                     nval-par4 *(E11 PAR4)
      PAR1 val-par1-1 PAR2 val-par2-1   PAR3 val-par3-2
          TABL nval-par4
                     nval-par4*(E11 , PAR4)
     ...  then loop on PARA3, then PAR2 and PARA1.

      "E22" ne22
          -idem-

      "E33" ne33
          -idem-

      "G12" ng12
          -idem-

      "G13" ng13
          -idem-

      "G23" ng23
          -idem-

      "NU12" nnu12
          -idem-

      "NU13" nnu13
          -idem-

      "NU23" nnu23
```

```
            -idem-

                             /LECTURE/
```

`rho`

Density of the material.

`ntem`

Number of values of temperature

`nvf`

Number of values of volumic fraction

`nang`

Number of values of angle between warp and weft

`nrct`

Number of values of ratio between warp and weft

`ptem`

Number of the temperature parameter

`pvf`

Number of the volumic fraction parameter

`pang`

Number of the angle parameter

`prct`

Number of the ratio between warp and weft parameter

`ne11`

Number of the abaque for E11

`val-par1-1`

First value of the parameter 1

`val-par2-1`

First value of the parameter 2

`val-par3-1`

First value of the parameter 3

`val-par3-2`

Second value of the parameter 3

`nval-par4`

Number of values of parameter 4

`LECTURE`

List of the elements concerned.

Comments:

1/ - It is possible to suppress the temperature dependant. In this case, one can use 3 parameters (from 1 to 3).

2/ - By defining ptem, prct, pang and pvf, it is possible to declare that temperature is parameter 1, volumic fraction is parameter 2 and any combination the user likes. It permits to use as general as possible an abaque of 4 parameters.

3/ - The values of angle, volumic fraction and ration between warp and weft have to be define by using the directive RTMANG, RTMVF and RTMRCT (page C63). The temperature is defined as initial values (command INIT TETA page E80).

Outputs:

The components of the ECR table are as follows:

ECR(1) : pressure

ECR(2) : Von mises criterion

ECR(3) : modulus E11

ECR(4) : modulus E22

ECR(5) : modulus E33

ECR(6) : modulus G12

ECR(7) : modulus G13

ECR(8) : modulus G23

ECR(9) : Poisson coefficient NU12

ECR(10) : Poisson coefficient NU13

ECR(11) : Poisson coefficient NU23

7.7.68 TVMC (LOI ELASTOPLASTIQUE POUR COMPOSITES)

Object:

Ce materiau permet de modeliser le comportement elastoplastique endommageable de composites a fibres courtes.

C'est le cas par exemple des composites injectes de type thermoplastique charge de fibres (verre, carbone, ...) comme ULTEM 2100, ou encore des compositesSMC-R de type polyester charge de fibres (verre, carbone).

Cette loi est utilisable pour les elements volumiques. Elle se decompose en trois etapes :

- homogeneisation micro-mecanique,
- endommagement,
- plasticite couplee a l'endommagement.

Syntax:

```
"TVMC"  "ROF" rhof  "ROM" rhom  "TAUX" taux  "EM"  em  "NUM"  num ...
   ...  "EF"  ef    "NUF" nuf   "R"    rap   "TVF" tvf "TE"   te  ...
   ...  "PH"  ph    "NF"  nf    "Y1C"  y1c   "Y2C" y2c "CRIT" choix  ...
   ...  "NFD1"  n1  "NFD2"  n2  "NFR"  n3    /LECTURE/
```

`rhof`

Masse volumique de la fibre.

`rhom`

Masse volumique de la resine (chargee ou non chargee).

`taux`

Taux de porosite.

`em`

Module d'Young de la matrice.

`num`

Coefficient de Poisson de la matrice.

`ef`

Module d'Young de la fibre.

`nuf`

Coefficient de Poisson de la fibre.

`rap`

Rapport de forme de la fibre (longueur sur diametre).

`tvf`

Taux volumique de fibres.

`te`

Orientation dans le plan de la fibre (inutilise ici).

`ph`

Orientation hors plan de la fibre (inutilise ici).

`nf`

Nombre d'orientations de fibres dans le plan.

`y1c`

Taux de restitution limite de la matrice en traction.

`y2c`

Taux de restitution limite de la matrice en cisaillement.

`choix`

Numero du critere definissant la forme de la surface de charge.

`n1`

Numero de la fonction definissant l'endommagement en traction-compression en X et Y .

`n2`

Numero de la fonction definissant l'endommagement en cisaillement.

`n3`

Numero de la fonction definissant la courbe de plasticite a ecrouissage isotrope.

`LECTURE`

List of the elements concerned.

Comments:

Le parametre "CRIT" peut prendre l'une des 4 valeurs suivantes :

1 = VON MISES,

2 = TRESCA,

3 = TSAI-HILL (en σ_1 et σ_4),

4 = TSAI-HILL (en σ_1, σ_2 et σ_4),

Outputs:

The components of the ECR table are as follows:

ECR(1): pression hydrostatique,

ECR(2): Y1 = taux de restitution d'energie en traction,

ECR(3): Y2 = taux de restitution d'energie en cisaillement,

ECR(4): D1 = endommagement en traction,

ECR(5): D2 = endommagement en cisaillement,

ECR(6): deformation plastique cumulee,

ECR(7) : limite elastique courante,

ECR(8:10): inusites,

ECR(11): vitesse du son locale (pour la stabilite).

7.7.69 HILL MATERIAL MODEL

Object:

This directive enables to choose the HILL model which is a model with isotropic plasticity associated with a HILL criterion. The elastic behaviour of the material can be orthotropic.

Syntax:

```
"HILL" "RO" rho   "YG1" yg1   "YG2" yg2    "YG3" yg3
                  "G12" g12   "G13" g13    "G23" g23
            "NU12" nu12   "NU13" nu13    "NU23" nu23
                  "XT1" xt1   "XT2" xt2    "XT3" xt3
            "RST1" rst1   "RST2" rst2    "RST3" rst3
  "TRAC"  npts*( sig  eps )  /LECTURE/

       /LECTURE/
```

`rho`

Density of the material.

`yg1`

Young's modulus - direction 1

`yg2`

Young's modulus - direction 2

`yg3`

Young's modulus - direction 3

`g12`

shear modulus - plane 12

`g23`

shear modulus - plane 23

`g13`

shear modulus - plane 13

`nu12`

shear modulus - plane 12

`nu23`

shear modulus - plane 23

`nu13`

shear modulus - plane 13

`xt1`

yield stress - direction 1

`xt2`

yield stress - direction 2

`xt3`

yield stress - direction 3

`rst1`

yield stress - plane 12

`rst2`

yield stress - plane 23

`rst3`

yield stress - plane 13

`"TRAC"`

This key-word introduces the yield curve.

`npts`

Number of points (except the origin) defining the yield curve.

`sig`

normalised stress.

`eps`

Equivalent plastic strain. Note that the first point must be always (1., 0.)

`LECTURE`

List of the elements concerned.

Outputs:

The components of the ECR table are as follows:

ecr(1) : Hydrostatic pressure
ecr(2) : Von Mises stress
ecr(3) : Equivalent plastic strain
ecr(7) : New elastic limit

7.7.70 GLASS MATERIAL

Object:

This option enables to choose a material that considers the strain rate effect of glass. A linear elastic material is used up to the failure. The failure limit `PSAR` uses the area under the stress-time curve (equivalent constant stress).

Syntax:

```
"GLAS"  "RO" rho  "YOUN" young  "NU" nu  "CORR" corr
        "FAIL" $[ VMIS ; PEPS ; PRES ; PEPR; PSAR ]$ "LIMI" limit
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`corr`

Stress corrosion fraction. Default value is 16.

`FAIL`

Introduces an element failure model, represented by a failure criterion and a by failure limit value. The available failure criteria are: `VMIS` for a criterion based upon Von Mises stress (isotropic criterion), `PEPS` for a criterion based upon the principal strain (see caveat below), `PRES` for a criterion based upon the hydrostatic stress, `PEPR` for a criterion based upon the principal strain if the hydrostatic stress is positive (traction): if the hydrostatic stress is negative (compression) there is no failure. `PSAR` for a criterion based upon equivalent constant stress of the duration of 60 s.

`limit`

Indicates the failure limit for the chosen criterion.

Comments:

When using a failure criterion based upon the principal strains (`PEPS` or `PEPR`) be aware that the criterion is based upon the *cumulated* strains. These are usually a good approximation of the total strains for elements using a convected reference frame for the stresses and strains (such as e.g. plate, shell or bar elements). The approximation is likely to be very bad, instead, for continuum-like elements, at least when there are large rotations.

Outputs:

The components of the ECR table are as follows:

ECR(1): current hydrostatic pressure

ECR(2): current equivalent stress (Von Mises)

ECR(3) Area under the (principal stress to the power of `CORR`)-time curve, the stress is dived by 1.E6 to avoid too big numbers.

ECR(4): equivalent constant stress of the duration 60 s.

ECR(5): sound speed

7.7.71 BL3S: Reinforced concrete law for DEM

Object:

This material law prescribes properties of the reinforced concrete for structures modeled with the discrete element method (DEM) via ELDI elements. Usually, both steel and concrete phases are present. Nevertheless, they may be used separately, i.e. it is possible to use only one material phase, either concrete or steel.

This model was first developed in J.Rousseau's PhD thesis then reviewed and further developed in A.Masurel's PhD thesis, with EDF financial support and collaboration with 3S-R Laboratory (Grenoble). For theoretical description of the laws see [965], [978].

Syntax:

```
 "BL3S" |[ "BETON"  "RO"   rho   "YOUN" youn  "NU"   nu
                    "T"    tens  "CO"   cohe  "PHII" phii
                    "PHIC" phic  "ADOU" adou
                  < "ALPH" alpha "BETA" beta  "GAMM" gamma >
                  < "CNEL" cnel  "CNPL" cnpl  "YUNL" yunl
                    "XI1"  xi1   "XI2"  xi2 >
                  < "ETA"  eta >
                  < "EPS1" eps1  "EPS2" eps2  "SIGC" sigc "DET2" det2
                    "AFIL" afil >
                  < "KRES" kres  "KSKN" kskn >
                  < "ROLR" rolr  "CDMR" cdmr >

         < "BIMA"   "YOUN" youn  "NU"   nu    "TN"   tn
                    "CN"   cn    "TE"   te    "TMAX" tmax
                    "UMAX" dmax  "PHII" phii  "PHIC" phic  >
                    /LECTURE/ ;

         < "ACIER"  "RO"   rho   "YOUN" youn  "NU"   nu
                    "T"    tens  "ECRO" sigmr "AMAX" amax
           < "BIMA" "YOUN" youn  "NU"   nu    "TN"   tn
                    "CN"   cn    "TE"   te    "TMAX" tmax
                    "UMAX" dmax  "PHII" phii  "PHIC" phic  >
                                                             >
                    /LECTURE/
        ]|
```

Parameters for concrete (BETON):

`rho`

Density of the material

`youn`

Young's modulus

`nu`

Poisson's ratio

`tens`

Maximum tensile strength (T > 0).

`cohe`

Cohesion

`phii`

Internal friction angle

`phic`

Contact friction angle

`adou`

Softening coefficient (ratio between elastic and softening slopes >0)

`alpha`

1st parameter for micro-macro relations K=f(E,nu,alpha,beta,gamma). The default value is 3.9 (see [971]).

`beta`

2nd parameter for micro-macro relations K=f(E,nu,alpha,beta,gamma). The default value is 3.03125 (see [971]).

`gamma`

3rd parameter for micro-macro relations K=f(E,nu,alpha,beta,gamma). The default value is 4.8115 (see [971]).

`cnel`

Local elastic compression limit

`cnpl`

Local plastic compression limit

`yunl`

Young's modulus for compression unload

`xi1`

Softening in compression

`xi2`

Hardening in compression

`eta`

Reduced damping coefficient on concrete cohesive links if needed

`eps1`

First limit of the strain rate effect (under EPS1 the behavior of concrete is considered as quasi-static)

`eps2`

Second limit of the strain rate effect formula

`sigc`

Static compressive strength used to calculate the first delta exponent of the strain rate effect law (first range)

`det2`

Second exponent of the strain rate effect law (second range)

`afil`

Weighting coefficient for the strain rate filtering (default value: 0.)

`kres`

Coefficient of restitution for a normal nonelastic shoc for granular medium (default value: 1.)

`kskn`

Ratio of tangential and normal contact stiffnesses for granular medium (default value: 0.)

`rolr`

Rolling stiffness for granular medium (default value: 0.)

`afil`

Rolling damping coefficient for granular medium (default value: 0.)

`LECTURE`

List of the elements concerned.

Parameters for steel (ACIER):

`rho`

Density of the material

`youn`

Young's modulus

`nu`

Poisson's ratio

`tens`

Maximum elastic stress (T > 0).

`sigmr`

Maximum stress for steel

`amax`

Maximum allongation (%)

`LECTURE`

List of the elements concerned.

Parameters for steel-concrete interface (BIMA):

`youn`

Young's modulus

`nu`

Poisson's ratio

`tn`

Maximum normal tensile strength (perpendicular to the steel bar)

`cn`

Maximum normal compression strength (perpendicular to the steel bar)

`te`

Elastic limit in the tangential direction

`tmax`

Maximum strenght in the tangential direction

`dmax`

Coefficient to define maximum tangential sliding (umax=dmax*uglis)

`phii`

Internal friction angle

`phic`

Contact friction angle

`LECTURE`

List of the elements concerned.

Comments:

If only concrete is modeled through the discrete element formulation, the sequence open by BETON keyword should be used only. In this case, reinforcement is modeled by the beam finite element model and steel-concrete links are defined by ACBE link model.

If both the concrete and the reinforcement are modeled by discrete elements, theer properties must be defined separately (keywords BETON and ACIER respectively), and it is necessary to define also a specific behavior for the steel-concrete interface. This can be done by using a sequence of parametres introduced by the BIMA option. This option should be used only once, either with BETON or ACIER definition. If the sequence BIMA is not specified, the steel-concrete interface behaves as a concrete without taking into account the main direction of the reinforcement.

Don't forget to use directive ARMA in CELDI to declare the steel discrete elements. ARMA calculates the main direction of the reinforcement needed to define normal and tangential forces for the BIMA links.

Outputs:

In the discrete element calculation BL3S material is used for the links. However, for post-processing purpose the number of active links and the degree of damage are reported onto the discrete elements.

The components of the ECR table are as follows:

ECR(1): number of COHE-type links per element at $t = t_0$

ECR(2): number of BIMA-type links per element at $t = t_0$

ECR(3): number of COHE-type links per element at $t \geq t_0$

ECR(4): number of BIMA-type links per element at $t \geq t_0$

ECR(5): degree of damage of COHE-type links per element

ECR(6): degree of damage of BIMA-type links per element

ECR(7): diameter of the discrete element.

7.7.72 LAMINATED SECURITY GLASS MATERIAL

Object:

This option enables to choose a material that considers laminated security glass. A linear elastic material is used up to the failure. After the failure, the material can react to compression but not more to tension. This material is recommended with a sandwich structure, where the interlayer can be built up with a elastoplastic material.

Syntax:

```
"LSGL"  "RO" rho  "YOUN" young  "NU" nu  <"CORR" corr>
        <"FAIL" $[ VMIS ; PEPS ; PRES ; PEPR; PSAR; VMPR ]$ "LIMI" limit>
        <"CR2D"> <"NEIG"> <"REDU" redu>
```

`rho`

Density of the material.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`corr`

Stress corrosion fraction. Default value is 16. This value is only used by the failure criterion `PASR`. See following reference: Beason, W. Lynn, Morgan, James R.: Glass failure prediction model. Journal of Structural Engineering, 110 (2), pp. 197-212, 1984.

`FAIL`

Introduces an element failure model, represented by a failure criterion and a by failure limit value. The available failure criteria are: `VMIS` for a criterion based upon Von Mises stress (isotropic criterion), `PEPS` for a criterion based upon the principal strain (see caveat below), `PRES` for a criterion based upon the hydrostatic stress, `PEPR` for a criterion based upon the principal strain if the hydrostatic stress is positive (traction): if the hydrostatic stress is negative (compression) there is no failure. `PSAR` for a criterion based upon equivalent constant stress of the duration of 60 s. `VMPR` for a criterion based upon Von Mises stress (isotropic criterion), if the hydrostatic stress is positive (traction): if the hydrostatic stress is negative (compression) there is no failure.

`limit`

Indicates the failure limit for the chosen criterion.

`CR2D`

Introduces two-dimensional cracks, which means that the direction of the principle stress or strain is used to introduce a first crack. This crack is implemented in such a way that only the stresses normal to the crack direction are set to 0 (in the case of tension). If the failure criterion is reached for the direction parallel to the crack, then the integration point fails in both directions.

`NEIG`

If this material is used for 3D calculations, the glass part of the model should mainly eroded after the erosion of the interlayer. By using the keyword `NEIG` erosion of an element of the `LSGL` material is only taken into account, if a neighbour element (e.g. interlayer of another `LSGL` element) is already eroded.

`redu`

In case of hydrostatic tension, the stresses are set to 0. Using keyword `REDU` the decreasing of the stresses can be smoothed. The tension stresses are multiplied with the value redu, which should be less than 1.0. Default value for redu is 0.0.

Comments:

When using a failure criterion based upon the principal strains (`PEPS` or `PEPR`) be aware that the criterion is based upon the *cumulated* strains. These are usually a good approximation of the total strains for elements using a convected reference frame for the stresses and strains (such as e.g. plate, shell or bar elements). The approximation is likely to be very bad, instead, for continuum-like elements, at least when there are large rotations.

The material should only be used with shell elements. The third component of the stresses and strains is neglected in the calculation of the failure criterion.

Outputs:

The components of the ECR table are as follows:

ECR(1): current hydrostatic pressure

ECR(2): current equivalent stress (Von Mises)

ECR(3) Area under the (principal stress to the power of `CORR`)-time curve, the stress is dived by 1.E6 to avoid too big numbers.

ECR(4): equivalent constant stress of the duration 60 s.

ECR(5): sound speed

ECR(6): failure flag (0=virgin Gauss Point, 1=failed Gauss Point)

ECR(7): angle of failure

ECR(8): status of the spalling: 0 no failure of the g.p.; -1 g.p. under compression; +1 g.p. under tension.

Note that in order to post-process the total strains (which were formerly inappropriately stored in the ECR table for JRC materials) one has to use the EPST table related to the element (like for CEA elements).

7.7.73 SMAZ: Mazars-linear elastic law with damage for SPHC elements

Object:

Isotropic linear elastic with Mazars damage for SPHC elements.

References:

1- Jacky MAZARS, "Application de la mécanique de l'endommagement au comportement non linéaire et à la rupture du béton de structure", Thèse de doctorat, Université Pierre et Marie Curie - Paris 6, 1984.

Syntax:

```
"SMAZ" "RO"   rho  "YOUN" young  "NU"   nu   "EPSD" epsd
       "DCRI" dcri "A"    a      "B"    b
       "TAUC" tauc "CSTA" csta                         /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`epsd`

Initial strain threshold.

`dcri`

Critical value of damage (=1 per default).

`a`

Parameter A of the tension law (asymptote of the curve stress-strain)

`b`

Parameter B of the tension law (shape of the curve stress-strain)

`tauc`

Characteristic time for delay-damage

`csta`

Parameter of the delay-damage (=1 per default)

Outputs:

The components of the ECR table are as follows:

ECR(1) : Pressure
ECR(2) : Von Mises criterion
ECR(3) : Equivalent strain
ECR(4) : Failure state (0: no failure, 1: failed)

7.7.74 SLIN: Linear elastic law with damage for SPHC elements

Object:

Isotropic linear elastic with damage for SPHC elements.

Syntax:

```
"SLIN" "RO"   rho  "YOUN" young  "NU"   nu   "EPSD" epsd
       "DCRI" dcri "EPSR" epsr
       "TAUC" tauc "CSTA" csta                          /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's ratio.

`epsd`

Initial strain threshold.

`dcri`

Critical value of damage (=1 per default).

`epsr`

Maximum strain before failure.

`tauc`

Characteristic time for delay-damage

`csta`

Parameter of the delay-damage (=1 per default)

Outputs:

The components of the ECR table are as follows:

ECR(1) : Pressure
ECR(2) : Von Mises criterion
ECR(3) : Equivalent strain
ECR(4) : Failure state (0: no failure, 1: failed)

7.7.75 JCLM

Object :

This directive allows to describe the behaviour of an elasto-plastic material that may undego some damage, according to the Lemaitre model. There is coupling between damage and plasticity, represented by the Johnson-Cook model. The damage evolution rate is a function of the triaxiality ratio of stresses and of the equivalent plastic strain rate. A failure criterion is impicitly contained within the model: rupture occurs when the damage exceeds a critical value. Two optional parameters allow to introduce a limitation of the damage rate (thanks to the delayed damage model) in order to avoid the mesh dependency.

Syntax:

```
"JCLM"  "RO" rho "YOUN" young "NU" nu
        "EPSD" epsd  "S0" s0  "DC" dc
        <"CSTA" csta "TAUC" tauc "NOCO" noco>
        "COA1" coa1 "COA2" coa2
        "CLB1" clb1 "CLB2" clb2 "SRRF" srrf /LECTURE/
```

`rho`

Density.

`young`

Young's modulus.

`nu`

Poisson's coefficient.

`epsd`

Damage threshold (i.e. equivalent plastic strain, weighted by a function of stress triaxiality, within which damage vanishes).

`s0`

Parameter driving the damage evolution rate.

`dc`

Critical damage defining the rupture criterion.

`csta`

Parameter of the delayed damage model

`tauc`

Characteristic time of the delayed damage model. (1/tauc) represents the maximum damage rate.

`noco`

Optional parameter indicating what to do when no convergence is reached in the material routine. The value 0 is the default and means that an error message is issued and the calculation is stopped. The value 1 indicates that the element (or more precisely, the element's current Gauss point) is made to fail (eroded).

`coa1`

1st constant in the Johnson-Cook model.

`coa2`

2nd constant in the Johnson-Cook model.

`clb1`

3rd constant in the Johnson-Cook model.

`clb2`

Hardening coefficient of the Johnson-Cook model.

`srrf`

Reference strain rate of the Johnson-Cook model.

`LECTURE`

List of concerned elements.

Comments:

A detailed description of the damage model can be found in the report DMT/98-026A, available on request.

The implementation of the Johnson-Cook model is described in reference [167].

This material is currently restricted to SPHC elements.

Outputs:

The components ov the ECR table are as follows for **Continuum elements**:

ECR(1) : pressure

ECR(2) : Von Mises criterion

ECR(3) : equivalent plastic strain

ECR(4) : plasticity multiplier

ECR(5) : damage

ECR(7) : new elastic limit

When the "erosion" algorithm is activated (see page A.30, Section 4.4, keyword `FAIL`), an element is considered as failed if `damage >= dc`.

7.7.76 VPJC: Von Mises elasto-thermo-viscoplastic material

Object :

This directive allows to define a Von Mises elasto-thermo-viscoplastic material with non-linear isotropic hardening governed by a modified Johnson-Cook model with explicit elastic predictor and return mapping algorithm, a Voce saturation type of hardening and a Cockcroft-Latham failure criterion. See report [373] for full details. It can be used in 3D, 2D plane strain, 2D plane stress or 2D axisymmetric cases. This material model was developed at NTNU (Trondheim, Norway).

The original Johnson-Cook model was first introduced in: G. R. Johnson and W. H. Cook. A constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperatures. Proceedings of the 7th International Symposium on Ballistics, Hague (1983), 541–547.

The so-called "modified" Johnson Cook material law, in which the strain-rate sensitivity term is adjusted so as to avoid non-physical softening, was introduced in: M. Ortiz and G. T. Camacho. Adaptive Lagrangian modelling of ballistic penetration metallic targets. Computer Methods in Applied Mechanics and Engineering 142 (1997), 269–301. See also: T. Børvik, O. S. Hopperstad, T. Berstad, M. Langseth. A computational model of viscoplasticity and ductile damage for impact and penetration. Eur. J. Mech. A/Solids 20 (2001), 685-712.

The Voce saturation type of hardening was proposed in: E. Voce. The relationship between stress and strain for homogeneous deformation. Journal of the Institute for Metals 74 (1948), 536–562.

The expression of the constitutive law is the following:

$$\sigma_y = \left[A + Q_1\left(1 - e^{-C_1 p}\right) + Q_2\left(1 - e^{-C_2 p}\right)\right]\left(1 + \dot{p}^*\right)^C\left(1 - T^{*m}\right) \tag{47}$$

and is the product of three factors (from left to right): a strain hardening term (in square brackets), a strain-rate hardening term and a temperature softening term. The symbols indicate the following:

- σ_y is the current yield stress of the material
- A is the initial yield stress of the material, sometimes also indicated as σ_0
- p is the equivalent (or cumulated) plastic strain, i.e. the energy-conjugated variable to the equivalent stress
- $\dot{p}$ is the equivalent plastic strain rate
- $\dot{p}^*$ is the dimensionless strain rate $\dot{p}^* = \frac{\dot{p}}{\dot{p}_0}$, with $\dot{p}_0$ the reference strain rate
- T^* is the dimensionless temperature $T^* = \frac{T-T_r}{T_m-T_r}$, with T the absolute temperature, T_r the absolute room temperature and T_m the absolute melting temperature
- Q_1, C_1, Q_2 and C_2 are material constants used in the first factor on the right-hand side of the material law (strain-hardening term)
- C is a material constant, the exponent appearing in the second factor, which represents the strain-rate hardening

- m is a material constant, the exponent appearing in the third factor, which represents the temperature softening

Temperature softening

The last term of the above equation accounts for the thermal softening of the yield stress at elevated temperatures. However, the evolution of the temperature remains to be established. The heat transfer is modelled by assuming adiabatic conditions. This implies that there is no heat transfer into or out of the system during plastic straining. The plastic energy dissipation D_p per unit volume in the form of heat (Watt per cubic meter) is given by:

$$D_p = \chi \sigma_{\mathrm{eq}} \dot{p} = \rho C_T \dot{T} \tag{48}$$

where:

- χ is the Taylor-Quinney coefficient, i.e. the fraction of plastic power that is converted to heat. The remaining fraction $1 - \chi$ is assumed to remain in the material due to structural rearrangements
- σ_{eq} is the equivalent stress
- $\dot{p}$ is the equivalent plastic strain rate
- ρ is the material density
- C_T is the material heat capacity
- $\dot{T}$ is the temperature rate due to adiabatic heating

From the above expression, the temperature rate $\dot{T}$ is obtained:

$$\dot{T} = \frac{D_p}{\rho C_T} = \frac{\chi \sigma_{\mathrm{eq}} \dot{p}}{\rho C_T} \tag{49}$$

and then this value is integrated in time at each Gauss point to obtain the current temperature at the point. The initial temperature is set to the room temperature T_r at each Gauss point. If during the calculation the temperature at a Gauss point reaches the melting temperature T_m, the Gauss point fails.

Gauss point failure and element erosion

The Cockcroft-Latham fracture criterion based on plastic work per unit volume is assumed. See: M. G. Cockcroft and D. J. Latham. Ductility and the workability of metals. Journal of the Institute of Metals 96 (1968), 33–39.

Material failure takes place at a Gauss point when a damage parameter D reaches the damage threshold D_c. The D_c parameter should be set by the user (see `DC` keyword below) such that $0 < D_c \leq 1$. The value 1 should be used when not considering damage softening. The damage is computed according to the following expression:

$$D = \frac{W}{W_c} = \frac{1}{W_c} \int_0^p \langle \sigma_1 \rangle \, dp \tag{50}$$

where:

- σ_1 is the maximum principal stress at the Gauss point

- The expression $\langle\sigma_1\rangle$ is equivalent to the function max(0,σ_1), which implies that only positive values of the maximum principal stress σ_1 (i.e. tensile stress) contribute to the damage evolution
- W_c is the failure material parameter, which can be found by integrating the major principal stress in a uniaxial tension test during the entire equivalent plastic strain path until the plastic strain at failure p_f. In this case (uniaxial traction) the major principal stress is just the (longitudinal) stress

An element's Gauss point is considered as *failed* if $D \geq D_c$, i.e. if the damage reaches the chosen threshold. If the "erosion" algorithm is activated (see GBA_0030, keyword `EROS`), an element is *eroded* as soon as a chosen fraction (see `ldam` parameter of the `EROS` keyword) of its Gauss points reach failure.

An additional optional parameter `PCAP` allows to activate a cap, i.e. an additional failure criterion, to the Cockcroft-Latham (CL) criterion. The basic CL criterion has limitations in correctly representing accumulation of damage in compressive stress states (low triaxiality). In these cases the user may add a "cap" threshold on the fracture surface that will cause GP failure and eventually element erosion when the equivalent plastic strain p becomes larger than a user-defined value p_{cap} (typically in the range of 1.0 to 1.5).

Syntax:

```
"VPJC"  "RO" rho "YOUN" young "NU" nu "ELAS" elas
       <"TOL" tol "MXIT" mxit>
        "QR1" qr1 "CR1" cr1 "QR2" qr2 "CR2" cr2
        "PDOT" pdot "C" c
        "TQ" tq "CP" cp <"TR" tr> "TM" tm "M" m
        "DC" dc "WC" wc <"PCAP" pcap> <"DFAI" dfai>
       <"SOLU" solu> <"DEBU" debu> <"RESI" resi>
        /LECTURE/
```

`rho`

Density ρ. Typically in kg/m^3.

`young`

Young's modulus E. Typically in Pa.

`nu`

Poisson's coefficient ν. Dimensionless.

`elas`

Initial yield stress (indicated as A above, or sometimes as σ_0). Typically in Pa.

`tol`

Tolerance for Newton-Raphson internal iterations. Dimensionless. The default is 10^{-5}.

`mxit`

Maximum number of Newton-Raphson internal iterations. The default is 50.

`qr1`

Material constant Q_1, asymptote of the first Voce hardening term. It has the dimension of a stress, typically in Pa.

`cr1`

Material constant C_1, hardening parameter of the first Voce hardening term. Dimensionless.

`qr2`

Material constant Q_2, asymptote of the second Voce hardening term. It has the dimension of a stress, typically in Pa.

`cr2`

Material constant C_2, hardening parameter of the second Voce hardening term. Dimensionless.

`pdot`

Reference strain rate $\dot{p}_0$ for the calculation of $\dot{p}^*$. Typically in s^{-1}.

`c`

Material constant C, hardening parameter (exponent) of the viscous term. Dimensionless. By setting $C = 0$ one can model a quasi-static test, in which the visco-plasticity effect is not included.

`tq`

Taylor-Quinney coefficient χ. Dimensionless.

`cp`

Specific heat capacity of the solid material C_T. Typically in J/(kg·K).

`tr`

Room temperature T_r in K for the calculation of T^*. The default is 293 K. This is also taken as the initial temperature of the material.

`tm`

Melting temperature T_m in K for the calculation of T^*.

`m`

Material constant m, hardening parameter of the temperature term. Dimensionless. By using the special value $m = 0$ the temperature softening effect is excluded from the model, i.e. the code assumes $T^{*m} = 0$, and therefore the temperature hardening term becomes $(1 - T^{*m}) = (1 - 0) = 1$. Note also that in this case the temperature is not updated, so that it remains to the room value T_r.

`dc`

Upper limit D_c of the damage D when softening occurs. Dimensionless. Material failure takes place at a Gauss point when the damage parameter D reaches D_c. The D_c parameter should be set by the user such that $0 < D_c \leq 1$. The value 1 should be used when not considering damage softening.

`wc`

Failure parameter W_c of the Cockcroft-Latham failure criterion. It has the dimension of work per unit volume, i.e. [J/m^3], i.e. of a stress, typically expressed in Pa. By setting W_c to a very large value the failure of the material (and the consequent element erosion, if specified by the user) can be excluded from the model.

`pcap`

Additional (optional) cap on the Cockcroft-Latham failure criterion. This represents a limiting value of the equivalent plastic strain which, if reached, causes failure of the element's Gauss Point and eventually erosion of the element once a sufficient number of its GPs have failed. Typical values of `pcap` might be in the range from 1.0 to 1.5. If omitted, the code sets the cap limit to 0 and this *de facto* disables the cap.

`dfai`

Optional switch to activate detailed printout on the listing at each time step of the failing GPs with the current VPJC material and of the (material) reason for which they are failing. By default (`DFAI 0`) only the eroded elements are printed. To activate the option set `DFAI 1`. Possible failure reasons include: the Cockcroft-Latham criterion (DC), the principal strain cap (PCAP), if specified, and the melting temperature (TM). By searching and counting the messages on the listing one may found out how many GPs have failed due to each detailed reason. This option may produce huge listings and is probably most useful only for debugging purposes. Note also that, irrespective of the setting of `dfai`, the total number of VPJC material-failed GPS for each reason is printed on the listing at each printing station (not at each time step), provided the `ECRI FAIL` keyword is specified.

`solu`

Solution algorithm. By default (or by specifying `SOLU 1`) a cutting plane algorithm is adopted, which requires internal Newton-Raphson iterations (up to a maximum number prescribed via `MXIT`). The cutting plane algorithm was originally developed for rate-independent plasticity and should be used with some care for rate-dependent plasticity models. This is due to the fact that the plastic strain rate $\dot{p}$ actually increases during the iterative update scheme and reaches the correct value of $\dot{p}$ only at the final iteration. The result is that the return to the dynamic yield condition $F = 0$ occurs at strain rates that are too low. Optionally, by specifying `SOLU 2`, one may choose a radial return solution algorithm. The radial return method also requires internal (Newton-Raphson) iterations and is a special case of the (implicit) backward Euler return map algorithm developed for the von Mises yield criterion with the associated flow rule. In this case, the return to the yield surface from the elastic trial state is radial to the yield surface in the deviatoric (stress) plane, which significantly simplifies the algorithm and makes the algorithm exceptionally stable and accurate. Note, however, that the radial return solution algorithm cannot be used with plane stress or uniaxial stress states (but can be used in 3D, 2D axisymmetric and 2D plane strain cases).

`debu`

Debugging option. By default (or by specifying `DEBU 0`) no debugging is activated. By specifying `DEBU 1`, whenever the maximum number of iterations `MXIT` is exceeded, before stopping the complete set of input arguments to the routine is written (to machine's precision) on the listing and on a binary file `_VPJC.dat`. This allows to debug the routine by reading back the data and feeding them to the material routine under debugging control. Note that activating this option will slightly slow down the execution since the complete set of input data to the routine must be stored each time the material routine is called.

`resi`

Optional keyword to decide what to do when MXIT is reached without convergence. By default (or by specifying `RESI 0`) the code simply stops, with an error message (and stores the faulty, state if DEBU 1 has been set). By specifying `RESI 1`, whenever the maximum number of iterations `MXIT` is exceeded, the code assumes that convergence has been reached anyway and the calculation continues.

`/LECT/`

List of the elements concerned.

Comments:

All parameters are mandatory except `TOL`, `MXIT` and `TR`, which by default have the values 10^{-5}, 50 and 293.0 K, respectively.

The various parameters can be grouped in the following classes:

- Elastic constants and density (`RO`, `YOUN` and `NU`).
- Yield stress and strain hardening (`ELAS`, `QR1`, `CR1`, `QR2` and `CR2`).
- Strain rate hardening (`PDOT` and `C`).
- Damage evolution (`DC` and `WC`).
- Adiabatic heating and temperature softening (`CP`, `TQ`, `TM`, `TR` and `M`).
- Convergence of internal iterative Newton-Raphson procedure (`TOL` and `MXIT`).

Orientatively, some values of the parameters for typical materials could be as follows

- Docol 600 DL medium-strength steel

```
VPJC RO 7850 YOUN 210.0E9 NU 0.33 ELAS 370.0E6
     QR1 236.4E6 CR1 39.3 QR2 408.1E6 CR2 4.5
     PDOT 5.E-4 C 0.001 TQ 0.9 CP 452
     TM 1800.0 M 1.0 DC 1.0 WC 473.0E6
```

- S355 structural steel

```
VPJC RO 7850 YOUN 210.0E9 NU 0.33 ELAS 333.1E6
     QR1 236.3E6 CR1 16.5 QR2 416.5E6 CR2 1.2
     PDOT 5.E-4 C 0.011 TQ 0.9 CP 452
     TM 1800.0 M 0.94 DC 1.0 WC 848.0E6
```

- X65 offshore pipeline steel

```
VPJC RO 7850 YOUN 208.0E9 NU 0.33 ELAS 299.0E6
     QR1 160.0E6 CR1 25.0 QR2 400.0E6 CR2 0.25
     PDOT 5.E-4 C 0.01 TQ 0.9 CP 452
     TM 1993.0 M 1.0 DC 1.0 WC 1595.0E6
```

- X65 steel

```
VPJC RO 7800.0 YOUN 2.08E11 NU 0.30 ELAS 465.5E6 mxit 20
     QR1 147.0E6 CR1 10.62 QR2 665.9E6 CR2 0.50
     PDOT 8.06E-4 C 0.0104 TQ 0.9 CP 452.0
     TM 1800.0 M 1.0 DC 1.0 WC 1562.0E6
     RESI 1
```

- Weldox 500E steel

```
VPJC RO 7850.0 YOUN 2.1E11 NU 0.33 ELAS 605E6 mxit 20
     QR1 139.0E6 CR1 10.26 QR2 709.0E6 CR2 0.48
     PDOT 5.E-4 C 0.0166 TQ 0.9 CP 452.0
     TM 1800.0 M 1.0 DC 1.0 WC 1516.0E6
     RESI 1
```

- Aluminium alloy 1050-H14

```
VPJC RO 2700 YOUN 70.0E9 NU 0.3 ELAS 80.0E6
     QR1 49.3E6 CR1 1457.1 QR2 5.2E6 CR2 121.5
     PDOT 5.E-4 C 1.4E-2 TQ 0.9 CP 910.0
     TM 893.0 M 1.0 DC 1.0 WC 54.0E6
```

- Aluminium alloy 6016-T4

```
VPJC RO 2700 YOUN 70.0E9 NU 0.3 ELAS 137.0E6
     QR1 19.1E6 CR1 592 QR2 170.0E6 CR2 11.4
     PDOT 5.E-4 C 1.0E-3 TQ 0.9 CP 910.0
     TM 893.0 M 1.0 DC 1.0 WC 140.0E6
```

- Aluminium alloy 6070-O

```
VPJC RO 2700 YOUN 70.0E9 NU 0.3 ELAS 38.8E6
     QR1 79.5E6 CR1 56.9 QR2 88.2E6 CR2 4.0
     PDOT 5.E-4 C 1.25E-2 TQ 0.9 CP 910.0
     TM 893.0 M 1.0 DC 1.0 WC 179.0E6
```

- Aluminium alloy 6070-T4

```
VPJC RO 2700 YOUN 70.0E9 NU 0.3 ELAS 172.7E6
     QR1 35.6E6 CR1 80.6 QR2 247.7E6 CR2 6.5
     PDOT 5.E-4 C 1.25E-2 TQ 0.9 CP 910.0
     TM 893.0 M 1.0 DC 1.0 WC 244.0E6
```

- Aluminium alloy 6070-T6

```
VPJC RO 2700 YOUN 70.0E9 NU 0.3 ELAS 350.0E6
     QR1 30.1E6 CR1 185.9 QR2 72.8E6 CR2 7.7
     PDOT 5.E-4 C 1.25E-2 TQ 0.9 CP 910.0
     TM 893.0 M 1.0 DC 1.0 WC 130.0E6
```

- Aluminium alloy 6070-T7

```
VPJC RO 2700 YOUN 70.0E9 NU 0.3 ELAS 292.5E6
     QR1 55.3E6 CR1 317.2 QR2 31.1E6 CR2 10.0
     PDOT 5.E-4 C 1.25E-2 TQ 0.9 CP 910.0
     TM 893.0 M 1.0 DC 1.0 WC 170.0E6
```

The material parameters are taken from the literature. See:

- J. K. Holmen, O.S. Hopperstad, T. Børvik. *Low velocity impact on multi-layered dual-phase steel plates.* International Journal of Impact Engineering **78** (2015), 161–177.
- J. K. Holmen, J. Johnsen, O.S. Hopperstad, T. Børvik. *Influence of fragmentation on the capacity of aluminium alloy plates subjected to ballistic impact.* European Journal of Mechanics A/Solids **55** (2016), 221–233.
- V. Aune, E. Fagerholt, K.O. Hauge, M. Langseth, T. Børvik. *Experimental study on the response of aluminium and steel plates subjected to airblast loading.* International Journal of Impact Engineering **90** (2016), 106–121.
- O.-G. Lademo, O. Engler, S. Keller, T. Berstad, K.O. Pedersen, O.S. Hopperstad. *Identification and validation of constitutive model and fracture criterion for AlMgSi alloy with application to sheet forming.* Materials and Design **30** (2009), 3005–3019.
- T. Børvik, S. Dey, A.H. Clausen. *Perforation resistance of five different high-strength steel plates subjected to small-arms projectiles.* International Journal of Impact Engineering **36** (2009), 948–964.
- M. Kristoffersen, F. Casadei, T. Børvik, M. Langseth, O.S. Hopperstad. *Impact against empty and water-filled X65 steel pipes – Experiments and simulations.* International Journal of Impact Engineering **71** (2014), 73–88.

Outputs:

The components of the ECR table are as follows (the name of the variable in the material routine is also given, whenever applicable):

ECR(1) : SIGMAH. Hydrostatic pressure ($\frac{1}{3}\sigma_{kk}$)

ECR(2) : PHI. Von Mises equivalent stress (σ_{eq})

ECR(3) : P. Equivalent plastic strain (p)

ECR(4) : PHITRIAL. Elastic trial equivalent (von Mises) stress

ECR(5) : F. Yield function (which should be close to 0.0)

ECR(6) : R. Total hardening of the material

ECR(7) : DDLAMBDA. Change of the incremental plastic multiplier (from one time step to another)

ECR(8) : DLAMBDA. Incremental plastic multiplier

ECR(9) : NRITER. Number of iterations to obtain convergence

ECR(10) : DLAMBDA / DT. Rate of plastic multiplier increment in time

ECR(11) : D. Damage (D), i.e. fraction of voids with respect to the gross cross-sectional area

ECR(12) : Failure indicator: 1.0 = Virgin Gauss Point, 0.0 = Failed Gauss Point

ECR(13) : T. Absolute temperature (T)

ECR(14) : WE. Cockcroft-Latham damage accumulation (W)

ECR(15) : Sound speed

ECR(16) : First principal stress (σ_1)

ECR(17) : Second principal stress (σ_2)

ECR(18) : Third principal stress (σ_3)

ECR(19) : RESNOR. Residual of the yield function, used to check convergence of the loop internal to the routine.

ECR(20) : Stress triaxiality

ECR(21) : Lode parameter

7.7.77 RIGI (Rigid Material)

Object :

This directive allows to define a rigid material to be associated with a rigid body. The geometrical characteristics of a rigid body are defined by using the `COMP RIGI` directive, see Page C.99B.

Syntax:

```
"RIGI"  "RO" rho
       <"YOUN" youn> <"NU" nu>
        /LECTURE/
```

`rho`

Density ρ. Typically in kg/m^3.

`youn`

Optional Young's modulus (for penalty contact calculations).

`nu`

Optional Poisson's coefficient (for penalty contact calculations).

`/LECT/`

List of the elements concerned.

Comments:

All elements listed in the `/LECT/` directive *must* belong to a rigid body declared in the `COMP RIGI` directive as described on Page C.99B.

The values of the density ρ is ignored by the code if the total mass, the center of gravity or the inertia tensor of the rigid body are prescribed by the user, see Page C.99B (`RIGI` directive) for details. However, even in this case a value for ρ *must* be specified in the present `RIGI` material for input completeness.

The optional values of Young's modulus E and Poisson's coefficient ν, if specified, are used to compute the 'rigid' material's bulk modulus

$$\kappa = \frac{E}{3(1-2\nu)}$$

for the calculation of penalty contact forces.

ECR(1) : empty at the moment.

7.7.78 DCMS (Damage in Coarsely Meshed Shells)

Object :

This directive may be used to model the onset of Damage, up to failure, in Coarsely Meshed metallic Shell (DCMS) structures. The DCMS material can only be used with shell elements, namely with elements subjected to plane stress conditions ($\sigma_z = 0$).

For the formulation of this material see the following references:

- Storheim M., Alsos H.S, Hopperstad O.S, Amdahl J. *A damage-based failure model for coarsely meshed shell structures.* International Journal of Impact Engineering 83 (2015) 59–75.
- Alsos H.S, Hopperstad O.S, Törnqvist R., Amdahl J. *Analytical and numerical analysis of sheet metal instability using a stress based criterion.* International Journal of Solids and Structures 45 (2008) 2042–2055.

Syntax:

```
"DCMS"  "RO" rho "YOUN" young "NU" nu "ELAS" elas
        "K" k "N" n "EPSY" epsy "GF" gf
        "IMES" imes "IDAM" idam
        /LECTURE/
```

`rho`

Density ρ. Typically in kg/m^3.

`young`

Young's modulus E. Typically in Pa.

`nu`

Poisson's coefficient ν. Dimensionless.

`elas`

Initial yield stress. Typically in Pa.

`k`

Power-law hardening coefficient.

`n`

Power-law hardening exponent.

`n`

Yield plateau strain.

`gf`

Fracture energy.

`imes`

Mesh scaling: 0 means no mesh scaling, 1 means mesh scaling.

`idam`

Damage coupling: 0 means no damage coupling, 1 means damage coupling.

`/LECT/`

List of the elements concerned.

Comments:

Blabla ...

Outputs:

The components of the ECR table are as follows (the name of the variable in the material routine is also given, whenever applicable):

ECR(1) : SIGH. Hydrostatic pressure.

ECR(2) : PHI. von Mises equivalent stress Φ.

ECR(3) : EPSP. Equivalent plastic strain ϵ_p.

ECR(4) : DAM. Damage D. The damage is limited to 0.95, that is $D = \min(0.95, 1 - ((P_u - \epsilon_p)/(P_u - P_c))$.

ECR(5) : TRIAX. Triaxiality τ.

ECR(6) : YF. Yield function Y_f.

ECR(7) : ITER. Number of iterations for plasticity N.

ECR(8) : ALFA. Alfa ratio $\alpha = s_2/s_1$ where s_1 is the maximum principal stress and s_2 the minimum principal stress.

ECR(9) : BETA. Beta coefficient $\beta = (2\alpha - 1)/(2 - \alpha)$.

ECR(10) : THICK. Element thickness t.

ECR(11) : SQRT(SAREA). Equivalent element length $L_e = \sqrt{A}$.

ECR(12) : THICK/SQRT(SAREA). Thickness/length ratio t/L_e.

ECR(13) : HSV(10). Integration point has reached BWH (Bressan, Williams, Hill) instability (0=no, 1=yes).

ECR(14) : PC. Plastic strain when BWH instability is reached P_c.

ECR(15) : PU. Plastic strain at element failure P_u.

ECR(16) : SIG1. First (maximum) principal stress s_1 of the plane stress state.

ECR(17) : SIG2. Second (minimum) principal stress s_2 of the plane stress state.

7.7.79 MOONEY-RIVLIN MATERIAL

Object:

This sub-directive defines a hyperelastic material of the Mooney-Rivlin type. An *incompressible* Mooney-Rivlin hyperelastic material is described by:

$$W = C_1(\overline{I}_1 - 3) + C_2(\overline{I}_2 - 3) \tag{51}$$

where W is the strain energy density function, C_1 and C_2 are empirically determined material constants and:

$$\overline{I}_1 = J^{-2/3} I_1 \qquad I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \tag{52}$$

$$\overline{I}_2 = J^{-4/3} I_2 \qquad I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2 \tag{53}$$

$$I_3 = J^2 = \lambda_1^2\lambda_2^2\lambda_3^2 \tag{54}$$

Here I_1 and I_2 are the first and second invariants of the unimodular component of the left Cauchy-Green deformation tensor and:

$$J = \det \underline{F} = \lambda_1\lambda_2\lambda_3 \tag{55}$$

with $\underline{F}$ the deformation gradient. For an incompressible material $J = 1$.

For a *compressible* Mooney-Rivlin material eq. (51) becomes:

$$W = C_1(\overline{I}_1 - 3) + C_2(\overline{I}_2 - 3) + K(\ln I_3)^2 \tag{56}$$

with K the bulk modulus and I_3 is the third invariant, given by eq. (54).

The material parameters C_1 and C_2 can be determined by EPX itself by a best fit procedure if a 1-D experimental stress-strain curve is available (see **Parameters Calibration mode** below).

The range of validity of this material model is as follows:

- 1 parameter (C_1) : $\epsilon < 30\%$ (Neo-Hookean).
- 2 parameters (C_1 and C_2) : $\epsilon < 100\%$.

Syntax:

Two input syntaxes are available. The first one is for the normal use of the material model, while the second one (introduced by the special keyword `PCAL`, for Parameters CALibration) is used to identify the material parameters.

```
"MOON" $ "RO" rho <"BULK" k> "C1" c1 "C2" c2 <"INIS" inis>
        <"GINF" ginf> <"G1" g1> <"TAU1" tau1> <"G2" g2"> <"TAU2" tau2>
                      <"G3" g3> <"TAU3" tau3> <"G4" g4"> <"TAU4" tau4>
                     <"G5" g5> <"TAU5" tau5> <"G6" g6"> <"TAU6" tau6>
        <"NFIB" nfib*(k1 k2)>
         /LECT/ ;
         "PCAL" npar <"BULK" k> "TRAC" npts * (strain stress)          $
```

Normal mode

`rho`

Density.

`k`

Compressibility coefficient. If omitted, the code takes $K = 0$ and an incompressible material is modelled.

`c1`

First coefficient of the potential C_1.

`c2`

Second coefficient of the potential C_2. If $C_2 = 0$, the model becomes a Neo-Hookean material.

`inis`

Initial stiffness (used to compute the sound speed in the material). If omitted, the code estimates it.

`ginf`

g_∞. Optional viscosity-related parameter.

`g1 ... g6`

$g_1 ... g_6$. Optional viscosity-related parameters.

`tau1 ... tau6`

$\tau_1 ... \tau_6$. Optional viscosity-related parameters.

`NFIB nfib`

Number of fibers to add anisotropy to the material. If present, this sub-directive must be the last one specified, i.e. just before the `/LECT/`.

`k1`

Parameter related to the anisotropy of the hyperelastic material. It accounts for the additional stiffness provided by the fibres. It has the dimension of a stress. It must be $K_1 > 0$.

`k2`

Parameter related to the anisotropy of the hyperelastic material. It contronls the non-linearity of the anisotropic response. This parameter is non-dimensional. It must be $K_2 \geq 0$.

`/LECT/`

List of the concerned elements.

Parameters Calibration mode

`PCAL npar`

Special keyword that activates the Parameters CALibration mode. If present, the `PCAL` keyword must immediately follow the `MOON` keyword. The `npar` value indicates the number of parameters that should be computed (which *must be* 2 for this material model).

`k`

Compressibility coefficient. If omitted, the code takes $K = 0$ and an incompressible material is modelled.

`TRAC`

Introduces the definition of the experimental traction curve. The number of points is `npts` and then exactly `npts` couples of values must be specified, which are interpreted as stress-strain pairs.

This mode is activated by the presence of the `PCAL` keyword immediately following the `MOON` keyword in the input data, as mentioned above. A best fit is performed in order to calculate the parameters. The traction curve data must be provided in engineering terms from a purely 1-D experiment (that is, lateral strains should *not* be restrained in the experiment.)

In this mode, the type and the number of elements is irrelevant since the material routine is called directly from the material reading procedure. Then the code computes the best fit and stops immediately. (However, note that at least one element must be defined in order to keep EPX happy.)

For this reason, the usual `/LECT/` at the end of the material directive is *not* included in this second syntax (since it would not be interpreted anyway.)

Outputs:

The components of the ECR table are as follows:

ECR(1): Pressure.

ECR(2): Von Mises Stress.

ECR(3): Normal transverse strain (shell elements) or tangential stiffness (solid elements).

ECR(4): Updated thickness (shell elements).

ECR(5): Initial thickness (shell elements) or initial volume (solid elements).

ECR(6): Energy potential.

ECR(7): Maximum time step for the element.

ECR(8-35): Unused.

7.7.80 OGDEN MATERIAL

Object:

This sub-directive defines a hyperelastic material of the Ogden type. The expression of the strain energy density is one of the following expressions:

$$\text{Type 1} \qquad W = \sum_{p=1}^{N} \frac{\mu_p}{\alpha_p} \left(\lambda_1^{*\alpha_p} + \lambda_2^{*\alpha_p} + \lambda_3^{*\alpha_p} - 3 \right) + K(J - 1 - \ln J) \tag{57}$$

$$\text{Type 2} \qquad W = \sum_{p=1}^{N} \frac{2\mu_p}{\alpha_p^2} \left(\lambda_1^{*\alpha_p} + \lambda_2^{*\alpha_p} + \lambda_3^{*\alpha_p} - 3 \right) + \frac{1}{2}K(J - 1)^2 \tag{58}$$

where $\lambda^* = \lambda J^{-\frac{1}{3}}$, K is the bulk modulus, μ_p and α_p are material parameters. The present implementation can go up to 4 terms ($N = 4$) plus the volumetric one if $K \neq 0$ in the expression of the potential W. At least the first term (α_1, μ_1) must be defined. The first form eq. (57) is the classical one, the second form eq. (58) is the one found in some codes, e.g. Abaqus.

The material parameters α_p and μ_p can be determined by EPX itself by a best fit procedure if a 1-D experimental stress-strain curve is available (see **Parameters Calibration mode** below).

Note that the range of validity of this material model is :

- $\epsilon < 700\%$ for third order.

Syntax:

Two input syntaxes are available. The first one is for the normal use of the material model, while the second one (introduced by the special keyword `PCAL`, for Parameters CALibration) is used to identify the material parameters.

Syntax

```
"OGDE" $ "RO" rho <"BULK" k>
                  "AL1" al1 <"AL2" al2> <"AL3" al3> <"AL4" al4>
                  "MU1" al1 <"MU2" al2> <"MU3" al3> <"MU4" al4>
                  <"INIS" inis> <"TYPE" type>
        <"GINF" ginf> <"G1" g1> <"TAU1" tau1> <"G2" g2"> <"TAU2" tau2>
                     <"G3" g3> <"TAU3" tau3> <"G4" g4"> <"TAU4" tau4>
                     <"G5" g5> <"TAU5" tau5> <"G6" g6"> <"TAU6" tau6>
        <"NFIB" nfib*(k1 k2)>
         /LECT/ ;
        "PCAL" npar <"BULK" k> "TRAC" npts * (strain stress)          $
```

Normal mode

`rho`

Density.

`k`

Compressibility coefficient. If omitted, the code takes $K = 0$ and an incompressible material is modelled.

`al1,al2,al3,al4`

Alpha coefficients of the potential (α_p). At least `al1` **must** be specified.

`mu1,mu2,mu3,mu4`

Mu coefficients of the potential (μ_p). At least `mu1` **must** be specified.

`inis`

Initial stiffness (used to compute the sound speed in the material). If omitted, the code estimates it.

`type`

Type of the formulation, i.e. either 1 for formula (57) or 2 for formula (58). If omitted, the code uses type 1, i.e. the classical formula.

`ginf`

g_∞. Optional viscosity-related parameter.

`g1 ... g6`

$g_1 ... g_6$. Optional viscosity-related parameters.

`tau1 ... tau6`

$\tau_1 ... \tau_6$. Optional viscosity-related parameters.

`NFIB nfib`

Number of fibers to add anisotropy to the material. If present, this sub-directive must be the last one specified, i.e. just before the `/LECT/`.

`k1`

Parameter related to the anisotropy of the hyperelastic material. It accounts for the additional stiffness provided by the fibres. It has the dimension of a stress. It must be $K_1 > 0$.

`k2`

Parameter related to the anisotropy of the hyperelastic material. It contronls the non-linearity of the anisotropic response. This parameter is non-dimensional. It must be $K_2 \geq 0$.

`/LECT/`

List of the concerned elements.

Parameters Calibration mode

`PCAL npar`

Special keyword that activates the Parameters CALibration mode. If present, the `PCAL` keyword must immediately follow the `OGDE` keyword. The `npar` value indicates the number of parameters that should be computed (which *must be* between 1 and 4 for this material model).

`k`

Compressibility coefficient. If omitted, the code takes $K = 0$ and an incompressible material is modelled.

`TRAC`

Introduces the definition of the experimental traction curve. The number of points is `npts` and then exactly `npts` couples of values must be specified, which are interpreted as stress-strain pairs.

This mode is activated by the presence of the `PCAL` keyword immediately following the `OGDE` keyword in the input data, as mentioned above. A best fit is performed in order to calculate the parameters. The traction curve data must be provided in engineering terms from a purely 1-D experiment (that is, lateral strains should *not* be restrained in the experiment.)

In this mode, the type and the number of elements is irrelevant since the material routine is called directly from the material reading procedure. Then the code computes the best fit and stops immediately. (However, note that at least one element must be defined in order to keep EPX happy.)

For this reason, the usual `/LECT/` at the end of the material directive is *not* included in this second syntax (since it would not be interpreted anyway.)

Outputs:

The components of the ECR table are as follows:

ecr(1) = Pressure

ecr(2) = Von misses stress

ecr(3) = Max principal Cauchy stress

ecr(4) = W (internal energy density)

ecr(5) = Von Mises natural strain

ecr(6) = Max principal natural strain

ecr(7) = Von Mises engineering strain

ecr(8) = Max principal engineering strain

ecr(9) = Max von mises stress historical

ecr(10) = Historical Max principal Cauchy stress

ecr(11) = Historical Max von Mises natural strain

ecr(12) = Historical Max principal natural strain

ecr(13) = Historical Max von Mises engineering strain

ecr(14) = Historical Max principal engineering strain

ecr(15) = Historical Max Pressure (traction)

ecr(16) = Historical Min Pressure (compression) ecr(17) = CSON0 (sound speed estimated by new method)

ecr(18) = CSON1 (sound speed estimated like for material HYPE TYPE 4) (the maximum between CSON0 and CSON1 is retained as speed of sound)

ecr(19) = Initial Volume (needed for the calculation of the internal energy)

ecr(20) = PI1. Pressure resulting from the Prony series (only when viscosity is enabled in the material model)

ecr(21:23) = LAMB(1:3) Principal stretches of the element

ecr(24:29) = Sich (1:6) (only when viscosity is enabled in the material model)

ecr(30:35) = Si1 (1:6) (only when viscosity is enabled in the material model)

7.7.81 BLATZ-KO MATERIAL

Object:

This sub-directive defines a hyperelastic material of the Blatz-Ko type. This material is still under development.

$$W = \frac{\mu\alpha}{2}\left[(I_1 - 3) + \beta(I_3^{-1/\beta} - 1)\right] + \frac{\mu(1-\alpha)}{2}\left[(\frac{I_2}{I_3} - 3) + \beta(I_3^{1/\beta} - 1)\right] \tag{59}$$

where W is the strain energy density function, $\alpha[0 \leq \alpha \leq 1]$ a material constant, $\beta = \frac{1-2\nu}{\nu}$ and being μ & ν the shear and the Poisson modulus respectively in small strains (in large strains it does not have physical sense).

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \tag{60}$$

$$I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2 \tag{61}$$

$$I_3 = J^2 = \left(\det \underline{F}\right)^2 = \lambda_1^2\lambda_2^2\lambda_3^2 \tag{62}$$

Here I_1, I_2 and I_3 are the first, second and third invariants of the unimodular component of the left Cauchy-Green deformation tensor, J the Jacobian with $\underline{F}$ the deformation gradient. For an incompressible material $J = 1$.

Note that for *incompressibility* ($J = I_3 = 1$) the Blatz-Ko material has n similar expression to the *Mooney-Riviln* material.

$$W = \frac{\mu\alpha}{2}(I_1 - 3) + \frac{\mu(1-\alpha)}{2}(I_2 - 3) \tag{63}$$

The material parameters C_1 and C_2 can be determined by EPX itself by a best fit procedure if a 1-D experimental stress-strain curve is available (see **Parameters Calibration mode** below).

The range of validity of this material model is as follows:

- 1 parameter (C_1) : $\epsilon < xx\%$ (Neo-Hookean).
- 2 parameters (C_1 and C_2) : $\epsilon < xx\%$.

Syntax:

Two input syntaxes are available. The first one is for the normal use of the material model, while the second one (introduced by the special keyword `PCAL`, for Parameters CALibration) is used to identify the material parameters.

```
"BLKO" $ "RO" rho <"ALPH" alpha> "NU" nu "MU" mu <"INIS" inis>
       <"GINF" ginf> <"G1" g1> <"TAU1" tau1> <"G2" g2"> <"TAU2" tau2>
                     <"G3" g3> <"TAU3" tau3> <"G4" g4"> <"TAU4" tau4>
                     <"G5" g5> <"TAU5" tau5> <"G6" g6"> <"TAU6" tau6>
       <"NFIB" nfib*(k1 k2)>
        /LECT/ ;
        "PCAL" npar <"NU" nu> "TRAC" npts * (strain stress)          $
```

Normal mode

`rho`

Density.

`alpha`

$\left[0 \leq \alpha \leq 1\right]$ Material constant

`nu`

For small strains, Poisson modulus (ν). For large strains does not have physical sense.

`mu`

For small strains, Shear modulus (μ). For large strains does not have physical sense.

`inis`

Initial stiffness (used to compute the sound speed in the material). If omitted, the code estimates it.

`ginf`

g_∞. Optional viscosity-related parameter.

`g1 ... g6`

$g_1 ... g_6$. Optional viscosity-related parameters.

`tau1 ... tau6`

$\tau_1 ... \tau_6$. Optional viscosity-related parameters.

`NFIB nfib`

Number of fibers to add anisotropy to the material. If present, this sub-directive must be the last one specified, i.e. just before the `/LECT/`.

`k1`

Parameter related to the anisotropy of the hyperelastic material. It accounts for the additional stiffness provided by the fibres. It has the dimension of a stress. It must be $K_1 > 0$.

`k2`

Parameter related to the anisotropy of the hyperelastic material. It contronls the non-linearity of the anisotropic response. This parameter is non-dimensional. It must be $K_2 \geq 0$.

`/LECT/`

List of the concerned elements.

Parameters Calibration mode

`PCAL npar`

Special keyword that activates the Parameters CALibration mode. If present, the `PCAL` keyword must immediately follow the `BLKO` keyword. The `npar` value indicates the number of parameters that should be computed (which *must be* 2 for this material model).

`k`

Compressibility coefficient. If omitted, the code takes $K = 0$ and an incompressible material is modelled.

`TRAC`

Introduces the definition of the experimental traction curve. The number of points is `npts` and then exactly `npts` couples of values must be specified, which are interpreted as stress-strain pairs.

This mode is activated by the presence of the `PCAL` keyword immediately following the `BLKO` keyword in the input data, as mentioned above. A best fit is performed in order to calculate the parameters. The traction curve data must be provided in engineering terms from a purely 1-D experiment (that is, lateral strains should *not* be restrained in the experiment.)

In this mode, the type and the number of elements is irrelevant since the material routine is called directly from the material reading procedure. Then the code computes the best fit and stops immediately. (However, note that at least one element must be defined in order to keep EPX happy.)

For this reason, the usual `/LECT/` at the end of the material directive is *not* included in this second syntax (since it would not be interpreted anyway.)

Outputs:

The components of the ECR table are as follows:

ECR(1): Pressure.

ECR(2): Von Mises Stress.

ECR(3): Normal transverse strain (shell elements) or tangential stiffness (solid elements).

ECR(4): Updated thickness (shell elements).

ECR(5): Initial thickness (shell elements) or initial volume (solid elements).

ECR(6): Energy potential.

ECR(7): Maximum time step for the element.

ECR(8-35): Unused.

7.8 FLUID MATERIALS

Object:

The following directives describe fluid materials for continuum elements.

Here are the different material types:

number	name	ref	law of behaviour
34	ADCR	7.8.19	homogeneous mixture with 3 components (1 liquid + 2 gases)
53	ADCJ	7.8.25	hypothetical core disruptive accident with law of type JWL for the bubble
57	BILL	7.8.26	specialised equation of state for the particle elements
59	BUBB	7.8.38	Balloon model for air blast simulations
68	CDEM	7.8.39	Discret Equation Method for Combustion
51	CHOC	7.8.22	Shock waves, Rankine-Hugoniot equation
110	DEMS	7.8.40	Discret Equation Method for Two Phase Stiffenened Gases
22	EAU	7.8.9	two-phase water (liquid + vapour)
49	EXVL	7.8.20	hydrogen explosion Van Leer
27	FLFA	7.8.15	rigid tube bundles (homogeneous acoustic model)
86	FLMP	7.8.35	Fluid multi-phase
7	FLUI	7.8.2	isothermal fluid (c = cte)
36	FLUT	7.8.30	fluid, to be specified by the user
73	GAZD	7.8.41	Detonation in gas Mixture
9	GAZP	7.8.4	perfect gas
118	GGAS	7.8.1	generic ideal gas material
52	GPDI	7.8.23	diffusive perfect gas Van Leer
48	GVDW	7.8.28	Van Der Waals gas
40	GZPV	7.8.24	perfect gas for Van Leer
28	HELI	7.8.10	helium
50	JWL	7.8.21	explosion (Jones-Wilkins-Lee model)
66	JWLS	7.8.29	Explosion (Jones-Wilkins-Lee for solids)
23	LIQU	7.8.14	incompressible (or quasi-) fluid
82	MCFF	7.8.34	multicomponent fluid material (far-field)
81	MCGP	7.8.33	multicomponent fluid material (perfect gas)
33	MHOM	7.8.16	pipe bundle (homogeneous asymptotic model)
25	MULT	7.8.13	multiple materials (coupled monodim.)
10	NAH2	7.8.7	sodium-water reaction (1 liquid and 1 gas)
56	PARO	7.8.11	friction and heat exchange for pipeline walls
39	PUFF	7.8.17	equation of state of type "PUFF"
54	RSEA	7.9.13	sodium-water reaction (1 liquid and 2 gases)
103	SG2P	7.8.36	Multicomponent Stiffened Gases - Conservative formulation
104	SGMP	7.8.37	Multicomponent Stiffened Gases models
24	SOUR	7.8.6	imposed time-dependent internal pressure
102	STIF	7.8.5	Stiffened Gas
101	TAIT	7.8.3	Tait Equation of State

Comments:

These materials are detailed in the following pages.

All pressures given as parameters are absolute pressures that must account for the external pressure. If one wants to avoid an unwanted transient expansion, it is necessary to specify the reference pressure "PREF", which must be the same for all fluid materials in a calculation.

For example, for a reservoir filled with gas at the relative pressure of 10 MPa (Pint - Pext = 10 MPa), it is necessary to specify an internal pressure of 10.1 MPa if the atmospheric pressure is 0.1 MPa. Then, two cases are possible:

1) The reservoir is initially in equilibrium:

The calculation aims at simulating the response of the reservoir to an overpressure which appears later on (shock, explosion, imposed velocity ...). The reference pressure must then be: pref = 10.1 MPa, so that the reservoir remains initially in equilibrium.

2) The reservoir is not initially in equilibrium:

The calculation aims at simulating the response of the reservoir to an an internal pressure which appears abruptly. The reference pressure must then be: pref = 0.1 MPa, so that the final status be correct.

7.8.1 GENERIC IDEAL GAS

Object:

Perfect gas ($P = \rho(\gamma - 1)E_{\text{internal}}$)

This option enables materials with a ideal gas behaviour to be used. It is an interface to convert the input to the appropriate material (GAZP 7.8.4, FLUT 7.8.30) for the elements used.

Syntax:

```
"GGAS" ![ "RO"  rho  "GAMMA"  gamma  ["PINI"  pini | "EINI" eini]
       ...  < "PREF"  pref > ]!  /LECTURE/
```

`rho`

Initial density.

`gamma`

Ratio c_P/c_V (supposed constant).

`pini`

Initial pressure.

`pref`

Reference pressure. Note that, by default, it is assumed `pref = pini` for CEA elements (GAZP) and pref=0 for JRC elements (FLUT).

`/LECTURE/`

List of the elements concerned.

Outputs:

The output variables are according to the material in which the generic material is converted.

7.8.2 FLUID

Object:

This option enables a fluid (liquid-like) behaviour for continuum elements to be input. The fluid (isothermal) can be perfect (no viscosity) or viscous.

The expression used to compute the absolute pressure p in the fluid is:

$$p = p_{\mathrm{ini}} + (\rho - \rho_{\mathrm{ini}})c^2$$

where p_{ini} is the fluid pressure in the initial state, ρ is the current density, ρ_{ini} is the initial density and c is the sound speed, which is considered constant.

By default the fluid is considered "free" (i.e. fluid alone, keyword `LIBR`). However, it is also possible to take into account the volume occupied by some fixed internal structures (which are not meshed) by specifying the optional keyword `POREUX`. Such a "porosity" may be specified either in 2D or in 3D, but only for the elements of type CAR1, CUBE and PRIS.

Syntax:

```
For a "free" fluid (no internal structures) :
-------------------------------------------

"FLUID"  < "LIBR" >   "RO" rho   "C" c   <"PINI" pini>    ...
    ...  <"PREF" pref >   <"PMIN" pmin >   <"VISC"  mu  >  ...
    ...  /LECTURE/

For a "porous" fluid (with internal structures) :
-----------------------------------------------

"FLUID"  "PORE"   "RO" rho   "C" c   <"PINI" pini>    ...
  ...  <"PREF" pref >   <"PMIN" pmin >   <"VISC"  mu  >  ...
  ...  "PORO" alpha   < "SMOU" sur >   < "BETA" beta >  ...
  ...   $ "KPER" kp ; "KPX" kpx  "KPY" kpy  < "KPZ" kpz > $ ...
  ...  /LECTURE/
```

`"LIBR"`

The fluid is "free", i.e. without internal structures. This is the default option.

`"PORE"`

The fluid is "porous", i.e. it occupies just one part of the meshed volume, the rest being occupied by some fixed internal structures.

`rho`

Initial density ρ_{ini} of the fluid.

`c`

Sound speed c in the fluid, considered constant.

`pini`

Absolute initial pressure p_{ini} in the fluid. By default, $p_{\text{ini}} = 0$.

`pref`

Absolute reference pressure p_{ref} in the fluid. By default, $p_{\text{ref}} = p_{\text{ini}}$ (even when $p_{\text{ini}} = 0$).

`pmin`

Absolute minimum pressure p_{min} in the fluid. By default, $p_{\text{min}} = 0$. Obviously, it must be $p_{\text{min}} \leq p_{\text{ini}}$. The minimum density ρ_{min} results then from the expression:

$$\rho_{\text{min}} = \rho_{\text{ini}} + \frac{p_{\text{min}} - p_{\text{ini}}}{c^2}$$

`mu`

Dynamic viscosity coefficient μ (2D or 3D).

`alpha`

Value of the porosity: ratio of the volume occupied by the fluid with respect to the total volume.

`sur`

Relative wet surface (value 1 by default).

`kp`

Head loss coefficient by unit length, assumed isotropic.

`kpx, kpy, kpz`

Head loss coefficient by unit length in the direction Ox (respectively Oy, Oz).

`beta`

Reduced damping coefficient for high frequencies. It is zero by default, and should always be very small.

`/LECTURE/`

List of the elements concerned.

Comments:

The parameters `RO` and `C` are compulsory.

Role of PREF:

When the reference pressure is different from the initial one, the fluid is not in equilibrium at the beginning. This is the case e.g. when a membrane is breaking at $t = 0$, releasing a compressed fluid. For further detail, see page C.300.

In various problems, studies relate to acoustic effects; since it is supposed that a fluid in equilibrium evolves under the effects of loading (motion of a piston, shock,...), in this case it must be: $p_{\text{ref}} = p_{\text{ini}}$.

If `PREF` is omitted, EUROPLEXUS considers that the fluid is in equilibrium and $p_{\text{ref}} = p_{\text{ini}}$ (even when $p_{\text{ini}} = 0$).

For a given minimum pressure p_{min}, the fluid pressure is always greater than or equal to that value, even if the density is decreasing. This is a very simple way to model cavitation. The default value of p_{min} is $p_{\text{min}} = 0$.

Viscosity:

In the presence of viscosity, the tensor of stresses in the fluid has the following form:

$$\sigma(i,j) = -P\,\delta(i,j) + 2\mu\,\dot{\epsilon}(i,j)$$

with:

P : pressure

$\delta(i,j)$: Kronecker's symbol

$\dot{\epsilon}(i,j)$: strain rate (derived from $\epsilon(i,j)$)

For water at 20 degrees Celsius: $\mu = 0.001$ SI units (Kg/(m*s)).

Porous fluid:

If the fluid is porous, the parameter `PORO` is mandatory. In this case an equivalent fluid is used by the code for the calculations, which occupies the entire volume of the element. However, the used variables (pressure, velocity, etc.) are those of the REAL fluid, so as to obtain directly the physical state of the fluid in the presence of internal structures.

If these internal structures generate a head loss, the parameter `kp` allows to model it in case this loss is isotropic. Otherwise, the parameters `kpx, kpy, kpz` allow to distinguish between the three directions in the global reference.

The former coefficients are given per unit length. For example, if the head loss is $\Delta P = 0.25$ bar over a length of $L = 2$ m, for a fluid of density $\rho = 1000\ kgm^{-3}$ with a velocity $V = 5\ ms^{-1}$, the coefficient will be $K_p = 1$ according to the formula:

$$\Delta P = \frac{1}{2} K_p\ L\ \rho V^2$$

The parameter `SMOU` (relative wet surface) is obsolete and may be omitted. It is only kept for compatibility with old input files.

Correlation between bulk modulus and sound speed:

This material model can be compared to that of a fluid with constant bulk modulus (e.g. the `FLUT` material with `NUM` 9) as follows. For the latter, the absolute pressure is given by:

$$p = p_{\text{ini}} + B\eta$$

where B is the bulk modulus (assumed constant and usually expressed in Pa) and η is the relative volume variation:

$$\eta = -\epsilon_V = \frac{V - V_{\text{ini}}}{V_{\text{ini}}} = 1 - \frac{\rho_{\text{ini}}}{\rho}$$

From these expressions one obtains:

$$p = p_{\text{ini}} + (\rho - \rho_{\text{ini}})\frac{B}{\rho}$$

By comparing this with the pressure expression of the FLUI material, one sees that:

$$c = \sqrt{\frac{B}{\rho}}$$

Therefore, strictly speaking the two models are different because in one the sound speed is assumed constant (so that the bulk modulus varies with the density) while in the other the bulk modulus is assumed constant (so that the sound speed varies with the density). However, by assuming that the density varies only slightly from the initial value ρ_{ini}, one obtains the following relation between c and B:

$$c \approx \sqrt{\frac{B}{\rho_{\text{ini}}}}$$

Outputs:

The components of the ECR table are as follows:

ECR(1): absolute pressure

ECR(2): density

Reference:

CEA report to appear.

7.8.3 TAIT EoS

Object:

This option enables a barotropic fluid (liquid-like) behaviour for continuum elements to be input. The Tait Equation of State (EoS) can be used to model liquids and is frequently used to model water in underwater-explosion simulations. For water, classical constants are: $\gamma = 7.15$ and $b = 331 MPa$.

The expression used to compute the absolute pressure P in the fluid is:

$$P = B\left(\left(\frac{\rho}{\rho_{\text{ref}}}\right)^{\gamma} - 1\right)$$

where P is the fluid pressure, ρ is the current density and ρ_{ref} is the reference density.

Syntax:

```
"TAIT"    "RO" rho   "PINI" pini <"PREF" pref >   <"PMIN" pmin >
   ...    "GAMM" gamma   "B" b
   ...    /LECTURE/
```

`rho`

Reference density ρ_{ref} of the fluid.

`pini`

Absolute initial pressure p_{ini} in the fluid.

`pref`

Absolute reference pressure p_{ref} in the fluid. By default, $p_{\text{ref}} = p_{\text{ini}}$.

`pmin`

Absolute minimum pressure p_{min} in the fluid. By default, $p_{\text{min}} = 0$. Obviously, it must be $p_{\text{min}} \leq p_{\text{ini}}$. The minimum density ρ_{min} results then from the expression:

$$\rho_{\text{min}} = \rho_{\text{ref}}\left(\frac{p_{\text{min}}}{B} + 1\right)^{\frac{1}{\gamma}}$$

`gamma`

first coefficient of the TAIT EoS.

`b`

second coefficient of the TAIT EoS.

`/LECTURE/`

List of the elements concerned.

Comments:

For the TAIT EoS, the initial density ρ_{ini} is computed from the expression:

$$\rho_{\text{ini}} = \rho_{\text{ref}} \left(\frac{p_{\text{ini}}}{B} + 1 \right)^{\frac{1}{\gamma}}$$

with:

p_{ini} : initial pressure, ρ_{ref} : reference density

The expression used for the sound speed is:

$$C = \sqrt{\frac{\gamma(P + B)}{\rho}}$$

Role of PREF:

When the reference pressure is different from the initial one, the fluid is not in equilibrium at the beginning. This is the case e.g. when a membrane is breaking at $t = 0$, releasing a compressed fluid. For further detail, see page C.300.

In various problems, studies relate to acoustic effects; since it is supposed that a fluid in equilibrium evolves under the effects of loading (motion of a piston, shock,...), in this case it must be: $p_{\text{ref}} = p_{\text{ini}}$.

If `PREF` is omitted, EUROPLEXUS considers that the fluid is in equilibrium and $p_{\text{ref}} = p_{\text{ini}}$.

For a given minimum pressure p_{min}, the fluid pressure is always greater than or equal to that value, even if the density is decreasing. This is a very simple way to model cavitation. The default value of p_{min} is $p_{\text{min}} = 0$.

Outputs:

The components of the ECR table are as follows:

ECR(1): absolute pressure

ECR(2): current density

ECR(3): sound speed

7.8.4 PERFECT GAS

Object:

Euler : perfect gas ($P = \rho(\gamma - 1)E_{\text{internal}}$);

Lagrange: adiabatic perfect gas ($P = k\rho^{\gamma}$).

In a 1-D case, the frictions against the walls can be taken into account, since the dissipated energy will heat up the gas (modification of the internal energy). To this end the user has to add a PARO material, which must be associated with GAZP by means of the MULT material (see pages C.370 and C.380).

Syntax:

```
"GAZP" ![ "RO"  rho  "GAMMA"  gamma  "PINI"  pini  <"VISC" mu > ...
       ... < "CV"  cv >   < "PREF"  pref > ]!  /LECTURE/
```

`rho`

Initial density.

`gamma`

Ratio c_P/c_V (supposed constant).

`pini`

Initial pressure.

`mu`

Dynamic viscosity of the gas (for 2-D and 3-D).

`cv`

Specific heat at constant volume c_V (used to compute the temperature).

`pref`

Reference pressure. Note that, by default, it is assumed `pref = pini`.

`/LECTURE/`

List of the elements concerned.

Comments:

The reference pressure pref enables the initial state to be defined. If `pref = pini`, the gas is in equilibrium just before the computation starts; it will be perturbated by an external action, by the motion of a piston, for instance. If `pref = 0`, the problem consist in a computation with initial stresses determined by `pini`. This is the case when a membrane which was seperating two gases at different states disappears at the initial instant.

If `cv` is omitted, the temperature is not computed. If it is present, the temperature is expressed in degrees Celsius.

Outputs:

The different components of the ECR table are as follows:

ECR(1): pressure

ECR(2): density

ECR(3): velocity of sound

ECR(4): maximum pressure ever experienced

ECR(5): minimum pressure ever experienced

ECR(6): dynamic pressure: ($P_{\mathrm{dyn}} = \frac{1}{2}\rho\, v^2$)

ECR(7): temperature (if c_V is not zero) in degrees Celsius

ECR(8): total specific energy ($E = h + \frac{1}{2}v^2$)

7.8.5 STIFFENED GAS

Object:

This Equation of State can be used for both liquids and gases. It takes the following form:

$$P = (\gamma - 1)\rho(e - q) - \gamma P_{inf}$$

Where e is the internal energy per unit mass, ρ the density. γ is an empirical constant for liquids. P_{inf} is a constant representing the molecular attraction between molecules (liquid) and q is an additional constant. This expression is identical to the ideal gas EoS when P_{inf} and q is zero.

Syntax:

```
"STIF" "RO"  rho  "PINI"  pini  < "PMIN"  pmin >   < "PREF"  pref >
       ...  "GAMMA"  gamma  "PI" pinf  "Q" q
       ...  <"QSRC" qsrc> <"SOUR" sour>
       ...   /LECTURE/
```

`rho`

Initial density.

`pini`

Initial initial pressure.

`pref`

Reference pressure. Note that, by default, it is assumed `pref = pini`.

`pmin`

Absolute minimum pressure `pmin` in the fluid. Note that, by default, it is assumed `pmin = 0`.

`gamma`

Ratio c_P/c_V (supposed constant) for gases and an empirical constant for liquid.

`pinf`

Constant parameter for liquid to take into account molecular attraction between molecules.

`q`

Internal energy of the fluid at a given reference state (most time one take `q = 0`).

`qsrc`

Value of an optional constant energy source term. This value is set in ECR(8) and taken into account only if `sour` is not null.

`sour`

Option for accounting for an energy source term.

`/LECTURE/`

List of the elements concerned.

Comments:

The reference pressure pref enables the initial state to be defined. If `pref = pini`, the gas is in equilibrium just before the computation starts; it will be perturbated by an external action, by the motion of a piston, for instance. If `pref = 0`, the problem consist in a computation with initial stresses determined by `pini`. This is the case when a membrane which was seperating two gases at different states disappears at the initial instant.

The expression used for the sound speed is:

$$C = \sqrt{\frac{\gamma(P + P_{inf})}{\rho}}$$

Outputs:

The different components of the ECR table are as follows:

ECR(1): pressure

ECR(2): density

ECR(3): sound speed

ECR(4) : total energy

ECR(5) : internal energy

ECR(8): energy source term

7.8.6 SOURCE

Object :

This instruction enables a time dependent pressure to be imposed, inside an element.

For fluids modelled in ALE, this material allows to create a source of mass flow, if it is used in conjunction with an imposed velocity directive. However, this source is limited to the case of a liquid (case "FLUI"), of a perfect gas ("GAZP"), of a two-phase mixture of water ("EAU") or of a liquid-gas mixture ("ADCR").

Syntax:

```
"SOUR"   $ "FLUI" ... ; "GAZP" ... ; "EAU" ... ; "ADCR" ... $

   ...  < "FONC" nufo  < "FACT" coef > >  /LECTURE/
```

`FLUI, GAZP, EAU, ADCR`

This keyword indicates the source material data which are strictly identical to those of the material with the same name.

For "FLUI" see 7.8.2 page C.305, for "GAZP" see 7.8.4 page C.310, for "EAU" see 7.8.9 page C.350, for "ADCR" see 7.8.19 page C.430,

`nufo`

Number of the 'FONCTION' allowing to define the pressure as a function of time

`coef`

Multiplying factor for the pressures given by the preceding function. By default coef=1.

`LECTURE`

List of the concerned elements.

Comments:

The "FONCTION" directive is described in 9.1 (page E.15).

The initial pressure, must correspond to the origin of the curve.

The element deforms only under the action of forces due to the imposed pressure (no stiffness). The temperature is assumed constant. In the case of water, for example, if the pressure increases one can pass from a liquid phase to a vapor phase, but always at the same temperature.

Outputs:

The different components of the ECR table are the same as the components for the material with the same name.

7.8.7 SODIUM-WATER REACTION ("NAH2")

Object:

Explosion caused by water injection into liquid sodium.

In 2D or 3D, one element or more (contiguous) elements may be affected by the chemical reaction. In 1D, just one "TUBE" or "TUYA" element must be used with this material.

In 1D or 3D there are two options for the water mass flow rate:

1) imposed curve as a function of time (keyword "DEBIT")

2) calculation of a water-filled pipeline meshed by elements of type TUBE or TUYA and coupling with the sodium mesh (keyword "DCOUP").

Syntax:

```
"NAH2"  "RO" rho  "C" c  "PINI" pinit   "PV" pv   "FACT" facteur
 ... < "PREF" pref > < "PMIN" pmin > < "CMIN" cmin > < "CH2" ch2 >
 ...$[ "DEBIT"  npt*(temps , debit) ;
       "DCOUP"   1     tini    qini ]$/LECTURE/
```

`rho`

Initial density (pure sodium).

`c`

Sound speed in the sodium.

`pinit`

Initial pressure.

`pref`

Reference pressure (see page C.300).

`pv`

Value of the product P*V for the unit mass of hydrogen at the initial temperature.

`facteur`

Number of gas moles formed starting from one mole of injected water.

`ch2`

Initial mass fraction for the hydrogen. By default, ch2 = 0 and as a maximum ch2 = 1.

`cmin`

Minimum mass fraction of the hydrogen in the pure sodium (1.E-8 by default).

`pmin`

Minimum pressure (zero by default).

`"DEBIT"`

Keyword that announces the introduction of the curve of total mass flow rate of water injected in the sodium for the whole set of elements concerned.

`npt`

Number of points defining the mass flow rate curve for the water.

`(temps, débit)`

Coordinates of the points (in axisymmetric, divide the mass flow rate by 2π, as the calculation refers to one radian).

`"DCOUP"`

The water mass flow rate at the outlet of a pipe is computed (1D) by directive "IMPE" "NAH2" (page C.610).

`tini`

Initial time.

`qini`

Initial mass flow rate.

`/LECTURE/`

List of the elements affected by the injection.

Comments:

For the dimensioning, an injection curve requires a space similar to that of a traction curve. The user will therefore have to specify "TRAC" n1 n2, with n1 the maximum number of curves to be entered (traction and injection), and n2 the maximum number of points.

In the elements affected by the reaction, it is assumed that the reaction is instantaneous, that the mixture of reacting components is always homogeneous and that the reaction is isothermal.

The "facteur" parameter allows to account for the vaporised 'soude'. If there is none, then facteur = 0.5.

If the volume fraction of hydrogen (printed as ECR(4)) is above 1, the program treats the mixture like pure hydrogen.

In a Lagrangian calculation (default option) the "NAH2" material is attached only to the elements where the reaction takes place. The "FLUI" material is used for the other elements.

In an Eulerian calculation (option "EULER" page A.30), the material "NAH2" is affected to ALL fluid elements. The mass flow rate curve for the water is only affected to the elements where the reaction occurs, for the others one must write:

```
"DEBIT"  0  /LECTURE/
```

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure
ECR(2) : density
ECR(3) : hydrogen concentration
ECR(4) : hydrogen volume occupation ratio
ECR(5) : total water mass flow rate for the set of elements
ECR(6) : water mass injected in each element
ECR(7) : sound speed in the Na+H2O mixture
ECR(8) : hydrogen mass per unit volume (in Eulerian)
ECR(10): phase indicator (1= saturated in H2; else 0)

7.8.8 SODIUM-WATER REACTION ("RSEA")

Object:

Explosion caused by water injection into liquid sodium.

It is possible to repeat this material as many times as needed, provided the injections occur in different elements.

There are two possibilities concerning the water mass flow rate:

1) a time function is invoked (keyword "NUFO")

2) compute a water-filled pipeline meshed with TUBE or TUYA elements and coupled with the sodium mesh (keyword DCOU).

Syntax:

```
"RSEA"  "PTOT" ptot   "PNA" pna     "RONA" rhona  "CSNA" csona
        "PBU"  pbu    "ROBU" rhobu  "NBU"  nbu    "GBU" gbu
      < "PARG" parg   "ROAR" rhoar  "GAR" gar >
      < "PSAT" psat   "ROSA" rhovap >
      < "XBU"  xbu  >  < "XAR"  xar  >  < "PREF" pref >
      < "CMIN" cmin >  < "BETA" beta >
      < "VINA" vina >  < "VIBU" vibu >  < "VIAR" viar >
      < $[ "NUFO" nufo  "COEF" coef  ;  "DCOU"   1  ]$ >
      < "FACT" facteur >
          /LECTURE/
```

`ptot`

Total pressure of the mixture.

`pna`

Zero pressure of sodium, defining the equation of state of the liquid, by means of the following rhona and csona parameters.

`rhona`

Zero density of sodium.

`csona`

Sound speed in the sodium.

`pbu`

Zero pressure of the hydrogen, defining the equation of state of the gas, by means of the following rhobu and nbu parameters.

`rhobu`

Zero density of the hydrogen.

`nbu`

Polytropic coefficient of the transformation followed by the hydrogen. For an isotermal: nbu = 1.

`gbu`

Ratio Cp/Cv for the hydrogen.

`parg`

Zero pressure of the argon, defining the equation of state of this gas, by means of the following rhoar and gar parameters.

`rhoar`

Zero density for the argon.

`gar`

Ratio Cp/Cv for the argon.

`psat`

Saturation pressure of the sodium vapor. A priori this is very low, and allows to treat correctly the possible cavitation phenomena.

`rhovap`

Density of the sodium vapor.

`xbu`

Initial mass fraction of the hydrogen. It allows to account for the presence of gas in the considered domain.

`xar`

Initial mass fraction of the argon. This refers to the subdomains that are filled with argon initially, such as the cover gas region or the zones located behind membranes.

`pref`

Reference pressure (see page C.300).

`cmin`

Maximum mass fraction of gas in the sodium in order to consider it as pure (1.E-8 by default).

`vina`

Dynamic viscosity of sodium.

`vibu`

Dynamic viscosity of the gas in the bubble.

`viar`

Dynamic viscosity of argon.

`beta`

Reduced damping coefficient for high frequencies. It is zero by default, and should always be very small (< 0.05).

`nufo`

Number of the adimensional function defined via the "FONCTION" directive of EUROPLEXUS. This function allows to describe the variation of injected water mass flow rate in time.

`coef`

Multiplicative factor por the precediing function. This allows to account for the units and the number of ruptured pipes.

`DCOU`

This keyword specifies that a coupled water flow calculation is desired. It is always followed by an integer value.

`facteur`

Number of gas moles formed by one mole of injected water.

`/LECTURE/`

List of the concerned elements.

Comments:

In the elements affected by the reaction, it is assumed that the reaction is instantaneous, and that the mixture of reacting materials is always homogeneous.

The "facteur" parameter allows to account for the vapor 'soude'. If there is none, then facteur = 0.5.

The mesh will be subdivided in as many zones as necessary, and for each of these an RSEA material will be defined, by possibly varying the initial concentrations and the total pressures, but the other parameters must be identical, so as to have exactly the same constitutive laws for the different components of each zone. Then, starting from the given concentration and the total pressure ptot, EUROPLEXUS will compute de density of the mixture. EUROPLEXUS will also recompute the gas concentrations in order to account for the sodium vapor, if psat is not zero.

The elements where the reaction occurs will be distinguished by one of two possible options: imposed injection or injection coupled with the calculation of water mass flow rate (DCOU).

If `psat` and `rhovap` are absent, or if one only of these values is given, it is the default value which is used: `psat` is taken equal to one thousandth of `ptot`. The value of `rhovap` is then proportional to `psat`, and corresponds to a monoatomic vapor at a temperature close to 300^oC.

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure,

ECR(2) : density of the two-phase mixture,

ECR(3) : sound speed in the mixture,

ECR(4) : void fraction,

ECR(5) : argon mass fraction,

ECR(6) : hydrogen mass fraction,

ECR(13) : water mass flow rate (dm/dt)

ECR(14) : mass of water injected since the beginning.

7.8.9 WATER

Object :

This directive allows to treat water and its vapour as an homogeneous mixture. It is also possible to treat a water vapor explosion when energy is released within liquid water.

Syntax :

```
 "EAU"   $[ "EQUI"                              ;
            "META"  "NBUL" nbul  "ALFN" alfn ]$   ...

    ...  "PINI"  pini   |[ "TINI" tini ; "TITR" x ]| ...
    ...  < "PREF" pref > < "BETA"  beta > ...
    ...  < "VISL"  mul   "VISV" muv   >   ...
    ...  <  "BETD" betd > ...

 For a direct injection:

      $ < "ENMA" enma    "FONC" numf    ...
        ...  < "XCOR" xcor >  < "MODE" mode ; "COEF" coef >  > $
        ...  < "DPROP" dpropag   "ORIGINE"   /LECTURE/       > $

 For an injection of corium particles:

    ...$ < "DIAM" diam    "CECH"  hh     ...
             ...   "TCOR" tcor   "VCOR" vcor   > $

 One ends this directive by:

    .../LECTURE/
```

`EQUI`

The mixture will be in equilibrium (same pressure and same temperature for the liquid and vapour phases).

`META`

The mixture will be metastable (same pressure but different temperatures for the liquid and vapour phases).

`nbul`

Number of vapour bubbles by unit volume (of the order of 1.E9).

`alfn`

Minimal void fraction for the nucleation of vapor bubbles (of the order of 1.E-4).

`pini`

Initial pressure of the mixture.

`tini`

Initial temperature of the equilibrium mixture (in degrees Celsius).

`x`

Initial mass title of the vapor, between 0 and 1. (eau=0, vapeur=1).

`pref`

Reference pressure (for its meaning see page C.300). By default, it is equal to the initial pressure. All reference pressures must be equal.

`beta`

Reduced damping coefficient for high frequencies. It is zero by default, and should always be very small (< 0.05).

`mul`

Dynamic viscosity of the water. Recall: below 1 bar, at 25^oC, mul = 9.E-4 Poiseuille or Pascal * second. This value drops rapidly as the temperature increases. By default mul = 0.

`muv`

Dynamic viscosity of the water vapor. Recall: below 1 bar, at 100^oC, muv = 1.3E-5 Poiseuille. This value increases with the temperature. By default, muv = 0.

`betd`

If equal to 1, the beta coefficient multiply the trace of the stress Matrix. If not equal to 1, the beta coefficient multiplied the the first value of the stress Matrix. By default, betd = 0.

For a direct injection of energy in the water:

`enma`

Specific power injected in the water. Multiplicative coefficient (dimensional) of the following function.

`numf`

Number of the non-dimensional function defined by the "FONCTION" directive of EUROPLEXUS. This function allows to vary the injected power in time.

`xcor`

Ratio betweeen the corium mass and the water mass contained within the element. The specific power (enma) applies only to the present corium. By default, xcor = 1.

`mode`

Choice of the injection mode: (0, 1, 2 or 3). The meaning is explained in the comments below. By default, mode = 0.

`coef`

Ratio between the limit density and the initial density. This allows to limit the injection. By default, coef = 0. Is only relevant for mode = 0 or 1.

`dpropag`

Propagation velocity of the energy injection signal for the elements of the considered domain. By default, the injection occurs simultaneously in all such elements.

`ORIGINE`

This keyword announces the reading of the element in which the injection is initiated. The injection then propagates with the speed dpropag in all directions.

For an injection by means of corium particles:

`diam`

Diameter of the particles.

`hh`

Heat exchange coefficient between a corium particle and the liquid water.

`tcor`

Initial temperature of the corium particles.

`vcor`

Volume fraction occupied by the corium.

`LECTURE`

List of the concerned elements.

Comments :

Do not forget to create the tables of physical properties of the water by means of directive "TEAU" or "TH2O" (page C.74).

The "TH2O" table is only working with equilibrated water.

If the mixture is single-phase, one should give the pressure and the temperature, but the title is irrelevant. If the mixture is two-phase, one should give the pressure and the title: EUROPLEXUS then computes the temperature.

The damping coefficient beta allows to damp out high-frequency oscillations caused by the discretisation. By default beta is zero. However, it is advised to use beta between 0.1% et 5%. One should be aware of the inevitable attenuations of lower frequencies, especially if the mesh is coarse. In fact, the eigenfrequencies of the structure are not very different from the frequencies associated with the finite elements.

If the viscosity has to be considered, the two parameters mul and muv must be related and given together.

Energy injection:

The "MODE" parameter allows to account for the evolution of fluid close to the injection zone, in a less brutal fashion compared with directive "COEF". Its meaning is as follows:

mode = 0 : the injected energy i s independent from the fluid mass and nature,

mode = 1 : the injected energy is proportional to the mass of water, but independent from its nature of liquid or vapor,

mode = 2 : the injected energy is proportional to the mass of liquid water,

mode = 3 : the injected energy is proportional to the volume of liquid water.

Modes 2 and 3 should not be used if the pressure exceeds the critical value (Pcrit = 221 bar).

The "COEF" directive allows to limit the quantity of injected energy: if the density during the computation becomes lower than the limit density, then the injection is stopped. This directive is brutal and not advisable. It is preferable to use the "MODE" directive.

One may obtain the energy quantity released in a certain region of the mesh by means of keyword "WINJ" in directive "REGION" (page G.100).

By assigning a propagation velocity associated with an origin element allows to avoid a brutal and instantaneous injection over an extensive domain, which is irrealistic: this option is recommended in case of a steam explosion calculation.

Initial pressure and temperature:

Initial pressure and temperature can be take in account with INIT MEDL VCVI ECRO option. The input MED file must contain fluid velocity and internal variables fields. The pressure must be the first component and the temperature must be the fifth of the internal variables field.

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure

ECR(2) : density of the mixture

ECR(3) : sound speed

ECR(4) : mass title of the vapor (vapor mass/total mass)

ECR(5) : temperature of the mixture for equilibrated water, liquid temperature for meta-stable

ECR(6) : enthalpy of the mixture

ECR(7) : temperature of the mixture for equilibrated water, vapor temperature for meta-stable

ECR(9) : void ratio or volume ratio of the vapor (vapor volume/total volume)

For meta-stable water:

ECR(21) : vapor relative density (vapor mass/total volume)

ECR(23) : index : 0 = equilibrium ; 1 = meta-stable

ECR(24) : specific enthalpy of the liquid water

In case of direct energy injection:

ECR(8) : power injected in the element

ECR(14) : corium mass within the element

In case of energy injection by particles:

ECR(19) : initial volume of corium within the element

ECR(20) : mean temperature of a corium particle

For a "BREC" element:

ECR(25) : Pipeline rupture area

ECR(26) : Mass flow

ECR(27) : Total ejected mass

7.8.10 HELIUM

Object :

This directive allows to treat helium and its liquid as an homogeneous mixture.

Syntax :

```
"HELI"   "PINI"  pini   |[ "TINI" tini ; "TITR" x ]| ...
      ...  < "PREF" pref > < "BETA"  beta >        ...
      ...  < "VISL"  mul   "VISV" muv   >          ...
      ...   /LECTURE/
```

`pini`

Initial pressure of the mixture.

`tini`

Initial temperature of the equilibrium mixture (in degrees Kelvin).

`x`

Initial mass title of the vapour, between 0 and 1. (liquid=0, vapour=1).

`pref`

Reference pressure (for its meaning see page C.300). By default, it is equal to the initial pressure. All reference pressures must be equal.

`beta`

Reduced damping coefficient for high frequencies. It is zero by default, and should always be very small (< 0.05).

`mul`

Dynamic viscosity of the liquid. By default mul = 0.

`muv`

Dynamic viscosity of the vapour. By default, muv = 0.

Comments :

Do not forget to create the tables of physical properties of helium by means of directive ”THEL” (page C.75).

If the mixture is single-phase, one should give the pressure and the temperature, but the title is irrelevant. If the mixture is two-phase, one should give the pressure and the title: EUROPLEXUS then computes the temperature.

The damping coefficient beta allows to damp out high-frequency oscillations caused by the discretisation. By default beta is zero. However, it is advised to use beta between 0.1% et 5%. One should be aware of the inevitable attenuations of lower frequencies, especially if the mesh is coarse. In fact, the eigenfrequencies of the structure are not very different from the frequencies associated with the finite elements.

If the viscosity has to be considered, the two parameters mul and muv must be related and given together.

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure

ECR(2) : density of the mixture

ECR(3) : sound speed

ECR(4) : mass title of the vapor (vapor mass/total mass)

ECR(5) : temperature of the mixture

ECR(6) : specific enthalpy of the mixture

7.8.11 WALL FRICTION AND WALL HEAT CONDUCTION

Object:

This directive allows, in association with the `MULT` material, to account for the effects of friction and/or heat conduction along pipe walls and cavity walls, for pipeline branches discretized either by 1D elements of type `TUBE`, `TUYA`, `CAVI`, `TUVF`, `TYVF`, `CAVF` or by 2D/3D continuum elements of type `Q4VF`, `CUVF`.

The friction coefficient can either be prescribed, by specifying the `PSIL` keyword, or be computed by the code as a function of the Reynolds number Re and of the relative roughness ϵ_r, by specifying the `RUGO` and `VISC` keywords, for a single-phase flow, the `RUGO`, `VISC` and `VISL` keywords for two-phase flow.

The heat conduction at the wall can be computed (only with certain types of fluid, typically the perfect gas `GAZP`), by specifying the wall temperatute `TPAR` and either a constant conductivity `COND` or a function of the fluid velocity `FONC`.

Syntax:

```
"PARO" $ "RUGO" rug $ "VISC" mu ; "VISL" mul  "VISV" muv $ ;
         "PSIL" kl                                         $
       < "TPAR" teta $ "COND" cof ; "FONC" numf $ ...
                     < "SURF" su > < "COEF" nbr > >
       /LECTURE/
```

`RUGO rug`

Absolute roughness ϵ_a of the pipe (warning, this parameter has the dimension of a length). The relative roughness is obtained as $\epsilon_r = \epsilon_a/D_h$, where D_h is the hydraulic diameter of the pipe (which coincides with the diameter D if the pipe has a circular cross-section).

`VISC mu`

Dynamic viscosity μ of the fluid (single-phase flow).

`VISL mul`

Dynamic viscosity μ_l of the liquid phase (two-phase flow).

`VISV muv`

Dynamic viscosity μ_v of the vapor phase (two-phase flow).

`TPAR teta`

Wall temperature T_w. Ignored for 2D/3D branches.

`COND cof`

Conductance k. Ignored for 2D/3D branches.

`SURF su`

Heat exchange surface S_h. Ignored for 2D/3D branches.

`PSIL kl`

Prescribed (constant) head loss coefficient per unit length ζ_L (1/m). Ignored for 2D/3D branches.

`COEF nbr`

Multiplicative coefficient n in the case of an assembly of identical pipes ($n = 1$ by default). Ignored for 2D/3D branches.

`FONC numf`

Number i of the `FONCTION` defining the conductance as a function of the fluid velocity. Ignored for 2D/3D branches.

`/LECTURE/`

List of the elements concerned.

Comments:

The `MULT` material is used (page C.380) to associate the wall characteristics defined by `PARO` with the corresponding internal fluid.

If the internal fluid is of type `NAH2`, `EAU` or `RSEA`, it is mandatory to specify the viscosities of both phases, μ_l for the liquid and μ_v for the vapor. In all other cases, the flow is supposed to be single-phase, and only one viscosity μ is required.

In the case of heat exchange with the wall, the keyword `SURF` is mandatory for the `CAVI` elements. For the elements of type `TUBE` and `TUYA` it may be omitted, and in this case EPX computes the exchange surface from the geometrical characteristics of the elements.

If prescribed, the ζ_L coefficient (keyword `PSIL`) allows to compute the head loss due to wall friction Δp in the following way:

$$\Delta p = \zeta_L L \frac{\rho v^2}{2}$$

where L is the length of the pipe, ρ the fluid density and v the fluid velocity.

If the user does not specify ζ_L, EPX uses the classical formulas from Idel'cik (I.E. Idel'cik. *Mémento des pertes de charge.* Edition Eyrolles, 1986) to compute the head loss coefficient per unit of relative length $\lambda(\mathrm{Re}, \epsilon_r)$ (a dimension-less number), then the total head loss coefficient of the pipe ζ (also a pure number) as:

$$\zeta = \lambda \frac{L}{D_h}$$

with L the pipe length and D_h the pipe hydraulic diameter, and finally the total head loss of the pipe:

$$\Delta p = \zeta \frac{\rho v^2}{2}$$

We see therefore that, if specified, the prescribed ζ_L coefficient (`PSIL`) corresponds to:

$$\zeta_L = \frac{\zeta}{L}$$

i.e. it represents the head loss coefficient per unit length of the pipe, and has the dimensions of the inverse of a length. This allows us to define also the head loss $\Delta p'$ per unit length of the pipe:

$$\Delta p' = \zeta_L \frac{\rho v^2}{2} = \frac{\Delta p}{L}$$

Outputs:

The internal variables related to the wall material are placed in the element's ECR table right after the internal variables for the fluid material (see the fluid documentation). Thus, if the fluid material has N internal variables, the components of the ECR table for the wall are as follows:

ECR(N+1) : Wall temperature T_w

ECR(N+2) : Wall conductance k

ECR(N+3) : Time at the previous step t_{old}

ECR(N+4) : Reynolds number Re

ECR(N+5) : Head loss coefficient per unit of relative length λ

ECR(N+6) : Total head loss Δp of the element (if pipe element)

ECR(N+7) : Head loss per unit length of the element $\Delta p'$ (if pipe element)

7.8.12 PIPE BREAK PARAMETERS

Object:

This directive allows, in association with the `MULT` material and elements of type `BREC` or elements of type `BIVF` to enter parameters for the computation of the fluid effects after the pipe break (outlet pressure, critical mass flow rate...).

Syntax:

```
"BREC" $[
          "DCRI" idcri ;
          "PIMP" ipimp < "CONT" cont "EPAI" epai "ALPH" alpha "PMOD" pmod  "PSAT coef">
       ]$
```

`idcri`

Mode for the critical mass flow rate computation (see comment below).

`ipimp`

Mode for the imposed pressure model (see comment below).

`cont`

Jet contraction ratio at critical section (default value: 0.84) (see comment below).

`epai`

Pipe thickness of the broken pipe (see comment below)

`alpha`

α parameter for `PIMP 3`. Lies between 0 and 1. Controls break opening. Not strictly equivalent to `RAP`.

`pmod`

Choice of the pressure calculation model for `PIMP 3` only (see comment below).

`coef`

If given, the normal jet force calculation is bypassed and replaced by `coef*PSAT`.

Comments:

The `MULT` material is used (page C.380) to associate the pipe break parameters defined by `BREC` with the corresponding internal fluid. Only the water material `EAU` is currenlty allowed for the fluid.

The keyword `DCRI` is used to impose a critical mass flow rate after the pipe break. Critical mass flow rate is computed using additional CL elements placed on both ends of the `BREC` element or the `BIVF` element. Two modes are allowed:

- Mode 0 : the break area is the one defined by additional CL elements. It is independent of the pipe geometry.
- Mode 1 : break area is computed inside the BREC element or BIVF element, according to the pipe geometry, taking into account the 'real' position of both parts of the broken pipe (as initially defined in the mesh).

The keyword `PIMP` is used to impose a pressure drop at the break with the imposed pressure being the pressure at saturated conditions, modified in order to take into account the break area [962]. This option is supposed to give a better representation of pressure wave generation at the break, focusing on the very first instant after break opening. Four modes are allowed:

- Mode 0 : no mass flow rate limitation is imposed at the break. In this case, the mass flow rate doesn't converge towards the critical mass flow rate.
- Mode 1 : the mass flow rate at the break is limited by the critical mass flow rate, calculated using Moody's model.
- Mode 2 : similar to `PIMP 1` + mass flow rate continuity with `P_BREC = (P_AMONT + P_AVAL)/2`.
- Mode 3 : dynamic break model able to treat break openings from 0 to $2A$ with exact flow continuity when needed.

Two optional keywords `CONT` and `EPAI` can be used in conjunctin with the keyword `PIMP`:

- cont: ratio between the critical area and break area (assumption of a jet contraction after the break)
- epai: pipe thickness at the break. This option is used to compute the jet impact generated by the flow onto the opposite broken pipe. If the keyword `CONT` is not given, the jet impact force is not calculated. The jet impact is evaluated with a simplified approach considering a liquid jet.

The keyword `PMOD` is used to choose between different approaches to compute the pressure when using the `PIMP 3` model. Four modes are allowed:

- `PMOD 0` : standard approach (and default choice if `PMOD` is missing)
- `PMOD 1` : use of a correlation function obtained from 3D code_safari simulations to compute the pressure at the break (see Figure 19 in [963]). This correlation is not validated for two-phase flows.
- `PMOD 2` : no head losses (Idel'cik) considered for the critical pressure
- `PMOD 3` : `PMOD 1` + `PMOD 2`
- `PMOD N ...` ($N > 3$) : [FOR ADVANCED USERS] if a value $N > 3$ is given for PMOD, the `PMOD 3` approach will be applied but the user-defined function number N will be used to compute the pressure instead of the default correlation function from code_safari.

For keyword `DCRI`, additional CL elements are needed for the mass flow rate to be calculated. If no CL elements are used, no critical mass flow rate is computed and no fow limitation is imposed. For keyword `PIMP`, `BREC` element can be used with or without CL elements, with no impact on the calculation If used, before the pipe break, the CL elements are automatically deactivated (see page D.590 for the definition of the break time).

7.8.13 MULTIPLE MATERIALS

Object:

This directive allows to assign several materials to the same element. For example, it is the case of a pipeline element, where one has to specify both the material for the internal fluid and the material of the wall plus, if necessary, a material describing the friction.

Syntax:

```
"MULT"  n1  n2  < n3 > /LECTURE/
```

`n1`

Number assigned to the first material.

`n2`

Number assigned to the second material.

`n3`

Number assigned to the third material.

`LECTURE`

List of the elements concerned.

Comments:

The materials concerned must be defined previously, and are referenced by their law index (see `LOI`, page C.100). This is either the number explicitly given by the `LOI` keyword, or the material definition order in the input file.

In the case of "TUBE" or "TUVF" 1D elements, or of "Q4VF"/"CUVF" 2D/3D continuum elements used to discretize pipeline branches, n1 will be the index of the fluid material and n2 the index of the friction material.

In the case of "TUYA" or "TYVF" elements, the fluid must be referenced first, the wall second, and the friction third, when present. For example, if one has defined the materials in the following order: the wall material first (1), then the fluid material (2), and finally the friction material (3), the "MULT" directive must be coded as follows:

```
"MULT"  2  1  3  /LECTURE/
```

Outputs:

The stresses and the hardening parameters will be those of the component materials. For example, for an element of pipeline, the printed stresses will be those of the associated beam (no printout of the stresses for the internal fluid), and the ECR(i) will give first the quantities related to the fluid material, then those related to the wall material.

7.8.14 LIQUID

Object:

This option enables the processing of an incompressible or quasi-incompressible fluid. The implicit algorithm of "LIAISONS" is used.

Syntax:

```
"LIQU"  "RO"  rho  < "C"  c >  < "PINI"  pini >   ...
   ...  < "PREF" pref >  < "VISC" visc >  < "RUGO" rugo >
/LECTURE/
```

`rho`

Density.

`c`

Velocity of sound (only for a compressible fluid).

`pini`

Initial pressure.

`pref`

Reference pressure (see page C.300).

`visc`

Twice the dynamic viscosity (2μ).

`rugo`

Absolute rugosity.

`LECTURE`

List of the elements concerned.

Comments:

This material only makes sense if the option "NAVIER" has been required for the definition of the problem.

If the material is incompressible, `c` is useless. On the contrary, `c` is necessary if the fluid is compressible, even at a low level. In this case `c` is read and then the value of $(1/c^2)$ is stored in the material property.

Warning:

It is essential to invert the connection matrix at each step. Do not forget to add the option "FREQ" 1 when using the instruction "LIAISON" (see page D.20).

Outputs:

The components of the ECR table are as follows:

ECR(1): absolute pressure of the element due to the viscous terms

ECR(2): density

ECR(3): additive term to the diagonal of B_L, the connections matrix.

ECR(4): additive term to the right-hand side of the connections system

ECR(5): multiplicative term of the pressure

ECR(6): friction coefficient (see M1FROT)

ECR(7): Reynolds number

ECR(8:10): unused

7.8.15 TUBE BUNDLES

Object:

Replaces a heterogeneous medium composed by a bundle of tubes submerged in a fluid, by an equivalent homogeneous isotropic medium in the acoustic sense. The densities and sound speeds will be different along the three directions in space.

In the case of helicoidal coaxial bundles (2D axisymmetric or 3D), the axis of the bundle must be along the Oz direction, the helices have all the same axial step and are regularly spaced.

In the case of a straight bundle, (2D or 3D), the bundle axis is Oz, and a side of the base 'motif' must be parallel to Ox or Oy.

There are two options for the definition of the three densities and of the three sound speeds:

a) The values are computed by EUROIPLEXUS as a function of the geometrical data (plane waves propagation).

b) The values have another origin, and are prescribed.

The possible combinations between options and geometries of the bundle are given in the following table:

Geometry	2D		3D	Value of "TYPE"
Option	DPLA	AXIS	TRID	
Triangular step	yes	no	yes	2*
Rectangular step	yes	yes	yes	1*
Imposed anisometry:				
Frame Ox,Oy,Oz	no	no	yes	2
Frame Or,Ot,Oz	no	yes	yes	1 in 3D,2 in AXIS

* These values are automatically affected to "TYPE" by EUROPLEXUS.

Syntax:

```
"FLFA"  "RO" rho  "C" c    < "PINI"  pini >  < "PREF" pref >
                           < "PMIN"  pmin > ...

$[ "DIAM" d  $[ "PRAD" pr  "PAXI" pa ]$ < "VISC" mu > < "COEF" coef>
             $[ "PTRI" pt  "BASE" ba ]$                            ;
```

```
       "ROX" rox  "ROY" roy  "ROZ" roz  "CX" cx   ...
                ...  "CY" cy  "CZ" cz  "TYPE" type "TAUX" taux     ;

       "ROR" ror  "ROT" rot  "ROZ" roz  "CR" cr   ...
                ...  "CT" ct  "CZ" cz  "TYPE" type "TAUX" taux     ]$

   ...  /LECTURE/
```

`rho`

Density.

`c`

Sound speed.

`pini`

Initial pressure.

`pref`

Reference pressure (see meaning on page C3.300).

`pmin`

Minimum pressure (see meaning on page C3.305).

`mu`

Fluid dynamic viscosity.

`coef`

Multiplicative factor for the friction (= 1 by default).

`d`

External diameter of the tubes.

`pr`

Radial step of the tubes.

`pa`

Axial step of the tubes.

`pt`

Equilateral triangular step.

`ba`

Direction of the triangle base (ba=1 or ba=2).

`rox, roy, roz`

Densities along directions Ox, Oy and Oz.

`cx, cy, cz`

Sound speeds along directions Ox, Oy and Oz.

`ror, rot, roz`

Densities along directions Or, Ot and Oz.

`cr, ct, cz`

Sound speeds along directions Or, Ot and Oz.

`type`

Type of bundle: 1 = helicoidal, 2 = straight.

`taux`

Volume fraction of the fluid (0 < taux < 1).

`LECTURE`

List of the concerned elements.

Comments:

The calculation may be done in Lagrangian or in Eulerian.

To conserv the fluid mass, an apparent fluid mass is used (printed in ECR(2)), corresponding to that of a fictitious liquid that would occupy the whole volume.

The modelisation chosen for the bundle implies anisotropy effects on inertia and compressibility. For each principal direction i of the bundle, the two parameters rhoi and rhoi*ci**2 must be defined. Hence the nodal masses are quite different from those computed from the apparent density.

However, for an Eulerian calculation, the fluxes involve the mass effectively transferred from an element to the other, i.e. the code uses the density of the free fluid and the total cross section of the passage. Consequently, the computed (and printed) velocity is that of a fictitious free fluid placed at the bundle entry (entry speed). In order to estimate the mean velocity of the fluid within the tubes, it is necessary to multiply the computed velocity by the ratio between the cross-sections.

If one has to impose an absorbing boundary condition at the bundle border using elements CL2D, CL3D ou CL3T, he must care that the product rho*c be the one corresponding to the considered direction; since the CLxD take as rho the value of the neighbouring element, i.e. the apparent density of the bundle, the sound of speed must be accordingly corrected within directive "IMPE ABSO".

The presence of keyword "VISC" followed by the value of the fluid viscosity triggers the calculation of the head losses in the bundle. The formulation given by I.E.Idel'cik is adopted

(Mémento des pertes de charge, Eyrolles, Paris, 1978) for the two principal directions of the bundle in the plane orthogonal to the tubes. The Blasius formula is used in the direction parallel to the tubes (the Reynolds number is then computed by means of the hydraulic diameter).

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure

ECR(2) : apparent density

Then if VISC is present:

ECR(3) : half-coefficient of friction along direction Ox or Or

ECR(4) : half-coefficient of friction along direction Oy or Ot

ECR(5) : half-coefficient of friction along direction Oz

7.8.16 HOMOGENEISATION OF TUBE BUNDLES

Object:

Replaces a heterogeneous medium composed by a tube bundle surrounded by fluid, by a homogenised medium (asymptotic homogenisation method).

Syntax :

```
"MHOM"  "RO"  rho  "C"  c  "EPSILON"  epsilon  "YSTAR"  ystar ...
   ...   "COEF" coef   "MTUBE" mtube  "KTUBE" ktube...
   ...    "NBTUBE"  nbtube*("BXX" bxx  "BXY" bxy  "BYY" byy ...
   ...          "CXX" cxx  "CXY" cxy  "CYY" cyy)     /LECTURE/
```

`rho`

Fluid density.

`c`

Sound celerity in the fluid.

`epsilon`

Size of the elementary cell.

`ystar`

Fluid surface in an increased elementary cell.

`coef`

Ratio y/ystar (y: total surface of the increased elementary cell).

`mtube`

Mass of a tube.

`ktube`

Stiffness of a tube.

`nbtube`

Number of tubes per elementary cell.

`bxx`

Value of beta-xx obtained by a homogeneisation pre-treatment.

`bxy`

Value of beta-xy obtained by a homogeneisation pre-treatment.

`byy`

Value of beta-yy obtained by a homogeneisation pre-treatment.

`cxx`

Value of eta-xx obtained by a homogeneisation pre-treatment.

`cxy`

Value of eta-xy obtained by a homogeneisation pre-treatment.

`cyy`

Value of eta-yy obtained by a homogeneisation pre-treatment.

`LECTURE`

List of the elements concerned.

7.8.17 PUFF

Object:

Equation of state of type PUFF, allowing to treat very fast mechanical phenomena for which the material behaviour is hydrodynamic.

Syntax:

```
"PUFF"  "RO"  rho   "MK"  mk                               ...
   ...  < "PINI"  pini   "PREF"  pref >                    ...
   ...  "GAMMA"  gamma   "D"  d   "S"  s                   ...
   ...  "GAMZ"  gamz   "CV"  cv                            ...
   ...  $[ "ES"  es                      "SIMPLE"   ;
           "GAM1" gam1   "N"  n   "EV"  ev   "COMPLEXE" ]$  ...
   ...                                                   /LECTURE/
```

`rho`

Initial density.

`mk`

Compressibility modulus.

`pini`

Value of the initial pressure.

`pref`

Value of the reference pressure.

`gamma`

Constant of perfect gases.

`d`

Parameter of the PUFF material.

`s`

Parameter of the PUFF material.

`gamz`

Gruneisen coefficient for the initial density.

`cv`

Specific heat at constant volume.

`gam1`

Parameter of the PUFF material (equals zero for SIMPLEs materials).

`n`

Parameter of the PUFF material. Example: n=0.5 for materials "SIMPLE"; n=1.67 for ceramic oxydes.

`es`

Sublimation enthalpy.

`ev`

energy at the beginning of vaporisation.

`SIMPLE`

SIMPLE material (in this case: gam1 = 0, n = 0.5).

`COMPLEXE`

PUFF material of type COMPLEXE.

`/LECTURE/`

List of the concerned elements.

Comments:

The energy will be under form of a field of initial temperatures (see directive INITIAL, page E.50).

Since the phenomenon is very rapid, it is supposed to be adiabatic.

The meaning of PINI and PREF is the same as for the FLUIDE material (page C3.305).

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure

ECR(2) : density

ECR(3) : temperature

7.8.18 MIEG (Mie-Grüneisen)

Object:

Equation of state of the Mie-Grüneisen type, allowing to treat very fast mechanical phenomena for which the material behaviour is hydrodynamic.

The Mie-Grüneisen equation of state is a relation between the pressure and the volume of a solid at a given temperature. It is used to determine the pressure in a shock-compressed solid. The most commonly used form of the equation (first-order) is:

$$p = \frac{\rho_0 C_0^2 \chi}{(1 - s\chi)^2} \left(1 - \frac{\Gamma_0}{2}\chi\right) + \Gamma_0 E \tag{64}$$

with:

$$\chi = 1 - \frac{\rho_0}{\rho} = 1 - \frac{V}{V_0} \tag{65}$$

where p is the absolute pressure, ρ_0 the initial density, ρ the current density, V the current volume, V_0 the initial volume, E the internal energy *per unit volume*, s and Γ_0 are (dimension-less) parameters.

Note that E is *not* the more commonly used specific internal energy (or internal energy per unit mass) i, but the internal energy per unit volume, which has the dimensions of a pressure (J/m^3=N/m^2=Pa). The relation between E and i is:

$$E = \rho i \tag{66}$$

In the current implementation the specific internal energy (per unit mass) i is assumed to be a function only of the temperature T and therefore i typically stays constant during the computation (since usually T does not vary). Also the speed of sound is assumed to be constant and indepenedent of the density ($C = C_0$).

Syntax:

```
"MIEG" "RO" ro "CO" c0 "S" s "GAMO" gam0 "ETA" eta "PREF" pref
       "PINI" pini
/LECT/
```

`ro`

Initial density ρ_0.

`c0`

Initial speed of sound C_0 (assumed as constant).

`s`

s parameter (dimension-less).

`gam0`

Γ_0 parameter (dimension-less).

`eta`

η parameter (for the viscosity). This has still to be implemented!

`pref`

Reference pressure p^{ref}.

`pini`

Initial (absolute) pressure p_0. The code will automatically evaluate the initial internal energy per unit mass i_0 (and the initial internal energy per unit volume $E_0 = \rho_0 i_0$) such that from the EoS (64) it results $p(0) = p_0$. Since in the initial conditions $\chi_0 = 0$, from (64) it follows that $E_0 = \rho_0 i_0 = p_0/\Gamma_0$ and $i_0 = p_0/(\rho_0\Gamma_0)$.

`/LECT/`

List of the concerned elements.

Comments:

All parameters are mandatory, including the reference pressure p^{ref}.

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure p.

ECR(2) : density ρ.

ECR(3) : specific internal energy (per unit mass) $i = E/\rho$.

7.8.19 ADCR

Object :

Modelling of the behaviour of a liquid-gas mixture. The mixture, which has three components, is assumed to be homogeneous and includes two phases.

By this model it is possible to analyse the consequences of an explosion in a liquid contained within a tank in the presence of a cover gas.

The calculation is A.L.E. only, and for elements CAR1 and TRIA (2D), or CUBE, PRIS and TETR (3D), or TUBE, TUYA, CAVI and BIFU (1D).

Syntax :

```
"ADCR"   "ROLI" roli   <"PLIQ"  pliq   > "CSON"  cson
   ...  <"PSAT" psat    "ROSA" rosat >  <"BETA"  beta  >
   ...   "ROBU" robu    "PBU"  pbu     "GBU"  gbu   "NBU"  nbu
   ...   "ROGA" roga    "PGAZ" pgaz    "GAMG" gamg
   ...   "PTOT" ptot    "CBU"  cbu     "CGAZ" cgaz
   ...  <"PREF" pref > <"VIBU" mubu > <"VILI" muli  >
   ...  <"CMIN" cmin > <"ENER" mene >  /LECTURE/
```

`roli, pliq`

Initial density and pressure of the liquid assumed alone, defining the state equation for the liquid. If "PLIQ" is absent, the pressure considered is that of the cover gas.

`cson`

Sound speed in the liquid.

`rosat, psat`

Density and pressure of the saturated liquid vapor at the temperature of the liquid, defining the equation of state for the vapor. These parameters are coupled: if one is present, the other must also appear. If they are omitted, they are supposed to be zero.

`beta`

Reduced damping coefficient for high frequencies. It is zero by default, and should always be very small (< 0.05).

`robu, pbu`

Initial density and pressure of the bubble gas, supposed alone, defining the equation of state for the gas.

`gbu`

Ratio Cp/Cv for the bubble gas.

`nbu`

Polytropic coefficient of the bubble gas.

`roga, pgaz`

Initial density and pressure of the cover gas, assumed alone, defining the equation of state of the gas.

`gamg`

Ratio Cp/Cv of gas.

`pref`

Reference pressure. By default, one takes that of liquid.

`cmin`

Maximum mass concentration of gas within the liquid, so that it is considered to be pure (1.E-8 by default).

`mene`

For CCFV only. Way in which the internal energy of each single component is computed. If 0, it is a fraction of the total internal energy (the mass fraction is used); if 1, it is computed using the EOS. For the liquid, the energy of the vapour is omitted. (0 by default; see also the description of WSUM for more details).

`muli`

Dynamic viscosity of liquid.

`mubu`

Dynamic viscosity of the gas in the bubble.

`ptot`

Total pressure (see also the comments below).

`cbu`

Mass concentration of the gas in the bubble (0 or 1).

`cgaz`

Initial mass concentration of the cover gas (0 or 1).

`/LECTURE/`

List of the elements concerned.

Remarks :

This material has been initially developed to treat the behaviour of fast reactors in the case of a containment accident (ADC in French), or of a hypothetical core disruptive accident (HCDA in English), but the adopted method lends itself to a more general use.

For this reason, some aliases are introduced. For the liquid, ROLI, PLIQ, CSON, VILI, are identical to RONA, PNA, CNA, VISO (sodium). For the cover gas, ROGA, PGAZ, GAMG, CAR are identical to ROAR, PARG, GAR and CAR (argon). For the bubble generated by the explosion, no aliases are available.

Comments :

The mesh will be subdivided into three zones (bubble, liquid, cover gas) and the ADCR material will be listed three times by varying each time the initial concentrations of the bubble and of the cover gas (0 or 1 depending on the case), but the other parameters must be identical, in order to have the same constitutive laws for the components of each zone. Then, starting from these concentrations and from the total pressure ptot, EUROPLEXUS will compute the density of the mixture. EUROPLEXUS will also recompute the concentrations in the gases in order to account for the liquid vapor, if psat is not zero.

It is possible, however, to use more than 3 zones, if for example the bubble or the liquid are subdivided into concentric zones. In such cases the total pressure ptot, varying from zone to zone, will define the initial state. EUROPLEXUS will automatically compute the mixture density using the constitutive law of each component. Of course, also in this case the other parameters such as robu, pbu, roli, roga, ... will have to be identical.

The gas generated by the explosion is assumed perfect and the state variables are linked by the following equation:

$$P_B = P_{B0}(\frac{\rho_B}{\rho_{B0}})^{n_B}$$

Here P_{B0} and ρ_{B0} are the initial values and n_B is the exponent. This exponent may be an arbitrary real number. The value $n_B = 1$ corresponds to an isothermal transformation while $n_B = \gamma_B$ to an adiabatic transformation.

The keyword `PBU`, `ROBU`, `NBU` and `GBU` allow to specify the parameters P_{B0}, ρ_{B0}, n_B and γ_B in the material data.

The behaviour of the cover gas is of the adiabatic perfect gas type and follows the equation:

$$P_A = P_{A0}(\frac{\rho_A}{\rho_{A0}})^{\gamma_A}$$

Here again, P_{A0} and ρ_{A0} are the initial values of the gas pressure and mass density, and γ_A the ratio of specific heats.

The keywords `PGAZ`, `ROGA` and `GAMG` allow to specify the parameters P_{A0}, ρ_{A0} and γ_A in the material data.

The liquid is assumed compressible and isothermal. The state equation is the same as for the FLUI material (page C.305). It is of the form:

$$P_L = P_{L0} + (\rho_L - \rho_{L0})c_L^2$$

Here P_{L0} and ρ_{L0} are the initial values, and c_L the sound speed, assumed constant.

The liquid pressure is not allowed to decrease below a minimal value corresponding to the saturation pressure of the vapor P_{sat}. The vapor (if it exists) then has a density ρ_{sat}.

The parameters P_{L0}, ρ_{L0}, c_L, P_{sat} and ρ_{sat} are defined by means of the keywords `ROLI`, `PLIQ`, `CSON`, `PSAT` and `ROSA`, respectively.

Within an element, the mixture is assumed homogeneous and each component is followed by the evolution of its mass concentration.

Initially, the composition is determined by parameters `CBU` and `CGAZ`, which impose the initial concentrations for the bubble and the cover gas, x_B and x_A. The concentration of the liquid may be computed as the difference, since:

$$x_A + x_B + x_L = 1$$

During the transient calculation, these concentrations evolve as a function of the mass flow across the elements, which determines the the mass density of the mixture and the proportions of each component.

It is then necessary to compute the corresponding pressure of the mixture by respecting the state equations. This is done by successive iterations.

It is also possible to assign dynamic viscosities to the liquid and to the gas (parameters `VILI` and `VIBU`).

Finally, the parameter `CMIN` allows to define the threshold of concentration below which one (or two) component(s) is (are) considered to be absent.

One may obtain the work of pressure forces in a region of the mesh by means of the "PDV" keyword of the "REGION" directive (page G.100).

Specific energies related to the liquid, the bubble and the cover gas can be computed and plotted in the post-treatment section (see page ED.110 for syntax).

Outputs :

The components of the ECR table are as follows:

ECR(1) : absolute pressure
ECR(2) : density of the two-phase mixture
ECR(3) : sound speed in the mixture
ECR(4) : mass concentration of the cover gas
ECR(5) : mass concentration of the bubble gas
ECR(6) : cover gas mass per unit volume
ECR(7) : bubble gas mass per unit volume
ECR(8) : cover gas mass increment

ECR(9) : bubble gas mass increment

ECR(10) : volume fraction occupied by the gases

7.8.20 EXVL—VAN LEER HYDROGEN DETONATION

Object:

Modeling of hydrogen detonation by Van Leer formulation.

Syntax:

```
"EXVL"  <"ROIN" roin>   "TINI" tini    "PINI"  pini
   ...  <"PREF" pref>   "TSEU" tseu
   ...   "ALPH" alph   <"GAMM" gamm >
   ...  <"CVME" cvme>   "CONS" cons
   ...   "MOO2" moo2    "GAO2" gao2    "COO2" coo2
   ...   "MON2" mon2    "GAN2" gan2    "CON2" con2
   ...   "MOH2" moh2    "GAH2" gah2    "COH2" coh2
   ...   "MOH"  moh     "GAH"  gah     "COH"  coh
   ...   "MOOH" mooh    "GAOH" gaoh    "COOH" cooh
   ...   "MEAU" meau    "GEAU" geau    "CEAU" ceau
   ...   "DEBX" debx    "DEBY" deby   <"DEBZ" debz >
   ...   "CPVA"         /LECTURE/
```

`roin`

Initial density of the mixture.

`tini`

Initial temperature of the mixture.

`pini`

Initial pressure of the mixture.

`pref`

Reference pressure.

`tseu`

Temperature at which the reaction is started.

`alph`

Parameter for the delay time of the reaction.

`gamm`

Ratio Cp/Cv of the mixture.

`cvme`

Mean Cv of the mixture.

`cons`

Constant R of perfect gases.

`moo2`

Oxygen molar mass.

`gao2`

Ratio Cp/Cv of the oxygen.

`coo2`

Volume concentration of the oxygen.

`mon2`

Molar mass of nitrogen.

`gan2`

Ratio Cp/Cv of nitrogen.

`con2`

Volume concentration of nitrogen.

`moh2`

Molar mass of hydrogen.

`gah2`

Ratio Cp/Cv of hydrogen.

`coh2`

Volume concentration of hydrogen.

`moh`

Molar mass of H.

`gah`

Ratio Cp/Cv of H.

`coh`

Volume concentration of H.

`mooh`

Molar mass of OH.

`gaoh`

Ratio Cp/Cv of OH.

`cooh`

Volume concentration of OH.

`meau`

Molar mass of water.

`geau`

Ratio Cp/Cv of water.

`ceau`

Volume concentration of water.

`debx`

Horizontal mass flow rate in x (density * velocity = mass flow rate)

`deby`

Vertical mass flow rate in y (density * velocity = mass flow rate)

`debz`

Mass flow rate in z (density * velocity = mass flow rate)

`cpva`

Keyword indicating that the Cp and Cv of the different components vary with temperature.

`/LECTURE/`

List of the concerned elements.

Comments:

This material may be used in EULERIAN with the option DPLA only.

When one uses the keyword "CPVA" the Cp and Cv of the various components are functions of the temperature (interpolation of the JANAF tables by a fourth-degree function). Generally during a detonation it is necessary to reduce the stability step at a value of the order of 0.1 micoseconds.

Outputs:

The different components of the ECR table are:

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : mass flow rate along x

ECR(5) : mass flow rate along y

ECR(6) : mass flow rate along z (in 3D)

ECR(18) : Mach number (u/c)

ECR(19) : temperature

ECR(20) : entropy

ECR(35) : concentration in O2

ECR(36) : concentration in N2

ECR(37) : concentration in H2

ECR(38) : concentration in H

ECR(39) : concentration in OH

ECR(40) : concentration in H2O

7.8.21 JWL—JONES-WILKINS-LEE LAW

Object:

State equation of JWL (Jones-Wilkins-Lee) type, allowing to treat explosive phenomena.

Syntax:

```
"JWL"  "RO" rho  <"ROS" ros>  "EINT" eint            ...
   ...  "A" a  "B" b  "R1" r1  "R2" r2  "OMEG" omeg  ...
   ...  <"BETA" beta>  <"PREF" pref>                 ...
   ...  /LECTURE/
```

`rho`

Initial density ρ_0.

`ros`

Optional density $\rho_{\rm sol}$ of the explosive solid phase, before detonation. **If** $\rho_{\rm sol}$ **is absent**, the code assumes $\rho_{\rm sol} = \rho_0$, which means that at the beginning of the simulation the detonation (assumed instantaneous for this material) has just occurred and the detonation products still occupy exactly the volume previously occupied by the solid explosive (the density has not yet changed). **If** $\rho_{\rm sol}$ **is present** (with $\rho_{\rm sol} > \rho_0$), then the simulation starts from a time successive to the detonation and it is assumed that the detonation products occupy a volume larger than the original volume of the solid explosive before detonation and have a uniform state (uniform bubble of detonation products), i.e. the same (initial) pressure, density and temperature (specific energy) everywhere in the detonation bubble.

`eint`

Initial specific internal energy $e_{\rm int,0}$ (internal energy per unit mass).

`a, b, r1, r2, omeg`

Coefficients A, B, R_1, R_2, ω of the state equation of JWL (see below).

`beta`

Reduced damping coefficient β for high frequencies. It is zero by default, and should always be very small ($\beta < 0.05$).

`pref`

Reference pressure $p_{\rm ref}$. By default it is $p_{\rm ref} = p_0$, that is, the reference pressure is taken equal to the initial pressure p_0 which results from the JWL equation by using the initial state values (ρ_0, $e_{\rm int,0}$ and possibly $\rho_{\rm sol}$) chosen by the user.

`/LECTURE/`

List of the elements concerned.

Comments:

The JWL equation of state gives the current value of pressure p according to the expression:

$$p = A \left(1 - \frac{\omega}{R_1 V}\right) e^{-R_1 V} + B \left(1 - \frac{\omega}{R_2 V}\right) e^{-R_2 V} + \omega \, \rho \, e_{\text{int}} \tag{67}$$

with:

ρ : current density,

e_{int} : current internal energy per unit mass,

V : the current ratio ρ_{sol}/ρ where ρ_{sol} is the density of the solid explosive before detonation (a constant).

The coefficients A, B, R_1, R_2 and ω are the equation of state (EoS) parameters, together with ρ_{sol} which represents the density of the solid explosive before detonation. R_1, R_2 and ω are dimensionless parameters, but A and B have the dimensions of a pressure.

Once exhausted the solid explosive, and after the expansion of the resulting combustion gases, the above formula tends asymptotically towards the perfect gas law:

$$p = \omega \, \rho \, e_{\text{int}}$$

Therefore, the parameter ω is related to the ratio γ between the specific heats C_p and C_v of the gas by the equation:

$$\omega = \gamma - 1 = \frac{C_p}{C_v} - 1$$

Often in the literature one does not find directly the value of $e_{\text{int},0}$ to be given in input, but the internal energy *per unit volume* E_0 of the explosive, which also has the dimension of a pressure, like A and B. In order to find $e_{\text{int},0}$ it is sufficient to divide E_0 by ρ_{sol}:

$$e_{\text{int},0} = E_0/\rho_{\text{sol}}$$

As an example, here are the values for TNT extracted from a publication of the Lawrence Livermore Laboratory by E. Lee, M. Finger, W. Collins (1973):

$A = 3.738$	$B = 0.03747$	$E_0 = 0.0600$
$R_1 = 4.15$	$R_2 = 0.90$	$\omega = 0.35$

The above listed pressures (A, B, E_0) are expressed in megabars (Mbar, with 1 Mbar = 10^{11} Pa), and the density of the solid TNT is $\rho_{\text{sol}} = 1630$ kg/m^3.

Note that the initial pressure p_0 in the material is *not* directly specified by the user, but it results from the equation of state (67) by using the initial state values chosen by the user (ρ_0, $e_{\text{int},0}$ and possibly ρ_{sol}):

$$p_0 = A \left(1 - \frac{\omega}{R_1 V_0}\right) e^{-R_1 V_0} + B \left(1 - \frac{\omega}{R_2 V_0}\right) e^{-R_2 V_0} + \omega \, \rho_0 \, e_{\text{int},0}$$

with $V_0 = \rho_{\text{sol}}/\rho_0$ (that is, $V_0 = 1$ if ρ_{sol} has been omitted).

When doing an ALE calculation, it is necessary that all the fluids contained in the same domain (which may therefore mix up with one another) have the same constitutive law. However, the initial status may be different at different locations. For example, if the explosion takes place in air, one may use the JWL (or JWLS) model both for the explosive and for the air itself. For the latter, use the limiting perfect gas behaviour of the preceding equation by specifying the corresponding density ρ_0, internal energy $e_{\text{int},0}$ and the density of the solid ρ_{sol}. In this case, one assumes that the γ values are the same for the air and for the combustion gases.

Typical use:

Two typical uses of the JWL model can be made, to simulate the detonation of an explosive charge.

In the **first case**, the simulation starts at the end of the detonation (chemical reaction with phase change) of the (typically solid) explosive charge and computes the expansion of the detonation products and their interaction with the surrounding medium (typically the atmosphere, which has a perfect-gas-like behaviour). The solid detonation process is not modelled, and is assumed to be instantaneous.

The initial conditions consist of a bubble of (just formed) gaseous detonation products which (still) occupies exactly the same volume as the solid charge, and thus has the same density ρ_{sol} as the solid explosive (e.g., 1630 kg/m^3 for TNT). The initial velocity of the gas in the bubble is assumed to be zero, and the initial conditions (pressure, temperature, sound speed) are those resulting from the JWL EoS, and are uniform over the whole bubble. In this case, the user specifies ρ_0 (which is equal to ρ_{sol}, for what has been stated above) but not ρ_{sol}. The code then automatically sets $\rho_{\text{sol}} = \rho_0$. The constant material parameters A, B, R_1, R_2, ω are chosen (from the literature) depending on the particular explosive material. The initial specific energy $e_{\text{int},0}$ is specified as $e_{\text{int},0} = E_0/\rho_{\text{sol}}$ where again E_0 is taken from the literature for the specific explosive.

This type of simulation may require a very fine mesh to represent the initial bubble of detonation products and therefore it can be too expensive in some cases.

In the **second case**, the simulation starts some time after the end of the detonation (chemical reaction with phase change) of the explosive charge. The initial situation is that of a bubble of detonation products which has already expanded to a certain degree and so has a density ρ_0 which is less than that of the solid explosive ($\rho_0 < \rho_{\text{sol}}$). This typically allows to use a (much) coarser mesh than in the previous case and may substantially reduce the cost of the simulation.

Like in the previous case, the initial velocity of the gas in the bubble is assumed to be zero, and the initial conditions (pressure, temperature, sound speed) are those resulting from the JWL EoS, and are uniform over the whole bubble. In this case, the user specifies both ρ_0 (which is less than ρ_{sol}) and ρ_{sol} (which is used in the EoS in order to compute V). The value of ρ_0 can be computed as $\rho_0 = \rho_{\text{bub},0} = (V_{\text{sol}}/V_{\text{bub},0})\rho_{\text{sol}}$ where V_{sol} is the volume of the solid charge (before detonation) and $V_{\text{bub},0}$ is the volume of the bubble (after detonation) in the assumed initial configuration.

The constant material parameters A, B, R_1, R_2, ω are chosen (from the literature) depending on the particular explosive material, like previously. However, the initial specific energy $e_{\text{int},0}$ is *not* simply equal to $e_{\text{int},0} = E_0/\rho_{\text{sol}}$ like in the previous case, because the detonation products have already expanded by a certain amount. If the pressure (assumed uniform) of the bubble in the initial configuration is known, or can be estimated, then the value of $e_{\text{int},0}$ can be obtained from the EoS. In any case, if the bubble is not much larger than the solid charge then the exponential terms prevail by far in the EoS so that the perfect gas term ($\omega\rho_0 e_{\text{int},0}$) containing $e_{\text{int},0}$ is probably negligible and an exact determination of $e_{\text{int},0}$ is not very important.

In **both typical scenarios** outlined above, another JWL material model (besides the one representing the detonation products) would typically be used in order to model the surrounding air, at least if the explosion takes place in the atmosphere. The interest of this choice, over the use of a different material such as e.g. GAZP in order to model the air, is that since all fluids are modelled by the same EoS (although in different initial conditions) an ALE or Eulerian description can be assumed which models the intemixing of detonation products with the air without needing a specific multi-component material model.

For this second JWL material, the user specifies both ρ_0, which is the standard density of the atmosphere and thus much less than ρ_{sol}, and ρ_{sol} (which is used in the EoS in order to compute

V). The constant material parameters A, B, R_1, R_2, ω should be taken equal to those of the "first" JWL material (the one used for the detonation products), in order to allow material mix-up. In any case, the contribution of the exponential terms in the EoS for the air material is negligible due to the very low density compared with the solid. Finally, since the desired initial pressure p_0 (typically the atmospheric pressure here, i.e 1 bar) is known, the value of $e_{\text{int},0}$ to be given in input such that an initial pressure p_0 will be computed by the code can be obtained from the EoS as:

$$e_{\text{int},0} \approx \frac{p_0}{\omega \rho_0} \qquad \text{for } \rho_0 \ll \rho_{\text{sol}} \tag{68}$$

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : internal energy per unit mass

7.8.22 CHOC—RANKINE-HUGONIOT SHOCK

Object

Equation of state derived from the Rankine-Hugoniot equations, allowing to treat phenomena of shock wave propagations. It is based upon a linear relationship that links the wave propagation velocity to the velocity of fluid particles (empirical relation).

Syntax:

```
"CHOC"  "RO"  rho    "A"  a    "B"  b
   ...  < "PMIN" pmin >                 /LECTURE/
```

`rho`

Initial density.

`a,`

Coefficients of the law.

`pmin`

Cavitation pressure (by default, pmin = 0).

List of the elements concerned.

Comments

Let c be the wave propagation speed and vp the velocity of the particles. These two velocities are related by the following linear relationship:

```
c = a + b * vp
```

The a quantity is the wave propagation speed at rest.

For details on this material, see the corresponding theoretical report.

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure

ECR(2) : density

ECR(3) : sound speed

7.8.23 GPDI—DIFFUSIVE VAN LEER PERFECT GAS

Object:

Diffusive Van Leer perfect gas.

Syntax:

```
"GPDI"   "ROIN" roin    "TINI" tini    "PINI"  pini
   ...  <"PREF" pref>   "GAMA" gama    "CLAM"  clam
   ...   "PLAM" plam    "CMU"  cmu     "PMU"   pmu
   ...   "CKAP" ckap    "PKAP" pkap   <"IGRA"  igra>
   ...  <"TMUR" tmur>  <"QMUR" qmur>  <"ICLI"  icli>
   ...  <"ECLI" ecli>   "DEBX" debx   <"DEBY"  deby>
   ...                  /LECTURE/
```

`roin`

Initial density of the mixture.

`tini`

Initial temperature of the mixture.

`pini`

Initial pressure of the mixture.

`pref`

Reference pressure.

`gama`

Ratio Cp/Cv of the gas.

`clam`

Constant lambda (Lamé coefficient).

`plam`

Slope of lambda.

`cmu`

Constant mu (Lamé coefficient).

`pmu`

Slope of mu.

`ckap`

Constant kappa (conductivity)

`pkap`

Slope of kappa.

`igra`

Choice of the gradient.

`tmur`

Wall temperature.

`qmur`

Wall flux.

`icli`

Boundary layer choice (0 or 1).

`ecli`

Thickness coefficient of the boundary layer.

`debx`

Horizontal mass flow rate in x (density * velocity = mass flow rate)

`deby`

Vertical mass flow rate in y (density * velocity = mass flow rate)

`/LECTURE/`

List of the concerned elements.

Comments:

This material may be used in EULERIAN only with the DPLA option.

If icli is equal 1, the boundary layer is taken into account.

If igrad is equal 0, the gradient is computed at the beginning of step n, if igrad is 1 the gradient estimation is done at the step n + 1/2. When igrad is 2, the gradient is computed at the end of the step.

Outputs:

The various components of the ECR table are as follows:

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : mass flow rate in x

ECR(5) : mass flow rate in y

ECR(18) : Mach number (u/c)

ECR(19) : temperature

ECR(20) : entropy

7.8.24 VAN LEER PERFECT GAS

Object:

Euler: perfect gas (P = rho * (gamma-1) * Einterne).

Syntax:

```
"GZPV"  "RO"  rho  "GAMMA"  gamma  "PINI"  pini  <"PREF" pref > ...
      "DEBX" debx "DEBY" deby  <"DEBZ" debz>     /LECTURE/
```

`rho`

Initial density.

`gamma`

Ratio Cp/Cv (supposed constant).

`pini`

Initial pressure.

`pref`

Reference pressure.

`debx`

Horizontal mass flow rate in x (density * velocity = mass flow rate).

`deby`

Vertical mass flow rate in y (density * velocity = mass flow rate).

`debz`

Mass flow rate in z (density * velocity = mass flow rate).

`/LECTURE/`

List of the concerned elements.

Comments:

Material usable in EULERIAN or ALE, with the option DPLA or TRIDI.

The reference pressure pref allow to define the initial state. if pref = pini, the gas is initially in equilibrium and will be perturbated by an external action, e.g.the motion of a piston. If pref = 0, the problem reduces to an initial stress problem whose velue corresponds to pini. It is the case of a membrane separating two gases in different states, which disappears at the initial calculation time.

Outputs:

The different components of the ECR table are as follows:

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : mass flow rate in x

ECR(5) : mass flow rate in y

ECR(6) : mass flow rate in z (in 3D)

ECR(18) : Mach number (u/c)

ECR(19) : temperature

ECR(20) : entropy

7.8.25 ADCJ

Object :

Modeling of the behaviour of a liquid-gas mixture. The mixture, which has 3 components, is assumed homogeneous and has 2 phases.

By this model it is possible to analyse the consequences of an explosion in a liquid contained within a tank in the presence of a cover gas.

This material is similar to material ADCR (page C.430) but the behaviour of the gas generated by the explosion is of type JWL instead of being a perfect gas (see page C.440).

The calculation is A.L.E. for elements CAR1 and TRIA (2D), or CUBE, PRIS and TETR (3D).

Syntax :

```
"ADCJ"   "ROLI" roli   <"PLIQ" pliq  >  "CSON" cson
   ... <"PSAT" psat    "ROSA" rosat >
   ...  "ROBU" robu    "A"    a         "B"    b
   ...  "R1"   r1      "R2"   r2        "OMEG" omega
   ...  "EIBU" eibu   <"PARA" param > <"ROBZ" robz >
   ...  "ROGA" roga    "PGAZ" pgaz      "GAMG" gamg
   ...  "PTOT" ptot    "CBU"  cbu       "CGAZ" cgaz
   ... <"PREF" pref > <"VILI" muli  >
   ... <"CMIN" cmin >  /LECTURE/
```

`roli, pli`

Initial density and pressure of liquid, assumed alone, defining the equation of state for the liquid. If "PLIQ" is absent, the assumed pressure is that of the cover gas.

`cson`

Sound speed in the liquid.

`rosat, psat`

Density and pressure of saturated liquid vapor, at the temperature of the liquid, defining the equation of state for the vapor. These parameters are coupled: if one is present, the other must also be given. If they are missing, they are assumed to be zero.

`robu`

Initial density of the bubble gas, assumed alone.

`a, b ,r1 ,r2, omeg`

Coefficients of the JWL state equation for the bubble (see C.440).

`eibu`

Initial specific internal energy of the bubble gas.

`param`

Number of integrations to solve the adiabaticity condition for a JWL gas. By default, param = 100, suggested value for a good precision level.

`robz`

Density of the bubble gas, defining the equation of state for the gas. By default, robz is equal to robu.

`roga, pgaz`

Initial density and pressure of the cover gas, assumed alone, defining the state equation of the gas.

`gamg`

Ratio Cp/Cv of the cover gas.

`pref`

Reference pressure. By default, one takes that of liquid.

`cmin`

Maximum mass concentration of gas in the liquid so that it is considered to be pure (1.E-8 by default).

`muli`

Dynamic viscosity of liquid.

`ptot`

Total pressure (see also the comments). In the case of the JWL gas, the pressure is re-computed strating from the energy.

`cbu`

Initial mass concentration of the bubble gas (0 or 1).

`cgaz`

Initial mass concentration of the cover gas (0 or 1).

`/LECTURE/`

List of the concerned elements.

Remarks :

This material has been initially developed to treat the behaviour of fast reactors in the case of a containment accident (ADC in French), or of a hypothetical core disruptive accident (HCDA in English), but the adopted method lends itself to a more general use.

For this reason, some aliases are introduced. For the liquid, ROLI, PLIQ, CSON, VILI, are identical to RONA, PNA, CNA, VISO (sodium). For the cover gas, ROGA, PGAZ, GAMG, CAR are identical to ROAR, PARG, GAR and CAR (argon).

Comments :

The mesh will be subdivided into three zones (bubble, liquid, cover gas) and the ADCJ material will be listed three times by varying each time the initial concentrations of the bubble and of the cover gas (0 or 1 depending on the case), but the other parameters must be identical, in order to have the same constitutive laws for the components of each zone. Then, starting from these concentrations and from the total pressure ptot, EUROPLEXUS will compute the density of the mixture. EUROPLEXUS will also recompute the concentrations in the gases in order to account for the liquid vapor, if psat is not zero.

It is possible, however, to use more than 3 zones, if for example the bubble or the liquid are subdivided into concentric zones. In such cases the total pressure ptot, varying from zone to zone, will define the initial state. EUROPLEXUS will automatically compute the mixture density using the constitutive law of each component. Of course, also in this case the other parameters such as robu, pbu, rona, roar, ... will have to be identical.

The gas generated by the explosion is assumed to follow a JWL behaviour. On this subject, see page C.440. The state variables are linked by the following equation:

$$P_B = A\left(1 - \frac{\Omega\eta}{R_1}\right) e^{-\frac{R_1}{\eta}} + B\left(1 - \frac{\Omega\eta}{R_2}\right) e^{-\frac{R_2}{\eta}} + \ \Omega\rho_B E_B$$

The variable η is the reduced mass density ($\eta = \frac{\rho_B}{\rho_{B0}}$), and E_B the specific internal energy.

The other parameters (A, B, R_1, R_2, Ω) are characteristic constants of the gas under consideration. It is remarked that if $A = B = 0$ and $\Omega = \gamma_B - 1$, the equation of state of a perfect gas is recovered:

$$P_B = (\gamma_B - 1)\rho_B\, E_B$$

The keywords `ROBU`, `EIBU`, `A`, `B`, `R1`, `R2` and `OMEG` allow to specify, respectively, the initial density ρ_{B0}, the initial internal energy E_{B0}, and the 5 constants of the JWL law.

The state variables P_B, ρ_B and E_B evolve during the calculation but remain linked by the state equation. iIn addition, it is assumed that the transformation followed by the bubble gas is adiabatic, which allows to eliminate one of these state variables, e.g. E_B. One then recovers an equation of the form:

$$P_B = f(\rho_B)$$

The other parameters are identical to those of the ADCR material (see page C.430).

One may obtain the work of pressure forces in a region of the mesh by means of the ”PDV” keyword of the ”REGION” directive (page G.100).

For more informations see reference [628].

Outputs :

The components of the ECR table are as follows:

ECR(1) : absolute pressure

ECR(2) : density of the two-phase mixture

ECR(3) : sound speed in the mixture

ECR(4) : mass concentration of the cover gas

ECR(5) : mass concentration of the bubble gas

ECR(6) : cover gas mass per unit volume

ECR(7) : bubble gas mass per un it volume

ECR(8) : mass increment of the cover gas

ECR(9) : mass increment of the bubble gas

ECR(10) : volume occupation rate of the gases

ECR(11) : partial pressure of the cover gas

ECR(12) : partial pressure of the bubble gas if ecr(5) > cmin, else initial pressure

ECR(13) : density of the cover gas

ECR(14) : density of the bubble gas if ecr(5) > cmin, else initial density

7.8.26 FLUID PARTICLE

Object:

This directive allows to specify a fluid behaviour for the particle elements (BILLE). The fluid is isothermal and perfect.

Syntax:

```
"BILLE" "FLUIDE" "RO" rho  "C" c  <"PINI" pini>
                 <"PREF" pref >   <"PMIN" pmin >
                 <"VISC" mu   >                  /LECTURE/
```

`rho`

Density.

`c`

Sound speed (constant).

`pini`

Value of the initial pressure.

`pref`

Value of the reference pressure.

`pmin`

Value of the minimum pressure (by default, pmin = 0).

`mu`

Dynamic viscosity.

`/LECTURE/`

List of the concerned elements.

Comments:

The first two parameters are mandatory. If the initial pressure is given, EUROPLEXUS will take it into account for the calculation of the absolute pressure (ECR(1)).

Rôle of PREF:

When the reference pressure is different from the initial pressure, the fluid is initially not in equilibrium. It is the case of a membrane which breaks at t = 0, thus releasing a compressed fluid.

In numerous problems the focus is on acoustic effects, and one assumes that a fluid initially in equilibrium evolves under the effects of a loading; in such cases one will take pref = pini.

If "PREF" is omitted, EUROPLEXUS considers that the fluid is in equilibrium and that pref = pini (even in the case that pini = 0).

The pressure in the fluid will always remain greater than or equal to the minimum pressure pmin, even though the density diminishes. This is a very simplified way of treating cavitation. The default value of pmin is pmin = 0.

If "PINI" is omitted, the initial pressure is null.

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure

ECR(2) : density

7.8.27 PRGL—POROUS JELLY

Object :

This directive allows to specify a behaviour simulating porous jelly (used in the bird impact studies onto turbine blades) for particle elements and SPH. For the description of this material, please consult the thesis of Antoine Letellier.

Syntax:

```
"PRGL"  "RO1" rho1    "RO2" rho2   "GAMM" gamma                   ...
  ...   "CSN1" csn1   "CSN2" csn2  "CVT1" cvt1    "CVT2" cvt2  ...
  ...   "PROP" prop   "PINI" pini  "PREF" pref    "PMIN" pmin  ...
  ...   <"VISC" mu >                                           ...

  ...                              /LECTURE/
```

`rho1`

Density of the fluid.

`rho2`

Density of the gas.

`gamma`

Perfect gas constant for the gas.

`csn1`

Sound speed for the fluid.

`csn2`

Sound speed for the gas.

`cvt1`

Coefficient expressing a linear relationship between the shock speed and the impact velocity for the fluid (see comments below).

`cvt2`

Idem for the gas.

`prop`

Fluid proportion in the mixture (in volume).

`pini`

Value of the initial pressure.

`pref`

Value of the reference pressure.

`pmin`

Value of the cavitation pressure.

`mu`

Dynamic viscosity.

`/LECTURE/`

List of the concerned elements

Comments:

The coefficients cvt1 and cvt2 are used in the following equation:

```
V_choc = V_son + cvt * V_impact
```

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure

ECR(2) : density

7.8.28 VAN DER WAALS GAS

Object :

This directive allows to specify a real gas material with a Van Der Waals behaviour.

In the 1-D case, the friction onto the walls may be accounted for, and the dissipated energy heats up the gas (modification of the internal energy). To this end, one must add a "PARO" material and associate it with "GVDW" by means of a "MULT" material (pages C.370 and C.380).

Syntax :

```
"GVDW"  "RO"  rho   "PINI"  pini   < "PREF"  pref >   ...
   ...  "RM"  rm    "CV"     Cv     ...
   ...  $[ "A"  a   "B"  b  ; "PCRI" pc  "TCRI" tc ]$ ...
   ...      /LECTURE/
```

`rho`

Initial density.

`pini`

Initial pressure.

`pref`

Reference pressure.

`rm`

Constant of perfect gases R divided by the molecular mass M (assumed constant).

`Cv`

Specific heat at constant volume.

`a`

Constant a of the gas (assumed constant).

`b`

Constant b of the gas (assumed constant).

`pc`

Pressure at the critical point.

`tc`

Temperature at the critical point.

`/LECTURE/`

List of the concerned elements.

Comments :

The state equation of a Van der Waals gas has the form:

$$P = \frac{r_m T}{(\frac{1}{\rho} - b)} - a\rho^2$$

or, equivalently:

$$P = \frac{r_m (e + a\rho)}{C_v(\frac{1}{\rho} - b)} - a\rho^2$$

The first form is obtained by the state variables P, ρ and T (respectively pressure, density and temperature), while the second uses P, ρ and e, i.e. the temperature is replaced by the specific internal energy.

Some theoretical complements are given in the report [657], which lists also the values of parameters a and b for some fluids.

These coefficients a and b are related to the critical pressure P_c and to the critical temperature T_c by the following expressions :

$$P_c = \frac{a}{27b^2} \qquad T_c = \frac{8a}{27br_m}$$

The parameter r_m is the ratio between the perfect gas constant (R=8.31441 $JK^{-1}mol^{-1}$) and the molar mass M of the gas. Pay attention to units: for example, for air it is $M = 0.029$ Kg.

The reference pressure pref allows to define the initial state. If pref = pini, the gas is initially in equilibrium and will be perturbed by an external action, e.g. motion of a piston. If pref = 0, the problem reduces to a calculation with initial stresses, defined by pini. It is the case of a membrane, that initially separates two gases in different conditions, which suddenly breaks at the initial time.

Outputs :

The various components of the ECR table are as follows:

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : temperature

ECR(5) : dynamic pressure: $(\frac{1}{2}\rho V^2)$

ECR(6) : total energy $(e + \frac{1}{2}V^2)$.

7.8.29 JWLS

Object:

State equation of JWL (Jones-Wilkins-Lee) type, similar to the JWL material on page C.440, but allowing also to account for the initial propagation of detonation (at an assumed constant speed) in the solid charge. The user may specify the initiaton point (trigger) of the detonation process in the (initially) solid charge.

The propagation of detonation (chemical reaction with phase change) in the initially solid charge can be spherical (by default) or planar.

Optionally, a simplified modelling of the afterburning effect can be added, i.e. the release of energy by additional chemical reactions (combustion) of the detonation products during their expansion after the detonation proper. (The afterburning effect cannot presently be taken into account by the JWL material model of page C.440.)

Syntax:

```
"JWLS"  "RO" rho  <"ROS" ros>  "EINT" eint  <"PINI" pini>    ...
   ...  "A" a  "B" b  "R1" r1  "R2" r2  "OMEG" omeg          ...
   ...  <"BETA" beta> <"PREF" pref>                          ...
   ...  <"D" d  "XDET" xdet  "YDET" ydet  <"ZDET" zdet>>     ...
   ...  <"PCJ" pcj>                                          ...
   ...  <"VXD" vxd  "VYD" vyd  <"VZD" vzd>>                  ...
   ...  <"AFTE" afte  "EAFT" eaft  "CONF" conf  "CHAR" char  ...
   ...   "TSTA" tsta  "TEND" tend                            ...
   ...   "AMIL" amil  "MMIL" mmil  "NMIL" nmil >             ...
   ...  /LECTURE/
```

`rho`

Initial density ρ_0.

`ros`

Optional density ρ_{sol} of the explosive solid phase, before detonation. **If ρ_{sol} is absent**, the code assumes $\rho_{sol} = \rho_0$. Then, two sub-cases may occur. In the first sub-case, which is the most typical use of JWLS, the explosive is still solid and the progressive detonation of the solid charge has to be modelled. This is recognized by the presence of `D` (the detonation speed) and of `XDET`, `YDET`, `ZDET` (the position of the trigger). In the second sub-case, the solid explosive has just (instantaneously) detonated (so it still occupies the same volume as the solid, the density has not changed yet) and the JWLS material behaves just like JWL. This is recognized by the absence of `D`, `XDET`, `YDET`, `ZDET` in the input. **If ρ_{sol} is present** (with $\rho_{sol} > \rho_0$), then the simulation starts from a time successive to the detonation and it is assumed that the detonation products occupy a volume larger than the original volume of the solid explosive before detonation and have a uniform state (uniform bubble of detonation products), i.e. the same (initial) pressure, density and temperature (specific energy) everywhere in the detonation bubble.

`eint`

Initial specific internal energy $e_{int,0}$ (internal energy per unit mass).

`pini`

Initial (absolute) pressure p_0 in the solid (undetonated) material. This quantity *must* be specified if d (detonation speed in the solid) is also specified, because the initial pressure in the solid cannot be obtained from the JWL EoS, which is only valid for the (gaseous) detonation products. If d is not specified (so that we start from an already detonated explosive) then p_0 *must not* be specified, since in this case the initial pressure will be computed from the JWL equation by using the initial state values (ρ_0, $e_{\mathrm{int},0}$ and possibly ρ_{sol}) chosen by the user.

`a, b, r1, r2, omeg`

Coefficients A, B, R_1, R_2, ω of the state equation of JWL (see below).

`beta`

Reduced damping coefficient β for high frequencies. It is zero by default, and should always be very small ($\beta < 0.05$).

`pref`

Reference pressure p_{ref}. By default it is $p_{\mathrm{ref}} = p_0$, that is, the reference pressure is taken equal to the initial pressure p_0 which results from the JWL equation by using the initial state values (ρ_0, $e_{\mathrm{int},0}$ and possibly ρ_{sol}) chosen by the user.

`d`

Velocity d (assumed constant) of the detonation wave (chemical reaction with phase change) in the solid charge. The wave shape is assumed to be spherical by default, but a planar wave can be chosen in alternative by specifying `vxd ...` (see below).

`xdet, ydet, zdet`

Coordinates of the detonation trigger point in the solid charge. In 2D `zdet` is ignored.

`pcj`

Chapman-Jouguet pressure. Note that this parameter may be specified but it is *unused in the present model*.

`vxd, vyd, vzd`

Components of a vector (not necessarily unitary, but non-zero) defining the direction of propagation of the detonation wave (chemical reaction with phase change) in the solid charge. In this case (i.e. if any of these three quantities is specified) the detonation wave in the solid is assumed to be planar rather than spherical (which is the default). In 2D `vzd` is ignored.

`afte`

Afterburning effect:

0 no afterburning,

1 linearly increasing afterburning pressure (from `tsta` to `tend`),

2 Miller's extension for afterburning.

`eaft`

Afterburning effect: additional energy for the afterburning (per kg) (afterburning options 1 and 2).

`conf`

Afterburning effect: volume of the confinement (afterburning options 1 and 2).

`char`

Afterburning effect: total mass of the charge (afterburning options 1 and 2).

`tsta`

Afterburning effect: start time when afterburning energy should be added for afterburning option 1.

`tend`

Afterburning effect: end time until which afterburning energy should be added for afterburning option 1.

`amil`

Afterburning effect: a coefficient in Miller's extension (afterburning option 2).

`mmil`

Afterburning effect: m exponent in Miller's extension (afterburning option 2).

`nmil`

Afterburning effect: n exponent in Miller's extension (afterburning option 2).

`/LECTURE/`

List of the concerned elements.

Comments:

The JWL state equation gives the value of the pressure according to the following formula (see also page C.440):

$$p = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \omega\,\rho\,e_{\mathrm{int}} + \frac{\omega\lambda Q}{V} \tag{69}$$

with:

ρ : current density,

e_{int} : current internal energy per unit mass,

V : the current ratio ρ_{sol}/ρ where ρ_{sol} is the density of the solid explosive before detonation (a constant),

λ : the fraction of reacted detonation products leading to afterburning pressure,

Q : the afterburning energy release.

If ρ_{sol} is omitted, the propagation of the detonation wave (chemical reaction) in the solid explosive charge is modelled. In this case the code assumes $\rho_{\mathrm{sol}} = \rho_0$ (i.e., the initial density ρ_0 to be specified in input is that of the solid) and it is mandatory to specify the detonation speed d and the position of the ignition point (trigger) x_{det}, y_{det}, (and z_{det} in 3D), in order to start up the reaction.

The coordinates x_{det}, y_{det}, (and z_{det} in 3D) define the position of the ignition point (trigger) in the initially solid charge where the reaction begins. From this point the reaction wave progresses with constant velocity d, and when it reaches the center of each finite element the reaction is (instantaneously) activated in that element, whose material passes from solid to gas.

Like for the `JWL` material, it is possible to use this constitutive law to approximate the behaviour of a perfect gas, such as the atmospheric air for example. To this end it is necessary to specify $\rho_{\mathtt{sol}}$ and to choose the initial values ρ_0 and $e_{\mathrm{int},0}$ for the gas such that the correct initial pressure (usually the atmospheric pressure) will result from the EoS. Note that in this case p_0 is not used by the model and should be omitted and it is also useless to specify d and the coordinates of the ignition point.

Like for the other fluid models, the reference pressure p_{ref} allows to account for an external pressure.

Typical use:

The typical use of the JWLS model to simulate the detonation of an (initially solid) explosive charge is described herafter. The advantage over the use of JWL is the possibility of modelling the advancing detonation (chemical reaction) front in the solid charge, which changes progressively phase, and (optionally) also to add afterburning effects.

The simulation starts at the beginning of the detonation (chemical reaction with phase change) of the (typically solid) explosive charge, at the instant that the detonation is triggered at a user-defined point in the solid charge. The code should first compute the advancement of the chemical reaction in the solid and then (like for the JWL material) the expansion of the detonation products and their interaction with the surrounding medium (typically the atmosphere, which has a perfect-gas-like behaviour). **The solid detonation process is modelled**, albeit very primitively, and is not assumed to be instantaneous, unlike for JWL.

The initial conditions consist of a mass of solid explosive material of density $\rho_0 = \rho_{\mathrm{sol}}$ (e.g., 1630 kg/m^3 for TNT). The user specifies ρ_0 (which is equal to ρ_{sol}, for what has been stated above) but not ρ_{sol}. The code then automatically sets $\rho_{\mathrm{sol}} = \rho_0$. The constant material parameters A, B, R_1, R_2, ω are chosen (from the literature) depending on the particular explosive material. The initial specific energy $e_{\mathrm{int},0}$ is specified as $e_{\mathrm{int},0} = E_0/\rho_{\mathrm{sol}}$ where again E_0 is taken from the literature for the specific explosive.

Then, the detonation speed d and the position of the trigger x_{det}, y_{det} (and z_{det} in 3D) are also specified, in order to activate the progressive detonation of the solid. A spherical wave is assumed by default, but alternatively the user can choose a planar wave by specifying also v_{xd}, v_{yd} (and v_{zd} in 3D). The afterburning model may optionally be activated by specifying its optional parameters.

Note that in this case the value of the initial pressure p_0 *must* be specified. This is the initial pressure in the solid phase (usually equal to the atmospheric pressure), which cannot be computed by the code (it does *not* result from the JWL EoS, because the equation applies only to the detonation products i.e. the gaseous phase).

This type of simulation may require a very fine mesh to represent the initial bubble of detonation products and therefore it can be very expensive in some cases. However, a price has to be paid for the added sophistication with respect to JWL.

Then, **another JWLS material model** (besides the one representing the solid charge, gradually converted into detonation products) would typically be used in order to model the surrounding air, at least if the explosion takes place in the atmosphere. The interest of this choice, over the use of a different material such as e.g. GAZP in order to model the air is that, since all fluids are modelled by the same EoS (although in different initial conditions), an ALE or Eulerian description can be assumed which models the intemixing of detonation products with the air without needing a specific multi-component material model.

For this second JWLS material, the user specifies both ρ_0, which is the standard density of the atmosphere and thus much less than ρ_{sol}, and ρ_{sol} (which is used in the EoS in order to compute V). The constant material parameters A, B, R_1, R_2, ω should be taken equal to those of the "first" JWLS material (the one used for the solid charge and detonation products), in order to allow material mix-up. In any case, the contribution of the exponential terms in the EoS for the air material is negligible due to the very low density compared with the solid. Since the pressure p_0 (typically the atmospheric pressure here, i.e 1 bar) is known, the value of $e_{\mathrm{int},0}$ to be given in input such that an initial pressure p_0 will be computed by the code can be obtained from the EoS as:

$$e_{\mathrm{int},0} \approx \frac{p_0}{\omega \rho_0} \qquad \text{for } \rho_0 \ll \rho_{\mathrm{sol}} \tag{70}$$

Finally, note that the initial pressure p_0 *must not* be specified in this case, since it will be computed by the code using the EoS.

Outputs:

The components of the ECR table are as follows:

ECR(1) : absolute pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : burnt (detonated) fraction: either 0 (for undetonated solid) or 1 (for gas, i.e. detonation products).

ECR(5) : internal energy per unit mass

ECR(6) : fraction of detonated reaction products (λ)

7.8.30 USER-DEFINED FLUID (FLUT)

Object:

This material is used with specialised elements of type "FLU1", "FLU3", "FL23", "FL24", "FL34", "FL35", "FL36" and "FL38". The subroutine describing the fluid's equation of state has to be written by the user (an example is given below).

Syntax:

```
"FLUT"  "RO" ro  "EINT" eint
       $[ "GAMM" gamm ; R r C0 c0 C1 c1 C2 c2 ]$
       < "CL" cl  "CQ" cq  "PB" pb  "PMIN" pmin
         "AHGF" ahgf  "ITER" iter  "ALF0" alf0
         "BET0" bet0  "KINT" kint  "NUM" num
         "VXFF" vxff "VYFF" vyff "VZFF" vzff
         "CONV" conv "PREF" pref "RREF" rref
         "RMIN" rmin "RMAX" rmax
         "IMIN" imin "IMAX" imax "RANG" rang
         "GENE" gene "GENM" genm             >
       < additional_data_for_JWLS_material    >
       /LECTURE/
```

`ro`

Initial mass density.

`eint`

Specific internal energy.

`gamm`

Constant value of the ($\gamma = c_p/c_v$) ratio; alternatively (but only for a perfect gas, i.e. NUM=1), the next four parameters may be given which are used to describe the dependence of c_p, and hence c_v, γ and the internal energy of the perfect gas upon temperature. To this end, we use the following relations: $c_p(T) = c_0 + c_1 T + c_2 T^2$ where T is the temperature in K, c_p and c_0 are typically expressed in J/kgK, c_1 in J/kg(K2) and c_2 in J/kg(K3). Then, the specific heat at constant volume c_v is given in J/kgK by the expression $c_v(T) = c_p(T) - R$, where R is the specific perfect gas constant of the gas considered, also expressed in J/kgK. Note that $R = R'/w$ where R' is the universal constant of perfect gases expressed in J/kmolK (which has the standard value of 8314.3) and w is the molar weight of the gas expressed in kmol/kg. Alternativley, one could express c_p and c_0 in J/kmolK, c_1 in J/kmol(K2) and c_2 in J/kmol(K3). In this case, c_v would result in J/kmolK from the expression $c_v(T) = c_p(T) - R'$, where R' is the universal constant of perfect gases defined above.

`cl`

Coefficient of linear artificial viscosity. Range is 0.0 to 0.8, default is 0.0.

`cq`

Coefficient of quadratic artificial viscosity. Range is 0.0 to 4.0, default is 0.0.

`pb`

Constant used in sound speed evaluation. For material 9 this is the reference pressure. For material 10 this is the index of the FONC used to describe the imposed pressure as a function of time.

`pmin`

Cut-off pressure. Default is 0.0.

`ahgf`

Anti-hourglass coefficient. Suggested value is 0.01, default is 0.0.

`iter`

There are two possibilities. If a number greater than or equal to 1 is given, then this quantity represents the (fixed) number of iterations for the calculation of tilde pressure and tilde specific energy. If, instead, one gives a (real) value smaller than 1 (for example `ITER 1.E-6`), then this quantity is interpreted as the tolerance for convergence of the tilde pressure and tilde specific energy, and the maximum number of iterations for convergence is in that case limited to 100. Finally, note that if one does not specify this quantity (or specifies 0), then by default just one iteration is performed.

`alf0`

Parameter used to compute the donor element weighting factor in connection with mass and energy transport across element boundaries. When alf0=0 mass and energy fluxes are centered; when alf0=1 the fluxes are full donor.

`bet0`

Parameter used to compute the donor element weighting factor in connection with momentum transport across element boundaries. When bet0=0 momentum flux is centered; when bet0=1 the flux is full donor.

`kint`

In the 2D case: represents the integration type for the forces due to momentum transport (FL24 element only) (-1: no momentum transport at all, to be used only for debugging purposes; 0: use centroid values, is the default; 1: use values at integration points, i.e. a 2×2 Gauss rule; 2: use a 3×3 Gauss rule, which is exact in axisymmetric cases). Note that the default value (kint = 0) is known to destroy symmetry even in 2D plane cases, so use at least kint = 1 if a perfectly symmetric solution is desired (e.g. in academic validation tests). In the 3D case: represents the integration type for nodal mass distribution (0: element mass/number of nodes (default); 1: Gauss integration).

`num`

Number of the material in the user's subroutine FLUTIL (see below). By default, num=1.

`vxff`

X-Component of the far-field velocity (this and the following two components are only used in the case that the FLUT material is used to specify a far-field status via a CLxx element); by default it is 0.0.

`vyff`

Y-Component of the far-field velocity; by default it is 0.0.

`vzff`

Z-Component of the far-field velocity; by default it is 0.0.

`conv`

Units conversion factor for the pressure; it is used only in empirical or semi-empirical user's laws; by default it is 1.0.

`pref`

Reference pressure (see Note below), by default it is 0.0.

`rref`

Reference mass density to be used in the material law; by default, it is assumed rref=ro, i.e. the reference density is assumed equal to the initial density.

`rmin`

The minimum value of the density that can be accepted; by default it is 0.

`rmax`

The maximum value of the density that can be accepted; by default it is set equal to the 'grand' quantity (usually of the order of 1.E12, but the actual number depends on the computer).

`imin`

The minimum value of the specific internal energy that can be accepted; by default it is 0.

`imax`

The maximum value of the specific internal energy that can be accepted; by default it is set equal to the 'grand' quantity (usually of the order of 1.E12, but the actual number depends on the computer).

`rang`

An integer defining the type of check that should be performed. When 0 is used no range check is performed (this is the default); when 1 is specified, a warning message is issued each time the validity ranges are violated but, in order to reduce the number of messages, the current value of the range is updated each time a message is issued. The last messages will therefore show the absolute minimum or maximum out-of-range values that have been used in the calculation; when 2 is specified, a warning message is issued each time the validity ranges are violated, so there may be a lot of messages in practical cases; finally, when 3 is used an error message is given the first time ranges are violated, and the calculation is stopped immediately.

`gene`

Associate energy generation to this material: gene is the number of the function (see "FONC" directive) used to describe the variation in time of the specific power (i.e., per unit mass) that will be generated in this FLUT material.

`genm`

Associate mass generation to this material: genm is the number of the function (see "FONC" directive) used to describe the variation in time of the specific mass (i.e., per unit mass) that will be generated in this FLUT material.

Additional data for JWLS material

For the special case of a Jones-Wilkins-Lee (JWLS) material (`NUM` = 11), the user may specify a set of additional parameters that are detailed below. This material is suitable for the modelling of explosives and is similar to CEA's JWL/JWLS materials, but adapted for use with JRC's specialized fluid elements.

The JWL state equation gives the value of the pressure according to the following formula (see also page C.440) :

$$P = A(1 - \frac{\omega}{R_1 V})\, e^{-R_1 V} + B(1 - \frac{\omega}{R_2 V})\, e^{-R_2 V} + \omega\, \rho\, e_{int}$$

with :

ρ : current density,

e_{int} : current internal energy per unit mass,

V : the ratio $\frac{\rho_{sol}}{\rho}$ where ρ_{sol} is the density of the explosive (specific volume).

The release of the chemical energy can be controlled by the burn mass fraction. The burn mass fraction smears the detonation front over a certain number of time steps.

$$P = P_{EOS} min(1, F_1))$$

with :

$$F_1 = \begin{cases} (t - t_1)d/(B_s \cdot l_e) & \text{for } t > t_1 \\ 0 & \text{for } t \leq t_1 \end{cases}$$

with :

t_1 : ignition time of the current element (calculated with the detonation velocity d),

B_S : controls the width of the burn wave

l_e : average element length

Syntax:

```
< <"ROS" ros>  "A" a  "B" b
  "R1" r1 "R2" r2
  <"D" d  "XDET" xdet "YDET" ydet  <"ZDET" zdet>>
  <"TDET" tdet> "PINI" pini <"BMF" bmf> >
```

`ros`

Density of the explosive in solid state (before detonation). If omitted, it is assumed `ROS = RO` i.e. the explosion starts from the solid state, whose density coincides with the initial density of the material (`RO` parameter given in the standard `FLUT` properties). In this case, it is mandatory to specify also the detonation speed `D` and the ignition point `XDET`, `YDET` and `ZDET` from which the detonation starts.

`a`

Coefficient A of the JWL equation of state. It has the dimensions of a pressure.

`b`

Coefficient B of the JWL equation of state. It has the dimensions of a pressure.

`r1`

Coefficient R_1 of the JWL equation of state. It has no dimensions.

`r2`

Coefficient R_2 of the JWL equation of state. It has no dimensions.

`d`

Detonation speed. The detonation is supposed to start at point `XDET`, `YDET` and `ZDET` and to propagate through the (solid) charge according to a spherical wave traveling with constant speed given by `d`.

`xdet, ydet, <zdet>`

Ignition point. If `zdet` is omitted, it is assumed equal to 0.

`tdet`

Starting time for the detonation. By default it is 0.

`pini`

Initial pressure (absolute) of the undetonated material.

`bmf`

Parameter for the burn mass fraction B_S. If the parameter equals 0 or is not defined, burn mass fraction is not activated. The suggested value is 2.5.

The parameter ω appearing in the JWL equation of state is not given explicitely since $\omega = \gamma - 1$ where $\gamma = C_p/C_v$ is the ratio of specific heats that is provided by means of the `gamm` parameter.

Like for CEA's materials `JWL` and `JWLS` it is possible to use this constitutive law to approximate the behaviour of a perfect gas. It is sufficient to give `ROS` and the initial values `RO` and `EINT` for the gas to find the corresponding pressure by the state equation. In this case `PINI` is not used by the model. In this case, it is useless to specify `D`, the coordinates of the ignition point and the starting time of the detonation.

Comments

The meaning of the reference pressure pref is as follows. The pressure value p resulting from the material equation of state is considered as the absolute pressure. Its value is stored in ECR(1), see below. However, in order to compute the internal forces, the "effective" pressure value (p' = p - pref) is used. This is useful when e.g. modeling a pressure vessel filled in by fluids and surrounded by the atmosphere in the outside part. In this case, if the material law for the inside fluid is given in absolute terms, we may proceed in two ways in order to take into account the outside pressure. The first possibility is to ignore pref (thus, pref=0.0) and explicitly impose an outside pressure of 1 atmosphere on the external surface of the model, either by the directive "CHAR" or by using specialized CLxx elements. However, this is likely to be too expensive for just representing a constant external pressure. The second possibility is to define pref=1 atmosphere for the internal fluids, so that only the pressure exceeding this value will be used in order to compute the forces.

If a material of this type is assigned to far-field boundary condition elements only, then all the above optional parameters are ignored if specified, except NUM, VXFF, VYFF and VZFF. On the other hand, VXFF, VYFF and VZFF are only used when the material is assigned to a far-field (CLxx) element.

The optional directives GENE and GENM allow to associate energy or mass generation, respectively, to a FLUT material. During the transient calculation, the generation "follows" this material, rather than being tied to a spatial zone (elements) like in the INJE injection model (see INJE directive). Another difference is that in the GENE model the given time function (FONC) represents the specific generated energy per unit time, and not the total energy per unit time like in the INJE model.

It should be noted that the behaviour of the GENE/GENM generation model will be different, depending on whether the associated FLUT material is a single-component, or part of a multi-phase multi-component (FLMP) material model.

In the first case, the generation will actually remain confined to the elements that are assigned the present material in the initial configuration, which is probably NOT what the user would expect (unless of course the generation zone boundary is Lagrangian, but in that case the generation model would coincide with the INJE model). This 'wrong' behaviour is due to the way the program deals with fluid transport across boundaries in the single-component model: even when fluid is transported each element retains its (initial) material index, so the generation information may not be transported to neighbours.

On the other hand, when the FLMP multiphase multicomponent model is used, then full tracking of each single component is performed, and therefore the generation model works as expected (generation information is transported to neighbour elements).

Mass generation requires some conventions as to what are the conditions of the injected mass, since this mass will also introduce corresponding energy, in the form of internal energy and possibly of momentum. Here it is assumed for simplicity that the mass generation occurs in the initial conditions of the corresponding material, and that the injection process does not perturbate the velocity field (i.e., the mass enters the element already at the current velocity).

Outputs:

The components of the ECR table are as follows:

ECR(1): current element fluid absolute pressure p

ECR(2): current element mass density

ECR(3): current element sound speed

ECR(4): current element specific internal energy

ECR(5): current element bulk modulus. Attention! Until recently this quantity was uncorrectly indicated as bulk modulus in the code. In reality, this is the derivative of pressure with respect to density, dp/dr, which is related to the true bulk modulus B by the relation: B = (dp/dr) * r. Note that the quantity is only used (and updated at each time step) if the user selects the anti-hourglass model, i.e. specifies a non-zero value for the AHGF coefficient.

ECR(6): current element pseudoviscous pressure

ECR(7): current elemen minimum pressure flag (0 if p>pmin, 1 if p=pmin)

ECR(8): maximum pressure ever experienced by this element

ECR(9): minimum pressure ever experienced by this element

ECR(10): fraction of detonated material (for JWLS only) (0 or 1)

The components of the SIG table are as follows:

SIG(1): current element fluid relative pressure (p - pref)

The following global results can be accessed via TPLOT when materials having either energy or mass generation are present in the calculation:

```
GENE: Total energy generated in materials with generation
GENM: Total mass generated in materials with generation
```

Comparing FE and FV solutions.

Frequently it is desirable to compare solutions obtained with Finite Element (FE) models to equivalent ones obtained with Finite Volumes (FV), typically for the case of perfect gases.

In the case of MCGP material used for Finite Volumes (see page C.550), the equivalence of initial conditions is not completely straightforward.

A procedure for converting between the two formulations is detailed on Page C.550.

Example of user-defined material subroutine.

The name of the subroutine is FLUTIL. The variables received in input and returned in output are explained in the comments.

```
C FLUTIL    SOUPLEX   ISPRA     89/04/19    21:02:26
      SUBROUTINE FLUTIL(NUM,rcur,rref,GAM,UP,PB,PMIN,conver,
     >                  pres,SOUND,XKP)
C-----------------------------------------------------------------------
C                                            F.CASADEI,J.P.HALLEUX 11-87
C USER'S EQUATION(S) OF STATE FOR FLUID MATERIAL(S) OF TYPE "FLUT"
C UPDATES FLUID PRESSURE, SOUND SPEED AND MINIMUM PRESSURE FLAG
C-----------------------------------------------------------------------
c Input:
c =====
C   NUM     = NUMBER OF CURRENT "FLUT" MATERIAL
C   rcur    = CURRENT ELEMENT MASS DENSITY
C   rref    = reference MATERIAL MASS DENSITY
C   GAM     = num=1-8: CP/CV, RATIO OF MATERIAL SPECIFIC HEATS
c             num=9 : Bulk modulus (same units as pressure)
C   UP      = CURRENT ELEMENT SPECIFIC INTERNAL ENERGY
C   PB      = num=1-8: CONSTANT USED IN SOUND SPEED EVALUATION
c             num=9 : Reference pressure
c             num=10: Index of FONC defining the pressure p(t)
C   PMIN    = CUT-OFF PRESSURE
c   conver  = units conversion factor for the pressure
c Output:
c ======
C   pres    = NEW     ELEMENT FLUID PRESSURE: pres=pres(rcur,UP)
C   SOUND   = NEW     ELEMENT SOUND SPEED
C   XKP     = NEW     ELEMENT MINIMUM PRESSURE FLAG (0 IF P>PMIN,
C                                                  1 IF P=PMIN)
C
      include 'R8AHOZ.INC'
c
      include 'ALLO.INC'
      include 'CONSTA.INC'
      include 'TEMPX.INC'
C
c========================================================================
C EQUATIONs OF STATE
C
      GOTO(1,2,3,4,5,6,7,8,9,10),NUM
      CALL ERRMSS('FLUTIL',' FLUT MATERIAL NUMBER OUT OF RANGE')
      STOP
C
C 1/ PERFECT GAS -------------------------------------------------------
C
    1 pres=(GAM-1.D0)*rcur*UP
      GO TO 100
C
C 2/ IT8 LOW DENSITY EXPLOSIVE CHARGE ----------------------------------
C    (pinc=[DYNES/CM2])
```

```
C
    2 v=rref/rcur
      T1=1.7039D+11*(1.0D0-1.0D0/(90.0D0*V))*EXP(-9.0D0*V)
      T2=1.1595D+10*(1.0D0-1.0D0/(24.0D0*V))*EXP(-2.4D0*V)
      t3=-1.02884d9/v
      t4=0.1D0*rcur*up
      pinc=t1+t2+t3
      pres=conver*pinc+t4
      GO TO 100
C
C 3/ APRICOT-4 AND IT8 LIQUID WATER -------------------------------------
C    (pinc=[DYNES/CM2])
C
    3 v=rref/rcur
      if(rcur.eq.rref) then
        t1=0.0d0
      ELSE
        am=1.0D0-V
        a2=am*am
        a3=2.086D0*am
        a3m=a3-1.0D0
        a4=a3m*a3m
        a5=0.8293D0*a2
        a6=2.796D0*am
        a7=sqrt(a4+a5)
        om=(a3-1.0D0+a7)/a6
        a8=(0.1483D0+2.086D0*om-1.398D0*om*om)*om
        a9=1.0D0-0.14D0*am/v
        t1=1.0D12*a9*a8
      END IF
      t2=0.28d0*rcur*up/v
      pinc=t1
      pres=conver*pinc+t2
      GO TO 100
C
C 4/ CONT PROBLEM EXPLOSIVE BUBBLE --------------------------------------
C    (pinc=[Pa])
C
    4 VV=rcur/rref
      IF(VV.GT.0.0D0) THEN
        pinc=1.0D7*VV**GAM
      ELSE
        pinc=0.0D0
      ENDIF
      pres=conver*pinc
      GO TO 100
C
C 5/ CONT PROBLEM LIQUID SODIUM AT 773 K AND ABOUT 10 MPA ---------------
C    (pinc=[Pa])
C
    5 VV=rcur/rref
```

```
      AMU=VV-1.0D0
      T1=4.440D3*AMU
      T2=4.328D9*AMU*ABS(AMU)
      T3=1.218D0*rcur*UP*(1.D0+AMU)
      pinc=t1+t2
      pres=conver*pinc+t3
      GO TO 100
c
C 6/ APRICOT-4 EXPLOSIVE GAS PRODUCTS -----------------------------------
C    (pinc=[DYNES/CM2])
c
    6 v=rref/rcur
      t1=6.70695d12*(1.0d0-0.25d0/(4.660599d0*v))*exp(-4.660599d0*v)
      t2=9.26460d10*(1.0d0-0.25d0/(0.991617d0*v))*exp(-0.991617d0*v)
      t3=0.25d0*rcur*up/v
      pinc=t1+t2
      pres=conver*pinc+t3
      go to 100
c
C 7/ WT0 LOW-DENSITY EXPLOSIVE CHARGE -----------------------------------
C    (pinc=[DYNES/CM2])
c
    7 v=rref/rcur
      t1=1.7039D11*(1.d0-1.d0/(90.0d0*v))*exp(-9.0d0*v)
      t2=1.1595D10*(1.d0-1.d0/(24.0d0*v))*exp(-2.4d0*v)
      t3=0.1d0*rcur*up
      pinc=t1+t2
      pres=conver*pinc+t3
      GO TO 100
c
C 8/ WT0 LIQUID WATER ---------------------------------------------------
C    (pinc=[DYNES/CM2])
c
    8 vv=rcur/rref
      if(vv.ge.1.d0) then
        t1=1.2222D11*vv*vv+5.1562D10-(1.2222D11+5.1562D10)*vv**1.28D0
      else
        t1=-1.2222D11*vv*vv-8.5937D10+(1.2222D11+8.5937D10)*vv**1.28D0
      endif
      pinc=t1
      pres=conver*pinc
      GO TO 100
c
C 9/ Liquid with bulk response -----------------------------------------
c
    9 v=rref/rcur
      eta=1.0d0-v
      p0=pb
      bulk=gam
      pres=p0+bulk*eta
      go to 100
```

```
c
C 10/ Imposed pressure ---------------------------------------------------
c
   10 ifonc=pb
      tcur=t
      call ffonct(ifonc,tcur,valfon,a(n91),a(n92))
      pres=valfon
      go to 100
C
c=========================================================================
C PRESSURE CUT-OFF TEST
C
  100 IF(pres.LE.PMIN) THEN
        pres=PMIN
        XKP=1.D0
      ELSE
        XKP=0.D0
      ENDIF
C
c=========================================================================
C SOUND SPEED
C
      goto(101,101,101,101,101,101,101,101,102,103),num
c
c materials 1-8
c
  101 SOUND=sqrt(GAM*(pres+PB)/rcur)
      go to 999
c
c material 9
c
  102 sound=sqrt(bulk/rcur)
      go to 999
c
c material 10
c
  103 sound=zero
      go to 999
C
  999 RETURN
      END
```

7.8.31 MATERIAL FOR MINERAL OIL PYROLISIS

Object

This material is used to simulate mineral oil pyrolisis phenomena subsequent to electrical arcs in oil-filled electrical apparatuses (e.g. transformers).

The material is part of the models developed by the CESI team (formerly at ENEL, Milano) in collaboration with JRC.

Rather than a new material, it is an extension of the user-defined FLUT type material (see Page C3.520). The extension is introduced by the keyword "PYRO", as explained in the syntax below.

References

More information on the formulation of this material model may be found in references [106, 160].

Syntax

```
"FLUT"  FLUT_material_data (see P. C.520)
      < "PYRO" "NC" nc "EACT" eact "RGAS" rgas "TREF" tref
               "ROIL" roil "KOIL" koil "TOIL" toil "PINI" pini
               "TINI" tini "QTAB" qtab "DHRO" dhro
               "NGAS" ngas
                ngas * ( "GAS" 'nomgas' "STEC" stec "PMOL" pmol
                               "DHR" dhr "CP" cp )
                         "CARB" 'nomcar' "STEC" stec "PMOL" pmol
                               "DHR" dhr "CP" cp                  >
         /LECTURE/
```

`nc`

Number of carbon atoms in oil molecule.

`eact`

Activation energy.

`rgas`

Gas constant.

`tref`

Reference temperature.

`roil`

Liquid oil density.

`koil`

Liquid oil thermal conductiviy.

`toil`

Liquid oil temperature.

`pini`

Initial pressure of the bubble.

`tini`

Initial temperature of the bubble.

`qtab`

Index of "FONCTION" for electrical power. This function will describe the power as a function of time.

`dhro`

Liquid oil enthalpy of formation.

`ngas`

Number of gas products.

`nomgas`

Name of gas product (8 chars max.).

`stec`

Stechiometric coefficient for this product in the pyrolisis reaction.

`pmol`

Molar weight of the product.

`dhr`

Molar enthalpy of formation of the product.

`cp`

Heat capacity at constant pressure of the product.

`nomcar`

Name of the carbon product.

Comments:

This model is still under development and testing and should therefore be used with great care.

Do not forget to dimension adequately, see keyword ”PYRO”, page A.70. Currently there may be up to 4 distinct pyrolisis bubbles in a calculation.

7.8.32 ADVECTION-DIFFUSION FLUID (ADFM)

Object:

This material is used with specialised elements of type "ADC8" or "ADQ4", for advection-diffusion calculations.

Syntax:

```
"ADFM" ![ "RO" rho  "EXPA" expa  "TREF" tref
        < "COND" cond   "CAPA" capa   "VISC" visc
          "LAPI" lapi                              > ]!
         /LECTURE/
```

`rho`

Initial mass density.

`expa`

Volumetric expansion coefficient.

`tref`

Reference temperature at which volumetric expansion is null.

`cond`

Thermal conductivity. By default, is f(T).

`capa`

Thermal capacity. By default is f(T).

`visc`

Dynamic viscosity. By default is f(T).

`lapi`

Lapidus viscosity. Default is 0.0.

Comments:

If omitted, thermal conductivity, capacity and viscosity are assumed to be temperature dependent. The user must insuch cases supply routines that return temperature dependent values.

7.8.33 MULTICOMPONENT FLUID MATERIAL (MCGP)

Object:

This material is used with specialised elements of type MCxx for multicomponent fluid flows. A mixture of calorically perfect gases is assumed, i.e. the internal energy is a function of the temperature only. This function may be different for each component and has a generic polynomial form.

The contribution of the CESI team (formerly at ENEL, Milano) to the development of this material model in collaboration with JRC is gratefully acknowledged.

Syntax:

```
"MCGP"  "NCOM" ncom  "R" r
         ncom * ( "COMP" 'nomcomp'
                  "PM" pm
                  "CV1" cv1 "CV2" cv2 "CV3" cv3 )
         /LECTURE/
```

`ncom`

Number of components in this material.

`r`

Universal constant of gases (R), must be expressed in J/(kmol K).

`nomcomp`

Name of the component (max 8 characters) in quotes.

`pm`

Molecular weight w of the component, in kg/kmol.

`cv1/2/3`

Coefficients of the expression of the specific heat at constant volume (c_v), which must be expressed in J/kmolK, as a function of absolute temperature T: $c_v(T) = c_{v1}+c_{v2}T+c_{v3}T^2$. The specific internal energy i results from $i(T) = c_vT = c_{v1}T + c_{v2}T^2 + c_{v3}T^3$. Note that i must be expressed in J/kmol. T is the temperature in K. Consequently, c_{v1} must be in J/kmolK, c_{v2} must be in J/kmol(K2) and c_{v3} must be in J/kmol(K3).

Comments:

Only one material of type multicomponent fluid is allowed in a model. This is not a restriction, since the number of components is arbitrary and component mass fractions can be locally zero.

The polytropic exponent $\gamma = c_p/c_v = (R + c_v)/c_v$, is determined by the code. Therefore, note that the units of the various c_v coefficients in the above expression for i should be consistent with the units used for R. For example, c_{v1} should be expressed in J/(kmol K).

Also the density is determined by the code.

Comparing FE and FV solutions.

Frequently it is desirable to compare solutions obtained with Finite Element (FE) models to equivalent ones obtained with Finite Volumes (FV), typically for the case of perfect gases. In the case of FLUT material used for Finite Elements (see page C.520), the equivalence of initial conditions is not completely straightforward. A procedure for converting between the two formulations is detailed hereafter.

The two fluid solvers have completely different ways to carry out the numerical discretization of the same governing equations (Euler equations); each of them has its specific formulation, its own set of variables and its own parameters, whose value has to be assigned in the input data.

More in detail, in the FE model the perfect gas state equation used to close the system of Euler equations has the form:

$$p = (\gamma - 1)\rho i,$$

where p is the pressure (Pa), ρ is the density (Kg/m^3), i is the internal energy per unit mass (J/Kg) and γ (-) is the ratio between the constant pressure and constant volume specific heats c_p (J/kmolK) and c_v (J/kmolK). The user must in this case provide in input the values of γ, ρ and i (see `MATE FLUT` on Page C.520).

In the FV model the same state equation takes the form:

$$p = RT\frac{\rho}{w},$$

where R is the universal constant of gases (J/kmolK), which has the standard value of 8314.3, T is the absolute temperature (K) and w is the molar weight (kg/kmol). Note that the state equation in the FV model could be more complex, taking into account a more general mixture of Joule gases. We consider here a single-component perfect gas for simplicity. The user must in this case provide in input the values of R, c_v and w for the material (see `MATE MCGP` above), plus the initial values of p and T at each node (and thus at each finite volume), via the directive `INIT MCOM` (see Page E.150).

Switching from FV to FE, an equivalent input can be obtained readily from the identities:

$$\gamma = \frac{R}{c_v} + 1 \qquad i = \frac{c_v}{w}T \qquad \rho = \frac{wp}{RT}$$

The inverse path is not so straightforward. The switch from FE to FV is not univocally determined unless the molar weight w is known. Indeed the physics of the problem only depends on the internal energy i (see above), which is proportional to the ratio T/w by means of the value:

$$c_v = \frac{R}{\gamma - 1}$$

Then it is possible to choose any couple T and w so as to have the appropriate i, but values of temperature would in general *not* be correct during a calculation.

As an example, consider the following set of initial conditions, which have been chosen without actual physical relevance and have been rounded in order to easily check the equivalence of the several parameters values in the FE and FV representation.

Assume we want to simulate two perfect gases, one initially at high pressure and the other initially at low pressure. Let $\gamma = 1.5$ and $\rho = 2$ kg/m^3 for both gases. If the HP-gas has an initial pressure of $p_H = 5.E5$ Pa, then we get from the equation of state in FE form: $i_H = p_H/(\gamma - 1)\rho = 5.E5$ J/kg. Similarly, for the LP-gas at, say, $p_L = 1.E5$ Pa we obtain $i_L = p_L/(\gamma - 1)\rho = 1.E5$ J/kg. These values completely define the FE material data.

To get an equivalent FV description, we must provide the constant of perfect gases, which in standard units is about $R = 1.E4$ J/kmolK, and we must choose a molar weight, say $w = 20$ kg/kmol for both gases. Then we obtain the specific heat at constant volume (same for both gases) from the relation $c_v = R/(\gamma - 1) = 2.E4$ J/kmolK.

Assuming for both gases the same initial density $\rho = 2$ kg/m^3 as in the FE case, we may compute the temperature from the relation $T = wp/\rho R$. For the H-P gas ($p_H = 5.E5$ Pa) this gives $T = 500$ K, while for the L-P gas ($p_L = 1.E5$ Pa) this gives $T = 100$ K.

7.8.34 MULTICOMPONENT FAR-FIELD FLUID MATERIAL (MCFF)

Object:

This material is used with specialised elements of type CL22, CL3I or CL3Q to specify far-field conditions of multicomponent flows. It specifies the constant physical state: $\rho(1)$, ... $\rho(\text{ncom})$, ρu, ρv, ρw, ρE, assumed outside the discretized fluid domain.

Unlike material MCGP, which must be unique in a single calculation, an arbitrary number of MCFF materials is allowed. However, note that the declaration of the MCGP material MUST precede the declaration of the MCFF(s) in the input data set.

The contribution of the CESI team (formerly at ENEL, Milano) to the development of this material model in collaboration with JRC is gratefully acknowledged.

Syntax:

```
"MCFF" "BDFO" bdfo "TEMP" temp "PRES" pres "VEL1" vel1
       "VEL2" vel2 "VEL3" vel3
         ncom * ( "COMP" 'nomcomp' "MFRA" mfra )
         /LECTURE/
```

`bdfo`

Option for boundary flux: 1 = Roe, 2 = Van Leer, 3 = Steger-Warming. Recall that the flux type in the bulk fluid is chosen (independently from the boundary flux type) by directive `OPTI MC NUFL`.

`temp`

Temperature of the far-field state.

`pres`

Pressure of the far-field state.

`vel1`

X-velocity of the far-field state.

`vel2`

Y-velocity of the far-field state.

`vel3`

Z-velocity of the far-field state.

`ncom`

Number of components (must be the same as for the MCGP material).

`nomcomp`

Name of the component (max 8 characters) in quotes, must be spelled exactly as in the definition of the MCGP material.

`mfra`

Mass fraction of the component.

Comments:

The key-words `TEMP` ... `VEL3` must precede the declaration of the mass fractions `COMP` ... `MFRA` in the input data set.

7.8.35 MULTIPHASE MULTICOMPONENT FLUID MATERIAL (FLMP)

Object:

This material is used with FLxx elements to describe multi-phase multicomponent fluid flows. In this formulation, more than one fluid material (liquids, perfect gases) may be present at the same time inside a generic finite element. The material is treated as a homogeneous mixture of the component fluids.

The velocity field is unique (i.e., all components have the same velocity. The pressure is defined at the element level as follows: if one or more liquids are present, they are subjected to the same pressure. If more than one gas is present, the gases in the mixture follow Dalton's law: the sum of the partial pressures of the gas components equals the pressure of the mixture.

This 'material' (type FLMP) is composed of several FLUT materials (see page C3.520).

Note: this material is still under development and testing. It has to be used with great care.

Syntax:

```
"FLMP" "NLIQ" nliq "NGAS" ngas
        nliq * ( "FLUT" liquid_material_description )
        ngas * ( "FLUT" gas_material_description    )
```

`nliq`

Total number of liquid materials in the mixture.

`ngas`

Total number of gas materials in the mixture.

Comments:

The liquid materials must precede the gas materials.

The program considers the first nliq FLUT-material descriptions encountered in the input file after the "FLMP" directive as descriptions of the liquid materials, and the successive ngas FLUT-material descriptions as descriptions of the gas materials.

The elements to which each FLUT material is associated are specified as usual via a /LECTURE/ directive at the end of each FLUT-material description. As a consequence, each element containing a FLMP mixture will effectively contain only one component (with a 100 per cent mass fraction) at the initial time. Because of this, it is not possible to effectively have more than one material in any element in the initial conditions. However, during the transient analysis the materials will mix up because of transport between adjacent elements, thus forming the mixture.

Outputs:

The components of the ECR table are as follows:

Positions 1-9 are equivalent to those of the FLUT material:

ecr(1): current element pressure of the fluid mixture

ecr(2): current AVERAGE density of the fluid mixture

ecr(3): current sound speed of the fluid mixture

ecr(4): current AVERAGE specific internal energy of the fluid mixture

ecr(5): current AVERAGE bulk modulus of the fluid mixture

ecr(6): current pseudoviscous pressure of the fluid mixture

ecr(7): current minimum pressure flag of the fluid mixture

ecr(8): maximum pressure ever experienced by the element

ecr(9): minimum pressure ever experienced by the element

ecr(10): number of effective components in the element

Then, for each component icom of the mixture:

```
iad=nfixmp+(icom-1)*necrmp (see FLUTMP.INC)
```

ecr(iad+1): current relative mass fraction of the component

ecr(iad+2): current density of the component

ecr(iad+3): current specific internal energy of the component

ecr(iad+4): current partial pressure of the component

ecr(iad+5): mass fraction of the component at the end of Lagrangian phase

ecr(iad+6): specific internal energy of the component at the end of Lag. ph.

There may be at most 4 different components in a FLMP material, at present. Thus, there is place for up to (10 + 6 x 4) = 34 components of ECR at each Gauss point of an element with a FLMP material.

7.8.36 SG2P—Multicomponent Stiffened Gases - Fully Conservative Formulatoin

Object:

Modeling of multicomponent flows involving extended Stiffened Gas Equation of State (EoS). Each component of the mixture is described by an Stiffened Gas EoS:

$$P = (\gamma - 1)\rho(e - q) - \gamma P_{inf}$$

Where e is the internal energy per unit mass, ρ the density. γ is an empirical constant for liquids. P_{inf} is a constant representing the molecular attraction between molecules (liquid) and q is an additional constant. This expression is identical to the ideal gas EoS when P_{inf} and q is zero. The governing equations are the Euler Equations in conservative form and a transport equation for the volume fraction (For more details see also [923]).

Syntax:

```
"SG2P"  "PINI"  pini  "PREF" pref  "PMIN" pmin
   ...  "NESP"  nesp

   ...

   ...  "COMP1"
   ...  "ROI"  roi
   ...  "GAMM" gamm  "PI" pinf  "Q"  q  "ALPH" alpha
   ...  "CP" cp  "CV"  cv  "QPRI"  qprim

   ...

   ...  "COMPnesp"
   ...  "ROI"  roi
   ...  "GAMM" gamm  "PI" pinf  "Q"  q  "ALPH" alpha
   ...  "CP" cp  "CV"  cv  "QPRI"  qprim

   ... /LECTURE/
```

`pini`

Initial pressure of the mixture.

`pref`

Reference pressure.

`pmin`

Absolute minimum pressure `pmin` in the fluid.

`nesp`

Number of components involved in the mixture

"COMP1", . . . , "COMPnesp"

Keywords which state that we will describe the properties of the components 1,. . . ,nesp.

`roi`

initial density of the component

`gamma`

Ratio c_P/c_V (supposed constant) for gases and an empirical constant for liquid.

`pinf`

Constant parameter for liquid to take into account molecular attraction between molecules.

`q`

Internal energy of the fluid at a given reference state (most time one take `q = 0`).

`alpha`

Initial volume fraction of the component

`cp`

Constant pressure specific heat

`cv`

Constant volume specific heat

`qprim`

parameter used in the determination of the entropy and free Gibbs energy of each component in case of phase change (Under Development !).

`/LECTURE/`

List of the elements concerned.

Comments:

The reference pressure pref enables the initial state to be defined. If `pref = pini`, the gas is in equilibrium just before the computation starts; it will be perturbed by an external action, by the motion of a piston, for instance. If `pref = 0`, the problem consist in a computation with initial stresses determined by `pini`. This is the case when a membrane which was separating two gases at different states disappears at the initial instant.

The sum of all initial volume fractions of the different components should be equal to 1 .

Outputs:

Then the different components of the ECR table are:

ECR(1) : pressure

ECR(2) : density of the mixture

ECR(3) : sound speed of the mixture

ECR(4) : free

ECR(4 + iesp) : mass fraction of the iesp-th component

Example:

We consider a mixture of three stiffened gases in a box The initial configuration consists to a 1 m × 1 m square box filled with a gas at rest at atmospheric pressure containing two concentric bubbles which are at rest as well, with different pressure and physical characteristics. The radius of the bubbles are 0.1 m and 0.25 m, respectively. The three different gases are denoted 1 (zone SS1) in the box, 2 in the middle bubble (ZONE SPH1)and 3 in the smaller one (ZONE SPH2) and are modeled as perfect gases ($pinf = 0$ and $q = 0$ in EoSs). For this example, more details can be found in [923].

The initial conditions are given:

$$\begin{cases} \gamma = 1.4, & \rho = 1.376363 \text{ kg.m}^{-3}, & p = 10^5 \text{ Pa} & \text{for gas 1 in the box} \\ \gamma = 1.667, & \rho = 0.192 \text{ kg.m}^{-3}, & p = 10^6 \text{ Pa} & \text{for gas 2 in the middle bubble} \\ \gamma = 1.249, & \rho = 3.1538 \text{ kg.m}^{-3}, & p = 5 \times 10^5 \text{ Pa} & \text{for gas 3 in the smaller bubble} \end{cases}$$

```
*
*                  GAS IN THE BOX
*                  --------------
*
    SG2P
*
         PINI 1.E5 PMIN 1e-3 PREF 1E5 NESP 3

*     COMP1
      COMP1
      ROI  1.376363
      PI   0
```

```
        GAMM 1.4
        ALPH 1
        Q    0
        CP   0
        CV   0
        QPRI 0

*       COMP2
        COMP2
        ROI  0.192
        PI   0.
        GAMM 1.667
        ALPH 0
        Q    0
        CP   0
        CV   0
        QPRI 0

*       COMP3
        COMP3
        ROI  0.192
        PI   0.
        GAMM 1.249
        ALPH 0
        Q    0
        CP   0
        CV   0
        QPRI 0
*
                                    LECT SS1 TERM
*
*                    GAS IN THE SMALLER BUBBLE
*                    -------------------------
*
        SG2P
*
           PINI 5E5 PMIN 1E-3 PREF 1E5 NESP 3

*       COMP1
        COMP1
        ROI  1
        PI   0.
        GAMM 1.4
        ALPH 0
        Q    0
        CP   0
        CV   0
        Qpri 0

*       COMP2
        COMP2
```

```
        ROI  0.192
        PI   0.
        GAMM 1.667
        ALPH 0
        Q    0
        CP   0
        CV   0
        Qpri 0

  *     COMP3
        COMP3
        ROI  3.1538
        PI   0.
        GAMM 1.249
        ALPH 1
        Q    0
        CP   0
        CV   0
        QPRI 0
                                    LECT SPH2 TERM
  *
  *             GAS IN THE MIDDLE BUBBLE
  *             ------------------------
  *
        SG2P
  *
           PINI 10E5 PMIN 1E-3 PREF 1E5 NESP 3

  *     COMP1
        COMP1
        ROI  0.181875
        PI   0.
        GAMM 1.4
        ALPH 0
        Q    0
        CP   0
        CV   0
        Qpri 0

  *     COMP2
        COMP2
        ROI  0.192
        PI   0.
        GAMM 1.667
        ALPH 1
        Q    0
        CP   0
        CV   0
        Qpri 0

  *     COMP3
```

```
        COMP3
        ROI  0.192
        PI   0.
        GAMM 1.249
        ALPH 0
        Q    0
        CP   0
        CV   0
        QPRI 0
*
                                    LECT SPH1 TERM
```

7.8.37 SGMP—Multicomponent Stiffened Gases models

Object:

Modeling of multicomponent flows involving extended Stiffened Gas Equation of State (EoS). Each component of the mixture is discribe by an Stiffened Gas EoS:

$$P = (\gamma - 1)\rho(e - q) - \gamma P_{inf}$$

Where e is the internal energy per unit mass, ρ the density. γ is an empirical constant for liquids. P_{inf} is a constant representing the molecular attraction between molecules (liquid) and q is an additional constant. This expression is identical to the ideal gas EoS when P_{inf} and q is zero. The governing equations are the Euler Equations in conservative form and a transport equation for the volume fraction (For more details see also [923, 879, 926]).

Syntax:

```
"SGMP"  "PINI"  pini   "PREF" pref  "PMIN" pmin
   ...  "NESP"  nesp  <"MODE" imod>

   ...

   ...  "COMP1"
   ...  "ROI"  roi
   ...  "GAMM" gamm  "PI" pinf  "Q"  q  "ALPH" alpha
   ...  "CP" cp  "CV"  cv  "QPRI"  qprim

   ...

   ...  "COMPnesp"
   ...  "ROI"  roi
   ...  "GAMM" gamm  "PI" pinf  "Q"  q  "ALPH" alpha
   ...  "CP" cp  "CV"  cv  "QPRI"  qprim

   ... /LECTURE/
```

`pini`

Initial pressure of the mixture.

`pref`

Reference pressure.

`pmin`

Absolute minimum pressure `pmin` in the fluid.

`nesp`

Number of components involved in the mixture

`imod`

Type of model used

1 multicomponents ALE extension of the two-phase flow model of Allaire et al. designed for interface problems (default value).

2 Multicomponents ALE extension of the two-phase flow model of Kapila et al.

"COMP1", . . . , "COMPnesp"

Keywords which state that we will describe the properties of the components 1,. . . ,nesp.

`roi`

initial density of the component

`gamma`

Ratio c_P/c_V (supposed constant) for gases and an empirical constant for liquid.

`pinf`

Constant parameter for liquid to take into account molecular attraction between molecules.

`q`

Internal energy of the fluid at a given reference state (most time one take `q = 0`).

`alpha`

Initial volume fraction of the component

`cp`

Constant pressure specific heat

`cv`

Constant volume specific heat

`qprim`

parameter used in the determination of the entropy and free Gibbs energy of each component in case of phase change (Under Development !).

`/LECTURE/`

List of the elements concerned.

Comments:

Theses models are **Only available** with the HLLC Solver (Option FCONV 6 which is the default value)

The reference pressure pref enables the initial state to be defined. If `pref = pini`, the gas is in equilibrium just before the computation starts; it will be perturbated by an external action, by the motion of a piston, for instance. If `pref = 0`, the problem consist in a computation with initial stresses determined by `pini`. This is the case when a membrane which was seperating two gases at different states disappears at the initial instant.

The sum of all initial volume fractions of the differents components should be equal to 1 .

Each phase is governed by its own EOS allowing the determination of the speed of sound of each phase: $c_k^2 = \left(p/\rho_k^2 - \partial_{\rho_k} e_k\right)\left(\partial_p e_k\right)^{-1}$.

For model 1 the mixture sound speed is some kind of average of the phase speed of sound (often call frozen sound speed [879]) and is designed for interface problems. For model 2 the mixture sound speed $\check{c}$ obeys the Wood formula [879]:

$$\frac{1}{\rho \check{c}^2} = \frac{\alpha_1}{\rho_1 c_1^2} + \frac{\alpha_2}{\rho_2 c_2^2} \tag{71}$$

Outputs:

Then the different components of the ECR table are:

ECR(1) : pressure

ECR(2) : density of the mixture

ECR(3) : sound speed of the mixture

ECR(3 + iesp) : mass fraction of the iesp-th component

ECR(3 + nesp + iesp) : volume fraction of the iesp-th component

ECR(3 + 2*nesp + iesp) : temperature of the iesp-th component (for phase change : Under Development)

ECR(3 + 3*nesp + iesp) : free Gibbs energy of the iesp-th component (for phase change : Under Development)

Example:

We consider a mixture of three stiffened gases in a box The initial configuration consists to a 1 m × 1 m square box filled with a gas at rest at atmospheric pressure containing two concentric bubbles which are at rest as well, with different pressure and physical characteristics. The radius of the bubbles are 0.1 m and 0.25 m, respectively. The three different gases are denoted 1 (zone SS1) in the box, 2 in the middle bubble (ZONE SPH1)and 3 in the smaller one (ZONE SPH2) and are modeled as perfect gases ($pinf = 0$ and $q = 0$ in EoSs). For this example, more details can be found in [923].

The initial conditions are given:

$$\begin{cases} \gamma = 1.4, & \rho = 1.376363 \text{ kg.m}^{-3}, & p = 10^5 \text{ Pa} & \text{for gas 1 in the box} \\ \gamma = 1.667, & \rho = 0.192 \text{ kg.m}^{-3}, & p = 10^6 \text{ Pa} & \text{for gas 2 in the middle bubble} \\ \gamma = 1.249, & \rho = 3.1538 \text{ kg.m}^{-3}, & p = 5 \times 10^5 \text{ Pa} & \text{for gas 3 in the smaller bubble} \end{cases}$$

```
*
*                  GAS IN THE BOX
*                  --------------
*
  SGMP
*
         PINI 1.E5 PMIN 1e-3 PREF 1E5 NESP 3 MODEL 1

*     COMP1
      COMP1
      ROI  1.376363
      PI   0
      GAMM 1.4
      ALPH 1
      Q    0
      CP   0
      CV   0
      QPRI 0

*     COMP2
      COMP2
      ROI  0.192
      PI   0.
      GAMM 1.667
      ALPH 0
      Q    0
      CP   0
      CV   0
      QPRI 0

*     COMP3
      COMP3
      ROI  0.192
      PI   0.
      GAMM 1.249
      ALPH 0
      Q    0
      CP   0
      CV   0
      QPRI 0
*
```

```
                                                 LECT SS1 TERM
*
*                 GAS IN THE SMALLER BUBBLE
*                 -------------------------
*
  SGMP
*
        PINI 5E5 PMIN 1E-3 PREF 1E5 NESP 3 MODEL 1

*     COMP1
      COMP1
      ROI  1
      PI   0.
      GAMM 1.4
      ALPH 0
      Q    0
      CP   0
      CV   0
      Qpri 0

*     COMP2
      COMP2
      ROI  0.192
      PI   0.
      GAMM 1.667
      ALPH 0
      Q    0
      CP   0
      CV   0
      Qpri 0

*     COMP3
      COMP3
      ROI  3.1538
      PI   0.
      GAMM 1.249
      ALPH 1
      Q    0
      CP   0
      CV   0
      QPRI 0
                                                 LECT SPH2 TERM
*
*                 GAS IN THE MIDDLE BUBBLE
*                 ------------------------
*
  SGMP
*
        PINI 10E5 PMIN 1E-3 PREF 1E5 NESP 3 MODEL 1

*     COMP1
```

```
        COMP1
        ROI  0.181875
        PI   0.
        GAMM 1.4
        ALPH 0
        Q    0
        CP   0
        CV   0
        Qpri 0

*       COMP2
        COMP2
        ROI  0.192
        PI   0.
        GAMM 1.667
        ALPH 1
        Q    0
        CP   0
        CV   0
        Qpri 0

*       COMP3
        COMP3
        ROI  0.192
        PI   0.
        GAMM 1.249
        ALPH 0
        Q    0
        CP   0
        CV   0
        QPRI 0
*
                                    LECT SPH1 TERM
```

7.8.38 BUBBLE MODEL

Object :

This directive simulates an explosion in air. It allows to load a structure without having to model the explosive as an initially solid material which changes phase to gas. Instead of the solid explosive a compressed bubble is used. The overpressure of this bubble is automatically calculated depending on the mass of the charge and the volume of the bubble.

The model can be used with either FE or VFCC models of the fluid domain. The BUBB material is automatically mapped to either `GAZP` or `FLUT` material, as appropriate. `GAZP` is used if the bubble and its neighbours are discretized by either VFCC (CUVF etc.) or CEA's fluid FE (CUBE etc.), while `FLUT` is used if the bubble and its neighbors are discretized by JRC's fluid FE (FL38 etc.).

Syntax:

```
"BUBB" "MASS" m /LECTURE/
```

`m`

Mass of the explosive in kilograms.

`/LECT/`

Elements concerned (bubble volume).

Comments :

The mass of the explosive is always the mass of the bubble as defined by the concerned elements. This has to be taken into account in simulations with symmetry conditions or in a case of a hemispherical explosion. At a border with symmetry, also the charge has to be cut. At a border of a hemispherical model, the charge must not be cut.

The BUBB material adopts the same material parameters as the fluid elements (or finite volumes) neighboring the bubble zone. Therefore the material for the neighbors has to be defined *before* the BUBB material itself.

Outputs:

The different components of the ECR table are the components of the `GAZP` or `FLUT` material to which the BUBB material is mapped. This depends on the elements used to discretize the fluid bubble: GAZP is used by either VFCC or CEA's fluid FE, while FLUT is used by JRC's fluid FE.

7.8.39 CDEM—Discrete Equation Method for Combustion

Object:

Extension of the Reactive Discrete Equation Method (RDEM method) proposed by Le Métayer *et al.* (see: O. Le Métayer, J. Massoni, R. Saurel. Modelling evaporation fronts with reactive Riemann solvers. Journal of Computational Physics **205**: 567–610, 2005) to the combustion case [873, 874, 891, 893, 921, 922], with the purpose of propagating a combustion front.

The combustion is supposed irreversible and complete; then at each point we can have either the burnt gas (or **burnt "phase"**) or the unburnt gas (or **unburnt "phase"**), interacting with each other only via the chemical reaction occurring at the combustion front. Then in the exact solution the fraction volume of each phase is either 0 or 1, presenting a discontinuity at the combustion front. But for numerical reasons both phases are present in each cell at any moment, with each phase occupying a certain volume fraction of the cell (of course the two volume fractions sum up to 1.0).

Each of the two phases has its own density, pressure, velocity and temperature, independent of the values for the other phase (the only coupling being the chemical reaction at the combustion front). Global values of pressure, density, temperature and velocity for the mixture of the two phases (i.e. for the cell) are computed as weighted averages of the values of the two phases, the weights being the respective volume fractions in the cell. This way of computing global values is consistent with the fact that in the exact solution only one phase is present at each point.

Note that this approach is radically different from the one used in other "multi-material" models available in the code. For example, in the multi-phase multi-component (non-reactive) fluid material model `FLMP` which can be used with fluid Finite Elements (not VFCCs), see GBC_0570, in case of a mixture of only gases each component is assumed to occupy the whole volume of the cell, so that the global pressure and density are the sums (not the weighted averages) of the values for each component, and moreover all components are supposed to have the same temperature (thermal equilibrium) and the same velocity.

In the CDEM model each phase is a mixture of different gases, i.e of different chemical species. If the concentration of species is exactly stoichiometric, then the unburnt phase contains only the reactants and the inerts (if any), while the burnt phase contains only the reaction products and the inerts (if any). However, the model is fully general and even non-stoichiometric concentrations can be considered, so that in general each phase may contain all the involved species (reactants, reaction products and inerts, if any).

Note that in general it is necessary to take into account the presence of inerts. Although they do not participate in the chemical reaction, their mass fraction can be important (consider e.g. nitrogen in the case of air) so that their heat capacity gives an important contribution to the global heat balance of the mixture.

The combustion is governed by an **irreversible exothermic** chemical reaction. Usually (in chemistry) this is written as follows, i.e. with reactants only on the left hand side and with reaction products only on the right hand side:

$$\sum_{r=1,\mathrm{nrea}} c_r \mathrm{A}_r \rightarrow \sum_{p=1,\mathrm{npro}} c_p \mathrm{A}_p$$

where `nrea` is the number of chemical species on the left-hand side of the chemical reaction (i.e., the number of reactants), while `npro` is the number of chemical species on the right hand side of the chemical reaction (i.e. the number of reaction products). Any inerts, which can be present in the mixture, are usually not explicitly included in the expression of the chemical reaction. Thus, the c_r and c_p coefficients in the above expression are strictly positive.

In the CDEM model this expression is re-arranged as follows, by bringing all terms to the left hand side and by letting also the inerts (if any) appear:

$$\sum_{i=1,\text{nesp}} c_i \text{A}_i \rightarrow 0$$

where `nesp` is the total number of chemical species present (i.e. the reactants, the reaction products and the inerts, if any): `nesp = nrea + npro + nine`. The coefficient c_i is thus strictly positive for reactants, strictly negative for reaction products and zero for inerts, if any.

The governing equations are the Euler Equations and a transport equation for the volume fraction [893, 921, 922]. The main conserved variables for each phase are the mass densities of the components, the momentum and the total energy (sensible + chemical + kinetic) per unit volume.

Syntax:

```
"CDEM"  "TINI" tini    "PINI"  pini  <"PREF" pref>
   ...  "KSI0" ksi0   "K0" k0
   ...  "TMAX" tmax    "R" rgas
   ...  "NESP" nesp    "ORDP" ordp    "NLHS" nlhs
   ...
   ...  "COMP1"
   ...  "MMOL"  mmol   "H0" h0    "CREA" crea
   ...  "CV0" cv0  "CV1" cv1 ... "CVordp" cvordp
   ...  "YMAS" ymas
   ...
   ...  . . .
   ...
   ...  "COMPnesp"
   ...  "MMOL"  mmol   "H0" h0    "CREA" crea
   ...  "CV0" cv0  "CV1" cv1 ... "CVordp" cvordp
   ...  "YMAS" ymas
   ...
   ... <"KOF" kof>
   ... <"UCDS" ucds>
   ... <"DIRE" dire>
   ... <"T0   " temp0>
   ... <"H    " hcoef>
   ... <"GX   " gx>
   ... <"GY   " gy>
   ... <"GZ   " gz>
   ... <"CFLA" 1  "SL   "  sl  "PSL " psl "TSL " tsl
         "DL " dl  "LE  " le  "PU  " pu
         "XIG " xig  "YIG " yig "ZIG " zig>
   ... <"CFLA" 2  "SL   "  sl  "PSL " psl "TSL " tsl
         "DL " dl  "LE  " le  "A   " acoef "B   " bcoef
         "R0 " r0  "XIG " xig  "YIG " yig "ZIG " zig>
 /LECT/
```

First, some **properties of the mixture** as a whole (unburnt plus burnt phases) are defined. The code accepts any consistent units set (under the user's responsibility). The SI units are given below in brackets for each quantity [·] just as a reference.

`tini`

Initial temperature of the mixture [K].

`pini`

Initial pressure of the mixture [Pa].

`pref`

Reference pressure [Pa].

`ksi0`

Initial volume fraction [–] of the burnt phase Ξ_{0b} i.e. volume of the burnt phase over total volume of the mixture (sum of burnt plus unburnt phases). Typical initial values would be 0.0 for an initially completely unburnt zone and 1.0 for an initially completely burnt zone (trigger). However, *for numerical reasons* it is advised to specify slightly different (non-round) values, e.g. 0.001 and 0.999, respectively. Note that the sum of Ξ_{0b} over the different initial zones is not necessarily 1.0. It is the sum $(\Xi_{0b} + \Xi_{0u})$, where Ξ_{0u} is the initial volume fraction of the unburnt phase (not explicitly defined and used in this model), which must be 1.0, of course. Note that the initial volume fractions of the burnt and unburnt phases Ξ_{0b} and Ξ_{0u} are totally unrelated with the initial mass fractions $Y_{i,u}$ of components in the unburnt state (see `ymas` below).

`k0`

Part of the fundamental flame speed `k` transported with the flow [m/s]. The fundamental flame speed is given by `k = k0 + k0f`, where `k0f` is optionally defined below (else it is 0). Note that, in alternative to assigning it by giving `k0` and `k0f`, the fundamental flame speed `k` can be automatically computed by the code. To this end, activate the `CFLA 1` optional keyword (see below). In this case a value for `k0` must still be specified, but it is simply ignored by the code.

`tmax`

Maximum value of the temperature for the computation of the specific heats [K]. For temperatures $T > T_{\max}$ the code takes $C_V(T) = C_V(T_{\max})$.

`rgas`

Gas constant R, equal to 8.3144621 in SI units [J/(mol·K)].

`nesp`

Total number of species [–] involved in the mixture: reactants, reaction products and inerts, if any.

`nlhs`

Number of species [–] in the left hand side of the chemical reaction, i.e. number of reactants. If there are any inerts, these are **not** counted here.

`ordp`

Temperature polynomial degree [–] for the constant volume specific heat computation.

Then, we specify the **properties of each species** (i.e. of each component) of the mixture. Note that the species must be listed in the order in which they appear in the chemical reaction equation.

"COMP1", . . . , "COMPnesp"

Keywords which state that we will describe the properties of the species 1,. . . ,nesp. Note, however, that the numbers 1,. . . ,nesp are only a visual indication for the user: the code interprets only the first four letters of each keyword (`COMP` in this case), so these digits (1, 2, etc.) are ignored. It is the User's responsibility to list the components in the correct order, as specified above.

`mmol`

Molar mass [kg/mol].

`h0`

Formation enthalpy [J/kg] at $T = 0$ K.

`crea`

Coefficient [–] in the chemical reaction (positive if the species is a reactant).

`cv0, ..., cvordp`

Coefficient of T^0, . . . , T^{ordp} for the computation of the constant volume specific heat. The expression used is $C_V(T) = C_{V0} + C_{V1}T + C_{V2}T^2 \ldots$ so that C_{V0} is in J/(Kg·K), C_{V1} is in J/(Kg·K^2), etc.

`ymas`

Initial mass fraction $Y_{i,u}$ of the current component [–] before the combustion occurs, i.e. in the **unburnt** state. This is the mass of the current component divided by the total mass of the unburnt phase in the cell. Note that the possible presence also of some burnt phase in the same cell is not considered for the evaluation of $Y_{i,u}$, so that the sum of all $Y_{i,u}$ for i ranging from 1 to the number of components of the burnt phase must equal 1.0. Note that here we **must** always specify the mass fraction of the **unburnt** phase, even in the case that the mesh portion associated with the currently described CDEM material is in reality initially occupied by the burnt phase! Note also that the initial mass fractions $Y_{i,u}$ of components in the unburnt state are totally unrelated with the initial volume fractions of the burnt and unburnt phases Ξ_{0b} and Ξ_{0u} (see `ksi0` above).

Next, one can define some **optional additional parameters** for the combustion.

`k0f`

Part of the fundamental flame speed [m/s] fixed in space (default value 0). The fundamental flame speed is given by `k = k0 + k0f`, where `k0` has been defined above in the general properties of the mixture. Note that, in alternative to assigning it by giving `k0` and `k0f`, the fundamental flame speed `k` can be automatically computed by the code. To this end, activate the `CFLA 1` optional keyword (see below). In this case a value for `k0` must still be specified, but it is simply ignored by the code.

`ucds`

Order of reconstruction [–] for the volume fraction.

0 The same limited reconstruction as in [874] (default value).

1 Limited reconstruction combined with the Upwind Downwind Controlled Splitting (see [891, 893, 921, 922]). At the moment, this is the recommended method (but note that it is not the one used by default!).

2 Anti-diffusive reconstruction combined with the Upwind Downwind Controlled Splitting (see [891, 893, 921, 922]).

3 Anti-diffusive reconstruction with tanh-correction, combined with the Upwind Downwind Controlled Splitting (in progress).

`dire`

Indicates how to compute the fundamental flame speed in multi-dimensional computations [–].

0 The fundamental flame speed is equal to ((k0 + k0f) $(\vec{n} \cdot \vec{n_f})$), where $\vec{n}$ and $\vec{n_f}$ are the normal to the flame surface and the normal to the interface of the finite volume cell (default value).

1 The fundamental flame speed is equal to (k0 + k0f). This should be used only for debugging purposes.

`temp0, hcoef`

Loss coefficients ([K], [J/(kg·K)], respectively) for the total energy `Q` exchanged with the surrounding environment, which can behave like a heat sink (default value is zero). The loss of energy `Q` per unit time and per unit volume of the gas is given by:

- For the unburnt phase, `QU` = α_u `hcoef`$(T_u -$ `temp0`$)$
- For the burnt phase, `QB` = α_b `hcoef`$(T_b -$ `temp0`$)$

In these formulas, α_u and α_b are the *current* volume fractions of the unburnt and burnt phases, respectively (while Ξ_{0b} and Ξ_{0u} used above are the *initial* values thereof), and T_u, T_b the corresponding temperatures.

`gx, gy, gz`

Components ($\vec{g} = (\mathtt{gx}, \mathtt{gy}, \mathtt{gz})$) [m/s^2] of the gravity acceleration for the computation of buoyancy force. Default values are zero. The buoyancy force is computed according to the following approximate formulae.

- $\alpha_u \vec{g}(\rho_u - \rho_u) = 0$ (buoyancy force per unit volume acting on the unburnt phase)
- $\alpha_b \vec{g}(\rho_b - \rho_u)$ (buoyancy force per unit volume acting on the burnt phase)

In these formulas, α_u and α_b are the *current* volume fractions of the unburnt and burnt phases, respectively (while Ξ_{0b} and Ξ_{0u} used above are the *initial* values thereof), and ρ_1, ρ_2 the corresponding mass densities. The buoyancy force contribution is typically irrelevant in detonation problems, but can become important in slow deflagration problems.

Finally, by setting `CFLA 1` and by specifying the following additional parameters, one may optionally require that the code itself computes the flame speed, as an alternative to specifying `k0` and `k0f` in the above set of input data. Note that the value of `k0` must be specified anyway, but will be simply ignored in this case.

`sl, psl, tsl, dl, pu, le, xig, yig, zig`

Parameters of the combustion model 1 ("CFLA" 1, see [919, 920]) to compute the flame speed. Formulas here implemented are the ones presented in [920]. The expression for the fundamental flame speed is given by formula (7)

$$K_0(x, y, z) = \mathrm{sl}\ \Theta_{TH}\Theta_{TURB}\Theta_{WRIN}.$$

Θ_{TH} given by formula (8),

$$\Theta_{TH} = \left(\frac{P}{\mathrm{psl}}\right)^{-0.5}\left(\frac{T}{\mathrm{tsl}}\right)^{2.2},$$

P and T being the local pressure and temperature of the unburnt mixture.
Θ_{TURB} given by formula (15),

$$\Theta_{TURB} = 1 + 1.334\overbrace{\gamma}^{0.6}\cdot\mathrm{pu}\cdot\left(\frac{u'}{\mathrm{sl}}\right)^{0.55}\left(\frac{L_t}{\mathrm{dl}}\right)^{0.15}(\mathrm{le})^{-0.3}$$

$$L_t = 0.2\ \overbrace{\Delta}^{\text{mesh size}}$$

$$u' = L_t\|S_{ij}\|, \quad S_{ij} = \frac{1}{2}\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right],$$

$\vec{u}$ being the local velocity of the unburnt mixture. Θ_{WRIN} is given by formula (16),

$$\Theta_{WRIN} = \max(1, R))^{1/3}, \quad R = \sqrt{(x - \mathrm{xig})^2 + (y - \mathrm{yig})^2 + (z - \mathrm{zig})^2},$$

R being expressed in meters.
The parameters involved in these formulas are the following ones.

- sl - fundamental laminar flame velocity (m/s in SI)
- psl - pressure at which sl is specified (Pa in SI)
- tsl - temperature at which sl is specified (K in SI)
- dl - laminar flame thickness (m in SI)
- le - effective Lewis number
- pu - user parameter
- xig - x-coordinate of the ignition point (m in SI)
- yig - y-coordinate of the ignition point (m in SI)
- zig - z-coordinate of the ignition point (m in SI)

As in the previous case, by setting `CFLA 2` and by specifying the following additional parameters, one requires that the code itself computes the flame speed, as an alternative to specifying `k0` and `k0f` in the above set of input data. Note that the value of `k0` must be specified anyway, but will be simply ignored in this case.

`sl, psl, tsl, dl, le, pu, xig, yig, zig, r0`

Parameters of the combustion model 2 ("CFLA" 2). The expression for the fundamental flame speed is given by

$$K_0(x, y, z) = \mathrm{sl}\ \Theta_{TH}\Theta_{TURB}.$$

Θ_{TH} given by

$$\Theta_{TH} = \left(\frac{P}{\mathrm{psl}}\right)^{-0.5} \left(\frac{T}{\mathrm{tsl}}\right)^{2.2},$$

P and T being the local pressure and temperature of the unburnt mixture.
Θ_{TURB} given by

$$\Theta_{TURB} = 1 + 1.334 \overbrace{\gamma}^{0.6} \left(\frac{u'}{\mathrm{sl}}\right)^{0.55} \left(\frac{L_t}{\mathrm{dl}}\right)^{0.15} (\mathrm{le})^{-0.3}$$

$$L_t = \begin{cases} \frac{1}{5} \cdot \Delta & \text{if} \quad R \leq \mathrm{r0} \\ 1 \cdot \Delta & \text{if} \quad R > \mathrm{r0} \quad \text{and} \quad ||\vec{\nabla}_S \vec{u}||_2 \leq g_{\mathrm{co}} \\ 1 \cdot \Delta + \frac{|\vec{u} \cdot \vec{n}|}{||\vec{\nabla}_S \vec{u}||_2} & \text{if} \quad R > \mathrm{r0} \quad \text{and} \quad ||\vec{\nabla}_S \vec{u}||_2 > g_{\mathrm{co}} \end{cases}$$

$$R = \sqrt{(x - \mathrm{xig})^2 + (y - \mathrm{yig})^2 + (z - \mathrm{zig})^2}.$$

The cut-off gradient is given by

$$g_{\mathrm{co}} = \frac{\mathrm{pu} \cdot \mathrm{sl}}{\Delta}.$$

$$\vec{\nabla}_S \vec{u} = \vec{\nabla} \vec{u} - \vec{n} \left(\vec{n} \cdot \vec{\nabla} \vec{u}\right)$$

$$u' = L_t \|S_{ij}\|, \quad S_{ij} = \frac{1}{2} \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right],$$

$\vec{u}$ being the local velocity of the unburnt mixture.

The parameters involved in these formulas are the following ones.

- sl - fundamental laminar flame velocity (m/s in SI)
- psl - pressure at which sl is specified (Pa in SI)
- tsl - temperature at which sl is specified (K in SI)
- dl - laminar flame thickness (m in SI)
- le - effective Lewis number
- pu - user parameter for the cut-off gradient
- xig - x-coordinate of the ignition point (m in SI)
- yig - y-coordinate of the ignition point (m in SI)
- zig - z-coordinate of the ignition point (m in SI)
- r0 - distance at which the turbulence is fully developed.

`/LECT/`

List of the elements (Cell-Centred Finite Volumes) to which the current material is associated.

Comments:

For the first species (`COMP1`), the coefficient of the chemical reaction `crea` should be equal to 1.

The sum of all initial mass fractions `ymas` should be equal to 1.

Outputs:

The different components of the ECR table are as follows. First, some values for the **whole mixture**:

ECR(1) : pressure p of the mixture, i.e. weighted average of the pressures of the unburnt and burnt phases p_u and p_b: $p = \alpha_u p_u + \alpha_b p_b$. The weighting coefficients α_u and α_b are the *current* volume fractions of the unburnt and burnt phases.

ECR(2) : density ρ of the mixture, i.e. weighted average of the densities of the unburnt and burnt phases ρ_u and ρ_b: $\rho = \alpha_u \rho_u + \alpha_b \rho_b$. The weighting coefficients are the *current* volume fractions of the unburnt and burnt phases.

ECR(3) : maximum between the sound speed in the unburnt phase and the sound speed in the burnt phase: $c = \max(c_u, c_b)$.

Then, some data for the **unburnt phase**:

ECR(4) : current volume fraction of the unburnt phase α_u. Note that, since the numerical schemes adopted in the CDEM model are LED (Local Extremum Diminishing), the value of α_u cannot increase above the maximum value initially specified in the whole domain and cannot decrease belove the minimum value initially specified in the whole domain

ECR(5) : density of the unburnt phase ρ_u.

ECR(6) : velocity along x of the unburnt phase $v_{x,u}$.

ECR(7) : velocity along y of the unburnt phase $v_{y,u}$.

ECR(8) : velocity along z of the unburnt phase $v_{z,u}$ (3D only, i.e. this data is missing in 2D cases).

ECR(6 + idim) : pressure of the unburnt phase p_u. Here `idim` is the space dimension (2 or 3).

Then, the same data but for the **burnt phase**:

ECR(7 + idim) : current volume fraction of the burnt phase α_b Note that, since the numerical schemes adopted in the CDEM model are LED (Local Extremum Diminishing), the value of α_b cannot increase above the maximum value initially specified in the whole domain and cannot decrease belove the minimum value initially specified in the whole domain.

ECR(8 + idim) : density of the burnt phase ρ_b.

ECR(9 + idim) : velocity along x of the burnt phase $v_{x,b}$.

ECR(10 + idim) : velocity along y of the burnt phase $v_{y,b}$.

ECR(11 + idim) : velocity along z of the burnt phase $v_{z,b}$ (3D only, i.e. this data is missing in 2D cases).

ECR(9 + (2 idim)) : pressure of the burnt phase p_b.

Finally, some **additional data**:

iespmax = min(nesp, 20 - (9 + (2 idim)))

ECR(9 + iesp + (2 idim)) : mass fraction of the iesp-th reagent species after the combustion occurs (iesp = 1, ..., nlhs; iesp $\leq$ iespmax).

ECR(9 + iesp + (2 idim)) : mass fraction of the iesp-th product species before the combustion occurs (iesp = nlhs + 1, ..., nesp - 1; iesp $\leq$ iespmax).

...

nn = min(20, (9+ (2 idim) + nesp)) = 9 + (2 idim) + iespmax

ECR(nn) : difference between the mass fractions of the first species in the unburnt phase and in the burnt phase.

ECR(21) : burnt surface per unit volume. When multiplied by the cell's volume, this is the total area of the burning surface over all faces of the current finite volume.

ECR(22) : fundamental flame speed (including `k0f`), or computed by the code in the case `CFLA 1/2`.

ECR(23) : absolute temperature of the mixture T [K]. This is computed internally as the weighted average of the temperatures of the unburnt and burnt phases T_u and T_b: $T = \alpha_u T_u + \alpha_b T_b$, where the weighting coefficients α_u and α_b are the *current* volume fractions of the unburnt and burnt phases.

ECR(24) : integral turbulent scale L_t computed by the code in the case `CFLA 1/2`; 0 otherwise

ECR(25) : rms turbulent velocity u' computed by the code in the case `CFLA 1/2`; 0 otherwise

Example:

Consider for example the combustion of a mixture of hydrogen, oxygen, water vapor and nitrogen. The chemical reaction is usually written without the inerts, as follows

$$H_2 + 0.5 \cdot O_2 \rightarrow H_2O$$

This can be re-written, by bringing all terms to the left hand side and by letting appear also the inerts (nitrogen in this case)

$$1 \cdot H_2 + 0.5 \cdot O_2 - 1 \cdot H_2O + 0 \cdot N_2 \rightarrow 0$$

Here `COMP1`, ..., `COMP4` represent H_2, O_2, H_2O and N_2, respectively (in this order!). Therefore, nesp=4 and nlhs=2. The constant volume specific heat coefficients are obtained via a fourth order regression of JANAF tables (ordp=4).

Assume that the fluid mesh is initially subdivided into two regions: a region called "burnt" containing (mostly) the burnt gases and a region called "unburnt" containing (mostly) the unburnt (fresh) gases.

One way of providing the input data for this problem is to specify two `CDEM` materials, one for each region, as follows.

```
CDEM ! This CDEM material is used to represent the burnt phase
   PINI 10.E5 PREF 1.e5  TINI 2000.0
   KSI0 0.999
```

```
      K0 45.2
      TMAX 6000.  R    8.31441
      NESP 4
      NLHS 2
      ORDP 4
      COMP1 ! H2
         MMOL 2.01594E-3 H0 -4.195E6  CREA 1.
         CV0 9834.91866 CV1 0.54273926  CV2 0.000862203836
         CV3 -2.37281455E-07 CV4 1.84701105E-11
         YMAS 0.1
      COMP2 ! O2
         MMOL 31.9988E-3  H0 -2.634E5  CREA 0.5
         CV0 575.012333 CV1 0.350522002 CV2 -0.000128294865
         CV3 2.33636971E-08 CV4 -1.53304905E-12
         YMAS 0.2
      COMP3 ! H2O
         MMOL 18.01534E-3 H0 -1.395D7 CREA -1.0
         CV0 1155.95625 CV1 0.768331151 CV2 -5.73129958E-05
         CV3 -1.82753232E-08 CV4 2.44485692E-12
         YMAS 0.3
      COMP4 ! N2
         MMOL 28.0134E-3 H0 -2.953D5 CREA 0.0
         CV0 652.940766 CV1 0.288239099 CV2 -7.80442298E-05
         CV3 8.78233606E-09 CV4 -3.05514485E-13
         YMAS 0.4
   LECT burnt TERM ! "burnt" is the name of the mesh zone
                   ! initially containing the burnt phase

   CDEM ! This CDEM material is used to represent the unburnt phase
      PINI 1.E5 PREF 1.e5  TINI 300.0
      KSI0 0.001
      K0 45.2
      TMAX 6000.  R    8.31441
      NESP 4
      NLHS 2
      ORDP 4
      COMP1 ! H2
         MMOL 2.01594E-3 H0 -4.195E6  CREA 1.
         CV0 9834.91866 CV1 0.54273926  CV2 0.000862203836
         CV3 -2.37281455E-07 CV4 1.84701105E-11
         YMAS 0.1
      COMP2 ! O2
         MMOL 31.9988E-3  H0 -2.634E5  CREA 0.5
         CV0 575.012333 CV1 0.350522002 CV2 -0.000128294865
         CV3 2.33636971E-08 CV4 -1.53304905E-12
         YMAS 0.2
      COMP3 ! H2O
         MMOL 18.01534E-3 H0 -1.395D7 CREA -1.0
         CV0 1155.95625 CV1 0.768331151 CV2 -5.73129958E-05
         CV3 -1.82753232E-08 CV4 2.44485692E-12
         YMAS 0.3
```

```
    COMP4 ! N2
       MMOL 28.0134E-3 HO -2.953D5 CREA 0.0
       CV0 652.940766 CV1 0.288239099 CV2 -7.80442298E-05
       CV3 8.78233606E-09 CV4 -3.05514485E-13
       YMAS 0.4
    LECT unburnt TERM ! "unburnt" is the name of the mesh zone
                      ! initially containing the unburnt phase
```

Note from the above example that the component parameters (`COMPn`) for the two materials must be identical, except the mass fractions (but be warned that the code does not check this!).

Alternatively (and perhaps more intuitively) one can define a *single CDEM material for the whole fluid mesh*, and then specify the initial conditions zone by zone by means of the `INIT VFCC` directive (for `CDEM` material), see GBE_0066. In the present example, this would correspond to the following input:

```
 CDEM ! This CDEM material is used to represent the whole gas
      ! (i.e. both the burnt and the unburnt zones)
    PINI 10.E5  ! This value will be overridden in the INIT directive
    PREF 1.e5
    TINI 2000.0 ! This value will be overridden in the INIT directive
    KSI0 0.999  ! This value will be overridden in the INIT directive
    K0 45.2     ! This value will be overridden in the INIT directive
    TMAX 6000.
    R 8.31441
    NESP 4
    NLHS 2
    ORDP 4
    COMP1 ! H2
       MMOL 2.01594E-3 HO -4.195E6  CREA 1.
       CV0 9834.91866 CV1 0.54273926  CV2 0.000862203836
       CV3 -2.37281455E-07 CV4 1.84701105E-11
       YMAS 0.1 ! This value will be overridden in the INIT directive
    COMP2 ! O2
       MMOL 31.9988E-3  HO -2.634E5  CREA 0.5
       CV0 575.012333 CV1 0.350522002 CV2 -0.000128294865
       CV3 2.33636971E-08 CV4 -1.53304905E-12
       YMAS 0.2 ! This value will be overridden in the INIT directive
    COMP3 ! H2O
       MMOL 18.01534E-3 HO -1.395D7 CREA -1.0
       CV0 1155.95625 CV1 0.768331151 CV2 -5.73129958E-05
       CV3 -1.82753232E-08 CV4 2.44485692E-12
       YMAS 0.3 ! This value will be overridden in the INIT directive
    COMP4 ! N2
       MMOL 28.0134E-3 HO -2.953D5 CREA 0.0
       CV0 652.940766 CV1 0.288239099 CV2 -7.80442298E-05
       CV3 8.78233606E-09 CV4 -3.05514485E-13
       YMAS 0.4 ! This value will be overridden in the INIT directive
 LECT fluid TERM ! "fluid" is the name of the mesh zone
                 ! initially containing both the burnt and
                 ! the unburnt phases
```

```
. . .

INIT ! Now we fine-tune the initial conditions
     ! for the CDEM material
   VFCC ! Initial conditions for the burnt phase
     VITX 0.0
     VITY 0.0
     VITZ 0.0
     PINI 10.E5
     TINI 2000.0
     KSI0 0.999
     K0 45.2
     Y1 0.1
     Y2 0.2
     Y3 0.3
     Y4 0.4
   LECT burnt TERM   ! "burnt" is the name of the mesh zone
                     ! initially containing (mostly) the burnt phase
   VFCC ! Initial conditions for the unburnt phase
     VITX 0.0
     VITY 0.0
     VITZ 0.0
     PINI 1.E5
     TINI 300.0
     KSI0 0.001
     K0 45.2
     Y1 0.1
     Y2 0.2
     Y3 0.3
     Y4 0.4
   LECT unburnt TERM ! "unburnt" is the name of the mesh zone
                     ! initially containing (mostly) the unburnt phase
```

In case of more complex initial distributions (e.g. varying element-by-element) of the properties, the `VFCC ... /LECT/` sub-directive of the `INIT` directive can be repeated as many times as necessary in order to set the initial conditions of each zone (or element), see GBE_0066.

Example of contents of the ECR table

We continue the above practical example with **4 species and 2 reactants** (i.e. 2 components on the left hand side of the chemical reaction).

In **2D space** (idim = 2), we have the following components of the ECR table:

- iespmax = min(nesp, 20 - (9 + (2 idim))) = min(4, 20 - 13) = 4
- nn = min(20, (9+ (2 idim) + nesp)) = 9 + (2 idim) + iespmax = 17
- ECR(9 + 1 + (2 idim)) = ECR(14) : mass fraction of the H_2 after the combustion occurs.

- ECR(9 + 2 + (2 idim)) = ECR(15) : mass fraction of the O_2 after the combustion occurs.
- ECR(9 + 3 + (2 idim)) = ECR(16) : mass fraction of the H_20 before the combustion occurs.
- ECR(nn) = ECR(17) : difference between the mass fraction of the H_2 in the unburnt phase and in the burnt phase.
- ECR(21) : burnt surface per unit volume.
- ECR(22) : fundamental flame speed (including `k0f`).
- ECR(23) : absolute temperature of the mixture T [K]. This is computed internally as the weighted average of the temperatures of the unburnt and burnt phases T_u and T_b: $T = \alpha_u T_u + \alpha_b T_b$, where the weighting coefficients α_u and α_b are the *current* volume fractions of the unburnt and burnt phases.
- ECR(24) : Unused.
- ECR(25) : Unused.

In **3D space** (idim = 3), we have the following components of the ECR table:

- iespmax = min(nesp, 20 - (9 + (2 idim))) = min(4, 20 - 15) = 4
- nn = min(20, (9+ (2 idim) + nesp)) = 9 + (2 idim) + iespmax = 19
- ECR(9 + 1 + (2 idim)) = ECR(16) : mass fraction of the H_2 after the combustion occurs.
- ECR(9 + 2 + (2 idim)) = ECR(17) : mass fraction of the O_2 after the combustion occurs.
- ECR(9 + 3 + (2 idim)) = ECR(18) : mass fraction of the H_20 before the combustion occurs.
- ECR(nn) = ECR(19) : difference between the mass fractions of the H_2 in the unburnt phase and in the burnt phase.
- ECR(21) : burnt surface per unit volume.
- ECR(22) : fundamental flame speed (including `k0f`).
- ECR(23) : absolute temperature of the mixture T [K]. This is computed internally as the weighted average of the temperatures of the unburnt and burnt phases T_u and T_b: $T = \alpha_u T_u + \alpha_b T_b$, where the weighting coefficients α_u and α_b are the *current* volume fractions of the unburnt and burnt phases.
- ECR(24) : Unused.
- ECR(25) : Unused.

Note that one can easily determine the mass fraction in both the burnt and the unburnt phases, as explained in [873]. Indeed, via the knowledge of $(Y_{\mathrm{H_2,u}} - Y_{\mathrm{H_2,b}})$, one can determine the other variations by using the molar mass (`mmol`) and the reaction coefficient (`crea`):

$$\frac{Y_{\mathrm{H_2,u}} - Y_{\mathrm{H_2,b}}}{2.01594 \cdot 10^{-3} \cdot 1} = \frac{Y_{\mathrm{O_2,u}} - Y_{\mathrm{O_2,b}}}{31.9988 \cdot 10^{-3} \cdot 0.5} = \frac{Y_{\mathrm{H_2O,u}} - Y_{\mathrm{H_2O,b}}}{18.01534 \cdot 10^{-3} \cdot (-1)}$$

Note also that the absolute temperature T_u, T_b [K] of each phase (unburnt or burnt) can be determined from the expression:

$$T = \frac{p}{R\rho}$$

where p is the absolute pressure [Pa], ρ is the density [kg/m^3] and R [J/(kg·K)] is given by:

$$R = \frac{R_m}{\sum \frac{Y_i}{W_i}}$$

Here $R_m = 8.314$ [J/(mol·K)] is the (molar) constant of gases, W_i is the molar mass [kg/mol] of the i-th gas and Y_i is the mass fraction [–] of the i-th gas.

7.8.40 DEMS—Discrete Equation Method for Two Phase Stiffened Gases

Object:

Modeling of two phase flows involving stiffened gases via the Discrete Equation method of Abgrall and Saurel 2003 (see also [884, 891]). The governing equations are the Euler Equations in conservative form (the main conserved variables for each phase are the mass densities of the components, the momentum, the total energy (sensible + chemical + kinetic) per unit volume) and a transport equation for the volume fraction.

Syntax:

```
"DEMS"  "PINI"  pini  <"PREF" pref>
   ...  "ALP1" alp1  "ROI1" roi1 "ROI2" roi2
   ...  "NESP"
   ...
   ...  "COMP1"
   ...  "GAMM" gamm "CP" cp "PI" pi
   ...  "YMA1" yma1
   ...  "YMA2" yma2
   ...  "MMOL"  mmol   "H0" h0

   ...
   ...  "COMPnesp"
   ...  "GAMM" gamm "CP" cp "PI" pi
   ...  "YMA1" yma1
   ...  "YMA2" yma2
   ...  "MMOL"  mmol   "H0" h0
   ...

   ...  <"RELA" rela> <'RHOM' rhom> <'EPSM' epsm>
   ...  <"UCDS" ucds>
   ...  <"ERE1" ere1>
   ...  <"ERE2" ere2>
   ...  <"ADCR" adcr>
   ...  <"MODE" nmod>
   ...  <"FONC" nfon>
```

`pini`

Initial pressure of the mixture.

`pref`

Reference pressure.

`alp1`

Initial volume fraction of the phase 1

`roi1`

Mass density of the phase 1

`roi2`

Mass density of the phase 2

`nesp`

Number of species involved in each phase

"COMP1", . . . , "COMPnesp"

Keywords which state that we will describe the properties of the species 1,. . . ,nesp.

`gamm`

Specific heat ratio

`cp`

Constant pressure specific heat

`pi`

Molecular attraction effect parameter

`yma1`

Mass fraction in the phase 1

`yma2`

Mass fraction in the phase 2

`mmol`

Molar mass.

`h0`

Formation enthalpy at $T = 0$ K.

`ucds`

High order reconstruction for the volume fraction.

0 The same limited reconstruction as in [874] (default value).

1 Limited reconstruction combined with the Upwind Downwind Controlled Splitting (see [891]).

2 Anti-diffusive reconstruction combined with the Upwind Downwind Controlled Splitting (see [891]).

3 Anti-diffusive reconstruction with tanh-correction, combined with the Upwind Downwind Controlled Splitting (in progress).

`rela` 1 Relaxation of the pressure and of the velocity (the pressure and the velocity are the same on the two phases).

21 As 1, with isentropic tranformation in the phase 1.

22 As 1, with isentropic tranformation in the phase 2.

23 As 1, with isentropic tranformation in the phase which presents less mass than the other (suggested option if one wants to relax).

0 No relaxation of the pressure and of the velocity (default value).

`rhom, epsm` When rela is equal to 21–23, we inject mass in the phase in which the isentropic transformation occurs to have rhom as threshold value for the minimum density, providing that the injected mass is lower than epsm times the mass of the other phase. Default values: 0 and 1.0D-6.

`ere1, ere2` Reference energies for the phase 1 and 2 (0 is their default value).

`adcr` 1 DEMS model is used for HCDA (hypothetical core disruptive accident, ADC in French) computations (see below).

0 DEMS model is not used for HCDA computations (default value).

`nmod` In case of HCDA computations (adcr equal to 1) it is possible to inject energy into the bubble. A negative value allows removal of energy (injection of a negative energy).

0 No energy injection (default value).

$\pm$ 1 Homogeneous energy injection into the bubble (we specify dE/dt)

$\pm$ 2 Homogeneous energy injection into the bubble (we specify dE/dVol)

`nfon` In the case imod $>$ 0, number of the function defined by the directive FONC in which we specify the power (W) as function of time (s).

Comments:

The sum of all initial mass fractions should be equal to 1 in each phase.

Outputs:

We define $\mathrm{nesp}_{\mathrm{ecr}} = \min(\mathrm{nesp}, 7 - \mathrm{ndim})$, which represents the number of species that are represented in the ECR table. Then the different components of the ECR table are:

ECR(1) : pressure

ECR(2) : density

ECR(3) : maximum of the sound speed in the two phases

ECR(4) : velocity along x

ECR(5) : velocity along y

ECR(6) : velocity along z (if existing)

ECR(4 + ndim) : volume fraction of the phase 1

ECR(5 + ndim) : density of the phase 1

ECR(6 + ndim) : velocity along x of the phase 1

ECR(7 + ndim) : velocity along y of the phase 1

ECR(8 + ndim) : velocity along z of the phase 1 (if existing)

ECR(6 + (2 * ndim)) : pressure of the phase 1

ECR(7 + (2 * ndim)) : mass fraction of the first component of the phase 1

ECR(6 + (2 * ndim) + $nesp_{ecr}$) : mass fraction of the $nesp_{ecr}$-th component of the phase 1

ECR(7 + (2 * ndim) + $nesp_{ecr}$) : volume fraction of the phase 2

ECR(8 + (2 * ndim) + $nesp_{ecr}$) : density of the phase 2

ECR(9 + (2 * ndim) + $nesp_{ecr}$) : velocity along x of the phase 2

ECR(10 + (2 * ndim) + $nesp_{ecr}$) : velocity along y of the phase 2

ECR(11 + (2 * ndim) + $nesp_{ecr}$) : velocity along z of the phase 1 (if existing)

ECR(9 + (3 * ndim) + $nesp_{ecr}$) : pressure of the phase 2

ECR(10 + (3 * ndim) + $nesp_{ecr}$) : mass fraction of the first component of the phase 2

ECR(9 + (2 * ndim) + (2 * $nesp_{ecr}$)) : mass fraction of the $nesp_{ecr}$-th component of the phase 2

Example.

We consider a mixture of two stiffened gases in a shock tube (two zones, Z_HP and Z_BP). The zone Z_HP is almost totally occupied by the phase 1 (volume fraction of the phase 1 equal to 0.9999) and it only contains the first stiffened gas. The zone Z_BP is almost totally occupied by the phase 2 (volume fraction of the phase 1 equal to 0.0001) and it only contains the second stiffened gas.

```
*                    ZONE 1
*                    ------
   DEMS
*
      PINI 9.12E3 PREF 1e0
      ALP1 0.9999 ROI1 1.271  ROI2 0.99
*
      NESP 2
*
```

```
      COMP ! AIR. H0 is false, but not used for the moment
         GAMM 1.4 CP 1010. PI 0.0
         YMA1 1.0   ! YMA1 = mass fraction in the phase 1
         YMA2 0.0   ! YMA2 = mass fraction in the phase 2
         MMOL 28.8E-3 H0 0.0
*
*
      COMP ! STIFFENED GAS.
         GAMM 7.0 CP 7990 PI 3.0E3
         YMA1 0.00
         YMA2 1.00
         MMOL 18E-3 H0 0.0
*
                                          LECT Z_HP TERM
*                 ZONE 2
*                 ------
   DEMS
*
      PINI 1.0E0 PREF 1e0
      ALP1 0.0001 ROI1 1.271  ROI2 0.99
*
*
      NESP 2
*
      COMP ! AIR. H0 is false, but not used for the moment
         GAMM 1.4 CP 1010. PI 0.0
         YMA1 1.0
         YMA2 0.0
         MMOL 28.8E-3 H0 0.0
* *
      COMP ! STIFFENED GAS.
         GAMM 7.0 CP 7990 PI 3.0E3
         YMA1 0.00
         YMA2 1.00
         MMOL 18E-3 H0 0.0
*
*
                                          LECT Z_BP TERM
```

Example HCDA computations (adcr = 1).

We consider a mixture involving 3 stiffened gases. Phase 1 is liquid and is completely occupied by sodium. Phase 2 is gaseous and can contain the bubble or the argon.

```
 DEMS
*
      PINI 1e5 PREF 0.0
      ALP1 1.0E-8    ROI1 856.  ROI2 1.0
*
      NESP 3
```

```
*
      COMP ! NA
         GAMM 2.0 CP 1230 PI 2.4E9
         YMA1 1.0   ! YMA1 = mass fraction in the phase 1
         YMA2 0.0   ! YMA2 = mass fraction in the phase 2
         MMOL 23.0E-3 H0 0.0
*
      COMP ! BULLE
         GAMM 1.4 CP 1000 PI 0.0
         YMA1 0.0
         YMA2 1.0
         MMOL 20E-3 H0 0.0
*
      COMP ! AR
         GAMM 1.67  CP 523 PI 0.0
         YMA1 0.0
         YMA2 0.0
         MMOL 40.0E-3 H0 0.0
*
      UCDS 1
      RELA 1
*
*     ERE1 =  (PINI + (gamma  PINF)) / (ROI1 * (gamma - 1)) =
*          =  ((1E5 + (2 * 2.4E9)) / (856 )) = 0.560759345794E+07
*
*     ERE21 =  (PINI + (gamma  PINF)) / (ROI1 * (gamma - 1)) =
*          =  ((1E5 + 0.0) / (1.0 * 0.4)) = 2.5E5
*
*
      ERE1  0.560759345794E+07
      ERE2  2.5E5
      ADCR  1
      MODE  1
      FONC  3
*
                    LECT FLUD TERM
*
      ...
*
*
    FONC 1 TABLE 3
                    0.     1.0e0
                    1e-5   1.0e0
                    1e+4   1.0e0
*
         2 TABLE 3
            0.     0.
                    1e-5   0.
                    1e+4   0.
*
*
```

```
*        FONC 3 is the power injected in the bubble as function of time
*
         3 TABLE  77
         0.000000E+00  -.200000E+06
         0.100000E-01  -.202020E+06
         0.200000E-01  -.204082E+06
         ...
         0.760000E+00  -.833333E+06
```

7.8.41 GAZD—Detonation in gas Mixture

Object:

The governing equations are the Euler Equations for ideal gases Mistures with temperature-dependent heat capacities. It means that the vibrational degrees of freedom of poly-atomic molecules are taken into account via the depence of specific heat capacities with respect to the temperature.

The experimental Temperature dependence of specific heat capacities can be found in the JANAF tables (NIST-JANAF Thermochemical tables - Fourth ed., Journal of Physical and Chemical Reference Data, Chase M.W.,1998).

In general it is necessary to take into account the presence of inerts. Although they do not participate in the chemical reaction, their mass fraction can be important (consider e.g. nitrogen in the case of air) so that their heat capacity gives an important contribution to the global heat balance of the mixture.

The combustion is governed by an **irreversible exothermic** chemical reaction. Usually this is written as follows, i.e. with reactants only on the left hand side and with reaction products only on the right hand side:

$$\sum_{r=1,\mathrm{nrea}} c_r \mathrm{A}_r \rightarrow \sum_{p=1,\mathrm{npro}} c_p \mathrm{A}_p$$

where `nrea` is the number of chemical species on the left-hand side of the chemical reaction (i.e., the number of reactants), while `npro` is the number of chemical species on the right hand side of the chemical reaction (i.e. the number of reaction products). Any inerts, which can be present in the mixture, are usually not explicitly included in the expression of the chemical reaction. Thus, the c_r and c_p coefficients in the above expression are strictly positive.

In the GAZD model this expression is re-arranged as follows,by bringing all terms to the left hand side and by letting also the inerts (if any) appear:

$$\sum_{i=1,\mathrm{nesp}} c_i \mathrm{A}_i \rightarrow 0$$

where `nesp` is the total number of chemical species present (i.e. the reactants, the reaction products and the inerts, if any): `nesp = nrea + npro + nine`. The coefficient c_i is thus strictly positive for reactants, strictly negative for reaction products and zero for inerts, if any.

The governing equations are the Euler Equations and the conserved variables are the mass density, the momentum, the total energy of the mixture and the mass fraction of the (nesp - 1) species defined.

Syntax:

```
"GAZD"  "TINI" tini    "PINI"  pini  <"PREF" pref>

   ...  "A" a  "B" b  "EA" Ea   "R" rgas
   ...  "TC"  Tcomb  "ALPH" alpha
   ...  "TMAX"  tmax "NESP" nesp    "ORDP" ordp    "NLHS" nlhs
   ...
   ...  "COMP1"
   ...  "MMOL"  mmol   "H0" h0    "CREA" crea
   ...  "CV0" cv0  "CV1" cv1 ... "CVordp" cvordp
```

```
    ...  "YMAS" ymas
    ...
    ...  . . .
    ...
    ...  "COMPnesp"
    ...  "MMOL"  mmol   "H0" h0    "CREA" crea
    ...  "CV0" cv0  "CV1" cv1 ... "CVordp" cvordp
    ...  "YMAS" ymas

  /LECT/
```

As generally the coefficients of the Arrhenius Law are given for SI units, it is safer to use SI inits for all dataset variables.

The SI units are given below in brackets for each quantity [·] just as a reference.

`tini`

Initial temperature of the mixture [K].

`pini`

Initial pressure of the mixture [Pa].

`pref`

Reference pressure [Pa].

`a`

Pre-exponential factor. The units of the this factor will vary depending on the order of the reaction.

`b`

Second factor that makes explicit the temperature dependence of the pre-exponential factor of the classical Arrhenius law.

`Ea`

activation energy [J/mol]

`rgas`

Gas constant R, equal to 8.3144621 in SI units [J/(mol·K)].

`tcomb`

Temperature at which the reaction is started [K].

`alpha`

Not used for instance.

`tmax`

Maximum value of the temperature for the computation of the specific heats [K]. For temperatures $T > T_{\max}$ the code takes $C_V(T) = C_V(T_{\max})$.

`nesp`

Total number of species involved in the mixture: reactants, reaction products and inerts, if any.

`ordp`

Temperature polynomial degree for the constant volume specific heat computation.

`nlhs`

Number of species in the left hand side of the chemical reaction, i.e. number of reactants. If there are any inerts, these are **not** counted here.

Then, we specify the **properties of each species** (i.e. of each component) of the mixture. Note that the species must be listed in the order in which they appear in the chemical reaction equation.

"COMP1", . . . , "COMPnesp"

Keywords which state that we will describe the properties of the species 1,. . . ,nesp. Note, however, that the numbers 1,. . . ,nesp are only a visual indication for the user: the code interprets only the first four letters of each keyword (`COMP` in this case), so these digits (1, 2, etc.) are ignored. It is the User's responsibility to list the components in the correct order, as specified above.

`mmol`

Molar mass [kg/mol].

`h0`

Formation enthalpy [J/kg] at $T = 0$ K.

`crea`

Coefficient [–] in the chemical reaction (positive if the species is a reactant).

`cv0, ..., cvordp`

Coefficient of T^0, . . . , T^{ordp} for the computation of the constant volume specific heat. The expression used is $C_V(T) = C_{V0} + C_{V1}T + C_{V2}T^2 \dots$ so that C_{V0} is in J/(Kg·K), C_{V1} is in J/(Kg·K^2), etc.

`ymas`

Initial mass fraction $Y_{i,u}$ of the current component before the detonation occurs, i.e. in the **unburnt** state. This is the mass of the current component divided by the total mass of the unburnt phase in the cell. The sum of all $Y_{i,u}$ for i ranging from 1 to the number of components of the burnt phase must equal 1.0.

`/LECT/`

List of the elements (Cell-Centred Finite Volumes) to which the current material is associated.

Comments:

The sum of all initial mass fractions `ymas` should be equal to 1.
The modified Arrhenius law has the form :

$$k = aT^b exp\left(\frac{-E_a}{RT}\right)$$

For the Hydrogen detonation in Air we can take the following constants:

- $a = 1.2 \cdot 10^{14}$ in SI units
- $b = -0.91$
- $E_a = 69.1\ kJ$
- R Gas constant equal to 8.3144621 in SI units
- T temperature in Kelvin

Outputs:

The different components of the ECR table are as follows:

ECR(1) : pressure p of the mixture.
ECR(2) : density ρ of the mixture.
ECR(3) : the sound speed of the mixture.
ECR(4) : temperature T of the mixture.
ECR(4 + iesp) : mass fraction of the iesp-th species
ECR(4 + nesp + 1) : free
ECR(4 + nesp + 2) : specific internal energy

Example:

Consider for example the combustion of a mixture of hydrogen, oxygen, water vapour and nitrogen. The chemical reaction is usually written without the inerts, as follows

$$H_2 + 0.5 \cdot O_2 \rightarrow H_2O$$

This can be re-written, by bringing all terms to the left hand side and by letting appear also the inerts (nitrogen in this case)

$$1 \cdot H_2 + 0.5 \cdot O_2 - 1 \cdot H_2O + 0 \cdot N_2 \rightarrow 0$$

Here `COMP1`, ..., `COMP4` represent H_2, O_2, H_2O and N_2, respectively (in this order!). Therefore, nesp=4 and nlhs=2. The constant volume specific heat coefficients are obtained via a fourth order regression of JANAF tables (ordp=4).

Assume that the fluid mesh is initially subdivided into two regions: a region called "ZONE1" to initiate the detonation and a region called "ZONE2" containing the unburnt gases where detonation propagates.

One way of providing the input data for this problem is to specify two `GAZD` materials, one for each region, as follows.

```
*                 ZONE No1 (to initiate the detonation)
*                 ========
   GAZD
*         a) initial conditions
*            ------------------
          PINI 2.020D6 PREF 1e5 TINI 2000
*
*         b) Arrhenius law
*            -------------
          a 1.2E14 b -0.91 Ea 69.1e3 R 8.314
          tc 350
          alpha 1E-3 !not used
*
*         c) gas material properties
*            -----------------------
          TMAX 6000 NESP 4 ORDP 4 NLHS 2
*
*      COMP1 (H2)
       COMP1
       MMOL 2.01594E-3 H0 -4.195E6  CREA 1.
       CV0 10310
       CV1 0.819
       CV2 0.00042075
       CV3 -1.284E-7
       CV4 1.01497E-11
       YMAS 0.03
*
*      COMP2 (O2)
       COMP2
       MMOL 31.9988E-3  H0 -2.634E5  CREA 0.5
```

```
       CV0 649.56
       CV1 0.2727
       CV2 -0.9984E-4
       CV3 1.8181E-8
       CV4 -0.7782E-12
       YMAS 0.21
*
*      COMP3 (H2O)
       COMP3
       MMOL 18.01534E-3 H0 -1.395D7 CREA -1.0
       CV0 1153.7
       CV1 0.548
       CV2 -4.087E-5
       CV3 -1.303E-8
       CV4 -1.743E-12
       YMAS 0.02
*
*      COMP4 (N2)
       COMP4
       MMOL 28.0134E-3 H0 -2.953D5 CREA 0.0
       CV0 741.97
       CV1 0.225
       CV2 -6.097E-5
       CV3 6.8611E-9
       CV4 -2.386E-13
       YMAS 0.74
*
                                         LECT ZONE1 TERM
*
*                     ZONE No2
*                     =========
    GAZD
*
*    a) Initial conditions
*       ------------------
*
       PINI 1.028D5 PREF 1e5 TINI 299
*
*    b) Arrhenius law
*       -------------
*
       a 1.2E14 b -0.91 Ea 69.1e3 R 8.314
       tc 800     ! temperature
       alpha 1E-3 ! not used
*
*   c) Gas material properties
*      ----------------------
*
       TMAX 6000 NESP 4  ORDP 4  NLHS 2
*
*      COMP1 (H2)
```

```
        COMP1
        MMOL 2.01594E-3 H0 -4.195E6  CREA 1.
        CV0 10310
        CV1 0.819
        CV2 0.00042075
        CV3 -1.284E-7
        CV4 1.01497E-11
        YMAS 0.03
*
*       COMP2 (O2)
        COMP2
        MMOL 31.9988E-3  H0 -2.634E5  CREA 0.5
        CV0 649.56
        CV1 0.2727
        CV2 -0.9984E-4
        CV3 1.8181E-8
        CV4 -0.7782E-12
        YMAS 0.21
*
*       COMP3 (H2O)
        COMP3
        MMOL 18.01534E-3 H0 -1.395D7 CREA -1.0
        CV0 1153.7
        CV1 0.548
        CV2 -4.087E-5
        CV3 -1.303E-8
        CV4 -1.743E-12
        YMAS 0.02
*
*       COMP4 (N2)
        COMP4
        MMOL 28.0134E-3 H0 -2.953D5 CREA 0.0
        CV0 741.97
        CV1 0.225
        CV2 -6.097E-5
        CV3 6.8611E-9
        CV4 -2.386E-13
        YMAS 0.74
                                            LECT ZONE2 TERM
```

Note from the above example that the component parameters (`COMPn`) for the two materials must be identical, except the mass fractions (but be warned that the code does not check this!).

7.8.42 HMEM—Homogeneous two-phase multi-miscible-component fluid

Object:

This material aims at modeling a two-phase flow, where each phase is composed of multiple miscible species. The main characteristics of the model are (for more details, see the **Comments** paragraph):

- the mixture is at **kinematic equilibrium** (both phases get the same velocity),
- the mixture is at **thermal equilibrium** (both phases get the same temperature),
- the mixture is at **mechanical equilibrium** (both phases get the same pressure),
- within each phase, the potential multiple species follow the **Dalton's law**,
- the governing equation of state for each species is the **stiffened gas** law (however, the model cannot deal with miscible species which are not gases),
- the sound velocity of the mixture is **Wood's sound velocity**,
- a **heat source term** can be defined in three different ways: constant in time, time dependent, dependent on the total volume of one species.

Syntax:

```
"HMEM"  "PTOT" ptot  <"PREF" pref>  "TEMP" temp
   ...  "NCP1" ncomp1 "NCP2" ncomp2 "ALPH" alpha

   ...  "COMP1"
   ...  "ZPRE" zpre "GAMM" gamma "QEOS" q
   ...  "PINF" pinf "CVOL" cv    "QSRC" qsrc

   ...  "COMPncp1"
   ...  "ZPRE" zpre "GAMM" gamma "QEOS" q
   ...  "PINF" pinf "CVOL" cv    "QSRC" qsrc

   ...  "COMPm"
   ...  "ZPRE" zpre "GAMM" gamma "QEOS" q
   ...  "PINF" pinf "CVOL" cv    "QSRC" qsrc

   ...  "COMPncp"
   ...  "ZPRE" zpre "GAMM" gamma "QEOS" q
   ...  "PINF" pinf "CVOL" cv    "QSRC" qsrc

   ...  <"ADCR" adcr>
   ...  <"MODE" nmod>
   ...  <"FONC" nfon>
   ...  <"SSPL" sspl>
```

`ptot`

Initial total pressure of the mixture.

`pref`

Reference pressure.

`temp`

Initial total temperature of the mixture.

`ncomp1`

Number of species in phase 1.

`ncomp2`

Number of species in phase 2.

`alpha`

Volume fraction of phase 1.

`"COMP1", ..., "COMPncp1"`

Keywords implying the description of the properties for the species `1`,. . . , `ncp1` in phase 1.

`"COMPm", ..., "COMPncp"`

Keywords implying the description of the properties for the species `ncp1+1`,. . . , `ncp1+ncp2` in phase 2.

`zpre`

Pressure fraction of the species within its phase.

`gamma`

Specific heat ratio of the species.

`q`

q constant in the stiffened gas EOS.

`pinf`

p^{∞} constant in the stiffened gas EOS.

`cv`

Heat capacity at constant volume of the species.

`qsrc`

Parameter related to an energy source term. If `qsrc`$\neq 0$ and

`nmod`$= 0$ then constant source term, with value `qsrc`,

`nmod`$\neq 0$ then time- or volume-dependent source term is applied with value provided by `nfon`.

`adcr` 1 HMEM model is used for HCDA (hypothetical core disruptive accident) computations (see below),

0 HMEM model is not used for HCDA computations (default value).

`nmod` Non-constant energy injection parameter.

0 No energy or constant energy injection (default value),

$\pm$ 1 Homogeneous energy injection into the species with `qsrc` $\neq 0$ (we specify dE/dt),

$\pm$ 2 Homogeneous energy injection into the species with `qsrc` $\neq 0$ (we specify dE/dVol).

`nfon` When `nmod`$\neq 0$, number of the function defined by the directive FONC in which we specify the power (W) as a function of time (s).

`sspl` 0 There is no operator splitting between the source term and the flux computation: the value used for the energy source is the value at the beginning of the time step.

1 There is an operator splitting between the source term and the flux computation: the value used for the energy source is the value computed after adding the fluxes to the conservative variables.

Comments:

First, let us comment some values of different parameters:

- The total number of species cannot currently be more than 10.
- In each phase, the sum of all pressure fractions must equal 1.
- In each phase, one cannot have multiple species when one species gets `pinf` $\neq 0$.

Then, let us provide some theoretical information about the HMEM mixture model. The thermodynamical derivation of a three component model with two miscible phases can be found in [939]. The present model can be considered as an extension of this work. The continuous equations of this model read:

$$\partial_t Y_i + \mathbf{u}^T \nabla Y_i = 0, \qquad i \in \Phi_1 \tag{72}$$

$$\partial_t Z_i + \mathbf{u}^T \nabla Z_i = 0, \qquad i \in \Phi_2 \tag{73}$$

$$\partial_t \rho + \mathrm{div}(\rho \mathbf{u}) = 0, \tag{74}$$

$$\partial_t(\rho \mathbf{u}) + \mathrm{div}(\rho \mathbf{u}\mathbf{u}^T) + \nabla p = 0, \tag{75}$$

$$\partial_t(\rho E) + \mathrm{div}(\rho E \mathbf{u} + p\mathbf{u}) = Q, \tag{76}$$

with Y_i the mass fractions of the species in phase 1, Z_i the mass fractions of the species in phase 2, u the mixture velocity, ρ the mixture density, p the mixture pressure, E the mixture total energy, Q the energy source term.
Within each phase, the species obey the Dalton's law, while the total pressure of both phases are equal:

$$\sum_{\Phi_1} p_i = \sum_{\Phi_2} p_i.$$

Let ρ_i and e_i be respectively the density and the specific internal energy of one species, then, this species equation of state reads:

$$p_i = \rho_i(\gamma_i - 1)(e_i - q_i) - \gamma_i p_i^{\infty}.$$

Let T be the mixture temperature, the equation of state of one species can also read:

$$p_i = \rho_i(\gamma_i - 1)C_{v,i}T - p_i^{\infty},$$

where $C_{v,i}$ is the heat capacity at constant volume.
Let α be the volume fraction of the phase 1, then one considers the following relations:

$$\begin{aligned} \rho Y_i &= \alpha\rho_i, & i \in \Phi_1, \\ \rho Z_i &= (1-\alpha)\rho_i, & i \in \Phi_1. \end{aligned}$$

The volume fraction α can easily be computed from the conservative variables, the equations of state and the pressure equality.
The total energy is defined by the sum of the mixture kinetic energy and its internal energy as follows:

$$E = \frac{1}{2}|u|^2 + \sum_{\Phi_1} Y_i e_i + \sum_{\Phi_2} Z_i e_i.$$

The energy source term Q reads :

$$Q = \sum_{\Phi_1} \rho Y_i Q_i + \sum_{\Phi_2} \rho Z_i Q_i$$

where the Q_i can take one of the following forms:

1. the energy source term per species is constant, thus Q_i get constant values,
2. the energy source term is a function F of time and is defined for the whole volume of a species:
$$\int_{\mathcal{D}} \alpha_i(t,\mathbf{x})Q_i(t,\mathbf{x}) = F(t),$$
where $\mathcal{D}$ is the spatial domain, α_i is the volume fraction of the species:
   - $\alpha_i = \alpha$ if $i \in \Phi_1$ and its mass fraction whithin phase 1 is above 0.9,
   - $\alpha_i = 1-\alpha$ if $i \in \Phi_2$ and its mass fraction whithin phase 2 is above 0.9,
3. the energy source term is a function G of the volume of the species ($V_i = \int_{\mathcal{D}} \alpha_i$):
$$\int_{\mathcal{D}} \alpha_i(t,\mathbf{x})Q_i(t,\mathbf{x}) = G(V_i(t)).$$

Finally, we assume that the mixture sound velocity c satisfies a Wood's relation and reads:

$$c = \left(\rho\left(\frac{\alpha}{\rho_{\Phi_1}c_{\Phi_1}^2} + \frac{1-\alpha}{\rho_{\Phi_2}c_{\Phi_2}^2}\right)\right)^{-1/2},$$

with $\rho_{\Phi_1} = \sum_{\Phi_1}\rho_i$, $\rho_{\Phi_2} = \sum_{\Phi_2}\rho_i$, c_{Φ_1} and c_{Φ_2} are the phasic sound velocities which can be computed from the equations of states and the temperature equality.

Outputs:

ECR(1) : mixture pressure p

ECR(2) : mixture density ρ

ECR(3) : mixture sound velocity c

ECR(4) : velocity $\mathbf{u}$ along x-axis

ECR(5) : velocity $\mathbf{u}$ along y-axis

ECR(6) : velocity $\mathbf{u}$ along z-axis (if existing)

ECR(4 + ndim) : volume fraction of phase 1 α

ECR(5 + ndim) : mixture temperature T

ECR(6 + ndim) : mass fraction of the first species

ECR(7 + ndim + ncp1 + ncp2) : FV cell volume fraction of the first species

Examples:

A first example can be found in the verification test named `bm_vfcc_hmem_0D.epx`. A unique FV cell is composed of two phases and two species per phase. All species are ideal gases. The FV cell is contracted, implying the isentropic compression of the mixture. Four cases are studied:

1. all species are the same ideal gas ($q = p^{\infty} = 0$), the cell keeps a constant volume. We thus check that the initial conditions provide the same values as an ideal gas law:

$$p = p_0,\ \rho = \rho_{1,0},\ c = \sqrt{\frac{\gamma_1 p_0}{\rho_0}},\ \alpha = \alpha_0,\ T = T_0,$$

2. all species are the same ideal gas, the cell is contracted from volume $V_0 = 1$ to volume $V = 0.81$. The final values should be the same as an ideal gas isentropic compression:

$$p = \frac{p_0}{V_1^{\gamma}},\ \rho = \frac{\rho_{1,0}}{V},\ c = \sqrt{\frac{\gamma_1 p}{\rho}},\ \alpha = \alpha_0,\ T = \frac{T_0}{V^{\gamma_1 - 1}},$$

3. the mixture is made of two identical phases, each one composed of two ideal gases with different properties ($\gamma_1 \neq \gamma_2$, $C_{v,1} \neq C_{v,2}$). The cell is contracted from volume $V_0 = 1$ to volume $V = 0.81$. The mixture should behave like an ideal gas with the following parameters:

$$C_v = Y_1 C_{v,1} + Y_2 C_{v,2},\ \gamma = \frac{Y_1 \gamma_1 C_{v,1} + Y_2 \gamma_2 C_{v,2}}{C_v},$$

$$p = \frac{p_0}{V^{\gamma}},\ \rho = \frac{\rho_0}{V},\ c = \sqrt{\frac{\gamma p}{\rho}},\ \alpha = \alpha_0,\ T = \frac{T_0}{V^{\gamma - 1}},$$

4. the mixture is made of two different phases, each one composed of a unique ideal gas ($\gamma_1 \neq \gamma_3$, $C_{v,1} \neq C_{v,3}$). The volume fraction α is chosen so that the initial density is identical to the previous test. The cell is contracted from volume $V_0 = 1$ to volume $V = 0.81$. The results must be the same as the previous test, except for the sound velocity, which reads:

$$c = \sqrt{\frac{\tilde{\gamma} p}{\rho}},\ \tilde{\gamma} = \left(\frac{\alpha}{\gamma_1} + \frac{1 - \alpha}{\gamma_3}\right)^{-1}.$$

======= ¿¿¿¿¿¿¿ master

7.9 IMPEDANCES

Object :

This directive enables impedances for elements with CLxx boundary conditions to be input.

There are three forms of the directive, depending upon whether the impedance concerns:

- Finite Elements (`IMPE`), or
- Elements using the Van Leer formulation (`IMPV`), or
- Cell-Centred Finite Volumes (VFCC) (`CLVF`)

The available options for `IMPE` are the following:

name	law of behaviour
ABSI	absorbing boundary (JRC implementation)
ABSO	absorbing boundary
ABST	total absorbing material
ABSZ	absorbing boundary (Zienkiewicz for geotechnical materials)
AIRB	air blast wave
DCRI	critical mass flow rate
DIAP	diaphragm with imposed pressure
FOND	closed bottom
FPLT	fragile plate
FSUI	following force
GRFS	grid model with fluid/structure coupling
GRIL	grid model
MEMB	safety membrane
NAH2	coupling of the water mass flow rate in sodium-water reaction
PCHA	head loss
PIMP	imposed pressure
POMP	pump model
PPLT	perforated plate (JRC implementation)
RDK2	rupture disk (JRC implementation 2)
RSEA	coupling of the water mass flow rate in sodium-water reaction (new model)
RUDI	rupture disk (JRC implementation)
RDMC	MC rupture disk (JRC implementation)
SFSI	NTNU's simplified Fluid Structure Interaction model
STAC	Stacey's 1st-order absorbing boundary (JRC implementation)
SVAL	safety valve (JRC implementation)
SWVA	swing check valve with fluid-structure coupling(EDF implementation)
VANN	closure of a valve
VISU	record data (e.g. FSI pressure) for visualization

Not all these options are available for all boundary condition elements. See the following table :

Option	CL1D	CL2D	CL3D	CL3T	CLTU	CL22	CL3Q	CL3I
ABSI						x	x	x
ABSO	x	x	x	x	x			
ABST								
ABSZ								
AIRB		x	x	x		x	x	x
DCRI	x		x		x			
DIAP	x	x			x			
FOND					x			
FPLT						x	x	x
FSUI					x			
GRFS		x	x	x				
GRIL	x	x	x	x	x			
MEMB	x	x			x			
NAH2	x				x			
PCHA	x	x	x	x	x			
PIMP	x	x	x	x	x	x	x	x
POMP	x				x			
PPLT						x	x	x
RDK2				x		x	x	x
RDMC				x			x	
RSEA	x				x			
RUDI						x	x	x
SFSI		x	x	x		x	x	x
STAC						x	x	
SVAL						x	x	x
SWVA	x				x			
VANN	x				x			
VISU		x	x	x		x	x	x

The available options for `IMPV` are the following:

name	law of behaviour
ABSO	absorbing boundary
INFI	conditions at infinity for a fluid
PIMP	imposed pressure
DEGP	imposed mass flow rate for a perfect gas
MUR	total reflexion (rigid obstacle)

Not all these options are available for all boundary condition elements. See the following table:

Option	CL1D	CL2D	CL3D	CL3T	CLTU	CL22	CL3Q	CL3I
INFI		x						
ABSO	?	?	?	?	?			

```
  PIMP  |  ?   |  ?   |  ?   |  ?   |  ?   |      |      |      |
  DEGP  |  ?   |  ?   |  ?   |  ?   |  ?   |      |      |      |
  MUR   |  ?   |  ?   |  ?   |  ?   |  ?   |      |      |      |
-------|------|------|------|------|------|------|------|------|
```

The available options for `CLVF` are the following:

name	law of behaviour
ABSO	absorbing boundary
INFI	Conditions at infinity for a fluid
PIMP	Imposed pressure
DEBI	Imposed mass flow rate
ESUB	Imposed mass flow rate, sub-sonic inflow
LOD1	Lodi, quasi-1D condition
FOUR	Fourier modes in 2D
RIEM	Riemann in 3D
LODG	Lodi 3D with generalized coordinates
CARM	Lodi 3D with multi-dimensional characteristics
ASYM	Asymptotic 3D
LIBR	Free impedance (can be programmed by the user)
FOND	Closed bottom
PFCT	Pressure function of time
DCRI	Critical mass flow rate
DIAP	Diaphragm
SVAL	Safety valve
INLM	Imposed mass flow rate and enthalpy for low Mach number injection

Not all these options are available for all boundary condition elements. See the following table:

```
Option | CL1D | CL2D | CL3D | CL3T | CLTU | CL22 | CL3Q | CL3I |
-------|------|------|------|------|------|------|------|------|
  ABSO |      |      |      |      |      |      |      |      |
  INFI |      |      |      |      |      |      |      |      |
  PIMP |      |      |      |      |      |      |      |      |
  DEBI |      |      |      |      |      |      |      |      |
  ESUB |      |      |      |      |      |      |      |      |
  LOD1 |      |      |      |      |      |      |      |      |
  FOUR |      |      |      |      |      |      |      |      |
  RIEM |      |      |      |      |      |      |      |      |
  LODG |      |      |      |      |      |      |      |      |
  CARM |      |      |      |      |      |      |      |      |
  ASYM |      |      |      |      |      |      |      |      |
  LIBR |      |      |      |      |      |      |      |      |
  FOND |      |      |      |      |      |      |      |      |
  DCRI |      |      |      |      |      |      |      |      |
  DIAP |      |      |      |      |      |      |      |      |
  SVAL |      |      |      |      |      |      |      |      |
  INLM |      |      |      |      |      |      |      |      |
```

```
-------|------|------|------|------|------|------|------|------|
```

Syntax :

```
"IMPE"       $  "ABSO" . . .  $
             $  "PCHA" . . .  $
             $  "PIMP" . . .  $
             $  "DIAP" . . .  $
             $  "GRIL" . . .  $
             $  "MEMB" . . .  $
             $  "GRFS" . . .  $
             $  "NAH2" . . .  $
             $  "RSEA" . . .  $
             $  "VANN" . . .  $
             $  "SWVA" . . .  $
             $  "DCRI" . . .  $
             $  "FOND" . . .  $
             $  "FSUI" . . .  $
             $  "POMP" . . .  $
             $  "PPLT" . . .  $
             $  "RUDI" . . .  $
             $  "STAC" . . .  $
             $  "RDMC" . . .  $
             $  "SVAL" . . .  $
             $  "RDK2" . . .  $
             $  "ABSI" . . .  $
             $  "AIRB" . . .  $
             $  "SFSI" . . .  $
             $  "FPLT" . . .  $
             $  "VISU" . . .  $

"IMPV"       $  "ABSO" . . .  $
             $  "INFI" . . .  $
             $  "PIMP" . . .  $
             $  "DEGP" . . .  $
             $  "MUR"  . . .  $

"CLVF"       $  "ABSO" . . .  $
             $  "INFI" . . .  $
             $  "PIMP" . . .  $
             $  "DEBI" . . .  $
             $  "ESUB" . . .  $
             $  "LOD1" . . .  $
             $  "FOUR" . . .  $
             $  "RIEM" . . .  $
             $  "LODG" . . .  $
             $  "CARM" . . .  $
             $  "ASYM" . . .  $
             $  "LIBR" . . .  $
```

```
$  "FOND" . . .  $
$  "PFCT" . . .  $
$  "DCRI" . . .  $
$  "DIAP" . . .  $
$  "SVAL" . . .  $
$  "INLM" . . .  $
```

Comments :

These key-words can be repeated as many times as necessary with different options each time (if need be). The keyword IMPE, IMPV or CLVF should not be separated from the options : ABSO , PCHA , PIMP , etc.

Beware that the CLVF models are still experimental and under development. Only the ABSO, LOD1, FOUR and RIEM models have been tested somewhat (the ABSO being by far the most used one), but are for the moment available only in 3D, for perfect gas material and for first-order in space and in time VFCC formulations. Furthermore, they may function with only some of the flux solvers available. For an overview of the state of the art of these developments see references [967] and [968].

7.9.1 ABSORBING MATERIAL

Object :

This option enables to specify absorbing or partially absorbing boundary conditions for 1-D, 2-D or 3-D elements.

This model is appropriate for CLxx elements developed at CEA, namely CL1D, CL2D, CL3D or CL3T. There exists a similar, but not identical, absorbing boundary model developed at JRC which is appropriate for their CLxx elements (CL22, CL3I or CL3Q), see page C.880.

Only pressure waves normal to the boundary are absorbed. The model consists simply in applying a fictitious external pressure $p = -\rho c v_n$, where ρ is the density of the material at the boundary, c its sound speed and v_n the normal component of the particle velocity at the boundary, in Lagrangian calculations, or of the relative (particle minus mesh) velocity in Eulerian or ALE calculations. The "internal" forces due to the absorbing boundary are finally computed by spatial integration of a modified pressure $\pi = (p + p_{\text{old}})/2$, where p_{old} is the value of π at the previous time integration step.

Syntax:

```
"IMPE"  "ABSO"  <"RO" rho>  <"C" c>   /LECTURE/
```

`rho`

Fixed, user-imposed value of the density. If omitted, the code will try to determine the density automatically.

`c`

Fixed, user-imposed value of the sound speed. If omitted, the code will try to determine the sound speed automatically. Since for a structural material the code is sometimes unable to determine the sound speed automatically, the value becomes useful in this case (and is of course constant). However, since the physical sound speed is fairly constant in such a case, the behaviour of the model should be quite good. A notable exception are materials `CAMC` and `CLAY`, for which the sound speed varies considerably: for these materials the code is indeed able to retrieve the current sound speed automatically, so that specifying `c` in these cases is unnecessary.

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL1D, CL2D, CL3D or CL3T)

Comments :

If the acoustic waves are to be absorbed, the `rho` and `c` parameters must be the same on both sides of the boundary. The effect will then be that of an infinite medium. In the opposite case, there will be partial reflections.

If the user has omitted `c` and the code is unable to determine it automatically, an error message is issued and the calculation is stopped.

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : density times normal velocity in the local reference frame

7.9.2 TOTAL ABSORBING MATERIAL

Object :

This option enables to specify absorbing boundary conditions for 3D elements. This model is based on a paraxial formulation and is available for CL3D or CL3T elements.

Pressure waves normal to the boundary and shearing waves parallel to the boundary are absorbed. The model consists simply in applying a fictitious external pressure $p = -\rho(c_p v_n + c_s v_p)$, where ρ is the density of the material at the boundary, c_p its longitudinal sound speed, c_s its transverse sound speed, v_n the normal component of the particle velocity at the boundary and v_p the parallel component, in Lagrangian calculations only. The "internal" forces due to the absorbing boundary are finally computed by spatial integration of a modified pressure $\pi = (p + p_{\text{old}})/2$, where p_{old} is the value of π at the previous time integration step.

Syntax:

```
"IMPE"  "ABST"  <"RO" rho>  <"CP" cp>  <"CS" cs> /LECTURE/
```

`rho`

Fixed, user-imposed value of density. If omitted, the code will try to determine it automatically.

`cp`

Fixed, user-imposed value of the longitudinal sound speed. If omitted, the code determines it using material parameters of the neighboring element through the following formula:

$$c_p = \sqrt{(\lambda + 2G)/\rho}$$

with

$$G = E/(2(1+\nu)), \lambda = E\nu/((1+\nu)(1-2\nu))$$

`cs`

Fixed, user-imposed value of the transverse sound speed. If omitted, the code determines it using material parameters of the neighboring element through the following formula:

$$c_s = \sqrt{G/\rho}$$

`LECTURE`

Reading procedure of the elements composing the boundary (CL3D or CL3T)

Comments:

This model works correctly only if 3D-elements in the neighborhood of the boundary have a linear elastic behavior and are provided with the laws LINE or VMJC.

Warning: If the user has omitted c_p and(or) c_s and the neighbor is not provided with the "LINE" or "VMJC" laws, the code is unable to determine it automatically. An error message is issued and the calculation is stopped.

Outputs:

The different components of the ECR table are as follows:

ECR(1) : pressure

ECR(2) : component of shearing in the first direction of boundary plan

ECR(3) : component of shearing in the second direction of boundary plan

ECR(4) : density

ECR(5) : density times normal velocity in the local reference frame

ECR(6) : density times normal velocity in the local reference frame

ECR(7) : density times first component of parallel velocity in the local reference frame

ECR(8) : density times second component of parallel velocity in the local reference frame

7.9.3 HEAD LOSS

Object :

This instruction enables localized head losses to be input.

Syntax :

```
"IMPE"  "PCHA"  "RO" rho  "K"  k  /LECTURE/
```

`rho`

Density.

`k`

Coefficient of a localized head loss.

`LECTURE`

Reading procedure of the element numbers (CL1D, CL2D or CL3D).

Comments :

The head loss (DP) is deduced from the density (rho) and the velocity (V) up-stream of the singularity:

```
DP = 0.5 * k * rho * V*V
```

The result is a resisting force which is always opposed to the velocity.

It is evident that this model may not be applied to the extremities of pipelines.

Outputs:

The different components of the ECR are as follows:

ECR(1) : pressure

ECR(2) : density

7.9.4 GRID

Object:

This instruction enables to model the influences of grids or rigid perforated plates on a fluid.

See also on page C4.650 directive GRFS.

Syntax:

```
"IMPE"  "GRIL"  "RO" rho  "C" c  "ALP" alpha  ...
          ...  "TAU" tau  /LECTURE/
```

`rho`

Density.

`c`

Velocity of sound in the fluid.

`alpha`

Dissipative impedance.

`tau`

Time constant.

`LECTURE`

Reading procedure of the element numbers (CL2D or CL3D).

Comments:

The model is based on the hypothesis of an acoustic propagation of plane waves.

The meaning of the parameters alpha and tau is as follows:

Let:

L : equivalent length of the grid holes

ST : total cross section

s : cross section open to flow

M : Mach number of the permanent flow up-stream of the singularity

xi : head loss coefficient

Then:

```
                                  ST      L
   alpha = xi * M         tau   = ---- * ------
                                  s      2*c
```

Remarks:

The ratio s / ST represents the perforation ratio of the plate.

In the steady-state regime the pressure drop across the plate assumes the form:

```
DP = alpha * rho * c * V
```

Recall that for an absorbing boundary alpha = i, since the pressure and mass flow rate fluctuations are in quadrature.

The equivalent length L is not equal to the plate thickness. To take into account three-dimensional effects, add a length equivalent to the diameter of the holes to that thickness.

Warning:

This directive allows to transmit the stresses from the plate to the fluid. It allows to modify the flow by taking into account the pressure drops introduced by a perforated plate. The directives "IMPE" "GRFS" should be used in order to correctly transfer the fluid stresses onto an equivalent shell structure representing the plate.

For an A.L.E. computation with a fluid-structure coupling of the perforated plate, the user has to mention twice the "FS2D" elements,which link together the plate and the fluid : first, in the instruction "GRILLE" "ALE" ... "FS" ..., in order to make the fluid nodes follow the motion of the grid; and then in the instruction "LIAISON" "FS" ..., in order to transmit correctly the forces of the fluid towards the plate. The fluid has to be meshed continuously through the plate.In this case, the elements "FS2D" are located inside the fluid and not in its surrounding area. All the other "FS2D" elements, normally located at the boundaries of the fluid, are mentioned only once in the instruction "GRILLE" "ALE" ... "FS" ..., for in A.L.E. the fluid-structure coupling is done automatically on the boundaries.

In a Lagrangian computation, for the same mesh this problem does not exist, because only the following instruction exists : "LIAS" "FS"...

Outputs :

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

7.9.5 IMPOSED PRESSURE

Object:

This instruction enables a pressure at the boundary of different elements to be imposed by the means of a "CLxx" element.

Syntax:

```
"IMPE"  "PIMP"  < "RO" rho >   "PRES" pres                   ...
         ...  < "PREF" pref >    < "ENTH" enth >           ...
         ...  < $[ "FONC" nufo ;                           ...
         ... obsolete:   "TABP" npt*( t , p ) ]$ >         ...
         ...  /LECTURE/
```

`rho`

Density.

`pres`

Constant imposed pressure, or multiplying factor for the ordinates of the following table or function if it exists.

`pref`

Reference pressure. Note that if a zero reference pressure is desired, it is mandatory to specify 'PREF 0' in the input file. This is because, if no value for PREF is specified, the code assumes PREF=PRES(t=0) so the initial imposed pressure has no effect, since p=PRES-PREF=0!

`enth`

Input enthalpy.

`npt`

Number of points defining the pressure curve.

`t , p`

Coordinates of a point on the curve (time , pressure).

`nufo`

Number of the function to be used to describe the pressure versus time.

`LECTURE`

Reading procedure of the number of the "CLxx" element defining the boundary.

Comments:

For the meaning of pref, see GBC_0300.

If the input enthalpy is zero, the code uses the enthalpy value of the neighbour element. Otherwise, the user's imposed value is taken into account. This possibility works only in Van Leer.

ATTENTION ! The keyword "TABP", that introduces the time function of the pressure, is obsolete. Use preferably the directive "FONC". Keyword "TABP" is maintained just to ensure compatibility with old input data sets.

The keywords "TABP" and "FONC" are mutually exclusive.

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(9) : enthalpy per unit volume (Van Leer only)

7.9.6 DIAPHRAGM

Object:

This directive introduces, at the end of a pipeline, a diaphragm that causes a localised pressure drop, and an external imposed pressure.

Syntax:

```
"IMPE"  "DIAP"  "RO" rho  "PFIN" pfin  <"PREF" pref> ...
          ...  "PINI" pini  "TAU" tau  "K" k  /LECTURE/
```

`rho`

Density.

`pfin`

External imposed pressure in steady-state flow.

`pref`

Reference pressure.

`pini`

Initial pressure at the diaphragm level.

`tau`

Time constant of the exponential function that transforms pinit into pfin.

`k`

Diaphragm head loss coefficient (>1 or = 1).

`LECTURE`

Reading procedure of the CL1D element forming the boundary.

Comments:

The meaning of pref is given on page C.300.

The imposed pressure passes from pini to pfin following an exponential function whose time constant is tau. It is possible to take tau = 0 to represent an abrupt change (depressurisation). However, by giving tau ¿ 0 it is possible to simulate a finite opening time of the diaphragm.

The K coefficient allows to account for the diaphragm cross section, that may be smaller than the tube diameter.

```
                            K = sup( Ko , ksi * R * R )
 -----------
         |_|                R is the ratio of cross-sections: R = S / s
     S    _  s
 _________|_|               ksi = 1 + 0.5 * ( 1 - 1/R )
                                    + eta * sqr ( 1 - 1/R )
                                    + lambda * long / Dh

  Ko is the coefficient corresponding to S = s : 1.06 < Ko < 1.10
```

The preceding formula is taken from IDEL'CIK for the openings with a thick diaphragm, and for large Reynolds numbers.

The eta coefficient varies along with the ratio long / Dh. It passes from 1.35 to 0 when this ratio goes from 0 to 2.4.

The long parameter is the length of the diaphragm (thickness of the bottom), and Dh the hydraulic diameter (h = 4 * area / perimeter).

The lambda parameter allows to define the head loss along the small tube equivalent to the diaphragm.

If the distribution of velocities at the outlet would be uniform, one would have Ko = 1.

Most often, it may suffice to use the IDEL'CIK formula for a thin diaphragm with sharp border:

```
ksi = (1 + 0.707 * sqrt( 1 - 1/R ) )**2
```

By full opening, take K = Ko, with Ko = 1.06.

Outputs:

The various components of the ECR table are as follows:

ECR(1) : pressure

ECR(2) : density

ECR(3) : mass velocity (rho * v)

7.9.7 MEMBRANE

Object:

Introduces a safety membrane to the extremity of a pipeline (1D), or on the axis of an axisymmetric reservoir (2D). The membrane rupture occurs: either when the pressure in the neighbouring element exceeds the rupture pressure, or when the time exceeds a prescribed value.

Syntax:

```
"IMPE"  "MEMB"  "RO" rho  "PINI" pini  "PFIN" pfin  ...
... <"PREF" pref>  "TAU" tau  "K" k $[ "PRUP" prup ;
                                       "TRUP" trup ]$ /LECTURE/
```

`rho`

Density.

`pini`

Initial pressure.

`pfin`

Imposed external pressure in steady-state flow.

`pref`

Reference pressure.

`tau`

Time constant of the exponential function that leads pini to pfin.

`k`

Head loss coefficient (>1 or = 1).

`prup`

Rupture pressure of the membrane.

`trup`

Rupture instant.

`LECTURE`

List of the concerned elements.

Comments:

In the "GEOM" directive, the elements with a material "MEMB" must be listed after the adjacent fluid elements.

Outputs:

The various components of the ECR table are as follows:

ECR(1) : pressure

ECR(2) : density

ECR(3) : mass velocity

ECR(5) : rupture instant of the membrane

ECR(6) : rupture indicator (0=intact, 1=broken)

7.9.8 CRITICAL MASS FLOW RATE

Object:

Computes the critical mass flow rate for a perfect gas or for a water-steam mixture at the extremity of a pipeline (1D).

Syntax:

```
"IMPE"  "DCRI"  "PINI" pini   "PFIN" pfin  < "PREF" pref >   ...
        "RAP" rapport   < "KSI" ksiz >   < "MOD" mode >      ...
       < "TAU" tau >  < "TRUP" trupt >  < "FONC" nufo >      ...
         /LECTURE/
```

`pini`

Initial pressure.

`pfin`

Imposed external pressure in steady-state conditions.

`pref`

Reference pressure.

`rapport`

Ratio of the cross-sections : S(exit)/S(upstream).

`ksiz`

Head loss coefficient at the outlet for the fluid.

`mode`

Choice of the critical mass flow rate model (for the two-phase water only : see below)

`tau`

Time constant of the exponential function leading from pini to pfin.

`trupt`

Rupture instant of the membrane. By default, trupt = 0.

`nufo`

function number for a progressive opening.

`LECTURE`

List of the concerned elements.

Comments:

The user may choose among four modes for the equilibrated two-phase water, which differ in the phase-to-phase sliding:

mode = 1 : homogeneous model

mode = 2 : MOODY model

mode = 3 : FAUSKE model

mode = 4 : DEMT model (developed by M. Lepareux)

For the three first modes, the results do not depend upon the size of the opening. On the contrary, the DEMT mode developed by Michel Lepareux [721] accounts for this effect provided the following value is not exceeded (rapport=ratio):

```
rapport < or = 0.75
```

For the liquids, the `ksiz` coefficient allows to account for the form of the outlet. By default, the value suggested by IDEL'CIK is retained for `ksiz`, corresponding to a straight pipe outlet and a thin diaphragm with sharp sides, i.e.:

$$ksiz = (1 + 0.707\sqrt{1 - rapport})^2$$

Of course, with the data of the upstream medium, the formula becomes:

$$ksi = \frac{ksiz}{rapport^2}$$

The old data input files included a parameter `K`, equal to 'ksi' with ksiz = 1. In order to better reproduce the phenomena, it is suggested to no longer use `K`, and to declare the two parameters 'ksiz' and 'rapport' instead.

Outputs:

The different components of the ECR table are as follows:

ECR(1) : pressure at the opening

ECR(2) : density of the donor element

ECR(3) : mass velocity (Q = rho*Vn) of the donor

ECR(4) : outlet pressure (Pext or Pcrit)

ECR(6) : indicator (0 if liquid; 1 if gas; mass title if two-phase mixture)

ECR(7) : Mach number at the outlet (only for perfect gases and two-phase water)

ECR(9) : maximum mass velocity (Qmax), if ECR(4) = Pcrit

ECR(10) : indicator (0 = virgin membrane, 1 = ruptured membrane)

7.9.9 CLOSED BOTTOM

Object:

This option allows to impose a closed bottom condition at the extremity of a pipeline, by means of a CLTU element.

Syntax:

```
"IMPE"  "FOND"  /LECTURE/
```

`LECTURE`

List of the elements concerned.

Comments:

This directive automatically ensures the fluid-structure coupling between the pipe and the internal fluid.

Warning

The couplings between degrees of freedom are done directly in the CLTU element, therefore it is necessary that the number of the CLTU element concerned be greater than all other elements that arrive in the same point (TUBE, TUYA, POUT). This in order to have, at the moment of computing the coupling, the resultant of the applied forces. A very simple way of proceeding is to declare the CLTU elements as the last ones in the GEOM directive.

7.9.10 PUMP

Object:

This option allows to impose on a pipeline, by means of a CL1D or CLTU element, a pump model represented by its characteristic curve.

Syntax:

```
"IMPE"  "POMP"  "RO" rho  "COEF" coef  "NUFO" nf "NFTS" nfr  /LECTURE/
```

`rho`

Density.

`coef`

Multiplicative coefficient allowing to define the functioning direction of the pump, and to convert the units.

`nf`

Number of the function to be used to describe the characteristic curve of the pump as a function of the volume flow rate.

`nfr`

Number of the function to start the pump progressively.

`LECTURE`

List of the concerned elements.

Comments:

The pressure difference is of the form:

$$\Delta P = C\, f(Q_v)$$

where C is coef, Q_v is the volume flow rate and f the function that models the characteristic.

Warning

The characteristic curve of the pump must be given by means of the keyword `FONCTION` in the following way: in abscissa the volume flow rate and in ordinate the height of the pump. Be careful that the chosen units are coherent! For example, pump height in Pascal and flow rate in m^3s^{-1}. In the case of a normal functioning of the pump, all these values (pressure and flow rate) are positive.

The coefficient `COEF` allows to use different units for the pressures, and its sign allows to orient the pump as a function of the positive orientation associated with the node where the pump is located.

Thus, if the numbers of the elements located at either part of the node where the pump is located are in growing order along the direction of the flow, then the `COEF` coefficient is positive.

If the flow is in the opposite direction than the normal (the fluid flows back through the pump), it is assumed that the head loss is zero. Furthermore, in accident calculations, it is prudent to foresee a characteristic (even zero) for very large flow rates.

Outputs:

The different components of the ECR table are as follows:

ECR(1) : pressure difference

ECR(2) : density

ECR(3) : mass velocity

7.9.11 FOLLOWING FORCE

Object:

This directive allows to impose, at the extremity of a pipeline, by means of a CLTU element, a "following force" applied along the direction of the last element of the pipeline.

Syntax:

```
"IMPE"  "FSUI"  "RO" rho  "FORC" fs  "NUFO" nf  /LECTURE/
```

`rho`

Density.

`fs`

Multiplicative coefficient for the force.

`nf`

Number of the function used to describe the force as a function of time.

`LECTURE`

List of teh concerned elements.

Comments:

A positive force will be directed towards the interior of the pipe.

The function to be used will be defined by means of the "FONC" directive described on page E.10.

Outputs:

The various components of the ECR table are as follows:

ECR(1) : pressure

ECR(2) : density

ECR(3) : following force

7.9.12 CRITICAL MASS FLOW RATE COUPLING (NAH2)

Object:

Computation of the critical mass flow rate of a water-steam mixture at the extremity of a pipeline (1D) accounting for the pressure produced by the hydrogen bubble generated by a sodium-water reaction. This material uses a model with 2 components (sodium and hydrogen) and two phases. The starting instant of the tube opening may be prescrivbed in advance (case of several pipes whose rupture times are different)

Syntax:

```
    "IMPE"  "NAH2"  "RO" rho  "PINI" pini  <"PREF" pref>
         ... "TAU" tau  "K" k "TUBE" ntube  "MOD" mode
         ...   <"TRUP" trup> <"PFIN" pfin> /LECTURE/
```

`rho`

Density.

`pini`

Initial pressure.

`pref`

Reference pressure.

`tau`

Time constant of the exponential (see DIAP page C.550).

`k`

Head loss coefficient (single-phase flow).

`ntube`

Total number of ruptured tubes.

`mode`

Choice of the critical flow rate model.

`trup`

Rupture instant (zero by default).

`pfin`

Imposed final pressure.

`LECTURE`

List of the concerned elements.

Comments:

The user may choose among four modes:

mode = 1 : homogeneous model

mode = 2 : MOODY model

mode = 3 : FAUSKE model

mode = 4 : DMT model (developed by M. Lepareux)

This directive is similar to "DCRI" and must be used in conjunction with the "NAH2" material within a "TUBE" or "TUYA" element.

Outputs:

The various components of the ECR table are as follows:

ECR(1) : pressure

ECR(2) : density

ECR(3) : Q = rho*Vn at the rupture (mass velocity).

ECR(4) : pressure at the outlet (Pext or Pcrit)

ECR(6) : indicator (0= single-phase ; 1= two-phase)

ECR(7) : status of the tube (0 = intact, 1 = ruptured)

ECR(9) : Qmax = (rho*Vn) maximum if one is in the critical regime. This parameter only makes sense for water or for gases.

7.9.13 CRITICAL MASS FLOW RATE COUPLING (RSEA)

Object:

Computation of the critical mass flow rate of a water-steam mixture at the extremity of a pipeline (1D) accounting for the pressure produced by the hydrogen bubble generated by a sodium-water reaction. This material is similar to the previous one (”NAH2” page C4.710), but is coupled to the ”RSEA” material, which uses three components (sodium, hydrogen and argon) and 2 phases.

Syntax:

```
"IMPE"  "RSEA"  "RO" rho  "PINI" pini  <"PREF" pref>
     ... "TAU" tau  "K" k "TUBE" ntube  "MOD" mode
     ...   <"TRUP" trup> <"PFIN" pfin> /LECTURE/
```

`rho`

Density.

`pini`

Initial pressure.

`pref`

Reference pressure.

`tau`

Time constant of the exponential (see DIAP page C.550).

`k`

Head loss coefficient (single-phase flow).

`ntube`

Total number of ruptured tubes.

`mode`

Choice of the critical flow rate model.

`trup`

Rupture instant (zero by default).

`pfin`

Final prescribed pressure.

`LECTURE`

List of the elements concerned.

Comments:

The user may choose among four modes:

mode = 1 : homogeneous model

mode = 2 : MOODY model

mode = 3 : FAUSKE model

mode = 4 : DMT model (developed by M. Lepareux)

This directive is similar to the "DCRI" directive and must be used in conjunction with the "RSEA" material within a "TUBE" or "TUYA" element.

Outputs:

The various components of the ECR table are as follows:

ECR(1) : pressure

ECR(2) : volumetric mass

ECR(3) : Q = rho*Vn at the rupture (mass velocity).

ECR(4) : outlet pressure (Pext or Pcrit)

ECR(6) : indicator (0 = single-phase ; 1 = two-phase)

ECR(7) : tube status (0 = intact, 1 = ruptured)

ECR(9) : Qmax = (rho*Vn) maximum if one is in the critical regime. This parameter makes sense only for water or for a gas.

7.9.14 "VANNE" - SAFETY AND REGULATING VALVES

Object:

This directive allows the user to model the behaviour of a safety and a regulating valve ("vanne") placed within a pipeline or at its extremity. It introduces a localised pressure drop with a variable pressure loss coefficient depending on the opening cross section of the valve. This impedance, available for the elements of type CL1D and CLTU, is useful to model water hammer effects ("coup de belier") in the pipeline systems.

For a safety valve, the beginning and the duration of the closure must be specified. For a regulating valve, the user has to specify a tabulated function allowing to govern the valve opening during the calculation (partial or complete opening or closure).

Syntax:

```
for a safety valve:

"IMPE"  "VANN"  "TFER" tferm   "TAU" tau   "SMIN" smin  "PREF" pref
                /LECTURE/

for a regulating valve:

"IMPE"  "VANN"  "SMIN" smini  "PREF" pref  "NFSL" numfo
                /LECTURE/
```

`tferm`

Initial time of the valve closure.

`tau`

Duration of the closure.

`smin`

Minimum cross section, below which the valve is considered as closed.

`pref`

Reference pressure.

`numfo`

Number of the function prescribing the time variation of the ratio $\frac{S_{free}}{S_{upstream}}$.

`LECTURE`

List of the elements concerned.

Comments:

The parameters `SMIN` and `PREF` are compulsory.

Safety valve:

Initially the valve is considered to be open. It starts to close at time `tferm`, and the closure has a duration of `tau`. It is assumed that the opening cross-section varies linearly between time `tferm` and `tferm` + `tau`, at which the valve is completely closed.

During the closure, the pressure drop varies as a function of the opening cross-section:

$$K(t) = (\frac{S_{upstream}}{S_{free}})^2 - 1$$

Its value therefore varies from zero (fully open valve) to K_{max}, which is determined by assuming that the closure is complete when $S_{free} <$ `SMIN`. In most cases the value 0.01 may be assumed for `SMIN`.

Once the valve closed, a blockage condition (CL1D) or closed end condition (CLTU) is applied to the node to which the element is attached. In order to know whether the valve is open or closed, EUROPLEXUS checks the value of ECR(6).

Regulating valve:

For the regulating valve a tabulated function given by the user prescribes the time variation of the valve cross section ($\frac{S_{free}}{S_{upstream}}$ ratio) allowing thus to govern the valve opening during the calculation.

Outputs:

The components of the ECR table are as follows:

ECR(1) : pressure drop

ECR(2) : density of the upstream element

ECR(4) : ratio of cross-sections ($\frac{S_{free}}{S_{upstream}}$)

ECR(6) : if =0 the valve is open, if =1 the valve is closed

ECR(7) : time

ECR(8) : pressure drop coefficient $K(t)$

7.9.15 SWING CHECK VALVE WITH FLUID-STRUCTURE COUPLING

Object:

This directive allows the user to enter along a pipeline an anti-backflow valve which can close rapidly when the flow is inversed. The valve disc dynamics is governed by its angular inertia as well as by different moments due to the disc weight and hydrodynamic forces. The disc motion causes a localised pressure drop taken into account via a variable head loss coefficient depending on the aperture of the valve disc. The model is attached to CL1D elements.

Syntax:

```
"IMPE"  "SWVA"  "MASS" mass  <"RO"  rho>   "ITOT" itot   <"PREF" pref>
                "STUB" stub  "DIST" dist  <"AINI" aini>  <"AMAX" amax>
                <"POPE" pope> "FNUM" nume  /LECTURE/
```

`mass`

Mass of the valve disc.

`rho`

Fluid density.

`itot`

Total moment of inertia accounting for the disc and added fluid inertia.

`pref`

Reference pressure.

`stub`

Flow-tube cross section.

`dist`

Length of the valve disc moment arm.

`aini`

Initial opening angle.

`amax`

Maximum opening angle.

`pope`

Opening pressure.

`nume`

Number of the singular head loss K(alpha) curve.

`LECTURE`

Reading procedure of the CL1D element forming the boundary.

Comments:

The meaning of pref is given on page C.300.

The head loss (DP) is deduced from the density (rho) and the velocity (V) up-stream of the singularity and it is function of variable head loss coefficient depending on the aperture angle of the disc:

```
DP = 0.5 * k(alpha) * rho * V*V
```

The result is a resisting force which is always opposed to the velocity.

The integration of the disc motion equation is abandoned after closure of the valve and EUROPLEXUS replaces the boundary condition by a zero velocity condition (case of CL1D). The valve can reopen when DP exceeds the opening pressure specified by the user.

Outputs:

The various components of the ECR table are as follows:

ECR(1) : pressure drop

ECR(2) : fluid density

ECR(3) : mass velocity (rho * v)

ECR(4) : reference pressure

ECR(5) : current angle of disc (degrees)

ECR(6) : current angular velocity of disc (rad/s)

ECR(7) : current time then t+dt

ECR(8) : current head loss coefficient

7.9.16 FLUIDE-STRUCTURE GRID

Object:

This directive allows to model for a fluid the influence of grids or perforated plates and to apply the resulting pressure drop to the structure (grid).

See also on page C.530 the GRILLE directive.

Syntax:

```
"IMPE"  "GRFS"  "RO" rho  "C" c  "ALP" alpha  ...
         ...  "TAU" tau  /LECTURE/
```

`rho`

Density.

`c`

Sound speed in the fluid.

`alpha`

Dissipative impedance.

`tau`

Time constant.

`LECTURE`

Lecture procedure of the elements concerned.

Comments:

The model assumes that plane acoustic waves are propagated.

The meaning of the alpha and tau parameters is as follows:

Let:

L : equivalent length of the grid holes

ST : total cross-section

s : flow cross-section

M : Mach number of the permanent upstream flow

k : head loss coefficient

Then:

```
                                  ST      L
   alpha = 0.5 * k * M    tau = ---- * ------
                                  s      2*c
```

Remarks:

The ratio s / ST represents the perforation ratio of the plate.

The head loss coefficient k takes the form:

```
DP = 0.5 * k * rho * V2
```

Recall that for an absorbing boundary alpha = i, since the pressure and flow rate fluctuations are in quadrature.

The equivalent length L is not equal to the plate thickness. To account for three-dimensional effects, to this thickness a further length must be added, of the order of the orifice diameter.

Warning:

EUROPLEXUS automatically searches for the structure nodes that 'touch' the boundary condition elements. It is then mandatory to mesh the structure in the same way as the boundary condition elements (same mesh density and same topology of the faces in contact).

Outputs:

The various components of the ECR table are as follows:

ECR(1) : pressure

ECR(2) : density

7.9.17 PERFORATED PLATE (JRC)

Object:

This instruction enables the modelling of a perforated structure (e.g. a plate) embedded in a fluid.

The pressure drop across the plate is computed according to the expression:

```
Deltap = zeta * rho * v * v / 2.0
```

Here zeta is the resistance coefficient, rho the fluid density and v the velocity normal to the plate in the undisturbed upstream region of the fluid.

Syntax :

```
"IMPE"  "PPLT"  "ZETA" zeta
        /LECTURE/
```

`zeta`

Resistance coefficient (assumed as constant in the present model).

`/LECT/`

Concerned elements.

Outputs:

The different components of the ECR table are as follows :

ECR(1) : current pressure drop across the plate

ECR(2) : density upstream the plate

ECR(3) : resistance coefficient

ECR(4) : structural node 1

ECR(5) : structural node 2

ECR(6) : structural node 3

ECR(7) : structural node 4

ECR(8) : unused

ECR(9) : unused

Note that the positions 4 to 7 contain up to 4 indexes of the structural nodes corresponding to the CLxx element's (fluid) nodes. These quantities are determined only once at the beginning of the calculation and never change. Furthermore, the resistance coefficient is also assumed as constant in the present implementation.

Comments:

Normally, the determination of the above mentioned node correspondence is performed automatically. However, in case of problems the user may either change the tolerance for node matching (see OPTI TOLC on page H.40) or force the node correspondence by using the directive COMP CNOD, see page C.92.

7.9.18 RUPTURE DISK (JRC)

Object:

This instruction enables the modelling of a rupture disk structure (e.g. a plate) embedded in a fluid.

The disk reacts to the pressure drop caused by a fluid on the two sides of the disk, until a certain deltap is reached, which causes the rupture of the disk.

Usually, the disk is modelled by a series of structural finite elements (plate, shell) and the fluid on both sides is discretized by continuum finite elements.

Special boundary condition elements (CLxx) are attached to the fluid nodes in order to connect the disk with the fluid. These elements are assigned the present IMPE RUDI material.

The disk rupture is caused by a fixed (nominal) deltap, which can occur at any point of the disk, in case this is discretized by several finite elements. When one element reaches this condition, failure is initiated also in all other elements at the same time.

A certain rupture time interval can be prescribed from failure initiation to failure completion in order to simulate the fact that in reality the disk is a mechanical system with inertia and can not break instantaneously.

Unlike in the models of safety valves, note that once the disk rupture is initiated at a certain point, it continues until full failure even if the deltap is reduced.

Syntax :

```
    "IMPE"  "RUDI"  "DPRU" dpru      < "TRUP" trup >
            /LECTURE/
```

`dpru`

Pressure difference (deltap) between the two sides that causes rupture of the disk. The deltap is measured between the fluid elements directly attached to the disk on each side. The deltap includes only the fluid pressure and not the pseudo-viscous pressure. However, the pseudo-viscous pressure is taken into account in the computation of the resistance forces developed by the disk.

`trup`

Rupture time interval of the disk. By default it is trup = 0 (instantaneous rupture). This can be specified > 0 in order to simulate the inertia of the disk and the gradual opening of the orifice.

`/LECT/`

Concerned elements.

Outputs:

The different components of the ECR table are as follows :

ECR(1) : current pressure drop across the disk (at this element), doesn't include the pseudoviscous pressure

ECR(2) : 0 for virgin disk, 1 for broken disk

ECR(3) : time at which failure is initiated

ECR(4) : structural node 1

ECR(5) : structural node 2

ECR(6) : structural node 3

ECR(7) : structural node 4

ECR(8) : unused

ECR(9) : unused

Note that the positions 4 to 7 contain up to 4 indexes of the structural nodes corresponding to the CLxx element's (fluid) nodes. These quantities are determined only once at the beginning of the calculation and never change.

Comments:

Normally, the determination of the above mentioned node correspondence is performed automatically. However, in case of problems the user may either change the tolerance for node matching (see OPTI TOLC on page H.40) or force the node correspondence by using the directive COMP CNOD, see page C.92.

7.9.19 STACEY'S 1ST ORDER ABSORBING BOUNDARY (JRC)

Object:

This instruction enables the modelling of an absorbing boundary according to Stacey's 1st-order law, see R. Stacey, "Improved transparent boundary formulations for the elastic-wave equation", Bull. Seis. Soc. Am., Vol. 78, pp. 2089-2097, December 1988.

The model is only available in conjunction with spectral elements and can be applied only to CL22 elements, in 2D, and CL3Q elements, in 3D.

Syntax :

```
"IMPE"  "STAC"  /LECTURE/
```

`/LECT/`

Concerned elements.

Outputs:

The components of the ECR table are as follows. If the material belongs to a CL22 element, then:

ECR(1) : unused
ECR(2) : unused
ECR(3) : unused
ECR(4) : unused
ECR(5) : unused
ECR(6) : unused
ECR(7) : unused
ECR(8) : unused
ECR(9) : unused

If the material belongs to a CL3Q element, then:

ECR(1) : x-component of 1st tangent vector
ECR(2) : y-component of 1st tangent vector
ECR(3) : z-component of 1st tangent vector
ECR(4) : x-component of 2nd tangent vector
ECR(5) : y-component of 2nd tangent vector

ECR(6) : z-component of 2nd tangent vector

ECR(7) : x-component of normal vector (outwards the associated MS38)

ECR(8) : y-component of normal vector (outwards the associated MS38)

ECR(9) : z-component of normal vector (outwards the associated MS38)

Remarks:

It has been noted that the use of this type of absorbing boundary conditions can in some cases reduce the stability step. If needed, the safety coefficient of the calculation may be reduced (from the default value of 0.5) by using the directive "OPTI CSTA", see Group H (Options).

Usually it has been found that OPTI CSTA 0.25 is sufficient to prevent instabilities (especially in 2D), but in some 3D cases it has been necessary to use OPTI CSTA 0.125.

7.9.20 RUPTURE DISK FOR MC FORMULATION (JRC)

Object:

This instruction enables the modelling of a rupture disk structure (e.g. a plate) embedded in a fluid modeled with the MC finite volume formulation.

The disk reacts to the pressure drop caused by a fluid on the two sides of the disk, until a certain deltap is reached, which causes the rupture of the disk.

The mechanical behaviour (deformability) of the disk is not taken into account, so there is no need to introduce structural elements.

The fluid mesh is not continuous, i.e. the rupture disk separates two distinct zones of the fluid domain, and the elements facing each other have coincident (same coordinates) fluid nodes on the discontinuity.

Special boundary condition elements (CLxx) are attached to the fluid element at one of the two sides of the aforementioned discontinuity, no matter which one of them. These elements are assigned the present IMPE RDMC material.

The disk rupture is caused by a fixed (nominal) deltap, which can occur at any point of the disk, in case this is discretized by several CLxx elements. When one element reaches this condition, failure is initiated also in all other elements at the same time.

Unlike in the models of safety valves, note that once the disk rupture is initiated at a certain point, it continues until full failure even if the deltap is reduced.

Syntax :

```
"IMPE"  "RDMC"  "DPRU" dpru

        /LECTURE/
```

`dpru`

Pressure difference (deltap) between the two sides that causes rupture of the disk. The deltap is measured between the fluid elements directly attached to the disk on each side.

`/LECT/`

Concerned elements.

Outputs :

The different components of the ECR table are as follows :

ECR(1) : current pressure drop across the disk (at this element)

ECR(2) : 0 for virgin disk, 1 for broken disk

ECR(3) : time at which failure is initiated

ECR(4) : fluid node opposite to CLxx element node 1

ECR(5) : fluid node opposite to CLxx element node 2

ECR(6) : fluid node opposite to CLxx element node 3

ECR(7) : fluid node opposite to CLxx element node 4

ECR(8) : index of fluid element attached to this CLxx

ECR(9) : index of fluid element opposed to this CLxx

Note that the positions 4 to 7 contain up to 4 indexes of the fluid nodes opposite to the CLxx element's (fluid) nodes. These quantities are determined only once at the beginning of the calculation and never change.

Comments:

Normally, the determination of the above mentioned node correspondence is performed automatically. However, in case of problems the user may either change the tolerance for node matching (see OPTI TOLC on page H.40) or force the node correspondence by using the directive COMP CNOD, see page C.92.

7.9.21 ABSORBING MATERIAL VAN LEER

Object :

This directive enables an absorbing boundary conditions for Van Leer elements to be input.

Syntax:

```
"IMPV"  "ABSO"  "RO" rho /LECTURE/
```

`rho`

Density.

`LECTURE`

Reading procedure of the numbers of the elements concerned.

7.9.22 CONDITION AT INFINITY VAN LEER

Object:

This directive allows to impose a rest condition at infinity for a fluid by means of a CL2D element.

Syntax:

```
"IMPV" "INFI" "RO" ro "PRES" press "PREF" pref "GAMA" ga /LECTURE/
```

`RO`

Density at infinity.

`PRES`

Pressure at infinity.

`PREF`

Reference pressure.

`GAMA`

Value of the ratio of specific values for perfect gases.

`LECTURE`

List of the elements concerned.

Comments:

The coupling with the GZPV material is automatically ensured.

7.9.23 IMPOSED PRESSURE VAN LEER

Object:

This instruction enables a pressure at the boundary of different Van Leer elements to be imposed by the means of a "CLxx" element.

Syntax:

```
    "IMPV"  "PIMP"  "RO" rho "PRES" pres < "PREF" pref >
        ... "GAMA" gamma  < "IMPO" impo >   /LECTURE/
```

`rho`

Density.

`pres`

Constant imposed pressure.

`pref`

Reference pressure.

`gama`

Ratio of specific heats.

`impo`

The value impo=0 corresponds to free pressure, density and velocity (absorbing), impo=1 to constant entropy and mass flow rate, and impo=2 to constant entropy and velocity.

Comments:

For the meaning of pref, see page C.300.

7.9.24 IMPOSED PERFECT GAS MASS FLOW RATE VAN LEER

Object:

This directive allows to impose a mass flow rate of perfect gas in case of Van Leer elements.

Syntax:

```
"IMPV" "DEGP" "RO" ro "PRES" press "PREF" pref "GAMA" ga
              "DEBX" dx "DEBY" dy "DEBZ" dz /LECTURE/
```

`ro`

Initial density.

`press`

Imposed initial pressure.

`pref`

Reference pressure.

`ga`

Value of the ratio of specific values for perfect gases.

`dx dy dz`

Components of mass flow rate.

`LECTURE`

List of the elements concerned.

7.9.25 RIGID OBSTACLE VAN LEER

Object:

This directive allows to impose a total reflection (rigid obstacle) condition in case of Van Leer elements.

Syntax:

```
"IMPV" "MUR" /LECTURE/
```

`LECTURE`

List of the elements concerned.

7.9.26 SAFETY VALVE (JRC)

Object

This instruction enables the modelling of fluid discharge from a pressurized vessel through a generic safety valve or (by a suitable choice of the parameters) through an orifice. The fluid passing through the valve or orifice can be either incompressible (typically a liquid) or compressible (a gas).

Alternatively, the model can also be used in the opposite flow direction in order to fill up (pressurize) a vessel from an external source. Therefore, we distinguish between two modes: **discharge** mode or **loading** mode. The two modes cannot be combined in the same device, since no reverse flow is allowed. However, one could of course attach two `SVAL` devices, one in discharge mode and the other in loading mode, to the same vessel (at different locations along the wall) if needed.

The input syntax includes also a set of (optional) parameters that allow a sort of "pressure regulation" functionality whereby the opening of the valve is subjected to a series of constraints which may also depend upon the (independent) pressure in a "master" fluid element not belonging to the zone of the fluid domain to which the valve is attached.

A - Discharge mode

The valve is characterized by three main parameters:

- A^{tube}, the area of the tube in which the valve is mounted;
- Δp^{min}, the pressure difference (between internal and external pressures) at which the valve starts to open;
- `mode` the functioning mode of the device: 0 means discharge mode, 1 means loading mode. The default value is 0, so this parameter may be omitted if discharge mode is required.

Other **optional** parameters are:

- Δp^{max}, the pressure difference at which the valve is fully open, by default $\Delta p^{\mathrm{max}} = \Delta p^{\mathrm{min}}$;
- Δt^{ope}, the time interval needed to completely open the valve under a positive step increment of the pressure difference $\Delta p > \Delta p^{\mathrm{max}}$, by default $\Delta t^{\mathrm{ope}} = 0$;
- Δt^{clo}, the time interval needed to completely close the valve under a negative step increment of the pressure difference $\Delta p < -\Delta p^{\mathrm{max}}$, by default $\Delta t^{\mathrm{clo}} = 0$;
- q^{max}, the maximum mass flow rate through the valve, by default $q^{\mathrm{max}} = \infty$;
- p^{ext}, the external pressure (assumed constant), by default $p^{\mathrm{ext}} = 0$;
- ρ^{ext}, the external density (assumed constant); this quantity must be specified in loading mode, but it must not be specified in discharge mode.
- i^{ext}, the external specific internal energy (assumed constant); this quantity must be specified in loading mode, but it must not be specified in discharge mode.
- A^{max}, the maximum opening area of the valve which must be $A^{\mathrm{max}} \leq A_{\mathrm{tube}}$, by default $A^{\mathrm{max}} = A^{\mathrm{tube}}$;

- C_c, the contraction coefficient of the fluid flow through the valve opening, i.e. the ratio between the area of the flow in the *vena contracta* and the opening area of the valve (assumed constant, independent of the current opening area), by default $C_c = 1$;

- γ, the ratio of specific heats $\gamma = C_p/C_v$ in case of compressible fluid flow. If omitted, the fluid being discharged is considered as incompressible;

- t^{act}, the activation time of the valve. The valve is guaranteed to be inactive (closed) for $t < t^{\text{act}}$, whatever be the conditions of the fluid. If not specified, the code assumes $t^{\text{act}} = -\infty$.

- t^{dea}, the de-activation time of the valve. The valve is guaranteed to be inactive (closed) for $t > t^{\text{dea}}$, whatever be the conditions of the fluid. If not specified, the code assumes $t^{\text{dea}} = \infty$.

- `emas`, the *master* fluid element whose pressure p^{mas} has to be monitored for pressure regulation purposes. Note that the pressure p^{mas} is independent from the opening or not of the current valve, i.e. it is not influenced (at least directly) from the opening or not of the valve. If specified, the master element should therefore belong to a zone of the fluid domain not directly connected with the fluid part to which the current valve is attached (but the code does not check this requirement).

- `esla`, the *slave* fluid element whose pressure p^{sla} has to be monitored for pressure regulation purposes. Note that the pressure p^{sla} directly depends upon the opening or not of the current valve. If specified, the slave element should therefore belong to the zone of the fluid domain directly connected with the fluid part to which the current valve is attached (but the code does not check this requirement).

- p^{dis}, the value of pressure in the slave element that, when reached, triggers the discharge through the current valve, i.e. starts the opening of the valve. This parameter must not be specified in loading mode. By default $p^{\text{dis}} = \infty$.

- p^{max}, the value of pressure in the slave element that, when reached, triggers the closing of the current valve. This parameter must not be specified in discharge mode. By default $p^{\text{max}} = \infty$.

- p^{ms1}, the value of pressure difference between the master and the slave elements at which the valve starts to open (in an attempt to keep the pressure difference below the chosen value: $\Delta p = p^{\text{mas}} - p^{\text{sla}} \leq p^{\text{ms1}}$.) By default $p^{\text{ms1}} = \infty$.

- p^{ms2}, the value of pressure difference between the master and the slave elements at which the valve becomes fully open. If $\Delta p = p^{\text{mas}} - p^{\text{sla}} \geq p^{\text{ms2}}$ then the valve is fully open, in an attempt to keep the pressure difference below the chosen value. By default $p^{\text{ms2}} = p^{\text{ms1}}$.

- `rval`, a *reference* valve (`SVAL`) element. The reference valve must be in discharge mode and the current valve must be in loading mode. If the opening area of the reference valve is $a^{\text{ref}} > 0$, then the (current) valve closes immediately ($a = 0$).

This model is part of the models developed by the CESI team (formerly at ENEL, Milano) in collaboration with JRC.

References

More information on the formulation of this model may be found in reference [94].

Syntax

```
    "IMPE"  "SVAL"  <"MODE" mode> "ATUB" atub "DPMI" dpmi
          < "DPMA" dpma "TOPE" tope "TCLO" tclo "QMAX" qmax
            "PEXT" pext "ROEX" roex "IEXT" iext
            "AMAX" amax "CC"   cc   "GAMM" gamm "TACT" tact
            "TDEA" tdea
            "EMAS" /LECT_emas/ "ESLA" /LECT_esla/
            "PDIS" pdis "PMAX" pmax "PMS1" pms1 "PMS2" pms2
            "RVAL" /LECT_rval/                             >
          /LECTURE/
```

`mode`

Functioning mode of the device: 0 means discharge mode, 1 means loading mode. If omitted, the code assumes value 0 (discharge mode).

`atub`

Cross-section of the safety valve flow tube.

`dpmi`

Pressure difference at which the valve starts to open.

`dpma`

Pressure difference at which the valve is fully open; by default, it is equal to Δp^{min}.

`tope`

Opening time interval; by default, it is 0.

`tclo`

Closure time interval; by default, it is 0.

`qmax`

Maximum mass flow rate; if omitted, by default it is infinite (no limit).

`pext`

External pressure (assumed constant); by default it is 0.

`roex`

External density (assumed constant); this quantity must be specified in loading mode, but it must not be specified in discharge mode.

`iext`

External specific internal energy (assumed constant); this quantity must be specified in loading mode, but it must not be specified in discharge mode.

`amax`

Maximum opening area of the valve. It must be $A^{\mathrm{max}} \leq A^{\mathrm{tube}}$. By default, it is $A^{\mathrm{max}} = A^{\mathrm{tube}}$.

`cc`

Flow contraction coefficient ($0 < C_c \leq 1$). By default it is $C_c = 1$.

`gamm`

Ratio of specific heats for the fluid being discharged ($\gamma = C_p/C_v$). If specified, the fluid is considered as compressible. If omitted, the fluid is considered as incompressible (γ is unused in that case).

`tact`

Activation time of the valve. The valve is guaranteed to be inactive (closed) for $t < t^{\mathrm{act}}$, whatever be the conditions of the fluid. If not specified, the code assumes $t^{\mathrm{act}} = -\infty$.

`tdea`

De-activation time of the valve. The valve is guaranteed to be inactive (closed) for $t > t^{\mathrm{dea}}$, whatever be the conditions of the fluid. If not specified, the code assumes $t^{\mathrm{dea}} = \infty$.

`EMAS`

Introduces the definition (`/LECT_emas/`) of the *master* fluid element whose pressure p^{mas} has to be monitored for pressure regulation purposes. Note that the pressure p^{mas} is independent from the opening or not of the current valve, i.e. it is not influenced (at least directly) from the opening or not of the valve. If specified, the master element should therefore belong to a zone of the fluid domain not directly connected with the fluid part to which the current valve is attached (but the code does not check this requirement).

`ESLA`

Introduces the definition (`/LECT_esla/`) of the *slave* fluid element whose pressure p^{sla} has to be monitored for pressure regulation purposes. Note that the pressure p^{sla} directly depends upon the opening or not of the current valve. If specified, the slave element should therefore belong to the zone of the fluid domain directly connected with the fluid part to which the current valve is attached (but the code does not check this requirement).

`pdis`

The value of pressure p^{dis} in the slave element that, when reached, triggers the discharge through the current valve, i.e. starts the opening of the valve. This parameter must not be specified in loading mode. By default, $p^{\mathrm{dis}} = \infty$.

`pmax`

The value of pressure p^{max} in the slave element that, when reached, triggers the closing of the current valve. This parameter must not be specified in discharge mode. By default, $p^{\mathrm{max}} = \infty$.

`pms1`

The value of pressure difference p^{ms1} between the master and the slave elements at which the valve starts to open (in an attempt to keep the pressure difference below the chosen value: $\Delta p = p^{\mathrm{mas}} - p^{\mathrm{sla}} \leq p^{\mathrm{ms1}}$.) By default, $p^{\mathrm{ms1}} = \infty$.

`pms2`

The value of pressure difference p^{ms2} between the master and the slave elements at which the valve becomes fully open. If $\Delta p = p^{\mathrm{mas}} - p^{\mathrm{sla}} \geq p^{\mathrm{ms2}}$ then the valve is fully open, in an attempt to keep the pressure difference below the chosen value. By default, $p^{\mathrm{ms2}} = p^{\mathrm{ms1}}$.

`RVAL`

Introduces the definition (`/LECT_rval/`) of a *reference* valve (`SVAL`) element. The reference valve must be in discharge mode and the current valve must be in loading mode. If the opening area of the reference valve is $a^{\mathrm{ref}} > 0$, then the (current) valve closes immediately ($a = 0$).

`LECTURE`

Reading procedure of the number of the "CLxx" element defining the boundary.

Determination of the current opening area of the valve

The calculation of the current opening area of the valve consists of three phases. In the *first phase*, we check whether at the current time t the valve is active or not: if $t < t^{\mathrm{act}}$ or $t > t^{\mathrm{dea}}$ then the valve is closed irrespective of fluid conditions ($a = 0$) and we skip the following two phases. Then, if `rval` has been specified, we also check the opening area of the reference valve: if $a^{\mathrm{ref}} > 0$ then the current valve is immediately closed ($a = 0$) and we skip the following two phases.

Otherwise ($t^{\mathrm{act}} \leq t \leq t^{\mathrm{dea}}$), the valve is active. The *second phase* consists of checking whether there are any pressure regulation constraints specified for the current valve, since such constraints override the normal opening calculations to be performed in the third phase. If no slave element `esla` was specified, there are no regulation constraints and so we go directly to the third phase. Otherwise there are some constraints, which depend upon the chosen functioning mode of the device.

- In *discharge mode*, if p^{dis} was given and $p^{\mathrm{sla}} \geq p^{\mathrm{dis}}$, then we set $a = A$ (valve fully open) and skip the third phase.

- In *loading mode*, if p^{max} was given and $p^{\mathrm{sla}} \geq p^{\mathrm{max}}$, then we set $a = 0$ (valve fully closed) and skip the third phase. Otherwise, we check any constraints on the master-slave pressure difference. If p^{ms1} was given, we compute the pressure difference $\Delta p = p^{\mathrm{mas}} - p^{\mathrm{sla}}$: if $\Delta p < p^{\mathrm{ms1}}$ the valve is completely closed ($a = 0$); else if $\Delta p > p^{\mathrm{ms2}}$ the valve is completely open ($a = A$); else $p^{\mathrm{ms1}} \leq \Delta p \leq p^{\mathrm{ms2}}$ and the valve is only partially open ($a = \frac{\Delta p - p^{\mathrm{ms1}}}{p^{\mathrm{ms2}} - p^{\mathrm{ms1}}} A$). Having computed a, we skip the third phase. Otherwise (p^{ms1} was not given) we go to the next phase.

The *third and last phase* is as follows. The *nominal* opening area of the valve a' is assumed to be a linear function of the differential pressure Δp between the internal fluid (p) and the external medium (p^{ext}):

$$\Delta p = p - p^{\mathrm{ext}}$$

$$\begin{array}{rl}
\text{for } \Delta p \leq \Delta p^{\mathrm{min}} & a' = 0 \\
\text{for } \Delta p^{\mathrm{min}} < \Delta p < \Delta p^{\mathrm{max}} & a' = \dfrac{\Delta p - \Delta p^{\mathrm{min}}}{\Delta p^{\mathrm{max}} - \Delta p^{\mathrm{min}}} A \\
\text{for } \Delta p \geq \Delta p^{\mathrm{max}} & a' = A
\end{array}$$

The *actual* opening area of the valve a at a given time depends on the opening or closure times, and on the valve opening reached at the previous time, a^{old}. Let v_a and v_c represent the velocity of aperture and closure of the valve:

$$\begin{aligned} v_a &= A/\Delta t^{\text{ope}} \\ v_c &= -A/\Delta t^{\text{clo}} \end{aligned}$$

Then:

$$\begin{array}{rl} \text{for } \; a' > a^{\text{old}} \; \text{ and } \; \Delta t^{\text{ope}} > 0 & \quad a = \min[(a^{\text{old}} + v_a \Delta t), a'] \\ \text{for } \; a' < a^{\text{old}} \; \text{ and } \; \Delta t^{\text{clo}} > 0 & \quad a = \max[(a^{\text{old}} + v_c \Delta t), a'] \\ \text{in all other cases} & \quad a = a' \end{array}$$

The value of a is constrained to be between 0 and A:

$$\begin{array}{rl} \text{if } \; a > A & \quad a = A \\ \text{if } \; a < 0 & \quad a = 0 \end{array}$$

In order to compute the mass flow rate through the valve, we distinguish two cases, depending upon the compressibility of the discharged fluid.

Incompressible or nearly incompressible fluid

The fluid being discharged is incompressible or nearly incompressible (e.g., a liquid). This situation is determined by the fact that the user has *not* specified a value for $\gamma = C_p/C_v$ in the input data. In this case the following relation is assumed to hold:

$$\Delta p = p - p^{\text{ext}} = \zeta \rho \frac{v_{\text{tube}}^2}{2} \tag{77}$$

where ζ is a dimension-less *resistance coefficient* which depends upon the geometry of the valve, ρ is the density of the fluid upstream the valve and v_{tube} is the velocity of the fluid in the tube upstream the valve.

By assuming steady state flow and a jet that expands back to fill the entire cross-section of the tube downsetream the valve, the resistance coefficient ζ is evaluated by:

$$\zeta = \left(\frac{1}{r_p C_c} - 1 \right)^2$$

where r_p is the current *perforation ratio* r_p of the valve, given by:

$$r_p = a/A^{\text{tube}}$$

Since the pressure drop Δp is known (we assume $\Delta p = p - p^{\text{ext}}$, without any limitations), from (77) we obtain the (nominal) fluid velocity in the tube upstream the valve:

$$v'_{\text{tube}} = \sqrt{\frac{2}{\zeta} \frac{p - p^{\text{ext}}}{\rho}}$$

and the current (nominal) mass flow rate is given by:

$$q' = A^{\text{tube}} \rho v'_{\text{tube}} = A^{\text{tube}} \sqrt{\frac{2}{\zeta} \left(p - p^{\text{ext}} \right) \rho}$$

Compressible fluid

The fluid being discharged is compressible. This situation is determined by the fact that the user has specified a value for $\gamma = C_p/C_v$ in the input data. (The given value of γ, assumed constant, should be equal to that of the fluid being discharged, i.e. the fluid upstream the safety valve.)

In this case the code assumes that the expansion of the fluid across the valve can be represented by a simple adiabatic transformation:

$$\frac{p}{\rho^\gamma} = \text{const.} \tag{78}$$

This is reasonable for a perfect gas but not, for example, if the fluid is a superheated vapor that becomes saturated during the expansion.

We compute the current *critical pressure* p_c corresponding to the current pressure p upstream the valve and to the chosen value of γ:

$$p_c = p\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

For example, if $\gamma = 1.4$ like for air, $p_c/p = 0.528$. The pressure in the valve orifice (i.e., in the zone where the cross-section area of the duct is minimum) cannot drop below the critical value. We therefore distinguish two cases, depending on the value of the external pressure p^{ext} with respect to p_c:

- if $p^{\text{ext}} \geq p_c$, then the fluid pressure in the valve orifice is $p_2 = p^{\text{ext}}$, the fluid velocity in the orifice is

  $$v_2 = \sqrt{2\frac{\gamma}{\gamma-1}\frac{p}{\rho}\left[1-\left(\frac{p_2}{p}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

  and the (nominal) mass flow rate is given by

  $$q' = S_2 v_2 \rho_2 = S_2 v_2 \rho\left(\frac{p_2}{p}\right)^{\frac{1}{\gamma}} = S_2\sqrt{2\frac{\gamma}{\gamma-1}p\rho\left[\left(\frac{p_2}{p}\right)^{\frac{2}{\gamma}} - \left(\frac{p_2}{p}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$

  where p and ρ are the pressure and density of the fluid upstream the orifice, respectively, use has been made of (78) to explicitate the density ρ_2 at the orifice and S_2 is the flow area of the *vena contracta* at the orifice $S_2 = C_c a$.

- if $p^{\text{ext}} < p_c$, then the fluid pressure in the valve orifice is equal to the critical pressure $p_2 = p_c$ and the (nominal) mass flow rate is given by

  $$q' = \psi S_2 \sqrt{p\rho}$$

  where S_2 has the same meaning as above and the coefficient ψ is given by

  $$\psi = \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}}\sqrt{2\frac{\gamma}{\gamma+1}}$$

Flow limitation and velocity

Finally, in both cases (incompressible or compressible flow) the current (effective) mass flow rate q is computed by taking into account a possible user-imposed maximum value $q^{\max}$ and by inhibiting any back flow through the valve:

$$\begin{array}{rl} \text{for } \; q^{\max} > 0 \;\text{ and }\; q' > q^{\max} & \qquad q = q^{\max} \\ \text{for } \; q' < 0 & \qquad q = 0 \;\; \text{(no back flow)} \\ \text{in all other cases} & \qquad q = q' \end{array}$$

The current (effective) fluid velocity in the upstream tube is then:

$$v_{\text{tube}} = \frac{q}{A^{\text{tube}}\rho}$$

Modelling of an orifice

In order to model a simple orifice in the wall of the pressurized tank, set A^{tube} to the area of the orifice and $\Delta p^{\min}$ to a very small value.

As concerns the optional parameters, leave out $\Delta p^{\max}$ and $A^{\max}$ so that it will be $\Delta p^{\max} = \Delta p^{\min}$ and $A^{\max} = A^{\text{tube}}$, leave Δt^{ope} to its default value of 0 and specify a huge value for Δt^{clo} so that the orifice will never close in practice.

B - Loading mode

Loading mode is activated by specifying `MODE 1` in the input data. In this mode, p^{ext} (assumed constant) must be specified since the default value of 0 is not appropriate. In order to completely define the external state (which in this case becomes the donor state) one must also give ρ^{ext} and i^{ext} (which are also assumed to be constant).

Outputs:

The different components of the ECR table are as follows :

ECR(1) : current pressure in the fluid element to which the valve is attached

ECR(2) : current nominal opening area

ECR(3) : current actual opening area

ECR(4) : previous time this element was treated

ECR(5) : previous actual opening area

ECR(6) : total ejected mass (in discharge mode) or injected mass (in loading mode)

ECR(7) : total ejected energy by mass transport (in discharge mode) or injected energy (in loading mode)

ECR(8) : current flow tube velocity

ECR(9) : current density in the fluid element to which the valve is attached

ECR(10) : current specific internal energy in the fluid element to which the valve is attached

7.9.27 RUPTURE DISK (JRC NEW)

Object

This instruction enables the modelling of a rigid rupture disk structure (e.g. a plate) embedded in a fluid.

This model is part of the models developed by the CESI team (formerly at ENEL, Milano) in collaboration with JRC.

The disk reacts to the pressure drop caused by a fluid on the two sides of the disk, until a certain deltap is reached, which causes the rupture of the disk.

In this particular model the disk structure is NOT represented, while the fluid on both sides is discretized by continuum finite elements.

Special boundary condition elements (CLxx) are attached to the fluid nodes in order to represent the action of the disk on the fluid. These elements are assigned the present IMPE RDK2 material.

The disk rupture is caused by a fixed (nominal) deltap, which can occur at any point of the disk, in case this is discretized by several CLxx elements. When one CLxx element reaches this condition, failure is initiated also in all other elements at the same time.

As long as the disk is not ruptured, it acts as a rigid boundary with infinite friction. In other words, all fluid nodes attached to the disk are completely blocked.

The blocking forces are instantly removed as the disk breaks.

References

More information on the formulation of this material model may be found in reference [131].

Syntax

```
"IMPE"  "RDK2"  "DPRU" dpru   /LECTURE/
```

`dpru`

Pressure difference (deltap) between the two sides that causes rupture of the disk. The deltap is measured between the fluid elements directly attached to the disk on each side. The deltap includes only the fluid pressure and not the pseudo-viscous pressure.

`/LECT/`

Concerned elements.

Outputs :

The different components of the ECR table are as follows :

ECR(1) : current pressure drop across the disk (at this element), doesn't include the pseudoviscous pressure

ECR(2) : 0 for virgin disk, 1 for broken disk

ECR(3) : time at which failure occurred

ECR(4) : unused

ECR(5) : unused

ECR(6) : unused

ECR(7) : unused

ECR(8) : unused

ECR(9) : unused

7.9.28 ABSORBING MATERIAL (JRC implementation)

Object :

This option enables to specify absorbing or partially absorbing boundary conditions for 2-D or 3-D elements developed at JRC (CL22, CL3I or CL3Q).

There exists a similar, but not identical, absorbing boundary model developed at CEA which is appropriate for their CLxx elements (CL1D, CL2D, CL3D or CL3T), see page C.610.

Only pressure waves normal to the boundary are absorbed. The model consists simply in applying a fictitious external pressure $p = -\rho c v_n$, where ρ is the density of the material at the boundary, c its sound speed and v_n the normal component of the particle velocity at the boundary, in Lagrangian calculations, or of the relative (particle minus mesh) velocity in Eulerian or ALE calculations. The "internal" forces due to the absorbing boundary are finally computed by spatial integration of the pressure p (and not, like in the `IMPE ABSO` material, of a modified pressure $\pi = (p + p_{\text{old}})/2$, where p_{old} is the value of π at the previous time integration step).

Syntax:

```
"IMPE"  "ABSI"  <"RO" rho>  <"C" c>  /LECTURE/
```

`rho`

Fixed, user-imposed value of the density. If omitted, the code will try to determine the density automatically.

`c`

Fixed, user-imposed value of the sound speed. If omitted, the code will try to determine the sound speed automatically. Since for a structural material the code is sometimes unable to determine the sound speed automatically, the value becomes useful in this case (and is of course constant). However, since the physical sound speed is fairly constant in such a case, the behaviour of the model should be quite good. A notable exception are materials `CAMC` and `CLAY`, for which the sound speed varies considerably: for these materials the code is indeed able to retrieve the current sound speed automatically, so that specifying `c` in these cases is unnecessary.

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL22, CL3I or CL3Q).

Comments :

If the acoustic waves are to be absorbed, the `rho` and `c` parameters must be the same on both sides of the boundary. The effect will then be that of an infinite medium. In the opposite case, there will be partial reflections.

If the user has omitted `c` and the code is unable to determine it automatically, an error message is issued and the calculation is stopped.

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : normal velocity in the local reference frame

7.9.29 ABSORBING MATERIAL (Zienkiewicz for geotechnical materials)

Object :

This option enables to specify absorbing or partially absorbing boundary conditions for 2-D or 3-D elements developed at JRC (CL22, CL3I or CL3Q).

The formulation of this model is due to Zienkiewicz (Computational Geomechanics) and is related to geotechnical materials only.

Both the pressure waves normal to the boundary and those tangential to the boundary are absorbed. The model consists simply in applying a fictitious external pressure $p = -\rho c v$, where ρ is the density of the material at the boundary, c its sound speed and v the appropriate component (normal or tangential) of the particle velocity at the boundary (in Lagrangian calculations). The "internal" forces due to the absorbing boundary are finally computed by spatial integration of the pressure p (and not, like in the `IMPE ABSO` material, of a modified pressure $\pi = (p + p_{\text{old}})/2$, where p_{old} is the value of π at the previous time integration step).

For the normal component one has:

$$p_n = \rho c_n v_n$$

where v_n is the particle velocity normal to the boundary and the normal sound speed c_n is computed by:

$$c_n = \sqrt{k/\rho}$$

where k is given by:

$$k = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$$

.

For the tangential component (2 components in 3D) one has:

$$p_t = \rho c_t v_t$$

where v_t is the particle velocity tangential to the boundary and the tangential sound speed c_t is computed by:

$$c_t = \sqrt{G/\rho}$$

where G (the shear modulus) is given by:

$$G = \frac{E}{2(1+\nu)}$$

.

Syntax:

```
IMPE  ABSZ  <RO rho>  <CN cn>  <CT ct> /LECTURE/
```

`rho`

Fixed, user-imposed value of the density. If omitted, the code will try to determine the density automatically.

`cn`

Fixed, user-imposed value of the normal sound speed. If omitted, the code will try to determine the sound speed automatically. Since for a structural material the code is sometimes unable to determine the sound speed automatically, the value becomes useful in this case (and is of course constant). However, since the physical sound speed is fairly constant in such a case, the behaviour of the model should be quite good. A notable exception are materials `CAMC` and `CLAY`, for which the sound speed varies considerably: for these materials the code is indeed able to retrieve the current sound speed automatically, so that specifying `cn` in these cases is unnecessary.

`ct`

Fixed, user-imposed value of the tangential sound speed. In 3D, this is the tangential speed in both tangential directions. If omitted, the code will try to determine the sound speed automatically. Since for a structural material the code is sometimes unable to determine the sound speed automatically, the value becomes useful in this case (and is of course constant). However, since the physical sound speed is fairly constant in such a case, the behaviour of the model should be quite good. A notable exception are materials `CAMC` and `CLAY`, for which the sound speed varies considerably: for these materials the code is indeed able to retrieve the current sound speed automatically, so that specifying `cn` in these cases is unnecessary.

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL22, CL3I or CL3Q).

Comments :

If the acoustic waves are to be absorbed, the `rho`, `cn` and `ct` parameters must be the same on both sides of the boundary. The effect will then be that of an infinite medium. In the opposite case, there will be partial reflections.

If the user has omitted `cn` or `ct` and the code is unable to determine them automatically, an error message is issued and the calculation is stopped.

Outputs:

The different components of the ECR table are as follows :

ECR(1) : normal pressure

ECR(2) : density

ECR(3) : normal sound speed

ECR(4) : normal velocity

ECR(5) : tangential sound speed

ECR(6) : tangential velocity

ECR(7) : tangential pressure

7.9.30 AIR BLAST WAVE

Object :

This directive simulates an explosion in the air (see References below). It allows to load the structures without having to model the fluid domain. It does not take into account **multiple** wave reflections on structural walls, but optionally allows to take into account in a very simplified way the first wave reflection at a wall (see below).

The position of the charge may be specified either by giving its coordinates (x, y and z) or the node at which the charge is placed.

Syntax:

```
"IMPE"  "AIRB"  |[ "X" x "Y" y <"Z" z> ; "NODE" /LEC1/ ]|
                "MASS" m $[ "TINT" t ; "TAUT" ]$ <"OPOS">
                <"ANGL">
                <"CUBE">
                <"COEF" cf>
                <"CONF" c>
                <"DECA" d>
                <"PMAX" pmax "TD" td "B" b>
                /LECTURE/
```

`x`

X-coordinate of the explosive source.

`y`

Y-coordinate of the explosive source.

`z`

Z-coordinate of the explosive source. This is 0 by default.

`NODE /LEC1/`

Introduces the node where the explosive charge is located. Typically, a `PMAT` element may be located at the charge position, so as to be able to visualize it.

`m`

Mass of the explosive in Kilograms.

`t`

Starting time of the explosion. By default it is equal to the initial time of the calculation.

`TAUT`

Indicates that the starting time is calculated automatically by the code, in such a way that the air blast wave reaches the first CLxx element shortly after the starting of the calculation. This is to avoid an "idle" calculation at the beginning of the transient.

`OPOS`

Indicates that only the part with the positive pressure (overpressure) is regarded. After the time of duration of the positive phase the pressure is set to 0.

`ANGL`

Indicates that the angle of incidence between the charge and the structural element is considered.

`CUBE`

Indicates that the cubic approach will be used for the calculation of the negative phase. By default the bilinear approach is used.

`cf`

The user can input a value to calibrate the decay coefficient of the air blast load. The calculated decay coefficient is multiplied by the inserted value in order to produce a load closer to experimental data.

`c`

Choice between different available explosion models, see the References below. By default it is 1 (unconfined, reflected, Kingery). The term "unconfined" below means that the explosion takes place in an unconfined space, as opposed to "half-confined" where the charge is placed close to a rigid ground and so the wave propagation occurs in a half-space (experimentally, the measured pressure is somewhat lower in this case because some of the energy is absorbed by the ground). The term "reflected" hereafter means that the model accounts for the pressure increase due to (first) wave reflection at a rigid wall as it is typically measured in experiments. The pressure value in this case may be between 2 and 8 times the incident pressure in the "non-reflected" case, i.e. without taking into account this first reflection.

1. unconfined (full space), reflected (Kingery)
2. unconfined (full space), not reflected (Kingery)
3. unconfined (full space), not reflected (Kinney)
4. half-confined (half space), reflected (Kingery)
5. half-confined (half space), not reflected (Kingery)
6. Blast parameters will be directly specified next

`CONF 6` indicates that the blast parameters $p_{\max}$, t_d and b appearing in the so-called modified Friedlander equation (see below) will be directly specified next and should not be calculated automatically by the code. In this case, no other parameters (except `CONF` of course) are accepted, only the positive pressure (overpressure) is considered and the pressure-time function is identical in each element. The **modified Friedlander equation** reads:

$$p(t) = p_0 + p_{\max}(1 - \frac{t}{t_d})^{-\frac{bt}{t_d}}$$

and expresses the pressure p as a function of time t, with p_0 the initial (normally the atmospheric) pressure, $p_{\max}$ the maximum overpressure (peak overpressure), t_d the duration of the positive pressure phase and b the decay parameter, which defines how rapidly the pressure decays.

`d`

Choice between different available decay coefficient equation models. Each equation is defined according to the explosion model chosen before (incident, reflected - spherical, hemispherical). The equations based on the Kingery-Bulmash data have been calculated by iteratively solving the Friedlander equation with the set of positive blast parameters proposed by Kingery-Bulmash. There are different equations for reflected or not reflected (incident) cases of unconfined (spherical) and half-confined (hemi-spherical) blast waves. An additional equation for the blast coefficient is available which is based on the Kinney and Baker data. The default blast decay equation is based on the Kingery-Bulmash data. The explosion model, that has already been defined by the parameter c, shows which of the blast wave decay equations (incident, reflected, spherical or hemispherical) will be used.

1. Blast wave decay equation based on Kinney data
2. Blast wave decay equation based on Kingery-Bulmash data (default)

`pmax`

Maximum overpressure p_{max} appearing in the modified Friedlander equation. This should only be given when `CONF 6` has been specified.

`td`

Duration of the positive pressure phase t_d appearing in the modified Friedlander equation. This should only be given when `CONF 6` has been specified.

`b`

Decay parameter b appearing in the modified Friedlander equation. This should only be given when `CONF 6` has been specified.

`/LECT/`

Elements concerned. These must be of type CLxx.

Comments :

This model requires that the user adopts the standard Unit system, i.e. metres, Kilograms, seconds.

Care must be taken in the orientation of the CLxx elements, in such a way that the pressure load resulting from the `AIRB` model acts in the right sense.

The force generated by a positive `AIRB` overpressure pushes the CLxx element in the sense of the normal to the element itself. This normal is determined by the numbering of the element in EUROPLEXUS.

Therefore, typically the CLxx elements must be oriented in such a way that their normal points **away from** the `AIRB` charge, or away from the direction from which the `AIRB` overpressure is expected to arrive.

This convention has been assumed because of the possibility of using `AIRB` model to load not directly a structure, but a fluid boundary. In this case, the CLxx elements must be attached to the fluid boundary (i.e. to continuum-like fluid elements) and the code always orients them (irrespective of the orientation chosen by the user) in such a way that the normal to the CLxx elements points **inside** the fluid.

A final *caveat*: since the orientation of the `AIRB` load is related to the orientation of the CLxx element, a problem may arise in case of extremely large rotations of the structure (and thus of the attached CLxx element), such as for example in the case of a rupturing structure which breaks up into large flying debris. In fact, if the element rotates by more than, say, 90 degrees, then the `AIRB` load may appear to act in the wrong direction. This is an inherent limitation of the model which may not be avoided, and the user should be aware of it.

The equations of Kingery are only usable up to a scaled distance of Z=40. Above this distance, diagrams of Baker are used (linearised in the double logarithmic scale).

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

References:

For more information on the physical models, consult the following references:

- Kingery, Charles N., Bulmash, Gerald: *Airblast Parameters from TNT Spherical Air Burst and Hemispherical Surface Burst*, Defense Technical Information Center, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, 1984.
- Baker, Wilfrid E.: *Explosions in the Air.* University of Texas Pr., Austin, 1973.
- Kinney, G.F., Graham, K.J.: *Explosive Shocks in Air.* Springer, Berlin, 1985.

7.9.31 NTNU's SIMPLIFIED FSI MODEL

Object :

This directive allows to load a structure by a blast-like pressure without discretizing also the fluid. It represents a very simplified approach to Fluid-Structure Interaction (FSI) modelling.

The model takes in input the time history of the (absolute) pressure (incident plus reflected wave) $p_{\text{rigid}}(t)$ that would be measured at the impacted wall if this wall would be rigid and blocked, plus some constants of the gas (typically the atmospheric air) which characterize the undisturbed state before arrival of the blast wave. Then, the model estimates the pressure p_{FSI} acting on the impacted wall as this wall moves and deforms with a certain velocity v_{wall}. Let:

- $p_{\text{rigid}}(t)$ be the time function of the (absolute) incident plus reflected blast pressure for a rigid wall. This may come from an experiment, from an analytical solution or from theoretical considerations.
- $\gamma = C_p/C_v$ be the ratio of heat capacities of the gas, assumed as constant.
- p_{atm} be the atmospheric pressure, i.e. the pressure of the gas before the arrival of the blast wave (a constant).
- ρ_{atm} be the atmospheric density, i.e the density of the gas before the arrival of the blast wave (a constant).

We assume that the wall is initially at rest and has not yet been reached by the blast wave. Therefore the code sets $v_{\text{wall}}(0) = 0$, $p_{\text{rigid}}(0) = p_{\text{atm}}$ and $\rho_{\text{rigid}}(0) = \rho_{\text{atm}}$. At the generic step t^{n+1} the code computes:

- The normal velocity of the wall (approximated by using the wall's half-step speed $v^{n+1/2}$):

$$v_{\text{wall}}^{n+1} = \underline{v}^{n+1/2} \cdot \underline{\hat{n}}^{n+1}$$

  where $\underline{\hat{n}}^{n+1}$ is the unit vector normal to the wall. This vector is assumed positive when entering the wall material.

- The pressure of the gas at the wall if it would be rigid, extracted from the given time function:

$$p_{\text{rigid}}^{n+1} = p_{\text{rigid}}(t^{n+1})$$

- The density of the gas at the wall if it would be rigid, by assuming that the gas is subjected to an isentropic compression from the initial undisturbed state:

$$\rho_{\text{rigid}}^{n+1} = \rho_{\text{atm}} \left(\frac{p_{\text{rigid}}^{n+1}}{p_{\text{atm}}} \right)^{1/\gamma}$$

- The sound speed of the gas at the wall if it would be rigid, from the EOS of an ideal gas:

$$c_{\text{rigid}}^{n+1} = \sqrt{\gamma \frac{p_{\text{rigid}}^{n+1}}{\rho_{\text{rigid}}^{n+1}}}$$

- Finally, the wall pressure accounting for FSI effects is obtained from:

$$p_{\text{FSI}}^{n+1} = p_{\text{rigid}}^{n+1} \left(1 + \frac{\gamma - 1}{2} \cdot \frac{-v_{\text{wall}}^{n+1}}{c_{\text{rigid}}^{n+1}} \right)^{\frac{2\gamma}{\gamma-1}}$$

- Additionally, the density of the gas at the moving wall is also computed, only for output and comparison purposes:

$$\rho_{\mathrm{FSI}}^{n+1} = \rho_{\mathrm{atm}} \left(\frac{p_{\mathrm{FSI}}^{n+1}}{p_{\mathrm{atm}}} \right)^{1/\gamma}$$

It should be noted that with the sign conventions assumed above, i.e. v_{wall} positive when directed away from the incoming blast, a positive wall velocity generates a reduced FSI pressure compared with a rigid wall. Conversely, if the wall moves towards the incoming blast (negative wall velocity), then the FSI pressure is larger than for a rigid wall.

The value obtained of p_{FSI}^{n+1} is used as the pressure of the CLxx element, i.e. the pressure (already accounting for FSI effects) acting on the moving wall. This pressure (diminished by the reference pressure) is used by the code to update the wall deformation and the wall velocity, for the next time step.

Syntax:

```
    "IMPE"  "SFSI" "GAMM" gamm "PATM" patm "RATM" ratm
                   < "PREF" pref > < "PFAC" pfac > "PFUN" pfun
                   /LECTURE/
```

`GAMM`

Ratio of specific heats $\gamma = C_p/C_v$ of the gas (atmosphere), assumed as constant.

`PATM`

Atmospheric pressure (absolute), expressed in Pa.

`RATM`

Atmospheric density, expressed in $\mathrm{kg/m^3}$.

`PREF`

Reference pressure expressed in Pa. Note that if a zero reference pressure is desired, it is mandatory to specify `PREF 0` in the input file. This is because, if no value for `PREF` is specified, the code assumes $P_{\mathrm{ref}} = P(t = 0)$ so the initial imposed pressure has no effect, since $p = P - P_{\mathrm{ref}} = 0$!

`PFAC`

Multiplicative factor ϕ of the pressure given in the following time function. By default $\phi = 1.0$. It may be useful to uniformly scale the time function.

`PFUN`

Index of the input time function representing the (absolute) incident plus reflected pressure (in Pa) vs. time (in s). See part E of the manual on how to define a function.

`/LECT/`

Elements concerned. These must be of type CLxx.

Outputs:

The different components of the ECR table are as follows :

ECR(1) : Pressure (absolute) acting on the moving wall, taking into account the FSI effects (p^{n+1}_{FSI}).

ECR(2) : Density of the gas at the moving wall, taking into account the FSI effects ($\rho^{n+1}_{\mathrm{FSI}}$).

ECR(3) : Pressure (absolute) incident plus reflected acting on the wall assumed as rigid (p^{n+1}_{rigid}), as extracted from the given time function. This can be useful to be compared with the pressure taking into account FSI effects ECR(1).

ECR(4) : Density at the moving wall, assumed as rigid ($\rho^{n+1}_{\mathrm{rigid}}$). This can be useful to be compared with the density taking into account FSI effects ECR(2).

References:

For more information on the physical models, consult the following references:

- Aune, V., Casadei, F., Valsamos, G.: *A simplified computational appraoch to account for fluid-structure interaction effects on blast loaded plates*, Techical Report, in preparation. 2020.

7.9.32 FRAGILE PLATE

Object:

This instruction enables the modelling of a fragile structure (e.g. a plate) embedded in a fluid.

The pressure drop across the plate is computed according to the expression:

```
Deltap = p_1 - p_2
```

Here p_1 and p_2 are the pressures on the two sides of the plate.

As long as the plate element holds, it prevents any fluid from passing trough it. As soon as the structural element fails, the structure is replaced by a cloud of debrtis particles and the fluid may start to flow through.

Syntax :

```
"IMPE"  "FPLT"
        /LECTURE/
```

`/LECT/`

Concerned elements.

Outputs:

The different components of the ECR table are as follows :

ECR(1) : current pressure drop across the plate
ECR(2) : unused
ECR(3) : unused
ECR(4) : structural node 1
ECR(5) : structural node 2
ECR(6) : structural node 3
ECR(7) : structural node 4
ECR(8) : unused
ECR(9) : unused

Note that the positions 4 to 7 contain up to 4 indexes of the structural nodes corresponding to the CLxx element's (fluid) nodes. These quantities are determined only once at the beginning of the calculation and never change.

Comments:

Normally, the determination of the above mentioned node correspondence is performed automatically. However, in case of problems the user may either change the tolerance for node matching (see `OPTI TOLC` on page H.40) or force the node correspondence by using the directive `COMP CNOD`, see page C.92.

7.9.33 DATA RECORDING FOR VISUALIZATION

Object:

This directive enables the recording of data for subsequent visualization in the form of iso-value maps (on a whole region of the mesh) or of time curves (one element at a time).

For example, one may want to record the fluid (over-)pressure acting on a structure embedded (immersed) in a fluid and coupled with the fluid by means of a FSI algorithm such as FLSW or FLSR. In this case, the CLxx element to which the material `IMPE VISU` is affected should be attached to the structure. By visualizing the CLxx elements and their “recorded” data in the form of iso-maps one obtains an exact view of the structural walls, with the data (e.g. FSI overpressure) acting on such walls.

Another example occurs in fluid-only simulations where the user may want to visualize the fluid (over-)pressure only along certain parts of the fluid domain surface (those where a structure, not represented in the model, is attached). In this case the CLxx element is attached directly to the fluid elements.

Syntax :

```
"IMPE"  "VISU" <$ "COUP" ; "DECO" $>
        /LECTURE/
```

`VISU`

Introduces the parameters of the current `IMPE VISU` material.

`COUP`

The FSI coupling is realized by means of a “strong” (coupled) approach (e.g. `FLSR` algorithm) so that the FSI forces are contained in the FLIA table.

`DECO`

The FSI coupling is realized by means of a “weak” (uncoupled) approach (e.g. `FLSW` algorithm) so that the FSI forces are contained in the FDEC table.

`/LECT/`

Concerned CLxx elements.

Outputs:

The different components of the ECR table are as follows:

ECR(1) : current FSI overpressure

ECR(2) : maximum FSI overpressure over time

ECR(3) : minimum FSI overpressure over time

ECR(4) : current area of the CLxx element (embedded case)

ECR(5) : x-component of the current unit normal to the CLxx element (embedded case)

ECR(6) : y-component of the current unit normal to the CLxx element (embedded case)

ECR(7) : z-component of the current unit normal to the CLxx element (embedded case)

ECR(8:10) : unused

Note, however, that the first three components are directly defined only if the CLxx element with IMPE VISU material is directly attached to a fuid element. If the CLxx element is attached to a structural element (embedded FSI) then these components are obtained by averaging of the nodal quantity `PFSI` over each element and this process is likely to introduce some smootghing of the results (especially if the "element" quantity ECR is then drawn in the form of iso-maps of an element field, whereby the data are usually projected back on the nodes).

The last four components are only defined if the CLxx element with IMPE VISU material is attached to a structural element (and the `COUP` or `DECO` keyword is specified).

In the case of a CLxx element with IMPE VISU material attached to a structural element the current, maximum and minimum FSI overpressure **directly evaluated at nodes** can be visualized by using the `PFSI`, `PFMI` and `PFMA` keywords, see Page ED.70 (time curves of nodal variables) and Page O.80 (iso-value maps of a nodal field).

Comments:

The `COUP` or `DECO` optional keywords are only used (and **must** be specified) if the CLxx element to which the IMPE VISU material is affected is attached to a structural element. If the CLxx element is directly attached to a fluid element, then these keywords **must not** be specified.

7.9.34 CLVF ABSORBING MATERIAL (SUPERSONIC OUTLET)

Object :

This option enables to specify absorbing or partially absorbing boundary conditions for 1-D, 2-D or 3-D Cell-Centred Finite Volumes (VFCC). From a mathematical point of view, this boundary condition well represents a supersonic outlet[1]: the state inside the fluid domain is copied outside (into the so called "ghost" cell) to evaluate the numerical flux. From a practical point of view this boundary condition can be applied also to other cases (even for inlets), but only in the case of a supersonic outlet it is guaranteed that all waves are absorbed.

Syntax:

```
"CLVF"  "ABSO"  "RO" rho /LECTURE/
```

`rho`

Density (**never used but here for historical reasons**).

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL1D, CL2D, CL3D or CL3T).

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : normal velocity

ECR(5) : tangential velocity

ECR(6) : tangential velocity (2nd component in 3d)

[1]For a theoretical overview of the CLVF boundary conditions implemented in Europlexus, one can read [837] from page 187. For this particular case, see Section "Frontière absorbante" at page 190.

7.9.35 CLVF CONDITIONS AT INFINITY (INFINITELY HUGE RESERVOIR)

Object :

This option works for perfect gases only (GAZP material). It enables to specify conditions at infinity for a fluid modelled by Cell-Centred Finite Volumes (VFCC)[2]. According to the values of the speed normal to the interface $u_{n,\text{int}}$ and of the Mach number M_{int} (evaluated using the normal speed) inside the fluid domain, we distinguish between different cases.

1. $M_{\text{int}} \leq 1$. We have a subsonic inlet ($u_{n,\text{int}} \leq 0$) or a subsonic outlet ($u_{n,\text{int}} \geq 0$). We enforce that in the "ghost" cell we have pressure, density and velocity at infinity (the last one is zero).
2. $M_{\text{int}} \geq 1$ and ($u_{n,\text{int}} > 0$). We have a supersonic outlet. Then, as in the case ABSO, the state inside the fluid domain is copied outside into the "ghost" cell.
3. $M_{\text{int}} > 1$ and ($u_{n,\text{int}} < 0$). We have a supersonic inlet. Then we stop the computation because we are not able to deal with this case.

Syntax:

```
"CLVF"  "INFI" "RO" rho "PRES" pres <"PREF" pref> "GAMA" gama
        /LECTURE/
```

`rho`

Density at infinity.

`pres`

Pressure at infinity.

`pref`

Reference pressure at infinity.

`gama`

Gamma (ratio of specific heats) at infinity.

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL1D, CL2D, CL3D or CL3T).

Outputs:

[2]For a theoretical overview of the CLVF boundary conditions implemented in Europlexus, one can read [837] from page 187. For this particular case, see Section "Impédance infinie at page 191.

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : normal velocity

ECR(5) : tangential velocity

ECR(6) : tangential velocity (2nd component in 3d)

7.9.36 CLVF IMPOSED PRESSURE (SUBSONIC OUTLET)

Object :

This option works for perfect gases only (GAZP material). It enables to specify an imposed external pressure P_{imp} on a fluid modelled by Cell-Centred Finite Volumes (VFCC)[3]. From a mathematical point of view, this boundary condition well represents a subsonic outlet. Indeed the "ghost" state takes into account one external information (the pressure) and the rest of information is taken inside the domain. According to the value of the parameter "IMPO" of the syntax, we distinguish between 6 different cases.

1. At the "ghost" cell we impose that we have the same entropy and the same momentum as in the internal domain. Namely $P = P_{\text{imp}}$ and
$$\rho = \rho_{\text{int}} \left(\frac{P}{P_{\text{int}}} \right)^{\frac{1}{\gamma}}$$
$$\vec{u} = \frac{\rho_{\text{int}} \vec{u}_{\text{int}}}{\rho}$$
2. At the "ghost" cell we impose that we have the same entropy and the same velocity as in the internal domain. Namely $P = P_{\text{imp}}$ and
$$\rho = \rho_{\text{int}} \left(\frac{P}{P_{\text{int}}} \right)^{\frac{1}{\gamma}}$$
$$\vec{u} = \vec{u}_{\text{int}}$$
3. We compute the density in the "ghost" cell by imposing that the "ghost" state and the internal state are on the same Hugoniot curve (while in cases 1 and 2 we impoe that the "ghost" state and the internal state are on the same isoentropic curve). Moreover, we impose that the "ghost" state presents the same velocity as the internal state.
4. We compute the density in the "ghost" state by imposing that the "ghost" state and the internal state are on the same Hugoniot curve. Moreover, we impose that the "ghost" state presents the same momentum as the internal state.
5. We enforce that the "ghost" state has the same entropy and the same (outlet) Riemann invariant as the internal state.
6. We enforce that the "ghost" state has the same density and velocity as the internal state.

Syntax:

```
"CLVF"  "PIMP" "RO" rho "PRES" pres <"PREF" pref> "GAMA" gama
        <"IMPO" impo>
        /LECTURE/
```

[3]For a theoretical overview of the CLVF boundary conditions implemented in Europlexus, one can read [837] from page 187. For this particular case, see Section "Pression imposée" at page 192.

`rho`

Density (**never used but here for historical reasons**).

`pres`

Pressure.

`pref`

Reference pressure.

`gama`

Gamma (ratio of specific heats).

`impo`

By default this is 2.

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL1D, CL2D, CL3D or CL3T).

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : normal velocity

ECR(5) : tangential velocity

ECR(6) : tangential velocity (2nd component in 3d)

7.9.37 CLVF IMPOSED MASS FLOW RATE (SUPERSONIC INLET)

Object :

This option works for perfect gases only (GAZP material). It enables to specify an imposed mass flow rate on the boundary of a fluid modelled by Cell-Centred Finite Volumes (VFCC)[4]. From a mathematical point of view, this boundary condition represents a supersonic inlet. We impose in the "ghost" state the specified boundary conditions (density, pressure and momentum).

Syntax:

```
"CLVF"  "DEBI" "RO" rho "PRES" pres "PREF" pref "GAMA" gama
        "DEBX" debx "DEBY" deby <"DEBZ" debz>
        /LECTURE/
```

`rho`

Density.

`pres`

Pressure.

`pref`

Reference pressure.

`gama`

Gamma (ratio of specific heats).

`debx`

X-component of the mass flow rate.

`deby`

Y-component of the mass flow rate.

`debz`

Z-component of the mass flow rate (3D only).

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL1D, CL2D, CL3D or CL3T).

[4]For a theoretical overview of the CLVF boundary conditions implemented in EUROPLEXUS, one can read [837] from page 187.

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : normal velocity

ECR(5) : tangential velocity

ECR(6) : tangential velocity (2nd component in 3d)

7.9.38 CLVF SUBSONIC INLET

Object :

This option works for perfect gases only (GAZP material). It enables to specify a subsonic inlet on the boundary of a fluid modelled by Cell-Centred Finite Volumes (VFCC)[5]. Indeed, we have one internal information taken into account and the rest of information is taken outside the domain. In the "ghost" state we take into account of the internal pressure (information taken inside) and we impose the values of the entropy, total enthalpy and flow direction of the state at infinity.

Syntax:

```
"CLVF"  "ESUB" "RO" rho "PRES" pres "PREF" pref "GAMA" gama
        "DEBX" debx "DEBY" deby <"DEBZ" debz>
        /LECTURE/
```

`rho`

Density at the infinity.

`pres`

Pressure at the infinity.

`pref`

Reference pressure.

`gama`

Gamma (ratio of specific heats).

`debx`

X-component of the mass flow rate at the infinity.

`deby`

Y-component of the mass flow rate at the infinity.

`debz`

Z-component of the mass flow rate at the infinity (3D only).

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL1D, CL2D, CL3D or CL3T).

[5] For a theoretical overview of the CLVF boundary conditions implemented in Europlexus, one can read [837] from page 187. This specific boundary condition has been applied to study the flow in a nozzle in [868], page 22.

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : normal velocity

ECR(5) : tangential velocity

ECR(6) : tangential velocity (2nd component in 3d)

7.9.39 CLVF LODI QUASI 1-D CONDITION

Object :

This option works for perfect gases only (GAZP material). It enables to specify a Lodi quasi 1-D condition on a fluid modelled by Cell-Centred Finite Volumes (VFCC). It is still experimental and under development. See references [967] and [968] for details.

Syntax:

```
    "CLVF"  "LOD1" "RO"   rho    "PRES" pres   "GAMA" gama
                   "VNOR" vnor  <"VTG1" vtg1> <"VTG2" vtg2>
                  <"COXA" coxa> <"COYA" coya> <"COZA" coza>
                  <"COXB" coxb> <"COYB" coyb> <"COZB" cozb>
                   "TYPE" type   "CELP" celp   "VITP" vitp
                   "LONP" lonp  <"ROP"  rop>  <"TABT" tabt>
                  <"TABO" tabo>
            /LECTURE/
```

`rho`

Density.

`pres`

Pressure.

`gama`

Gamma (ratio of specific heats).

`vnor`

Normal velocity (give a negative value for an undefined velocity at an exit).

`vtg1`

Tangential velocity (first component).

`vtg2`

Tangential velocity (second component).

`coxa, coya, coza`

XA, YA, ZA coefficients.

`coxb, coyb, cozb`

XB, YB, ZB coefficients.

`type`

Type of boundary condition.

`celp`

Reference sound speed.

`vitp`

Reference normal speed.

`lonp`

Reference normal length.

`rop`

Reference density.

`tabt`

Unknown.

`tabo`

Unknown.

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL1D, CL2D, CL3D or CL3T).

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : normal velocity

ECR(5) : tangential velocity

ECR(6) : tangential velocity (2nd component in 3d)

7.9.40 CLVF FOURIER MODES IN 2D

Object :

This option works for perfect gases only (GAZP material). It enables to specify a Fourier modes in 2D condition on a fluid modelled by Cell-Centred Finite Volumes (VFCC). It is still experimental and under development. See references [967] and [968] for details.

Syntax:

```
    "CLVF"  "FOUR" "RO"   rho    "PRES" pres   "GAMA" gama
                   "VNOR" vnor  <"VTG1" vtg1> <"VTG2" vtg2>
                  <"COXA" coxa> <"COYA" coya> <"COZA" coza>
                  <"COXB" coxb> <"COYB" coyb> <"COZB" cozb>
                   "TYPE" type   "CELP" celp   "VITP" vitp
                   "LONP" lonp  <"ROP"  rop>  <"TABT" tabt>
                  <"TABO" tabo>
            /LECTURE/
```

`rho`

Density.

`pres`

Pressure.

`gama`

Gamma (ratio of specific heats).

`vnor`

Normal velocity (give a negative value for an undefined velocity at an exit).

`vtg1`

Tangential velocity (first component).

`vtg2`

Tangential velocity (second component).

`coxa, coya, coza`

XA, YA, ZA coefficients.

`coxb, coyb, cozb`

XB, YB, ZB coefficients.

`type`

Type of boundary condition.

`celp`

Reference sound speed.

`vitp`

Reference normal speed.

`lonp`

Reference normal length.

`rop`

Reference density.

`tabt`

Unknown.

`tabo`

Unknown.

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL1D, CL2D, CL3D or CL3T).

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : normal velocity

ECR(5) : tangential velocity

ECR(6) : tangential velocity (2nd component in 3d)

7.9.41 CLVF RIEMANN 3-D CONDITION

Object :

This option works for perfect gases only (GAZP material). It enables to specify a Riemann 3-D condition on a fluid modelled by Cell-Centred Finite Volumes (VFCC). It is still experimental and under development. See references [967] and [968] for details.

Syntax:

```
"CLVF"  "RIEM" "RO"   rho    "PRES" pres   "GAMA" gama
               "VNOR" vnor  <"VTG1" vtg1> <"VTG2" vtg2>
              <"COXA" coxa> <"COYA" coya> <"COZA" coza>
              <"COXB" coxb> <"COYB" coyb> <"COZB" cozb>
               "TYPE" type  <"TABT" tabt>
        /LECTURE/
```

`rho`

Density.

`pres`

Pressure.

`gama`

Gamma (ratio of specific heats).

`vnor`

Normal velocity (give a negative value for an undefined velocity at an exit).

`vtg1`

Tangential velocity (first component).

`vtg2`

Tangential velocity (second component).

`coxa, coya, coza`

XA, YA, ZA coefficients.

`coxb, coyb, cozb`

XB, YB, ZB coefficients.

`type`

Type of boundary condition.

`tabt`

Unknown.

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL1D, CL2D, CL3D or CL3T).

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : normal velocity

ECR(5) : tangential velocity

ECR(6) : tangential velocity (2nd component in 3d)

7.9.42 CLVF TIME-DEPENDENT PRESSURE

Object :

This option works for perfect gases only (GAZP material). It enables to specify an imposed time-dependent outside pressure on a fluid modelled by Cell-Centred Finite Volumes (VFCC). It is still experimental and under development. See references [967] and [968] for details.

Syntax:

```
"CLVF"  "PFCT" "COEF" coef "FONC" fonc <"PREF" pref>
        /LECTURE/
```

`coef`

Scaling coefficient.

`fonc`

Index of the time function.

`pref`

Reference pressure.

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL1D, CL2D, CL3D or CL3T).

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : normal velocity

ECR(5) : tangential velocity

ECR(6) : tangential velocity (2nd component in 3d)

7.9.43 CLVF CRITICAL MASS FLOW RATE

Object:

Computes the critical mass flow rate for a perfect gas or for a water-steam mixture at the extremity of a pipeline (1D).

Syntax:

```
    "CLVF"  "DCRI" "PINI" pini   "PFIN" pfin  < "PREF" pref >   ...
            "RAP" rapport   < "KSI" ksiz >   < "MOD" mode >     ...
            < "TAU" tau >  < "TRUP" trupt >  < "FONC" nufo >    ...
            < "CL" cl >  < "LISS" liss >     < "XMIN" xmin >    ...
            < "CB" cb >  < "TPBR" tpbr >                        ...
/LECTURE/
```

`pini`

Initial pressure.

`pfin`

Imposed external pressure in steady-state conditions.

`pref`

Reference pressure.

`rapport`

Ratio of the cross-sections : S(exit)/S(upstream).

`ksiz`

Head loss coefficient at the outlet for the fluid.

`mode`

Choice of the critical mass flow rate model (for the two-phase water only : see below)

`tau`

Time constant of the exponential function leading from pini to pfin.

`trupt`

Rupture instant of the membrane. By default, trupt = 0.

`nufo`

function number for a progressive opening.

`cl`

Choice of boundary conditions approach (`CL 2` for two-phase water only : see below) `liss`

Smoothing coefficient between critical mass flow models (for ATHIS-like model `-MOD 6-` only : see below)

`xmin`

Threshold value to adjust the transition between models (for ATHIS-like model `-MOD 6-` only : see below)

`cb`

Coefficient used to define the critical pressure for pure liquid (for ATHIS-like model `-MOD 6-` only : see below)

`tpbr`

Maximum value of S(exit)/S(upstream) (`rapport`) for which a special treatment for very small breaks is applied (for ATHIS-like model `-MOD 6-` only : see below)

`LECTURE`

List of the concerned elements.

Comments:

The user may choose among 6 models for two-phase water :

mode = 1 : homogeneous model

mode = 2 : MOODY model

mode = 3 : FAUSKE model

mode = 4 : DEMT model (developed by M. Lepareux)

mode = 5 : HENRY-FAUSKE model

mode = 6 : ATHIS-like composite model

For the three first models, the results do not depend upon the size of the opening. On the contrary, the DEMT model developed by Michel Lepareux [721] accounts for this effect provided the following value is not exceeded (rapport=ratio):

```
rapport < or = 0.75
```

For the liquids, the `ksiz` coefficient allows to account for the form of the outlet. By default, the value suggested by IDEL'CIK is retained for `ksiz`, corresponding to a straight pipe outlet and a thin diaphragm with sharp sides, i.e.:

$$ksiz = (1 + 0.707\sqrt{1 - rapport})^2$$

Of course, with the data of the upstream medium, the formula becomes:

$$ksi = \frac{ksiz}{rapport^2}$$

The old data input files included a parameter `K`, equal to 'ksi' with ksiz = 1. In order to better reproduce the phenomena, it is suggested to no longer use `K`, and to declare the two parameters 'ksiz' and 'rapport' instead.

The user may notice that setting $rapport = 1$ does not lead to the cancellation of ksi. If the user wants to completely remove the influence of this term, it is needed to explicitly add $ksi = 0$ in the command line.

The user may choose among 2 boundary conditions approaches:

cl = 1 : the standard approach based on a pressure head loss

cl = 2 : a more advanced approach, only valid for two-phase water, that combines the critical pressure and mass flow with the use of Water/Steam tables to properly describe the state of the water/steam mixture in critical conditions. Note that this approach also takes into account partial openings introducing a head loss. It is important to mention that for small values of $rapport$ ($rapport < 0.1$), the CSTA must be reduced (CSTA < 0.25) to guarantee the simulation stability.

The default value is cl = 1.

Three extra keywords `LISS`, `XMIN` and `CB` are added to tune the HENRY-FAUSKE and ATHIS-like composite models:

'liss' is a parameter that allows the smoothing of the transition between critical flow models based on the value of the vapor quality. It has to lie between 0 and 1 and is set by default to 0 (no smoothing).

'xmin' is parameter that let the user tune the threshold values that control the transition between the critical flow models. It has to lie between 0 and $1e^{-4}$ and is set by default to $1e^{-5}$. Let x be the vapor quality of the mixture, then it acts as follows for he HENRY-FAUSKE model:

$$\begin{cases} \text{pure liquid approach} & \text{if } 0 < x < \texttt{XMIN} \\ \text{subcooled conditions} & \text{if } \texttt{XMIN} < x < 10^\star\texttt{XMIN} \\ \text{two-phase conditions} & \text{if } 10^\star\texttt{XMIN} < x > (1 - \texttt{XMIN}) \\ \text{perfect gas approach} & \text{if } x > (1 - \texttt{XMIN}) \end{cases}$$

and for the ATHIS-like composite model:

$$\begin{cases} \text{pure liquid approach} & \text{if } 0 < x < \texttt{XMIN} \\ \text{Henry-Fauske model} & \text{if } \texttt{XMIN} < x < 1000^\star\texttt{XMIN} \\ \text{homogeneous model} & \text{if } 1000^\star\texttt{XMIN} < x > (1 - \texttt{XMIN}) \\ \text{perfect gas approach} & \text{if } x > (1 - \texttt{XMIN}) \end{cases}$$

'cb' controls the critical pressure for the pure liquid approach in the ATHIS-like model. $Pcrit = cb \times Psat$. Its default value is 0.8.

'tpbr' controls the activation of a slightly modified version of the ATHIS-like model for very small breaks. If $rapport < tpbr$ then it is activated, otherwise the normal ATHIS-like treatment is applied. Its default value is 0.

Outputs:

The different components of the ECR table are as follows:

ECR(1) : pressure at the opening

ECR(2) : density of the donor element

ECR(3) : mass velocity (Q = rho*Vn) of the donor

ECR(4) : outlet pressure (Pext or Pcrit)

ECR(5) : break opening instant

ECR(6) : indicator (0 if liquid; 1 if gas; mass title if two-phase mixture)

ECR(7) : Mach number at the outlet (only for perfect gases and two-phase water)

ECR(8) : Head loss coefficient (xk)

ECR(9) : maximum mass velocity (Qmax), if ECR(4) = Pcrit

ECR(10) : indicator (0 = virgin membrane, 1 = ruptured membrane)

7.9.44 SAFETY VALVE FOR VFCC (JRC)

Object

This instruction enables the modelling of fluid discharge from a pressurized vessel through a generic safety valve or (by a suitable choice of the parameters) through an orifice. The fluid passing through the valve or orifice can be either incompressible (typically a liquid) or compressible (a gas).

Alternatively, the model can also be used in the opposite flow direction in order to fill up (pressurize) a vessel from an external source. Therefore, we distinguish between two modes: **discharge** mode or **loading** mode. The two modes cannot be combined in the same device, since no reverse flow is allowed. However, one could of course attach two `SVAL` devices, one in discharge mode and the other in loading mode, to the same vessel (at different locations along the wall) if needed.

The input syntax includes also a set of (optional) parameters that allow a sort of "pressure regulation" functionality whereby the opening of the valve is subjected to a series of constraints which may also depend upon the (independent) pressure in a "master" fluid element not belonging to the zone of the fluid domain to which the valve is attached.

A - Discharge mode

The valve is characterized by three main parameters:

- A^{tube}, the area of the tube in which the valve is mounted;
- Δp^{min}, the pressure difference (between internal and external pressures) at which the valve starts to open;
- `mode` the functioning mode of the device: 0 means discharge mode, 1 means loading mode. The default value is 0, so this parameter may be omitted if discharge mode is required.

Other **optional** parameters are:

- Δp^{max}, the pressure difference at which the valve is fully open, by default $\Delta p^{\mathrm{max}} = \Delta p^{\mathrm{min}}$;
- Δt^{ope}, the time interval needed to completely open the valve under a positive step increment of the pressure difference $\Delta p > \Delta p^{\mathrm{max}}$, by default $\Delta t^{\mathrm{ope}} = 0$;
- Δt^{clo}, the time interval needed to completely close the valve under a negative step increment of the pressure difference $\Delta p < -\Delta p^{\mathrm{max}}$, by default $\Delta t^{\mathrm{clo}} = 0$;
- q^{max}, the maximum mass flow rate through the valve, by default $q^{\mathrm{max}} = \infty$;
- p^{ext}, the external pressure (assumed constant), by default $p^{\mathrm{ext}} = 0$;
- ρ^{ext}, the external density (assumed constant); this quantity must be specified in loading mode, but it must not be specified in discharge mode.
- i^{ext}, the external specific internal energy (assumed constant); this quantity must be specified in loading mode, but it must not be specified in discharge mode.
- A^{max}, the maximum opening area of the valve which must be $A^{\mathrm{max}} \leq A_{\mathrm{tube}}$, by default $A^{\mathrm{max}} = A^{\mathrm{tube}}$;

- C_c, the contraction coefficient of the fluid flow through the valve opening, i.e. the ratio between the area of the flow in the *vena contracta* and the opening area of the valve (assumed constant, independent of the current opening area), by default $C_c = 1$;
- γ, the ratio of specific heats $\gamma = C_p/C_v$ in case of compressible fluid flow. If omitted, the fluid being discharged is considered as incompressible;
- t^{act}, the activation time of the valve. The valve is guaranteed to be inactive (closed) for $t < t^{\mathrm{act}}$, whatever be the conditions of the fluid. If not specified, the code assumes $t^{\mathrm{act}} = -\infty$.
- t^{dea}, the de-activation time of the valve. The valve is guaranteed to be inactive (closed) for $t > t^{\mathrm{dea}}$, whatever be the conditions of the fluid. If not specified, the code assumes $t^{\mathrm{dea}} = \infty$.
- `qmom`, a flag that controls the flux of momentum: 0 (the default) means that no flux of momentum is computed, 1 means that the flux of momentum is computed. This parameter is used only when the valve is attached to a VFCC fluid volume.
- `emas`, the *master* fluid element whose pressure p^{mas} has to be monitored for pressure regulation purposes. Note that the pressure p^{mas} is independent from the opening or not of the current valve, i.e. it is not influenced (at least directly) from the opening or not of the valve. If specified, the master element should therefore belong to a zone of the fluid domain not directly connected with the fluid part to which the current valve is attached (but the code does not check this requirement).
- `esla`, the *slave* fluid element whose pressure p^{sla} has to be monitored for pressure regulation purposes. Note that the pressure p^{sla} directly depends upon the opening or not of the current valve. If specified, the slave element should therefore belong to the zone of the fluid domain directly connected with the fluid part to which the current valve is attached (but the code does not check this requirement).
- p^{dis}, the value of pressure in the slave element that, when reached, triggers the discharge through the current valve, i.e. starts the opening of the valve. This parameter must not be specified in loading mode. By default $p^{\mathrm{dis}} = \infty$.
- p^{max}, the value of pressure in the slave element that, when reached, triggers the closing of the current valve. This parameter must not be specified in discharge mode. By default $p^{\mathrm{max}} = \infty$.
- p^{ms1}, the value of pressure difference between the master and the slave elements at which the valve starts to open (in an attempt to keep the pressure difference below the chosen value: $\Delta p = p^{\mathrm{mas}} - p^{\mathrm{sla}} \leq p^{\mathrm{ms1}}$.) By default $p^{\mathrm{ms1}} = \infty$.
- p^{ms2}, the value of pressure difference between the master and the slave elements at which the valve becomes fully open. If $\Delta p = p^{\mathrm{mas}} - p^{\mathrm{sla}} \geq p^{\mathrm{ms2}}$ then the valve is fully open, in an attempt to keep the pressure difference below the chosen value. By default $p^{\mathrm{ms2}} = p^{\mathrm{ms1}}$.
- `rval`, a *reference* valve (`SVAL`) element. The reference valve must be in discharge mode and the current valve must be in loading mode. If the opening area of the reference valve is $a^{\mathrm{ref}} > 0$, then the (current) valve closes immediately ($a = 0$).

This model is similar to the material `IMPE SVAL` described on page C.860 but can be used with VFCCs instead of Finite Elements in the fluid domain.

References

More information on the formulation of this model may be found in reference [94].

Syntax

```
"CLVF"  "SVAL"  <"MODE" mode> "ATUB" atub "DPMI" dpmi
      < "DPMA" dpma "TOPE" tope "TCLO" tclo "QMAX" qmax
        "PEXT" pext "ROEX" roex "IEXT" iext
        "AMAX" amax "CC"   cc   "GAMM" gamm "TACT" tact
        "TDEA" tdea "QMOM" qmom
        "EMAS" /LECT_emas/ "ESLA" /LECT_esla/
        "PDIS" pdis "PMAX" pmax "PMS1" pms1 "PMS2" pms2
        "RVAL" /LECT_rval/                              >
      /LECTURE/
```

`mode`

Functioning mode of the device: 0 means discharge mode, 1 means loading mode. If omitted, the code assumes value 0 (discharge mode).

`atub`

Cross-section of the safety valve flow tube.

`dpmi`

Pressure difference at which the valve starts to open.

`dpma`

Pressure difference at which the valve is fully open; by default, it is equal to Δp^{min}.

`tope`

Opening time interval; by default, it is 0.

`tclo`

Closure time interval; by default, it is 0.

`qmax`

Maximum mass flow rate; if omitted, by default it is infinite (no limit).

`pext`

External pressure (assumed constant); by default it is 0.

`roex`

External density (assumed constant); this quantity must be specified in loading mode, but it must not be specified in discharge mode.

`iext`

External specific internal energy (assumed constant); this quantity must be specified in loading mode, but it must not be specified in discharge mode.

`amax`

Maximum opening area of the valve. It must be $A^{\max} \leq A^{\text{tube}}$. By default, it is $A^{\max} = A^{\text{tube}}$.

`cc`

Flow contraction coefficient ($0 < C_c \leq 1$). By default it is $C_c = 1$.

`gamm`

Ratio of specific heats for the fluid being discharged ($\gamma = C_p/C_v$). If specified, the fluid is considered as compressible. If omitted, the fluid is considered as incompressible (γ is unused in that case).

`tact`

Activation time of the valve. The valve is guaranteed to be inactive (closed) for $t < t^{\text{act}}$, whatever be the conditions of the fluid. If not specified, the code assumes $t^{\text{act}} = -\infty$.

`tdea`

De-activation time of the valve. The valve is guaranteed to be inactive (closed) for $t > t^{\text{dea}}$, whatever be the conditions of the fluid. If not specified, the code assumes $t^{\text{dea}} = \infty$.

`qmom`

Flag that controls the flux of momentum: 0 (the default) means that no flux of momentum is computed, 1 means that the flux of momentum is computed. This parameter is used only when the valve is attached to a VFCC fluid volume.

`EMAS`

Introduces the definition (`/LECT_emas/`) of the *master* fluid element whose pressure p^{mas} has to be monitored for pressure regulation purposes. Note that the pressure p^{mas} is independent from the opening or not of the current valve, i.e. it is not influenced (at least directly) from the opening or not of the valve. If specified, the master element should therefore belong to a zone of the fluid domain not directly connected with the fluid part to which the current valve is attached (but the code does not check this requirement).

`ESLA`

Introduces the definition (`/LECT_esla/`) of the *slave* fluid element whose pressure p^{sla} has to be monitored for pressure regulation purposes. Note that the pressure p^{sla} directly depends upon the opening or not of the current valve. If specified, the slave element should therefore belong to the zone of the fluid domain directly connected with the fluid part to which the current valve is attached (but the code does not check this requirement).

`pdis`

The value of pressure p^{dis} in the slave element that, when reached, triggers the discharge through the current valve, i.e. starts the opening of the valve. This parameter must not be specified in loading mode. By default, $p^{\text{dis}} = \infty$.

`pmax`

The value of pressure $p^{\max}$ in the slave element that, when reached, triggers the closing of the current valve. This parameter must not be specified in discharge mode. By default, $p^{\max} = \infty$.

`pms1`

The value of pressure difference p^{ms1} between the master and the slave elements at which the valve starts to open (in an attempt to keep the pressure difference below the chosen value: $\Delta p = p^{\mathrm{mas}} - p^{\mathrm{sla}} \leq p^{\mathrm{ms1}}$.) By default, $p^{\mathrm{ms1}} = \infty$.

`pms2`

The value of pressure difference p^{ms2} between the master and the slave elements at which the valve becomes fully open. If $\Delta p = p^{\mathrm{mas}} - p^{\mathrm{sla}} \geq p^{\mathrm{ms2}}$ then the valve is fully open, in an attempt to keep the pressure difference below the chosen value. By default, $p^{\mathrm{ms2}} = p^{\mathrm{ms1}}$.

`RVAL`

Introduces the definition (`/LECT_rval/`) of a *reference* valve (`SVAL`) element. The reference valve must be in discharge mode and the current valve must be in loading mode. If the opening area of the reference valve is $a^{\mathrm{ref}} > 0$, then the (current) valve closes immediately ($a = 0$).

`LECTURE`

Reading procedure of the number of the "CLxx" element defining the boundary.

Determination of the current opening area of the valve

The calculation of the current opening area of the valve consists of three phases. In the *first phase*, we check whether at the current time t the valve is active or not: if $t < t^{\mathrm{act}}$ or $t > t^{\mathrm{dea}}$ then the valve is closed irrespective of fluid conditions ($a = 0$) and we skip the following two phases. Then, if `rval` has been specified, we also check the opening area of the reference valve: if $a^{\mathrm{ref}} > 0$ then the current valve is immediately closed ($a = 0$) and we skip the following two phases.

Otherwise ($t^{\mathrm{act}} \leq t \leq t^{\mathrm{dea}}$), the valve is active. The *second phase* consists of checking whether there are any pressure regulation constraints specified for the current valve, since such constraints override the normal opening calculations to be performed in the third phase. If no slave element `esla` was specified, there are no regulation constraints and so we go directly to the third phase. Otherwise there are some constraints, which depend upon the chosen functioning mode of the device.

- In *discharge mode*, if p^{dis} was given and $p^{\mathrm{sla}} \geq p^{\mathrm{dis}}$, then we set $a = A$ (valve fully open) and skip the third phase.
- In *loading mode*, if $p^{\max}$ was given and $p^{\mathrm{sla}} \geq p^{\max}$, then we set $a = 0$ (valve fully closed) and skip the third phase. Otherwise, we check any constraints on the master-slave pressure difference. If p^{ms1} was given, we compute the pressure difference $\Delta p = p^{\mathrm{mas}} - p^{\mathrm{sla}}$: if $\Delta p < p^{\mathrm{ms1}}$ the valve is completely closed ($a = 0$); else if $\Delta p > p^{\mathrm{ms2}}$ the valve is completely open ($a = A$); else $p^{\mathrm{ms1}} \leq \Delta p \leq p^{\mathrm{ms2}}$ and the valve is only partially open ($a = \frac{\Delta p - p^{\mathrm{ms1}}}{p^{\mathrm{ms2}} - p^{\mathrm{ms1}}} A$). Having computed a, we skip the third phase. Otherwise (p^{ms1} was not given) we go to the next phase.

The *third and last phase* is as follows. The *nominal* opening area of the valve a' is assumed to be a linear function of the differential pressure Δp between the internal fluid (p) and the external medium (p^{ext}):

$$\Delta p = p - p^{\text{ext}}$$

$$\begin{array}{rl} \text{for } \ \Delta p \leq \Delta p^{\min} & a' = 0 \\ \text{for } \ \Delta p^{\min} < \Delta p < \Delta p^{\max} & a' = \dfrac{\Delta p - \Delta p^{\min}}{\Delta p^{\max} - \Delta p^{\min}} A \\ \text{for } \ \Delta p \geq \Delta p^{\max} & a' = A \end{array}$$

The *actual* opening area of the valve a at a given time depends on the opening or closure times, and on the valve opening reached at the previous time, a^{old}. Let v_a and v_c represent the velocity of aperture and closure of the valve:

$$\begin{aligned} v_a &= A/\Delta t^{\text{ope}} \\ v_c &= -A/\Delta t^{\text{clo}} \end{aligned}$$

Then:

$$\begin{array}{rl} \text{for } \ a' > a^{\text{old}} \ \text{ and } \ \Delta t^{\text{ope}} > 0 & a = \min[(a^{\text{old}} + v_a \Delta t), a'] \\ \text{for } \ a' < a^{\text{old}} \ \text{ and } \ \Delta t^{\text{clo}} > 0 & a = \max[(a^{\text{old}} + v_c \Delta t), a'] \\ \text{in all other cases} & a = a' \end{array}$$

The value of a is constrained to be between 0 and A:

$$\begin{array}{rl} \text{if } \ a > A & a = A \\ \text{if } \ a < 0 & a = 0 \end{array}$$

In order to compute the mass flow rate through the valve, we distinguish two cases, depending upon the compressibility of the discharged fluid.

Incompressible or nearly incompressible fluid

The fluid being discharged is incompressible or nearly incompressible (e.g., a liquid). This situation is determined by the fact that the user has *not* specified a value for $\gamma = C_p/C_v$ in the input data. In this case the following relation is assumed to hold:

$$\Delta p = p - p^{\text{ext}} = \zeta \rho \frac{v_{\text{tube}}^2}{2} \tag{79}$$

where ζ is a dimension-less *resistance coefficient* which depends upon the geometry of the valve, ρ is the density of the fluid upstream the valve and v_{tube} is the velocity of the fluid in the tube upstream the valve.

By assuming steady state flow and a jet that expands back to fill the entire cross-section of the tube downstream the valve, the resistance coefficient ζ is evaluated by:

$$\zeta = \left(\frac{1}{r_p C_c} - 1 \right)^2$$

where r_p is the current *perforation ratio* r_p of the valve, given by:

$$r_p = a/A^{\text{tube}}$$

Since the pressure drop Δp is known (we assume $\Delta p = p - p^{\text{ext}}$, without any limitations), from (79) we obtain the (nominal) fluid velocity in the tube upstream the valve:

$$v'_{\text{tube}} = \sqrt{\frac{2}{\zeta}\frac{p - p^{\text{ext}}}{\rho}}$$

and the current (nominal) mass flow rate is given by:

$$q' = A^{\text{tube}}\rho v'_{\text{tube}} = A^{\text{tube}}\sqrt{\frac{2}{\zeta}\left(p - p^{\text{ext}}\right)\rho}$$

Compressible fluid

The fluid being discharged is compressible. This situation is determined by the fact that the user has specified a value for $\gamma = C_p/C_v$ in the input data. (The given value of γ, assumed constant, should be equal to that of the fluid being discharged, i.e. the fluid upstream the safety valve.)

In this case the code assumes that the expansion of the fluid across the valve can be represented by a simple adiabatic transformation:

$$\frac{p}{\rho^\gamma} = \text{const.} \tag{80}$$

This is reasonable for a perfect gas but not, for example, if the fluid is a superheated vapor that becomes saturated during the expansion.

We compute the current *critical pressure* p_c corresponding to the current pressure p upstream the valve and to the chosen value of γ:

$$p_c = p\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

For example, if $\gamma = 1.4$ like for air, $p_c/p = 0.528$. The pressure in the valve orifice (i.e., in the zone where the cross-section area of the duct is minimum) cannot drop below the critical value. We therefore distinguish two cases, depending on the value of the external pressure p^{ext} with respect to p_c:

- if $p^{\text{ext}} \geq p_c$, then the fluid pressure in the valve orifice is $p_2 = p^{\text{ext}}$, the fluid velocity in the orifice is

$$v_2 = \sqrt{2\frac{\gamma}{\gamma-1}\frac{p}{\rho}\left[1 - \left(\frac{p_2}{p}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

  and the (nominal) mass flow rate is given by

$$q' = S_2 v_2 \rho_2 = S_2 v_2 \rho\left(\frac{p_2}{p}\right)^{\frac{1}{\gamma}} = S_2\sqrt{2\frac{\gamma}{\gamma-1}p\rho\left[\left(\frac{p_2}{p}\right)^{\frac{2}{\gamma}} - \left(\frac{p_2}{p}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$

  where p and ρ are the pressure and density of the fluid upstream the orifice, respectively, use has been made of (80) to explicitate the density ρ_2 at the orifice and S_2 is the flow area of the *vena contracta* at the orifice $S_2 = C_c a$.

- if $p^{\text{ext}} < p_c$, then the fluid pressure in the valve orifice is equal to the critical pressure $p_2 = p_c$ and the (nominal) mass flow rate is given by

$$q' = \psi S_2 \sqrt{p\rho}$$

where S_2 has the same meaning as above and the coefficient ψ is given by

$$\psi = \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \sqrt{2\frac{\gamma}{\gamma+1}}$$

Flow limitation and velocity

Finally, in both cases (incompressible or compressible flow) the current (effective) mass flow rate q is computed by taking into account a possible user-imposed maximum value q^{max} and by inhibiting any back flow through the valve:

$$\begin{array}{rl}
\text{for } \; q^{\text{max}} > 0 \; \text{ and } \; q' > q^{\text{max}} & \quad q = q^{\text{max}} \\
\text{for } \; q' < 0 & \quad q = 0 \;\; \text{(no back flow)} \\
\text{in all other cases} & \quad q = q'
\end{array}$$

The current (effective) fluid velocity in the upstream tube is then:

$$v_{\text{tube}} = \frac{q}{A^{\text{tube}}\rho}$$

Modelling of an orifice

In order to model a simple orifice in the wall of the pressurized tank, set A^{tube} to the area of the orifice and Δp^{min} to a very small value.

As concerns the optional parameters, leave out Δp^{max} and A^{max} so that it will be $\Delta p^{\text{max}} = \Delta p^{\text{min}}$ and $A^{\text{max}} = A^{\text{tube}}$, leave Δt^{ope} to its default value of 0 and specify a huge value for Δt^{clo} so that the orifice will never close in practice.

B - Loading mode

Loading mode is activated by specifying `MODE 1` in the input data. In this mode, p^{ext} (assumed constant) must be specified since the default value of 0 is not appropriate. In order to completely define the external state (which in this case becomes the donor state) one must also give ρ^{ext} and i^{ext} (which are also assumed to be constant).

Outputs:

The different components of the ECR table are as follows :

ECR(1) : current pressure in the fluid element to which the valve is attached

ECR(2) : current nominal opening area

ECR(3) : current actual opening area

ECR(4) : previous time this element was treated

ECR(5) : previous actual opening area

ECR(6) : total ejected mass (in discharge mode) or injected mass (in loading mode)

ECR(7) : total ejected energy by mass transport (in discharge mode) or injected energy (in loading mode)

ECR(8) : current flow tube velocity

ECR(9) : current density in the fluid element to which the valve is attached

ECR(10) : current specific internal energy in the fluid element to which the valve is attached

7.9.45 CLVF LOW MACH INJECTION INLET

Object :

This option works for perfect gases only (GAZP material). It enables to specify inlet boundary injection for a fluid at low Mach regime, modelled by Cell-Centred Finite Volumes (VFCC). We specify the momentum and the internal enthalpy and the rest of information is taken inside the domain. In the "ghost" state we take into account of the internal state. We suppose that tangential speeds are zero.

Syntax:

```
"CLVF"  "INLM" "PREF" pref "GAMA" gama "H0" h0 "MOME" mome
        "FUN1" n1 "FUN2" n2
        /LECTURE/
```

`pref`

Reference pressure.

`gama`

Gamma (ratio of specific heats).

`h0`

Internal enthalpy (positive)

`mome`

Normal momentum (positive)

`n1`

Number of the function which specifies the time evolution of the coefficient which multiplies h0

`n2`

Number of the function which specifies the time evolution of the coefficient which multiplies mome

`LECTURE`

Reading procedure of the numbers of the elements composing the boundary (CL2D, CL3D).

Outputs:

The different components of the ECR table are as follows :

ECR(1) : pressure

ECR(2) : density

ECR(3) : sound speed

ECR(4) : normal velocity

ECR(5) : tangential velocity

ECR(6) : tangential velocity (2nd component in 3d)

7.10 MECHANISMS

Object:

This option allows to assign behaviour laws to the elements of a mechanical joint ”MECA” or ”LIGR” that link together two sub-structures.

For the ”MECA” element : There are currently 5 directives, with several sub-directives.

FORC : Imposed force as a function of time over a slider (‘glissière’).

COUP : Imposed couple as a function of time over a pivot.

FOCO : Force and couple imposed on a sliding pivot.

MOCC : Electric motor with continuous current, on a pivot.

RESS : Linear or non-linear spring.

For the ”LIGR” element : There is only 1 directive.

LIGR : Linear or non-linear spring.

Options	Sub-directives		Element
	mandatory	optional	
FORC	FONC	INER	MECA
COUP	FONC	INER	MECA
		ASSE	MECA
FOCO	FONC	INER	MECA
MOCC	FONC	INER	MECA
	ELEC	REDU	MECA
		TACH	MECA
		ASSE	MECA
RESS	/	/	MECA
LIGR	/	/	LIGR

Syntax:

```
$  "FORC"  |  <"INER" ...> |  /LECTURE/    $
```

```
               $          |   "FONC" ...  |               $
               $                                          $
               $  "COUP"  |  <"INER" ...> |  /LECTURE/    $
               $          |   "FONC" ...  |               $
               $          |  <"ASSE" ...> |               $
               $                                          $
"MECA"         $  "FOCO"  |  <"INER" ...> |  /LECTURE/    $
               $          |   "FONC" ...  |               $
               $                                          $
               $  "MOCC"  |  <"INER" ...> |  /LECTURE/    $
               $          |   "ELEC" ...  |               $
               $          |   "FONC" ...  |               $
               $          |  <"REDU" ...> |               $
               $          |  <"TACH" ...> |               $
               $          |  <"ASSE" ...> |               $
               $                                          $
               $  "RESS"                     /LECTURE/    $
               $                                          $
               $  "LIGR"                     /LECTURE/    $
```

`LECTURE`

Index of the associated mechanism element.

Comments:

It is not necessary to systematically give a material law to elements of type ”MECA” or ”LIGR”. It this is missing, one will have a simple kinematic joint.

7.10.1 IMPOSED FORCE

Object:

This directive allows to introduce a driving force on a junction of type ‘glissière’ (slider).

Syntax:

```
"FORC"     |     "FONC" ...     |   /LECTURE/
           |    <"INER" ...>    |
```

Comments:

The behaviour law is defined by an imposed force F(t) un the axis of the slider.

The force is computed by the function: A : F(t) = Function A.

The B function is redundant.

Outputs:

ECR(5) : relative displacement of the slider since the start of the calculation
ECR(6) : relative velocity
ECR(7) : applied force

7.10.2 MOTOR COUPLE

Object:

This directive allows to define a motor couple on a connection of type ‘pivot’ (simple pin joint).

Syntax:

```
"COUP"     |     "FONC" ...     |   /LECTURE/
           |    <"INER" ...>    |
           |    <"ASSE" ...>    |
```

Comments:

The law of behaviour is define by a motor couple C(t) on the axis of the pivot.

If the motor is not a servomotor: C(t) = Function A. In this case, the B function is redundant.

If the motor is a servomotor: C(t) is computed by the control function.

Outputs:

ECR(1) : angular displacement of the motor from the calculation origin (in radians)
ECR(2) : angular velocity (rad / s)
ECR(3) : couple on the arm

7.10.3 IMPOSED FORCE AND COUPLE

Object:

This directive is a combination of the 2 preceding ones ("FORC" and "COUP"), and is applied to sliding pivots ("PIGL").

Syntax:

```
"FOCO"     |     "FONC" ...     |   /LECTURE/
           |    <"INER" ...>    |
```

Comments:

The behaviour law is defined by an imposed force F(t) on the slider axis, and by a motor couple C(t) around this axis.

The force is computed from function A: F(t) = Function A.

The couple is computed from function B: C(t) = Function B.

Outputs:

ECR(1) : angular displacemenet of the motor from the beginning of the calculation (in radians)

ECR(2) : angular velocity (rad / s)

ECR(3) : couple on the arm

ECR(5) : relative displacement of the slider from the beginning of the calculation

ECR(6) : relative velocity

ECR(7) : applied force

7.10.4 DIRECT CURRENT MOTOR

Object:

This directive allows to specify a motor couple on a junction of type 'pivot' (simple pin joint). The behaviour and the material characteristics are those of a direct current motor.

Syntax:

```
"MOCC"       |      "INER" ...     |    /LECTURE/
             |      "ELEC" ...     |
             |      "FONC" ...     |
             |     <"REDU" ...>    |
             |     <"TACH" ...>    |
             |     <"ASSE" ...>    |
```

Comments:

* U(t) - Tension at the motor poles

* C(t) - Motor couple at the outlet shaft

* tetap - Angular velocity of the motor shaft

The other variables are defined in the electric parameters.

The behaviour law is of the following type.

If the motor is not a servo-motor: U(t) = Function A. The B function is then redundant.

If the motor is a servo-motor: U(t) is computed from the control mechanism:

```
C(t)=(Kc*N*U(t)/R)-(N*N*tetap(Ff+Kc*Kc/R))-(N*Fs)
```

(for the meaning of parameters Kc, N, R, etc., consult pages C.760 and C.770).

Outputs:

ECR(1) : angular displacement of the motor since the beginning of the calculation (in radians)

ECR(2) : angular velocity (rad / s)

ECR(3) : couple on the arm

7.10.5 SPRING

Object:

This directive allows to introduce stiffnesses on the free d.o.f.s of mechanismsn in order to model linear or non-linear springs.

Syntax:

```
 "RESS"        ("K   "  k | "KFON"  kfon)
               ("C   "  c | "CFON"  cfon)
               "STAK"  stak    "STAC"  stac    /LECTURE/
```

`k`

Longitudinal stiffness for the linear spring.

`kfon`

Function number describing the longitudinal non-linear behavior. The function gives the force depending on the displacement.

`c`

Rotational stiffness for the linear spring.

`cfon`

Function number describing the rotational non-linear behavior. The function gives the moment depending on the angular displacement.

`stak`

Estimation of the maximal longitudinal oscillation period.

`stac`

Estimation of the maximal rotational oscillation period.

Comments:

This directive may be used in conjunction with a mechanism defined by a 2-nodes "MECA" element and an "ARTI" connection (except a ROTULE) on this very element.

The stiffnesses introduced in the articulated systems are associated with the free d.o.f.s: for example, for a sliding pivot, the stiffness K corresponds to the translational d.o.f. ('glissière'), while the stiffness C corresponds to the free rotational d.o.f. (pivot).

The direction of the displacement for the non-linear spring is defined according to the local axis of the "MECA" element or, in case of merging points, thanks to the axis defined for the connection.

Outputs:

ECR(1) : angular displacement since the beginning of the calculation (in radians)

ECR(2) : angular velocity (rad / s)

ECR(3) : applied couple

ECR(5) : relative displacement of the slider since the beginning of the calculation

ECR(6) : relative velocity

ECR(7) : applied force

ECR(8) : initial length of the MECA element

7.10.6 LIGR

Object:

This directive allows to introduce stiffnesses in rotation around the axis "AXE1" and "AXE2" (local axis of the shell) in order to model linear or non-linear springs. The axis "AXE1" and "AXE2" are defined in the "LINK COUP ARTI TGGR" (See D.270) or "LINK COUP ARTI CRGR" (See D.275) directives.

Syntax:

```
 "LIGR"         ("KR1   "  kr1 | "KFR1"  kfr1)
                ("KR2   "  kr2 | "KFR2"  kfr2)
                <"FROT  "  frot >             /LECTURE/
```

`kr1`

Rotational stiffness for the linear spring around the axis "AXE1".

`kfr1`

Function number describing the rotational non-linear behavior. The function gives the moment depending on the relative angular displacement around the axis "AXE1".

`kr2`

Rotational stiffness for the linear spring around the axis "AXE2".

`kfr2`

Function number describing the rotational non-linear behavior. The function gives the moment depending on the relative angular displacement around the axis "AXE2".

`frot`

Frottement according to the perpendicular axis to the plan defined by "AXE1" and "AXE2".

Comments:

This directive may be used in conjunction with a mechanism defined by a multi-nodes "LIGR" element and an "ARTI TGGR" or an "ARTI CRGR" connection on this element.

The frottement according to the perpendicular axis to the plan defined by "AXE1" and "AXE2" make sense only for an "ARTI CRGR" connection.

Outputs:

ECR(1) : angular displacement since the beginning of the calculation around the axis "AXE1" (in radians)

ECR(2) : angular velocity (rad / s) around the axis "AXE1"

ECR(3) : applied couple around the axis "AXE1"

ECR(5) : angular displacement since the beginning of the calculation around the axis "AXE2" (in radians)

ECR(6) : angular velocity (rad / s) around the axis "AXE2"

ECR(7) : applied couple around the axis "AXE2"

7.10.7 FUNCTIONS RELATED TO MECHANISMS

Object:

This directive allows to specify the functions used for the articulated systems (mechanisms).

Syntax:

```
 "FONC"         "COEA"  coea     "NUFA"  nufa     ...
          ...  <"COEB"  coeb>   <"NUFB"  nufb>    ...
```

`coea`

Multiplying coefficient of function A.

`coeb`

Multiplying coefficient of function B.

`nufa`

Index of function A.

`nufb`

Index of function B.

Comments:

This directive is mandatory for articulated systems.

7.10.8 MECHANISM INERTIA

Object:

This directive allows to enter the values of mass and inertia for the articulated systems (mechanisms).

Syntax:

```
 "INER"            "MMT1" m1      "IMT1" i1          ...
              ...  "MMT2" m2      "IMT2" i2          ...
```

`m1`

Added mass on the first node of the mechanism.

`i1`

Added rotational inertia on the first node of the mechanism.

`m2`

Added mass on the second node of the mechanism.

`i2`

Added rotational inertia on the second node of the mechanism.

Comments:

The needed values are the additional inertias which have not been taken into account in the structures connected by the articulated system.

Rotational inertias are added along the axis of the mechanism.

Warning:

In the case of the direct current motor "MOCC", it is assumed that the rotor is placed on the first node, and the stator on the second node of the mechanism. Verify that the mesh conforms to this convention.

7.10.9 SERVOMECHANISM

Object:

This directive allows to specify a servo-mechanism.

The servo-control law is of the type P.I.D. (Proportional - Integrated - Derived):

```
F(t) = K0 - Ki * (I-Ic) - Kp * (A-Ac) - Kv * (A'-Ac')
```

with:

I = integral of the angular position from 0 to t,

Ic = integral of the command for the position.

Syntax:

```
"ASSE"   <"KP" kp>   <"KV" kv>   <"KI" ki>   <"K0" k0>
```

`k0`

Off-set tension constant.

`kp`

Parameter for the control in position.

`kv`

Parameter for the control in velocity.

`ki`

Parameter for the integral control.

Comments:

If this directive is missing, the mechanism is considered non-controled.

7.10.10 ELECTRIC PARAMETRES

Object:

This directive allows to specify the electric parameters of a direct current motor.

Syntax:

```
  "ELEC"  "R" r  <"KC" kc>   <"TNSN" tnsn> ...
          ... <"INTS" is> <"FFMT" ffmt>  <"FSMT" fsmt>
```

`r`

Electric resistance of the motor.

`kc`

Torque constant per Ampère.

`tnsn`

Saturation tension in Volt.

`is`

Saturation intensity in Ampère.

`ffmt`

Viscous friction coefficient.

`fsmt`

Torque constant for dry friction.

Comments:

The friction values are those of the motor alone.

7.10.11 REDUCER

Object:

This directive allows to add the characteristics of a reducer to a mechanism of type motor.

Syntax:

```
"REDU"   <"MRD1" m1>   <"MRD2" m2>   <"IRD1" i1>  <"IRD2" i2>  ...
        ...   <"FFRD" ff>  <"FSRD" fs>  <"N" n>   ...
```

`m1`

Added mass on the first node of the mechanism.

`i1`

Added rotational inertia on the first node of the mechanism.

`m2`

Added mass on the second node of the mechanism.

`i2`

Added rotational inertia on the second node of the mechanism.

`n`

Reduction ratio.

`ff`

Viscous friction coefficient.

`fs`

Torque constant for dry friction.

Comments:

The rotational inertias are applied along the axis of the mechanism.

Warning:

In the case of the direct current motor "MOCC", it is assumed that the rotor is placed on the first node, and the stator on the second node of the mechanism. Verify that the mesh conforms to this convention.

7.10.12 TACHYMETRIC GENERATOR

Object:

This directive allows to add the characteristics of a tachymetric generator to a mechanism of type motor.

Syntax:

```
  "TACH"   <"MGT1" m1>   <"MGT2" m2>   <"IGT1" i1>  <"IGT2" i2>
             ... <"JASS" jbras>
```

`m1`

Added mass on the first node of the mechanism.

`i1`

Added rotational inertia on the first node of the mechanism.

`m2`

Added mass on the second node of the mechanism.

`i2`

Added rotational inertia on the second node of the mechanism.

`jbras`

Inertia seen by the mechanism.

Comments:

The "JASS" parameter is only used for the stability step calculation. An estimation, even in first approximation, is sufficient.

The rotational inertias are applied along the axis of the mechanism.

Warning:

In the case of the direct current motor "MOCC", it is assumed that the rotor is placed on the first node, and the stator on the second node of the mechanism. Verify that the mesh conforms to this convention.

7.11 ASSIGNING MATERIALS TO MULTILAYER SHELL ELEMENTS

Object:

When using sandwiches composed of multiple layers in certain shell elements it is necessary to assign a (possibly different) material to each layer.

Sandwiches and layers are defined in the Geometry Complements section via the `SAND` directive, see page C.45.

In order to assign a given material to certain layers, first declare the material with all its properties as usual and list via the `/LECT/` directive all the elements that have that material, including sandwich elements that possess this material in at least one layer. Then, after the `/LECT/` directive, list all the layers which have the material (each layer is identified by a progressive index, as explained on page C.45).

Syntax :

```
"MATE" "Material_Definition"

       ( /LECT/   < "LAYE" /LECT_LAY/ > )
```

`Material_Definition`

Definition of the material and its properties (see preceding sections), except the elements to which it is assigned.

`/LECT/`

Elements possessing this material.

`/LECT_LAY/`

Layers of the `/LECT/` elements that possess the given material. Each layer is identified by an index, as explained on page C.45.

Comments:

Note that the `/LECT/` directive (with its optional `LAYE` subdirective) may be repeated more than once for the same material. This allows e.g. to assign the same material to a few unlayered elements, then to a group of layered elements (i.e. a sandwhich) in layers 1 and 3, then to another group of layered elements (i.e. another sandwhich) in layers 2 and 4, and so on. For example:

```
"MATE" "Material_Definition"
       LECT 1 2 3 TERM
       LECT 4 6 TERM  LAYE LECT 1 3 TERM
       LECT 5 8 TERM  LAYE LECT 2 4 TERM
       . . .
```

The only element types that accept layers are ED01, COQI, CQD3, CQD4, CQD6 and CQD9. Sinc version 2005, Q4MC and T3MC are also available.

In order to be accepted in a layer, the material type must be available for the unlayered element type as well.

All layers of multilayer elements (sandwiches) must be explicitely assigned a material.

7.12 JOINT PROPERTIES

7.12.1 BUSHING ELEMENT

Object:

All the characteristics of the bushing element have to be given of the material type called "JOINT PROPERTIES". This sub-directive allow the definition of a stiffness or a damping in providing both the amplitude and the number of the function, which describes the force-displacement (force-velocity) or torque-rotation (torque-angular velocity) law. Nevertheless a simplified syntax is allowed for the case of linear laws, which can be expressed only by a constant stiffness/damping coefficient.

Note that two models have been implemented. The first one is "BSHT" with only translation degrees of freedom and the second one is "BSHR" with rotational degrees of freedom too. In the latter case the stiffness and/or damping can be applied also to the rotational degrees of freedom.

A suitable criteria to properly introduce a model of rupture in the riveted joints can be used. This criteria is based on the rigid behaviour of the joints; the rupture occurs when the following limit curve is reached :

```
(N/Nu)**a + (T/Tu)**b >= 1
```

Four different laws of behaviour can be used :

1) Bushing with elastic behaviour;

2) Bushing with plastic behaviour;

3) Bushing with elastic behaviour and elliptic rupture criteria;

4) Bushing with plastic behaviour and elliptic rupture criteria;

Syntax:

1) Generic data

Each behaviour is declared by a different sub-directive.

1) Case 1

```
"JPRP"  "BUSH"
```

2) Case 2

```
"JPRP"  "BPLA"
```

3) Case 3

```
"JPRP"  "BELC"
```

4) Case 4

```
"JPRP"  "BPEC"
```

- 2) Data concerning the law of behaviour

```
<"KTXC" ktxc <"KTXN" ktxn>> <"KTYC" ktyc <"KTYN" ktyn>> <"KTZC" ktzc <"KTZN" ktzn>>
<"KRXC" krxc <"KRXN" krxn>> <"KRYC" kryc <"KRYN" kryn>> <"KRZC" krzc <"KRZN" krzn>>

<"DTXC" dtxc <"DTXN" dtxn>> <"DTYC" dtyc <"DTYN" dtyn>> <"DTZC" dtzc <"DTZN" dtzn>>
<"DRXC" drxc <"DRXN" drxn>> <"DRYC" dryc <"DRYN" dryn>> <"DRZC" drzc <"DRZN" drzn>>

<"V1X " v1x "V1Y " v1y "V1Z " v1z >
<"V2X " v2x "V2Y " v2y "V2Z " v2z >
<"EX  " ex  > <"EY  " ey  > <"EZ  " ez  >
<"LOCA" loca>
<"DISP" disp>
<"RADB" radb>
```

`ktxr`

Amplitude multiplying the function describing X-translational stiffness or constant X-translational stiffness if the function KTXN is not given (REAL).

`ktxn`

Number of the function describing X-translational stiffness (INTEGER).

`ktyr`

Amplitude multiplying the function describing Y-translational stiffness or constant Y-translational stiffness if the function KTYN is not given (REAL).

`ktyn`

Number of the function describing Y-translational stiffness (INTEGER).

`ktzr`

Amplitude multiplying the function describing Z-translational stiffness or constant Z-translational stiffness if the function KTZN is not given (REAL).

`ktzn`

Number of the function describing Z-translational stiffness (INTEGER).

`krxr`

Amplitude multiplying the function describing X-rotational stiffness or constant X-rotational stiffness if the function KTXN is not given (REAL).

`krxn`

Number of the function describing X-rotational stiffness (INTEGER).

`kryr`

Amplitude multiplying the function describing Y-rotational stiffness or constant Y-rotational stiffness if the function KTYN is not given (REAL).

`kryn`

Number of the function describing Y-rotational stiffness (INTEGER).

`krzr`

Amplitude multiplying the function describing Z-rotational stiffness or constant Z-rotational stiffness if the function KTZN is not given (REAL).

`krzn`

Number of the function describing Z-rotational stiffness (INTEGER).

`dtxr`

Amplitude multiplying the function describing X-translational damping or constant X-translational damping if the function KTXN is not given (REAL).

`dtxn`

Number of the function describing X-translational damping (INTEGER).

`dtyr`

Amplitude multiplying the function describing Y-translational damping or constant Y-translational damping if the function KTYN is not given (REAL).

`dtyn`

Number of the function describing Y-translational damping (INTEGER).

`dktzr`

Amplitude multiplying the function describing Z-translational damping or constant Z-translational damping if the function KTZN is not given (REAL).

`dtzn`

Number of the function describing Z-translational damping (INTEGER).

`drxr`

Amplitude multiplying the function describing X-rotational damping or constant X-rotational damping if the function KTXN is not given (REAL).

`drxn`

Number of the function describing X-rotational damping (INTEGER).

`dryr`

Amplitude multiplying the function describing Y-rotational damping or constant Y-rotational damping if the function KTYN is not given (REAL).

`dryn`

Number of the function describing Y-rotational damping (INTEGER).

`drzr`

Amplitude multiplying the function describing Z-rotational damping or constant Z-rotational damping if the function KTZN is not given (REAL).

`drzn`

Number of the function describing Z-rotational damping (INTEGER).

`v1x v1y v1z`

cartesian components for vector V1 of the user defined frame.

`v2x v2y v2z`

cartesian components for vector V2 of the user defined frame.

`ex ey ez`

eccentricity of the user defined frame from node 1

`loca`

location of the user defined frame origin between node 1 and node 2

`disp`

flag for taking into account initial position (default 0).

`radb`

flag for the use of the radial bushing element formulation.

- 3) Data concerning the elliptic criteria:

```
<"NULT " nult "TULT " tult  >
<"COEA " coea "COEB " coeb  >
```

`NULT`

ultimate axial effort

`TULT`

ultimate radial effort

`COEA`

coefficient a of the elliptic criteria

`COEB`

coefficient b of the elliptic criteria

Comments:

As default the force-position and force-velocity laws are defined in the global reference frame: however a user-defined properties frame (x1, x2, x3) is accepted via the directives V1X, V1Y, V1Z, V2X, V2Y, V2Z. After the two vectors V1 and V2 have been defined, the code applies a normalization to obtain the unit versors v1 and v3, and computes the v3 versor as:

```
{v3}={v1}^{v2}
```

The laws are assumed to be diagonal in the properties frame (x1, x2, x3), that is the force Fi along xi depends only upon the relative position ui and relative velocity vi along the xi local direction.

The user can also define a point P in the properties frame where the force and the torque should be applied: this must be done using the parameter LOCA and, if needed the eccentricity parameters EX, EY, EZ. The effect of the parameter LOCA, which must be a real number in the interval [0,1], is to move the application point on the segment AB: it is actually the percentage of the position of P along AB. The default is LOCA 0.0. If offsets ex, ey, ez are also defined, their effect is to translate along the directions (x, y, z) of the global frame, the point P, from its position P' defined by LOCA parameter.

Outputs:

The components of the ECR table are as follows:

ECR(1): Translation force Fx1 between the two nodes along x1 local axis

ECR(2): Translation force Fy1 between the two nodes along y1 local axis

ECR(3): Translation force Fz1 between the two nodes along z1 local axis

ECR(4): Torque Tx1 between the two nodes around x1 local axis

ECR(5): Torque Ty1 between the two nodes around y1 local axis

ECR(6): Torque Tz1 between the two nodes around z1 local axis

ECR(7): Relative position between the two nodes along x1 local axis

ECR(8): Relative position between the two nodes along y1 local axis

ECR(9): Relative position between the two nodes along z1 local axis

ECR(10): Relative rotation between the two nodes around x1 local axis

ECR(11): Relative rotation between the two nodes around y1 local axis

ECR(12): Relative rotation between the two nodes around z1 local axis

ECR(13): Relative translation velocity between the two nodes along x1 local axis

ECR(14): Relative translation velocity between the two nodes along y1 local axis

ECR(15): Relative translation velocity between the two nodes along z1 local axis

ECR(16): Relative angular velocity between the two nodes around x1 local axis

ECR(17): Relative angular velocity between the two nodes around y1 local axis

ECR(18): Relative angular velocity between the two nodes around z1 local axis

ECR(25): Value of the rupture elliptic criteria

8 GROUP D—LINKS

Object:

To introduce links between degrees of freedom. Links may be subdivided into three broad categories:

- **Coupled** links, which are treated (implicitly) by a method of Lagrange multipliers. This ensures proper coupling between all the imposed links, provided of course the specified conditions are compatible.
- **Decoupled** links, which are imposed via ad-hoc direct methods. In this case the conditions should be independent from one another, and the user is responsible for ensuring this property.
- **"Liaisons"**, which are treated using the former LIAISON directive for compatibility purposes. These links can be either coupled or uncoupled (see below).

Following the above subdivision, this directive admits three forms, characterized by the respective sub-directives: `LINK COUP`, `LINK DECO` or `LINK LIAI`. The complete syntax is summarized below. For each variation of the main directive (`COUP`, `DECO` or `LIAI`) the available link types are listed in the relevant column, so as to provide a compact overview.

Syntax:

```
$ LINK COUP          $ LINK DECO          $ LINK LIAI          $
$ <NONP>             $                    $                    $
$ <SOLV  . . .>      $                    $ <SOLV  . . .>      $
$ <RENU ; NORE>      $                    $ <RENU ; NORE>      $
$ <VERI> <ARRA>      $                    $ <FREQ ifreq>       $
$ <SPLT $ DOF  ;     $                    $ <VERI>             $
$         NODE ;     $                    $                    $
$         DOMA ;     $                    $                    $
$         PART ;     $                    $                    $
$         NONE $>    $                    $                    $
$ <SOL2>             $                    $                    $
$ <GPCG  . . .>      $                    $                    $
$ <UPDT /CTIME/>     $                    $                    $
```

8.1 LIST OF LINKS

	COUP	DECO	LIAI	
8.6	BLOQ	BLOQ	BLOQ	Blockages
8.7	TBLO	TBLO	BLOQ	Time limited blockages
8.8	GUID			
8.9	CONT	CONT	CONT	
8.10	RADI		RADI	
8.11	RELA		RELA	Relations
8.12	TREL			Time limited relations

8.13	ARMA	ARMA	ARMA	
8.14	CROS	CROS		
8.15		ACBE		Rebar (FEM)-concrete (DEM) link
8.16	LCAB			Link between prestressing cables and concrete
8.17	ARLQ			Shell-3D mesh coupling (ARLEQUIN framework)
8.18	DEPL	DEPL	DEPL	Imposed motions, displacement
8.18	VITE	VITE	VITE	Imposed motions, velocity
8.18	ACCE	ACCE	ACCE	Imposed motions, acceleration
8.19	COQM		COQM	Connections between shells and solid elements
8.20	INTE			Interfaces
8.21	FLST			Fluid-structure coupling
8.22	FLSR	FLSR		Fluid-structure coupling
8.23	FLSX	FLSX		Fluid-structure coupling
8.24.1	FS		FS	
8.26	IMPA	IMPA	IMPA	Impacts and unilateral conditions
8.27			JEUX	
8.28	BUTE			Limited directional displacement
8.29	GLIS	GLIS	GLIS	Master-slave sliding contact
8.30			MPEF	Method of particles and forces
8.31			SPHY	Smoothed particle hydrodynamics method (SPH)
8.32	EDEF			Connecting finite and discrete element models
8.33	BIFU		BIFU	Bifurcation connection
8.34	ADHE			Adhesion connection
8.35	TUBM		TUBM	Tubm connection (3d-1d junction)
8.36	TUYM		TUYM	Tuym connection (3d-1d junction)
8.37	TUYA		TUYA	Tuya connection (3d-1d junction)
8.38	SOLI		SOLI	Rigid body (solide indeformable)
	COMP		COMP	????
8.39	ARTI		ARTI	Articulation
8.40	ROTA		ROTA	Rotation
8.41	MENS		MENS	Imposed time-dependent rotational motion
8.42	TMEN			Time-limited imposed rotational motion
8.43	DIST		DIST	Constant distance connection
8.44	BARY		BARY	Barycentric junction
8.45	RIGI	RIGI	RIGI	Rigid junction
8.46	GLUE			Gluing together two meshes (glue)
8.47			SPLI	Contacts defined by spline functions
8.48			COLL	Collisions
8.49	FSA		FSA	Fluid-structure sliding of ale type (FSA)
8.50	FSR		FSR	Rigid-boundary/fluid sliding of ale type
8.51	PINB	PINB	PINB	Impact/contact by pinball model (PINB)
8.52	GPIN	GPIN		Contact/impact by generalized pinball model (GPIN)
8.53		FSS		Fluid-structure sliding (FSS)
8.54	SH3D		SH3D	Node to shell connector

8.55		FLSW		Weak fluid-structure coupling (FLSW)
8.56	MAP2		MAP2	Node on facet element
8.56	MAP3		MAP3	Node on facet element
8.56	MAP4		MAP4	Node on facet element
8.56	MAP5		MAP5	Node on facet element
8.56	MAP6		MAP6	Node on facet element
8.56	MAP7		MAP7	Node on facet element
8.57	FESE			Finite-element/spectral-element interface
8.58	NAVI			Navier-stokes (incompressibility)
8.59	BREC			Pipeline rupture connection
8.60		PELM		Surface pressure measured in an element (PELM)
8.61		ADAP		Uncoupled hanging links
8.62	ENGR	ENGR		Prescribed damage for gradient damage materials
8.63		DRAG		Drag force on fluid-embedded 3D beam/bar elements
8.64		EQBM		Equivalent beam kinematics for continuum elements
8.65	SLID			Sliding surfaces for smooth contact
8.66	KFIL	KFIL		Reading links form k-file
8.67		CPLM		Dynamic fluid (mass) coupling between beams (Fritz 1972)
8.68	BIVF			Pipeline connection with or without rupture

`COUP`

Introduces the set of coupled links. All coupled links must be declared within this set (the keyword `COUP` may not be repeated).

`DECO`

Introduces the set of decoupled links. All decoupled links must be declared within this set (the keyword `DECO` may not be repeated).

`LIAI`

Introduces the set of "liaison" links. All "liaison" links must be declared within this set (the keyword `LIAI` may not be repeated).

Comments:

The `COUP` and `LIAI` subdirectives are mutually exclusive. However, the may be combined with the `DECO` links within the same calculation, with the following syntax:

```
LINK $[COUP ; LIAI]$
      (declare all coupled/"liaison" links here ...)
LINK DECO
      (declare all uncoupled links here ...)
```

The subdirective `LIAI` is not compatible with the other types of links. Only the coupled links declared with `LINK COUP` may be used also in conjunction with *domain decomposition* (see the `STRU` directive), while this is not the case for the `LINK LIAI` directive.

Beware that, for the moment, only the `BLOQ`, `DEPL`, `VITE` and `ACCE` models are accepted in calculations with sub-domains.

Note that he availability of each link formulation introduced above with one or more of the link types is given in their specific manual page below.

Warning:

The `LINK COUP` directive allows to build a coupling matrix between the different degrees of freedom appearing in the connections. This matrix must be invertible, and a problem occurs in this sense if the different connections are not independent from each other.

In principle, EUROPLEXUS is able to eliminate the redundant relations in order to be able to invert the connections matrix. But since this elimination is a trial-and-error process, it is preferable when possible to avoid this situation. If this is not possible, it is recommended to start by giving the most complex connections (solids or articulations), and to finish by giving the simplest ones (relations or blockages).

Comments:

Be sure to check the various options available in relation to connections: see Page H.160.

8.2 LINK CATEGORY

Object:

Choose between the available categories for links (see GBD_0010).

Syntax:

```
$[ COUP ; DECO ; LIAI ]$
```

`COUP`

Introduces the set of coupled links. All coupled links must be declared within this set (the keyword `COUP` may not be repeated).

`DECO`

Introduces the set of decoupled links. All decoupled links must be declared within this set (the keyword `DECO` may not be repeated).

`LIAI`

Introduces the set of "liaison" links. All "liaison" links must be declared within this set (the keyword `LIAI` may not be repeated).

8.3 OPTIONS FOR COUPLED LINKS

Object:

Syntax:

```
LINK COUP
     <NONP>
     <SOLV  |[ CHOL                                    ;
               PARD                                    ;
               SPLI < TYPE  imet > < PCON ipre >
                    < PITE  prec > < IPA1 ip1  >
                    < IPA2  ip2  > < RPAR rp   >
                    < INIS  inig >                  ]| >
$[ RENU ; NORE ]$ <VERI>
<ARRA>
<SPLT |[ DOF  ; NODE ; DOMA ; PART ; NONE ]| >
<SOL2>
<GPCG < PREC prec > < APRE apre > < DUMP > >
<UPDT /CTIME/>
```

`NONP`

Accept the occurrence of non-permanent links (such as Lagrangian contacts for example) during the calculation even though there are no non-permanent links explicitly declared in the input. This optional keyword should be used only in the special case that there are no non-permanent links explicitly declared in the input, but at the same time there is some other model which might introduce non-permanent links during the course of the calculation. For example, the Lagrangian contact between SPH particles and structures treated by the `SPHY COQU` or `SPHY STRU` directive, when the `LAGC` keyword is also specified in the calculation type. In this case the model may add coupled, non-permanent links during the course of the calculation, which is only accepted if either some non-permanent links are explicitly declared, or if the present `NONP` keyword is specified. In the second case, just add `LINK COUP NONP` to your input.

`imet`

iterative solver number i, default 8

`ipre`

preconditioner number k, default 3

`prec`

tolerance on residual, default 1.D-6

`ip1`

first integer parameter, default 20

`ip2`

second integer parameter, default 10

`rp`

real parameter, default 1.D-4

`inig`

initial guess, default 0.0

`GPCG`

MPI Only - Use a Global Preconditioned Conjugate Gradient algorithm for the solver.

`PREC prec`

MPI Only - Relative precision for GPCG solver (see comment below)

`APRE apre`

MPI Only - Absolute precision for GPCG solver (see comment below)

`DUMP` Additional information is printed on the listing output during the iterations of the GPCG algorithm if the keyword `DUMP` is used.

Comments:

The `SOLV` directive is fully described in 8.4 (page D.20).

Concerning imposed motions (directives `DEPL`, `VITE` and `ACCE`), note that no dimensions are needed relative to the motions themselves. Hovever, dimensioning relative to the time tables describing such motions is still necessary (see keywords `FNOM`, `FTAB`).

The `ARMATURE` directive is described in 8.13 (page D.125).

The optional keyword `RENU` makes it possible to renumber the links in order to minimize the size of the matrix.

By default, links are renumbered (option `RENU`).

If the optional keyword `NORE` is specified, the links are taken in the order of their definition, and the matrix can be very large and ill-conditioned. If `RENU` (or nothing) is specified, then the connections are renumbered in an attempt to minimize the size of the matrix.

The optional keyword `VERI` can be used to verify a posteriori that the imposed links are effectively satisfied. This option produces heavy output and CPU overhead and should therefore be used only for debugging purposes.

The optional keyword `ARRA` can be used to choose storage of the links in a dynamic array rather than in a doubly linked list of doubly linked lists. This may increase efficiency (but is still under development).

The optional keyword `SPLT` can be used to choose the desired strategy for splitting the constraints into groups. The following possibilities are currently available:

- DOF requests dof-based splitting. This is the default and normally needs not being specified explicitly.
- NODE requests node-based splitting.
- DOMA requests subdomain-based splitting. Of course, this is only effective in calculations with domain decomposition.
- PART requests splitting based upon intrinsic node level factor. Of course, this is only effective in calculations with space partitioning.
- NONE requests no splitting. All constraints end up in a single, big group.

The optional keyword SOL2 can be used to choose closed-form solution for groups of links containing just two links (in addition to groups containing just one link). By default, all groups of links containing more than one links are solved by the general numerical method (Choleski's method). In some cases, closed-form solution may be more efficient.

The optional keyword GPCG toggles the use of a specific Preconditioned Conjugate Gradient solver for links coupling several subdomains within parallel MPI framework. The precision of the solution is computed in terms of relative residual with respect to the norm of the right-hand side vector. Default precision is 10^-5 and it can be changed using the keyword PREC. An additional precision acting on the absolute norm of the residual can be entered using the keyword APRE. It is useful in the rare cases where the norm of the right-hand side vector is very small. Additional information is printed on the listing output during the iterations of the algorithm if the keyword DUMP is used.

The optional keyword UPDT can be used to introduce an update frequency for time-varying links, in order to save CPU time. This is especially useful for fluid-structure interaction, when links are classically updated at each time-step, with a frequency obtained from the CFL condition, whereas their update should follow the physical structural velocity, often much smaller than sound speed in the different media.

As far as GLIS models are concerned, only 3D models (sliding surface) are currently available. For 2D models (sliding lines), please use decoupled or "liaison" links.

The EDEF directive is described in 8.32 (page D.189).

8.4 OPTIONS FOR "LIAISON" LINKS

Object:

The option "SOLV" makes it possible to change the resolution method in order to reduce the time spent to solve large matrix systems. For iterative solvers ("SPLI" keyword) the data structure uses the CSR format (Compressed Sparse Rows), well suited for iterative solution and used in the SPLIB library.

The option "RENUM" makes it possible to renumber the connections in order to minimize the size of the matrix.

The optional keyword "FREQ" can be used to avoid the inversion of the connection matrix at each computation step, in the cases where this is possible (see below).

The optional keyword "VERI" can be used to verify a posteriori that the imposed liaisons are effectively satisfied. This option produces heavy output and CPU overhead and should therefore be used only for debugging purposes.

Syntax:

```
< "SOLV"  |[ "CHOL"                                     ;
             "PARD"                                     ;
             "SPLI" < "TYPE"  imet > < "PCON" ipre > ...
              ...   < "PITE"  prec > < "IPA1" ip1  > ...
              ...   < "IPA2"  ip2  > < "RPAR" rp   > ...
              ...   < "INIS"  inig >                    ]| >

< $[ "RENU" ; "NORE" ]$ >  < "FREQ"  ifreq > <"VERI">
```

`imet`

iterative solver number i, default 8

`ipre`

preconditioner number k, default 3

`prec`

tolerance on residual, default 1.D-6

`ip1`

first integer parameter, default 20

`ip2`

second integer parameter, default 10

`rp`

real parameter, default 1.D-4

`inig`

initial guess, default 0.0

`ifreq`

The matrix will be inverted each ifreq computation step; by default, ifreq is 1, i.e. the matrix is inverted at each step. This has only effect in Lagrangian computations. In ALE or Eulerian cases, the matrix is inverted anyway at each time step (like if ifreq=1) because the nodal masses are continuously changing due to transport.

Comments:

If the option "CHOL" is specified, the standard direct solver is used. This is the default option.

When the keyword "PARD" is specified, the library **PARDISO** is used. The package **PARDISO** is a thread-safe, high-performance, robust, memory efficient and easy to use software for solving large sparse symmetric and unsymmetric linear systems of equations on shared-memory and distributed-memory multiprocessors. This package is include in MKL library provided by the Intel compiler.
http://www.pardiso-project.org/
http://software.intel.com/

When the keyword "SPLI" is specified, the iterative solver is used. SPLIB is a library of iterative solvers with preconditioners for symmetric and nonsymmetric systems. It has been adapted for large matrix systems in the EUROPLEXUS code and uses the Compressed Sparse Row format (CSR).
http://www.netlib.org/utk/papers/iterative-survey/node61.html

The integer parameter `imet` specifies which SPLIB solver to use :

`imet = 1` : Bi-Conjugate Gradients

`imet = 2` : Conjugate Gradients with AA'y = b, x = A'y

`imet = 3` : Conjugate Gradients with A A' x = A'b

`imet = 4` : Conjugate Gradients Squared (CGS)

`imet = 5` : Conjugate Gradients Stabilized

`imet = 6` : GMRES(ip2)

`imet = 7` : Transpose free QMR

`imet = 8` : Template version of Conjugate Gradients Stabilized

`imet = 9` : Template version of GMRES(ip2)

The integer parameter `ip2` used in GMRES solvers defines the Krylov subspace size (default value 10). When an `imet` of zero or less is specified, CG-Stabilization is used.

The integer parameter `ipre` specifies which preconditioner to use :

`ipre = 0` : no preconditioner

`ipre = 1` : ILU(ip1)

`ipre = 2` : MILU(ip1,rp)

`ipre = 3` : ILUT(ip1,rp)

`ipre = 4` : SSOR(rp)

`ipre = 5` : TRID(ip1)

`ipre = 6` : ILU0

`ipre = 7` : ECIMGS(rp)

The integer parameter `ip1` indicates the levels of fill-in to allow for ILU and MILU and the block size to use in the tridiagonal preconditioner TRID. For ILUT, `ip1` is the maximum

additional entries allowed per row in the preconditioner compared to the original matrix. The real parameter `rp` is the relaxation parameter, the amount of multiply discarded fill-in entries before adding them to the diagonal. For SSOR it is the relaxation parameter. For ILUT, it is the drop tolerance.

For ECIMGS, `rp` specifies the sparsity pattern of the preconditioner :

- $rp = 0$: use the non zero pattern of the matrix

- $0 < rp < 1.$: use a sparser pattern than that of the matrix

- $rp = 1.$: use a diagonal pattern

- $rp > 1.$: use a denser pattern with int(rp) levels of fill-in

It is greatly recommanded to use default values by entering only the following key words : ”LIAIS” ”SOLV” ”SPLIB”.

More informations to use SPLIB options can be found in this paper : “SPLIB : A library of iterative methods for sparse linear systems” by R. Bramley and X Wang, department of computer science - Indiana University, 1995.

For information about methods implemented, see for example the following reference by Y. Saad : “Iterative Methods for Sparse Linear Systems”. This book can be found at http://www-users.cs.umn.edu/˜saad

By default, connections are renumbered (option ”RENU”).

If the option ”NORE” is specified, the connections are taken in the order of their definition, and the matrix can be very large and ill-conditioned. If ”RENU” (or nothing) is specified, then the connections are renumbered in an attempt to minimize the size of the matrix.

If the connections are simple fixed displacements, a new numeration is useless because the matrix is diagonal.

The option FREQ is not compulsory. If it is not specified, a new computation is done at every time step.

When the coefficients of the relations between the degrees of freedom depend on the updated geometry (see COQM and FS), it is necessary to perform new computations and to invert the matrix at each time step during a EUROPLEXUS run. This operation is very costly if there are many coupled degrees of freedom. The keyword "FREQ" requests a new computation and an inversion only every ifreq computation steps.

In the case of an incompressible fluid or an A.L.E or Eulerian computation it is necessary to invert the matrix at each time step because the nodal masses are continuously changing due to transport. Therefore, the code ignores the user-supplied value for ifreq in these cases.

The same holds for an incompressible calculation, or for a calculation involving non-deformable sub-structures (keywords "NAVIER" and "SOLIDE").

8.5 AUXILIARY FILE

Object:

This directive allows to read the connections data from an auxiliary file.

Syntax:

```
< "FICHIER"   'nom.fic'  >
```

In certain cases the data may be bulky. It is then recommended to store them on an auxiliary file to shorten the main input data file. The auxiliary file is activated by means of the keyword "FICHIER" that precedes the file name (complete under Unix). In the main data file then only the keywords "LIAISON" "FICHIER" remain.

The auxiliary file (in free format) contains the whole set of connections data, except the keyword "LIAISON". To return to the main input data, the auxiliary file must be terminated by the keyword "RETOUR".

8.6 BLOCKAGES

Object:

To prescribe a zero displacement to (i.e., to block) a degree of freedom, that is to say to ensure the relation U(i) = 0.

Compatibility: `COUP`, `DECO`, `LIAI`

Syntax:

```
"BLOQ"  ( /LECDDL/  /LECTURE/  )
```

`/LECDDL/`

Reading procedure of the degrees of freedom concerned.

`/LECTURE/`

Reading procedure of the numbers of the blocked nodes.

Comments:

It is possible to repeat the same blockage several times. Indeed, when a boundary is described, it is often simpler to use the implicit definition of the procedure /LECTURE/; in this case the points which are located at the ends are written twice. The EUROPLEXUS program eliminates these double definitions before it builds up the matrix.

Note, however, that the program is unable to eliminate the repeated points if e.g. several "BLOQ" keywords are used.

A time-limited version (`TBLO`) of the `BLOQ` directive, which acts only until a certain time and then is automatically removed, is also available, see Page D.31.

8.7 TIME-LIMITED BLOCKAGES

Object:

To prescribe a zero displacement to (i.e., to block) a degree of freedom, that is to say to ensure the relation U(i) = 0, up to a certain time or a certain event. After the chosen time (or event), the blockage is automatically released.

Compatibility: `COUP`, `DECO`

Syntax:

```
"TBLOQ"  ( /LECDDL/ $ "UPTO" t ; "TRIG" $ /LECTURE/  )
```

`/LECDDL/`

Reading procedure of the degrees of freedom concerned.

`UPTO t`

Time up to which the blockage is imposed. After this time, the blockage is automatically released.

`TRIG`

The blockage is imposed only until a trigger is activated. The trigger refers to the `TRIG` keyword which activates mesh refinement in some adaptivity models, see `OPTI ADAP TRIG` on Page H.180. After this time, the blockage is automatically released.

`/LECTURE/`

Reading procedure of the numbers of the blocked nodes.

Comments:

It is possible to repeat the same blockage several times. Indeed, when a boundary is described, it is often simpler to use the implicit definition of the procedure /LECTURE/; in this case the points which are located at the ends are written twice. The EUROPLEXUS program eliminates these double definitions before it builds up the matrix.

Note, however, that the program is unable to eliminate the repeated points if e.g. several "BLOQ" keywords are used.

8.8 GUID: Sliding channel

Object:

This directive aims to model a piping guide, i.e. the support that blocks the transverse displacement of the piping at a given node, while keeping free its longitudinal motion.

The sliding direction is prescribed by giving 3 parameters DIRX, DIRY and DIRZ, which correspond to 3 components of the direction vector. Rotational degrees of freedom are left free.

Compatibility: `COUP`

Syntax:

```
"GUIDE"  "DIRX" rx "DIRY" ry "DIRZ" rz   /LECTURE/  )
```

`rx ry rz`

Components that define the direction of the guide.

`/LECTURE/`

Reading procedure of the number or of the name of the node concerned.

Comments:

Definition of the local frame (x,y,z) with respect to the global frame (X,Y,Z):

- Local x-axis is collinear with the sliding direction specified by the user through the triplet DIRX, DIRY, and DIRZ.
- Local z-axis is orthogonal to x-axis and it is situated in the plane described by the axes x and Z. Positive projection on Z is used.
- Local y-axis completes the direct orthogonal axis system.

If the slider direction is vertical, the local x-axis is collinear with the sliding direction, the y-axis is collinear with Y-axis, and z-axis completes the direct orthogonal axis system.

To obtain the reaction forces in the local frame corresponding to the guide, one must define the node as a REGION and give the same components of the direction vector.

8.9 GEOMETRIC BILATERAL RESTRAINTS (CONTACTS)

Object:

The following instructions are used to automatically write relations imposed by boundary conditions of geometrical origin. For instance, the user wants certain nodes of an element to stay on a given structure, or to impose symmetry conditions for one part of the boundary.

Compatibility: `COUP`, `DECO`, `LIAI`

Syntax:

```
"CONT"
    |  "PLAN"  ...      |
    |  "SPHE"  ...      |
    |  "CYLI"  ...      |
    |  "CONE"  ...      |
    |  "TORE"  ...      |
    |  "SPLA"  ...      |
```

Comments:

Do not forget to dimension (see "RELA" n1 n2, page A80).

Here n1 represents the maximum number of nodes in contact and n2 is equal to 2 for 2-D computations and 3 for 3-D computations.

It is very important to note that the behaviour of these directives (except PLAN and SPLA) is different, according to the fact that the constraints coefficients are considered to be constant, or allowed to vary in time (the desired behaviour may be chosen via the OPTI CONT option, described in Section H). By default the constraint coefficients are determined on the initial configuration and are kept constant in time. This treatment is always adequate for the PLAN and SPLA types of constraint (since the normal to the plane does not vary in time anyway). However, for the other directives it is only adequate if the nodes do not move, i.e. for Eulerian nodes. In this case, the directives represent a handy shortcut for specifying constraints with coefficients different from point to point (but constant in time), without having to write such conditions explicitly in the input file.

But when the nodes move in time, i.e. for Lagrangian or ALE nodes, the use of constant coefficients in time is no longer adequate. The coefficients should be recomputed at each time step, which may be a costly operation. The user may require this updating of the coefficients by specifying the OPTI CONT VARI option, see Section H. Using variable coefficients has as effect that the nodes move by remaining on the imposed surface with first-order accuracy.

The instructions are described in detail on the following pages.

8.9.1 PLANE/LINEAR RESTRAINT (CONTACT PLAN)

Object:

The specified nodes lay (and remain) on a plane normal to a given vector. In 2D, the plane reduces to a straight line. Only translational degrees of freedom are blocked.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"PLAN"  |[  "NX" x  "NY" y  < "NZ" z > ;
            "NR" r  "NZ" z            ;
            "POIN" /LECT1/            ;
            "AUTO"                    ]| /LECT2/
```

`x y`

Components of the normal vector (2-D).

`x y z`

Components of the normal vector (3-D).

`r z`

Components of the normal vector (Axisymmetric).

`POIN /LECT1/`

Must specify a node belonging to the mesh, either via its index or via its CASTEM 2000 name. The coordinates of this node are taken as the components of the normal.

`AUTO`

The components of the normal are determined automatically from the position of the nodes listed in /LECT2/. Therefore, in this case, the nodes contained in the following /LECT2/ list must lie on the same line (in 2D) or plane (in 3D). In the 3D case, of course, the listed nodes must define a plane (not be along the same line).

`/LECT2/`

Numbers of the nodes concerned.

Comments:

It is not necessary that the normal vector be unitary, since it is automatically normalised by the program. Furthermore, it is not necessary that the nodes initially belong to the same line or plane (except in the AUTO case).

The difference between this directive and the CONT SPLA directive (see below) is that CONT PLAN blocks only translational degrees of freedom, while CONT SPLA blocks both translational and rotational degrees. Therefore, the two directives are identical for nodes of continuum elements, which do not possess rotational degrees of freedom. However, for structural nodes (with rotations), CONT PLAN represents a hinge while CONT SPLA represents a symmetry line or plane (the relevant rotations are automatically blocked in that case).

8.9.2 SPHERICAL/CIRCULAR RESTRAINT

Object:

The specified nodes lay on (a) sphere(s) of given center. In 2D, the sphere reduces to a circle.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"SPHE"  |[  "CX" x  "CY" y  < "CZ" z >  ;
            "CR" r  "CZ" z              ;
            "CENT" /LECT1/              ]|    /LECT2/
```

`x y`

Coordinates of the center of the sphere (2-D).

`x y z`

Coordinates of the center of the sphere (3-D).

`r z`

Coordinates of the center of the sphere (Axisymmetric).

`"CENT" /LECT1/`

Node at the center of the sphere. Points should be sufficiently far from the sphere center so as to define the radial direction with sufficient accuracy.

`/LECT2/`

Nodes located at the surface of the sphere.

Comments:

This constraint only ensures that, at each time step, the displacement increment of the specified nodes be tangent to the (current) sphere. For finite displacement increments, therefore, the nodes will only approximately remain on the initial spherical surface. It is not necessary that the nodes initially belong to the same sphere.

This directive blocks only translational degrees of freedom.

In case variable coefficients are specified (via the OPTI CONT VARI option), remember to dimension adequately by the DIME VCON directive). Each sphere/circle requires 3 coefficients.

8.9.3 CYLINDRICAL RESTRAINT

Object:

The specified nodes lay on (a) circular cylinder(s) of given axis. At each step the displacement increment along the axial direction is free, while that in the plane orthogonal to the axis is tangent to a circle.

The instruction only applies to a 3-D analysis. In 2D, the SPHE directive described in the previous Section may be used to obtain a circular restraint.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"CYLI"  |[ "P1X" x1  "P1Y" y1  "P1Z" z1 ; "POI1" /LECT1/ ;
           "P2X" x2  "P2Y" y2  "P2Z" z2 ; "POI2" /LECT2/ ]| /LECT3/
```

`x1 y1 z1`

Coordinates of a point of the cylinder axis.

`"POI1" /LECT1/`

Node at the first point of the cylinder axis.

`x2 y2 z2`

Coordinates of another point of the axis.

`"POI2" /LECT2/`

Node at the other point of the cylinder axis.

`/LECT3/`

Nodes concerned. Points should be sufficiently far from the cylinder axis so as to define the radial direction with sufficient accuracy.

Comments:

This constraint only ensures that, at each time step, the displacement increment of the specified nodes be tangent to the cylinder (current or initial, depending on OPTI CONT option). For finite displacement increments, therefore, the nodes will only approximately remain on the initial cylindrical surface. It is not necessary that the nodes initially belong to the same cylinder.

This directive blocks only translational degrees of freedom.

In case variable coefficients are specified (via the OPTI CONT VARI option), remember to dimension adequately by the DIME VCON directive). Each cylinder requires 6 coefficients.

8.9.4 CONICAL RESTRAINT

Object:

The specified nodes lay on (a) cone(s) of given axis.

The instruction only applies to a 3-D analysis.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"CONE"  $[ "SX" x1  "SY" y1  "SZ" z1 ; "APEX" /LECT1/ ]$
        $[ "PX" x2  "PY" y2  "PZ" z2 ; "POIN" /LECT2/ ]$ /LECT3/
```

`x1 y1 z1`

Coordinates of the apex of the cone.

`"APEX" /LECT1/`

Node at the cone apex.

`x2 y2 z2`

Coordinates of a point on the cone axis different from the apex.

`"POIN" /LECT2/`

Node along the cone axis different from the apex.

`/LECT3/`

Nodes concerned. Points should be sufficiently far from the cone axis so as to define the radial direction with sufficient accuracy.

Comments:

This constraint only ensures that, at each time step, the displacement increment of the specified nodes be tangent to the cone (current or initial, depending on OPTI CONT option). For finite displacement increments, therefore, the nodes will only approximately remain on the initial conical surface. It is not necessary that the nodes initially belong to the same cone.

This directive blocks only translational degrees of freedom.

In case variable coefficients are specified (via the OPTI CONT VARI option), remember to dimension adequately by the DIME VCON directive). Each cone requires 6 coefficients.

8.9.5 TOROIDAL RESTRAINT

Object:

The specified nodes lay on (a) torus(es) of given axis and center.

This instruction only applies to a 3-D analysis.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"TORE"  |[ "P1X" x1  "P1Y" y1  "P1Z" z1 ; "POI1" /LECT1/ ;
           "P2X" x2  "P2Y" y2  "P2Z" z2 ; "POI2" /LECT2/ ;
           "P3X" x3  "P3Y" y3  "P3Z" z3 ; "CENT" /LECT3/ ]|  /LECT4/
```

`x1 y1 z1`

Coordinates of a point on the torus (circular) axis.

`"POI1" /LECT1/`

First node on the torus (circular) axis.

`x2 y2 z2`

Coordinates of another point on the circular axis.

`"POI2" /LECT2/`

Second node on the torus (circular) axis.

`x3 y3 z3`

Coordinates of the center of the torus.

`"CENT" /LECT3/`

Node at the torus center.

`/LECT4/`

Nodes concerned.

Comments:

This constraint only ensures that, at each time step, the displacement increment of the specified nodes be tangent to the torus (current or initial, depending on OPTI CONT option). For finite displacement increments, therefore, the nodes will only approximately remain on the initial torical surface. It is not necessary that the nodes initially belong to the same torus.

This directive blocks only translational degrees of freedom.

In case variable coefficients are specified (via the OPTI CONT VARI option), remember to dimension adequately by the DIME VCON directive). Each torus requires 9 coefficients.

8.9.6 PLANE/LINE OF SYMMETRY RESTRAINT

Object:

The specified nodes lay (and remain) on (a) plane(s) of given normal vector, that defines the symmetry. In 2D, the plane reduces to a straight line.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"SPLA"  |[  "NX" x  "NY" y  < "NZ" z > ;
            "NR" r  "NZ" z             ;
            "POIN" /LECT1/             ;
            "AUTO"                     ]| /LECT2/
```

`x y`

Components of the normal vector (2-D).

`x y z`

Components of the normal vector (3-D).

`r z`

Components of the normal vector (Axisymmetric).

`POIN /LECT1/`

Must specify a node belonging to the mesh, either via its index or via its CASTEM 2000 name. The coordinates of this node are taken as the components of the normal.

`AUTO`

The components of the normal are determined automatically from the position of the nodes listed in /LECT2/. Therefore, in this case, the nodes contained in the following /LECT2/ list must lie on the same line (in 2D) or plane (in 3D). In the 3D case, of course, the listed nodes must define a plane (not be along the same line).

`/LECT2/`

Numbers of the nodes concerned.

Comments:

It is not necessary that the nodes initially belong to the same plane (except in the AUTO case).

The difference between this directive and the CONT PLAN directive (see above) is that CONT PLAN blocks only translational degrees of freedom, while CONT SPLA blocks both translational and rotational degrees. Therefore, the two directives are identical for nodes of continuum elements, which do not possess rotational degrees of freedom. However, for structural nodes (with rotations), CONT PLAN represents a hinge while CONT SPLA represents a symmetry line or plane (the relevant rotations are automatically blocked in that case).

Remember to dimension adequately with 'SYME' (see page A.80).

When AUTO is used, the search for enough non-coincident nodes, among those contained in LECT2, so as to define a line in 2D or a plane in 3D is affected by a tolerance. In case of necessity, this tolerance may be set by OPTI TOLC, see page H.40.

8.10 IMPOSED CIRCULAR SHAPE

Object:

The displacements of the specified nodes are constrained to be in the radial direction with respect to a point (center) and to have the same modulus. If the nodes lie initially on the same circle, they remain on a circle, whose radius may vary with time.

The instruction is available for a 2-D and 3-D analysis.

For an Eulerian computation (no mesh displacements), the fluid velocities are radial and of the same modulus.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"RADI" "SPHE" "CENT" /LECTURE/
        ...   "CONT" /LECTURE/
```

`"CENT" /LECTURE/`

Number of the node at the center of the circle.

`"CONT" /LECTURE/`

Numbers of the nodes concerned.

Comments:

The instruction is used to avoid instabilities e.g. when a gas bubble collapses after an initial expansion.

For n points (n > or = 2), EUROPLEXUS writes (idim*n - 1) relations.

8.11 RELATIONS

Object:

Several displacement (or velocity) components are linked by constant coefficients during the whole computation.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"RELA"  ngroup*(
              ... nrel  nterm*( coef icomp $[ nuneu ipas ;
                                           /LECTURE/ <SHIF s> ]$ )
              ... "EGAL"  /LECDDL/  /LECTURE/                           )
```

`ngroup`

Number of relation sets.

`nrel`

Number of relations to be generated in a set.

`nterm`

Number of terms in a relation of the set.

`coef`

Coefficient of a term.

`icomp`

Displacement component of the node "nuneu" involved in the relation.

`nuneu`

Number of the node concerned.

`ipas`

Increment on the number of the node "nuneu" in order to get the next relation of the set.

`LECTURE`

List of concerned nodes.

`SHIFT s`

Force circular permutation of the list (see example below). The increment in traversing the list circularly is indicated by the `s` quantity (normally 1).

/LECDDL/

Reading procedure of the numbers of the blocked nodes.

EGAL

Indicates the equality along the component /LECDDL/ of the motion of the nodes defined by the following /LECT/.

Comments:

Each displacement will be specified by the number of the node (nuneu) and its component (icomp). Formula of the relation:

```
0 = coef(1)*U(1) + coef(2)*U(2) +  . . . + coef(k)*U(k)
```

There are two ways to define a set of relations. The first is to give the node number `nuneu` and the step `ipas`. The second is to use the procedure /LECTURE/, which allows to use object names created by GIBI. In this latter case, on passes from one relation to the next one in a set by taking the next node in the procedure /LECTURE/ associated with each term. In this case, there must be exactly `nrel` nodes in each one of the lists specified via the /LECT/ procedures (assuming that the optional SHIF keyword has not been specified).

The optional SHIF keyword can be used to force a circular permutation of the list. In this case, the number of nodes in the lists need not be the same. For example, assume that one wants to impose the same displacement along z (i.e. global direction 3) to all nodes of an object named "face1". Then the command would be:

```
RELA 1  0 2
     1. 3 LECT face1 TERM
    -1  3 LECT face1 TERM SHIFT 1
```

Note that in this case the number of relations `nrel` can be set to 0 because the code computes it automatically.

Example:

```
RELA  5  2  2    1.  1 288 1    -1. 1 6 1
         1  3    3.4 2 287 0    -1. 2 5 0    1. 1 5 0
         3  2    0.5 3 115 7    -1. 3 9 5
         5  2    1.  3    LECT toto TERM
               -1.  3    LECT tata TERM
         EGAL        13   LECT 228 321 842 TERM
```

There are five groups. The first group has 2 relations of 2 terms, the second 1 relation of 3 terms, the third 3 relations of 2 terms, the fourth 5 relations of 2 terms and the last one 2 relations of 2 terms.

In the first group, d.o.f 1 of node 288 has been linked to d.o.f 1 of node 6 (first relation), then d.o.f 1 of node 289 to d.o.f 1 of node 7 (second relation). In fact ipas=1 for the two terms.

In the second group, d.o.f. 2 of node 287 has been linked to d.o.f. 2 of node 5 and to d.o.f. 1 of the same node 5. There is just one relation since ipas = 0 for the three terms.

On the contrary, in the third group, ipas=7 for the first term and 5 for the second. Therefore, d.o.f 3 of node 115 has to be linked to d.o.f 3 of node 9 (first relation of the group), then d.o.f 3 of node 122 to d.o.f 3 of node 14 (2nd relation), and finally d.o.f 3 of node 129 to d.o.f 3 to node 19 (3rd relation).

In the fourth group, there are 5 relations between the d.o.f. 3 of the nodes belonging to objects 'toto' and 'tata' taken in the order in which they appear.

In the fifth group, there are 4 equalities between the d.o.f. 1 and 3 of nodes 228, 321 and 842.

```
Ux(228) = Ux(321)  ;   Uz(228) = Uz(321)
Ux(321) = Ux(842)  ;   Uz(321) = Uz(842)
```

8.12 TREL: Time limited relations

Object:

Several displacement (or velocity) components for two given nodes are linked by an equality relationship that can be cancelled at a given time of computation.

Compatibility: `COUP`

Syntax:

```
"TREL" /LECDDL/ UPTO tsup /LECTURE/
```

`/LECDDL/`

Indicate the dof components to be linked.

`tsup`

Time at which the relation set is cancelled.

`LECTURE`

Reading procedure for the names of the two linked nodes.

Comments:

Example of the syntax:

```
TREL 123 UPTO 1.E-3 LECT NF1_1 NF2_1 TERM
```

8.13 ARMATURES

Object:

In calculations of structures made of reinforced concrete, this directive allows to link the displacements of the nodes belonging to continuum-like elements made of concrete, with those of bar-like elements made of steel.

Decoupled treatment of this link consists in introducing a penalty spring between the reference position of a steel node in the corresponding concrete element and its actual position.

The default spring's stiffness is obtained from concrete element through the formula:

$$k = GL$$

with:

G : bulk modulus of concrete element's material,

L : radius of a sphere whose volume equals concrete element's volume.

Compatibility: `COUP`, `DECO`, `LIAI`

Syntax:

```
"ARMA" <"FAST" <$HGRI hgri ; NMAX nmax ; DELE dele$> <DGRI> >
       <"TSTA" ista> <"CSTI" cstif>
        "BETO" /LECTURE/
        "FERR" /LECTURE/
       <"EACH" n>
       <"FROT" "TABL" npts*(si,taui)>
```

`FAST`

Perform fast search of the couplings instead of the default brute-force search.

`HGRI`

Specifies the size of the fast search grid cell. Each cell has the same size in all spatial directions and is aligned with the global axes.

`NMAX`

Specifies the maximum number of cells along one of the global axes.

`DELE`

Specifies the size of the fast search grid cell as a multiple of the length of the largest coupled concrete (continuum-like) element (see `BETO` below). Element "diameters" are computed only along each global spatial direction and the maximum is taken. For example, by setting `DELE 2` the size of the cell is two times the length of the largest coupled concrete element. By default, i.e. if neither `HGRI`, nor `NMAX`, nor `DELE` are specified, the code takes `DELE 1.01`.

`DGRI`

Dump out the grid of cells used for fast searching on the listing. For brevity, the print is done only the first time that the grid is computed.

`ista`

`DECO` only: flag for stability control over the penalty spring's stability (default: 1, see comment below)..

`cstif`

`DECO` only: coefficient multiplying default stiffness of the penalty spring (default: 1.0).

`BETO`

Introduces the list of the concrete (continuum-like) elements.

`EACH`

Optional keyword that allows to link only one every `n` of the reinforcement bar elements to be defined next (`FERR`.) Only the first node of each selected element is linked. By default `n`=1, that is each element (and every bar node) is linked. This keyword can be used to tentatively decrease the number of links without un-refining the reinforcement mesh, if there are too many links. However, since the numbering of the elements is arbitrary, linking (the first node of) every n-th bar element might be inappropriate (depending on the mesh) so it is advised to visually check the result of taking `n` > 1 (e.g. by activating `OPTI LINK VISU`).

`FERR`

Introduces the list of the steel or reinforcement (bar-like) elements. Each node of these elements will be linked to the matching concrete element (if any).

`FROT`

Optional keyword creating a steel-concrete connection in which the tangential efforts depend on the slip between reinforcement and concrete. It requires the definition of the curve $\tau(s)$ which will be entered in a classical way: first, the number of npts points describing the curve and then the list of npts couples $s - \tau(s)$. The first point must correspond to beginning of the plasticity, thus defining the rigidity per unit area k_b and the elastic limit of the interface τ_{elas}.

This option is available with coupled and decoupled links.

Remarks:

If nodes (belonging to concrete elements or steel elements) involved in an "ARMA" connection are also subject to other types of links, such as blockages for example, it's necessary that all links are treated in the same way : coupled or decoupled.

Comments:

The concrete elements must be of continuum-like type 2D or 3D. The steel or reinforcement elements must be of bar-like type (e.g. BR3D in 3D or BARR in 2D).

If `ista` equals 2, stiffness of the penalty spring is limited so that the associated stability time-step is not smaller that the reference concrete element's one.

Up to two named node groups are automatically created for each occurrence of the `ARMA` directive. The first group has the form `_ARMAnnnn` where `nnnn` is a 4-digit number (`0001`, `0002` etc.) indicating the index of the current `ARMA` directive in the input file. This group contains the reinforcement bar nodes which were actually linked to the concrete. The second group has the form `_NARMnnnn` and contains the reinforcement bar nodes which were *not* linked, despite having been declared in the `FERR /LECTURE/` directive, because a matching concrete element could not be found. Obviously, this second group is created only if there are any non-matching nodes. The groups can be visualized in the OpenGL graphical module for direct visual inspection of which nodes were actually glued (or not glued.)

8.14 CROS: Interconnection of reinforcement bars

Object:

This directive allows the user to automatically interconnect crossing longitudinal and transverse reinforcement bars (rebars) to constitute rebar cages (carcasses) frequently used to reinforce the concrete structures. In the real life, the rebars in the cages are usually connected either by welding, tying steel wire, or with mechanical connections.

Links are created between the elements of longitudinal reinforcement and the nodes of transverse reinforcing steel (stirrups).

Both coupled and decoupled links are implemented: the coupled links are treated using Lagrange multipliers method whereas the decoupled ones are solved by the penalty method.

Only the translation degrees of freedom are concerned by this link.

Nodes of the transverse rebars may eventually coincide with the nodes of the longitudinal rebars but should remain distinct.

Compatibility: `COUP`, `DECO`

Syntax:

```
"CROS"  < "TSTA" ista> < "CSTI" cstif >
        "LONG" /LECTURE/
        "TRAN" /LECTURE/
```

`ista`

`DECO` only: flag for stability control over the penalty spring's stability (default: 1, see comment below)..

`cstif`

`DECO` only: coefficient multiplying default stiffness of the penalty spring (default: 1.0).

`LONG`

Introduces the list of longitudinal rebar elements.

`TRAN`

Introduces the list of transverse rebar elements.

Comments:

Both the longitudinal and transverse rebars must be modelled as POUT elements.

If `ista` equals 2, stiffness of the penalty spring is limited so that the associated stability time-step is not smaller that the reference longitudinal steel element's one.

8.15 ACBE: Rebar (FEM)-Concrete (DEM) link

Object:

This directive allows creating nonlinear links between a steel reinforcement bar (rebar) modelled as FEM beam and plein concrete modelled by the discrete element method (DEM). Only one link between a given discrete element and a finite element beam may be created. Each link contains a normal and a tangential component.

A decoupled (DECO) link model is implemented only.

Syntax:

```
 "ACBE"  < "TSTA" ista> < "CSTI" cstif >
         "BETO" "COEF" c1 /LECTURE/
         "ARMA" "COEF" c2 /LECTURE/
         "YOUN"  youn  "TN" tn "CN" cn "ADUN" adun
        < "AMOR"  amor >
         "FTAN" "NUMF" nf
```

`ista`

Flag for stability control over the penalty link's stability (default: 1, see comment below).

`cstif`

Coefficient multiplying default stiffness of the link (default: 1.).

`BETO`

Introduces the list of discrete elements concerned.

`c1`

Coefficient defining the interaction range for the discrete elements.

`ARMA`

Introduces the list of rebar (POUT type) elements concerned.

`c2`

Coefficient defining the interaction range for the beam elements.

`youn`

Young's modulus used to calculate the normal stiffness of the link (kn=youn*S/L).

`tn`

Maximum normal tensile strength (perpendicular to the rebar direction)

`cn`

Maximum normal compression strength (perpendicular to the rebar direction)

`adun`

Softening coefficient (ratio between elastic and softening slopes >0)

`amor`

Reduced damping coefficient applied on steel-concrete links if needed

`nf`

Number of the function describing the tangential behaviour of the link.

Comments:

If `ista` equals 2, stiffness of the penalty spring is limited so that the associated stability time-step is not smaller that the reference concrete element's one.

8.16 LCAB: Link between prestressing cables and concrete

Object:

This directive allows creating kinematic relations between the nodes of prestressing cables modelled as FE bars (BR3D) and the nodes of plain concrete modelled through a FE thick shell model (T3GS,Q4GS). First, a projection of cable nodes onto concrete mesh is done to determine cable node to concrete element correspondence, and then, node by node relations are written.

Adherent and sliding conditions are implemented. In the adherent case, the cable-concrete links act in 3 space directions. For the purely sliding case, only 2 relations per cable node are written (in the normal directions to the cable), the relation in the tangential direction is not written. Those relations are updated at each time step in order to account for the cable direction change when sliding in a curvilinear case.

It is possible to add friction to the sliding case. To do this, RNFR friction-spring elements must be added to the model and declared in the directive GEOM (just after BR3D cables elements). RNFR elements are of SEG2 type with the nodes that coincide geometrically at the beginning of the calculation: the first RNFR node corresponds to cable' node (except for the cables' extremity nodes) and the second one is automatically connected to a concrete point having the same global coordinates and being related to concrete element nodes by ADHE-type relations. The RNFR elements are detected automatically when using LINK LCAB FROT option, thus there is no need to declare them in the present directive. It should be noted that RNFR elements cannot be used outside the LCAB directive.

For theoretical description see [979].

This link model is implemented in coupled (LINK COUP) version only.

Syntax:

```
"LCAB" $[ "ADHE" ; "GLIS" ; "FROT" ]$
        "BETC" /LECTURE/
        "CABL" /LECTURE/
```

`ADHE`

Fully adherent option.

`GLIS`

Perfectly sliding option.

`FROT`

Sliding with friction.

`BETC`

Introduces the list of concrete shell (T3GS,Q4GS type) elements concerned.

`CABL`

Introduces the list of cable (BR3D type) elements concerned.

Comments:

This directive may by repeated as many times as necessary.

8.17 ARLQ: Shell-3D mesh coupling within ARLEQUIN framework

Object:

This directive allows linking in a continuous way two (or more) sub-domains used to model a slender structure, some sub-domains modeled as thick shells (Reissner-Mindlin kinematics) and others represented through a 3D hexahedra-type mesh. The shell and 3D sub-domains are glued in a weak sense within an overlapping zone using the Arlequin method ([980]).

The following hypotheses must be satisfied:

- only Q4GS quadrangular shell and CUBE,CUB8 hexahedron elements can be used,

- the shell and 3D meshes in the gluing zone must be hierarchic.

This link model is implemented in coupled (LINK COUP) version only.

Syntax:

```
"ARLQ" < "ROTA" >
        "COQU" /LECTURE/
        "VOLU" /LECTURE/
```

`ROTA`

Optional key-word to be used to add the gluing of rotations.

`COQU`

Introduces the list of shell (Q4GS) elements of the gluing zone.

`VOLU`

Introduces the list of 3D (CUBE,CUB8) elements of the gluing zone.

Comments:

This directive may by repeated as many times as necessary.

8.18 IMPOSED MOTIONS

Object:

These instructions define imposed motions (displacements, velocities or accelerations) depending on time, for different degrees of freedom.

Compatibility: `COUP`, `DECO`, `LIAI`

Syntax:

```
"DEPL"  ( /LECDDL/  coef  "FONC"  ifonc  < "TLIM" tlim > /LECTURE/  )
"VITE"  ( /LECDDL/  coef  "FONC"  ifonc  < "TLIM" tlim > /LECTURE/  )
"ACCE"  ( /LECDDL/  coef  "FONC"  ifonc  < "TLIM" tlim > /LECTURE/  )
```

`/LECDDL/`

Reading procedure of the different d.o.fs concerned.

`coef`

Multiplying factor of the values of the function.

`ifonc`

Number of the function to be used.

`tlim`

Time after which the imposed motion is deactivated.

`/LECTURE/`

Reading procedure of the numbers of the nodes concerned.

Comments:

The function to be used will be defined by means of the principal instruction "FONC" which enables the user to choose a tabulated function (linear interpolation between the points), or a function programmed by the user by means of a subroutine.

At a time t, the imposed motion is : coef*F(t). In this case, only one function is to be defined, if the motions vary only in amplitude.

If the same d.o.f is submitted to several motions, EUROPLEXUS only takes into account the motion which has been defined first.

Motion can be imposed temporarilly using the "TLIM" keyword.

8.19 CONNECTIONS BETWEEN SHELLS AND SOLID ELEMENTS

Object:

The purpose is to link together the degrees of freedom at the boundary of two parts of the structure. One part is meshed with shells, the other with solid elements. This link is available only for two-dimensional computations (plane or axisymmetric).

Compatibility: `COUP`, `LIAI`

Syntax:

```
"COQM"  ngroup*(  nco  nma  /LECTURE/  )
```

`ngroup`

Number of groups of shell and solid element connections.

`nco`

Number of the shell node linked to a solid element.

`nma`

Number of the solid node linked to a shell.

`/LECTURE/`

Reading procedure to input the other solid element nodes which are connected (no compulsory order).

Comments:

```
        M1  x---------
            I
  (shell)   I
  --------x x  M0 (nma)          R(i) : distance M0-Mi
         /  I                    D(i) : normal displacement
      nco   x  Mi                       of Mi
            I    (solid element)
       Mp   x----------
```

A ”shell-solid element” relation is represented by the following p+2 equations.

2 equations for the displacements:

U(1,nco) = U(1,nma)

U(2,nco) = U(2,nma)

p equations for the rotations of p other solid element nodes:

U(3,nco) = R(i) * D(i)

8.20 INTERFACES

Object:

This directive allows to define an interface between two lines or two surfaces. Link relations are created so that the velocity field is continuous through the interface. In the case of non-matching meshes on both sides of the interface, continuity is imposed in a weak sense.

This directive is very similar to the INTERFACE directive used in the sub-domain calculation framework.

Compatibility: `COUP`

Syntax:

```
"INTERFACE"   |[ "COMP"    ;
                   "MORTAR"  ;
                   "OPTIMAL" ]| <"TOLE" tole> ...

          ... |[ "SIDE"    ;
                 "SCOARSE" ;
                 "SFINE"   ]| /LECTURE/ ...

          ... |[ "SIDE"    ;
                 "SCOARSE" ;
                 "SFINE"   ]| /LECTURE/
```

`"COMP"`

Keyword declaring an interface with matching meshes.

`"MORTAR"`

Keyword declaring an interface with non-matching meshes, treated by the mortar method (see comment below).

`"OPTIMAL"`

Keyword declaring an interface with non-matching meshes, treated by the optimal method.

`tole`

Tolerance given to find matching nodes (default=1.E-3).

`"SIDE"`

Keyword introducing the support of both sides of the interface for `COMP` and `OPTI` cases (see note below).

`"SCOARSE"`

Keyword introducing the support of the side of the interface with coarse mesh in the `MORTAR` case (see note below).

`"SFINE"`

Keyword introducing the support of the side of the interface with fine mesh in the `MORTAR` case (see note below).

Comments:

There MUST NOT be any coincident nodes between the two sides of an interface.

When using the mortar method, the side of the interface whose mesh is used to discretize Lagrange multipliers has to be specified. It is the mesh introduced by the `SFINE` keyword, the other mesh being introduced by the `SCOARSE` keyword.

When using interfaces with non-matching meshes, so-called `CLxx` elements (see pages INT.90 and INT.100) have to be affected to meshes of both sides of the interface. These elements **must** be given the “phantom” material (`MATE FANT`) with density equal to zero.

The treatment of non-matching meshes with 3D solid elements is restricted to hierarchical meshes. In this case, the mortar method and the optimal method are identical, and a mortar interface has to be declared.

The **mortar** method may be used with any element types in 2D, but only with shell element types in 3D. When using the **mortar** method with linear interfaces (2-noded element sides), there must be at least one geometrical point that has the same coordinates, within the tolerance `tole` defined above, in the two facing meshes. This is necessary because the interface model uses the point’s coordinates internally in order to define a reference frame on the interface.

8.21 FLUID-STRUCTURE COUPLING (FLST)

Object:

This directive allows to specify the coupling between a fluid and a structure modelled by topologically independent meshes.

Compatibility: `COUP`

Syntax:

```
FLST <SLID> STRU /LECTS/ FLUI /LECTF/
           <DGRI> $[ HGRI hgri ; NMAX nmax ; DELE dele ]$
```

`/LECTS/`

List of structural **nodes** concerned. They must be declared as Lagrangian.

`/LECTF/`

List of fluid **elements** concerned.

`DGRI`

Dump out the grid of cells used for fast searching on the listing. For brevity, the print is done only the first time that the grid is computed.

`HGRI`

Specifies the size of the grid cell. Each cell has the same size in all spatial directions and is aligned with the global axes.

`NMAX`

Specifies the maximum number of cells along one of the global axes.

`DELE`

Specifies the size of the grid cell as a multiple of the diameter of the largest coupled fluid element. Element "diameters" are computed only along each global spatial direction and the maximum is taken. For example, by setting `DELE 4` the size of the cell is four times the diameter of the largest coupled fluid element. By default, i.e. if neither `HGRI`, nor `NMAX`, nor `DELE` are specified, the code takes `DELE 3`.

8.22 FLUID-STRUCTURE COUPLING (FLSR)

Object:

This directive allows to specify a “strong” coupling (`LINK COUP`) between a fluid and a structure modelled by topologically independent meshes. It is similar to `FLSW` (see page D.555) but uses a strong approach (constraint on velocity imposed by Lagrange multipliers) rather than a weak approach (direct application of the fluid pressure).

The present `FLSR` directive is (primarily) intended for use with Finite Elements (FE) modeling of the fluid. It can also be used with a node-centred Finite Volume (NCFV) discretization of the fluid domain, but *not* with cell-centred Finite Volumes (VFCC) in the fluid (use `FLSW` instead).

The fluid mesh may be either fully general (unstructured) or regular (structured), as specified by the `STFL` directive described on page C.68. In the latter case, the search operations are faster.

The FSI coupling is realized between structural points (ultimately, structural nodes) on one side, and *fluid entities* on the other side. The fluid entities are fluid nodes in this case, since in the FE method the velocities are discretized at the nodes of the FE.

The `FLSR` command should be typically utilized as a `COUP` type of link (strong coupling). Note, however, that a decoupled master/slave approach version of the `FLSR` algorithm also exists and can be activated by specifying `FLSR` within the (`LINK DECO`) directive. However, this part of the implementation is still incomplete and experimental. Note also that `LINK COUP FLSR` and `LINK DECO FLSR` are mutually exclusive: only one of such directives (at most) can be used in any given calculation.

As indicated by the brackets in the syntax, the `STRU` data block can be repeated at will, in order to define one or more FSI interaction (structure) zones, each with its own set of parameters. The `STRU /LECTS/` keyword *must* be the first one of each zone being defined.

Compatibility: `COUP`, `DECO`.

Syntax:

```
FLSR  |[ FLUI /LECTF/ ; STFL ]|
      $[ HGRI hgri ; NMAX nmax ; DELE dele ]$
      <DGRI>
      <BFLU bflu $[/LECTURE/]$>
      <DVOF dvof $[/LECTURE/]$>

    ( STRU /LECTS/
      $[ R r ; GAMM gamm ; PHIS phis ; GAMI gami ]$
      <FSCP fscp>
      <ADAP LMAX lmax <SCAL scal> >                 )
```

Basic fluid-related parameters

`FLUI`

The fluid mesh to be coupled with the structure is fully general (unstructured). The concerned elements are specified next.

`/LECTF/`

List of fluid **elements** concerned. The fluid mesh is unstructured.

`STFL`

The fluid mesh to be coupled with the structure is regular (structured). The concerned **elements** need not be specified. In fact, they are simply the elements generated by the `STFL` directive described on page C.68, which must in this case have been specified previously in the input file.

Fast search of coupled fluid entities

The next three keywords (`HGRI`, `NMAX` or `DELE`) are used to set the size of the spatial grid used for the *fast search* of fluid nodes contained within the influence domain of the structure. Fast search speeds up the calculation and is *absolutely essential* in medium and even more in large size simulations. For this reason, fast search is *always active* in the present FSI model. Note that this may be unlike other types of search in EPX. For example, in the pinball contact model (`PINB`) fast search of pinballs contact is *not* active by default (an option has to be activated).

By default, i.e. if neither `HGRI`, nor `NMAX`, nor `DELE` are specified, the code takes `DELE 1.01`.

A (regular) spatial grid is built up and used for the fast search. The fluid nodes contained in a cell are tested for inclusion in the structural influence subdomains contained either in the same cell or in a direct neighbor cell (there are up to 8 such cells in 2D, up to 26 cells in 3D). The cell grid can be optionally dumped out on the listing by the `DGRI` keyword.

For the calculation to be as fast as possible, the fast search grid must have the minimum size ensuring correctness of results, i.e. such that a (barely) sufficient number of interacting entities is detected, and thus no spurious fluid passage occurs across the structure. If h_F denotes the size of the fluid mesh and h_S the size of the structure mesh, then the grid size h_G must be:

$$h_G = \phi \cdot \max(h_F, h_S) \tag{81}$$

where $\phi > 1$ is a safety factor. A value $\phi = 1.01$ should be sufficient. Since a single grid is used for the search over the whole computational domain, h_F and h_S in the above expression must be the *maximum* sizes of the fluid and structural elements which are susceptible of interacting, i.e. which belong to the `/LECTF/` and `LECTS/` sets defined above, respectively.

In calculations *without adaptivity* one has normally $h_F < h_S$ for accuracy reasons (especially if shells are used to discretize the structure), so that the grid size is (normally) dictated by the largest coupled structural element. For the case of adaptive calculations, see the Remarks at the end of this manual page.

`HGRI`

Specifies the size of the fast search grid cell. Each cell has the same size in all spatial directions and is aligned with the global axes.

`NMAX`

Specifies the maximum number of cells along one of the global axes.

`DELE`

Specifies the size of the fast search grid cell as a multiple of the length of the largest coupled **structural** element. Element "diameters" are computed only along each global spatial direction and the maximum is taken. For example, by setting `DELE 2` the size of the cell is two times the length of the largest coupled structural element. By default, i.e. if neither `HGRI`, nor `NMAX`, nor `DELE` are specified, the code takes `DELE 1.01`.

`DGRI`

Dump out the grid of cells used for fast searching on the listing. For brevity, the print is done only the first time that the grid is computed.

Flux blocking parameters

Next come some additional parameters for the blocking of fluxes.

`BFLU`

Type of treatment of numerical fluxes (density and energy, but **not** momentum) in fluid models, when used in conjunction with the present `FLSR` directive. This directive applies to fluids modelled by multicomponent node-centered Finite Volumes (NCFV, i.e. MCxx 'elements') and to any fluid modelled by CEA Finite Elements.

In both cases, the value 0 (default) indicates that fluxes are freely computed.

For MCxx elements, the value 1 indicates that fluxes are blocked between two fluid nodes (or points) which are both within the influence domain of the structure. For CEA fluid elements, it indicates that the fluxes are blocked through a face for which one node at least is within the influence domain of the structure.

For MCxx elements, the value 2 indicates that fluxes are blocked between two fluid nodes (or points) of which at least one lies within the influence domain of the structure. For CEA fluid elements, it indicates that the fluxes are blocked through a face for which all nodes are within the influence domain of the structure.

With CEA fluid elements, the defined treatment can be restricted to the influence domain of a subset of structure elements using the `LECTURE` procedure.

Combination of `FLSR` with the VOFIRE algorithm

The next keyword allows to fine-tune the interaction between `FLSR` FSI algorithm and the VOFIRE anti-dissipation algorithm (`VOFI`) in case of need.

`DVOF`

Locally deactivate VOFIRE anti-dissipative scheme when used in conjunction with the present `FLSR` directive.

The value 0 (default) indicates that no deactivation occurs.

The value 1 indicates that VOFIRE anti-dissipation is deactivated for fluid elements, for which one node at least is within the influence domain of the structure.

The value 2 indicates that VOFIRE anti-dissipation is deactivated for fluid elements, for which all nodes are within the influence domain of the structure.

The defined deactivation can be restricted to the influence domain of a subset of structure elements using the `LECTURE` procedure.

Structural influence domain(s)

The following block of data, introduced by the keyword `STRU`, can be repeated any number of times (but it must be specified at least once) to define one or more FSI zones, each with different interaction parameters. For each such zone:

`STRU`

Introduces the structure mesh to be coupled with the fluid. The concerned elements are specified next.

`/LECTS/`

List of structural **elements** concerned. All their nodes must be declared as Lagrangian.

The next four keywords (`R`, `GAMM`, `PHIS` or `GAMI`) are used to set the **size** (thickness) of the **structural influence domain** surrounding the structure elements defined above by `/LECTS/`. All fluid nodes contained within this influence domain will be coupled to the structure.

Therefore, the correct size of the influence domain is related to the size of the fluid mesh in the vicinity of the embedded structure. On one hand, if the influence domain is too thin, then some interactions between the structure and the fluid enetities might be overlooked, thus resulting in spurious passage of fluid across the structure (*leakage*). On the other hand, if the inluence domain is too thick, too much fluid will be interacting with the structure (excessive added mass effect). The optimal value is then the minimum value which ensures structure tightness (no leakage).

By default, i.e. f neither `R` nor `GAMM` nor `PHIS` nor `GAMI` are specified, the code performs an automatic determination of influence spheres at each coupled structural node by using the default value of `GAMM` ($\gamma = 1.01$). For the choice of `R`, `GAMM`, `PHIS` or `GANI` in adaptive calculations see the `ADAP` keyword below and the comments at the end of this page.

`R`

Prescribed (fixed) radius R of influence spheres at each coupled structural node. In the special, but frequent, case of a uniform structured fluid mesh (uniform square or cube elements) it is suggested to take R slightly larger than the semi-diagonal of a fluid element. This means that, for a 2D uniform square fluid mesh of side L_Φ one should take $R = 0.71L_\Phi$ while for a 3D uniform cube fluid mesh of side L_Φ one should take $R = 0.87L_\Phi$.

`GAMM`

Coefficient γ for the automatic determination of influence spheres at each coupled structural node, based on the size of the enclosing fluid element (which must thus be found by the code by means of a fast search algorithm, see the remarks at the end of this manual page). The sphere radius is $R = \gamma R_F = \gamma\delta L_\Phi$ where L_Φ is the local length (size) of the fluid mesh, δ is a coefficient related to the space dimension d of the problem ($\delta = \frac{\sqrt{d}}{2}$, i.e. about 0.71 in 2D and about 0.87 in 3D calculations). The quantity indicated as R_F above is the “natural” size of the sphere radius, i.e. the radius of a sphere (circle in 2D) which exactly encompasses all nodes of a regular element (regular cube in 3D or regular quadrilateral in 2D). By default it is $\gamma = 1.01$. This value should ensure “tightness” of the structure, at least for a regular mesh. By increasing the value, tightness is safer but the amount of fluid “attached” to the structure also increases. By decreasing the value, some local spurious passage of fluid across a solid structure might occur.

`PHIS`

Coefficient ϕ_s for the automatic determination of influence spheres at each coupled structural node. The sphere radius is equal to ϕ_s times the minimum structural element length at the concerned node. By default it is $\phi_s = 0.3$. This option should be rarely used. It is advisable to use `GAMM` instead.

`GAMI`

Same as `GAMM` but radius is computed only at the initial step, that is, the radius is *not* updated during the calculation. This may be convenient (to save some CPU) in calculations with Eulerian fluid mesh (that never changes) and without adaptivity.

Additional coupling parameters

Next come some additional parameters for the the type of coupling.

`FSCP`

Type of coupling between fluid nodes and corresponding structural points, when used in conjunction with the present `FLSR` directive. The value 0 (default) indicates that coupling occurs only in the direction normal to the structure. The value 1 indicates that coupling occurs along all spatial directions.

FSI-driven adaptivity

Finally, there are some optional keywords related to automatic (FSI-driven) adaptivity of the fluid mesh near the structure.

`ADAP`

Activates mesh adaptivity for automatic refinement and un-refinement of the fluid mesh specified by `/LECTF/` in the vicinity of the structure specified by `/LECTS/`. Note that this type of mesh adaptivity is at the moment incompatible with other types of adaptivity such as those activated by the `WAVE` or `INDI` directives.

`LMAX`

Introduces `lmax`, the desired maximum adaptive refinement level $L^{\max}$ of the fluid mesh in the vicinity of the structure. This value should be greater than 1, since level 1 is attributed to the base mesh (no refinement). Each level corresponds to a halving of the mesh size with respect to the immediately previous level.

`SCAL`

Introduces `scal` (s), an optional scaling factor to be used in the determination of fluid elements to be refined. By default `scal` is equal to 1. When scaling the structural influence domain by successive powers of two in order to identify, at each refinement level, the fluid elements to be refined or un-refined, the code finally multiplies the result by this factor. Using a value of s greater than one, e.g. 1.5 or 2, correspondingly enlarges the zone of fluid mesh around the structure which is refined and this may result in a smoother mesh transition (for example, as an alternative to the option `OPTI ADAP RCON`). Note, however, that s has no influence on the size of the structural influence domain used for the final search of fluid entities (fluid nodes or fluid cell interfaces) interacting with the structure. This search is always done by the smallest influence domain $R_{L_{\max}} = R_1/2^{L_{\max}-1}$, i.e. *without* taking into account the s factor.

In **FSI adaptive calculations**, the size of the structural influence domain specified in input by `R`, `GAMM` or `PHIS` (`GAMI` is not appropriate with adaptivity) is related to the *base* (i.e. the coarsest) fluid mesh size, not to the refined one (for the user's convenience) and is then scaled automatically by the code whenever necessary, up to the maximum chosen refinement value given by the `ADAP LMAX` keyword. Therefore, in order to try out different adaptive refinement levels in the vicinity of the structure the user needs only to change `LMAX` in the input directive (all other parameters `R` etc. remain the same).

In **FSI adaptive calculations**, that is when the `FLSR ADAP LMAX` optional keyword has been specified, one is **certain** that the fluid mesh in the vicinity of the structure will be constantly refined to the maximum level (minimum size) specified for the fluid (`LMAX`), given by:

$$h_F^{\text{refined}} = h_F^{\text{base}}/2^{L_{\max}-1} \tag{82}$$

For this reason, in the equation (81) for the determination of the grid size `HGRI` (h_G) one can use h_F^{refined} instead of the base fluid mesh $h_F^{\text{base}} = h_F$, obtaining thus:

$$h_G = \phi \cdot \max(h_F^{\text{refined}}, h_S) \tag{83}$$

One should make sure to use (83) instead of (81) since it is likely to be $h_F^{\text{refined}} < h_S$, while it is typically $h_F > h_S$, so this may lead to important savings of CPU time.

Remarks:

In case of automatic determination of influence spheres based on the `GAMM` keyword in conjunction with an **unstructured** fluid grid, a fast search over the coupled fluid elements is needed in addition to the normal fast search over the coupled structural elements. Scope of this second search is to detemine, for each structural node, which is the fluid element currently containing the node. For this purpose, the code uses a fast search algorithm by means of the same parameters (`DGRI`, `HGRI`, `NMAX`, `DELE`) specified above for the search over structural elements. Note, however, that as concerns this second search if `DELE` is specified it refers to the size of the fluid element rather than to the size of the structural element. However, if a **structured** fluid grid is specified, then no additional search is needed because the containing fluid element can be detected directly.

Make sure you consult the additional **options** related to the functioning of the `FLSR` model in pages H.155 and H.160.

References

The `FLSR` model was first described in report [250]. A short description of the model is also given in reference [244]. Finally, reference [294] describes the use of `FLSR` in conjunction with Node-Centered Finite Volumes (NCFV).

8.23 FLUID/IMMERSED STRUCTURE INTERACTION (FLSX)

Object:

This directive allows to specify the coupling between a fluid and a structure modelled by topologically independent meshes. The fluid can either be in finite elements or in finite volumes. This directive is more recent than FLSR and FLSW directive and is expected to provide more accurate solutions. At this time, the fluid mesh must have all of its nodes declared as EULE (i.e. Eulerian, **not** ALE). This directive only works in a 3D space. At this time, only thin structures are supported (the mesh of the structure must only contain shell elements).

Compatibility: `COUP` (for FE fluid meshes), `DECO` (for FV fluid meshes).

Syntax:

```
FLSX     STRU /LECTS/
         FLUI /LECTF/
        <LSPC lspc>
        <LORD lord>
```

`STRU`

Introduces the structure mesh coupled with the fluid. This mesh can be meshed totally independently from the fluid mesh. The concerned elements are specified next.

`/LECTS/`

List of the **structural elements** concerned. All their nodes must be declared Lagrangian in the `GRIL` directive.

`FLUI`

Introduces the fluid mesh coupled with the structure. The concerned elements are specified next.

`/LECTF/`

List of the **fluid elements** concerned. All their nodes must be declared Eulerian in the `GRIL` directive (note that nodes not explicitly mentioned in the `GRIL` directive are Eulerian by default).

The two options `LSCP` and `LORD` are effective only if the fluid is treated with finite elements. In this case, the FLSX coupling results from a finite-element discretization of the constraint:

$$\int_\Gamma [(v_s(x) - v_f(x)) \cdot n_s(x)]\, \lambda(x)\, dx,\ \forall \lambda \in L^2(\Gamma)$$

where Γ is the mid-surface of the structure, v_f and v_s the fluid and structure velocity respectively, n_s the normal to Γ, and λ a test function. The two options `LSCP` and `LORD` specify the finite-element space on which the Lagrange multiplier related to the test function λ is discretized. If

LSCP is set to 0 (default), the Lagrange multiplier is defined on a finite element space generated from the mesh of the structure. If LSCP is set to 1, the Lagrange multiplier is defined on the "restriction" to the structure mesh at each time step of a finite-element space generated from the mesh of the fluid. LORD, which can be 0 or 1 (default), is the polynomial degree of interpolation used to generate the finite-element space for the Lagrange multiplier.

LSCP

Finite-elements fluid only.
Specifies which mesh is used to generate a finite-element space for the lagrange multiplier enforcing the coupling. If set to 0 (default), the mesh of the structure is used. If set to 1, the mesh of the fluid is used.

LORD

Finite-elements fluid only.
Specifies the polynomial degree of interpolation used to generate the finite-element space for the Lagrange multiplier. If set to 0, constant-value elements are used. If set to 1 (default), linear elements are used.

8.24 FLUID-STRUCTURE INTERACTIONS

Object:

This is aimed at linking together the degrees of freedom at the boundary of 2 parts of the structure:

- one part meshed with shells or solid elements;

- one solid element part meshed with a fluid material.

This possibility exists for two- and three-dimensional computations.

This connection may be expressed in two ways:

- By using specific fluid-structure elements FS2D or FS3D: directive "FS";

Without using fluid-structure elements: directive "FSA".

Compatibility: `COUP`, `LIAI`

Comments:

The first directive is available for a Lagrangian or an ALE calculation. Instead, the second is only valid for ALE problems.

The elements FS2D and FS3D behave like incompressible fluids. In order to avoid spurious effects (related to the flow along the boundary), the thickness of this boundary zone must be as small as possible, and possibly 0.

The "FS" directive is described in the next page, while for the "FSA" directive please consult page D.260.

8.24.1 FLUID-STRUCTURE CONNECTION (FS)

Object:

The contact between the fluid and the structure is modelled by elements FS2D and FS3D. This directive is available for Lagrangian and ALE calculations.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"FS"  /LECTURE/
```

`/LECTURE/`

Numbers of the FS2D, FS3D or FS3T elements composing the boundary.

Comments:

The FS2D, FS3D and FS3T elements are in fact incompressible fluids. In order to avoid any parasitic effects (due to a potential flow along the boundary), the thickness of that boundary zone has to be as small as possible and even equal to zero.

It is strongly advised to use the new directives "FSA" and "FSR".

8.25 UNILATERAL RESTRAINT [OBSOLETE]

Foreword:

This directive is now obsolete, use the IMPACT directive described below (page D.170) which allows to compute at the same time the shock parameters (impulse, reaction, ...).

8.26 IMPACT

Object:

As for unilateral restraints, certain nodes of the structure must remain in the same half-space. However, the boundary is linked to the position of a material point and can be mobile. Impacts are possible in 2D or 3D.

The method of Lagrange multipliers may be activated by adding the keyword "LAGC" in the problem type (see page A.30). This method allows to couple the calculation of contact forces with the permanent connections (relations, boundary conditions, ...). It also allows to take into account the form of a projectile 'nose' in the case of a non-deformable projectile.

Compatibility: `COUP`, `DECO`, `LIAI`

Syntax:

```
"IMPACT" "DDL" iddl "COTE" alpha       ...

          ... < "NEZ" |[ "HEMI" "RAYO" rayon1                   ;
                         "PLAT" "LARG" larg1  < "LONG" long1 > ;
                         "CONE" "LARG" larg2  < "ANGL" beta  > ;
                         "CYLI" "RAYO" rayon2 ]| >

          ... <"FROT" "MUST" must "MUDY" mudy "GAMM" gamm >

          ...  "PROJ" /LECTURE/  |["CIBL" /LECTURE/ ; "CIBD" /LECTURE/]|
```

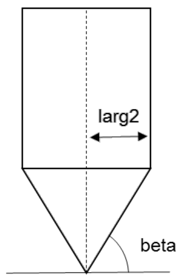


Figure 5: Conical impacter

`iddl`

Component concerned. Indicates the first direction.

`alpha`

Enables one to choose between the 2 half-spaces separated by the plane of equation $x = x_0$. It must be an integer. Typically, one uses either $+1$ or -1.

`rayon1`

Radius of a projectile with hemispherical nose.

`larg1`

Width of a projectile with rectangular flat nose. It is in the second direction obtained by circular permutation of the Euclidean frame.

`long1`

Only in 3D, length of the rectangular projectile nose. It is in the third direction (obtained by circular permutation).

`larg2`

Width of a projectile with a conical nose.

`beta`

Half-angle of the cone (in degrees).

`ray2`

Radius of the projectile with cylindrical nose.

`FROT`

Introduces the (optional) declaration of friction characteristics.

`must`

Static friction coefficient μ_s: $(0 < \mu_s < 1)$.

`mudy`

High-velocity (dynamic) friction coefficient μ_d: $(0 < \mu_d < \mu_s < 1)$.

`gamm`

Coefficient γ of the friction law. This law is similar to the one used for sliding lines and sliding surfaces (see page D.180). The friction coefficient μ varies from μ_s to μ_d as the relative tangential velocity V_r of the two bodies increases. The passage is governed by the exponential decay law: $\mu = \mu_d + (\mu_s - \mu_d)e^{(-\gamma V_r)}$.

`PROJ`

Introduces the number of the material point located on the boundary (if relevant, it is the tip of the projectile "nose").

`CIBL`

Introduces the numbers of the nodes which are submitted to the impact.

`CIBD`

Used for ELDI elements only to take into account the elements' radius for contact detection. Introduces the numbers of the discrete elements which are submitted to the impact.

Comments:

The boundary plane is perpendicular to one of the axes of the general coordinate system. This axis is defined by the component `iddl`, just as for unilateral contacts.

The half-space admissible for a point M (of the target) of coordinate x is such that, if x_0 is the abscissa of the material point:

$$\alpha(x - x_0) \geq 0$$

These impacts are available in 2-D or 3-D.

It is suggested to displace the projectile in such a way that the impact occurs after at least one time step.

Do not forget to dimension the keywords "IMPA" and "PSIM" correctly, see (page A.80).

The "NEZ" directive is available **only** with the LAGC option. When it is present, only those "CIBLE" nodes which are in contact with the geometric boundary thus defined, will be considered.

Without the option "LAGC":

It should be noted that the nodes which undergo shocks may not be connected by other imposed relations (LIAISONS).

The shock between the material point (projectile) and the point(s) of the target is treated elastically. The energy and impulse will therefore be conserved during the impact. This requires a modification of the time step so that the impact instant coincides with the beginning of a time step.

This effect introduces a small error in the work of forces during the impact, of the order: dW =F * v * dt. It is therefore advisable to shorten the time step in order to obtain better energy conservation.

These recommendation are irrelevant with the option "LAGC".

8.27 GAPS (”JEUX”)

Object :

This is an impact between the (uncoupled) nodes along the direction defined by the user. This directive is available in 2D and 3D. In 3D, the gap must be defined also along a direction normal to the first one.

Compatibility: `LIAI`

Syntax:

```
In 2D:

  "JEUX"    "AXE1" a1x a1y       "JEU1"  jeu1
     ...    "NOE1"  /LECTURE/
     ...    "NOE2"  /LECTURE/

In 3D:

  "JEUX"    "AXE1" a1x a1y a1z   "AXE2" a2x a2y a2z
     ...    "JEU1"  jeu1     "JEU2" jeu2a jeu2b
     ...    "NOE1"  /LECTURE/
     ...    "NOE2"  /LECTURE/
```

`a1x,a1y (,a1z)`

Components of the first vector of the local reference.

`a2x,a2y,a2z`

Components of the second vector of the local reference (3D only).

`jeu1`

Gap along the direction of the first vector.

`jeu2a,jeu2b`

Gap along the direction of the second vector (3D only).

`NOE1`

Announces the first group of nodes.

`NOE2`

Announces the second group of nodes.

Comments:

To each node P1 belonging to the first group, is associated one node P2 of the second group, and reciprocally. In 3D, in the local frame of origin P1, defined by vectors AXE1 and AXE2, the impact occurs when: 1) the abscissa of point P2 is less than jeu1; 2) and the ordinate of point P2 lies between jeu2a and jeu2b.

In 2D, in the local reference of origin P1 of which AXE1 is the first axis, the impact occurs when the abscissa of point P2 is less than jeu1.

The direction defined by vector(s) AXE1 (or AXE2) does not change during the calculation.

Do not forget to dimension, by keyword ”NBJEUX” (see page A.80).

8.28 BUTEE: Limited displacement

Object :

This directive allows limiting the displacement of a node along the direction defined by the user, once a prescribed distance is covered. This directive can be repeated several times. It is operational in MPI.

Compatibility: `LINK COUP`

Syntax:

```
"BUTEE"  "DIRE" vx vy vz
         "DMAX" dmax
         /LECTURE/
```

`vx,vy,vz`

Components of the vector indicating the direction of blocking.

`dmax`

Distance above which the displacement is blocked in the prescribed direction.

`/LECTURE/`

Name of the node for which the displacement is to be limited.

8.29 GLIS: Sliding lines and sliding surfaces

Object:

This directive defines one or more couple(s) of mutually sliding lines (2D) or sliding surfaces (3D). In 3D the "master" and "slave" objects may be composed of continuum elements or shells. In 2D they are composed by an ordered series of nodes.

In 3D, a self-contact (or auto-contact) model is available. A self-contacting surface is both master and slave at the same time.

When a master surface is composed by shells (`CMAI`) and the contact should be checked only on one side of the shell, it is necessary to define this side (independently from the inherent orientation of the shell elements) by declaring the "external" or the "internal" half-space of each shell element by using the position of a node or of a point in space (see `EXTE` or `INTE` below).

However, this method is not always practical, especially in the presence of shells with large curvature, comples shapes, junctions etc. If contact should be possible from *both* sides of a shell, then *two* sliding surfaces, one using the `DIRE` (direction of the geometric normal to the shell) and the other using the `REVE` keywords (reverse direction) can be defined, as an alternative to using the `EXTE` or `INTE` method. Note that in this case (i.e., with `DIRE` or `REVE`), the keyword `SELF` is mandatory.

General options for this directive are available, in particular to define the method for calculating facet normals (see H.160, Section 12.18).

Compatibility: `COUP`, `DECO`, `LIAI`

`LIAI` only: the method of Lagrange multipliers may be activated by adding the keyword `LAGC` in the problem type (see page A.30, Section 4.4). This method allows to couple the computation of contact forces with the permanent connections (relations, boundary conditions, ...).

Penalty method is only available in 3D with `DECO` keyword. If not activated, the same uncoupled algorithm is used as with `LIAI` and `LAGC` deactivated (see above and comments below).

Syntax:

```
"GLIS" nglis * ( < "FROT" "MUST" must "MUDY" mudy "GAMM" gamm >
                 < "PENA" > < "PFSI" rfac > < "PGAP" rgap >
                 < "SELF" > < "ELIM" < "UPDT" /CTIM/ > >
                 < "COHE" > < "MULT" >
                 |[ |[ "MAIT" <"NODE"> /LECT/ ;
                       "CMAI" /LECT/ |[ "EXTE" $ /LECT/ ; "POIN" x y z $ ;
                                        "INTE" $ /LECT/ ; "POIN" x y z $ ;
                                        "DIRE" ;
                                        "REVE"
                                    ]|
                    ]|
                    ![ |[ "ESCL" ; "CESC" ; "PESC" <"PESA"> ]|  /LECT/ ]! ;
                    "AUTO" "FACE" iface /LECT/                    ;
```

```
                    "DECO" <"SYME"> <"DBLE"> <"ELIM" <"UPDT" /CTIM/>>
                           /LECT/
                 ]|
                 < "COPT" 1 >
               )
```

`nglis`

Number of couples of lines (or surfaces) (`MAIT`, `ESCL`) or `AUTO`.

`FROT`

Introduces the (optional) declaration of friction characteristics.

`must`

Static friction coefficient μ_s: $(0 < \mu_s < 1)$.

`mudy`

High-velocity (dynamic) friction coefficient μ_d: $(0 < \mu_d < \mu_s < 1)$.

`gamm`

Coefficient γ of the friction law. This law is similar to the one used for the `IMPA` sirective (see page D.170). The friction coefficient μ varies from μ_s to μ_d as the relative tangential velocity V_r of the two bodies increases. The passage is governed by the exponential decay law: $\mu = \mu_d + (\mu_s - \mu_d)e^{(-\gamma V_r)}$.

`PENA`

`DECO` only: toggles the use of penalty method to compute contact forces (see comment below).

`rfac`

`DECO` only: scale factor for the automatically computed contact stiffness (see comment below).

`rgap`

Value of the gap between master surface and slave nodes (3D only). Default value is zero in the case of solid master elements and half of shell's thickness in the case of shell master elements.

`SELF`

Toggles self-contact treatment for shells (3D only, see comment below).

`ELIM`

Toggles the elimination of the not visible faces (for each slave node) of the master elements in the detection of the contact (sometimes necessary option when the 3D master elements contain only a single element in the thickness). This elimination is only once realized during the initialization of the problem. The keyword UPDT can be used to introduce a regular update of this sorting. Indeed, the relative movement of the various elements of structure can require to redefine for each slave node the not visible faces of the master elements.

`COHE`

This keyword enters within the framework of the automatic separation of elements (See page A.63, Section 4.6.1, keyword `DECO`). Compulsory to update the list of the sliding surfaces and the list of the slave nodes.

`MULT`

This keyword activates an option allowing the writing of several contact connections on the same slave node as long as these connections have sufficiently different directions. This option is very useful in the presence of corners on the master surface.

`MAIT /LECTURE/`

Numbers of the master nodes (in 2D) or numbers of the continuum elements (in 3D).

`MAIT NODE /LECTURE/`

In 3D continuum elements: numbers of the master nodes belonging to the sliding surface. Please note, in the presence of erosion, this way of declaring the master elements does not allow the internal elements of the volume to be taken into account in the contact if the elements on the surface become eroded.

`CMAI /LECTURE/`

Numbers of the master elements of the structure meshed by shell elements ("COQUES") (in 3D).

`EXTE /LECT/`

A node defining (located in) the half-space external to the shell.

`EXTE POIN x y z`

Coordinates of a point defining (located in) the half-space external to the shell.

`INTE /LECTURE/`

A node defining (located in) the half-space internal to the shell.

`INTE POIN x y z`

Coordinates of a point defining (located in) the half-space internal to the shell.

`DIRE /LECTURE/`

The half-space external to the shell is in the direction of the geometric normal to the element. The `DIRE` and `REVE` keywords are typically used to define *two* sliding surfaces for the *same* set of master shells, one using the geometric normal direction and the other using the opposite direction. The `SELF` keyword is mandatory in the definition of a sliding surface using either `DIRE` or `REVE`.

`REVE /LECTURE/`

The half-space external to the shell is in the opposite direction of the geometric normal to the element. The `DIRE` and `REVE` keywords are typically used to define *two* sliding surfaces for the *same* set of master shells, one using the geometric normal direction and the other using the opposite direction. The `SELF` keyword is mandatory in the definition of a sliding surface using either `DIRE` or `REVE`.

`ESCL /LECTURE/`

Numbers of the slave nodes (in 2D) or numbers of the slave elements (in 3D).

`CESC /LECTURE/`

Numbers of the slave elements (in 3D) if the structure is meshed by shell elements (COQUES).

`PESC /LECTURE/`

3D only. Numbers of the slave nodes.

`PESA`

Optional keyword to choose the strategy used to define the slave nodes updating strategy in adaptivity. It is only related to cases with adaptivity in the contacting parts, where the (base) slave nodes are defined directly via the `PESC` keyword (not via a set of slave elements). A list of base slave elements must be built internally because, unlike for elements, there is no notion of descendent node(s) of a base node in adaptivity. By default a base element is a base slave element if at least one of its nodes is a base slave node in the list `PESC /LECT/` given by the user. When the `PESA` keyword is specified after `PESC`, then a base element is a base slave element if all of its nodes are base slave nodes in the list `PESC PESA /LECT/` given by the user.

`AUTO FACE iface`

Number (local) of the face of the elements submitted to self-contact.

`DECO /LECTURE/`

Numbers of the continuum elements (only CUB8). The keyword "DECO" can appear only once and must be positioned in last position. The keyword "DECO" enters within the framework of the automatic separation of elements (See page A.63, Section 4.6.1, keyword `DECO`). This directive allows to treat self-contact and contacts between various pieces of wood coming from the automatic separation of elements. The creation of a new node causes the activation of a coupled link. In this link the slave node is the new node of the wood and the master faces are the free faces of the wood except the faces containing the new node and the faces already eliminated by the previous links. During the initialization NPTMAX_DECO (See page A.63, Section 4.6.1, keyword `DECO`) links are created but not actived (option by default). For each new node a coupled links is actived. More explanations can be found in [928].

`SYME`

With this keyword the master faces of each new actived coupled link are the free faces of the wood except the faces containing the new node.

`DBLE`

With this keyword (2*NPTMAX_DECO) links (See page A.63, Section 4.6.1, keyword `DECO`) are created during the initialization but not actived. For each new node two coupled links are actived. In the first link the slave node is the new node. In the second link the slave node is the initial node.

`ELIM`

With this keyword the not visible faces (for the new slave node) of the master elements are eliminated in the detection of the contact. This elimination is only once realized during the initialization of the new actived link (option by default). The keyword UPDT can be used to introduce a regular update of this sorting. Indeed, the relative movement of the various elements of structure can require to redefine for the slave node the not visible faces of the master elements.

`COPT 1`

If `COPT 1` is activated, the thickness of the slave surface is taken into account.

Comments:

Sliding lines (2D):

The order of the nodes determines the orientation of the contour and defines in that way the inner side of the two domains after a rotation of +90 degrees.
Example. We consider DOM1 and DOM2, in contact on P1P2 and P6P5.

```
P4--------P3
|   DOM1   |
P1--------P2
P5--------P6
|   DOM2   |
P8------- P7
```

```
GLISS   1
MAIT     LECT P1P2 TERM
ESCL     LECT P6P5 TERM
```

where P1P2 (respectively P6P5) is an oriented line the first node of which is P1 (respectively P6) and the last one is P2 (respectively P5).

The *slave* nodes must be located just at or above the boundary of the region defined by the line of the *master* nodes.

Without the `LAGC` option, it is preferable that the two lines have similar mesh densities. But, if the *master* domain presents a high convexity, it is better to have *master* segments which are a bit longer than the *slave* segments in front of them. This is aimed at minimizing the interpenetration of the two domains. It is suggested to fix a point of the master line (blocked material point) to avoid the interpenetration of the two domains.

With the `LAGC` option, the recommendations of the preceding paragraph are irrelevant.

When the “erosion” algorithm is activated (See page A.30, Section 4.4, keyword `FAIL`), the sliding surfaces are updated at each time step by eliminating the failed elements.

Sliding surfaces (3D):

For the sliding surfaces, the master and slave entities are defined by the elements composing them (possibly these are GIBI objects). If continuum elements are used, then it is not necessary to define the "inner" or "outer" sides of such entities. However, when shell elements are used, it is mandatory to define the outer half-space of the shell structure by choosing a node, whose coordinates are used to identify the half-space. This method is not always practical, e.g. with shells of complicated shape, of large curvature, with junctions, etc. Alternatively, *two* sliding surfaces may be declared, one with the `DIRE` and the other with the `REVE` keyword, using the *same* shell object as master surface, and by specifying the `SELF` keyword for each of these.

The `SELF` keyword is necessary if contact on both sides of a shell should be considered with the same set of slaves (typically, the nodes of the shell itself). It prevents contact from being detected if a slave node has penetrated the shell by an amount greater than the gap (see `PGAP` keyword). Without this, each slave node would initially be found in contact with either side of the shell.

With the `MAIT NODE` option, the master entity must be defined by the nodes belonging to the sliding surface.

It is not admitted to define master objects (nor slave objects) formed by continuum and shell elements at the same time.

Remark (2D and 3D):

The sliding nodes may not be linked by other imposed relations (LIAISONS), except in the case where the treatment of sliding lines (or surfaces) is done by the method of Lagrange multipliers (option `LAGC`).

Self-contact:

This directive indicates that the surface formed by the set of faces defined by the user may be in contact. This surface is both master and slave at the same time.

Penalty method:

When using the penalty method to compute contact forces, contact stiffness is computed automatically from the stiffness of master elements using the following formulae :

$$k = r_{\text{fac}} \frac{GS^2}{V}$$

in the case of solid master elements, with :

G : bulk modulus of master element's material,

S : area of contacting face,

V : volume of master element.

$$k = r_{\text{fac}} \frac{GS}{L}$$

in the case of shell master elements, with :

G : bulk modulus of master element's material,

S : area of master element,

L : maximum length of master element's edges.

8.30 METHOD OF PARTICLES AND FORCES

Object:

This directive activates the (internal) interactions occurring among a set of particles ("billes") representing a soft body, according to the so-called Method of Particles and Forces (MPEF).

Optionally, the user may require that the particles also interact with some structure, composed either of continuum or of shell elements. By omitting the definition of the structure, interaction occurs only between the particles themselves.

Compatibility: `LIAI`

Syntax:

```
"MPEF" nbpef * (     "BILL" /LECTURE/
                < $[ "STRU" /LECTURE/                     ;
                     "COQU" /LECTURE/ "EXTE" /LECTURE/ ]$ > )
```

`nbpef`

Number of pairs (`BILL`, `STRU`) or (`BILL`, `COQU`) or of single `BILL` groups (in case no structure is specified).

`"BILL" /LECTURE/`

Numbers of the nodes belonging to the `BILL` elements.

`"STRU" /LECTURE/`

Numbers of the "master" elements of the solid structure, meshed by continuum elements.

`"COQU" /LECTURE/`

Numbers of the "master" elements of the solid structure, meshed by shell elements.

`"EXTE" /LECTURE/`

Number of a node defining the "external" half-space to the solid shell structure. Here "external" means simply the side of the shell onto which the particles are going to impact. If the impact is going to occur on both sides of the shell, or if the shape of the shell is such that there exists no point that can be used to uniquely define the "external" space (think e.g. of a spherical structure impacted from outside the sphere), the present algorithm is inappropriate.

Comments:

If the structure domain presents a large convexity, it is advisable that the faces of the elements of the structure be longer than the diameter of the neighbouring particles. This in order to minimize the interpenetration between the two domains.

The data relative to this method are similar to those of the SPH method, described on page D.187.

8.31 SMOOTHED PARTICLE HYDRODYNAMICS METHOD (SPH)

Object:

This directive activates the (internal) interactions occurring among a set of particles (“billes”) representing a soft body, according to the so-called Smoothed-Particle Hydrodynamics (SPH) method.

Optionally, the user may require that the SPH particles also interact with some structure, composed either of continuum or of shell elements. By omitting the definition of the structure, interaction occurs only between the particles themselves.

If a structure is specified in the directive described below, the interaction between the particles and the structure is treated by an algorithm of the ‘sliding surfaces’ type. The code offers also other alternative (more general and more robust) methods to describe the interaction between the SPH particles and a structure, see comments below.

Compatibility: `LIAI`

Syntax:

```
"SPHY" nbpef * (     "BILL" /LECTURE/
               < $[ "STRU" /LECTURE/                   ;
                    "COQU" /LECTURE/ "EXTE" /LECTURE/ ]$ > )
```

`nbpef`

Number of pairs (`BILL`, `STRU`) or (`BILL`, `COQU`) or of single `BILL` groups (in case no structure is specified).

`"BILL" /LECTURE/`

Numbers of the nodes belonging to the `BILL` elements.

`"STRU" /LECTURE/`

Numbers of the “master” elements of the solid structure, meshed by continuum elements.

`"COQU" /LECTURE/`

Numbers of the “master” elements of the solid structure, meshed by shell elements.

`"EXTE" /LECTURE/`

Number of a node defining the “external” half-space to the solid shell structure. Here “external” means simply the side of the shell onto which the particles are going to impact. If the impact is going to occur on both sides of the shell, or if the shape of the shell is such that there exists no point that can be used to uniquely define the “external” space (think e.g. of a spherical structure impacted from outside the sphere), the present algorithm is inappropriate. In such cases the user may utilize one of the alternative contact models mentioned in the comments below.

Comments:

The data relative to this method are similar to those of the PEF method, described on page D.185.

If a structure is specified in the directive described above, the interaction between the particles and the structure is treated by an algorithm of the 'sliding surfaces' type. Use is made of Lagrange multipliers, but by default the imposed contact constraints are **decoupled** from other constraints imposed e.g. via LIAI or LINK directives.

To force coupling of the SPH contact constraints with other constraints, add the optional `LAGC` keyword in the calculation type, see Page A.30.

Sometimes contact detection and enforcement with the above method may be imprecise. In such cases, alternative (more general and robust) contact models can be used.

One possibility is to use the sliding surface algorithm via the `LIAI` or `LINK` directives. To this end, specify only the `BILL` keyword in the `SPHY` directive. Then, use the `LIAI` or `LINK` directive with the `GLIS` keyword to detect the contact. The `LINK` form of the directive can use either Lagrange multipliers (strong formulation, either in a coupled or in a decoupled manner, `COUP` or `DECO`), or a penalty method (weak formulation). On the "master" side, the `MAIT` keyword is used to specify a structure made of continuum elements, or the `CMAI` keyword for a shell structure. The SPH particles are then listed after the `PESC` keyword, that treats each particle as a "slave" material point. See page D.180 for further details.

Another possibility is to use the pinball method. To this end, specify only the `BILL` keyword in the `SPHY` directive. Then, embed pinballs both in the SPH particles themselves (with a diameter equal to the diameter of the particles) and in the impacted structure. The `LIAI` or `LINK` forms of the pinball contact method can be applied. The latter can use either Lagrange multipliers (strong formulation, either in a coupled or in a decoupled manner, `COUP` or `DECO`), or a penalty method (weak formulation). See page D.480 for further details.

8.32 EDEF: Connecting finite and discrete element models

Object:

This directive defines a bridging (recovering) zone allowing to couple a set of discrete elements (ELDI) with a 3D finite element model (meshed with the CUB8 element only) or a shell model (Q4GS elements only).

The coupling equations are solved using Lagrange multipliers. To simplify, a diagonal matrix is used. It's possible to couple discrete elements by using the complete matrix through the LINK procedure.

Compatibility: `COUP`

Syntax:

```
"EDEF" nbcoup
       nbcoup*("NCOU"  ncouches
              "ELDI"  /LECTURE/
              "FRON"  /LECTURE/ )
```

`nbcoup`

Number of combined finite/discrete zones to connect.

`"NCOU"`

Number of finite element range defining the combined finite/discrete element zone.

`"ELDI" /LECTURE/`

List of the discrete elements concerned to research in the combined finite/discrete element zone.

`"FRON" /LECTURE/`

List of nodes forming the border of the finite elements mesh in the bridging finite/discrete element zone.

8.33 BIFURCATION CONNECTION

Object:

Writes the relations that ensure the conservation of mass flow rate for the fluid, and the equality of mechanical d.o.f.s if necessary (case of 1D coupled fluid calculation).

This directive may only be used in 1D.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"BIFU"   < LIBR >   /LECTURE/
```

`/LECTURE/`

Numbers of the BIFU elements for which the conservation of flow rate must be imposed.

Comments:

This directive may only be used in 1D, coupled or not, and for the junctions between the following elements:

```
      |  TUBE  |  TUYA  |  POUT  |
---------------------------------
TUBE  |   yes  |   yes  |    -   |
TUYA  |   yes  |   yes  |   no   |
POUT  |    -   |   no   |   no   |
```

In the case of a bifurcation linking an element TUBE with an element TUYA, there may be only two nodes connected in the directive /LECTURE/ (no multiple branches).

In the case of bifurcations (even multiple) between TUYA, the 6 mechanical d.o.f.s are connected (continuity of the beam). In order to avoid these connections (for example in the case of a ‘soufflet’), add the keyword ”LIBR”. On the contrary, between a TUBE and a TUYA the 6 mechanical d.o.f.s are left free, and the keyword ”LIBR” is irrelevant.

Outputs:

The various components of the ECR table are as follows:

ECR(1) : density (all materials)

ECR(6) : internal energy (water)

8.34 ADHESION CONNECTION

Object:

This link can describe adhesion connections between a slave surface and a master surface. The contact can be opened, when a failure criterion is reached. From this point on, the link can not sustain any tension forces. But it can still react to compression forces, when the gap is closed. The model is extended to MPI calculations.

Compatibility: `COUP`

Syntax:

```
"ADHE"  "AUTO" auto <"CRIT" "TENS" tens >
        "LIST" "MAST" /LECTURE/
               "SLAV" /LECTURE/
```

`auto`

Maximum distance for the automatic search.

`tens`

Maximum tensile strength for the definition of the failure.

`/LECTURE/`

Objects which should be taken into account for the automatic search.

8.35 TUBM CONNECTION (3D-1D JUNCTION)

Object:

Write the relations ensuring the conservation of mass flow rate for the fluid (Eulerian formulation) across a junction of type "TUBM". This liaison is only needed when the fluid connected by the junction is represented by Finite Elements (fluid velocity defined at nodes). If Cell-Centred Finite Volumes are used for the fluid (velocities defined at the cell centroids) then this liaison is not necessary.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"TUBM"  /LECTURE/
```

`/LECTURE/`

Numbers of the "TUBM" elements (or names of the GIBI objects), which form the junctions.

8.36 TUYM CONNECTION (3D-1D JUNCTION)

Object:

Write the relations ensuring the conservation of mass flow rate for the fluid (moving meshes) across a junction of type "TUYM". This liaison is only needed when the fluid connected by the junction is represented by Finite Elements (fluid velocity defined at nodes). If Cell-Centred Finite Volumes are used for the fluid (velocities defined at the cell centroids) then this liaison is not necessary.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"TUYM"  /LECTURE/
```

`/LECTURE/`

Numbers of the "TUYM" elements (or names of the GIBI objects), which form the junctions.

8.37 TUYA CONNECTION (3D-1D JUNCTION)

Object:

Automatically writes the mechanical relations among d.o.f.s of a pipeline meshed by beams and a pipeline meshed by thin shells.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"TUYAU"  "CENTRE" /LECTURE/
         "LISTE"  /LECTURE/
```

`"CENT" /LECTURE/`

Number of the node (or name of the object) corresponding to the extremity of the pipeline meshed by beams.

`"LIST" /LECTURE/`

Number(s) of the node(s) (or name of the object) corresponding to the circle, extremity of the pipeline meshed by thin shells.

Comments:

This directive automatically writes the relations between the displacements of nodes belonging to the shells and the beam. All rotations are supposed to be equal.

All nodes involved by the link (including the `CENT` node) must have 6 dofs, since the imposed relations involve also the rotations. Therefore, the `CENT` node cannot be simply represented by a (stand-alone) `PMAT`, which has only 3 dofs. In such a case, it is sufficient to attach a (dummy) beam or shell element to the `CENT`.

8.38 RIGID BODY (SOLIDE INDEFORMABLE) CEA Implementation

Object:

This directive defines the sub-structures that will be considered as rigid bodies.

It also allows to impose the inertia tensor of the solid, or to leave EUROPLEXUS compute it starting from the mesh, or from a composition of simple homogeneous solids.

The directive may be used in two ways:

- The solid is meshed, i.e. its form is represented by a set of elements
- The solid is not meshed, i.e. one imposes that a small number of points be rigidly connected.

Compatibility: `COUP`, `LIAI`

Syntax:

```
 "SOLI" nsol*( ... )

  1st case - Solid meshed by elements:

         "ELEM" /LECTURE/  "PLIE" /LECTURE/ ...
                $  <  "COMP" ncomp*( "INER"  ... )   >   $
                $  <  "INER"  ...    >                   $

  2nd case - Rigidly connected points:

         "POIN" /LECTURE/
```

`nsol`

Number of non-deformable solids.

`"ELEM" /LECTURE/`

Numbers of the elements composing the solid.

`"PLIE" /LECTURE/`

Numbers of the points of the solid to be conserved because they take part in a connection (linked points).

`ncomp`

Number of homogeneous simple solids whose combination allows to compute the inertia tensor. In the case that ncomp = 1, this parameter is optional.

`"INER"`

This option allows to introduce the parameters of inertia of a solid, that will replace the ones computed starting from the mesh and the initial materials.

`"POIN" /LECTURE/`

Numbers of the points rigidly linked (case of the non-meshed solid).

Comments:

A sub-structure described like a non-deformable solid will reduce to a system of four material points. The calculation will be done with these points, and the solid will then be reconstructed to be viaualized.

The linked points (participation in a connection) will be conserved in the calculation in order to be able to write down the connection relation.

The other points are not conserved in the calculation. However, they are used for the calculation of the inertia tensor. Care must then be taken that the discretization be sufficient, else the parameters related to the solid will be imprecise, and the computation will be affected by errors.

The "INER" directive is optional. It imposes to the solid inertia values coming from an external calculation. If it is absent, EUROPLEXUS computes inertias from the mesh.

If you impose the inertia tensor via "INER", you may limit the mesh to the minimum indispensable, by directly connecting the linked points (wireframe mesh). In any case, at least ONE free point per solid is necessary, i.e. two linked points will be connected by at least two beam elements.

In the case of complex solids, it is interesting to mesh them finely from the beginning, and to let EUROPLEXUS compute the inetria tensor. The option VERIF is enough for that. For the real dynamic calculation, a coarser mesh (wireframe) will be sufficient, and one will then impose the previously found inertia tensor, by means of the INER directive.

In the case that the solid is not meshed (directive "POIN"), all points of the list will be considered linked. The inertia tensor data is then useless.

Dimension sufficiently by means of directives "SOLI", "PLIE" and "PLIB" (page A.80).

8.38.1 INERTIA

Object:

This directive allows to specify inertia parameters for a non-deformable solid. It also allows to compute the inertia tensor starting from simple shapes.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"COMP"  ncomp*(    "INER"    "MASS"  m  ...
               ... <"XG" xg>    <"YG" yg>    <"ZG" zg>   ...
               ... <"IXX" ixx>  <"IYY" iyy>  <"IZZ" izz> ...
               ... <"IXY" ixy>  <"IXZ" ixz>  <"IYZ" iyz> )
```

`"COMP"`

Announces that the inertia tensor is composed by assembly of simple tensors.

`ncomp`

Number of inertia tensors to be read in order to compute the inertia tensor of the composite solid.

`"INER"`

Announces the beginning of the data relative to an inertia tensor.

`m`

Mass of the isolated solid (without taking into account the added masses).

`xg,yg,zg`

Coordinates of the center of gravity of the solid isolated in the general reference frame (frame of the mesh).

`ixx,iyy,izz`

Diagonal elements of the inertia tensor of the isolated solid, in the general frame translated to the center of gravity of the solid.

`ixy,iyz,ixz`

Off-diagonal elements of the inertia tensor of the isolated solid, in the general frame translated to the center of gravity of the solid.

Comments:

If one single inertia tensor is given (ncomp = 1), the keywords < "COMP" ncomp > are optional. One may start directly by the keyword "INER".

If the "INER" directive is absent, the inertia values will be computed from the initial mesh and densities.

The inertia tensor has the following form:

```
   | ixx  ixy  ixz |
   |               |
I= | ixy  iyy  iyz |
   |               |
   | ixz  iyz  izz |
```

If some parameters are not explicitly given, they are supposed to be zero by default.

In case of complex solids, it is interesting to discretise them finely, and let EUROPLEXUS compute the inertia tensor with high precision. When this operation is terminated, one can take a coarser mesh, by imposing the formerly obtained inertia terms. In this way, the output files will be smaller. But the precision of the calculation will ne the same.

8.39 ARTICULATION

Object:

This directive allows to link two sub-structures by means of a kinematic relationship.

Compatibility: `COUP`, `LIAI` for `VERR`, `ROTU`, `PIVO`, `GLIS`, `PIGL` and `DRIT`

Compatibility: `COUP` for `TGGR` and `CRGR`

Syntax:

```
"ARTI"
     |  "VERR"  ...    |
     |  "ROTU"  ...    |
     |  "PIVO"  ...    |
     |  "GLIS"  ...    |
     |  "PIGL"  ...    |
     |  "DRIT"  ...    |
     |  "TGGR"  ...    |
     |  "CRGR"  ...    |
```

Comments:

Articulations `VERR`, `ROTU`, `PIVO`, `GLIS`, `PIGL` and `DRIT` may only be defined by means of a mechanism element ”MECA”. It is therefore necessary that such elements be present in the mesh.

Articulations `TGGR` and `CRGR` may only be defined by means of a mechanism element ”LIGR”.

The linked sub-structures may be described as either non-deformable or deformable.

The various types of articulations are described in the following pages.

8.39.1 RIGID ARTICULATION (VERR)

Object:

This directive allows to join two sub-structures by means of a blocked articulation, i.e. a rigid connection.

Compatibility: `COUP`, `LIAI`

Syntax:

```
 "VERR"  /LECTURE/  ...

         ... ( "NOEU" /LECTURE/  "VOIS" $[  "ABSENT"       ;
                                            "INDEF"  isol  ;
                                            /LECTURE/      ]$ )
```

`"VERR" /LECTURE/`

Number of the "MECA" element to be rigidly connected.

`"NOEU" /LECTURE/`

Number of the node of the "MECA" element to which the following neighbour will be associated.

`"VOIS" "ABSENT"`

There is no need to define a neighbour because the nodes of this sub-structure already have 6 d.o.f.s. The node of the mechanism is then sufficient.

`"VOIS" "INDEF" isol`

The neighbour is part of the non-deformable solid isol. The points resulting from the decomposition will be used. It seems that this directive cannot be used when the solid is defined by "POIN" (not meshed solid).

`"VOIS" /LECTURE/`

Number of the points forming the neighborhood (the point belonging to the mechanism must be excluded).

Comments:

The two sub-structures are rigidly connected. The six degrees of freedom are coupled on both parts of the mechanism.

The couple "NOEU" "VOIS" must be described twice, i.e. for each of the two points of the mechanism.

8.39.2 PIVOT

Object:

This option allows to link two sub-structures by a frictionless hinge.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"PIVOT" /LECTURE/    ...
        ...   "AXE"  "VX" vx  "VY" vy  "VZ" vz  ...

        ... ( "NOEU" /LECTURE/  "VOIS" $[  "ABSENT"       ;
                                           "INDEF"  isol  ;
                                           /LECTURE/      ]$ )
```

`"PIVOT" /LECTURE/`

Number of the ”MECA” element of the hinge.

`vx,vy,vz`

Components of the initial direction of the hinge axis.

`"NOEU" /LECTURE/`

Number of the node of the ”MECA” element to which the following neighborhood will be associated.

`"VOIS" "ABSENT"`

There is no need to define a neighborhood because the nodes of this sub-structure already possess 6 d.o.f.s. The first node of the mechanism is then sufficient.

`"VOIS" "INDEF" isol`

The neighbourhood is part of the non-deformable solid isol. The points resulting from the decomposition will then be used. It seems that this directive cannot be used when the solid is defined by ”POIN” (not meshed solid).

`"VOIS" /LECTURE/`

Numbers of the points forming the neighbourhood (the point belonging to the mechanism must be excluded).

Comments:

The pivot axis is modified accounting for the motions of the sub-structures.

The pair "NOEU" "VOIS" must be described twice, once for each of the 2 points of the mechanism.

Special care must be taken for the neighborhood. In fact, these parts will be considered as rigid for the calculations of angular relations.

8.39.3 PIN JOINT (ROTU)

Object:

This option allows to connect two sub-structures by a friction-less pin joint ("rotule").

Compatibility: `COUP`, `LIAI`

Syntax:

```
 "ROTU"  /LECTURE/  ...

         ... ( "NOEU" /LECTURE/  "VOIS" $[  "ABSENT"       ;
                                            "INDEF"  isol  ;
                                            /LECTURE/      ]$ )
```

`"ROTU" /LECTURE/`

Number of the "MECA" element of the pin joint.

`"NOEU" /LECTURE/`

Number of the node of the "MECA" element to which the following neighborhood will be associated.

`"VOIS" "ABSENT"`

There is no need to define a neighborhood because the nodes of this sub-structure already possess 6 d.o.f.s. The first node of the mechanism is then sufficient.

`"VOIS" "INDEF" isol`

The neighbourhood is part of the non-deformable solid isol. The points resulting from the decomposition will then be used. It seems that this directive cannot be used when the solid is defined by "POIN" (not meshed solid).

`"VOIS" /LECTURE/`

Numbers of the points forming the neighbourhood (the point belonging to the mechanism must be excluded).

Comments:

The two sub-structures are linked in translation but free in rotation.

The pair "NOEU" "VOIS" must be described twice, once for each of the 2 points of the mechanism.

8.39.4 SLIDER (GLISSIERE)

Object:

This option allows to connect two sub-structures by a friction-less slider ("glissière").

Compatibility: `COUP`, `LIAI`

Syntax:

```
"GLIS"  /LECTURE/    ...
        ...   "AXE"  "VX" vx  "VY" vy  "VZ" vz  ...

        ... ( "NOEU" /LECTURE/  "VOIS" $[  "ABSENT"       ;
                                           "INDEF"  isol  ;
                                           /LECTURE/      ]$ )
```

`"GLIS" /LECTURE/`

Number of the "MECA" element of the pin joint.

`vx,vy,vz`

Components of the initial direction of the axis.

`"NOEU" /LECTURE/`

Number of the node of the "MECA" element to which the following neighborhood will be associated.

`"VOIS" "ABSENT"`

There is no need to define a neighborhood because the nodes of this sub-structure already possess 6 d.o.f.s. The first node of the mechanism is then sufficient.

`"VOIS" "INDEF" isol`

The neighbourhood is part of the non-deformable solid isol. The points resulting from the decomposition will then be used. It seems that this directive cannot be used when the solid is defined by "POIN" (not meshed solid).

`"VOIS" /LECTURE/`

Numbers of the points forming the neighbourhood (the point belonging to the mechanism must be excluded).

Comments:

The slider axis is modified to account for the motion of the sub-structures.

The pair "NOEU" "VOIS" must be described twice, once for each of the 2 points of the mechanism.

The axis defined by "AXE" is used only in case of a spring ("RESS") on the connection (to compute the forces coming from the spring) or in case of merging points of the MECA element. In general case, the sliding axis is defined by the two points of the MECA element (local axis of the element).

8.39.5 SLIDING PIVOT

Object:

This option allows to connect two sub-structures by a friction-less sliding pivot.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"PIGL"  /LECTURE/    ...
        ...   "AXE"  "VX" vx  "VY" vy  "VZ" vz  ...

        ... ( "NOEU" /LECTURE/  "VOIS" $[  "ABSENT"       ;
                                           "INDEF"  isol  ;
                                           /LECTURE/      ]$ )
```

`"PIGL" /LECTURE/`

Number of the ”MECA” element of the sliding pivot.

`vx,vy,vz`

Components of the initial direction of the axis.

`"NOEU" /LECTURE/`

Number of the node of the ”MECA” element to which the following neighborhood will be associated.

`"VOIS" "ABSENT"`

There is no need to define a neighborhood because the nodes of this sub-structure already possess 6 d.o.f.s. The first node of the mechanism is then sufficient.

`"VOIS" "INDEF" isol`

The neighbourhood is part of the non-deformable solid isol. The points resulting from the decomposition will then be used. It seems that this directive cannot be used when the solid is defined by ”POIN” (not meshed solid).

`"VOIS" /LECTURE/`

Numbers of the points forming the neighbourhood (the point belonging to the mechanism must be excluded).

Comments:

The sliding pivot's axis is modified to account for the motion of the sub-structures.

The pair "NOEU" "VOIS" must be described twice, once for each of the 2 points of the mechanism.

The rotational axis is supposed to be identical with the sliding axis. This single axis is defined with the "AXE" keyword. Nevertheless, for the sliding behavior, the axis defined by "AXE" is used only in case of a spring ("RESS") on the connection (to compute the forces coming from the spring) or in case of merging points of the MECA element. In general case, the sliding axis is defined by the two points of the MECA element (local axis of the element).

8.39.6 IMPOSED RELATIVE DISPLACEMENT (DRIT)

Object:

This DRIT directive (Déplacement Relatif Imposé en fonction du Temps = Prescribed Time-dependent Relative Displacement) allows to link two sub-structures by an actuator ("vérin") whose length is a prescribed time function.

Compatibility: `LIAI`

Syntax:

```
"DRIT"  /LECTURE/    ...
        ...   "AMPLI"  ampli   "FONCTION" ifonc    ...

        ... ( "NOEU" /LECTURE/  "VOIS" $[  "ABSENT"       ;
                                           "INDEF"  isol  ;
                                           /LECTURE/      ]$ )
```

`"DRIT" /LECTURE/`

Number of the "MECA" element of the "DRIT" mechanism.

`ampli`

Amplification coefficient.

`ifonc`

Number of the function defined by the "FONCTION" directive (see page E.10).

`"NOEU" /LECTURE/`

Number of the node of the "MECA" element to which the following neighborhood will be associated.

`"VOIS" "ABSENT"`

There is no need to define a neighborhood because the nodes of this sub-structure already possess 6 d.o.f.s. The first node of the mechanism is then sufficient.

`"VOIS" "INDEF" isol`

The neighbourhood is part of the non-deformable solid isol. The points resulting from the decomposition will then be used.

`"VOIS" /LECTURE/`

Numbers of the points forming the neighbourhood (the point belonging to the mechanism must be excluded).

Comments:

The relative displacement between the two nodes of the element is equal to the product ampli * F(ifonc,t).

The pair "NOEU" "VOIS" must be described twice, once for each of the 2 points of the mechanism.

8.39.7 CONNECTION BETWEEN SHELL AND BEAM (TGGR)

Object:

This option allows to link a node from a shell with a node from a beam. Both nodes are linked in translation. They can be connected in rotation around the axis "AXE1" and "AXE2" (local axis of the shell) by means of two springs ("MECA" "LIGR").

Not available with `LIAI`.

Syntax:

```
"TGGR"  /LECTURE/    ...
    ...   "AXE1"  "VX" vx  "VY" vy  "VZ" vz  ...
    ...   "AXE2"  "VX" vx  "VY" vy  "VZ" vz  ...

    ... ( "NOGR" /LECTURE/  )
```

`"TGGR" /LECTURE/`

Number of the "LIGR" element.

`"AXE1" vx,vy,vz`

Components of the first vector (local axis of the shell).

`"AXE2" vx,vy,vz`

Components of the second vector (local axis of the shell).

`"NOGR" /LECTURE/`

Number of the node of the "LIGR" element which belong to the shell.

Comments:

The pivot axis "AXE1" and "AXE2" are modified accounting for the motions of the shell.

8.39.8 CONNECTION BETWEEN SHELL AND BEAM (CRGR)

Object:

This option allows to link a node from a shell with the beam's node which is the closer. Both nodes are linked in translation in the plane defined by the vectors "AXE1" et "AXE2" and free in translation in the perpendicular direction of this plane. They can be connected in rotation around the axis "AXE1" and "AXE2" (local axis of the shell) by means of two springs ("MECA" "LIGR") (See C.965).

Not available with `LIAI`.

Syntax:

```
"CRGR"  /LECTURE/    ...
    ...   "AXE1"  "VX" vx  "VY" vy  "VZ" vz  ...
    ...   "AXE2"  "VX" vx  "VY" vy  "VZ" vz  ...

    ... ( "NOGR" /LECTURE/  )
    ... ( "NOCR" /LECTURE/  )

    ... < "DMAX" dmax  >
```

`"CRGR" /LECTURE/`

Number of the "LIGR" element.

`"AXE1" vx,vy,vz`

Components of the first vector (local axis of the shell).

`"AXE2" vx,vy,vz`

Components of the second vector (local axis of the shell).

`"NOGR" /LECTURE/`

Number of the node of the "LIGR" element which belong to the shell.

`"NOCR" /LECTURE/`

List of the nodes of the "LIGR" element which belong to the beam and are candidates for the connection.

`"DMAX" dmax`

Optional : allows to introduce a test on the distance between both nodes of the connection. If the distance is superior to dmax then the connection is broken.

Comments:

The pivot axis "AXE1" and "AXE2" are modified accounting for the motions of the shell.

The relative perpendicular to the plan motion of the beam is free. The beam's node considered in the link is modified accounting for the relative axial motion of the beam.

8.40 ROTATION

Object:

In the case of a rotating structure, this directive allows to define the symmetry condition with respect to a rotating plane, whose axis and rotation velocity are prescribed by the user.

This directive allows, for example, to model just one sector of a rotating disk instead of the whole disk.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"ROTATION"    "ORIG"   x0 y0  < z0 >
            < "VECT"   vx vy    vz >
              "FONC"   ifonc
              ...                          /LECTURE/
```

`xo,yo,zo`

Coordinates of the origin point (z0 is redundant in 2D).

`vx,vy,vz`

Components of the vector defining the rotation axis. These data are not necessary in 2D (see comments below).

`ifonc`

Number of the function defining the rotation velocity (in rad/s) as a function of time.

`LECTURE`

Numbers of the concerned nodes.

Comments:

This directive may be used at most once in a calculation.

The rotation axis is supposed fixed. The velocity of the rotation varies in time according to the user-specified function.

In 2D plane calculations, the rotation axis is normal to the plane xOy.

8.41 IMPOSED TIME-DEPENDENT ROTATIONAL MOTION

Object:

In the case of a rotating structure, this directive allows to impose a global motion of rotation to a set of nodes. The axis of rotation and the rotation velocity (as a function of time) are prescribed by the user.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"MENS"        "POINT"   x0 y0  < z0 >
            < "VECTEUR"   vx vy    vz >
              "FONCTION"  ifonc
              /LECTURE/
```

`xo,yo,zo`

Coordinates of the origin point (tail of the rotation axis). Note that z0 is redundant in 2D.

`vx,vy,vz`

Components of the vector defining the rotation axis. These data are not necessary in 2D (see comments below).

`ifonc`

Number of the function defining the rotation velocity (in rad/s) as a function of time.

`LECTURE`

Numbers of the concerned nodes.

Comments:

This directive may be used at most once in a calculation.

The rotation axis is supposed fixed. The velocity of rotation varies in time according to the user-specified function.

In 2D plane calculations, the rotation axis is normal to the plane xOy.

A time-limited version (`TMEN`) of the `MENS` directive, which acts only until a certain time and then is automatically removed, is also available, see Page D.321.

8.42 TIME-LIMITED IMPOSED ROTATIONAL MOTION

Object:

In the case of a rotating structure, this directive allows to impose a global motion of rotation to a set of nodes. The axis of rotation and the rotation velocity (as a function of time) are prescribed by the user. The rotation is imposed up to a prescribed time. After that time, the imposed condition is automatically removed.

Compatibility: `COUP`

Syntax:

```
    "TMEN"          "POINT"   x0 y0  < z0 >
                  < "VECTEUR"   vx vy    vz >
                    "FONCTION"  ifonc
                    "UPTO"  t
                    /LECTURE/
```

`xo,yo,zo`

Coordinates of the origin point (tail of the rotation axis). Note that z0 is redundant in 2D.

`vx,vy,vz`

Components of the vector defining the rotation axis. These data are not necessary in 2D (see comments below).

`ifonc`

Number of the function defining the rotation velocity (in rad/s) as a function of time.

`t`

Time up to which the rotation is imposed. After this time, the rotation is automatically released.

`LECTURE`

Numbers of the concerned nodes.

Comments:

This directive may be used at most once in a calculation.

The rotation axis is supposed fixed. The velocity of rotation varies in time according to the user-specified function.

In 2D plane calculations, the rotation axis is normal to the plane xOy.

8.43 CONSTANT DISTANCE CONNECTION (”DIST”)

Object:

Automatic prescription of the 3D mechanical relations of constant distance between position of a point and that of another point or set of points.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"DISTANCE"  $ /LECTURE/ ; CENT /LECTC/ LIST /LECTL/ $
```

`/LECTURE/`

Numbers of the two nodes (or name of the object, containing only two nodes) whose distance must be kept constant during the calculation.

`CENT /LECTC/`

Master node, serving as a reference for all other node. The /LECTC/ must contain only one node.

`LIST /LECTL/`

Slave node(s), whose distance with respect to the master node must be kept constant. The /LECTL/ can contain any number of nodes (1 or greater).

8.44 BARYCENTRIC JUNCTION

Object:

Automatic prescription of mechanical relations (links) such that the displacement of a point equals the **mean value** of the displacements of a set of points, i.e. the displacement of the barycenter of the set of points (considered all with the same weight).

Compatibility: `COUP`, `LIAI`

Syntax:

```
BARY  CENT /LECT/
      LIST /LECT/
     <VECT <VX vx> <VY vy> <VZ vz>>
```

`CENT /LECT/`

Number of the node (or name of the object) corresponding to the “central” (or reference) node. This node may be located anywhere and does not need to be at (or close to) the true center of the following points set.

`LIST /LECT/`

Numbers of the nodes (or name of the object) corresponding to the set of nodes, whose *mean* displacement will be identical to that of the reference node.

`VECT`

Introduces the optional definition of a direction (vector) along which the constraint will act. By default, the constraint acts along all space directions.

`VX, VY, VZ`

Introduce the optional components of the vector `vx`, `vy`, `vz`. By default, they are zero. At least one non-zero component must be specified. The `vz` component may only be specified in 3D. Note that only the direction, not the norm, of the vector counts. The vector is always normalized to unit length internally.

Comments:

By default (no `VECT` specified) this directive imposes the following (vectorial) condition on nodal velocities $\underline{v}$:

$$\underline{v}_C - (\underline{v}_1 + \underline{v}_2 + \cdots + \underline{v}_N)/N = \underline{0}$$

which corresponds to the following 2 or 3 scalar *independent* links:

$$v_{Cx} - (v_{1x} + v_{2x} + \cdots + v_{Nx})/N = 0$$

$$v_{Cy} - (v_{1y} + v_{2y} + \cdots + v_{Ny})/N = 0$$
$$v_{Cz} - (v_{1z} + v_{2z} + \cdots + v_{Nz})/N = 0 \quad \text{(3D only)}$$

where C is the "central" node defined by `CENT` and $1, 2, \cdots, N$ are the N nodes defined by `LIST`.

When a vector $\underline{V}$ is specified by `VECT`, then the following single condition on nodal velocities is imposed:

$$\underline{v}_C \cdot \underline{V} - \frac{1}{N}(\underline{v}_1 - \underline{v}_2 - \cdots - \underline{v}_N) \cdot \underline{V} = \underline{0}$$

which corresponds to the following scalar link (assuming a 2D case):

$$v_{Cx}V_x + v_{Cy}V_y - \frac{1}{N}(v_{1x}V_x + v_{1y}V_y + \cdots + v_{Nx}V_x + v_{Ny}V_y) = 0$$

Note that the above conditions, both without and with the definition of a vector `VECT`, do *not* strictly ensure that the displacements of all nodes in the set will be all equal among them. To obtain this effect, use the `RIGI` link, see page D.326.

8.45 RIGID JUNCTION

Object:

Automatic prescription of mechanical relations (links) such that:

1. the displacement of each point in a certain set of points equals the displacement of a reference point, like if all these points were all rigidly connected among them, or
2. the displacements of each point in a certain set of points are all equal, like if all these points were all rigidly connected among them.

Note that the first definition requires the choice of a reference node while in the second one no reference node is indicated and all nodes play the same role.

The two alternative definitions given above are logically equivalent, but they lead to two different forms of the links matrix. It was found by practical experimentation that in some applications (where the number of points to be rigidly linked is very high) the second form is much more efficient computationally, as far as the solution of the links system is concerned.

If the decoupled form of the link is chosen (`DECO`), then only the second form of the directive is possible.

Compatibility: `COUP`, `LIAI`, `DECO`

Syntax:

```
RIGI <CENT /LECT/>
      LIST /LECT/
     <VECT <VX vx> <VY vy> <VZ vz>>
```

`CENT /LECT/`

(Optional) number of the node (or name of the object) corresponding to the “central” or reference node. This node may be located anywhere and does not need to be at (or close to) the true center of the following points set. Choosing a reference node activates the first form of the rigid junction. This form of the directive is only accepted if coupled links (`COUP` or `LIAI`) are chosen.

`LIST /LECT/`

If `CENT` has been specified (first form of the directive), these are the numbers of the nodes (or name of the object) corresponding to the set of nodes, whose displacement will be identical to that of the reference node. Otherwise (second form of the directive) these are the numbers of the nodes (or name of the object) corresponding to the set of nodes, whose displacement will be identical among them.

`VECT`

Introduces the optional definition of a direction (vector) along which the constraint will act. By default, the constraint acts along all space directions.

`VX, VY, VZ`

Introduce the optional components of the vector `vx`, `vy`, `vz`. By default, they are zero. At least one non-zero component must be specified. The `vz` component may only be specified in 3D. Note that only the direction, not the norm, of the vector counts. The vector is always normalized to unit length internally.

Comments:

Let us define N as the number of nodes in the `LIST` sub-directive. Consider the first form of the directive (`CENT` has been specified). By default (no `VECT` specified) this directive imposes the following set of N (vectorial) conditions on nodal velocities $\underline{v}$:

$$\underline{v}_C - \underline{v}_1 = \underline{0}$$

$$\underline{v}_C - \underline{v}_2 = \underline{0}$$

$$\cdots$$

$$\underline{v}_C - \underline{v}_N = \underline{0}$$

which corresponds to the following $2N$ or $3N$ scalar *independent* links:

$$v_{Cx} - v_{1x} = 0$$

$$v_{Cy} - v_{1y} = 0$$

$$v_{Cz} - v_{1z} = 0 \quad \text{(3D only)}$$

$$\cdots$$

$$v_{Cx} - v_{Nx} = 0$$

$$v_{Cy} - v_{Ny} = 0$$

$$v_{Cz} - v_{Nz} = 0 \quad \text{(3D only)}$$

where C is the "central" node defined by `CENT` and $1, 2, \cdots, N$ are the N nodes defined by `LIST`.

When a vector $\underline{V}$ is specified by `VECT`, then the following N conditions on nodal velocities are imposed:

$$\underline{v}_C \cdot \underline{V} - \underline{v}_1 \cdot \underline{V} = \underline{0}$$

$$\underline{v}_C \cdot \underline{V} - \underline{v}_2 \cdot \underline{V} = \underline{0}$$

$$\cdots$$

$$\underline{v}_C \cdot \underline{V} - \underline{v}_N \cdot \underline{V} = \underline{0}$$

which correspond to the following N scalar links (assuming a 2D case):

$$v_{Cx}V_x + v_{Cy}V_y - v_{1x}V_x - v_{1y}V_y = 0$$

$$v_{Cx}V_x + v_{Cy}V_y - v_{2x}V_x - v_{2y}V_y = 0$$

$$\cdots$$

$$v_{Cx}V_x + v_{Cy}V_y - v_{Nx}V_x - v_{Ny}V_y = 0$$

In the <u>second form</u> of the directive (`CENT` has *not* been specified), when no `VECT` is specified this directive imposes the following set of N (vectorial) conditions on nodal velocities $\underline{v}$:

$$\underline{v}_1 - \underline{v}_2 = \underline{0}$$

$$\underline{v}_2 - \underline{v}_3 = \underline{0}$$

$$\ldots$$

$$\underline{v}_{N-1} - \underline{v}_N = \underline{0}$$

$$\underline{v}_N - \underline{v}_1 = \underline{0}$$

When a vector $\underline{V}$ is specified by `VECT`, then the following N conditions on nodal velocities are imposed:

$$\underline{v}_1 \cdot \underline{V} - \underline{v}_2 \cdot \underline{V} = \underline{0}$$

$$\underline{v}_2 \cdot \underline{V} - \underline{v}_3 \cdot \underline{V} = \underline{0}$$

$$\ldots$$

$$\underline{v}_{N-1} \cdot \underline{V} - \underline{v}_N \cdot \underline{V} = \underline{0}$$

$$\underline{v}_N \cdot \underline{V} - \underline{v}_1 \cdot \underline{V} = \underline{0}$$

The reason why the solution of the linear system of constraints may become (very) slow for large N in the first form of the equations is that the same node C appears in *all* equations. The bandwidth of the constraints matrix might become quite large.

The second (*circular*) form of the equations is computationally more efficient because the nodes involved keep changing from an equation to the other (each node appearing only in two of the vector constraint equations), so that the bandwidth of the constraints matrix can be made small upon proper renumbering of the links and the solution becomes (much) more efficient.

8.46 GLUE: Gluing together two meshes

Object:

Glue together two incompatible (non-conforming) structural meshes. The nodes of the *slave* mesh are linked to the faces of the *master* mesh so that their relative position with respect to the face does not change during motion and deformation. Common rotation is allowed.

Compatibility: `COUP`, `DECO`

Syntax:

```
GLUE  <DMAX d> <LOOS>  <SELF>
                       SLAV        /LECT1/
                       MAST <ALLF> /LECT2/
```

`DMAX d`

Optional maximum distance *d* of a slave node from a master face for the node to be considered on the face. If omitted, only a small tolerance of approximately 1 % of the face size is admitted for the node to be considered on the face. The specification of `DMAX d` may be useful when the two meshes to be glued together are separated by a (small but non-negligible) gap.

`LOOS`

Optional keyword which enforces only a loose (as opposed to a strict) satisfaction of the gluing constraint. If `LOOS` is not specified (as per default) and a slave node has no corresponding master face, then an error message is issued and the code stops. However, in the above case of no matching face, if the `LOOS` keyword has been specified, then no link is imposed to the slave node and the gluing condition is simply ignored for this node.

`SELF`

Optional keyword, which allows the gluing of part of a body upon itself. In this case, a slave node may belong to one or more master elements, which is not the case without this keyword. When the option is active, the search algorithm automatically skips all master elements that contain the slave node under consideration (if any).

`SLAV /LECT1/`

List of the slave *nodes*.

`MAST /LECT2/`

List of the master *elements*. If a master alement is of continuum type, then by default only its *external* faces are considered as valid candidates to become master faces, while internal faces are ignored.

`ALLF`

This optional keyword causes *all* faces (both external and internal) of the (continuum) master elements to be considered as valid candidates to become master faces. For shell master elements, no distinction is made between internal and external faces and the `ALLF` keyword, if present, has no effect.

Comments:

Each slave node is checked against all faces of the master elements, until a face is found on which the slave node is initially located (within a small tolerance). Unless `LOOS` is specified, this face *must* exist and be unique, and is denoted the master face.

The initial position of the slave node with respect to the nodes of the corresponding master face allows to compute the shape functions (coefficients) of the relations (links) that keep together the two entities during the (common) motion and deformation of the model. The relations involve translational degrees of freedom only (two relations in 2D, three in 3D).

Up to two named node groups are automatically created for each occurrence of the `GLUE` directive. The first group has the form `_GLUEnnnn` where `nnnn` is a 4-digit number (`0001`, `0002` etc.) indicating the index of the current `GLUE` directive in the input file. This group contains the nodes which were actually glued. The second group has the form `_NGLUnnnn` and contains the nodes which were *not* glued, despite having been declared in the `SLAV /LECT1/` directive, because a matching master face could not be found. Obviously, this second group is created only if there are any non-matching nodes and if the user has specified the `LOOS` keyword. The groups can be visualized in the OpenGL graphical module for direct visual inspection of which nodes were actually glued (or not glued.)

8.47 CONTACTS DEFINED BY SPLINE FUNCTIONS

Object:

In the case of a rotating structure, this directive allows to define the possible contacts between the rotating parts (blades) with the fixed wall (carter). The geometrical forms of these parts are defined by means of spline functions starting from the positions of mesh nodes. This interpolation allows thus to approximate the real geometry of such structures.

Compatibility: `LIAI`

Syntax:

```
"SPLINE"
nspline * (      "SURFACE"   /LECTURE/     ...
            ...  "COURBE"  ncourbe * ( "LIGNE" /LECTURE/ )     ...
            ...  "METC"  metc   "METS"  mets   "NPTT"  nptt    ...
            ...  "DEGC"  degc   "DGST"  dgst   "DGSZ"  dgsz    ...
            ...  "EPAIS" epais  "FREQ"  freq                       )
```

`nspline`

Number of splines.

`SURFACE`

Defines the nodes forming the surface. This surface MUST be a cylinder,

`ncourbe`

Number of curves that may get in contact with the surface.

`LIGNE`

Introduces the nodes that compose a curve. **The user must enter these nodes in the order of their position along the curve.**

`metc`

Method for the modelisation of the curve (see comments below).

`mets`

Method for the modelisation of the surface (see comments below).

`nptt`

Number of nodes of the surface lying on the same circumference.

`degc`

Degree for the modelisation of the curve.

`dgst`

Degree for the modelisation of the surface, circumferential direction.

`dgst`

Degree for the modelisation of the surface, axial direction Oz.

`epais`

Thickness of the shell elements composing the surface.

`freq`

Frequency of the updationg of surface nodes.

Comments:

The methods for the modelisation (of the curve and of the surface along the circumferential and axial directions) may assume the values: 1 (direct), 2 (interpolation) or 3 (smoothing by least squares).

The surface MUST be a cylinder of axis Oz. Furthermore, the nodes composing it must be regularly spaced.

8.48 COLLISIONS

Object :

This directive allows to simulate the contact and/or shock without friction between the envelopes of 3D rigid bodies.

Compatibility: `LIAI`

Syntax :

```
"COLL"    "REST"  crest    "SGEO"  tolgeo    "SVIT"  tolvit
        ( "CHAI"
             ( "SOLI"  nusoli
                    "SURF"  /LECTURE/
                    "EPAI"  epais
                    "ORIE"  xp  yp  zp       )     )
     "CONT"
        ( "CHA1"  nucha1    "CHA2"  nucha2   )
     "FCON"
```

`COLL`

This keyword announces the data relative to collisions.

`crest`

Energy restitution coefficient.

`tolgeo`

Geometric tolerance of the contact.

`tolvit`

Kinematic tolerance of the contact.

`CHAI`

This keyword announces the data relative to a chain.

`SOLI`

This keyword announces the data relative to one of the solids that define the chain.

`nusoli`

Number of the solid associated to the chain. This number corresponds to the order under which the solid has been listed under the sub-directive "SOLIDE" of the directive "LIAISON".

`/LECTURE/`

Reading procedure of the triangular elements defining the envelope of the chain, i.e. the contact surfaces.

`epais`

Thickness of the contact surfaces.

`xp, yp, zp`

Coordinates of a point interior to the envelope, used to define the orientation of the triangular elements.

`CONT`

This keyword allows to introduce the list of pairs of chains for which contact may take place.

`nucha1`

Number of the first chain of the pair.

`nucha2`

Number of the second chain of the pair.

`FCON`

This keyword announces the end of the collisions data.

Warning :

It is mandatory:

- to mesh the surfaces by triangular elements;
- to declare these elements as “phantoms” by directive ”MATE”,
- to define the data block ”SOLIDE” before the block ”COLLISIONS”,
- to specify in ”DIME” the dimensioning parameter:

```
"CSCO" nbpcon
```

With:

`nbpcon`

Maximum number of contact points.

Comments :

The coefficient of energy restitution is between 0 and 1. For crest = 0, one obtains a perfectly soft shock, while for crest = 1 one gets a perfectly elastic shock (the energy is conserved).

The thickness of surfaces must be of the order of the size of elements at most. If this value is too small, it is possible that the interpenetration of the two surfaces will not be detected.

The contact geometric tolerance determines the distance starting from which one considers that there is contact.

The kinematic tolerance must be of the order of the time step. The larger this tolerance, the more the discontinuity at the velocity level due to a shock is ignored.

If a contact surface is fixed (instead of being defined via a rigid body), it is sufficient to declare `nusoli = 0`. In this case it is redundant to block the concerned nodes, since it is done automatically by the code.

References :

For further information, please consult the reference [672].

8.49 FLUID-STRUCTURE SLIDING OF ALE TYPE (FSA)

Object:

To define fluid-structure sliding of the ALE type according to the FSA model developed at JRC Ispra.

The program writes for each node subjected to this type of sliding a 'liaison' that forces the fluid (slave) velocity to be equal to the structure (master) velocity along the normal to the FS interface. In the tangent direction (tangent plane in 3D), the fluid velocity is free.

In the case of a curved interface, the normal direction is determined at each step by taking into account all the element faces that lie along the fluid-structure boundary and include the node under consideration (influence domain) and by imposing that the net flux of mass out of some faces be balanced by the flux entering the other faces.

Since the geometry varies in time, the coefficients of the liaison have to be recalculated and the matrix inverted at each step.

The nodes declared in this directive should be fluid nodes and be declared as Eulerian in the `GRIL` directive. The program then automatically searches for each slave node a corresponding master node: this is defined as the Lagrangian node having the same coordinates as the slave node (within a small tolerance) and if it exists (nodally **conforming** FS interface), it must be unique. Usually this will be a structural node, but it could be also a fluid (Lagrangian) node, in case the sliding takes place along a fluid-fluid interface.

If no such node exists, then the FS interface is nodally **non-conforming** and the program searches a Lagrangian master **face** on which the slave fluid node lies. The motion of the fluid node is automatically set so as to follow the motion of the master face.

Note that the treatment of non-conforming FS interfaces requires a special optional keyword (`NCFS`) to be explicitly chosen by the user. If this keyword is not specified and a non-conforming node is found, then an error message is issued and the calculation is stopped. This is to make sure that the user intentionally wanted to specify a non-conforming interface and there was not just an error in mesh specification.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"FSA" <"STRU" /LECT_STRU/> <"NCFS"> /LECTURE/
```

`STRU /LECT_STRU/`

Optional sub-directive used to tell the code in which object (`/LECT_STRU/`) it should search to determine the "structural" (i.e. the Lagrangian) nodes corresponding to the FSA fluid nodes that will be specified in the final `/LECTURE/`. By default, the search is extended to the whole mesh.

`NCFS`

The FS interface may contain non-conforming fluid nodes.

`/LECTURE/`

List of fluid (slave) nodes subjected to FSA sliding.

Comments:

The fluid nodes subjected to FSA sliding should preferably be declared Eulerian in the grid movement directive (`GRILL`). The program will automatically consider these nodes as manually rezoned when it encounters the `LIAI FSA` directive. The user might also declare these nodes as automatically rezoned in `GRILL` (e.g., as a consequence of an `AUTO AUTR` directive), with no effect on the results, but in this case the dimensioning for automatically rezoned nodes (`DIME NBLE`) should include these nodes, although this is not necessary for the actual computation.

Beware that the behaviour of the FSA algorithm may be modified by setting appropriate options, see page H.120. In particular, the `FSCR` option activates the correction of normals based on equilibrium considerations (FSCR algorithm).

Occasionally, the automatic search for the master node corresponding to a slave node might fail. The code then reports the concerned node number by an appropriate error message. This may happen because either the code finds zero nodes, or it finds more than one Lagrangian nodes matching the slave node.

In the first case, the tolerance for node matching determination might be too small, e.g. due to the fact that mesh coordinates are generated by an external, and not too precise, mesh generator. The user may adjust this tolerance, see `OPTI TOLC` on page H.40.

The second case may occur for example when there are superposed structures (coincident nodes) in the initial mesh. In such cases, there are two possibilities. Either the user specifies the required nodes correspondence by the `COMP CNOD` directive, see page C.92, but this is only practical if there are just a few of these nodes. Or, the user specifies the `STRU /LECT_STRU/` optional sub-directive, so that the search for matching structural (more precisely, Lagrangian) nodes is confined to the specified object `/LECT_STRU/` rather than to the whole mesh. This is the method of choice e.g. in case a large shell structure is subjected to FSA on one side, and to Lagrangian sliding (say, by `GLIS`) on the other side, so that the number of "superposed" structural nodes is potentially large.

8.50 RIGID-BOUNDARY/FLUID SLIDING OF ALE TYPE

Object:

To simplify the description of fluid sliding along inviscid, rigid boundaries. The simplification lies in the fact that the program automatically computes the correct sliding conditions, in particular the normal (or possibly the 2 normals, in 3D cases) to the rigid boundary and automatically prescribes the relevant "connections" (liaisons).

For complex geometric shapes this is very convenient with respect to the "manual" prescription of all such connections.

This condition is similar to the "FSA" condition, but with the following differences:

- Since the boundary is rigid, there is no need to represent it by a structure. The sliding condition therefore involves only a fluid node.

- The geometry of the boundary does not vary in time, therefore the coefficients of the liaison are constant and do not need to be recalculated during the transient.

- The program does not search for a Lagrangian node having the same coordinates as the fluid node.

The nodes declared in this directive (/LECT/) should all be fluid nodes and be declared as Eulerian in the GRIL directive.

Compatibility: `COUP`, `LIAI`

Syntax:

```
"FSR"  /LECTURE/
```

`/LECTURE/`

List of fluid nodes subjected to FSR sliding.

Comments:

The fluid nodes subjected to FSR sliding should preferably be declared Eulerian in the grid movement directive (GRILLE). The program will automatically consider these nodes as Eulerian when it encounters the LIAI FSR directive. The user might also declare these nodes as automatically rezoned in GRILLE (e.g., as a consequence of an AUTO AUTR directive), with no effect on the results, but in this case the dimensioning for automatically rezoned nodes (DIME NBLE) should include these nodes, although this is not necessary for the actual computation.

8.51 IMPACT/CONTACT BY PINBALL MODEL (PINB)

Object:

The purpose is to define impact and contact conditions between Lagrangian subdomains (typically two or more solid bodies) by means of the "pinball" model. The model is inspired to a formulation proposed by Belytschko and co-workers in the papers: (*i*) Ted Belytschko and Mark O. Neal, "Contact-Impact by the Pinball Algorithm with Penalty and Lagrangian Methods", Int. J. Num. Meths. Eng., Vol. 31, pp. 547-572 (1991), and (*ii*) T. Belytschko and I.S. Yeh, "The splitting pinball method for contact-impact problems", CMAME, 105, pp. 375-393, (1993).

The user defines the elements that may enter in contact with one another and a pinball (a sphere or circle) is associated to these elements. Interpenetration is detected by comparing the distance of the centers of two pinballs with the sum of their radii. If this condition is satisfied, equal normal velocity is enforced by the method of Lagrange multipliers and the corresponding contact forces are computed.

Optionally, contact may be verified on a hierarchy of "descendent" pinballs derived from the "parent" pinballs described above by recursively halving the pinball dimensions. This allows finer spatial resolution of the contact conditions.

The uncoupled version of the pinball algorithm (`DECO` keyword) uses a penalty method instead of (coupled) Lagrange multipliers.

Compatibility: `COUP`, `DECO`, `LIAI`

Syntax:

```
PINB $[ PENA <SFAC sfac> <CSHE> ]$
     ( ![ $[BODY ; SELF]$
       < "FROT" "MUST" must "MUDY" mudy "GAMM" gamm >
       < $[DMIN dmin ;
           MLEV mlev ;
           DIAM diam < ADAD < UPTO lmax > >
                     < ADNP < UPTO lmax > > ]$ >
       < HARD hard >
       < $[ < KDIS kdis > < KVEL kvel > ; RPEN < NPEN npen > ]$ > ]!
       /LECT/ )
     < EXCL $[ (PAIR n1 n2) ; ALL ]$ >
     < INCL $[ (PAIR n1 n2) ; ALL ]$ >
     < ADAP LMAX lmax <SCAL scal> <SCAS scas> <NOUN> >
```

The input consistes of several parts. The first part is related to the chosen **solution method**. If `LINK COUP` or `LIAI` has been chosen, then this part may be skipped. If `LINK DECO` has been chosen, this part is mandatory.

`PENA`

DECO only: mandatory keyword (ignored with COUP or LIAI), must immediately follow the PINB keyword and indicates that a penalty method is used.

SFAC sfac

DECO only: optional scaling coefficient ϕ for the automatic determination of the contact stiffness (see Comments below). By default it is 1.0.

CSHE

Correct penalty forces when shells are involved in the contact. A correction (multiplicative) factor ϕ is evaluated and added into the formula that computes the penalty force between continuum elements. The ϕ factor takes into account the different types of contact between shells, which can involve element (parent) pinballs, face pinballs, corner pinballs and vertex pinballs. This keyword is incompatible with the REDU option for pinballs (see page H.160) which eliminates the redundant constraints.

Next, comes the description of the bodies in contact, or more precisely the description of **pinball sets** to be embedded in the contacting bodies. The BODY or SELF (in order to activale self-contact) sub-directives should be repeated as many times as necessary to define all the contacting pinball sets.

BODY

Introduces the declaration of a set of pinballs that form one of the bodies that may come in contact with other bodies. There may not be contact between pinballs belonging to the same body.

SELF

Introduces the declaration of a set of pinballs that form one of the bodies that may come in contact with other bodies. In this case, there may be contact between different pinballs belonging to this body (this model is called self-contact or auto-contact).

The next sub-block of data concerns the optional definition of **friction characteristics** of the body (i.e. of the pinballs set).

FROT

Introduces the specification of (optional) friction characteristics for the current contacting body. A simple Coulomb dry friction model is assumed.

MUST must

Specifies the limiting friction coefficient for the static case μ_S. This is the value assumed when no sliding occurs between the contacting surfaces. It must be $(0 \leq \mu_S \leq 1)$.

MUDY mudy

Specifies the friction coefficient for the dynamic (or kinetic) case μ_K. This is the (asymptotic) value assumed at very large (infinite) relative velocity of the contacting surfaces. It must be $(0 \leq \mu_K \leq \mu_S \leq 1)$.

GAMM gamm

Parameter (γ) of the law of variation of the friction coefficient (μ) with the relative tangential sliding velocity (v_r) of the contacting surfaces. It must be $\gamma \geq 0$. The friction coefficient μ varies from μ_S to μ_K as the relative tangential velocity v_r of the two bodies increases. The transition between the two regimes is governed (smoothly) by the exponential decay law: $\mu = \mu_K + (\mu_S - \mu_K)e^{-\gamma|v_r|}$. Note that for $\gamma = 0$ we have $\mu = \mu_S$, *independently* from the relative velocity $|v_r|$ *and* from the value chosen for $\mu = \mu_K$.

The following sub-block of data basically defines the **size of the pinballs** belonging to the current body (i.e. of the current pinballs set). Three alternatives are possible: choosing the minimum diameter, choosing the maximum refinement level, or choosing a fixed diameter. In the latter case, only one pinball per element is ever generated.

`DMIN dmin`

Minimum diameter of descendent pinballs that will be generated from the set being declared. By default, this value is 0 for continuum elements (the size is then governed by `mlev`, see below), or it is the element thickness for beam or shell elements. For the choice of `DMIN` in adaptive calculations see the `ADAP` keyword below and the comments at the end of this page. Note that a **modification** in the effects of `DMIN` has been introduced recently. Thus, in order to repeat an old calculation which uses `DMIN` made with EPX version 3208 of 20 February 2017 or earlier, one should divide the old input value of `DMIN` by two, in order to obtain "exactly" the same results as previously (in the rare cases where this might have an importance).

`MLEV mlev`

Maximum hierarchy level for descendent pinballs that will be generated from the set being declared. The value 0 means that no descendents are generated (contact forces are computed based on interpenetration between parent or 0-level pinballs). The pinball radius is roughly divided by two at each new level produced. If specified, `mlev` must be greater or equal to 0. If not specified, `mlev` has to be computed. If `dmin` ($d_{\min}$) is given, then the maximum level is computed such that the minimum pinball diameter is *of the order* of $d_{\min}$. More precisely, the (0-level) pinball diameter is repeatedly halved until the result $d_{\min}^{\text{eff}}$ is equal to or less than *twice* the chosen value $d_{\min}$. This algorithm guarantees that $2d_{\min} \geq d_{\min}^{\text{eff}} > d_{\min}$. If `dmin` is not given, for beam/shell elements `mlev` is computed by repeated halvings such that the minimum pinball diameter is of the order of (more precisely: equal to or less than) *twice* the element thickness h, that is: $2h \geq d_{\min}^{\text{eff}} > h$. For continuum elements and for other element types, the default `mlev` value is 0. For the choice of `MLEV` in adaptive calculations see the `ADAP` keyword below and the comments at the end of this page.

`DIAM diam`

Fixed pinball diameter, typically to be associated with elements of the material-point type (PMAT). These elements have just one node and thus their pinball radius may not be computed by the code but must be provided by the user. In special cases this keyword can be used to assign a chosen pinball diameter also to elements *not* of the material point type, e.g. continuum elements. By default, the pinball diameter is never updated during the transient calculation even though the associated element undergoes large deformations, unless the `UPDR` option is specified. So make sure *not* to specify the `UPDR` option if you want the imposed pinball diameter to stay constant. When `diam` is specified, `dmin` may not be specified and `mlev` must be 0 (i.e., either unspecified, or specified to be 0). This means that no hierarchic pinballs are generated when `diam` is specified, i.e. only one pinball of the chosen diameter is associated with each element of the body. The pinball is placed at the centroid of the element. For the choice of `DIAM` in adaptive calculations see the `ADAP` keyword below and the comments at the end of this page.

`ADAD`

Adapt the diameter chosen by `DIAM`. Specifying this optional keyword (after choosing a diameter D by the `DIAM` command) adapts the diameter of pinballs associated with descendents of the elements in the current body, when such elements are refined by adaptivity. That is, first-generation descendents receive one pinball each (no hierarchy is possible with `DIAM`) with a diameter one half of the ancestor's diameter (i.e. $D/2$), second-generation descendents get a diameter $D/4$ and so on. The default behaviour when `DIAM` is set but `ADAD` is *not* activated, is that in case of adaptive refinement of the body's elements, the diameter of the newly generated pinballs (one per element) is constant and equal to D. The default rule seems appropriate, for example, if the body is a thin plate discretized by shells and for which a `DIAM` is chosen (as an alternative to other possible pinball strategies, such as hierarchic pinballs for example). In such a case one probably wants the diameter of pinballs to be equal to the thickness of the plate and to remain constant along with mesh adaptive refinement. In other applications, however, one may prefer that the imposed-diameter pinballs be scaled down as the mesh is refined, and this is the purpose of the `ADAD` keyword.

`UPTO lmax`

Limit the diameter adaptation mechanism activated by the `ADAD` keyword up to level `lmax` of the hierarchy. By default, adaptation is performed at all levels when `ADAD` is specified. This optional keyword can be used to avoid obtaining too small diameter pinballs in cases with deep mesh refinement (large hierarchy levels).

`ADNP`

Adapt nodal pinballs (more precisely: *propagate* nodal pinballs in adaptivity). This optional keyword has only effect if the pinballs of the current body are so-called *nodal* pinballs, and is ignored otherwise. So-called nodal pinballs are pinballs associated with material point elemengts (`PMAT`) attached (as typically mass-less geometrical supports) to the nodes of a body which is discretized by continuum or structural elements. They are not *real* nodal pinballs (directly associated with the nodes), because in the current implementation each pinball always requires an associated *element*. When the elements of the body are refined due to adaptivity, new nodes are created. By default, i.e. *without* specifying the `ADNP` optional keyword, no new pinballs would be created, because technically it is the continuum or structural elements which are refined and not the `PMAT` material point elements. By activating `ADNP`, each newly created node will receive a (new) `PMAT` element with an associated pinball. Note that the diameter of the newly created pinballs will be scaled or not, depending on the setting or not of the `ADAD` optional keyword described above for the current body.

`UPTO lmax`

Limit the pinball propagation mechanism activated by the `ADNP` keyword up to level `lmax` of the hierarchy. By default, propagation is performed at all levels when `ADNP` is specified. This optional keyword can be used to avoid obtaining too many (descendant) pseudo-nodal pinballs in cases with deep mesh refinement (large hierarchy levels).

Next comes an optional definition of some **additional parameters** (hardness, added penalty-like coefficients or penetration removal strategy) and the **list of the elements** forming the current body, i.e. the elements into which the pinballs of the current set should be embedded.

The optional penalty-like coefficients may be used to eliminate the progressive penetration phenomenon which may occur in case of smooth and prolonged contact between bodies. The contact Lagrange multiplier λ is corrected by a scaling factor ϕ: $\lambda_p = \phi\lambda$, where ϕ depends upon the penetration p and the penetration rate $\dot{p}$ between the two contacting pinballs:

$$\phi(p, \dot{p}) = 1 + k_d \frac{p}{R_{\max}} + k_v \frac{\dot{p}\Delta t}{R_{\max}} \tag{84}$$

where $R_{\max} = \max(R_A, R_B)$ is the largest of the radii of the two pinballs, Δt is the current time increment, k_d is a penetration-related coefficient and k_v is a penetration-rate-related coefficient. By setting $k_d = k_v = 0$ (which is the default) we obtain $\phi = 1$ so that no correction is applied to the Lagrange multiplier ($\lambda_p = \lambda$).

From (84), e.g. by setting $k_d = 1.0$ and $k_v = 0.0$ the value of the reaction would become double the normal one ($\phi = 2.0$) when the penetration reaches the larger pinball radius $R_{\max}$. Similarly, by setting $k_d = 0.0$ and $k_v = 1.0$ the value of the reaction would become double the normal one ($\phi = 2.0$) when the penetration rate multiplied by Δt, i.e. when the increment of penetration over one time step, reaches the larger pinball radius $R_{\max}$.

Another technique to tentatively avoid the progressive penetration phenomenon, alternative to the use of penalty-like coefficients, is the specification of the `RPEN` optional keyword. This causes the correction of the RHS of the contact constraint in such a way that any existing penetration will tend to be removed in the next step(s). The `NPEN` optional sub-keyword allows to choose in how many (n) time steps the penetration should ideally be removed (by default, $n = 1.0$ time step).

Instead of the standard pinball constraint constraint:

$$(v_A - v_B) \cdot \hat{n}_{AB} \leq 0 \tag{85}$$

a correction of the RHS is introduced, leading to:

$$(v_A - v_B) \cdot \hat{n}_{AB} \leq -\frac{p}{\max(n_A, n_B)\Delta t} \tag{86}$$

where p is the penetration.

This completes the definition of the current set of pinballs.

`HARD hard`

Optional "hardness' value to be associated with the body. This information is only used in conjunction with options `OPTI PINS MASL` or `OPTI PINS MAS2`, see page H.160, in order to eliminate constraints in multiple flat contact situations. Values of hardness are arbitrary. The only important thing is the relative value of hardness of two bodies that come into flat contact. The body with lower hardness behaves like a "slave", and the other one as a "master". It is advised to use simple integer values, e.g. 1, 2, 3 etc.

`KDIS kdis`

Penetration (displacement) related coefficient k_d for the elimination of progressive penetration when a LM-based pinball algorithm is used. This coefficients has no effect if the penalty version of the pinball algorithm is used. By default it is $k_d = 0$, i.e. no correction of the reaction is applied based on the penetration to eliminate the progressive penetration phenomenon. This keyword is incompatible with `RPEN` and `NPEN`.

`KVEL kvel`

Penetration-rate (velocity) related coefficient k_v for the elimination of progressive penetration when a LM-based pinball algorithm is used. This coefficients has no effect if the penalty version of the pinball algorithm is used. By default it is $k_v = 0$, i.e. no correction of the reaction is applied based on the penetration rate to eliminate the progressive penetration phenomenon. This keyword is incompatible with `RPEN` and `NPEN`.

`RPEN`

Remove penetration by activating the correction of the RHS of the contact constraint expression. This keyword is incompatible with `KDIS` and `KVEL`.

`NPEN npen`

Number of steps n in which the penetration shoudl be removed. By default $n = 1.0$. This keyword is incompatible with `KDIS` and `KVEL`.

`/LECT/`

List of the elements that will be associated with a (parent or 0-level) pinball of the set being described. For continuum-like bodies, these should typically contain only those elements along the body surface which are likely to come in contact with other objects.

Having defined all the pinball sets, next comes an optional definition of **pairs of sets** that should be excluded from contact. By default, the pinballs of each set are checked for contact against all pinballs of any other set (or even with pinballs of the *same* set if the `SELF` keyword has been used to define the current set). Occasionally, the user may want to disable some of these contacts. If the number of contact coompinations to be excluded is large, it may be conveninet to first exclude all combinations by the `EXCL ALL` directive and then to included the wanted combinations by `INCL PAIR`.

`EXCL`

Introduces a list of body pairs to be excluded from contact search.

`ALL`

Exclude all pairs. Then some pairs can be included by the `INCL` directive, see below.

`PAIR n1 n2`

The body pairs of indexes $n1$ and $n2$ (in the bodies list declared above) are to be excluded from contact search.

`INCL`

Introduces a list of body pairs to be included in the contact search. BY default, all combinations are included.

`ALL`

Include all pairs. This should be rarely useful since it is the default.

`PAIR n1 n2`

The body pairs of indexes $n1$ and $n2$ (in the bodies list declared above) are to be included in the contact search.

The last part of the input is also optional and concerns the activation of **contact-driven mesh adaptivity**.

`ADAP`

Activates *contact-driven mesh adaptivity*, i.e. automatic refinement and un-refinement of the mesh elements containing pinballs, based on contact detection (and on contact anticipation). Note that this type of mesh adaptivity is at the moment incompatible with other types of adaptivity such as those activated by the `WAVE` or `INDI` directives.

`LMAX lmax`

Introduces `lmax`, the desired maximum adaptive refinement level $L^{\max}$ of the structure mesh (elements) in the vicinity of contacting surfaces. This value should be greater than 1, since level 1 is attributed to the base mesh (no refinement). Each level corresponds to a halving of the mesh size with respect to the immediately previous level. The element level should not be confused with the pinball level, see details in the comments below.

`SCAL scal`

Introduces `scal`, an optional scaling factor ϕ_n to be used in the determination of elements to be refined belonging to non self-contacting bodies. By default $\phi_n = 1.0$. When scaling the structural influence domain by successive powers of two in order to identify, at each refinement level, the structure elements to be refined or un-refined, the code finally multiplies the result by this factor. Using a value of ϕ_n greater than one, e.g. 1.5 or 2, correspondingly enlarges the zone of structure mesh which is refined and this may result in a smoother mesh transition (for example, as an alternative to the option `OPTI ADAP RCON`).

`SCAS scas`

Introduces `scas`, an optional scaling factor ϕ_s to be used in the determination of elements to be refined belonging to self-contacting bodies. By default $\phi_s = 0.55$. The use of values of ϕ_s lower than 1.0 is necessary in self-contacting bodies in order to avoid a so-called *chain reaction*, i.e. immediate and uniform refinement of all the elements belonging to the self-contacting body up to the maximum chosen level. Theoretical values of ϕ_s can be determined for regular meshes made of continuum elements (see Table in the comments below), but not so easily for other cases. In practice, some experimentation is needed.

`NOUN`

When this optional keyword is specified, *no* element *unsplitting* is performed by the contact-driven adaptivity algorithm. That is, the mesh is refined near the contacting surfaces, but never unrefined.

This completes the definition of the input data.

Choice of the scaling factor for self-contacting bodies

The theoretical maximum scaling factors to be used for self-contacting bodies are shown in the following Table.

Comments:

Case	Encompassing pinballs	Equivalent pinballs
2D continuum (squares)	$\frac{\sqrt{2}}{2} = 0.707$	$\frac{\sqrt{\pi}}{2} = 0.886$
3D continuum (cubes)	$\frac{1}{\sqrt{3}} = 0.577$	$\sqrt[3]{\frac{\pi}{6}} = 0.806$

Table 15: Maximum scaling factor $\phi_{\max}$ for self-contact in 2D and 3D regular continuum meshes.

By default, each pinball (belonging to a certain body) is checked for contact with any other pinball belonging to a different body. If the current pinball's body is declared by the `SELF` keyword rather than `BODY`, then the pinball is checked for contact with any other pinball (including those belonging to the same body). A list of non-contacting body pairs can be optionally declared by the `EXCL` keyword.

For example, assume we have the following input:

```
PINB ... BODY ... /LECT1/ ! first body
         SELF ... /LECT2/ ! second body, is self-contacting
         BODY ... /LECT3/ ! third body
         EXCL PAIR 2 3
```

Then, the pinballs in the first body interact with those of the other two bodies, the pinballs of the second body interact with those of the first and second body, while the pinballs of the third body interact with those of the first body.

The exclusion mechanism can be useful, e.g., in the presence of contact on both sides of a (thin) shell, say a thin reservoir filled of liquid, which is impacted externally by a projectile The user may want to specify that the shell is in contact both with the liquid (internally) and with the projectile (externally), but direct contact between the projectile and the liquid may not occur.

Be sure to consult also the options related to the pinball model in Section H, see Page H.160, and the interactive commands for the visualization of pinballs and of contacts, see Pages A.25 and O.10.

When using penalty method to compute contact forces, contact stiffness is computed automatically from the stiffness of master elements using the following formulae:

$$k = \phi \frac{GS^2}{V}$$

in the case of solid master elements, with :

ϕ : optional scaling coefficient `sfac` given in input. By default $\phi = 1$.

G : bulk modulus of master element's material,

S : area of contacting face,

V : volume of master element.

$$k = \phi \frac{GS}{L}$$

in the case of shell master elements, with :

ϕ : optional scaling coefficient `sfac` given in input. By default $\phi = 1$.

G : bulk modulus of master element's material,

S : area of master element,

L : maximum length of master element's edges.

The bulk modulus G of the material is:

$$G = \frac{E}{3(1+\nu)}$$

where:

E : Young's modulus of master element's material,

ν : Poisson's coefficient of master element's material.

Distinction between element level and pinball level

Note that the above value of L_{max} refers to the maximum refinement level *of the elements* (adaptivity) $L_{\text{max}}^{\text{adap}}$, and not of the pinballs (contact) $L_{\text{max}}^{\text{pinb}}$. This distinction is unfortunate and is only needed due to historical reasons: the pinball models was developed and implemented in EPX long before the adaptivity model. The relation between the levels is as follows: a base (not refined) element in adaptivity has by convention $L^{\text{adap}} = 1$, while a base (parent) pinball in the contact model has by convention $L^{\text{pinb}} = 0$. Thus, it should be kept in mind that:

$$L^{\text{adap}} = L^{\text{pinb}} + 1$$

It seems preferable and more consistent with other adaptivity directives of EPX to use the `LMAX` keyword in the `PINB` ... `ADAP` directive to define $L_{\text{max}}^{\text{adap}}$ rather than $L_{\text{max}}^{\text{pinb}}$. In any case, it should be rarely necessary to use a hierarchic pinball method *in combination* with contact-driven adaptivity, so the level of the generated pinballs (attached to the smaller and smaller elements) will be zero, and the user can safely ignore this.

References

Examples of application of the contact model by the pinball method are presented in the following papers: [268].

8.52 CONTACT/IMPACT BY GENERALIZED PINBALL MODEL (GPIN)

Warning:

The present directive is currently still under implementation and validation. It may not be used yet for production runs. It is possible that not all keywords listed below be implemented yet.

Object:

The purpose is to define contact and impact conditions between Lagrangian subdomains (typically two or more solid bodies) by means of a variant of the "pinball" model, called "generalized pinballs" method. The model is inspired to the original pinball formulation proposed by Belytschko and co-workers in the papers: (*i*) Ted Belytschko and Mark O. Neal, "Contact-Impact by the Pinball Algorithm with Penalty and Lagrangian Methods", Int. J. Num. Meths. Eng., Vol. 31, pp. 547-572 (1991), and (*ii*) T. Belytschko and I.S. Yeh, "The splitting pinball method for contact-impact problems", CMAME, 105, pp. 375-393, (1993). However, generalized pinballs (GPINs) are not only spherical, but may assume other shapes (rectangles in 2D, cylinders, triangular prisms and hexahedra in 3D).

The user defines the elements that may enter in contact with one another and GPINs of the appropriate shapes are automatically associated with (typically the surface of) these elements. Interpenetration is detected by checking couples of GPINs. If this condition is satisfied, equal normal velocity is enforced by the method of Lagrange multipliers and the corresponding contact forces are computed.

Unlike the standard pinball model (`PINB`, see page D.480), the generalized pinball model does not admit (and does not need) hierarchical pinballs.

The uncoupled version of the generalized pinball algorithm (`DECO` keyword) uses a penalty method instead of (coupled) Lagrange multipliers.

Compatibility: `COUP`, `DECO`.

Syntax:

```
"GPIN" $[ "PENA" <"SFAC" sfac> ]$
          ( $[ "BODY" ; "SELF" ]$
              < $[ "NOCG" ; "SHCG" < "ANGL" angl > < "ABS" > ]$ >
              < "FROT" "MUST" must "MUDY" mudy "GAMM" gamm >
            /LECT/ )
          ( "DIAM" diam /LECT/ )
       < "MASL" ("PAIR" m s) >
       < "EXCL" ("PAIR" n1 n2) >
```

`PENA`

`DECO` only: mandatory keyword (ignored with `COUP`), must immediately follow the `GPIN` keyword and indicates that a penalty method is used.

`sfac`

`DECO` only: optional coefficient ϕ for the automatic determination of the contact stiffness (see comments below). By default it is 1.0.

`BODY`

Introduces the declaration of a set of generalized pinballs (GPINs) that form one of the bodies that may come in contact with other bodies. There may not be contact between GPINs belonging to the same body. Some restrictions apply to the elements that can be declared, see the comments below.

`SELF`

Introduces the declaration of a set of GPINs that form one of the bodies that may come in contact with other bodies. In this case, there may be contact between different GPINs belonging to this body (this model is called self-contact or auto-contact). Some restrictions apply to the elements that can be declared, see the comments below.

`NOCG`

Do not create corner GPINs (C-GPINs) for this body. This has only effect in 3D. By default, C-GPINs are cerated in 3D for all corners (both sharp and not sharp) of continuum bodies and for all corners (both sharp and not sharp) and all free edges of plate/shell bodies.

`SHCG`

Create corner GPINs (C-GPINs) only at *sharp* corners and at free edges for this body. For the definition of sharp corners see the description of the `ANGL` keyword below. This has only effect in 3D.

`ANGL`

Sets the minimum angle α_0 (between two 3D faces with a common side) beyond which the side is considered to be a sharp corner. By default, this angle is 60 degrees. Let n_1 and n_2 be unit normals to the two faces. Then the scalar product $n_1 \cdot n_2 = \cos\alpha$ is equal to the cosine of α, the angle between the normals (which is also the angle between the faces). Thus the corner is sharp if $\cos\alpha < \cos 60°$, i.e. when $\alpha < 60°$.

`ABS`

Consider the absolute value of the above scalar product instead of the signed value. This has the following effect: when two faces have a common side and opposite (or nearly opposite) normals, the side is *not* considered sharp (while by default it would be). This option may be useful in the presence of complex 3D shell structures, because it is not always easy (and sometimes even impossible) to orient them consistently. With this option many "spurious" sharp corners disappear. Thus with this option the rule becomes: the corner is sharp when $|\alpha| < 60°$.

`FROT`

Introduces the specification of (optional) friction characteristics for the current contacting body. A simple Coulomb dry friction model is assumed.

`MUST`

Specifies the limiting friction coefficient for the static case μ_S. This is the value assumed when no sliding occurs between the contacting surfaces. It must be $(0 \leq \mu_S \leq 1)$.

`MUDY`

Specifies the friction coefficient for the dynamic (or kinetic) case μ_K. This is the (asymptotic) value assumed at very large (infinite) relative velocity of the contacting surfaces. It must be $(0 \leq \mu_K \leq \mu_S \leq 1)$.

`GAMM`

Parameter (γ) of the law of variation of the friction coefficient (μ) with the relative tangential sliding velocity (v_r) of the contacting surfaces. It must be $\gamma \geq 0$. The friction coefficient μ varies from μ_S to μ_K as the relative tangential velocity v_r of the two bodies increases. The transition between the two regimes is governed (smoothly) by the exponential decay law: $\mu = \mu_K + (\mu_S - \mu_K)e^{-\gamma|v_r|}$. Note that for $\gamma = 0$ we have $\mu = \mu_S$, *independently* from the relative velocity $|v_r|$ *and* from the value chosen for $\mu = \mu_K$.

`/LECT/`

List of the **elements** whose nodes (and then faces) will be associated with GPINs of the set being described.

`DIAM`

Introduces the declaration of a “contact diameter” to be associated with the nodes specified next. The nodes specified must be a sub-set of the nodes belonging to the elements listed in the previous `BODY` or `SELF` declarations. Some restrictions apply to the nodes that can be declared, see the comments below.

`diam`

Generalized pinball diameter (contact diameter) to be associated with P-GPINs attached to the nodes specified by the following `/LECT/`.

`/LECT/`

List of the **nodes** concerned.

`MASL`

Introduces a list of body pairs acting as master/slave with respect to each other. By default, body pairs not mentioned in this list act as both master and slave with respect to each other.

`PAIR m s`

The body of indexs `m` acts as a master when contacting body of index `s`, which acts as a slave. It must be `1 <= m <= B`, `1 <= s <= B` and `m /= s`, with `B` the total number of bodies previously declared.

`EXCL`

Introduces a list of body pairs to be excluded from contact search.

`PAIR n1 n2`

The body pairs of indexes $n1$ and $n2$ (in the bodies list declared above) are to be excluded from contact search.

Comments:

A point GPIN (P-GPIN) is associated to each **node** to which a contact diameter has been assigned via the `DIAM` directive. Then, the other GPIN types (L-GPINs in 2D, or L/T/Q-GPINs in 3D) are built for each **element face** whose nodes have *all* received a contact diameter.

The following **restrictions** apply to the elements that are declared in the `BODY` (or `SELF`) directive, and to the nodes that are declared in the `DIAM` directive described above:

- An element cannot belong to more than one body at the same time, therefore each element index can appear in at most one `BODY` or `SELF` declaration.
- A node potentially subjected to contact, and therefore with an assigned `DIAM`, cannot belong to more than one body at the same time.

Since a P-GPIN is attached to each such node, and this P-GPIN (like any other GPIN) must have one and only one associated body index, for obvious reasons, it follows that:

- The nodes which are common to elements belonging to more than one body cannot have an associated `DIAM`, and therefore cannot participate in the contact.
- In other words, (the elements of) two or more bodies can have some nodes in common, but no one of such nodes can have an associated `DIAM`, because it cannot participate in the contact.

By default, each GPIN (belonging to a certain body) is checked for contact with any other GPIN (of suitable type) belonging to a different body. If the current GPIN's body is declared by the `SELF` keyword rather than `BODY`, then the GPIN is checked for contact with any other GPIN of suitable type (including those belonging to the same body). A list of non-contacting body pairs can be optionally declared by the `EXCL` keyword.

For example, assume we have the following input:

```
GPIN ... BODY ... /LECT1/ ! first body
         SELF ... /LECT2/ ! second body, is self-contacting
         BODY ... /LECT3/ ! third body
         DIAM ... /LECT123/ ! same diameter at all nodes
         EXCL PAIR 2 3
```

Then, the GPINs in the first body interact with those of the other two bodies, the GPINs of the second body interact with those of the first and second body, while the GPINs of the third body interact with those of the first body.

The exclusion mechanism can be useful, e.g., in the presence of contact on both sides of a (thin) shell, say a thin reservoir filled of liquid, which is impacted externally by a projectile The user may want to specify that the shell is in contact both with the liquid (internally) and with the projectile (externally), but direct contact between the projectile and the liquid may not occur.

Be sure to consult also the options related to the generalized pinball model in Section H, see Page H.160, and the interactive commands for the visualization of generalized pinballs and of contacts, see Pages A.25 and O.10.

When using penalty method to compute contact forces, contact stiffness is computed automatically from the stiffness of master elements using the following formulae :

$$k = \phi \frac{GS^2}{V}$$

in the case of solid master elements, with :

G : bulk modulus of master element's material,

S : area of contacting face,

V : volume of master element.

$$k = \phi \frac{GS}{L}$$

in the case of shell master elements, with :

G : bulk modulus of master element's material,

S : area of master element,

L : maximum length of master element's edges.

The bulk modulus G of the material is:

$$G = \frac{E}{3(1+\nu)}$$

where:

E : Young's modulus of master element's material,

ν : Poisson's coefficient of master element's material.

8.53 FLUID-STRUCTURE SLIDING BY "FSS"

Object:

The purpose is to define fluid-structure sliding lines of the ALE, Lagrangian or fixed type according to the models developed at JRC Ispra.

These directives are obsolete and are maintained only for compatibility with old input files. Use the "LINK COUP FSA" or "LINK COUP FSR" directives instead.

Compatibility: `DECO`

Syntax:

```
"FSS"  | "ALE"  . . . |
       | "LAGR" . . . |
       | "FIXE" . . . |
```

Comments:

These directives use a rather primitive input syntax that obliges the user to use node indexes and often leads to complex and lengthy input data. A simplification of the input structure to allow the use of GIBI objects is foreseen, but not yet available.

FLUID-STRUCTURE SLIDING OF THE ALE TYPE

Object:

Defines fluid-structure sliding lines of the ALE type according to the model developed at JRC Ispra. In this type of sliding, the couples of nodes remain permanently aligned. Thus, there is sliding of the fluid along the structure or with respect to another (master) fluid, but the mesh does not slide. This type of sliding is useful for permanently submerged parts of a structure.

```
        s2  m2  m4 s4
         / /    / /
- - -----0 0----0 0----- - -
         | |    | |
         | | me | |
         | |    | |
      F  | | S  | |  F
         | | or | |
         | | F  | |
         | |    | |
         | |    | |
- - -----0 0----0 0----- - -
         / /    / /
        s1 m1  m3 s3
```

```
F = fluid element
S = structural element
```

Note:

Nodes (s1, m1) (s2, m2) (s3, m3) (s4, m4) are coincident in the real geometry.

Master (structural or fluid) nodes are Lagrangian, while slave nodes are treated by the ALE formulation and are constrained to follow the corresponding master nodes.

Compatibility: `COUP`

Syntax:

```
    "ALE"   "NCOT" nasle * ( /LECTURE/ )
            "NPOI" nasln
 where:

    /LECTURE/ = LECT me m1 m2 s1 s2 m3 m4 s3 s4 c1 c2 TERM
```

`nasle`

Number of ALE sliding element side couples of the type shown in the above sketch, to be described by the following /LECTURE/.

`me`

Master element index.

`m1, m2`

Nodes defining the first master element side.

`s1, s2`

Nodes defining the first slave element edge.

`m3, m4`

Nodes defining the second master element side (default is 0 0, i.e. sliding occurs along one side only of the master element).

`s3, s4`

Nodes defining the first slave element edge (default is 0 0, i.e. sliding occurs along one side only of the master element).

`c1, c2`

Key to define the type of connection for nodes (s1, m1, m3, s3) and (s2, m2, m4, s4), respectively. Normally these values are both 1, that means ALE sliding. A value of 0 means connection without sliding: this allows to rapidly eliminate a sliding condition, i.e. as if the nodes were rigidly connected, without modifying too much the input. Note that, when a sliding condition is eliminated by posing c1 or c2 equal 0, the corresponding slave node must be declared Lagrangian in the GRILLE directive. Finally a third possibility, indicated by the value -1, is used to model a so-called U-bend ALE sliding. This is useful for situations where a thin structure is permanently submerged in a fluid, in order to model the U-shaped flow around a tip in the structure (represented by the shell element thickness). In this case, the two structural nodes on the tip have different normals (while for 'inner' nodes the normal is unique), so a special treatment is needed.

`nasln`

Total number of nodes defining each of the (slave or master) ale sliding lines.

Comments:

If a negative value is given for m1, m2, s1, s2, m3, m4 s3 or s4, then the corresponding node is not considered in the ALE sliding process. This feature is useful when modeling e.g. a continuous fluid-structure interface of which one part has a sliding condition of the ALE type, while the rest has a condition of the Lagrangian type. In this case, the element couple at the transition between the two conditions will have one couple of ALE sliding nodes, and the other one Lagrangian. This Lagrangian couple of nodes, say m2 and s2, should have negative indexes.

Finally, note that in this type of sliding the number of nodes in the fluid and in the structure must coincide (the nodes themselves must coincide two by two), so the mesh size is necessarily the same on both sides and it is not possible to use a finer mesh on one of the sides with respect to the other.

FLUID-STRUCTURE SLIDING OF THE LAGRANGIAN TYPE

Object:

Defines fluid-structure sliding lines of the Lagrangian type according to the model developed at JRC Ispra. In this type of sliding, the couples of nodes do not remain permanently aligned. Thus, there is sliding of the fluid mesh along the structure. This type of sliding is useful when the interface nodes cannot be kept permanently aligned, e.g. near free surfaces. The first side of the sliding line consists of fluid nodes only; the second side may consist either of structural or of (master) fluid nodes.

```
     first side  second side
              f2 s2
               / /
      - - -----0 0----0
               | |    |
            fe | | se |
               | |    |
             F | | S  |
               | | or |
               | | F  |
               | |    |
               | |    |
      - - -----0 0----0
               / /
              f1 s1

  F = fluid element
  S = structural element
```

Compatibility: `COUP`

Syntax:

```
   "LAGR"   "NCT1" lsle1 * ( /LECTURE1/ )
            "NPOI" lsln1
            "NCT2" lsle2 * ( /LECTURE2/ )
            "NPOI" lsln2
where:

   /LECTURE1/ = LECT fe f1 f2 TERM
   /LECTURE2/ = LECT se s1 s2 TERM
```

`lsle1`

Number of element sides on the first side (slave side) of the Lagrangian sliding line.

`fe`

Index of the fluid (slave) element.

`f1, f2`

Indexes of the nodes of the slave edge (first side).

`lsln1`

Total number of nodes defining the slave edges.

`lsle2`

Number of element edges on the second side (master side) of the Lagrangian sliding line.

`se`

Index of the structural (or master fluid) element.

`s1, s2`

Indexes of the nodes of the master edge (second side).

`lsln2`

Total number of nodes defining the master edges.

Comments:

If a negative value is given for f1, f2, s1 or s2, then the corresponding node is not considered in the Lagrangian sliding proocess. This feature is useful when modeling e.g. a continuous fluid-structure interface of which one part has a sliding condition of the ALE type, while the rest has a condition of the Lagrangian type. In this case, the element couple at the transition between the two conditions will have one couple of ALE sliding nodes, and the other one Lagrangian. The ALE couple of nodes, say m2 and s2, should have negative indexes.

In this type of sliding, the number of nodes on the fluid side may be different from that on the structural side, since the nodes don't have to be aligned in the initial configuration, as it is the case for ALE sliding. It is therefore possible to use meshes of different size for the fluid with respect to the structure.

FLUID-STRUCTURE SLIDING OF THE FIXED TYPE

Object:

Defines fluid-structure sliding lines of the fixed type according to the model developed at JRC Ispra. This type of sliding is sometimes useful to model rigid inviscid boundaries. Nodes belonging to a fixed sliding line are treated as Lagrangian. The fixed boundary is defined via a series of points identified by their coordinates.

```
                  x
                 /
    - - -----0  /
            /  /
      F    /  /
          /  /
- - -----0  x
         |  |
    F    |  |
         |  |
         |  |
- - -----0  |
            |
            x

   F = fluid element
   0 = fluid node
   x = fixed point defining fixed sliding line
```

Compatibility: `COUP`

Syntax:

```
"FIXE"   "NPOI" n1fsl /LECTURE/
         "NFIX" n2fsl * ( xcoor ycoor )
```

`n1fsl`

Number of nodes on the fixed sliding line.

`n2fsl`

Number pf fixed points used to define the fixed boundary.

`xcoor, ycoor`

Coordinates of the fixed point.

8.54 NODE TO SHELL CONNECTOR

Object:

This element is used in order to connect node to a master edge of shell. Note that the "SH3D" directive is a subdirective of the "LIAI" directive but it is needed to define an element which defines the nodes (master and slave) of the liaisons. It is listed in this Section because it consists in the definition of kinematic constraints between the dof of one slave node and 2 master nodes.

Compatibility: `COUP`, `LIAI`

```
        N4-----------N3
        |            |
        |            |
        |            |
        |            x S
        |            |
        |            |
        N1 --------- N2

    N1,N2,N3,N4 = nodes shell
    S           = Slave node
```

Syntax:

```
    "SH3D OPT 2"
             ( /LECTURE/)
```

`/LECTURE/`

Reading procedure of the elements

Comments:

Note that in the "GEOM" directive the definition of the element must be in this order : N1 N2 S ie the slave node is defined after the two master nodes.

8.55 WEAK FLUID-STRUCTURE COUPLING 2 (FLSW)

Object:

This directive allows to specify a “weak” coupling (`LINK DECO`) between a fluid and a structure modelled by topologically independent meshes. It is similar to `FLSR` (see page D2.143) but uses a weak approach (direct application of the fluid pressure onto the structure) rather than a strong approach (constraint on velocity imposed by Lagrange multipliers).

The present `FLSW` directive is only intended for use with cell-centered Finite Volumes (CCFV) modeling of the fluid. For a certain period, it was also possible to use `FLSW` with Finite Element (FE) modeling of the fluid. In this case, the code internally used a decoupled master/slave approach version of the `FLSR` algorithm. However, this possibility was considered misleading and it was removed as of July 2019 (the code gives an error message and stops if one tries to use FE in the FLSW fluid domain). Note, however, that the decoupled master/slave approach version of the `FLSR` algorithm can be (directly) accessed via the `LINK DECO FLSR` directive, see page D.143. Therefore, in order to repeat an old calculation that used the `LINK DECO FLSW` command with a FE fluid mesh, just replace it by `LINK DECO FLSR`.

The fluid mesh may be either fully general (unstructured) or regular (structured), as specified by the `STFL` directive described on page C.68. In the latter case, the search operations are faster. The `COMP STFL` directive produces by default a Finite Element regular mesh for the fluid domain (which is not suited for use in conjunction with the present `FLSW` model). To create a regular cell-centred Finite Volume mesh instead, for use with `FLSW`, add the extra `VFCC` keyword to the `COMP STFL` directive (see page C.68).

The FSI coupling is realized between structural points (ultimately, structural nodes) on one side, and *fluid entities* on the other side. The nature of the fluid entities depends upon the chosen options. They are fluid *cell centroids* if the `VOLU` keyword (or nothing) is specified (this is the default), while they are fluid *cell interfaces* if the `FACE` keyword is specified (see below for details).

As indicated by the brackets in the syntax, the `STRU` data block can be repeated at will, in order to define one or more FSI interaction (structure) zones, each with its own set of parameters. The `STRU /LECTS/` keyword *must* be the first one of each zone being defined.

Compatibility: `DECO`

Syntax:

```
 FLSW  |[ FLUI /LECTF/ ; STFL ]|
       $[ HGRI hgri ; NMAX nmax ; DELE dele ]$
         <DGRI>
         <VOLU ; FACE>

     ( STRU /LECTS/
       $[ R r ; GAMM gamm ; PHIS phis ; GAMI gami ]$
       <BFLU bflu> <FSCP fscp>
       <ADAP LMAX lmax <SCAL scal> >                )
```

Basic fluid-related parameters

FLUI

The fluid mesh to be coupled with the structure is fully general (unstructured). The concerned elements are specified next.

/LECTF/

List of fluid **elements** concerned. The fluid mesh is unstructured.

STFL

The fluid mesh to be coupled with the structure is regular (structured). The concerned **elements** (volumes) need not be specified. In fact, they are simply the elements (volumes) generated by the `COMP STFL` directive described on page C.68, which must in this case have been specified previously in the input file. Since by default the `COMP STFL` directive produces Finite Elements for the fluid domain, make sure to add the `VFCC` optional keyword to that directive (see page C.68), so that cell-centered Finite Volumes are created instead.

Fast search of coupled fluid entities

The next three keywords (`HGRI`, `NMAX` or `DELE`) are used to determine the size of the spatial grid used for the *fast search* of fluid entities (nodes, or cell interfaces if the `FACE` keyword is specified, see below) contained within the influence domain of the structure. Fast search speeds up the calculation and is *absolutely essential* in medium and even more in large size simulations. For this reason, fast search is *always active* in the present FSI model. Note that this may be unlike other types of search in EPX. For example, in the pinball contact model (`PINB`) fast search of pinballs contact is *not* active by default (an option has to be activated).

By default, i.e. if neither `HGRI`, nor `NMAX`, nor `DELE` are specified, the code takes `DELE 1.01`.

A (regular) spatial grid is built up and used for the fast search. The fluid entities (centroids or interfaces) contained in a cell of the search grid are tested for inclusion in the structural influence subdomains contained either in the same cell or in a direct neighbour cell (there are up to 8 such cells in 2D, up to 26 cells in 3D). The cell grid can be optionally dumped out on the listing by the `DGRI` keyword.

For the calculation to be as fast as possible, the fast search grid must have the minimum size ensuring correctness of results, i.e. such that a (barely) sufficient number of interacting entities is detected, and thus no spurious fluid passage occurs across the structure. If h_F denotes the size of the fluid mesh and h_S the size of the structure mesh, then the grid size h_G must be:

$$h_G = \phi \cdot \max(h_F, h_S) \tag{87}$$

where $\phi > 1$ is a safety factor. A value $\phi = 1.01$ should be sufficient. Since a single grid is used for the search over the whole computational domain, h_F and h_S in the above expression must be the *maximum* sizes of the fluid and structural elements which are susceptible of interacting, i.e. which belong to the `/LECTF/` set defined above and to the `/LECTS/` set(s) defined below, respectively.

In calculations *without adaptivity* one has normally $h_F < h_S$ for accuracy reasons (especially if shells are used to discretize the structure), so that the grid size is (normally) dictated by the largest coupled structural element. For the case of adaptive calculations, see the Remarks at the end of this manual page.

HGRI

Specifies the size of the fast search grid cell. Each cell has the same size in all spatial directions and is aligned with the global axes.

`NMAX`

Specifies the maximum number of cells along one of the global axes.

`DELE`

Specifies the size of the fast search grid cell as a multiple of the length of the largest coupled **structural** element. Element "diameters" are computed only along each global spatial direction and the maximum is taken. For example, by setting `DELE 2` the size of the cell is two times the length of the largest coupled structural element. By default, i.e. if neither `HGRI`, nor `NMAX`, nor `DELE` are specified, the code takes `DELE 1.01`.

`DGRI`

Dump out the grid of cells used for fast searching on the listing. For brevity, the print is done only the first time that the grid is computed.

Additional search parameters

Next come some additional parameters for the geometric search.

`VOLU`

For use with Cell Centered Finite Volumes only. The search for fluid entities "contained" in the influence domain of the structure is based upon the element volume, more precisely on the position of the element centroid. This is the default.

`FACE`

For use with fluid Cell Centered Finite Volumes only. The search for fluid entities "contained" in the influence domain of the structure is based directly upon the "faces" (interfaces) between neighboring cells. The centroid of the face is considered rather than the centroid of the finite volume. In this case, there is no difference between using `BFLU` 1 or `BFLU` 2, see below. However, please note that by omitting `BFLU` or by specifying `BFLU 0` (the default value for `BFLU`) no numerical fluxes are blocked. So, if `FACE` is used and fluxes must be blocked (as is normally the case), one must specify either `BFLU` 1 or `BFLU` 2 (with no difference in the results).

Structural influence domain(s)

The following block of data, introduced by the keyword `STRU`, can be repeated any number of times (but it must be specified at least once) to define one or more FSI zones, each with different interaction parameters. For each such zone:

`STRU`

Introduces the structure mesh to be coupled with the fluid. The concerned elements are specified next.

`/LECTS/`

List of structural **elements** concerned. All their nodes must be declared as Lagrangian.

The next four keywords (`R`, `GAMM`, `PHIS` or `GAMI`) are used to set the **size** (thickness) of the **structural influence domain** surrounding the structure elements defined above by `/LECTS/`. All fluid entities as defined above (cell centroids or cell interfaces) contained within this influence domain will be coupled to the structure.

Therefore, the correct size of the influence domain is related to the size of the fluid mesh in the vicinity of the embedded structure. On one hand, if the influence domain is too thin, then some interactions between the structure and the fluid entities might be overlooked, thus resulting in spurious passage of fluid across the structure (*leakage*). On the other hand, if the influence domain is too thick, too much fluid will be interacting with the structure (excessive added mass effect). The optimal value is then the minimum value which ensures structure tightness (no leakage).

By default, i.e. if neither `R` nor `GAMM` nor `PHIS` nor `GAMI` are specified, the code performs an automatic determination of influence spheres at each coupled structural node by using the default value of `GAMM` ($\gamma = 1.01$). For the choice of `R`, `GAMM`, `PHIS` or `GAMI` in adaptive calculations see the `ADAP` keyword below and the comments at the end of this page.

`R`

Prescribed (fixed) radius R of influence spheres at each coupled structural node. In the special, but frequent, case of a uniform structured fluid mesh (uniform square or cube elements) it is suggested to take R slightly larger than the semi-diagonal of a fluid element. This means that, for a 2D uniform square fluid mesh of side L_Φ one should take $R = 0.71L_\Phi$ while for a 3D uniform cube fluid mesh of side L_Φ one should take $R = 0.87L_\Phi$.

`GAMM`

Coefficient γ for the automatic determination of influence spheres at each coupled structural node, based on the size of the *enclosing fluid element* (which must thus be found by the code by means of a fast search algorithm, see the remarks at the end of this manual page). The sphere radius is $R = \gamma R_F = \gamma\delta L_\Phi$ where L_Φ is the local length (size) of the fluid mesh, δ is a coefficient related to the space dimension d of the problem ($\delta = \frac{\sqrt{d}}{2}$, i.e. about 0.71 in 2D and about 0.87 in 3D calculations). The quantity indicated as R_F above is the "natural" size of the sphere radius, i.e. the radius of a sphere (circle in 2D) which exactly encompasses all nodes of a regular element (regular cube in 3D or regular quadrilateral in 2D). By default it is $\gamma = 1.01$. This value should ensure "tightness" of the structure, at least for a regular mesh. By increasing the value, tightness is safer but the amount of fluid "attached" to the structure also increases. By decreasing the value, some local spurious passage of fluid across a solid structure might occur.

`PHIS`

Coefficient ϕ_s for the automatic determination of influence spheres at each coupled structural node. The sphere radius is equal to ϕ_s times the minimum structural element length at the concerned node. By default it is $\phi_s = 0.3$. This option should be rarely used. It is advisable to use `GAMM` instead.

`GAMI`

Same as `GAMM` but radius is computed only at the initial step, that is, the radius is *not* updated during the calculation. This may be convenient (to save some CPU) in calculations with Eulerian fluid mesh (that never changes) and without adaptivity.

Additional flux and coupling parameters

Next come some additional parameters for the fluxes and for the type of coupling.

`BFLU`

Type of treatment of numerical fluxes (density and energy, but **not** momentum) in fluid models, when used in conjunction with the present `FLSW` directive. The value 0 (default) indicates that fluxes are freely computed. The value 1 indicates that fluxes are blocked between two fluid entities which are both within the influence domain of the structure. The value 2 indicates that fluxes are blocked between two fluid entities of which at least one lies within the influence domain of the structure. If the `FACE` keyword has been specified (see above), there is no difference between using `BFLU` 1 or `BFLU` 2. However, please note that by omitting `BFLU` or by specifying `BFLU 0` (the default value for `BFLU`) no numerical fluxes are blocked. So, if `FACE` is used and fluxes must be blocked (as is normally the case), one must specify either `BFLU` 1 or `BFLU` 2 (with no difference in the results).

`FSCP`

Type of coupling between fluid entities and corresponding structural points, when used in conjunction with the present `FLSW` directive. The value 0 (default) indicates that coupling occurs only in the direction normal to the structure. The value 1 indicates that coupling occurs along all spatial directions.

FSI-driven adaptivity

Finally, there are some optional keywords related to automatic (FSI-driven) adaptivity of the fluid mesh near the structure.

`ADAP`

Activates mesh adaptivity for automatic refinement and un-refinement of the fluid mesh specified by `/LECTF/` in the vicinity of the structure specified by `/LECTS/`. Note that this type of mesh adaptivity is at the moment incompatible with other types of adaptivity such as those activated by the `WAVE` or `INDI` directives.

`LMAX`

Introduces `lmax`, the desired maximum adaptive refinement level $L^{\max}$ of the fluid mesh in the vicinity of the structure. This value should be greater than 1, since level 1 is attributed to the base mesh (no refinement). Each level corresponds to a halving of the mesh size with respect to the immediately previous level.

`SCAL`

Introduces `scal` (s), an optional scaling factor to be used in the determination of fluid elements to be refined. By default `scal` is equal to 1. When scaling the structural influence domain by successive powers of two in order to identify, at each refinement level, the fluid elements to be refined or un-refined, the code finally multiplies the result by this factor. Using a value of s greater than one, e.g. 1.5 or 2, correspondingly enlarges the zone of fluid mesh around the structure which is refined and this may result in a smoother mesh transition (for example, as an alternative to the option `OPTI ADAP RCON`). Note, however, that s has no influence on the size of the structural influence domain used for the final search of fluid entities (fluid nodes or fluid cell interfaces) interacting with the structure. This search is always done by the smallest influence domain $R_{L_{\max}} = R_1/2^{L_{\max}-1}$, i.e. *without* taking into account the s factor.

In **FSI adaptive calculations**, the size of the structural influence domain specified in input by `R`, `GAMM` or `PHIS` (`GAMI` is not appropriate with adaptivity) is related to the *base* (i.e. the coarsest) fluid mesh size, not to the refined one (for the user's convenience) and is then scaled automatically by the code whenever necessary, up to the maximum chosen refinement value given by the `ADAP LMAX` keyword. Therefore, in order to try out different adaptive refinement levels in the vicinity of the structure the user needs only to change `LMAX` in the input directive (all other parameters `R` etc. remain the same).

In **FSI adaptive calculations**, that is when the `FLSW ADAP LMAX` optional keyword has been specified, one is **certain** that the fluid mesh in the vicinity of the structure will be constantly refined to the maximum level (minimum size) specified for the fluid (`LMAX`), given by:

$$h_F^{\text{refined}} = h_F^{\text{base}}/2^{L_{\max}-1} \tag{88}$$

For this reason, in the equation (87) for the determination of the grid size `HGRI` (h_G) one can use h_F^{refined} instead of the base fluid mesh $h_F^{\text{base}} = h_F$, obtaining thus:

$$h_G = \phi \cdot \max(h_F^{\text{refined}}, h_S) \tag{89}$$

One should make sure to use (89) instead of (87) since it is likely to be $h_F^{\text{refined}} < h_S$, while it is typically $h_F > h_S$, so this may lead to important savings of CPU time.

Remarks:

In case of automatic determination of influence spheres based on the `GAMM` keyword in conjunction with an **unstructured** fluid grid, a fast search over the coupled fluid elements is needed in addition to the normal fast search over the coupled structural elements. Scope of this second search is to determine, for each structural node, which is the fluid element currently containing the node. For this purpose, the code uses a fast search algorithm by means of the same parameters (`DGRI`, `HGRI`, `NMAX`, `DELE`) specified above for the search over structural elements. Note, however, that as concerns this second search if `DELE` is specified it refers to the size of the fluid element rather than to the size of the structural element. However, if a **structured** fluid grid is specified, then no additional search is needed because the containing fluid element can be detected directly.

Make sure you consult the additional **options** related to the functioning of the `FLSW` model in pages H.155 and H.160.

References

The `FLSW` model is similar to `FLSR` of page D.143 in many aspects. It was first described in report [317]. Improvements to the `FLSW` model were proposed in reference [903].

8.56 NODE ON FACET ELEMENT

Object:

Note that the "MAPi" directive (i = 2,..7) is a subdirective of the "LIAI" directive but it is needed to define an element which defines the nodes (master and slave) of the liaisons. It is listed in this Section because it consists in the definition of kinematic constraints between the dof of one slave node and master nodes.

The purpose is to to glue one slave node to a master face. It can be used in 2-D (the face is a line) or in 3-D.

Compatibility: `COUP`, `LIAI`
Different cases can be used and are listed below.

Name	Dimension	Npt	Dof	Nb. of liaisons	Remarks
MAP2	2	3	2	2	point on solid line
MAP3	3	4	3	3	point on triangular solid facet
MAP4	3	5	3	3	point on quadrangular solid facet
MAP5	2	3	3	3	point on 2D shell line
MAP6	3	4	6	6	point on triangular shell facet
MAP7	3	4	6	6	point on quadrangular shell facet

Note:

In 3-D the slave node S should be on the face.

```
    MAP2      |         MAP7

      N1      |      N1-------N2
       |      |      |         |
       |      |      |      S  |
     S x      |      |      x  |
       |      |      |         |
      N2      |      N3-------N4
              |
              |

  N1,N2,N3,N4 = Master nodes
  S           = Slave node
```

Syntax:

```
"MAPi"
     ( /LECTURE/ )
```

`/LECTURE/`

Reading procedure of the elements.

Comments:

Note that in the "GEOM" directive the declaration of the element must be in this order : S N1 N2 (N3 N4), ie the slave node is the first node of the list.

8.57 FINITE-ELEMENT/SPECTRAL-ELEMENT INTERFACE

Object:

This directive allows to specify the interface between a Finite Element domain and a Spectral Element domain in a coupled analysis.

It replaces the former principal directive `FESE`, which is no longer accepted. The difference is that FE/SE interfacing is now coupled with any other (coupled) links specified in the calculation (`LINK COUP`), while formerly the FE/SE interface conditions were treated as a separate set of conditions.

Compatibility: `COUP`

Syntax:

```
"FESE" "FNOD" /LECT1/
       "SNOD" /LECT2/
```

`/LECT1/`

List of Finite Element nodes along the FE/SE interface.

`/LECT2/`

List of (micro) Spectral Element nodes along the FE/SE interface.

Remarks:

The model is quite general and accepts the node lists in any order. It is even possible to define interfaces formed by several disjoint lines (or surfaces, in 3D).

The only restriction is that FE and (micro) SE nodes must lie with sufficient precision on the interface, which is defined geometrically by the macro Spectral Element faces.

Furthermore, note that to every macro Spectral Element node on the interface, there must exist one and only one FE node in LECT1 that has the same coordinates. This is necessary in order to ensure that to every FE face on the interface there correspond one and only one opposite macro Spectral Element face (the reverse is not true, in general).

8.58 NAVIER-STOKES (INCOMPRESSIBILITY)

Object:

This directive allows to specify an incompressible or quasi-incompressible behaviour for selected fluid elements. These elements must possess the LIQU material (see page C.390).

It replaces the former NAVI problem type directive (see page A.30) which automatically generated liaison conditions for all elements containing a LIQU material.

Compatibility: `COUP`

Syntax:

```
"NAVI" /LECT/
```

`/LECT/`

List of Finite Elements concerned. These must possess the LIQU material.

Remarks:

With this directive, it is not allowed to specify the NAVI keyword in the problem type. Use either the old (NAVIER problem type) directive or the present one, but not together in the same run.

For the moment, only elements of type CAR1, TUBE and TUYA are accepted.

Be aware the verification of a link of type NAVI, as activated by the optional keyword VERI of the LINK directive (see page D2.10), makes sense only when the corresponding LIQU material is perfectly incompressible. In fact, when the material is (even slightly) compressible, as indicated by a finite sound speed `C` specified in the material parameters, an extra term is added to the diagonal of the assembled links matrix during the solution process. Therefore, it is normal that the original link specification does not hold any more.

8.59 PIPELINE RUPTURE CONNECTION

Object:

This FSI model allows modelling a break of a pipeline discretized with TUYA elements. Prior to the pipeline rupture instant, the conservation of the internal fluid mass flow rate and the continuity of the mechanical degrees of freedom are ensured.

Compatibility: `COUP`

Syntax:

```
"BREC"   < "TRUP" trup >   /LECTURE/
```

`trup`

Rupture instant (no breaking by default).

`/LECTURE/`

Number or the name of the BREC element.

Comments:

This directive may only be used to connect two TUYA elements.

Outputs:

The components of the ECR table are as follows:

ECR(25): pipeline rupture area (water)

ECR(26): mass flow (water)

ECR(27): total ejected mass (water)

8.60 SURFACE PRESSURE MEASURED IN AN ELEMENT (PELM)

Object:

This directive allows to apply the value of ECRO 0 (known as pressure in a fluid) on structural facets (referred to as slave facets), which is measured in a given fluid element of the model (referred to as master element).

It is typically useful when a cavity is modelled by an equivalent pipe network instead of a full 3D mesh, but the pressure on its structural envelop must still be taken into account. Reference element would then be one of the TUBE or TUYA elements used for the cavity and the facets the structural envelop. Compatibility: `DECO`

Syntax:

```
PELM   ( MAIT /LECTURE/
         ESCL /LECTURE/
         < NOEX /LECTURE/ >
         < |[ INTE ; EXTE ]| /LECTURE/ >
         < PREF pref >
         < VFCC > )
```

`pref`

Reference pressure.

`VFCC`

Option to signal that the fluid is computed with VFCC

Comments:

Only one master element must be provided for each set of slave facets.

If slave elements are 3D continuum elements, pressure is applied on any of their free facets, along the inward normal direction.

If slave elements are 3D shell elements, keywords INTE or EXTE are used to enter a node defining the internal or external side of the structure respectively and again, pressure is applied along the inward normal direction. Option NOEX allows excluding some slave nodes from applying pressure.

No retroaction occurs from the structure onto the fluid element, which is licit only in the case of a large cavity which imposes its pressure and for limited structural displacements.

The way pressure is applied on the slave nodes in 3D depends on the method used to model the fluid. In FE, the pressure repartition is related to the shape function of the element whereas in FV, the pressure is basically divided by the number of nodes. Then option VFCC is used to tell Europlexus that the fluid is modelled with the Finite Volume Method and then the pressure of the fluid on the structure should be applied accordingly.

8.61 UNCOUPLED HANGING LINKS

Object:

This directive allows to toggle uncoupled master/slave algorithm to handle hanging links with ADAPTIVITY instead of the fully coupled Lagrange Multipliers approach.[MPI only].

Compatibility: `DECO`

Syntax:

```
ADAP
```

Comments:

No further subdirective is currently needed.

8.62 PRESCRIBED DAMAGE FOR GRADIENT DAMAGE MATERIALS

Object:

This directive defines imposed damage values for gradient damage materials `ENGR`, see 7.7.24. Concretely this routine will simply update the lower and upper bounds of the damage minimization problem.

Compatibility: `COUP`, `DECO`

Syntax:

```
"ENGR" ( alpha0 /LECTURE/ )
```

`alpha0`

Prescribed damage value.

`LECTURE`

List of the nodes concerned.

8.63 DRAG FORCES ON 3D BEAMS/BARS EMBEDDED IN A FLUID

Object:

This directive allows to model the fluid-dynamic drag forces acting on 3D beam/bar elements embedded in a fluid. Such elements are represented by 2-node segments (SEG2 geometrical shapes). The model is somewhat similar to the flying debris model described on Page C.66.

The fluid surrounding the 3D beams/bars may be modeled either as a uniform field with constant properties (velocity, density), or as an evolving fluid field, discretized by Finite Elements or Finite Volumes, or even as a combination of the two (e.g., FE fluid field near the explosive source, uniform field far away).

The drag pressure acting on a 3D beam/bar element (or a part thereof) is computed according to the following expression:

$$p_D = C_D \frac{1}{2} \rho_F (v_R^{\perp})^2$$

where C_D is the drag coefficient (an empirical number given by the user), ρ_F is the local density of the fluid and $v_R^{\perp}$ is the component of the relative (fluid minus structure) velocity in the plane normal to the 3D segment. Then, the drag force F_D exerted by the fluid on the structure is computed by multiplying the drag pressure by the exposed area of the segment:

$$F_D = p_D A = p_D L D$$

with L the length of the segment (or part thereof) and D its diameter.

One may also activate a feed-back mechanism whereby the drag forces generated by the fluid on the structure are applied (with the minus sign) to the fluid itself. This is currently the default when the fluid is discretized by FE (but not by VFCC). Note, however, that in general it is preferable to deactivate the feedback mechanism (see option `NOFB` below), since it perturbs the fluid flow, while the drag formula (whose coefficient C_D is determined experimentally) assumes an unperturbed fluid flow. In other words, in order to compute the relative velocity v_R to be introduced in the formula, the fluid velocity should be taken at a certain distance from the structure, where the effect of the structure is not felt. Furthermore, note that at the moment feedback forces are only applied (by default, i.e. without the `NOFB` option) when the fluid is discretized by Finite Elements (FE). They cannot be applied (with or without `NOFB`) to a fluid discretized by Cell-Centred Finite Volumes (VFCC).

In practical applications, the fluid mesh is typically (much) finer than the structural mesh composed of 3D structural members such as beams or bars. Therefore, wherever appropriate, to improve the accuracy of the drag force calculation each structural segment is subdivided into several parts, each one of the length of a typical fluid element.

Syntax:

```
DRAG <ROF rof> <VFX vfx> <VFY vfy> <VFZ vfz>
      STRU /LECTS/
     <FLUI /LECTF/>
     <(HF hf /LECTS2/)>
      (CD cd /LECTS3/)
```

```
< $ HGRI hgri ; NMAX nmax ; DELE dele $ <DGRI> >
< $ FBAC ; NOFB $ >
```

`rof`

Density of the (default) uniform fluid field in which the 3D beams/bars are embedded. This value is 0.0 by default, meaning that by default the 3D beams/bars move in vacuum (if they are not coupled with a discretized fluid domain by the `FLUI` keyword). Note that the drag force acting on a 3D beam/bar depends on the density but also on the drag coefficient (`CD`, see below).

`vfx, vfy, vfz`

Components of the velocity of the surrounding uniform fluid field. These values are 0.0 by default.

`STRU`

Introduces the `/LECTS/` of the 3D beam/bar elements. Only elements with a SEG2 geometrical shape are accepted.

`FLUI`

Introduces the `/LECTF/` of the discretized fluid domain with which the 3D beams/bars motion should be coupled. When a 3D beam/bar traverses this domain, the (local) fluid velocity and density are automatically computed by the code, instead of using the constant user-given values `rof`, `vfx`, `vfy`, `vfz` described above. A fast search algorithm based on a grid of cells (as in bucket sorting) is used to compute the fluid element (if any) encompassing each 3D beam/bar element.

`HF hf`

Size of the fluid elements coupled with each of the 3D beam/bar elements specified in the following `/LECTS2/` directive in order to compute the local drag pressure and then the local drag force. As indicated by the parentheses, the `HF hf` sub-directive may be repeated as many times as necessary to assign a size `hf` to each one of the structure elements previously listed in the `STRU` directive. If omitted, the code computes automatically the local size of the coupled fluid elements to each structural beam/bar element.

`CD cd`

Drag coefficient C_d assigned to the 3D beam/bar elements specified in the following `/LECTS3/` directive. As indicated by the parentheses, the `CD cd` sub-directive must be repeated as many times as necessary to assign a drag coefficient `cd` to each one of the structure elements previously listed in the `STRU` directive.

`HGRI`

Specifies the size of the grid cell for fast search operations. Each cell has the same size in all spatial directions and is aligned with the global axes. Note that the size of this grid is related to the size of the **structural** elements specified in `STRU`, not of the fluid elements specified in `FLUI`.

`NMAX`

Specifies the maximum number of cells along one of the global axes.

`DELE`

Specifies the size of the grid cell as a multiple of the diameter of the largest coupled **structural** element. Element "diameters" are computed only along each global spatial direction and the maximum is taken. For example, by setting `DELE 2` the size of the cell is twice the diameter of the largest coupled structural element declared in the `FLUI` directive. By default, i.e. if neither `HGRI`, nor `NMAX`, nor `DELE` are specified, the code takes `DELE 1.01`.

`DGRI`

Dump out the initial grid of cells used for fast searching on the listing. For brevity, the print is done only the first time that the grid is computed, that is, at step 0.

`FBAC`

Activate the feed-back mechanism whereby the drag forces generated by the fluid on the structure are also applied (with the minus sign) to the fluid itself. This is the default, although in many cases it is preferable to deactivate the feedback mechanism, since it perturbs the fluid flow while the drag formula assumes an unperturbed fluid flow (the fluid velocity should be taken at a certain distance from the structure, where the effect of the structure is not felt). Furthermore, note that at the moment feedback forces can only be applied when the fluid is discretized by Finite Elements (FE), not by Cell-Centred Finite Volumes (VFCC).

`NOFB`

Deactivate the feed-back mechanism whereby the drag forces generated by the fluid on the structure are also applied (with the minus sign) to the fluid itself. If the fluid is modelled by VFCC, activating or not the feedback mechanism has no influence on the solution because the feedback is not available for this type of fluid discretization.

8.64 EQBM: Equivalent beam kinematics for continuum elements

Object:

This directive allows to associate an equivalent beam to a set of continuum elements in 2D or 3D so that the kinematics of the elements is computed through the beam.

This allows in particular to define the loading on the continuum elements and to compute the bending response with the beam, avoiding a refined mesh through the section to get the correct solution. The loading can come in particular from an external coupling with the envelop of the continuum elements defined as the coupling interface.

ATTENTION: the proposed implementation is decoupled only at this stage, coupled links cannot be applied to nodes of the continuum elements.

Compatibility: `DECO`

Syntax:

```
EQBM nset * ( BEAM /LECTURE/ SLAVE /LECTURE/ ) FINT fint FREQ freq TFREQ freq
```

`nset`

Number of declared sets of slave continuum elements and master beam.

`BEAM`

Enter the elements of the master beam.

`SLAVE`

Enter the slave continuum elements, with meshing constraints (see comment below).

`FINT`

If `fint` is set to 1, internal forces will be taken into account (only external forces are by default) which will enable the use of EQBM in an FSI context (tested with VFCC only). Set to 0 by default or if not specified.

`FREQ`

If `freq` is specified, forces/moments computed via EQBM and applied to the master beam nodes are printed in the listing every `freq` timesteps. No printing by default or if not specified.

`TFREQ`

If `tfreq` is specified, forces/moments computed via EQBM and applied to the master beam nodes are printed in the listing every `tfreq` seconds. No printing by default or if not specified.

Comments:

For each set, the meshes for the beam and the continuum are linked: the nodes of the continuum elements must lie on the sections of the beam. The detection criterion to associate a slave node to a master node is the following :

$$|crit| \leq tole$$

where

$$crit = \frac{1}{2L_{master\_beam\_elm}}(\mathbf{x}_{slave} - \mathbf{x}_{master}) \cdot \mathbf{n}_{master\_beam\_elm}$$

and

$$tole = L^2_{master\_beam\_elm}/10$$

Practically, a local frame is attached to each node of the beam with normal direction aligned with the beam and the two other vectors defining a plane where the nodes of the continuum elements are searched and will receive the kinematics of the section computed at the beam node.

If nodes of continuum elements do not belong to a section, they will receive no motion from the beam. Their motion will be deduced from the constitutive model affected to the continuum elements with no control over the accuracy of the global response of the system. This is thus advised against.

In general, EQBM is designed to have a beam node at the center of every section of a 2D or 3D mesh of a beam. The 1D beam mesh and the 2D (or 3D) mesh are supposed to match. Every other use of EQBM is untested and comes with no warranty.

8.65 SLIDING SURFACES FOR SMOOTH CONTACT

Object:

This directive specifies a sliding surface algorithm for smooth contact between solid bodies meshed by either continuum or shell elements. The algorithm is best suited for smooth contact between mechanical parts (without or with friction), and with limited deformation of the contacting parts. The strategy used is loosely inspired by `GLIS`, see Page D.180, while trying to avoid some of its pitfalls. It is meant to work both in 2D (sliding lines) and in 3D (sliding surfaces).

Each sliding surface is composed of a master surface, formed by a set of master faces, and by a set of slave nodes. Each master surface must be entirely meshed either with continuum elements or with shell elements. In other words, continuum and shell elements may not be mixed up in the same master surface.

Compatibility: `COUP` (A `DECO` version may become available later).

Syntax:

```
"SLID" nslid * ( "SURF"
                 < "DUMP" >
                 < "SLOW" > < "NOUP" >
                 < "UNIL" < " REVE" > >
                 < "FROT" "MUST" must "MUDY" mudy "GAMM" gamm >
                 < "PHI" phi ; "THIC" thic > < "RHO" rho >
                   "EMAS" /LECT/ "NMAS" > /LECT/
                                 "NSLA" > /LECT/
               )
```

`nslid`

Number of sliding lines (2D) or surfaces (3D).

`SURF`

Introduces the data relative to one sliding surface. This keyword acts as a separator between the data of a surface and those of the next one. It must be the first keyword in the data of each surface.

`DUMP`

Dump out on the listing information about the contacts relative to the present sliding surface at every time step. This optional keyword can generate huge data and should therefore be activated only for debugging purposes.

`SLOW`

Use brute force search algorithm for the penetration checks. Each slave node is checked for penetration into every master surface. This will considerably slow down the computation in medium and large applications, but it may allow to detect problems in the faster search (based upon preliminary exclusion tests) which is used by default. This optional keyword should therefore be used only for debugging purposes.

`NOUP`

Do not update the characteristic length of master faces. By default the characteristic length is updated at every step. The unit normal to each master face is always updated at very step irrespective of the presence or not of the `NOUP` keyword.

`UNIL`

This optional keyword applies only to master surfaces composed of shell elements and it is ignored for continuum master surfaces. It causes the code to build only one penetration domain instead of two domains for each shell master face. In this way the penetration is *unilateral* instead of bilateral. Note that bilateral penetration can be still activated by defining two equal but mutually opposite, or *conjoint*, master surfaces (by using the `REVE` keyword described next for one of them). However, when using this double-surface technique, each slave node must belong to only one of the two conjoint master surfaces. The keyword assumes that the master surface is orientable (simply connected) and that the shell elements composing the master surface are consistently oriented so that their geometric normals all point to the same side of the shell structure. The orientation of shell elements (in 3D) can be checked visually by a graphical tool such as the embedded OpenGL-based visualizer.

`REVE`

This optional keyword applies only to master surfaces composed of shell elements and it is ignored for continuum master surfaces. The keyword has only effect if the `UNIL` optional keyword has also been previously specified for this master surface. The effect is that the unilateral penetration domain is built on the reverse or "negative" side of the shell (i.e. in the direction opposite to the oriented normal) rather than on its positive side. The keyword assumes that the master surface is orientable (simply connected) and that the shell elements composing the master surface are consistently oriented so that their geometric normals all point to the same side of the shell structure. The orientation of shell elements (in 3D) can be checked visually by a graphical tool such as the embedded OpenGL-based visualizer.

`FROT`

Introduces the (optional) declaration of friction characteristics.

`MUST must`

Static friction coefficient μ_s: $(0 < \mu_s < 1)$.

`MUDY mudy`

High-velocity (dynamic) friction coefficient μ_d: $(0 < \mu_d \leq \mu_s < 1)$.

`GAMM gamm`

Coefficient γ of the friction law. This law is similar to the one used for the `IMPA` directive (see page D.170). The friction coefficient μ varies from μ_s to μ_d as the relative tangential velocity V_r of the two bodies increases. The passage is governed by the exponential decay law: $\mu = \mu_d + (\mu_s - \mu_d)e^{(-\gamma V_r)}$.

`PHI phi THIC thic`

Optional coefficients ϕ and θ that control the thickness H of the penetration domain. The effect of specifying (or omitting) ϕ and/or θ is detailed in the Comments below.

`RHO rho`

Coefficient ρ that controls the horizontal protrusion R of the penetration domain of each master face beyond the face limits (nodes). If specified, it must be $\rho > 0$. The code always takes $\rho = 0$ (no protrusion) on master nodes along the perimeter of the master surface. For master nodes inside the master surface (not along its perimeter), the code takes the value specified in input ($\rho > 0$), or a default value of $\rho = 0.05$ if omitted, when the master surface is a locally concave continuum or a locally convex shell. When the master surface is a locally convex continuum or a locally concave shell, the code takes $\rho = 0$ (no protrusion). The concavity or convexity of the master surface is referred to the surface as viewed from the approaching penetrating slave node, so in the case of (bilateral) shells it depends upon which side of the surface the penetration occurs from.

`EMAS /LECT/`

Set of the master elements that are used to build up the master faces. All elements of the set must be of the same class (i.e., either all continuum elements or all shell elements).

`NMAS /LECT/`

Set of the master nodes that are used to build up the master faces. An element's face is considered a master face if and only if the element belongs to the set of master elements and all its nodes belong to the set of master nodes.

`NSLA /LECT/`

Set of the slave nodes that interact with the master faces.

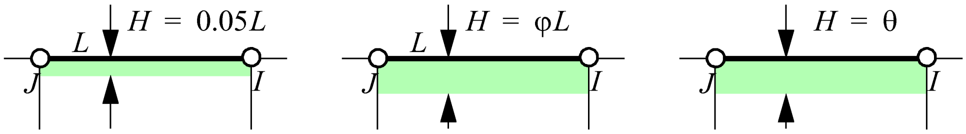
Comments:

The optional parameters `PHI` (ϕ) and `THIC` (θ) may be used to control the thickness H of the penetratable domain. Their effect is slightly different depending on the nature of the master surface:

- For a *continuum* master face the code builds up one penetratable domain per master face and the precise meaning of ϕ and θ is summarized in the following Table and Figure. By default (neither ϕ nor θ specified) the code takes $H = 0.05L$ where L is the characteristic length of the master face. Thus, H varies from face to face in general. The default value of ϕ (0.05) may be overridden by specifying $\phi > 0$ in the input, so that the code takes $H = \phi L$.
  To set a constant thickness H of the penetratable domain over the whole master surface, the θ parameter may be specified and the code sets $H = \theta$. In this case, specifying also the ϕ parameter is invalid.

`PHI` (ϕ)	`THIC` (θ)	Thickness	Image
—	—	$\phi = 0.05$ (default), $H = \phi L$	(a)
> 0	—	$H = \phi L$	(b)
—	> 0	$H = \theta$	(c)
> 0	> 0	Invalid combination	—

Table 16: Meaning of `PHI` and `THIC` for continuum master faces.



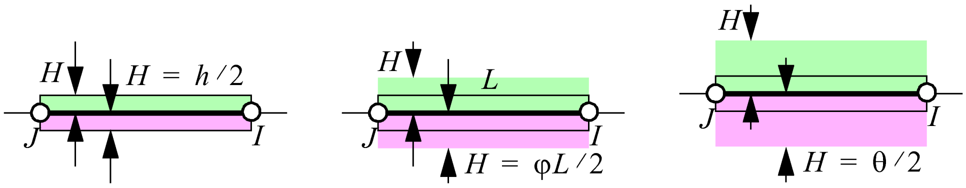
(a) Default (b) $\phi > 0$ (c) $\theta > 0$

Figure 6: Meaning of `PHI` and `THIC` for continuum master faces.

- For a *bilateral shell* master face the code builds up two equal and opposite penetratable domains and the precise meaning of ϕ and θ is summarized in the following Table and Figure.
  By default (neither ϕ nor θ specified) the code takes $H = h/2$ where h is the thickness (`EPAI`) that has been assigned to the master face's shell element. Thus, H follows the physical properties of the shell and varies from face to face in general. By specifying the value of ϕ the code takes $H = \phi L/2$. In this way the thickness may be made independent of the physical shell thickness h and proportional to the face's characteristic length L, like for a continuum master face.
  To set a constant thickness H of the penetratable domain over the whole master surface, the θ parameter may be specified and the code sets $H = \theta/2$. In this case, specifying also the ϕ parameter is invalid.

`PHI` (ϕ)	`THIC` (θ)	Effect	Image
—	—	$H = h/2$	(a)
> 0	—	$H = \phi L/2$	(b)
—	> 0	$H = \theta/2$	(c)
> 0	> 0	Invalid combination	—

Table 17: Meaning of `PHI` and `THIC` for bilateral shell master faces.



(a) Default (b) $\phi > 0$ (c) $\theta > 0$

Figure 7: Meaning of `PHI` and `THIC` for bilateral shell master faces.

- For a *unilateral shell* master face the code builds up just one penetratable domain and the precise meaning of ϕ and θ is summarized in the following Table and Figure.
  By default (neither ϕ nor θ specified) the code takes $H = h/2$ where h is the thickness (`EPAI`) that has been assigned to the master face's shell element. Thus, H follows the physical properties of the shell and varies from face to face in general. By specifying the value of ϕ the code takes $H = \phi L/2$. In this way the thickness may be made independent of the physical shell thickness h and proportional to the face's characteristic length L like for a continuum master face.
  By specifying θ the penetratable domain is composed of two parts. If ϕ is omitted, The first part faces the incoming slave node and has a (variable) thickness $h/2$ (i.e. half the physical thickness of the shell) like in the default case. The second part, on the opposite side of the shell, has a (constant) thickness θ. Thus the total thickness of the penetratable domain is $H = h/2+\theta$. The effect is adding an extra thickness θ to the default behaviour. This may be useful in the case of very thin shells (h very small) in order to avoid missing some penetrations. To distinguish this particular case from the next one (where ϕ may be 0), ϕ is automatically set to the special value -1.0.
  Finally, by specifying also ϕ in addition to θ the thickness of the first part is set constant and equal to $\phi/2$ so that the total thickness becomes constant and equal to $H = \phi/2 + \theta$. Note that this is the only case in which it is possible to explicitly specify $\phi = 0$, thus getting $H = \theta$ and completely eliminating the first part of the penetratable domain, like if the shell was a continuum.

`PHI` (ϕ)	`THIC` (θ)	Effect	Image
—	—	$H = h/2$	(a)
> 0	—	$H = \phi L/2$	(b)
—	> 0	$\phi = -1,\ H = h/2+\theta$	(c)
≥ 0	> 0	$H = \phi/2+\theta$	(d)

Table 18: Meaning of PHI and THIC for unilateral shell master faces.

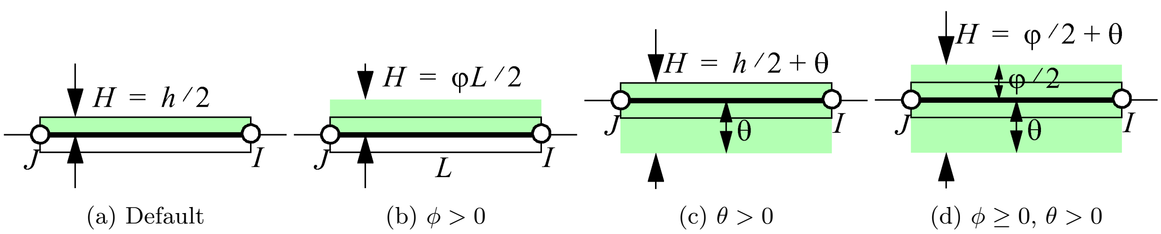


Figure 8: Meaning of PHI and THIC for unilateral shell master faces.

8.66 READING LINKS FROM K-FILE

Object:

This directive activates the reading of the links from LS-DYNA k-files. Until now, the following directives are considered: CONSTRAINED_SPOTWELD, CONSTRAINED_SPOTWELD_ID, CONSTRAINED_NODAL_RIGID_BODY. All are converted in RELA links.

The links are converted in EPX links.

Compatibility: `COUP` and `DECO`.

Syntax:

```
"KFIL"
```

8.67 DYNAMIC FLUID (MASS) COUPLING BETWEEN BEAMS (CPLM)

Object:

This directive is used to represent a dynamic coupling between two points of a structure. The coupling is based on the dynamic response of two points connected by a constrained mass of fluid. The points represent the centerlines of concentric cylinders. The fluid is contained in the annular space between the two cylinders. The cylinders may be circular or have an arbitrary cross-section and are modeled with beam elements (`POUT`). Their motions are assumed to be small with respect to the fluid channel thickness. The fluid is assumed to be incompressible. (see: R. J. Fritz. "The Effect of Liquids on the Dynamic Motions of Immersed Solids". ASME Journal of Engineering for Industry. February, 1972)

The coupling affects two DOFs per node: translations in the global x and z directions. The axes of the cylinders are assumed to be in the global y direction. An implicit time integration of the coupling forces is performed leading to the direct inversion of the coupling mass matrix. Compatibility: `DECO`

Syntax:

```
CPLM     NCOU ncou
       ( M1 m1
         M2 m2
         MH mh
         NINT /LECTURE/
         NEXT /LECTURE/ )*ncou
```

`ncou`

Number of two-node couples.

`m1, m2, mh`

Terms of the coupling mass matrix.

`NINT`

Node of the internal beam.

`NINT`

Node of the external beam.

Comments:

The coupling forces are expressed as:

$$\begin{pmatrix} (F_x)_1 \\ (F_x)_2 \\ \\ (F_z)_1 \\ (F_z)_2 \end{pmatrix} = \begin{pmatrix} -\mathtt{mh} & \mathtt{m1}+\mathtt{mh} & & \\ \mathtt{m1}+\mathtt{mh} & -(\mathtt{m1}+\mathtt{m2}+\mathtt{mh}) & & \\ & & & \\ & & -\mathtt{mh} & \mathtt{m1}+\mathtt{mh} \\ & & \mathtt{m1}+\mathtt{mh} & -(\mathtt{m1}+\mathtt{m2}+\mathtt{mh}) \end{pmatrix} \begin{pmatrix} (\ddot{u}_x)_1 \\ (\ddot{u}_x)_2 \\ \\ (\ddot{u}_z)_1 \\ (\ddot{u}_z)_2 \end{pmatrix}$$

with $(\ddot{u}_x)_i$ the acceleration of node i in the x-direction where the index 1 denotes the node of the internal beam whereas the index 2 denotes the node of the external beam. The terms of the coupling mass matrix are given by the users who can used the formula proposed by Fritz or another estimation of mass terms.

This directive should only be used once. All the two-node couples have thus to be defined with the directive. For example, considering 3 two-node couples, the syntax should be:

```
LINK DECO CPLM NCOU 3
     M1 m11 M2 m21 MH mh1 NINT LECT Ni1 TERM NEXT LECT Ne1 TERM
     M1 m12 M2 m22 MH mh2 NINT LECT Ni2 TERM NEXT LECT Ne2 TERM
     M1 m13 M2 m23 MH mh3 NINT LECT Ni3 TERM NEXT LECT Ne3 TERM
```

Warning:

For restart computations, it is necessary to repeat the directive `CPLM`.

8.68 PIPELINE RUPTURE CONNECTION

Object:

This FSI model allows modelling a break of a pipeline discretized with TYVF elements. Prior to the pipeline rupture instant, the conservation of the internal fluid mass flow rate and the continuity of the mechanical degrees of freedom are ensured.

Compatibility: `COUP`

Syntax:

```
"BIVF"   < "TRUP" trup > < "LIBR" >   /LECTURE/
```

`trup`

Rupture instant (no breaking by default).

`LIBR`

If this keyword is present, the continuity of the mechanical degrees of freedom is desactivated.

`/LECTURE/`

Number or the name of the BIVF element.

Comments:

This directive may only be used to connect two TYVF elements.

Outputs:

The components of the ECR table are as follows:

ECR(25): pipeline rupture area (water)

ECR(26): mass flow (water)

ECR(27): total ejected mass (water)

9 GROUP E—FUNCTIONS AND INITIAL CONDITIONS

Object :

The directives described in this Section allow to introduce functions in a variety of forms, necessary for the description of materials, loads, or initial conditions of a calculation.

We distinguish functions of the form $y = f(x)$ (directive `FONC`, page E.15), from the functions depending from a parameter p, which are of the form $y = f(x, p)$ (directive `ABAQ`, page E.30).

The abcissa x will most often be the time t in case of a load function, but it is possible to use arbitrary variables for x, y or p.

A special energy injection model (developed at JRC) is also described on page E.38.

9.1 FUNCTIONS

Object :

This directive defines functions in the form $y = f(x)$. These may be used e.g. for imposed motions or other conditions which depend upon time, and also to define material properties.

Syntax :

```
"FONC" (  < "NUM" > ifonc |[ "TABL" npts*(xi,yi)              ;
                             "ROUT" <"PARA" n p1 p2 ... pn>   ;
                           < "LSQU" deg > "TABL" npts*(xi,yi) ;
                             "HARM"  nhar*(C c <TYPE type>
                                          $[ OMEG omeg ; FREQ freq ]$
                                          $[ PHIR phir ; PHID phid ]$
                                          <TMIN tmin> <TMAX tmax>)
                             "COSC"  <COEF coef> TEND tend ]| )
```

`"NUM"`

Optional keyword introducing the number of the function.

`ifonc`

Number of the function necessary to identify it when it will be used.

`"TABL"`

The function is defined by a table (sequence of pairs). See below page E.20.

`"ROUT"`

The function is computed by means of the subroutine `TABANA` written by the user. See page E.25. Optionally, a list of parameters may be passed to the routine.

`"LSQU"`

The function is defined by a table (sequence of pairs). See below page E.20. But a least square polynomial fitting is performed in order to store the function as a polynomial. The fitting quality can be controled in the listing by the mean of standard deviation. If the least square polynomial fitting fails, the function is stored as a table and the computation goes on.

`deg`

Maximum degree (deg > 0) of the polynomial which fits the table function. Be careful not to use too high degrees: it does not give good results because of too many oscillations.

`"HARM"`

The function is defined as a combination of harmonic functions.

`"COSC"`

Progresive evolution based on a cosine function until a given time to reach a constant value.

Comments :

The key-word `FONC` may appear at most once, at the beginning of the sequence relative to the functions.

Warning :

If there are imposed displacements, dimension also `FCOE`, see page A.80.

9.1.1 TABLE FUNCTION

Object :

To define a function $y = f(x)$ by the means of couples of points.

Syntax :

```
"TABL"  npts*( xi , yi )
```

`npts`

Number of couples (xi, yi) defining the table.

`xi , yi`

Abscissa (time for example) and value (ordinate) of the function at point i.

Comments :

The value of the function at time t (or at the abscissa x) is determined by a linear interpolation.

9.1.2 SUBROUTINE *TABANA*

Object :

To define a function by the means of a subroutine written by the user. Optionally, a list of parameters may be passed to the routine.

Syntax :

```
"ROUT" <"PARA" n p1 p2 ... pn>
```

`"PARA"`

Optional keyword introducing a list of parameters to be passed to the routine. These parameters will be made available in subroutine TABANA by means of the `COMMON /CTABANA/`.

`n`

Number of parameters to be passed. The maximum is 10.

`p1, p2, ...  pn`

The `n` parameters to be passed.

Comments :

The user has to write a subroutine which computes the function at every time.

```
      SUBROUTINE TABANA(IFONC,T,COEF,DERIV)
*
*     cette routine permet d'entrer une table sous forme analytique
*
*    ifonc     : numero de la fonction
*    t         : temps du calcul en sec. ou + generalement abscisse
*    coef      : valeur de la fonction ifonc au temps ou abscisse t
*    deriv     : derivee de la fonction ifonc en t (seulement pour courbe
*                de traction du materiau lem2)
*
*  attention !  la fonction 2 est utilisee par le benchmark :
*                     bm_rob_smr
*
      USE M_FONCTIONS
*
      IMPLICIT NONE
*
*---   variables globales :
      INTEGER, INTENT(IN)  :: IFONC
      REAL(8), INTENT(IN)  :: T
      REAL(8), INTENT(OUT) :: COEF, DERIV
*
*---   variables locales :
      REAL(8) :: T0,T1,T2,X,XV,ALPHA,ALPHAV,XF,ALPHAF,TF,Y2
      REAL(8) :: F_0, T_BAR, TAU, TT, VV, FAC, V_SUR_F
      REAL(8), PARAMETER :: PIGR = 3.14159265359D0
*
      REAL(8), EXTERNAL :: FOLCO1
*
      DERIV=0.D0
*
      SELECT CASE (IFONC)
*
      CASE(1)   ! 0 AVANT T0, RAMPE DE T0 A T1, 1 APRES T1
         T0 = 0D0
         T1 = 5D-3
         IF(T < T0) THEN
            COEF = 0
         ELSEIF(T >= T0 .AND. T <= T1)  THEN
            COEF = T/T1
         ELSE
            COEF = 1
```

```
         ENDIF
*
      CASE(2)   ! CAS DU BENCH
         T0 = 0D0
         T1 = 0.5D0
         T2 = 1.5D0
         IF(T <= T0) THEN
            COEF = 0D0
         ELSEIF(T > T0 .AND. T <= T1)  THEN
            COEF = 673D0*T - 508D0
         ELSEIF(T > T1 .AND. T <= T2)  THEN
            COEF = 148D0*EXP(-5.5D0*(T-T1)) + 8D0
         ELSEIF(T > T2)  THEN
            COEF = 240D0
         ENDIF
*
      CASE (3) ! FC FOR PARTITIONS PAPER: applied sinusoidal force
*
* p_tabana(1) = f_0       max. value of applied sinusoidal force
* p_tabana(2) = t_bar     period of applied sinusoidal force
*
        IF (N_TABANA < 2) THEN
          CALL ERRMSS ('TABANA', 'TOO FEW PARAMETERS ENTERED')
          STOP 'TABANA : N_TABANA < 2'
        ENDIF
        F_0   = P_TABANA(1)
        T_BAR = P_TABANA(2)
        COEF = FOLCO1 (F_0, PIGR, T, T_BAR)
*
      CASE (4) ! FC FOR PARTITIONS PAPER: velocity for sinusoidal force
*
* p_tabana(1) = f_0       max. value of applied sinusoidal force
* p_tabana(2) = t_bar     period of applied sinusoidal force
* p_tabana(3) = tau       traversal time of bar length
* p_tabana(4) = v_sur_f   ratio between v and F (=c/SE)
*                         (v = velocity, F = applied force,
*                          c = sound speed, S = bar cross-section,
*                          E = Young's modulus)
*
        IF (N_TABANA < 4) THEN
          CALL ERRMSS ('TABANA', 'TOO FEW PARAMETERS ENTERED')
          STOP 'TABANA : N_TABANA < 4'
        ENDIF
        F_0     = P_TABANA(1)
        T_BAR   = P_TABANA(2)
        TAU     = P_TABANA(3)
        V_SUR_F = P_TABANA(4)
        COEF = FOLCO1 (F_0, PIGR, T, T_BAR)
        FAC = -2.D0
        TT = T - (TAU+TAU)
        DO WHILE (TT >= 0.D0)
          VV = FOLCO1 (F_0, PIGR, TT, T_BAR)
          COEF = COEF + FAC*VV
          FAC = -FAC
          TT = TT - (TAU+TAU)
        END DO
        COEF = V_SUR_F*COEF
*
      CASE (5) ! FC FOR PARTITIONS PAPER: velocity for constant force
*
* p_tabana(1) = f_0       max. value of applied sinusoidal force
* p_tabana(2) = t_bar     period of applied sinus. force (unused here)
* p_tabana(3) = tau       traversal time of bar length
* p_tabana(4) = v_sur_f   ratio between v and F (=c/SE)
*                         (v = velocity, F = applied force,
*                          c = sound speed, S = bar cross-section,
*                          E = Young's modulus)
*
        IF (N_TABANA < 4) THEN
          CALL ERRMSS ('TABANA', 'TOO FEW PARAMETERS ENTERED')
          STOP 'TABANA : N_TABANA < 4'
        ENDIF
        F_0     = P_TABANA(1)
        TAU     = P_TABANA(3)
        V_SUR_F = P_TABANA(4)
        COEF = F_0
        FAC = -2.D0
        TT = T - (TAU+TAU)
        DO WHILE (TT >= 0.D0)
          VV = F_0
          COEF = COEF + FAC*VV
          FAC = -FAC
          TT = TT - (TAU+TAU)
        END DO
        COEF = V_SUR_F*COEF
*
      CASE DEFAULT
        CALL ERRMSS('TABANA',
     &     'VOUS AVEZ APPELE LE SS-PROGRAMME TABANA SANS LE CREER ')
        STOP 'TABANA NON ECRIT !'
      END SELECT
*
      END SUBROUTINE TABANA
*=====================================================================
      REAL(8) FUNCTION FOLCO1 (F_0, PIGR, T, T_BAR)
*
      IMPLICIT NONE
*
      REAL(8), INTENT(IN) :: F_0, PIGR, T, T_BAR
```

```
*
      FOLCO1 = 0.5D0*F_0*(1.D0+SIN(PIGR*((2.D0*T/T_BAR)-0.5D0)))
*
      END FUNCTION FOLCO1
```

The arguments have the following meaning:

`IFONC` : number of the function (input);

`T` : computing time (input);

`COEF` : value of the function at time (abscissa) `T` (output);

`DERIV` : value of the function derivative at the abscissa `T` (output). This is mandatory for some materials.

Warning :

It is strongly advised to foresee adequate error messages, like in the above example on the function number.

9.1.3 HARMONIC FUNCTION

Object :

To define a harmonic function of the form (sum of n terms): $y = C_1 \cos(\omega_1 t + \phi_1) + C_2 \cos(\omega_2 t + \phi_2) + \cdots$, where for the i-th term C_i is a coefficient, ω_i is the pulsation in rad/s and ϕ_i is the phase in rad. Note, however, that if the user prefers, the frequency f (in Hz) can be specified, in place of ω. Also, the phase can be specified in degrees if so preferred.

Syntax :

```
HARM nhar*( VHAR
            C c <TYPE type>
            $OMEG omeg ; FREQ freq$
           <$PHIR phir ; PHID phid$> )
            <TMIN tmin> <TMAX tmax>
```

`nhar`

Number of terms in the sum of harmonic functions.

`VHAR`

Mandatory keyword that introduces the reading of the set of values for the i-th term.

`c`

Coefficient of the i-th harmonic term.

`type`

Type of the i-th harmonic term: 1 means sine, 2 means cosine. By default it is 1 (sine).

`omeg`

Pulsation (angular frequency) ω of the i-th harmonic term in rad/s. Recall that it is $\omega = 2\pi f$ where f is the frequency in Hz.

`freq`

Frequency f of the i-th harmonic term in Hz. Recall that the pulsation (angular frequency) is then $\omega = 2\pi f$ in rad/s.

`phir`

Phase ϕ of the i-th harmonic term *in radians*.

`phid`

Phase ϕ of the i-th harmonic term *in degrees*.

`tmin`

Time $t_{\min}$ at which the harmonic function (all terms) starts. The function is 0 for $t < t_{\min}$. By default, the function acts over the entire time scale.

`tmax`

Time $t_{\max}$ at which the harmonic function (all terms) ends. The function is 0 for $t > t_{\max}$. By default, the function acts over the entire time scale.

Comments :

The value of the function at time t (or at the abscissa x) is determined by computing the above analytical expression.

If both `PHIR` and `PHID` are omitted, a phase of 0 is assumed for the concerned harmonic component.

9.1.4 SWEEP SINE FUNCTION

Object :

To define a sweep sine function of the form: $y = C \sin\left(\frac{1}{2\pi}\left(f_i + \frac{(f_e - fi)t}{D}\right)t\right)$, where f_i and f_e are initial and final frequencies, D is the sweep duration.

The function is extended for time greater than D with a regular sine with f_e frequency.

Syntax :

```
"SSWP"  "C"    coef
        "FINI" freq_ini
        "FEND" freq_end
        "SWPD" duration
```

`coef`

Multiplicative coefficient.

`FINI`

Initial frequency.

`FEND`

Final frequency.

`SWPD`

Sweep duration.

9.1.5 ABAQUE : PARAMETRISED TABLE FUNCTION

Object :

To define a set of parametrised functions in the form $y = f(x, p)$ where p is a parameter.

Syntax :

```
"ABAQ" ( "SET" ifonc "PARA" flot "TABL"  npts*( ti , fi ) )
```

`"SET"`

Mandatory keyword to describe a parametrised function.

`ifonc`

Number of the function necessary to identify it when it will be used.

`"PARA"`

Announces the value of the parameter.

`flot`

Value of the parameter.

`npts`

Number of couples (ti, fi) defining the table relative to the parameter flot.

`ti,fi`

Abscissa and ordinate of the function at point i.

Comments :

The value of the function for an abscissa t is obtained by linear interpolation.

The "PARA" sequence must appear at least twice.

Warning :

Do not forget to dimension sufficiently (directives "FNOM" and "FTAB", page A.90).

9.1.6 PROGRESSIVE COSINE UNTIL CONSTANT

Object :

To define a progressive function with a cosine form, in order to reach a given value and limit acceleration related to the loading. Function has the following form: $y(t \leq tend) = \frac{1}{2} coef\,(1 - cos(t/tend\;\pi))\,; y(t > tend) = coef$. $coef$ represents the amplitude and $tend$ the time where the progressive evolution remains constant as a function of t.

Syntax :

```
"COSC"  <"COEF" coef>
        "TEND" tend
```

`coef`

Multiplicative coefficient, 1.0 by default.

`tend`

Final evolution time where function value will remain constant and equal to COEF.

9.2 ENERGY INJECTION HISTORY (JRC)

Object

This instruction defines the energy injected in: i) fluid elements of types FLxx (JRC model) or CUBE, PRIS, TETR (CEA model), or ii) multicomponent fluid finite volumes (MCxx elements). This directive is extended to fluid finite volumes (MCxx elements) using the `MCVO` keyword.

References

More information on the formulation of this model may be found in reference [131].

Syntax

```
"INJE"  "QTAB" ifon   |[ "MASS" ; "VOLU" ;
                         "MCMA" ; "MCVO" ]|
                      /LECT/
```

`ifon`

Number of the function (see `FONC`) used to describe the variation in time of the total injected power.

`MASS`

This keyword applies only in the case of fluid elements, see i) above. The injected power will be distributed among the different elements that form the energy injection zone proportionally to the mass of each element. This is probably the best choice for an energy injection zone bounded by a Lagrangian surface, because in this case the mass of the zone stays constant in time.

`VOLU`

This keyword applies only in the case of fluid elements, see i) above. The injected power will be distributed among the different elements that form the energy injection zone proportionally to the volume of each element. This is probably the best choice for an energy injection zone bounded by an Eulerian surface, because in this case the volume of the zone stays constant in time.

`MCMA`

This keyword applies only in the case of fluid finite volumes, see ii) above. Unlike the `MASS` model, in this case the energy injection is associated to one (or more) particular component(s) of the gas mixture. The presence of such component(s) identifies, at each instant, the current injection zone. The injected power will be distributed among the different control volumes (nodes) that form the current energy injection zone, proportionally to the mass of the chosen component(s) at each node.

`MCVO`

This keyword applies only in the case of fluid finite volumes, see ii) on page E.38. The injected power will be distributed among the different control volumes that form the energy injection zone, proportionally to the volume of each node. This model is similar to `VOLU`.

`/LECT/`

In the `MASS` or `VOLU` cases, these are the elements defining the injection zone. In the `MCMA` case, these are the selected gas components. Finally, in the `MCVO` case, these are the control volumes (nodes) defining the injection zone.

Comments:

The `INJE` directive can be repeated as many times as necessary. An additional injection zone is defined each time. At present, up to 5 different zones can be defined.

One may define zones associated with finite elements, and other zones associated with finite volumes, in the same run.

Note that the `FONC` of index ifon describes the **total** injected power for the zone, as a function of time. This power is distributed at each instant among the various elements that form the injection zone according to either the mass or the volume of the element in relation to the total mass or volume of the zone.

The following global results can be accessed via TPLOT, for each injection zone that has been defined:

```
INJVxxxx : Volume of injection zone number xxxx
INJMxxxx : Mass of injection zone number xxxx
INJQxxxx : Power injected in injection zone number xxxx
INJIxxxx : Energy injected in injection zone number xxxx
```

Note that energy injection may also be applied to finite elements (only of FLxx types) having the `FLMP` multiphase multicomponent material. In that case, the injected energy is distributed among all fluid components currently present in the element proportionally to their respective relative mass fractions.

EUROPLEXUS offers another (completely distinct) mechanism for prescribing energy (or even mass) generation, namely via the `GENE` and `GENM` parameters of the user's fluid (`FLUT` or `FLMP`) material. The main difference is that in that case, the generation applies to the material rather than to a spatial zone (elements or nodes). Another difference is that in that case the given time function (`FONC`) represents the specific generated energy per unit time, and not the total energy per unit time.

9.3 INITIAL CONDITIONS

Object:

The directives in this section enable the input of initial conditions relative to displacements, velocities, stresses, temperatures etc.. The temperature can be entered directly or under the form of injected energy.

Syntax:

```
"INIT"
   < "FICH" 'nom_fich' >
   < "DEPL"  . . . >
   < "VITE"  . . . >
   < "VRIG"  . . . >
   < "VITC"  . . . >
   < "VFCC"  . . . >
   < "SPHE"  . . . >
   < "CONT"  . . . >
   < "TETA"  . . . >
   < "TNOD"  . . . >
   < "ENER"  . . . >
   < "GRAD"  . . . >
   < "GRAV"  . . . >
   < "DEBI"  . . . >
   < "ROTA"  . . . >
   < "ALIC"  . . . >
   < "MCOM"  . . . >
   < "CQST"  . . . >
   < "CQDF"  . . . >
   < "MEDL"  . . . >
   < "STAT"  . . . >
   < "DMAS"  . . . >
   < "EQUI"  . . . >
   < "CRAK"  . . . >
   < "ADAP"  . . . >
   < "IMAT"  . . . >
   < "SKIP"  . . . >
   < "DELA"  . . . >
   < "MAPB"  . . . >
   < "ENGR"  . . . >
   < "MAPP"  . . . >
```

Comments:

The key-word "INIT" may appear at most once, at the beginning of the sequence relative to the initial conditions.

9.3.1 AUXILIARY FILE

Object:

This directive allows to read the initial conditions data from an auxiliary file.

Syntax:

```
< "FICHIER"   'nom.fic'  >
```

In certain cases the data may be bulky. It is then recommended to store them on an auxiliary file to shorten the main input data file. The auxiliary file is activated by means of the keyword "FICHIER" that precedes the file name (complete under Unix). In the main data file then only the keywords "INITIAL" "FICHIER" remain.

The auxiliary file (in free format) contains the whole set of initial conditions data, except the keyword "INITIAL". To return to the main input data, the auxiliary file must be terminated by the keyword "RETOUR".

9.3.2 INITIAL DISPLACEMENTS

Object:

The initial conditions concern the nodes of the mesh.

The coordinates of the original mesh are modified.

Syntax:

```
"DEPL" ( icomp  xm  /LECTURE/ )
```

`icomp`

Number of the component to which the initial condition applies.

`xm`

Value of the displacement.

`LECTURE`

List of the numbers of the nodes concerned.

Comments:

An initial displacement enables the modification of the geometry for a few points without using the meshing program again.

If several values must be entered, it is not necessary to repeat the number of the component.

Example :

```
"INIT"  "DEPL"  1  3.1  LECTURE  1 2 TERM
                2  1.5  LECTURE  3   TERM
        "VITE"  1  0.2  LECTURE  5 PAS 1 10 TERM
```

9.3.3 INITIAL VELOCITIES

Object:

These initial conditions are relative to the nodes of the mesh.

- `VITE` : prescribed initial particle (material) velocity
- `VITG` : prescribed initial mesh velocity (only available in an ALE calculation)

Syntax:

```
|[ "VITE" ; "VITG" ]|
        ( icomp   vi  /LECTURE/                         )
        ( "RADI"  vr  "CENT" /LECTURE/  "SURF" /LECTURE/ )
        $[ "FILE" ifich ; "LIST" ... ]$
        ( "NOEU" n vx vy <vz>                           )
```

`icomp`

Number of the component where the initial condition is located.

`vi`

Value of the prescribed velocity according to the component icomp.

`RADI CENT SURF`

Prescribe a radial velocity (see comments below).

`vr`

Modulus of the prescribed radial velocity (see comments below).

`FILE`

Velocities are read from a file, as defined next.

`ifich`

Data-set (logical unit number) or file name (in quotes) of the file from which initial nodal velocities are to be read. The data have to be written on the file according with the following (fixed) format. For 3D calculations there are 4 data per line, i.e. (NODE, VX, VY, VZ), and the format is (I6,3E12.5). For 2D calculations there are 6 data per line, i.e. (NODE, VX, VY, NODE, VX, VY) and the format is 2(I6,2E12.5). Note that **all nodes** of the mesh must be specified in this case, even those having zero initial velocities, because the code reads on from the file until the total number of nodes in the model has been reached.

`LIST`

Velocities are read from a list, which directly follows the `LIST` keyword in the input file (starting on a new line). The format of this list is exactly the same as for the `FILE` option described above. This syntax allows to embed in the input file data originally contained in a separate file, without any format changes, but it should be avoided for newly written inputs.

`n vx vy <vz>`

Velocity components of node n are vx vy (and vz in 3D).

`LECTURE`

List of the numbers of the nodes concerned.

Comments:

If several values must be entered, it is possible to repeat the number of the component or the word "RADI".

If the prescribed initial velocity is a radial one the user just has to put the word "RADI" followed by the velocity modulus, and thereafter the word "CENT", to give the number of the central node and to enter the series of nodes having the same radial velocity, after the word "SURF". EUROPLEXUS then automatically computes the initial components of the velocity in the global coordinate system.

Warning: the positive direction goes from the center to the exterior.

Example :

```
"INIT"  "VITE"   1    -0.2  LECTURE  5 PAS 1 10 TERM
                 2    -0.3  LECTURE  5 PAS 1 10 TERM
              "RADI"   1.5  "CENT"  LECTURE  pcen  TERM
                            "SURF"  LECTURE  psur  TERM
```

9.3.4 INITIAL VELOCITIES FOR RIGID BODIES

Object:

To prescribe initial velocities for rigid bodies.

Syntax:

```
"VRIG" ( icomp vi /LECTURE/ )
```

`icomp`

Index of the component of the initial velocity. See comments below for the meaning of each component.

`vi`

Prescribed value of the initial velocity according to the component `icomp`. See comments below for details.

`LECTURE`

List of the indexes of the rigid bodies concerned (see directive `COMP RIGI`).

Comments:

If several values must be entered, it is possible to repeat the index of the component.

The initial velocities must be expressed in the global reference frame X, Y, Z (the rotational values are then converted internally to the local reference frame, as appropriate). The meaning of the various components is as follows:

- In 2D calculations, `icomp` 1 is v_X, 2 is v_Y and 6 is the rotational velocity $\omega = \omega_Z$. Components 3 (v_Z), 4 (ω_X) and 5 (ω_Y) must be 0 in 2D and may *not* be specified.
- In 3D calculations, `icomp` 1 is v_X, 2 is v_Y, 3 is v_Z, 4 is the rotational velocity ω_X, 5 is ω_Y and 6 is ω_Z.

9.3.5 INITIAL VELOCITIES FOR CELL-CENTRED FINITE VOLUMES

Object:

These initial conditions are relative to the cell centers of a mesh composed of Cell-Centred Finite Volumes.

Syntax:

```
("VITC"  "VITX" vx  "VITY" vy  <"VITZ" vz>  /LECTURE/)
```

`vx`

Initial velocity along x-axis.

`vy`

Initial velocity along y-axis.

`vz`

Initial velocity along z-axis (3D only).

`LECTURE`

List of the numbers of the elements concerned.

9.3.6 INITIAL CONDITIONS FOR CELL-CENTRED FINITE VOLUMES

Object:

These initial conditions are relative to the cell centers of a mesh composed of Cell-Centred Finite Volumes. For the moment, we can only impose these initial conditions in GAZP and CDEM materials. These new imposed initial conditions override the ones imposed when applying the material to the concerned elements.
Point-symmetric initial conditions specifying primitive variables can be imposed for perfect gases (GAZP) using an input file.
Point-symmetric initial conditions specifying conservative variables can be imposed for any gas using an input file.
Plane-symmetric initial conditions specifying conservative variables can be imposed for any gas using an input file.

Syntax for perfect gas (GAZP) material:

```
("VFCC"  "VITX" vx  "VITY" vy  <"VITZ" vz>  "PINI" pini "RHO" rho /LECTURE/)
```

`vx`

Initial velocity along x-axis.

`vy`

Initial velocity along y-axis.

`vz`

Initial velocity along z-axis (3D only).

`pini`

Initial pressure.

`rho`

Initial density.

`LECTURE`

List of the numbers of the elements concerned.

Syntax for perfect gas (GAZP) material in the point symmetric case.

```
("SPHE" "VFCC" "GAZP" 'nom.fic')
```

In 'nom.fic' one should specify: the number of centers of symmetry, the number of data for each region, the center of each region and the data: radius and density, radial velocity, pressure (as function of the radius). In the example below we have 2 centers of symmetry, 19 data for the first center ((0. 0.) with $0 < r < 0.1$) and 21 data for the second one ((1. 0.), with $0 < r < 0.2$). EOFI is the last line of 'nom.fic'.

```
2
19
21
1   0.000000E+00  0.000000E+00
 0.000000E+00  0.110000E+01 -0.700000E+03  0.110000E+06
 0.555556E-02  0.110374E+01 -0.687716E+03  0.110374E+06
 0.111111E-01  0.111495E+01 -0.675432E+03  0.111495E+06
 0.166667E-01  0.113364E+01 -0.663148E+03  0.113364E+06
 0.222222E-01  0.115980E+01 -0.650864E+03  0.115980E+06
 0.277778E-01  0.119344E+01 -0.638581E+03  0.119344E+06
 0.333333E-01  0.123456E+01 -0.626297E+03  0.123456E+06
 0.388889E-01  0.128315E+01 -0.614013E+03  0.128315E+06
 0.444444E-01  0.133921E+01 -0.601729E+03  0.133921E+06
 0.500000E-01  0.140275E+01 -0.589445E+03  0.140275E+06
 0.555556E-01  0.147377E+01 -0.577161E+03  0.147377E+06
 0.611111E-01  0.155226E+01 -0.564877E+03  0.155226E+06
 0.666667E-01  0.163822E+01 -0.552593E+03  0.163822E+06
 0.722222E-01  0.173166E+01 -0.540309E+03  0.173166E+06
 0.777778E-01  0.183258E+01 -0.528026E+03  0.183258E+06
 0.833333E-01  0.194097E+01 -0.515742E+03  0.194097E+06
 0.888889E-01  0.205684E+01 -0.503458E+03  0.205684E+06
 0.944444E-01  0.218018E+01 -0.491174E+03  0.218018E+06
 0.100000E+00  0.231100E+01 -0.478890E+03  0.231100E+06
2   0.100000E+01  0.000000E+00
 0.000000E+00  0.170000E+01 -0.300000E+03  0.170000E+06
 0.100000E-01  0.170517E+01 -0.278883E+03  0.170517E+06
 0.200000E-01  0.172068E+01 -0.257766E+03  0.172068E+06
 0.300000E-01  0.174653E+01 -0.236649E+03  0.174653E+06
 0.400000E-01  0.178272E+01 -0.215532E+03  0.178272E+06
 0.500000E-01  0.182925E+01 -0.194415E+03  0.182925E+06
 0.600000E-01  0.188612E+01 -0.173298E+03  0.188612E+06
 0.700000E-01  0.195333E+01 -0.152181E+03  0.195333E+06
 0.800000E-01  0.203088E+01 -0.131064E+03  0.203088E+06
 0.900000E-01  0.211877E+01 -0.109947E+03  0.211877E+06
 0.100000E+00  0.221700E+01 -0.888300E+02  0.221700E+06
 0.110000E+00  0.232557E+01 -0.677130E+02  0.232557E+06
 0.120000E+00  0.244448E+01 -0.465960E+02  0.244448E+06
 0.130000E+00  0.257373E+01 -0.254790E+02  0.257373E+06
 0.140000E+00  0.271332E+01 -0.436200E+01  0.271332E+06
 0.150000E+00  0.286325E+01  0.167550E+02  0.286325E+06
 0.160000E+00  0.302352E+01  0.378720E+02  0.302352E+06
```

```
   0.170000E+00  0.319413E+01  0.589890E+02  0.319413E+06
   0.180000E+00  0.337508E+01  0.801060E+02  0.337508E+06
   0.190000E+00  0.356637E+01  0.101223E+03  0.356637E+06
   0.200000E+00  0.376800E+01  0.122340E+03  0.376800E+06
 EOFI
```

Syntax for any gas in the point symmetric case.

```
  ("SPHE" "VFCC" "CONS" 'nom.fic')
```

In 'nom.fic' one should specify: the number of centers of symmetry, the number of data for each region and the number of conservative variables, the center of each region and the data: radius and conservative variables (as function of the radius). In the example below we have 2 centers of symmetry, 19 data and 3 conservative variables for the first center ((0. 0.) with $0 < r < 0.1$) and 21 data and 4 conservative variables for the second one ((1. 0.), with $0 < r < 0.2$). EOFI is the last line of 'nom.fic'. Concerning the data, in the first column there is the radius, in the second one the density, then the momentum and the total energy follow. Other eventual variables depend on the type of material.

```
  2
  19  3
  21  4
  1   0.000000E+00  0.000000E+00
   0.000000E+00  0.110000E+01 -0.700000E+01  0.110000E+06
   0.555556E-02  0.110374E+01 -0.687716E+01  0.110374E+06
   0.111111E-01  0.111495E+01 -0.675432E+01  0.111495E+06
   0.166667E-01  0.113364E+01 -0.663148E+01  0.113364E+06
   0.222222E-01  0.115980E+01 -0.650864E+01  0.115980E+06
   0.277778E-01  0.119344E+01 -0.638581E+01  0.119344E+06
   0.333333E-01  0.123456E+01 -0.626297E+01  0.123456E+06
   0.388889E-01  0.128315E+01 -0.614013E+01  0.128315E+06
   0.444444E-01  0.133921E+01 -0.601729E+01  0.133921E+06
   0.500000E-01  0.140275E+01 -0.589445E+01  0.140275E+06
   0.555556E-01  0.147377E+01 -0.577161E+01  0.147377E+06
   0.611111E-01  0.155226E+01 -0.564877E+01  0.155226E+06
   0.666667E-01  0.163822E+01 -0.552593E+01  0.163822E+06
   0.722222E-01  0.173166E+01 -0.540309E+01  0.173166E+06
   0.777778E-01  0.183258E+01 -0.528026E+01  0.183258E+06
   0.833333E-01  0.194097E+01 -0.515742E+01  0.194097E+06
   0.888889E-01  0.205684E+01 -0.503458E+01  0.205684E+06
   0.944444E-01  0.218018E+01 -0.491174E+01  0.218018E+06
   0.100000E+00  0.231100E+01 -0.478890E+01  0.231100E+06
  2   0.100000E+01  0.000000E+00
   0.000000E+00  0.170000E+01 -0.300000E+01  0.170000E+06  0.170000E+01
   0.100000E-01  0.170517E+01 -0.278883E+01  0.170517E+06  0.170517E+01
   0.200000E-01  0.172068E+01 -0.257766E+01  0.172068E+06  0.172068E+01
   0.300000E-01  0.174653E+01 -0.236649E+01  0.174653E+06  0.174653E+01
   0.400000E-01  0.178272E+01 -0.215532E+01  0.178272E+06  0.178272E+01
```

```
  0.500000E-01  0.182925E+01 -0.194415E+01  0.182925E+06  0.182925E+01
  0.600000E-01  0.188612E+01 -0.173298E+01  0.188612E+06  0.188612E+01
  0.700000E-01  0.195333E+01 -0.152181E+01  0.195333E+06  0.195333E+01
  0.800000E-01  0.203088E+01 -0.131064E+01  0.203088E+06  0.203088E+01
  0.900000E-01  0.211877E+01 -0.109947E+01  0.211877E+06  0.211877E+01
  0.100000E+00  0.221700E+01 -0.888300E+00  0.221700E+06  0.221700E+01
  0.110000E+00  0.232557E+01 -0.677130E+00  0.232557E+06  0.232557E+01
  0.120000E+00  0.244448E+01 -0.465960E+00  0.244448E+06  0.244448E+01
  0.130000E+00  0.257373E+01 -0.254790E+00  0.257373E+06  0.257373E+01
  0.140000E+00  0.271332E+01 -0.436200E-01  0.271332E+06  0.271332E+01
  0.150000E+00  0.286325E+01  0.167550E+00  0.286325E+06  0.286325E+01
  0.160000E+00  0.302352E+01  0.378720E+00  0.302352E+06  0.302352E+01
  0.170000E+00  0.319413E+01  0.589890E+00  0.319413E+06  0.319413E+01
  0.180000E+00  0.337508E+01  0.801060E+00  0.337508E+06  0.337508E+01
  0.190000E+00  0.356637E+01  0.101223E+01  0.356637E+06  0.356637E+01
  0.200000E+00  0.376800E+01  0.122340E+01  0.376800E+06  0.376800E+01
 EOFI
```

Syntax for any gas in the plane-symmetric case.

```
 ("PLAN" "VFCC" "CONS" 'nom.fic')
```

In 'nom.fic' one should specify: the number of symmetric conditions, the number of data for each region and the number of conservative variables, the center of each region, the direction and the data: distance from the plane and conservative variables (as function of the distance from the plane). In the example below we have 1 plane-symmetric initial condition, 19 data and 3 conservative variables. The first plane is in ((0. 0.) with $0 < d < 0.1$ and the normal to the plane is $(1.0, 0.0)$). EOFI is the last line of 'nom.fic'. Concerning the data, in the first column there is the distance, in the second one the density, then the momentum and the total energy follow. Other eventual variables depend on the type of material.

```
 1
 19  3
 1   0.000000E+00  0.000000E+00  1.0 0.0
  0.000000E+00  0.110000E+01 -0.700000E+01  0.110000E+06
  0.555556E-02  0.110374E+01 -0.687716E+01  0.110374E+06
  0.111111E-01  0.111495E+01 -0.675432E+01  0.111495E+06
  0.166667E-01  0.113364E+01 -0.663148E+01  0.113364E+06
  0.222222E-01  0.115980E+01 -0.650864E+01  0.115980E+06
  0.277778E-01  0.119344E+01 -0.638581E+01  0.119344E+06
  0.333333E-01  0.123456E+01 -0.626297E+01  0.123456E+06
  0.388889E-01  0.128315E+01 -0.614013E+01  0.128315E+06
  0.444444E-01  0.133921E+01 -0.601729E+01  0.133921E+06
  0.500000E-01  0.140275E+01 -0.589445E+01  0.140275E+06
  0.555556E-01  0.147377E+01 -0.577161E+01  0.147377E+06
  0.611111E-01  0.155226E+01 -0.564877E+01  0.155226E+06
  0.666667E-01  0.163822E+01 -0.552593E+01  0.163822E+06
  0.722222E-01  0.173166E+01 -0.540309E+01  0.173166E+06
```

```
   0.777778E-01  0.183258E+01 -0.528026E+01  0.183258E+06
   0.833333E-01  0.194097E+01 -0.515742E+01  0.194097E+06
   0.888889E-01  0.205684E+01 -0.503458E+01  0.205684E+06
   0.944444E-01  0.218018E+01 -0.491174E+01  0.218018E+06
   0.100000E+00  0.231100E+01 -0.478890E+01  0.231100E+06
 EOFI
```

Syntax for the CDEM material:

```
("VFCC" "VITX" vx "VITY" vy <"VITZ" vz> "PINI" pini "TINI" tini

        "KSI0" ksi0 "K0" k0 "Y1" y1  "Y2" y2 "Y3" y3 ... /LECTURE/)
```

See the CDEM material for the meaning of each term.

9.3.7 INITIAL STRESSES

Object:

To prescribe initial stresses to different elements.

Syntax:

```
"CONT" ( icomp  sig /LECTURE/ )
```

`icomp`

Number of the component to which the initial condition applies.

`sig`

Value of the initial stress.

`LECTURE`

List of the numbers of the elements concerned.

Comments:

The components of the stress tensor are stored in a one-dimensional array. The number of the components depends on the element. See the description of the elements available page INT.80 .

The initial stresses are provided at the integration points of the element.

If there are several integration points in one element, an initial value is given to the component icomp of all the points concerned.

If the initial stresses are the result of a static load, it may be more adequate to use EUROPLEXUS for the necessary computations, by using a quasi static damping (see the instruction "OPTION"). A restart after that first computation, by changing the load, will provide the desired result.

Be careful and respect the writing conventions for the stress tensor of each element (see GBG_0020).

9.3.8 INITIAL TEMPERATURES

Object:

To prescribe different temperatures on certain elements. The values are either directly read from the input file, or as the results of a DELFINE file.

Syntax:

```
Direct reading:

"TETA"   (  ti  /LECTURE/   )

Reading from a DELFINE file:

"TETA"  "DELFINE" ndelfine    "TDELFINE"  tdelfine
```

`ti`

Initial temperature.

`LECTURE`

List of the numbers of the elements concerned.

`ndelfine`

Logical unit number of the DELFINE file.

`tdelfine`

Time written on file DELFINE. The field of temperatures at that instant is considered as the initial temperature field for the EUROPLEXUS computation.

Comments:

The definition of a temperature is compulsory for a isotropic Von Mises material dependant on temperature (VMIS TETA) as well as for the material PUFF. By default it is supposed to be equal to zero.

If the user wants to impose to the material VMIS TETA a field of initial stresses due to heating, he has to use the instruction "ENERGIE" (see page E.90).

9.3.9 NODAL TEMPERATURES FOR ADVECTION-DIFFUSION (JRC)

Object:

To prescribe initial nodal temperatures for advection-diffusion problems. These can optionally be read from a separate data-set.

Syntax:

```
"TNOD"  |[ ( tnod  /LECTURE/) ;
             "FILE"  ifich      ;
         $ "LIST"  ...         $
```

`tnod`

Initial temperature.

`/LECTURE/`

List of concerned nodes.

`FILE`

Temperatures are read from a file, as defined next.

`ifich`

Unit number of data-set containing nodal temperatures in the form (node index, T). Values are read using format (4(i6,e12.5)).

`LIST`

Temperatures are read from a list, which directly follows the `LIST` keyword in the input file (starting on a new line). The format of this list is exactly the same as for the `FILE` option described above. This syntax allows to embed in the input file data originally contained in a separate file, without any format changes, but it should be avoided for newly written inputs.

9.3.10 INITIAL ENERGY SUPPLY

Object:

The directive is used to input the temperature field and the field of the corresponding initial stresses generated by a supply of external energy.

The instruction can be used only in connection with the material VMIS TETA (Von Mises isotrope dependant on temperature).

Syntax:

```
"ENERGIE" ( "CV" cv   "ALPHA" alpha  "DEPOSE" wd  /LECTURE/ )
```

`cv`

Specific heat.

`alpha`

Coefficient of linear expansion.

`wd`

Supplied energy.

`LECTURE`

List of the numbers of the elements concerned.

Comments:

The definition of a temperature is compulsory for an isotropic Von Mises material depending on temperature. By default it is supposed to be equal to zero.

For this material, the phenomenum is considered isothermal and the temperature remains constant during the computation.

A supplied energy result in an initial stress sig0:

```
sig0 = E * alpha * ( wd / cv )
```

Here E represents Young's modulus. Obviously, the temperature increment relative to the supplied energy is taken into account:

```
DT = wd / cv.
```

9.3.11 INITIAL BENDING STRESSES DUE TO TEMPERATURE GRADIENT

Object:

The instruction inputs a field of initial bending stresses, generated by a temperature gradient through the thickness of shell elements.

Syntax:

```
 "GRADIENT"  gradt                          ...
...  (   $[   "ALPH"   alpha                     ;
              "ALP1"   alp1      "ALP2"  alp2    ]$  /LECTURE/  )
```

`gradt`

Temperature gradient (along the normal to the element).

`alpha`

Coefficient of linear expansion (isotropic materials).

`alph1,alph2`

Coefficients of linear expansion (orthotropic material) in the orthotropy coordinate system relative to the element CMC3.

`LECTURE`

List of the numbers of the elements concerned.

Comments:

The orientation the normal depends on the numbering of the nodes of the element (see Maxwell's cork-screw rule).

This option concerns only the following shell elements: COQUE, COQ3, COQ4, CMC3, and the following materials: LINEAIRE, VMIS ISOTROPE, VMIS TETA, ORTHOTROPE.

For isotropic materials, the initial stress sigf0 is :

```
sigf0 = - alpha * gradt * epaisseur * young / (1-nu)
```

9.3.12 GRAVITY LOADING

Object:

This directive allows to introduce an initial stress field due to gravity (or to hydrostatic pressure, for the fluids) that equilibrates the body weight at the initial time. In the case of pipelines (elements "TUBE" or "TUYA"), it is preferable to use directive "INIT" "DEBI" (page E.120).

Syntax:

```
"GRAVITE"    "PTSL" xcoor ycoor < zcoor >    "PSL" psl
             "G"     gx    gy   <   gz  >   < "STRUC" >
             "COUCH"   ncouch*(  "RO" rho   "H"  h )
              ...       /LECTURE/
```

`xcoor, ycoor, zcoor`

Coordinates of the point defining the free surface supposed normal to the vector defining the body weight.

`psl`

Initial pressure at the free surface.

`gx gy gz`

Components of the weight.

`STRUC`

Indicates that the concerned elements are associated to a structural material (the stress field is computed in the global reference frame).

`ncouch`

Number of layers composed by different materials.

`rho`

Density of the layer.

`h`

Height of the layer.

`LECTURE`

Numbers of the elements subjected to gravity.

```
                          psf

            |     |     |     |     |     |
            |     |     |     |     |     |
            v     v     v     v     v     v
            -------------------------------  .......   free surface
            |                             |       |
    |       |        layer no. 1 (rho1)   |       | h
    | G     |                             |       |  1
    |       |-----------------------------| ......V
    v       |        layer no. 2 (rho2)   |       | h
            |-----------------------------| ......V  2
            |                             |       |
            |                             |       |
            |        layer no. 3 (rho3)   |       | h
            |                             |       |  3
            |                             |       |
            |-----------------------------| ......V
            .                             .
            .                             .
```

Comments:

The component <gz> of the acceleration is only used in a 3D calculation.

The pressure is associated to the elements' Gauss points.

The gravity may only be used with continuum elements; the elements of type shell, beam, bar are excluded.

In the case of fluid materials gravity may only be taken into account with the following material laws:

number	name	fluid material law
7	FLUI	isothermal fluid (c = cte)
8	CAVI	liquid with cavitation
21	ECOU	isothermal fluid flow
10	NAH2	sodium-water reaction
34	ADCR	confinement accident (fast neutrons)
53	ADCJ	confinement accident with JWL gas
22	EAU	two-phase water (liquid + vapour)

Warning:

In order to obtain a state of equilibrium at t = 0, it is necessary to use the directive CHARGEMENT CONSTANT GRAVITE (see page F.30). The stresses computed will then be equilibrated by the forces applied to the nodes of the structure defined by the directive "CHARG CONST GRAV".

For the fluid materials for which the density is re-computed, it is necessary to do a first calculation of just one step (for example) so as to obtain the correct values of the density RHO.

9.3.13 PRESCRIBED CONSTANT FLOW RATE

Object:

This directive allows to specify a field of initial pressures in the branch of a pipeline, which equilibrates at the initial time instant the forces due to head losses, so as to obtain a constant mass flow rate. The hydrostatic pressure is also accounted for, in the case that a gravity load is also prescribed.

This directive may be used only in 1D: elements "TUBE" or "TUYA".

Syntax:

```
 "DEBIT"
        "LIGN" "PENT" pent   "DEBI" dmas   < "GRAV"  gx gy gz >

               "ORIG"        /LECTURE/
               "LIST"        /LECTURE/
```

`LIGN`

Keyword introducing the reading of the data relative to a pipeline branch.

`pent`

Inlet pressure of the pipeline branch.

`dmas`

Imposed mass flow rate in the pipeline branch.

`gx,gy,gz`

Gravity components.

`ORIG`

Keyword announcing the reading of the node number at the inlet of the pipeline branch.

`LIST`

Keyword announcing the reading of the element numbers of the pilpeline branch.

Comments:

In the case of a complex pipeline, it is mandatory to decompose it in several elementary branches, for each of which the directive "LIGN" "PENT" ... will be repeated.

The pressure is applied at the element centers.

The velocities in each node of the branch will be computed by EUROPLEXUS, as a function of the mass flow rate (dmas) and of the local diameters.

If there is a gravity loading, do not forget to prescribe also "CHARGE" "CONST" "GRAVITE" (page F.30) for the rest of the calculation. In fact, the directive "INIT" "DEBI" computes only the initial status.

There is just one d.o.f. for the elements of type "TUBE", therefore only the weight component along the axis is taken into account for the kydrostatic pressure.

This directive may be used only for the pipelines, i.e. with elements "TUBE", "TUYA", "CAVI", "BIFU", "CL1D" and "CLTU".

It is currently possible to account for the initial mass flow rate only for the following materials:

```
number | name  |  fluid material law
-------|-------|----------------------------------------
   7   | FLUI  |  isothermal fluid ( c = cte )
   8   | CAVI  |  liquid with cavitation
  21   | ECOU  |  isothermal fluid flow
  10   | NAH2  |  sodium-water reaction
  22   | EAU   |  two-phase water (liquid + vapour)
-------|-------|----------------------------------------
```

Example:

```
                    p1 (pressure)
            pt1   *
                  |
                  |
                  v
                  |flowrate1
                  |
                  |
                  |
                  |
                  v
    p2 (pressure) | pt2   flowrate2
                  +*----->----------->----- p3 (pressure)
            pt3  *
                /
               /
              /
             /  flowrate3
            /
           /
          /
         /
        /
     p4 (pressure)
```

```
 In this example the directive will become:

  "INITIAL"

       "DEBIT"
                 "LIGN" "PENT" p1    "DEBI"  debit1
                        "ORIG"       "LECT"   pt1    "TERM"
                        "LIST"       "LECT"  ligne1  "TERM"

                 "LIGN" "PENT" p2   "DEBI"   debit2
                        "ORIG"      "LECT"    pt2    "TERM"
                        "LIST"      "LECT"   ligne2  "TERM"

                 "LIGN" "PENT" p3   "DEBI"   debit3
                        "ORIG"      "LECT"    pt3    "TERM"
                        "LIST"      "LECT"   ligne3  "TERM"
```

Remarks:

In the preceding example, if one just knows the inlet pressure and the mass flow rate in the branch ‘ligne1’, the following procedure may be followed to obtain the equilibrium status:

- A first EUROPLEXUS calculation is performed for just 1 time step, by taking as initial pressure the inlet pressure p1 for all the pipeline branches with the desired mass flow rates (flowrate1, flowrate2 and flowrate3).

- On the EUROPLEXUS listing, the head losses are printed for each branch of the pipeline. By knowing the head losses in the branch 'ligne1', the outled pressure for this branch may be deduced: p = p1 - pcha1 which corresponds to the inlet pressures for the branches 'ligne2' and 'ligne3' of our example.

- For the real calculation, the initial conditions to be assumed are then an initial pressure p1 for the branch 'ligne1' and an initial pressure p2 = p1 - pcha1 for the branches 'ligne2' and 'ligne3'. The output pressures of branches 'ligne2' and 'ligne3' are respectively equal to p3 = p2 - pcha2 = p1 - pcha1 - pcha2 and p4 = p2 - pcha3 = p1 - pcha1 - pcha3; where pcha2 and pcha3 indicate the head losses in the branches 'ligne2' and 'ligne3'.

- In order to obtain an even better precision, one must take care that the inlet pressure of the branch and the initial pressure of the fluid elements in the branch be coherent. This implies using a "MATERIAU" directive per branch, with the same elements as for the initial mass flow rate.

9.3.14 INITIAL ROTO-TRANSLATIONAL VELOCITY

Object:

This directive allows to initialise the velocity field for a structure undergoing an initial rotational and an (optional) superposed translational motion. At each node of the structure, the values of initial translational velocity components (resulting from the roto-translational global motion of the body) are evaluated. If a node also possesses rotational degrees of freedom (e.g. because it belongs to a shell or a beam) then also the rotational components of velocity are initialized.

Note that the present directive does *not* initialize the stress field generated by centrifugal forces in the structure. This initialization must be done by a suitable separate input directive, if the structure must be initially in equilibrium.

Syntax:

```
"ROTA"    "ORIG" ox oy <oz>
          "AXIS" ax ay az
          "OMEG" omeg
       <$ "VAXE" vaxe ; "VTRA" vx vy <vz> $>
          /LECT/
```

The data consist of two parts. The first part is mandatory and defines the rotational components of the velocity.

`ORIG ox oy <oz>`

Coordinates O_x, O_y, O_z of the "origin" point O for the rotation (O_z must not be specified in 2D).

`AXIS ax ay az`

Components a_x, a_y, a_z of the vector defining the rotation axis $\overrightarrow{a}$. These data *must not* be specified in 2D because in this case the rotation axis is supposed to be normal to the plane and directed "upwards", i.e. a positive initial rotational velocity produces a counter-clockwise rotation. The defined vector $\overrightarrow{a}$ need not be unitary in length, since it is normalized to unit length internally immediately after reading: $\hat{\overrightarrow{a}} = \overrightarrow{a}/||\overrightarrow{a}||$. Rotation is then assumed to occur around an axis parallel to $\hat{\overrightarrow{a}}$ and passing through the "origin" O that has been defined above. The former keyword for this parameter (`VECT` instead of `AXIS`) is obsolescent and deprecated, but it is still accepted for backward compatibility.

`OMEG omeg`

Rotational velocity ω in rad/s around an axis parallel to $\hat{\overrightarrow{a}}$ through O, that is $\overrightarrow{\omega} = \omega\hat{\overrightarrow{a}}$.

The second part of the directive is optional and defines an initial translational velocity $\overrightarrow{v_0}$ to be combined with the initial rotational velocity $\overrightarrow{\omega}$. The `VAXE` form is a special syntax that can be used when $\overrightarrow{v_0}$ is directed along the axis of rotation $\hat{\overrightarrow{a}}$, that is if $\overrightarrow{v_0} = v_a\hat{\overrightarrow{a}}$, and is maintained for backward compatibility of old input files. The `VTRA` form is more general (although in principle redundant, as explained in the comments below), since it allows to define a generic translational velocity $\vec{v_0}$ not necessarily directed along the axis of rotation $\hat{\vec{a}}$. If both keywords are omitted, the initial translational velocity will be zero.

`VAXE vaxe`

Initial *axial* velocity v_a, i.e. initial translational velocity directed along the axis of rotation $\hat{\vec{a}}$ defined above. This keyword is only available in 3D, since in 2D no velocity along the axis of rotation (which is normal to the plane) may occur.

`VTRA vx vy <vz>`

Initial translational velocity $\vec{v_0}$, of components v_x, v_y, v_z. The z component must be specified in 3D and must *not* be specified (it is zero) in 2D.

The directive is concluded by specifying the nodes of the structure submitted to the initial roto-translational velocity.

`/LECT/`

Numbers of the nodes belonging to the initially roto-translating structure.

Comments:

This directive initializes, for each node I defined by the preceding `/LECT/`, a translational velocity equal to:

$$\vec{v_I} = \vec{\omega} \times \overrightarrow{OI} + \vec{v_0} = \omega \hat{\vec{a}} \times \overrightarrow{OI} + \vec{v_0} \qquad (90)$$

If the `VAXE` form is used for the translational velocity, then this reduces to:

$$\vec{v_I} = \omega \hat{\vec{a}} \times \overrightarrow{OI} + v_a \hat{\vec{a}} \qquad (91)$$

When the concerned node I has also rotational degrees of freedom, its initial rotational velocity components are initialised as well:

$$\vec{\omega}_I = \vec{\omega} = \omega \hat{\vec{a}} \qquad (92)$$

In principle, *any* rigid body motion can be described by the superposition of the rotation around a given axis (called the instantaneous axis of rotation) plus a translation *along this same axis*. Therefore, the `VAXE` form of this input directive is sufficient to define any roto-translational state of initial velocity, provided the instantaneous axis of rotation is known (i.e., not only as a direction, but also thhrough its position in space, as given by one of its points).

However, in practice a user may prefer to think of the motion as the superposition of a rotation around a particular axis (typically, but not necessarily, passing through the centre of gravity G of the body) plus a translation in a direction *not* parallel to this axis. Since the analytical determination of the “true” rotational axis (instantaneous axis of rotation as defined above) is not immediate in such a case, the `VTRA` form of the command can come handy, since it can be used directly.

In 2D, it is supposed that the rotation axis is normal to the plane.

It is also necessary to define the initial field of the stresses generated by the centrifuge forces, else the structure will not satisfy the equations of motion at the initial time.

9.3.15 INITIALISATIONS FROM A PREVIOUS ALICE FILE

Object:

This directive allows to initialise the geometry, the stress field and the field of hardening parameters starting from the ALICE file of a previous EUROPLEXUS calculation.

Syntax:

```
    "ALICE"  ndfic
             < "MFRO"     omega   >
             < "ECRO"             >
             < "TEMPS"    temps   >
             < "NPAS"     npas    >
             < "POINT"    noe1 noe2 >
             < "ELEMENT"  iel1 iel2 >
```

`ndfic`

Logical unit number of the preliminary ALICE file.

`omega`

Activate “mise a froid” for the structure according to the `omega` parameter.

`ECRO`

Initialize the `ECR` array. By default, `ECR` is not initialized: one makes a preliminary calculation with a very large elastic limit, which yields an elastic solution. In the following calculation, the true material curve is used (one starts with zero plastic deformation).

`temps, npas`

Time or step number of the ALICE file starting from which one reads the fields of displacement, stress and hardening parameters necessary for the initialisation of the present calculation.

`noe1,noe2`

The initialisation will only occur for the nodes between **noe1** and **noe2**.

`iel1,iel2`

The initialisation will only occur for the elements between **iel1** and **iel2**.

Comments:

The meshes of the current calculation an of the preliminary one may be different. But it is **MANDATORY** that all nodes and elements of the preliminary calculation **MAINTAIN THE SAME NUMBERS** in the present one. The present mesh must therefore be a superset of the previous one.

When the directives "TEMPS" or "NPAS" are not given, EUROPLEXUS initialises starting from the last step of the preliminary calculation.

When the directive "POINT" (respectively "ELEM") is not present, EUROPLEXUS initialises for all points (respectively all elements).

9.3.16 INITIAL STATUS OF MULTICOMPONENT FLOW (JRC)

Object:

The instruction defines initial conditions for multicomponent fluid flows.

Syntax:

```
"MCOM"   "TEMP"                $ ( val  /LECT/ )         $
                               $ "CHAM"  /LCHP/  /LECT/   $

         "PRES"                $ ( val  /LECT/ )         $
                               $ "CHAM"  /LCHP/  /LECT/   $

         "VEL1"                $ ( val  /LECT/ )         $
                               $ "CHAM"  /LCHP/  /LECT/   $

         "VEL2"                $ ( val  /LECT/ )         $
                               $ "CHAM"  /LCHP/  /LECT/   $

         "VEL3"                $ ( val  /LECT/ )         $
                               $ "CHAM"  /LCHP/  /LECT/   $

                (     "COMP"   'namecomp'
                      "MFRA"   $ ( val  /LECT/ )         $
                               $ "CHAM"  /LCHP/  /LECT/   $ )
```

`TEMP`

Introduces the value(s) of temperature.

`PRES`

Introduces the value(s) of pressure.

`VEL1`

Introduces the value(s) of x-velocity.

`VEL2`

Introduces the value(s) of y-velocity.

`VEL3`

Introduces the value(s) of z-velocity.

`COMP`

Introduces the component (identified by its name `namecomp`). The name must be spelled exactly as in the declaration of the MCGP material, up to 8 characters.

`MFRA`

Introduces the value(s) of mass fraction.

`val`

Value.

`LCHP`

Values in the form of a CASTEM2000 'champoint'.

`LECTURE`

List of the numbers of the nodes concerned.

Remarks:

Normally, the `COMP ... MFRA` directive should be repeated at least `ncom` times, where `ncom` is the total number of components of THE multicomponent material of type `MCGP` declared in the `MATE` directive. Note that only one material of type multicomponent (`MCGP`) is allowed within a model.

If values are not specified for a certain zone, they will be set to 0.

9.3.17 INITIAL TENSOR OF STRESS

Object:

To prescribe initial tensor of stress to different elements.

Syntax:

```
"CQST" ( igauss sig /LECTURE/ )
```

`igauss`

Number of the gauss point.

`sig`

Values of the initial components of stress tensor.

`LECTURE`

List of the numbers of the elements concerned.

Comments:

The components of the stress tensor are stored in a one-dimensional array. The number of the components depends on the element. See the description of the elements available page INT.80 .

The initial stresses are provided at the integration points of the element. Bending stresses can then be taken into account.

Be careful and respect the writing conventions for the stress tensor of each element (see page G.20).

The table gives the position of the integration points for the Q4GS shell element.

```
--------------------------------------------
| N. Point Gauss |  XSI  |  ETA  |  ZETA  |
--------------------------------------------
|       1        |   -1  |  -1   | -0.9.. |
|       2        |    1  |  -1   | -0.9.. |
|       3        |    1  |   1   | -0.9.. |
|       4        |   -1  |   1   | -0.9.. |
|       5        |   -1  |  -1   | -0.5.. |
|       6        |    1  |  -1   | -0.5.. |
|       7        |    1  |   1   | -0.5.. |
```

```
|        8         |    -1  |    1    | -0.5..  |
|        9         |    -1  |   -1    |  0      |
|       10         |     1  |   -1    |  0      |
|       11         |     1  |    1    |  0      |
|       12         |    -1  |    1    |  0      |
|       13         |    -1  |   -1    |  0.5..  |
|       14         |     1  |   -1    |  0.5..  |
|       15         |     1  |    1    |  0.5..  |
|       16         |    -1  |    1    |  0.5..  |
|       17         |    -1  |   -1    |  0.9..  |
|       18         |     1  |   -1    |  0.9..  |
|       19         |     1  |    1    |  0.9..  |
|       20         |    -1  |    1    |  0.9..  |
--------------------------------------------------
```

For a shell element and a non linear material (such as von Mises material or Hyperelastic material), the stress tensor has 8 components : 3 components of membrane-bending (xx, yy, xy), 3 components that are zero and 2 components of shear (yz, xz).

9.3.18 INITIAL TENSOR OF STRAIN

Object:

To prescribe initial tensor of strain to different elements.

Syntax:

```
"CQDF" ( igauss strain /LECTURE/ )
```

`igauss`

Number of the gauss point.

`strain`

Values of the initial components of strain tensor.

`LECTURE`

List of the numbers of the elements concerned.

Comments:

The components of the strain tensor are stored in a one-dimensional array. The number of the components depends on the element. See the description of the elements available page INT.80 .

The initial strains are provided at the integration points of the element. Flexural strains can then be taken into account.

Be careful and respect the writing conventions for the strain tensor of each element (see page G.20).

The table gives the position of the integration points for the Q4GS shell element.

```
--------------------------------------------
| N. Point Gauss |  XSI  |  ETA  |  ZETA  |
--------------------------------------------
|       1        |   -1  |  -1   | -0.9.. |
|       2        |    1  |  -1   | -0.9.. |
|       3        |    1  |   1   | -0.9.. |
|       4        |   -1  |   1   | -0.9.. |
|       5        |   -1  |  -1   | -0.5.. |
|       6        |    1  |  -1   | -0.5.. |
|       7        |    1  |   1   | -0.5.. |
```

```
|       8         |   -1  |   1   | -0.5.. |
|       9         |   -1  |  -1   |  0     |
|      10         |    1  |  -1   |  0     |
|      11         |    1  |   1   |  0     |
|      12         |   -1  |   1   |  0     |
|      13         |   -1  |  -1   |  0.5.. |
|      14         |    1  |  -1   |  0.5.. |
|      15         |    1  |   1   |  0.5.. |
|      16         |   -1  |   1   |  0.5.. |
|      17         |   -1  |  -1   |  0.9.. |
|      18         |    1  |  -1   |  0.9.. |
|      19         |    1  |   1   |  0.9.. |
|      20         |   -1  |   1   |  0.9.. |
--------------------------------------------
```

For a shell element and a non linear material (such as von Mises material or Hyperelastic material), the strain tensor has 8 components : 3 membrane components (xx, yy, xy), 3 bending components (xx, yy, xy) and 2 components of shear (yz, xz).

9.3.19 INITIALISATIONS FROM A MED FILE

Object:

This directive allows to read displacements, velocities, stresses, internal variables, strains, fluid velocities and grid velocities from a MED file created by EPX or Code_Aster only. The coordinates of the original mesh are modified. If reading of stresses is not specified, EUROPLEXUS calculates the initial stress field and the initial internal forces from the displacements (available in sequential version only).

Syntax:

```
"MEDL"
        < "CONT" >
        < "ECRO" >
        < "VCVI" >
        < "WGRI" >
        < "NITE"    niter    >
```

`niter`

Number of iterations to calculate the initial conditions. Default value : NITE = 1

Comments:

This directive detects if the file comes from EPX or Code_Aster with field's names.

The directive "CONT" allows reading both displacements and corresponding stresses stored in the MED file (they must be present). Velocities and strains are also read if present in the file.

If the file comes from Code_Aster, only BR3D, T3GS, Q4GS, TETR, CUB8, CAR1 and CAR4 elements' values can be initialised. Others values are ignored. When using "CONT" option, no iterations are needed because stresses are not calculated from displacements.

When "ECRO" is present, internal variables are read from the MED file.

"VCVI" is used to take in account initial fluid velocities for VFCC elements. This option is only available with ADCR and EAU materials and must be associated with option "ECRO".

"WGRI" activates the taking into account of the grid velocities field as initial state. It's available in ALE only.

The directive "NITE" allows to initialize a non-linear initial status. At least one material has a non-linear behaviour or the initial displacements, rotations are large.

9.3.20 INITIALISATIONS FROM A STATIC ANALYSIS

Object:

This directive allows to read results from a former static analysis performed to compute the initial state of the current model. Results are entered by means of displacement fields. Several fields can be given if the static analysis is non-linear, so that the non-linear loading path can be correctly followed. For each field, the corresponding displacement can be applied within a certain number of iterations.
The coordinates of the original mesh are modified.
From displacements EUROPLEXUS calculates the initial stress field and the initial internal forces.

Syntax:

```
"STAT"  ifich
```

`ifich`

Number of the logical unit of the formatted file or file name in quotes.

Comments:

In order for the initial state to be in equilibrium, keyword (`INIT`) `EQUI` must also be used (e.g. `INIT STAT ifich EQUI`).

The formatted file is structured as follows:
On the first line, with the format ('NSTP ',I10,' NBNO ',I10), are given the number of displacement fields *nstep* and the number of nodes *nbnodes* for all fields.
The file then contains *nstep* blocks, each block corresponding to one displacement field.
On the first line of each block, with the format ('NCYC ',I10) is given the number of iterations used to apply the corresponding displacement field.
Then, *nbnodes* lines follow, each containing field values for one node of the mesh.

Node line structure is the following:

Format: (I10,1X,I2,*ncomp*(1X,A2,1X,E12.5))

1st integer: number of the node in the EUROPLEXUS model
2nd integer: *ncomp*=number of dofs to be read

For each dof:

Character: Name of the dof:

```
'UX','UY','RZ' for 2D problems
'UR','UZ','RT' for axisymmetrical problems
'UX','UY','UZ','RX','RY','RZ' for 3D problems
```

Real: Value of the displacement field for this dof

9.3.21 PRESCRIBED MASS FLOW RATE

Object:

This directive allows to specify a prescribed mass flow rate in a pipeline.

This directive may be used only in 1D.

Syntax:

```
"DMAS" dmas /LECTURE/
```

`dmas`

Value of the imposed mass flow rate.

`/LECT/`

List of node numbers.

9.3.22 PRESCRIBED INITIAL EQUILIBRIUM

Object:

This directive allows to impose initial equilibrium conditions over the whole mesh or in a region specified by the user.

The code computes external applied forces which exactly equilibrate the **internal** forces (e.g. resulting from an initial stress state) in the initial configuration and adds these (constant) force values to the other prescribed external forces at every time step during the transient computation.

In other words, at step 0 the code computes the **equilibrating** forces:

$$F_{\mathrm{eq}} = F_{\mathrm{int}}$$

Then, at every time step (including step 0) these equilibrating forces are added to the other imposed **external** forces:

$$F_{\mathrm{ext}} = F_{\mathrm{ext}} + F_{\mathrm{eq}}$$

Optionally, by specifying the keyword `FTOT`, the above equilibration procedure is applied to the **total** forces (i.e., to the difference between internal and external forces) rather than to the internal forces alone. In this case, at step 0:

$$F_{\mathrm{eq}} = F_{\mathrm{int}} - F_{\mathrm{ext}}$$

and then:

$$F_{\mathrm{ext}} = F_{\mathrm{ext}} + F_{\mathrm{eq}}$$

Syntax:

```
"EQUI" $[ "FINT" ; "FTOT" ]$ </LECTURE/>
```

`/FINT/`

Equilibrium takes into account only initial internal forces: this is the default behaviour.

`/FTOT/`

Equilibrium takes into account both initial internal forces and initial external forces.

`/LECT/`

List of node numbers for which initial equilibrium is prescribed. By default (no `/LECT/` specified) all nodes in the mesh are taken.

Comments:

The use of `/LECT/` to specify the zone subjected to initial equilibrium may be useful in some special cases. For example, assume a stratified (layered) soil subjected to an internal explosion (gas bubble). The soil has initial (hydrostatic-like) stresses due to soil weight, and must be initially equilibrated. However, the fluid (explosive bubble) should not be equilibrated. In this case the `/LECT/` would specify just the soil sub-domain (or just its envelope, in case e.g. gravity load is applied to the whole problem).

The use of the `FTOT` optional keyword may be useful in case e.g. there are some "external" forces that should be equilibrated as well in the initial configuration. For example, fluid-structure interaction forces.

As indicated by the syntax, several zones of imposed equilibrium can be declared, by choosing in each zone the appropriate type of equilibrium (internal or total). For example:

```
EQUI FTOT LECT zone1 TERM
     FINT LECT zone2 TERM
```

Note that the initialization of the equilibrating forces is done at the initial step of a calculation containing the present `EQUI` directive. In practice, in most cases, this means at step 0 of the calculation.

However, this feature may be exploited, in conjunction with the use of restart, in order to start the equilibration of forces at a time different from the initial time.

For example: perform a first run with saving for restart and without the `EQUI` directive. In this way, no equilibration takes place at the initial time. Then, restart the calculation by specifying the `EQUI` directive: the equilibrating forces are computed at the restart time and are applied thereafter (even in case of successive restarts).

```
1) first run (without EQUI but with QUAS STAT and some blockages):
. . .
LINK COUP BLOQ 12 LECT absr TERM
ECRI ... FICH SAUV LAST
OPTI QUAS STAT 1. 105. UPTO 0.E0
CALC TINI -50.E-3 TEND 0.D0
. . .

2) restart run (without QUAS STAT but with EQUI,
   blockages are removed):
. . .
REPR 'xxxx.sau' POSI 1
LINK COUP ! empty directive to remove the previous links
EQUI FTOT LECT zone1 TERM
     FINT LECT zone2 TERM
. . .
```

9.3.23 PRESCRIBED INITIAL CRACK IN SPHC MODEL

Object:

This directive allows to define one or several initial crack(s) in a SPHC model (SPH approach for shells - see Page GBC_0093).

Each crack is defined by a set of segments between given stress-points. Every stress-point located on the path of a crack is supposed to have failed at initial time.

Syntax:

```
"CRAK" ncrk * ( /LECTURE/ )
```

`ncrk`

Number of initial cracks.

`/LECTURE/`

Ordered list of stress-points defining the segments of a crack.

9.3.24 INITIAL CONDITIONS FOR ADAPTIVITY

Object:

This directive allows to impose initial conditions for adaptive calculations, namely mesh refinement operations to be performed in the initialization phase of a calculation (see sub-directives `SPLI` and `ROUT`). These operations are performed starting from the *base* mesh, i.e. the mesh provided in input by means of the `GEOM` directive.

Furthermore, by means of the sub-directive `IMAT` it is possible to fine-tune the initial state (i.e. at step 0) or to re-initialize (at a given time or step subsequent to the beginning of the simulation) the physical state of the material in an adapted mesh by means of the sub-directive `IMAT`.

Syntax:

```
ADAP < ( SPLI LEVE leve /LECTURE/ ) >
     <   ROUT CASE ncas >
     <   IMAT <TIME t> <NPAS n>
              nimat*( MATE mat OBJE /LECT/
                      $ ( $ INSI ; OUTS $ $ SURF ; VOLU $ /LECT/ ) ; $
                      $ SPHE CX cx CY cy <CZ cz> R r                $ ) >
```

`SPLI`

Split the specified object to the specified level of refinement. Recall that the base mesh has level 1. The first splitting (level 2) halves the elements size, the second splitting (level 3) further halves the mesh size (1/4) and so on. Note that splitting can be applied both to base elements and to descendent elements. The splitting operations can be defined in any order, but they are applied in the natural order, i.e. by growing element index.

`LEVE`

Specifies the level `leve` of the split operation.

`/LECT/`

List of element to be split to the specified level.

`ROUT`

Initializations are performed by a user-written routine INIT_ADAP_ROUT *after* any split and unsplit operations specified by this same directive.

`CASE`

Introduces the case number `ncas`. Different cases correspond to different initializations which are programmed in the INIT_ADAP_ROUT user subroutine.

`IMAT`

Initialize (or re-initialize) the material properties (i.e. the physical state) of the material in an adapted mesh. By default, i.e. if neither `TIME` nor `NPAS` are specified, initializations are performed immediately *after* the split operations done, at step 0, either by the `WAVE` directive or by some FSI-driven adaptivity (`FLSR` or `FLSW`).

`TIME`

Time at which the (re-)initialization of the material state must be performed. If neither `TIME` nor `STEP` are specified, the (re-)initialization is performed at step 0, i.e. at the initial time of the simulation. If both `TIME` and `STEP` are specified, the (re-)initialization is performed at whatever of the two comes first.

`NPAS`

Time step at which the (re-)initialization of the material state must be performed. If neither `TIME` nor `STEP` are specified, the (re-)initialization is performed at step 0, i.e. at the initial time of the simulation. If both `TIME` and `STEP` are specified, the (re-)initialization is performed at whatever of the two comes first.

`nimat`

Number of different `IMAT` zones, to be defined next. Note that for each zone a special elements group named `_IMATxxxx` is created, which can be used to visualize the elements that have been effectively re-initialized. Here `xxxx` is the zone index (`0001`, `0002` etc.). However, at the moment of this writing, such groups are available only during a direct execution of the code (i.e. not from a results file such as the ALIC file).

`MATE mat`

Index of the material (as declared in the `MATE` directive) to be assigned to the elements defined in the following.

`OBJE`

The elements in the following `/LECT/` are the candidates for the assignment of the initial material properties (subjected to the following conditions).

`INSI`

The material `mat` has to be assigned to the elements inside the following defined surface or volume. Since the geometrical operations necessary to determine whether a point is or not inside a volume (or surface) are complicated and subjected to errors related to tolerances in the tests, it is always advisable to use *simplex* elements (TRI3 shape in 2D and TET4 shape in 3D) to define the volume, instead of using more complex element shapes such as QUA4, CUB8 etc. In fact, for TRI3 and QUA4 the inverse mapping is analytical while this may not be the case of the other geometric shapes.

`OUTS`

The material `mat` has to be assigned to the elements outside the following defined surface or volume. Since the geometrical operations necessary to determine whether a point is or not inside a volume (or surface) are complicated and subjected to errors related to tolerances in the tests, it is always advisable to use *simplex* elements (TRI3 shape in 2D and TET4 shape in 3D) to define the volume, instead of using more complex element shapes such as QUA4, CUB8 etc. In fact, for TRI3 and QUA4 the inverse mapping is analytical while this may not be the case of the other geometric shapes.

SURF

The (surfacic) elements in the following /LECT/ define an oriented surface (not necessarily closed, nor simply connected). All elements belonging to the surface must be consistently oriented. See the comments below for the precise algorithm used to decede whether a given poind is “inside” or “outside” the surface.

VOLU

The (volumetric) elements in the following /LECT/ define a volume.

SPHE

The active elements (among the candidates defined by the OBJE directive) which lie within the sphere defined below are re-assigned the initial material properties. An element lies within the sphere if its centroid lies within the sphere.

CX

X-coordinate of the sphere’s center.

CX

X-coordinate of the sphere’s center.

CY

Y-coordinate of the sphere’s center.

CZ

Z-coordinate of the sphere’s center (3D only).

R

Radius of the sphere.

Comments:

As indicated by the brackets, the SPLI sub-directive can be repeated as many times as necessary to specify all the parts of the mesh to be initially split.

Also, as indicated by the (inner) brackets, the INSI, OUTS, SURF, VOLU, /LECT/ block can be repeated as many times as needed (including zero times) to define the portion of the object OBJE /LECT/ to which the chosen material properties must be applied. The elements retained are those belonging to the OBJE defined and satisfying all the specified conditions (if any). Example 1:

```
... IMAT 1 MATE 3 OBJE LECT toto TERM
```

would assign the properties of material 3 to the entire object toto (without any conditions). This is the same as normal material assignment and therefore it is not necessary to use IMAT for this.

Example 2:

```
... IMAT 1 MATE 3 OBJE LECT toto TERM INSI VOLU LECT v1 TERM
```

would assign the properties of material 3 to the elements (more precisely, to the active descendent elements) of object `toto` whose centroid lies within the volume `v1` (at the initial time).

Example 3:

```
... IMAT 1 MATE 3 OBJE LECT toto TERM INSI VOLU LECT v1 TERM
                                      OUTS SURF LECT s1 TERM
```

would assign the properties of material 3 to the elements (more precisely, to the active descendent elements) of object `toto` whose centroid lies within the volume `v1` *and* outside surface `s1` (at the initial time).

If smooth refinement of the mesh is desired, in addition to the splitting specified, use can be made of the `OPTI ADAP RCON` optional directive.

Note the difference between prescribing, say, initial velocities by means of the `INIT VITE` directive or by means of the `INIT ADAP ROUT` directive. The `INIT VITE` directive can only prescribe velocity values for the *base* mesh nodes. If the mesh is then split by means of the `INIT ADAP SPLI` directive, the velocity values in the descendent nodes are *linearly* interpolated starting from those at the base nodes. On the contrary, the `INIT ADAP ROUT` directive applies the desired initialization to the adapted mesh, i.e. to both the base and the descendent nodes in the same way. No interpolation is done in this case, and therefore the prescription of, say, initial velocities is more precise than in the other case if the initial velocity field is non-linear.

An example of use of the `IMAT` sub-directive is as follows. Assume one wants to simulate the explosion of a solid charge. The bomb domain needs to be discretized very finely in the first steps of the calculation, until the solid charge has detonated and the pressure waves start to expand. Thereafter, the mesh should be un-refined to recover CPU efficiency (large time increment). The initial mesh refinement of the bomb region can be specified by the `WAVE` directive, until a certain time `T1` (see page B.200). The region is discretized coarsely (base mesh) and the refinement is done at step 0 by the `WAVE` directive. In the `MATE` directive, air material (via e.g. `JWLS`) is assigned to the whole fluid coarse mesh, including the bomb. Then when `WAVE` refines the mesh, the air material is automatically propagated to all descendent elements. By using the `IMAT` sub-directive it is then possible to (re-)assign an initial solid explosive material to the effective (fine-meshed) bomb region, while (fine) elements outside the bomb remain with the air material inherited from the base mesh. It is not possible to do this fine-tuning by the `MATE` directive because, when `MATE` is read, mesh refinement has *not* taken place yet.

Another example of use of the `IMAT` sub-directive is the case of a tank with a curved geometry filled with air at higher pressure than the atmosphere. We want to use a regular fluid mesh with the structure immersed in it and to adaptively refine the fluid mesh near the tank walls by means of the `FLSR ADAP` or `FLSW ADAP` directives. The `IMAT` technique may be used to assign high pressure only to the active fluid elements (parents and descendents) which are strictly contained within the curved tank.

Finally, as a practical example of using the `TIME` (or `NPAS`) parameter, consider the case that we want to set the conditions of a gas contained in a tank, but only for the gas elements that are located between two moving and deforming membranes. The gas is modelled in Eulerian so the gas elements that satisfy the above condition are not constant in time, but depend upon the motion of the (Lagrangian) membranes. Assume that the membrane (surfacic) elements are consistently oriented, and that the second membrane is located in the positive (or "external") half-space of the first membrane while the first membrane is located in the negative (or "internal") half space of the second membrane.

The positive half-space with respect to a surface is the one to which the (oriented) normal to the surface is pointing to, as indicated by the vectors `n1` and `n2` in the sketch below:

```
            |                   |
this        |        this       |        this
gas is      |        gas        |        gas
not         |--> n1  is         |--> n2  is not
affected    |        affected   |        affectd
            |                   |
            |                   |
          mem1                mem2
```

Then, one would specify two conditions: the gas element must be "outside" with respect to the first membrane and "inside" the second membrane:

```
INIT DELA TIME 1.E-3
          IMAT 1 MATE 2 OBJE LECT gas TERM
                        OUTS SURF LECT mem1 TERM
                        INSI SURF LECT mem2 TERM
```

This would (re-)set the conditions of the (Eulerian) gas that happens to be contained between the two (moving) membranes at time 1.E-3 to the state specified by material number 2 in the input data file.

The algorithm used to decide whether a given point P lies "inside" or "outside" the surface S is as follows:

1. Find the element s of S closest to P, by considering the distance between P and the centroid G of s.

2. Let $\mathbf{n}$ be the (unit or not) outside normal to s.

3. If $\overrightarrow{GP} \cdot \mathbf{n} > 0$, then P is outside S, else P is inside S.

9.3.25 MATERIAL RE-INITIALIZATION WITHOUT ADAPTIVITY

Object:

This directive allows to re-initialize material properties within a chosen volume or surface. Its syntax is identical to the `INIT ADAP IMAT` directive described on page E.230, but it applies to non-adaptive calculations (although the usefulness of such a directive in non-adaptive cases is perhaps marginal).

For example, it can be used instead of normal material assignment by the `MATE` directive when the mesh zone to which the material belongs has a weird shape that has not been identified as a named geometrical object in the mesh generator, nor can it be simply defined in EPX itself by means of the `COMP GROU` diretive. In such cases, an auxiliary (fake) mesh `OBJE` (see below) may be defined in the mesh generator and used to define the domain in which material initialization should occur.

Syntax:

```
IMAT <TIME t> <NPAS n>
     nimat*( MATE mat OBJE /LECT/
             $ ( $ INSI ; OUTS $ $ SURF ; VOLU $ /LECT/ ) ; $
             $ SPHE CX cx CY cy <CZ cz> R r                 $ )
```

For the description of the various parameters, see the `INIT ADAP IMAT` directive described on Page E.230.

Comments:

An example of use of the `IMAT` sub-directive is the case of a tank with a curved geometry (a surface) filled with air at higher pressure than the atmosphere. We want to use a regular fluid mesh with the structure (meshed by shells) immersed in it. The `IMAT` technique may be used to assign high pressure only to the fluid elements which are strictly contained within the curved tank surface.

9.3.26 SKIPPING ELEMENTS

Object:

This directive allows to completely skip from the calculation the elements defined by the command. The skipping can occur from a certain time and/or up to a certain time.

A special form of the command (`VFCC`) is available if one wants to skip all VFCC "elements" (Cell-Centred Finite Volumes). In fact, choosing just part (or all) of the VFCCs present in a calculation with the normal command (`/LECT/`) would not work since most VFCC calculations involve *interfaces* between elements (volumes) and not the elements (volumes) themselves.

Syntax:

```
SKIP  ( <UPTO upto> <FROM from> $ /LECT/ ; VFCC $ )
```

`UPTO upto`

Time at which skipping of the elements defined next has to cease. By default, skipping never ceases (`upto`=∞).

`FROM from`

Time at which skipping of the elements defined next has to begin. By default, skipping begins from the initial time (`from`=$-\infty$).

`/LECT/`

List of concerned elements.

`VFCC`

Select all VFCCs present in the calculation.

Comments:

Skipping an element has the same effect as if the element would (temporarily) have the phantom (`FANT`) material. The element is not computed, and this allows to save CPU time.

This is different from the effect of the `NOCR` option, whereby the element is computed, but it does not contribute to the definition of the critical time step.

9.3.27 INITIAL CONDITIONS BY READING MAP FILE (BLAST LOADING)

Object:

This directive allows to read the results of a previous blast simulation (1D, 2D or 3D) and map it to the recent mesh. The centre of the mapping can be defined (POS). Until know only mapping from 1D to 3D is possible.

The file can be written by the ECRI MAPB command (see 11.7).

Syntax:

```
MAPB 'file.map'
      | SPHE POS x y z <TARR>;
        <ADAP nada > /LECT/ |
```

`file.map`

Name of the file, where the previous blast simulation is stored.

`x, y, z`

Position (x, y, z) where the blast map should be mapped.

`TARR`

The time that is used for the calculation until the mapping file is written is used as initial time. This value will be overwritten by TINI in CALC.

`nada`

Introduces the adaptivity for mapping. In that case, the mapping is performed, and immediately after, the mesh is adapted. In order to get better mapping results, the mapping is performed again. The variable nada gives the number of iterations that should be taken in order to reach the best results. For the adaptivity, the correct dimensioning must be defined (GBA_0062) and an adaptivity procedure must be defined (GBB_0210).

`/LECT/`

List of elements where the pressure is applied.

Comments:

The results of a 1D blast simulation can be written by using the mapb operator as part of ECRI (see GBG_0070).

At this time only mapping from 1D (TUBE or TUVF) into the material GAZP are possible. The use of volume centred finite volumes is recommend since the results are more accurate.

9.3.28 INITIAL DAMAGE FOR GRADIENT DAMAGE MATERIALS

Object:

This directive defines initial damage values for gradient damage materials `ENGR`, see 7.7.24. This initial condition introduces an *a priori* state of the damage field. Because of the irreversibility condition, setting the value of 1 to a selection of nodes amounts to model an initial crack in the structure.

Syntax:

```
"ENGR" ( alpha0 /LECTURE/ )
```

`alpha0`

Prescribed initial damage value $0 \leq \alpha_0 \leq 1$, knowing that 0 corresponds to an undamaged state and 1 to the crack.

`LECTURE`

List of the nodes concerned.

9.3.29 INITIALIZATION FROM A MAP FILE

Object:

This directive allows to read the results of a previous simulation (stored in a so-called map file) and map it to the current mesh.

The map file must have been previously generated by the `ECRI MAPP` command (see Section 11.7).

Syntax:

```
MAPP <FORM> <nmapp> <MATC>
     <$HGRI hgri ; NMAX nmax ; DELE dele$> <DGRI>
     OBJE /LECT/
```

`FORM`

The map file is formatted (ASCII). By default, an unformatted (binary) map file is assumed.

`nmapp`

Name of the map file, included in quotes.

`MATC`

The optional `MATC` keyword declares (under the User's responsibility) that the target object perfectly matches the source object, i.e. the two objects are composed by the same elements (although perhaps with different element and node indexes). This greatly facilitates and speeds up the solution mapping (since no interpolation, and only a relatively simple search is needed) and should be used whenever possible.

`HGRI`

Specifies the size of the fast search grid cell. Each cell has the same size in all spatial directions and is aligned with the global axes.

`NMAX`

Specifies the maximum number of cells along one of the global axes.

`DELE`

Specifies the size of the fast search grid cell as a multiple of the length of the largest element from which the mapping is performed ("from" elements). Element "diameters" are computed only along each global spatial direction and the maximum is taken. For example, by setting `DELE 2` the size of the cell is two times the length of the largest "from" element. By default, i.e. if neither `HGRI`, nor `NMAX`, nor `DELE` are specified, the code takes `DELE 1.01`.

`DGRI`

Dump out the grid of cells used for fast searching on the listing. For brevity, the print is done only the first time that the grid is computed.

`OBJE`

Introduces the object (in the current mesh) to be mapped to the physical conditions present in the map file.

`/LECT/`

List of elements forming the object to be mapped (in the current mesh).

Comments:

See directive `ECRI MAPP` on page GBG_0070 for a description of how to create the map file.

9.3.30 INITIALIZATION FROM A GMAP FILE

Object:

This directive allows to read the results of a previous simulation (stored in `.gmap` file) and map it to the current mesh.

The map file must have been previously generated by the `ECRI GMAP` command (see Section 11.7). Note that the `GMAP` keyword must be repeated as much as necessary.

By default, all mesh elements can applicate for mapping. Otherwise, BBOX and/or OBJE options can be used/combined to shrink the application list.

Current assumptions:

- Only finite-volume-based data is to be dumped and mapped;
- Material consistency between the first and the second simulation;
- "JWL"-like materials (to be improved);
- Mesh dimension of the second calculation must be **equal or higher** than the first one.

Syntax:

```
ngmap * ( GMAP <FORM> file
              norig * ( ORIG x y <z> <ux uy <uz>> <vx vy vz>
                        < BBOX xmin ymin <zmin> xmax ymax <zmax> >
                        < OBJE /LECT/ >
                      )
        )
```

FORM

The mapping file is formatted (ASCII). By default, an unformatted (binary) map file is assumed.

file

Name of the map file, included in quotes or logical unit.

nmapp

Number of GMAP instances.

norig

Number of mapping operators for a given file. Note that if there is an overlapping no checks will be performed.

ORIG

Frame features for the projection, meaning:

- 1D ⇒ 1D/2D/3D: projection origin;
- 2D ⇒ 2D/3D: projection origin, and a direction vector;
- 3D ⇒ 3D: projection origin, and two basis vectors.

BBOX

Set a bounding box to shrink finite-volume applicants by their location.

OBJE

Set a group to shrink finite-volume applicants with an element group.

Comments:

See directive `ECRI GMAP` on page GBG_0070 for a description of how to create the map file.

10 GROUP F—LOADS

Object:

These instructions determine the loads. The directive "LOAD" is an alias of the "CHAR" directive.

Syntax:

```
$ "CHARGE" ; "LOAD" $
    < "CONSTANTE"  . . .                 >
    < ndcha  $[  "FACTORISEE"  . . .  ;
                 "PROGRAMMEE"  . . .  ]$ >
    < "ADDF" . . .                       >
    < "SPEC" . . .                       >
    < "FCTE" . . .                       >
    < "FIMP" . . .                       >
    < "FDYN" . . .                       >
    < "AIRB" . . .                       >
```

`ndcha`

Number of the temporary disc (logical unit number) where the loads are stored (disk of time-dependent loads). **This data is optional**: by default ndcha=1.

The various sub-directives, detailed in the following pages, are summarized hereafter:

```
1/ Constant loads :
        "CONSTANTE"   $ "GRAVITE"     gx  gy  < gz >          $
                      $ "ROTATION"    omega          /LECTURE/ $

2/ Factorized loads :
      "FACTORISEE"  <ndfact>  (  |  ( "DEPLA"  . . .  )  |
                                 |  ( "FORCE"  . . .  )  |
                                 |  ( "PRESS"  . . .  )  |
                              "TABLE"  . . .  )

3/ Programmed loads :
    "PROGRAMMEE"  ndprog  $  "FORCE"     . . .   $
                          $  "PRESSION"  . . .   $
                             "ROUTINE"   . . .
                          <  "ROUTINE"   . . .   >
4/ Generalized loads for advection-diffusion calculations (JRC)
    "ADDF"   $  "TIMP" . . . $
             $  "FLUX" . . . $
             $  "QGEN" . . . $
             $  "CONV" . . . $
             $  "RADI" . . . $
             $  "PRES" . . . $
             $  "VELO" . . . $
             $  "BLOQ" . . . $
             $  "VPLA" . . . $
             $  "VLIN" . . . $

5/ Seismic-like loads for use with spectral elements (JRC)
    "SPEC"  |  "POIN"  . . .   |
            |  "PLAN"  . . .   |
            |  "SISM"  . . .   |


6/ New Constant loads:
   FCTE  NODE /LECT/ $ FORC f ; MOME m $ VECT x y z

7/ Imposed time-dependent loads:
   FIMP  NODE /LECT/ $ FORC f ; MOME m $ VECT x y z NUFO nf

8/ Dynalpy loads:
   FDYN  NODE /LECT/ PZER p0 COEF c VECT x y z ELEM e

9/ Air Blast (AIRB) loading:
   AIRB  |[ "X" x "Y" y <"Z" z> ; "NODE" /LEC1/ ]|
              "MASS" m $[ "TINT" t ; "TAUT" ]$ <"OPOS">
              <"ANGL">
              <"CUBE">
              <"COEF" cf>
              <"CONF" c>
              <"DECA" d>
              <"PMAX" pmax "TD" td "B" b>
```

```
<"SHAD" /LECS/>
/LECT/
```

Comments:

1/- CONSTANTES

The constant loads act all along the calculation. It is the case of body weight or of a fixed acceleration.

2/- FACTORISEES

The defined loads are multiplied by a coefficient which varies in time and is interpolated from a table:

$$Q(t) = A * C(t)$$

3/- PROGRAMMEES

The loads will be read and computed for some elementary times which are fixed a priori by the user in a subroutine given by him (FPROG or PPROG). EUROPLEXUS will then perform a linear interpolation to determine the loads at the precise instants of the calculation.
1/ Constant loads:
FCTE NODE /LECT/ $ FORC f ; MOME m $ VECT x y z

2/ Imposed time-dependent loads:
FIMP NODE /LECT/ $ FORC f ; MOME m $ VECT x y z NUFO nf

3/ Dynalpy loads:
FDYN NODE /LECT/ PZER p0 COEF c VECT x y z ELEM e

4/- `FCTE`

The constant loads act all along the calculation. It is the case of body weight or of a fixed load.

5/- `FIMP`

The defined loads are multiplied by a coefficient which varies in time and is interpolated from a table:

$$Q(t) = A * C(t)$$

6/- `FDYN`

These loads are only related to 1-D elements of type TUBE or TUYA.

7/- `AIRB`

These loads result from an air blast wave. The parameters are similar to those available in the `IMPE AIRB` directive, see Page C.882, but here the load is applied directly to a region of structural elements rather than by using special CLxx elements. This facilitates the treatment of element erosion and of mesh adapptivity.

These instructions are described in detail on the following pages.

10.1 AUXILIARY FILE

Object:

This directive allows to read the initial conditions data from an auxiliary file.

Syntax:

```
"CHARGE"   ndcha  < "FICHIER"   'nom.fic'  >
```

In certain cases the data may be bulky. It is then recommended to store them on an auxiliary file to shorten the main input data file. The auxiliary file is activated by means of the keyword "FICHIER" that precedes the file name (complete under Unix). In the main data file then only the keywords "CHARGE" "FICHIER" remain.

The auxiliary file (in free format) contains the whole set of load data, except the keyword "CHARGE". To return to the main input data, the auxiliary file must be terminated by the keyword "RETOUR".

10.2 CONSTANT LOADS

Object:

This directive allows to introduce constant accelerations (most often gravity) during the whole computation. It also gives the possibility to compute a structure in a rotating frame (with a constant rotation speed). Definition of sinusoidal acceleration is available (PERIODE and PHASE). Is is also possible that the acceleration is linear and then keeps a constant value (RAMPE).

Syntax:

```
"CONSTANTE"   |[  "GRAVITE"     gx  gy  < gz >  /LECTURE/  ;
                  "ROTATION"    omega           /LECTURE/  ]|
                <"PERIODE">  Tx   Ty   Tz
                <"PHASE">  Phix Phiy Phiz
                <"RAMPE">    tx   ty   tz
```

`gx gy gz`

Components of the acceleration or of the gravity.

`omega`

Rotation speed (rad/s).

`Tx Ty Tz`

Period of the sinusoidal acceleration

`Phix Phiy Phiz`

Phase of the sinusoidal acceleration

`tx ty tz`

Time after which acceleration is constant

`LECTURE`

Numbers of the concerned nodes.

Comments:

The component $< g_z >$ of the acceleration only makes sense for a three-dimensional computation.

Forces due to gravity or the acceleration of a moving frame are applied to the nodes of the structure defined in the directive `/LECTURE/`.

In the case of a calculation in a rotating frame, it is assumed thet the rotation axis is Oz. The forces applied to the nodes are:

$$F_x = M\omega^2 x$$

$$F_y = M\omega^2 y$$

$$F_z = 0$$

This force applies to the nodes specified by the following `/LECTURE/` directive.

If all nodes are concerned, it is sufficient to put the word `TOUS` in place of the directive `/LECTURE/`.

In the case of pipelines, it is important to couple this directive with "INIT" "DEBIT" (page E.120) so as to avoid the transient due to sudden application of gravity.

For the tubes and the pipelines, the rotation constant charge does not make sense. Note that, although there is just one d.o.f. for the elements of type `TUBE`, the gravity vector may have an arbitrary orientation.

For a sinusoidal acceleration, the amplitud is defined by the component of the acceleration and is multiply by a sinus function. The user has to define the period of the function and the phase. If a component is not exited, the period and the phase for this component have to be zero.

The ramp acceleration is defined by a linear part that starts from zero at the initial time and then grow linearly to pass by the point tx=gx (for example). Then after tx, the acceleration is kept constant at a gx level. If a component is not exited, the time for this component has to be zero.

10.3 FACTORIZED LOADS

Object:

This directive allows to input loads varying in time, of the following type: Q(t) = A * C(t), with:

- A as a base value (displacement, force or pressure);

- C(t) as a coefficient whose values, depending on time, are supplied by a table.

Syntax:

```
"FACT"  ndfact
       (     ( "DEPLA"  . . . )
             ( "FORCE"  . . . )
             ( "PRESS"  . . . )
             ( "ACCE"   . . . )

             "TABLE" . . .
        )
```

`ndfact`

Number of the disc (logical unit number) on which the data of the factorized loads are stored. **This data is optional**: by default ndfact=2.

Comments:

The instruction "FACT" cannot be used more than once.

On the contrary, the sequence terminating with the "TABLE" directive may be repeated as many times as necessary.

Warning:

The instruction "TABL" is mandatory. For the case of charges constant in time, just give a two-entry table with the same value in both entries, i.e. of the form "TABL 2 t1 v t2 v", where v is the (constant) value, t1 is less or equal to the initial time of the computation and t2 is greater or equal to the final time of the computation.

10.3.1 DISPLACEMENT

Object:

This option enables displacements depending on time to be prescribed.

Syntax:

```
"DEPLA"  /LECDDL/  d0  /LECTURE/
```

`LECDDL`

Reading procedure of the numbers of the degrees of freedom concerned.

`d0`

Base value of the imposed displacement. The instruction "TABL" must follow to determine the variation in time, **even for constant displacements** (see note below).

`LECTURE`

Numbers of the nodes concerned.

Comments:

The displacements of the nodes defined by the procedure LECTURE and along the directions determined by LECDDL, are of the following type:

$$D(t) = D0 * C(t)$$

C(t) is provided by the first array met after that option (see "TABL").

That option can be used as many times as necessary .

If the imposed displacement is a blockage (d0 = 0), it is better to use the option "BLOQUE" of the instruction "LIAISON" (page D.30).

Warning:

The instruction "TABL" is mandatory. For the case of charges constant in time, just give a two-entry table with the same value in both entries, i.e. of the form "TABL 2 t1 v t2 v", where v is the (constant) value, t1 is less or equal to the initial time of the computation and t2 is greater or equal to the final time of the computation.

10.3.2 FORCE

Object:

This option enables nodal forces, varying in time, to be imposed.

Syntax:

```
"FORCE"  /LECDDL/  f0  /LECTURE/
```

`LECDDL`

Reading procedure of the numbers of the degrees of freedom concerned.

`f0`

Base value of the imposed force. The instruction "TABL" must follow to determine the variation in time, **even for constant forces** (see note below)

`LECTURE`

Numbers of the nodes concerned.

Comments:

The forces applied to the nodes defined by the procedure LECTURE and according to the directions determined by LECDDL, have an intensity of:

$$F(t) = F0 * C(t)$$

C(t) is provided by the first array (TABLE) met after that option (see "TABL", page F.150).

That option may be used as often as necessary.

For an textbfaxisymmetric computation, the force must be divided by 2π:

```
          real force
F0 = --------------
             2*pi
```

Warning:

The instruction "TABL" is mandatory. For the case of charges constant in time, just give a two-entry table with the same value in both entries, i.e. of the form "TABL 2 t1 v t2 v", where v is the (constant) value, t1 is less or equal to the initial time of the computation and t2 is greater or equal to the final time of the computation.

10.3.3 PRESSURE

Object:

This option introduces a pressure (expressed in real number form) which is exerted on a segment set (2-dimensional case) or on a surface composed of shell elements (2-dimensional or 3-dimensional case), or on the faces of solid elements (3-dimensional case).

Syntax:

```
"PRESSION"
    | ( "SEGMENT"  . . . ) |
    | ( "COQUE"    . . . ) |
    | ( "FACE"     . . . ) |
    | ( "NODE"     . . . ) |
    | ( "ELDI"     . . . ) |
```

Comments:

The word ”PRES” is the first keyword of the option.

There is no need to repeat ”PRES” to re-define a new line or surface corresponding to the same table (the one which immediately follows the word ”PRES”).

On the contrary, it is compulsory to define again the word ”PRES” if it is necessary to create lines or surfaces relative to another table.

SEGMENT PRESSURE

Object:

This directive is mainly used to apply a pressure to 2D continuum elements (in 3D cases, use `PRES FACE`). It allows to enter a pressure which is exerted on a certain number of adjacent segments or lines, in the case of 2-dimensional computation. The pressure may vary in time (factorized loads) or be hydrostatic.

Syntax:

```
"SEGMENT"  |[   p0                ;
              "HYDRO"  rho  g  z0  ]|  /LECTURE/
```

`p0`

Base value p_0 of the pressure. The instruction `TABL` must follow to determine the variation in time, even for constant pressures (see note below).

`HYDRO`

Keyword that announces a hydrostatic pressure. The pressure field is generated by the presence of a "vertical" acceleration of gravity, acting along the y-axis in 2D or the z-axis in 3D.

`rho`

Density ρ of the liquid which generates the pressure.

`g`

Acceleration of gravity g applied to the fluid in the "vertical" direction, i.e. along the y-axis in 2D or the z-axis in 3D. The value should normally be negative (see also comments below).

`z0`

Vertical level z_0 of the free surface of the fluid, supposed horizontal.

`LECTURE`

Numbers of the nodes composing the pressure line. Each couple of subsequent nodes forms a segment. For example, if the list contains the three indexes 25, 4, 39, then two segments are considered: (25, 4) and (4, 39). Special care must be taken if one uses the name of GIBI object(s) to define the line(s) subjected to pressure, see comments below.

Comments:

The user has the choice between a pressure p_0 which varies in time and a hydrostatic pressure. It is not allowed to define both at the same time without re-using the word `SEGM`.

For a defined basic value p_0, the pressure intensity is:

$$p(t) = p_0 C(t)$$

$C(t)$ is provided by the first array (`TABL`) met after the option `PRES` (see also `TABL`).

If a hydrostatic pressure is defined (keyword `HYDR`), the pressure is only applied to the segments of the line at levels z, such that:

$$g(z - z_0) \geq 0$$

From the previous expression it appears that, since the hydrostatic pressure should be exerted on segmentes at $z < z_0$, then the value of g specified should normally be negative.

Moreover, the intensity of the pressure is:

$$p = \rho g(z - z_0)$$

The values ρ, g, z_0 may be negative.

Each new option `SEGM` defines a different line.

If the line of segments is defined by giving the name of a GIBI object, make sure that the line is oriented, i.e. that the nodes are listed from one extremity to the other in the correct order (not randomly, as it may sometimes occur in some mesh generators).

If there is more than one line, and the lines are disjoint from one another (i.e. the final node of one line is not the initial node of the next one), then the `PRES` directive must be repeated (one directive for each line). Otherwise, a “spurious” segment joining the final node of a line to the initial node of the next one in the list would also be considered as subjected to pressure. This is particularly dangerous if more than one GIBI object is listed in the same `LECT`. In case of doubt, it is always safer to use a separate `PRES` directive for each line.

Sign of the pressure:

The order in which the points of the line are read by means of the procedure `LECT`, defines the orientation of the contour of that line. The normal vector ($\vec{n}$) results from a rotation of $\pi/2$ of the contour itself.

Positive values will create forces in the orientation of the normal ($\vec{n}$) thus obtained.

Warning:

The keyword `TABL` is mandatory. For the case of charges constant in time, just give a two-entry table with the same value in both entries, i.e. of the form `TABL 2 t1 v t2 v`, where `v` is the (constant) value, `t1` is less or equal to the initial time of the computation and `t2` is greater or equal to the final time of the computation.

SHELL PRESSURE

Object:

This directive is mainly used to apply a pressure to 2D or 3D shell elements. For two- or three-dimensinal computations, this option enables a pressure to be entered, which is exerted on a surface composed of shell elements. The pressure may vary in time (factorized loads) or be hydrostatic.

Syntax:

```
"COQUE"  |[    p0     ;
             "HYDRO"  rho  g  z0               ;
             "HYDRO"  rho  gx gy gz  x0 y0 z0 ]|  /LECTURE/
```

`p0`

Base value of the pressure (non hydrostatic case). The instruction "TABL" must follow to determine the variation in time, even for constant pressures (see note below).

`HYDRO`

Hydrostatic pressure.

`rho`

Density of the fluid which generates the pressure.

For two-dimensional computations:

`g`

Acceleration applied to the fluid.

`z0`

Level of the free surface, which is supposed horizontal.

`LECTURE`

Numbers of the shell elements submitted to the pressure.

For three-dimensional computations:

`gx, gy, gz`

Components of the acceleration vector (G) which is applied to the fluid.

`x0, y0, z0`

Coordinates of a point located on the surface supposed horizontal.

`LECTURE`

Numbers of the shell elements submitted to the pressure.

Comments:

The user has the choice between a pressure p0 which varies in time and a hydrostatic pressure. It is impossible to define both at the same time, without re-using the word "COQUE".

If a basic value p0 has been defined,the pressure intensity is:

$$P(t) = P0 * C(t)$$

C(t) is provided by the first array met after the option "PRESS" (see TABLE).

If a hydrostatic pressure is defined (keyword HYDR), the pressure is applied to the points on the surface of coordinates X,Y,Z such that :

$$gx * (x\text{-}x0) + gy * (y\text{-}y0) + gz * (z\text{-}z0) > 0 \text{ (or= 0)}$$

The pressure intensity will be for these points:

$$P = rho * (gx * (x\text{-}x0) + gy * (y\text{-}y0) + gz * (z\text{-}z0))$$

In a two-dimensional case, the definition of the hydrostatic pressure is the same as for the sub-directive "SEGMENT".

For a three-dimensional computation, see the definition of hydrostatic pressure with the sub-directive "FACE".

Each new option "COQUE" defines a new pressure surface.

Sign of the pressure:

The normal vector on the surface is oriented according to the numeration of the shell nodes. Positive pressures will create forces in the orientation of that normal.

The orientation of the normal is given by the following rule (Maxwell's cork-screw rule). An observer placed at the centre of the shell element which is crossed by the normal from the bottom to the top, must be able to notice that the shell element is numbered in increasing order, by rotating in a trigonometric sense (anticlockwise).

Warning:

If the mesh developped by means of "COCO" is used, the elements are not necessarily oriented in the same way (this has to be explicitly requested).

If the mesh is entered by the user, all elements have to be numerated so that their orientation is coherent. A shell surface composed of elements which are oriented in a different way, may produce errors and confusion concerning the direction of the pressures from the data point of view as well as from the results.

The instruction "TABL" is mandatory. For the case of charges constant in time, just give a two-entry table with the same value in both entries, i.e. of the form "TABL 2 t1 v t2 v", where v is the (constant) value, t1 is less or equal to the initial time of the computation and t2 is greater or equal to the final time of the computation.

FACE PRESSURE

Object:

This directive is mainly used to apply apressure to 3D continuum elements. For a three-dimensional computation, this option enables a pressure to be entered, which is exerted on a surface composed of the sides of solid elements. The pressure may vary in time (factorized loads) or be hydrostatic.

Syntax:

```
"FACE" iface  |[    p0                               ;
                   "HYDRO"  rho  gx gy gz  x0 y0 z0 ]|  /LECTURE/
```

`iface`

Number of the side (face) of the elements read by the procedure. LECTURE

`p0`

Base value of the pressure (non hydrostatic). The instruction "TABL" must follow to determine the variation in time, even for constant pressures. (see note below).

`HYDRO`

Hydrostatic pressure.

`rho`

Density of the fluid which generates the pressure.

`gx, gy, gz`

Components of the acceleration vector (G) applied to the fluid.

`x0, y0, z0`

Coordinates of a point of the free surface which is supposed horizontal.

`LECTURE`

Numbers of the elements submitted to the pressure.

Comments:

The user has the choice between a pressure P0 which varies in time and a hydrostatic pressure. It is impossible to define both at the same time without re-using the word "FACE".

For a defined basic value P0, the intensity of the pressure is:

P(t) = P0 * C(t)

C(t) is provided by the first array met after the option "PRESS" (see TABLE).

Hydrostatic pressure:

If a hydrostatic pressure is defined (keyword HYDR), it is applied to the points of the pressure surface of coordinates X,Y,Z such that:

gx * (x-x0) + gy * (y-y0) + gz * (z-z0) > 0 (or = 0)

For these points, the intensity is:

P = rho * (gx * (x-x0) + gy * (y-y0) + gz * (z-z0))

The free surface of the liquid is composed of the plane which passes through the point M0 of coordinates (x0, y0, z0) and perpendicular to the vector (G) whose components are : (gx,gy,gz).

If the vector (G) is drawn with the point M0 as origin, the pressure will be applied to the points M of the pressure surface which are located in the half-space containing (G).

The pressure intensity at point M is:

P = rho * g * h

Here h represents the distance between M and the free surface; g represents the gravity.

The vector (G) with its 3 components enables the surface of a liquid (horizontal) to be entered, when the vertical axis of the mesh is distinct from the physical vertical line. In this case, the surface is an inclined plane in the coordinate system of the mesh.

Each new definition of the option "PRES" "SEGMENT" generates a new pressure surface.

Sign of the pressure:

The normal to the face of an element is the outward normal of that element. A positive pressure creates a force in the orientation of that normal.

Warning:

The instruction "TABL" is mandatory. For the case of charges constant in time, just give a two-entry table with the same value in both entries, i.e. of the form "TABL 2 t1 v t2 v", where v is the (constant) value, t1 is less or equal to the initial time of the computation and t2 is greater or equal to the final time of the computation.

NODE PRESSURE

Object:

This directive is mainly used to apply a pressure to continuum elements (2D or 3D). This option enables a pressure to be entered, which is exerted on a surface composed of the nodes belonging to the edge of structure. The pressure may vary in time (factorized loads) or be hydrostatic.

Syntax:

```
"NODE"      |[    p0                                ;
                "HYDRO"  rho   gx gy gz   x0 y0 z0 ]|  /LECTURE/
```

`p0`

Base value of the pressure (non hydrostatic). The instruction "TABL" must follow to determine the variation in time, even for constant pressures. (see note below).

`HYDRO`

Hydrostatic pressure.

`rho`

Density of the fluid which generates the pressure.

`gx, gy, gz`

Components of the acceleration vector (G) applied to the fluid.

`x0, y0, z0`

Coordinates of a point of the free surface which is supposed horizontal.

`LECTURE`

Numbers of the nodes belonging to the edge of structure, submitted to the pressure.

Comments:

The user has the choice between a pressure P0 which varies in time and a hydrostatic pressure. It is impossible to define both at the same time without re-using the word "NODE".

For a defined basic value P0, the intensity of the pressure is:

$$P(t) = P0 * C(t)$$

C(t) is provided by the first array met after the option "PRESS" (see TABLE).

Hydrostatic pressure:

This directive is decribed in 10.3.3 (page F.130).

Sign of the pressure:

The normal to the face of an element is the outward normal of that element. A positive pressure creates a force in the orientation of that normal.

Warning:

The instruction "TABL" is mandatory. For the case of charges constant in time, just give a two-entry table with the same value in both entries, i.e. of the form "TABL 2 t1 v t2 v", where v is the (constant) value, t1 is less or equal to the initial time of the computation and t2 is greater or equal to the final time of the computation.

PRESSURE ON DISCRETE ELEMENTS

Object:

This directive is used to apply pressure on the outer surface of a cylinder made of discrete elements (ELDI). The pressure may vary in time (factorized loads).

Syntax:

```
"ELDI"      |[   p0 ;
                "PAX1"  x1 y1 z1
                "PAX2"  x2 y2 z2
                "RAD "  r
                <"TOLE"  tol>  ]|  /LECTURE/
```

`p0`

Base value of the pressure. The instruction "TABL" must follow to determine the variation in time, even for constant pressures (see note below).

`PAX1, x1, y1, z1`

Coordinates of the first point defining the axis of the cylindre.

`PAX2, x2, y2, z2`

Coordinates of the second point defining the axis of the cylindre. WARNING: PAX1 and PAX2 define the direction of the cylinder's axis but are also used as the height to calculate the area of its surface. So, the distance between the two points must be equal to the cylinder's height.

`RAD rad`

Cylinder's radius.

`TOLE tol`

Pressure is only applied on the elements that are tangent to the outer surface of the cylinder. Tol value defines the relative precision considered to determine whether the element is tangent or not. Default value: 1E-2.

`LECTURE`

Group of discrete elements where the search of tangent elements is done.

Comments:

A procedure selects the elements that are tangent to the outer surface of the cylindre. For each selected element, the pressure application area is calculated with the element's radius r. In fact, we consider this area is the area of the circle of radius r ($A = \pi * r^2$).

For a defined peak value P0, the intensity of the pressure is:

$$P(t) = P0 * C(t)$$

So, for each selected element, the applied force modulus is:

$$F(t) = P(t) * A$$

This force is applied in the direction of the normal vector V to the cylinder at the considered element. C(t) is provided by the first array met after the option "PRESS" (see TABLE).

Forces adjustment:

In practice, the sum of selected elements' areas is always significantly lower than cylinder's surface area. An adjustment is done to correct this point by multiplying the calculed force by the ratio of the cylinder's outer surface area and the sum of the selected elements cross section areas.

Sign of the pressure:

The normal to the cylinder outer surface at the considered element is the outward normal. A positive pressure creates a force in the direction of that normal.

Warning:

The instruction "TABL" is mandatory. For the case of charges that are constant in time, just give a two-entry table with the same value in both entries, i.e. of the form "TABL 2 t1 v t2 v", where v is the (constant) value, t1 is less or equal to the initial time of the computation and t2 is greater or equal to the final time of the computation.

10.3.4 ADDITIONAL ACCELERATION

Object:

This option enables additional acceleraration depending on time to be prescribed.

Syntax:

```
"ACCE"  /LECDDL/  g0  /LECTURE/
```

`LECDDL`

Reading procedure of the numbers of the degrees of freedom concerned.

`g0`

Base value of the acceleration to be added. The instruction "TABL" must follow to determine the variation in time, **even for constant displacements** (see note below).

`LECTURE`

Numbers of the nodes concerned.

Comments:

The external forces applied on the nodes defined by the procedure LECTURE and along the directions determined by LECDDL, are of the following type:

$$F(t) = g0 * M * C(t)$$

M is the nodal mass. C(t) is provided by the first array met after that option (see "TABL").

That option can be used to enter gravity like forces depending on time (for example, deceleration forces inside a tank during a crash).

Warning:

The instruction "TABL" is mandatory. For the case of charges constant in time, just give a two-entry table with the same value in both entries, i.e. of the form "TABL 2 t1 v t2 v", where v is the (constant) value, t1 is less or equal to the initial time of the computation and t2 is greater or equal to the final time of the computation.

10.3.5 TABLE

Object:

The tables provide the different values of the coefficients C(t) which appears in the options of the instruction "CHARGE FACTORISEE" (factorised load).

The C(t) functions are continuous, linear by parts and therefore defined by points. They can linearly interpolate more complex functions.

Syntax:

```
"TABLE"   npts*( tk  ck )
```

`npts`

Number of couples (tk, ck) defining the table.

`tk`

Elementary time.

`ck`

Multiplying factor at the time tk: ck=C(tk).

Comments:

Each array refers to the options "DEPL", "FORC", "PRES" which are defined in the data set before the table and follow the preceeding table, if it exists. The first table refers to all options defined after the key-word "FACT". It is not allowed to have two consecutive tables in the data set.

If the time $t1 = 0$ is not specified in the table, the point of origin (0, 0) is assumed to belong to the curve.

The last time used in the array must be greater than the final time of the computation.

10.4 PROGRAMMED LOADS

Object:

This option enables the user to enter forces or pressures applied to certain nodes or certain elements of the structure, for time instants defined by the user himself.

In this case, the values are defined at each time by linear interpolation.

Syntax:

```
"PROG"  ndprog    $  "FORCE"    . . .     $
                  $  "PRESSION" . . .     $
                     "ROUTINE"  . . .
                  <  "ROUTINE"  . . .     >
```

`ndprog`

Number of the disc (logical unit number) where the programmed loads are stored. This disc is temporary (the data is destroyed after the creation of a disc of loads depending on time ndcha).

Comments:

The word "PROG" is the first key-word of the option. It may be used only once in the EUROPLEXUS data set.

There are 2 subdirectives "PRES" and "FORC" which respectively enable pressures or forces to be input.

For each of them, the user has to initially provide a list, which contains according to the circumstances:

- The numbers of the nodes defining the pressure line or the numbers of the elements to which pressures are applied.

- The numbers of the degrees of freedom and the numbers of the nodes to which forces are applied.

The list is entered by the means of the pocedures LECTURE and LECDDL.

There are three ways to enter the values of the forces and pressures at the different time increments.

1/- The user directly inserts, into the data set, the cards which each correspond to one time increment. Each card successively contains :

- The value of the time increment concerned.

- The values of the pressures and forces determined according to the preceeding list.

2/- The user has at his disposal or creates a data file with an imposed standard writing format. The file must successively store several sets of values, each corresponding to one time increment. Each set sequentially defines :

- The value of the time increment concerned

- The values of the pressures and forces determimed in the same way as the cards.

3/- Regarless of the program, the user provides a subroutine which computes the values of the forces or pressures for each time increment before the program runs. These values are stored in array F or P according to the list.

The data can be read on a file the format of which is not standard, or the values can be directly entered by the means of an analytic formula chosen by the user.

The keywords "ROUTINE" introduce respectively the data associated with each of the subroutines FPROG and PPROG, written by the user.

ATTENTION: the data relative to FPROG are read first.

If there are only forces (or only pressures), a single keyword "ROUTINE" is sufficient to introduce the corresponding data.

10.4.1 FORCE

Object:

For each time increment, this option enables nodal forces to be applied to certain nodes of the structure and according to certain directions (degrees of freedom).

Syntax:

```
$ "FORCE" "DDL" /LECDDL/  /LECTURE/  ...             $
$ "MXTF" ntmax  | "CART" ( "INST" ti f1 ... fn ) |    $
$               | "BAND"  nb                     |    $
$               | "ROUTINE"                      |    $
```

`LECDDL`

Reading procedure of the degrees of freedom to which the forces are applied.

`LECTURE`

Reading procedure of the numbers of the nodes to which the forces are applied.

`ntmax`

Maximum number of time instants for which the loads are defined.

`CART`

Keyword which enables the input of cards.

`BAND`

Keyword which enables the data on a file to be read.

`nband`

File number.

`ROUT`

Keyword which enables the user to provide a computation subroutine. After the word ROUT, and on a new card, the user can, if he wants, provide the data which is read by the subroutine in the order of the writing.

Comments:

The directive "FORCE" may be used at most once.

For an axisymmetric calculation, the forces must be divided by 2π, since the calculation refers to ONE radians.

The elements of the list defined by LECDDL and LECTURE are stored according to their nodes and each node according to its degree of freedom, in the order of their definitions in the procedures LECTURE and LECDDL.

For example :

"FORC" "DDL" 123 "LECT" 7 8 10 "TERM"

will define the list n(1,7) n(2,7) n(3,7) n(1,8) n(2,8) n(3,8) n(1,10) n(2,10) n(3,10) where n(i,j) represents the i th degree of freedom of the node j . The 7 th element of this list is the first degree of freedom of the 10 th node.

The parameter ntmax represents the maximum number of time increments for which the loads are defined. At the most ntmax cards or ntmax data sets can be read on the file. If a subroutine is entered, it is used ntmax times.

The user must choose between 3 input modes for the data :

CARD ("CART")

FILE ("BAND")

SUBROUTINE ("ROUTINE")

Only one can be used.

File:

The parameter nband repesents the number of the file from which the data is read. The file has been first defined at the level of the control cards.

The different sets of values are written on that file. Each set contains:

- the value of the time increment to which the data of the set is associated;

- the values of the forces F(j,t), as for the cards.

The number of the values F(j,t) must corresponds to the number of the elements defined in the LECDDL-LECTURE list, that is to say s values (s : number of nodes ; x : number of degrees of freedom). The j th value F(j,t) represents the value of the force applied to the node at time t, according to the direction defined by the j th element of the list.

The values are written on the file unformatted.

If the user reaches the end of the file before he has read all nt value sets, EUROPLEXUS considers that there are no more values to be read. In this case, the loading is finished and the program goes to the next option or instruction.

If there are more than nt data sets, the loading is considered as finished after the reading of the nt th set.

In both cases, the last time increment must be greater than the final time of computation defined in the instruction "CALCUL".

The reading of the nband number leads EUROPLEXUS to read the file automatically.

Subroutine:

The key-word "ROUT" must be the last data of the card. It automatically calls the user's subroutine. At the most, the latter will be used nt times (but if he wants, the user can stop the subroutine before the nt th . After each call, the subroutine provides the EUROPLEXUS program with an array (F or P) which contains as many values as elements defined in the LECDDL-LECTURE list. The j th value of the table is the value of the node to which a force is applied according to the direction determined by the j th element of the list. If he wants, the user can provide, after the word "ROUTINE", the data which are written on new cards. This data is read sequentially and in the order required by the subroutine. For more explanations, see the chapter "PROGRAMMED LOADS-SUBROUTINE".

10.4.2 CARDS

Object :

This suboption enables loads (forces or pressures) to be read on cards.

Syntax :

```
"CARTES" ( "INSTANT" ti f1 ... fs ) "TERMINE"
```

`INSTANT`

First keyword of each card.

`ti`

Time instant to which the data of the card is associated.

`f1 ... fs`

Value of the force applied to the node and degree of freedom defined at the j th place of the list entered by LECDDL-LECTURE, at time ti. There are s fj values per card (s representing the product of the number of degrees of freedom and the number of nodes).

`TERMINE`

This key-word denotes that there is no more data to be read. The loading is finished and the program takes the next option.

Comments:

At the maximum, the word "INSTANT" is written nt times.

Each card must include, after the value of the time increment ti, as many fj values as elements defined in the LECDDL-LECTURE list, that is to say s values. The j th fj value is the value of the force which is applied, at time ti, to the node and according to the direction defined by the j th element of the list. All the numerical values are read in free format.

The word "TERM" indicates that there is no more data to be read. The program considers the loading as finished and takes the next option or instruction.

The last time increment to be read must be greater than to the final time of computation defined in the instruction "CALCUL".

The word "CARTE" leads EUROPLEXUS to read the cards automatically.

10.4.3 PRESSURE

Object:

This option enables the following pressures (expressed in real number form) to be entered for each time instant:

- a pressure which is exerted on a set of adjacent segments or ”pressure line”, for two-dimensional computations.

- a pressure which is exerted on shell elements defining a surface, for two- and three-dimensional computations.

- a pressure which is exerted on the faces of solid elements defining a ”pressure surface”.

Syntax:

```
$ "PRESS"       | "SEGM" /LECTURE/         |  ...     $
$               | "COQU" /LECTURE/         |          $
$               | "FACE"  iface  /LECTURE/ |          $
$ "MXTP" ntmax  | "CART" ( "INST" ti f1 ... fn ) |    $
$               | "BAND"  nb                     |    $
$               | "ROUTINE"                      |    $
```

`SEGM`

This concerns two-dimensional computations; the user enters a pressure line. Then, the procedure LECTURE is used for the input of the numbers of the nodes composing the line. On the whole, there are s + 1 nodes defining s segments.

`COQU`

This concerns two- or three-dimensional computations; the user enters a surface composed of shell elements. Then, the numbers of the shell elements are entered by the procedure LECTURE.

`FACE`

This concerns three-dimensional computations; the user enters a surface composed of the faces of solid elements.

`iface`

Number of the solid element face belonging to the surface. In this case, the procedure LECTURE is used for the input of the solid elements concerned.

`ntmax`

Maximum number of time instants where the pressures are defined.

Comments:

The input syntax of the data is the same as for the "PROGRAMMED FORCES".

The words "CART" "BAND" "ROUTINE" and the parameters ntmax and nb have the same signification as for the "PROGRAMMED FORCES".

As for the latter, the j-th value defined after the time increment, on the cards or in the data sets written on the file, gives the value of the pressure which is exerted, at that time increment, on the j-th element of the list provided by the procedure LECTURE.

The j th element of the array provided by the subroutine has the same meaning (see the chapter "PROGRAMMED FORCES").

For a two-dimensional computation, the options "SEGM" and "COQU" can be used one after the other.

For example :

```
"PRES"  "SEGM"  "LECT" 1 2 3 4 "TERM"
        "COQU"  "LECT" 9 13 18 "TERM"
```

The list given by the two procedures LECTURE is respectively composed by the 3 segments 1-2 2-3 3-4, and by the 3 shells 9 13 18. The 6-th element of the list represents the shell number 18.

For three-dimensional computation, the options "COQU" and "FACE" can be used one after the other.

For example :

```
"PRES"  "COQU"  "LECT" 9 10 25  "TERM"
        "FACE" 3 "LECT" 16 2 12 "TERM"
```

The list given by the two procedures LECTURE is respectively composed of the shell elements 9 10 25, and the solid elements 16 2 12. The 4-th element of the list repesents the solid element number 16.

If there are two procedures LECTURE, the list which must take into account the values of the cards, data sets or tables may be obtained by putting the 2 lists defined by the procedures end to end, in the order of their definitions (the second list follows the first).

If he wants, the user can define several times the words "SEGM" "COQU" or "COQU" "FACE" with the corresponding lists, and in any order. The principle used to obtain the final list on which the loads are defined is the same one used if there are only two LECTURE procedures.

Examples:

```
1/ 2-D     "PRES"  "SEGM"  /LECTURE/
           "COQU"  /LECTURE/
           "SEGM"  /LECTURE/

2/ 3-D     "PRES"  "FACE" 1 /LECTURE/
           "COQU"   /LECTURE/
           "FACE" 4 /LECTURE/
```

For the conventions relative to the pressure signs, see the chapter on FACTORIZED LOADS and the corresponding options.

10.4.4 ROUTINE

Object:

This is a FORTRAN subroutine provided by the user and compiled independently from the program.

There is one subroutine for the forces (FPROG) and one for the pressures (PPROG). For each time increment, these subroutines create an array (F for forces and P for pressures), containing the values of the forces and the pressures according to the list supplied by the LECDDL - LECTURE procedures of the options "PROG" "FORC" or "PROG" "PRES".

Syntax:

1. Programmed forces :

```
SUBROUTINE FPROG(KAR,IMP,IPT,T,N,NUF,FEP,TAB)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION FEP(*),TAB(*),NUF(2,*)
. . .
  FORTRAN data set to compute the forces
. . .
RETURN
END
```

2. Programmed pressures :

```
SUBROUTINE PPROG(KAR,IMP,IPT,T,N,IPOS,NUP,PRP,PRF,TAB)
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION IPOS(N),NUP(*),PRP(*),PRF(N),TAB(*)
. . .
  FORTRAN data set to compute the pressures
. . .
RETURN
END
```

`KAR`

Input variable. At the origin, it is a number of the file the value of which is 0 by default (card reader). It can be read or defined again inside the subroutine. If KAR is negative at the exit of the subroutine EUROPLEXUS considers that the loading is finished and stops the operation.

`IMP`

Input variable, number of the output (listing) file. It may be used to write messages to the listing. The value of IMP cannot be defined again inside the subroutine.

`IPT`

Input variable. It is a pointer which is increased by 1 by PLEXIS-3C after each use of the subroutine. IPT is equal to 1 at the first call. The value of IPT cannot be defined again inside the subroutine.

`T`

Output variable. At the exit of the subroutine T must be equal to the value of the elementary time linked to the values of the forces and the pressures (array FEP or PRP).

`FEP or PRP`

Output arrays. At the exit of the subroutine, they must respectively mention the values of the forces and the pressures, according to the list provided by the procedures LECDDL and LECTURE of the options "PROG" "FORC" and "PROG" "PRES".

`N`

Input variable equal to the number of the elements on the list. The arrays FEP and PRP are automatically dimensioned at N. The value of N must not be defined again inside the subroutine.

`NUF`

Indexes of nodes and ddls where a force is applied. NUF(1,K) = number of k-th node in the list; NUF(2,K) = associated ddl.

`IPOS`

Pointer on NUP and PRP: KDEB = IPOS(I) : address of beginning of face I; KFIN = IPOS(I+1) - 1 : address of the end of face I; NBNF = IPOS(I+1) - IPOS(I) : number of nodes of face I.

`NUP(KDEB:KFIN)`

Indexes of nodes of face I.

`PRP(KDEB:KFIN)`

Pressures on nodes of face I.

`PRF`

Work array (dimension N). For example, pressures applied on the N faces at time T.

`TAB`

Work array. It enables (if necessary) to store values during the run of the subroutine (see example).

Comments:

The user's subroutine is called automatically nt times (nt is the maximum number of elementary times). It has been defined in the options "PROG" "FORC" and "PROG" "PRES".

However the user can stop the calling sequences before having achieved nt calls, by giving a negative value to NB at the exit of the subroutine (the call relative to the negative definition of NB is not taken into account).

If the user wants to define loads for n elementary times, with n inferior to nt, the value of NB must be negative at the (n+1)-th call. In any case, the last elementary time which has been computed must be superior to the final time of computation defined in the instruction "CALCUL".

SAMPLE ROUTINE FPROG

Here is the sample routine FPROG contained in the program:

```
C FPROG     SOUPLEX   LPRE      91/06/07    19:19:31
      SUBROUTINE FPROG(KAR,IMP,IPT,T,N,NUF,FEP,TAB)
C
C  OBJET : LIRE LES FORCES AUX NOEUDS POUR UN INSTANT CONSIDERE
C  -----
C
C ===> EN RETOUR : CHARGER T ET REMPLIR  FEP CORRECTEMENT
C
C     KAR  : NUMERO DU FICHIER DE LECTURE ET INDICATEUR D'ARRET
C     IMP  : NUMERO DU FICHIER DE SORTIE (IMPRIMANTE)
C     IPT  : NUMERO DE L'INSTANT CONSIDERE
C     T    : VALEUR DU TEMPS CONSIDERE
C     N    : NOMBRE DE NOEUDS OU UNE FORCE EST APPLIQUEE
C     NUF(1,K) : NUMERO DU KIEME NOEUD DE LA LISTE
C     NUF(2,K) : DDL CONCERNE
C     FEP(K)   : FORCE CORRESPONDANTE
C     TAB  : TABLEAU DE TRAVAIL (DIM AJUSTABLE AVEC "TRAV" )
C
C ===> IMPORTANT : NE PAS MODIFIER  IPT, N, NUF.
C
C     SI KAR EST MIS < 0 , ON ARRETE LA LECTURE AVANT D'AVOIR EPUISE
C     TOUS LES INSTANTS PREVUS
C
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
      CHARACTER*(10) MOT
C
      PARAMETER (NFORC=20)
C
      DIMENSION NUF(2,*),FEP(*),TAB(NFORC,2)
      DIMENSION X(3)
C
C
      IF(KAR.LE.0) RETURN
C
      READ (KAR,*) MOT
      IF(MOT.EQ.'TERMINE') GOTO 91
      IF(MOT.NE.'INSTANT') GOTO 90
C
C---   LECTURE D'UN BLOC  (A T DONNE : NP COUPLES R,F )
      READ (KAR,*) T,NP
      IF(NP.GT.NFORC) GOTO 88
      READ (KAR,*) (TAB(K,1),TAB(K,2),K=1,NP)
C
      WRITE (IMP,*) ' ===> INSTANT : ',T
      CALL DPRINT(IMP,NP,TAB(1,1),'RAYON')
```

```
      CALL DPRINT(IMP,NP,TAB(1,2),'VALEUR')
C
C---   COORDONNEES DU CENTRE :
      XC=0
      YC=0
C
C---   CALCUL DES FORCES PAR INTERPOLATION LINEAIRE
      DO 50 K=1,N
      NUPO=NUF(1,K)
      CALL QUIDNE(0,NUPO,LON,X)
      IF(LON.NE.3) GOTO 89
      DX=X(1)-XC
      DY=X(2)-YC
      R=SQRT(DX*DX+DY*DY)
      CALL DITPL1(NP,TAB(1,1),TAB(1,2),R,F,DFSDR,NX,IER)
      IF(IER.NE.0) GOTO 87
      FEP(K)=F
   50 CONTINUE
      RETURN
C
C---   ERREURS ET SORTIE
   87 CALL ERRMSS('FPROG','INTERPOLATION INCORRECTE')
      STOP
   88 CALL ERRMSS('FPROG','IL Y A TROP DE VALEURS')
      STOP
   89 CALL ERRMSS('FPROG','IL N Y A PAS 3 COORDONNEES')
      STOP
   90 CALL ERRMSS('FPROG','SYNTAXE INCORRECTE')
      STOP
   91 KAR=-KAR
      RETURN
C
      END
```

SAMPLE ROUTINE PPROG

Here is the sample routine PPROG contained in the program:

```
C PPROG     SOUPLEX   LPRE      91/06/07    19:19:12
      SUBROUTINE PPROG(KAR,IMP,IPT,T,N,IPOS,NUP,PRP,PRF,TAB)
C
C  OBJET : LIRE LES PRESSIONS AUX NOEUDS POUR UN INSTANT CONSIDERE
C  -----
C
C ===> EN RETOUR : CHARGER T ET REMPLIR  PRP CORRECTEMENT
C
C     KAR  : NUMERO DU FICHIER DE LECTURE ET INDICATEUR D'ARRET
C     IMP  : NUMERO DU FICHIER DE SORTIE (IMPRIMANTE)
C     IPT  : NUMERO DE L'INSTANT CONSIDERE
C     T    : VALEUR DU TEMPS CONSIDERE
C     N    : NOMBRE DE FACES SOUS PRESSION
C     IPOS : POINTEUR SUR NUP ET PRP :
C               KDEB = IPOS(I) : ADRESSE DU DEBUT DE LA FACE I
C               KFIN = IPOS(I+1)-1 : ADRESSE DE LA FIN DE LA FACE I
C               NBNF = IPOS(I+1)-IPOS(I) : NBR DE NOEUDS DE LA FACE I
C     NUP(KDEB:KFIN) : NUMEROS DES NOEUDS DE LA FACE I
C     PRP(KDEB:KFIN) : PRESSION AUX NOEUDS DE LA FACE I
C     PRF  : TABLEAU DE TRAVAIL (DIM N) : PAR EXEMPLE :
C               PRESSIONS APPLIQUEES SUR LES N FACES AU TEMPS T
C     TAB  : TABLEAU DE TRAVAIL (DIM AJUSTABLE AVEC "TRAV" )
C
C ===> IMPORTANT : NE PAS MODIFIER  IPT, N, IPOS, NUP.
C
C     SI KAR EST MIS < 0 , ON ARRETE LA LECTURE AVANT D'AVOIR EPUISE
C     TOUS LES INSTANTS PREVUS
C
C     SI NUP(K) EST > 10000 : IL S'AGIT D'UN NOEUD APPARTENANT A UN
C     ELEMENT DE COQUE (SINON EL. MASSIF), LE NUMERO EST ALORS
C        NUCO=MOD(NUP(K),10000)
C
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
      CHARACTER*(10) MOT
C
      PARAMETER (NPRES=20)
C
      DIMENSION IPOS(N),NUP(*),PRP(*),PRF(N),TAB(NPRES,2)
      DIMENSION X(3)
C
C
      IF(KAR.LE.0) RETURN
C
      READ (KAR,*) MOT
      IF(MOT.EQ.'TERMINE') GOTO 91
```

```
      IF(MOT.NE.'INSTANT') GOTO 90
C
C---   LECTURE D'UN BLOC  (A T DONNE : NP COUPLES R,P )
      READ (KAR,*) T,NP
      IF(NP.GT.NPRES) GOTO 88
      READ (KAR,*) (TAB(K,1),TAB(K,2),K=1,NP)
C
      WRITE (IMP,*) ' ===> INSTANT : ',T
      CALL DPRINT(IMP,NP,TAB(1,1),'RAYON')
      CALL DPRINT(IMP,NP,TAB(1,2),'VALEUR')
C
C---   COORDONNEES DU CENTRE :
      XC=0
      YC=0
C
C---   CALCUL DES PRESSIONS PAR INTERPOLATION LINEAIRE
      DO 50 IFA=1,N
      KDEB=IPOS(IFA)
      KFIN=IPOS(IFA+1)-1
      NBNF=IPOS(IFA+1)-KDEB
      PRF(IFA)=0
      DO 40 K=KDEB,KFIN
      NUCO=MOD(NUP(K),10000)
      CALL QUIDNE(0,NUCO,LON,X)
      IF(LON.NE.3) GOTO 89
      DX=X(1)-XC
      DY=X(2)-YC
      R=SQRT(DX*DX+DY*DY)
      CALL DITPL1(NP,TAB(1,1),TAB(1,2),R,P,DPSDR,NX,IER)
      IF(IER.NE.0) GOTO 87
      PRP(K)=P
      PRF(IFA)=PRF(IFA)+P
  40  CONTINUE
      PRF(IFA)=PRF(IFA)/NBNF
  50  CONTINUE
      RETURN
C
C---   ERREURS ET SORTIE
  87  CALL ERRMSS('PPROG','INTERPOLATION INCORRECTE')
      STOP
  88  CALL ERRMSS('PPROG','IL Y A TROP DE VALEURS')
      STOP
  89  CALL ERRMSS('PPROG','IL N Y A PAS 3 COORDONNEES')
      STOP
  90  CALL ERRMSS('PPROG','SYNTAXE INCORRECTE')
      STOP
  91  KAR=-KAR
      RETURN
C
      END
```

EXAMPLE 1

Problem:

The user wants to enter FORCES into the directions x and y (degrees of freedom 1 and 2). These forces are applied to the nodes 1, 3, 5, 7, 9, 11.

Their values are the same for all the nodes,for both directions; these values are defined by analytical formulas:

F = 2.5 * Sin(pi * t) For t .LE. 20 milliseconds

F = 2.9 * Sin(2 * pi * t) For t .GT. 20 milliseconds

The programming concerns 51 elementary times, a value is calculated for each millisecond from 0 to 50.

At each elementary time, the user must provide 2*6=12 values stored in array F (2 degrees of freedom and 6 nodes).

The user's subroutine:

```
      SUBROUTINE FPROG(KAR,IMP,IPT,T,N,NUF,F,TAB)
C
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
      DIMENSION F(*),TAB(*)
      DATA PI/3.1416/
C
      T=1E-3*(IPT-1)
      IF(IPT.GT.21) GOTO 20
      DO 10 I=1,N
 10   F(I) = 2.5 * DSIN( PI * T )
      RETURN
 20   IF(IPT.GT.51) GOTO 40
      DO 30 I=1,N
 30   F(I) = 2.9 * DSIN( 2*PI * T )
      RETURN
 40   KAR=-KAR
      RETURN
      END
```

Data of the instruction "CHARGE":

```
"CHARGE" 1 "PROG" 2 "FORCE" "DDL" 12 "LECT" 1 PAS 2 11 "TERM"
                  "MXTF" 60  "ROUTINE"
```

Comments:

The user can directly define these coefficients inside the subroutine. There are no data cards of the user behind the word "ROUTINE".

The value of ntmax must be superior or equal to 51, since the subroutine has performed a test in order to stop the loading at this value.

EXAMPLE 2

Problem:

The user has at his disposal a file containing data sets (elementary times and loads). It is supposed that there are a hundred values of pressure per elementary time and each data set is written under the form : (F10.5,100F15.7).

The user wants to enter only one elementary time out of ten (numbers 10, 20, 30, ...) from the initial file. For each elementary time, the user selects the pressures occupying the ranks 1, 3, 7, 9, 11, 12 and 15 among the initial data sets. Therefore, 7 values must be taken into account. The file has to be read completely and contains no more than 100 value sets. The file has been defined by number 9 at the level of the control cards.

The user's subroutine:

```
      SUBROUTINE PPROG(KAR,IMP,IPT,T,N,IPOS,NUP,P,PRF,TAB)
C
      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
      DIMENSION P(*),TAB(*),IPOS(*),NUP(*),PRF(*)
      DIMENSION NV(7)
      DATA NV/1,3,7,9,11,12,15/
C
      IF(IPT.GT.1) GOTO 10
C-----   THE PRESSURES ARE EQUAL TO ZERO AT T=0
      T=0
      DO 5 I=1,N
  5   P(I)=0
C-----   READING OF THE NUMBER OF THE FILE AND THE LENGTH OF THE SETS
      READ(KAR,*) NB,NMAX
      RETURN
 10   DO 20 I=1,10
      READ(KAR,1000,END=50) T,(TAB(I),I=1,NMAX)
1000  FORMAT(F10.5,100F15.7)
 20   CONTINUE
C-----   AT THE END OF THE LOOP ON RECORDS HAVE BEEN SKIPPED
      DO 30 I=1,7
 30   P(I)=TAB(NV(I))
      RETURN
 50   KAR=-KAR
      RETURN
      END
```

Data of the instruction "CHARGE":

```
"CHARGE" 1 "PROG" 2 "PRESS" "COQUE" "LECT" 1 2 3 5 "TERM"
                            "FACE" 3 "LECT" 7 9 11 "TERM"
                 "MXTP" 101 "ROUTINE"
                 9 100
```

Comments:

The subroutine gives an example of use of the work array TAB.

The data are read at the first call and the value of the pressures at t = 0 is fixed on zero. The user selects 7 values (N = 7).

At the following calls, 9 records on the file are skipped in order to get positionned on the sets 10, 20, 30, ... 100, at the end of the reading loop. Then, the right values supplied by the work array TAB must be stored in another array (P).

At the end of the file, the value of NB is -9 to inform the EUROPLEXUS program that the loading is finished.

10.5 ADVECTION-DIFFUSION "LOADS" (JRC)

Object:

This option enables the user to enter generalized loads for advection-diffusion calculations (see also keyword "ADDF" in Section A). These 'loads' include:

```
- imposed time-dependent temperatures
- imposed time-dependent heat fluxes
- imposed time-dependent heat generation
- imposed time-dependent heat convection
- imposed time-dependent heat radiation
- imposed time-dependent external pressure
- imposed time-dependent velocity
- imposed zero velocity
- imposed velocity parallel to a plane
- imposed velocity parallel to a line
```

Syntax:

```
"ADDF"
    $  "TIMP" . . . $
    $  "FLUX" . . . $
    $  "QGEN" . . . $
    $  "CONV" . . . $
    $  "RADI" . . . $
    $  "PRES" . . . $
    $  "VELO" . . . $
    $  "BLOQ" . . . $
    $  "VPLA" . . . $
    $  "VLIN" . . . $
```

The single sub-options are described below.

Comments:

The word "ADDF" is the first key-word of the option . It should be used only once in the EUROPLEXUS data set.

10.5.1 PRESCRIBED TEMPERATURE

Object:

To prescribe time-dependent nodal temperatures in an advection-diffusion calculation.

Syntax:

```
"TIMP"  nti*( "NOEU" /LECTURE/
              "TPOI" ntp*(T,t))
```

`nti`

Number of groups of nodes using the same time function to describe a prescribed temperature.

`/LECTURE/`

List of nodal point indexes.

`ntp`

Number of (Temperature, time) couples used for the time evolution.

`T`

Temperature.

`t`

Associated time.

Comments:

Remember to dimension sufficiently for the number of groups (nti) and of time points (ntp), see Section A.

10.5.2 PRESCRIBED HEAT FLUX

Object:

To prescribe a time-dependent normal heat flux on element faces in an advection-diffusion calculation.

Syntax:

```
"FLUX"  ntf*( "NELE" nel /LECTURE/
              "TPOI" ntp*(flux,t))
```

`ntf`

Number of groups of nodes using the same time function to describe a prescribed edge heat flux.

`nel`

Number of elements in the group.

`/LECTURE/`

The 4*nel nodes defining element faces, in the form nel * (n1, n2, n3, n4).

`ntp`

Number of (flux, time) couples used for the time evolution.

`flux`

Heat flux.

`t`

Associated time.

Comments:

Remember to dimension sufficiently for the number of groups (ntf) and of time points (ntp), see Section A.

10.5.3 PRESCRIBED HEAT GENERATION

Object:

To prescribe a time-dependent volumetric heat generation in an advection-diffusion calculation.

Syntax:

```
"QGEN"  ntq*( "FIRS" n1 "LAST" n2
              "TPOI" ntp*(Q,t))
```

`ntq`

Number of groups of elements using the same time function to describe a prescribed volumetric heat generation. Each group must contain elements with consecutive indexes.

`n1`

Index number of the first element in the group.

`n2`

Index number of the last element in the group.

`ntp`

Number of (heat gen., time) couples used for the time evolution.

`Q`

Volumetric heat generation.

`t`

Associated time.

Comments:

Remember to dimension sufficiently for the number of groups (ntq) and of time points (ntp), see Section A.

10.5.4 PRESCRIBED CONVECTIVE HEAT TRANSFER

Object:

To prescribe a convective heat transfer condition in an advection-diffusion calculation.

Syntax:

```
"CONV"  ntb*( "NELE" nel /LECTURE/
              "TPOI" ntp*(H,T,t))
```

`ntb`

Number of groups of elements using the same time function to describe a prescribed time-dependent convective heat transfer on one edge.

`nel`

Number of elements in the group.

`/LECTURE/`

The 4*nel nodes defining element faces, in the form nel * (n1, n2, n3, n4).

`ntp`

Number of (heat transf. coef., flux, time) triples used for the time evolution.

`H`

Heat transfer coefficient.

`T`

Temperature.

`t`

Associated time.

Comments:

Remember to dimension sufficiently for the number of groups (ntb) and of time points (ntp), see Section A.

10.5.5 PRESCRIBED RADIATION HEAT TRANSFER

Object:

To prescribe a radiation heat transfer condition in an advection-diffusion calculation.

Syntax:

```
"RADI"  nrad*( "NELE" nel /LECTURE/
               "TPOI" ntp*(Hr,T,t))
```

`nrad`

Number of groups of elements using the same time function to describe a prescribed time-dependent radiation heat transfer on one face.

`nel`

Number of elements in the group.

`/LECTURE/`

The 4 * nel nodes defining element faces, in the form nel * (n1, n2, n3, n4).

`ntp`

Number of (radiation heat transf. coef., flux, time) triples used for the time evolution.

`Hr`

Radiation heat transfer coefficient.

`T`

Temperature.

`t`

Associated time.

Comments:

Remember to dimension sufficiently for the number of groups (nrad) and of time points (ntp), see Section A.

10.5.6 PRESCRIBED TIME-DEPENDENT PRESSURE

Object:

To prescribe a time-dependent external pressure in an advection-diffusion calculation.

Syntax:

```
"PRES"  npres*( "NELE" nel /LECTURE/
                "TPOI" ntp*(p,t))
```

`npres`

Number of groups of elements using the same time function to describe a prescribed time-dependent external pressure on one face.

`nel`

Number of elements in the group.

`/LECTURE/`

The 4*nel nodes defining element faces, in the form nel * (n1, n2, n3, n4).

`ntp`

Number of (pressure, time) couples used for the time evolution.

`t`

Associated time.

Comments:

Remember to dimension sufficiently for the number of groups (npres) and of time points (ntp), see Section A.

10.5.7 PRESCRIBED VELOCITIES

Object:

To prescribe time-dependent nodal fluid velocities in an advection-diffusion calculation.

Syntax:

```
"VTIM"  nvel*( "NOEU" /LECTURE/
               "TPOI" ntp*(v,t)
               $[ "PERP"                   ;
                  "PARA" "ANG1" a1 "ANG2" a2 ]$ )
```

`nvel`

Number of groups of nodes using the same time function to describe a prescribed time-dependent velocity.

`/LECTURE/`

Indexes of the nodes in the group.

`ntp`

Number of (velocity, time) couples used for the time evolution.

`v`

Velocity.

`t`

Associated time.

`"PERP"`

The nodal velocity should be perpendicular to the boundary.

`"PARA"`

The velocity should be parallel to a line defined by the following angles.

`a1,a2`

Angles of the velocity direction in spherical coordinates: a1 is the angle between the global x axis and the projection of the velocity vector on the xy plane, a2 is the angle between the z axis and the velocity vector.

Comments:

Remember to dimension sufficiently for the number of groups (nvel) and of time points (ntp), see Section A.

10.5.8 PRESCRIBED PARALLEL VELOCITIES

Object:

To prescribe null nodal fluid velocities or velocities parallel to a plane or to a line in an advection-diffusion calculation.

Syntax:

```
"VELO" $[ "BLOQ" /LECTURE/                      ;
          "VPLA" /LECTURE/                      ;
          "VLIN" "NOEU" /LECTURE/
             $[ "PERP"                       ;
                "PARA" "ANG1" a1 "ANG2" a2 ]$ ]$
```

`"BLOQ"`

The following nodes will have null velocity at all times.

`"VPLA"`

The following nodes will have a velocity parallel to a plane tangent to the local boundary.

`"VLIN" "NOEU"`

The following nodes will have a velocity parallel to a line defined as follows.

`"PERP"`

The nodal velocity should be perpendicular to the boundary.

`"PARA"`

The velocity should be parallel to a line defined by the following angles.

`a1,a2`

Angles of the velocity direction in spherical coordinates: a1 is the angle between the global x axis and the projection.

Comments:

Sub-directives ”BLOQ”, ”VPLA” and ”VLIN”, if present, should appear in this order.

10.6 SEISMIC-LIKE LOADS FOR USE WITH SPECTRAL ELEMENTS

Object:

To impose seismic-like loads in a domain discretized by spectral elements, for the simulation of earthquakes and wave-propagation problems.

There are two main classes of loadings:

```
- punctual sources, introduced by the keyword "POIN";

- plane wave sources, introduced by the keyword "PLAN";

- seismic moment sources, introduced by the keyword "SISM".
```

10.6.1 PUNCTUAL SEISMIC LOAD SOURCES

Object:

This directive specifies punctual sources of loadings for spectral elements. The load is computed as the product of a time function and a function of space:

```
f(x,y,z,t) = h(t) * g(x,y,z)
```

Syntax:

```
"POIN" <"NODP" /LECT/> |[ "BET" ; "COS" ]|
                       |[ "DELT" ; "SPRE" ; "PRES" ; "SHEA" ]|
                       "SOUR" "AMP" amp "T0" t0
                       "BETA" beta "ALFA" alfa
                       <"X" x0 "Y" y0 <"Z" z0>>
                       <"NX" nx "NY" ny <"NZ" nz> >
```

"NODP"

The load will be applied to the node specified in the following /LECT/. Only one nodal point must be specified. This directive may be used in alternative to the load point coordinates X, Y, Z.

"BET"

The time function h(t) has the form:

```
h(t) = amp * (1 - 2*beta*(t - t0)^2) *
       exp(-beta * ((t - t0)^2)
```

"COS"

The time function h(t) has the form:

```
h(t) = amp * cos(Pi*beta*(t - t0)) *
       exp(-0.5*beta^2 * ((t - t0)^2)
```

"DELT"

The spatial distribution is punctual (delta function), i.e. the force only acts in the point (node) specified below by (x0, y0, z0). Note that this force is an absolute one, i.e. it does not depend on the nodal volume.

"SPRE"

The spatial distribution is a radial function:

```
g(x,y,z) = exp( - alfa^2 * R^2 )
```

.

where R**2 is the distance from point (x0, y0, z0). Note that this force is a volume force, i.e. it is scaled for each node by the nodal volume. All points at the same distance R from (x0, y0, z0) have the same same value of g(x,y,z), but note that the direction of the force is NOT radial, but is defined by (nx, ny, nz).

"PRES"

Similar to SPREAD but the direction is radial, thus there is no need to define (nx, ny, nz). Like SPRE, this force is volumetric, i.e. scaled by the nodal volume:

```
f_x = h(t) * 2 * alfa^2 * (x - x0) *
      exp( - alfa^2 * R^2 )

f_y = h(t) * 2 * alfa^2 * (y - y0) *
      exp( - alfa^2 * R^2 )

f_z = h(t) * 2 * alfa^2 * (z - z0) *
      exp( - alfa^2 * R^2 )
```

"SHEA"

Similar to PRES but the force is directed along the tangential direction (and not along the radial one). Also here (nx, ny, nz) are redundant. Furthermore, this kind of loading is only available in 2D. Like SPRE, this force is volumetric, i.e. scaled by the nodal volume. The components are:

```
f_x = - h(t) * 2 * alfa^2 * (y - y0) *
        exp( - alfa^2 * R^2 )

f_y = h(t) * 2 * alfa^2 * (x - x0) *
      exp( - alfa^2 * R^2 )
```

"SOUR"

Introduces a source, that will be characterized by its parameters AMP, T0 etc.

amp

Amplitude of the time function.

t0

The value appearing in the expression of h(t). This time corresponds to the maximum of the time function: h(t0) = amp.

beta

The beta value appearing in the expression h(t). It governs the exponential decay of the time function. Note that it is possible to avoid the exponential decay in time of the load by specifying a negative value for beta. In this case, the exponential function is eliminated from the expression of h(t), and the absolute value of beta is used. In the BET case:

```
h(t) = amp * (1 - 2*abs(beta)*(t - t0)^2)
```

.

In the COS case:

```
h(t) = amp * cos(Pi*abs(beta)*(t - t0))
```

`alfa`

The alfa value appearing in the expression g(x,y,z). It governs the exponential decay of the space function.

`x, y, z`

Coordinates of the source. The load will be applied to the node closest to point x,y,z. If these are given, use of NODP is not permitted.

`nx, ny, nz`

Define the normal direction for DELTA or SPREAD.

Comments:

These loads are all volumetric (specific) forces, except in the case of DELT. This is in order to avoid mesh dependency of the total energy introduced in the system.

Therefore, amp represents the total force (per unit volume) acting on all affected nodes at time t0, and this quantity varies in time according to h(t).

In the special case of DELT, the user is responsible of calibrating the (non-volumetric) force with respect to the nodal mass of the application point.

10.6.2 PLANE WAVE SEISMIC LOAD SOURCES

Object:

This directive specifies loading sources in the form of distributed loadings for spectral elements. The load is applied to all nodal points (typically) along a plane (or a line in 2D) and varies in time according to the same time function in all loaded points (except in the case "DLEN", see below).

Syntax:

```
"PLAN" |[ "BET" ; "COS" ]|
       "SOUR" "AMP" amp "T0" t0
                        "BETA" beta <"DLEN" dlen>
                        "NX" nx "NY" ny <"NZ" nz>
                        "NOEU" /LECTURE/
```

`"BET"`

The time function h(t) has the form:

```
h(t) = amp * (1 - 2*beta*(t - t0)^2) *
       exp(-beta * ((t - t0)^2)
```

`"COS"`

The time function h(t) has the form:

```
h(t) = amp * cos(Pi*beta*(t - t0)) *
       exp(-0.5*beta^2 * ((t - t0)^2)
```

`"SOUR"`

Introduces a source, that will be characterized by its parameters AMP, T0 etc.

`amp`

Amplitude of the time function at t = t0.

`t0`

The value appearing in the expression of h(t). This time corresponds to the maximum of the time function: h(t0) = amp.

`beta`

The beta value appearing in the expression h(t). It governs the exponential decay of the time function.

`dlen`

If this value is given, then the loading model of ELSE is strictly used. In this model the load applied to nodal points is proportional to the time derivative of the function h(t), in order to obtain h(t) as an imposed displacement. The nodal force is then:

```
F = 2*rho*c*(dh/dt)*vol*fac
```

.

where rho is the density, c is the wave propagation speed, vol is the nodal volume and fac is a scaling factor, defined as:

```
fac = 2 / (dlen * W)
```

.

where W is the Gauss-Lobatto weight. The physical meaning of dlen is the maximum height of the spectral elements strip in which the load is prescribed. Note, however, that in this case the following restriction applies (coming from the ELSE implementation): the line of nodal points affected by the load must coincide with the one given in ELSE (typically, an horizontal row of nodes, in a region where the mesh must be structured). Therefore, this option makes only sense for strict comparisons between ELSE and Ahnse.

`nx, ny, nz`

Define the direction for the loading source.

`/LECT/`

Nodal points in which the loading acts. The code does NOT require that the given nodes actually lie on a line or a plane (3D). The use may therefore specify a non-linear or non-planar source if so desired.

Comments:

These loads are volumetric (specific) forces. This is in order to avoid mesh dependency of the total energy introduced in the system.

Therefore, amp represents the total force (per unit volume) acting on all affected nodes at time t0, and this quantity varies in time according to h(t).

10.6.3 SEISMIC MOMENT LOADS

Object:

This directive specifies loading sources in the form of seismic moment loadings for spectral elements. The load is applied to a 'fault' defined by a series of nodes, introduced by the keyword `NOEU`. The program verifies the alignment of the given nodes along a line in 2D and on a plne in 3D. As a special case, a single fault node can be specified (pointwise loading).

A slipping vector must be defined by keywords `SX`, `SY`, `SZ`. The user can also specify the normal to the fault by the keywords `NX`, `NY`, `NZ`. If the normal is missing, the program assumes it coincident with the slipping vector.

The load applied to each nodal point varies in time according to the distance from the ipocenter, defined by its coordinates `X`, `Y`, `Z`. The time delay in each point depends upon the above mentioned distance and on the speed of transversal wave propagation. This speed is automatically evaluated by the code, or can alternatively be imposed by the keyword `VRUP`.

Syntax:

```
 "SISM" |[ "BET" ; "COS" ]|
        "SOUR" "AMP" amp "T0" t0
                         "BETA" beta
                         "SX" sx "SY" sy <"SZ" sz>
                         <"NX" nx "NY" ny <"NZ" nz>>
                         "X" x "Y" y <"Z" z>
                         <"VRUP" vrup>
                         "NOEU" /LECTURE/
```

`"BET"`

The time function `h(t)` has the form:

```
h(t) = amp * (1 - 2*beta*(t - t0)^2) *
       exp(-beta * ((t - t0)^2)
```

`"COS"`

The time function `h(t)` has the form:

```
h(t) = amp * cos(Pi*beta*(t - t0)) *
       exp(-0.5*beta^2 * ((t - t0)^2)
```

`"SOUR"`

Introduces a source, that will be characterized by its parameters `AMP`, `T0` etc.

`amp`

Amplitude of the time function at `t = t0`.

`t0`

The value appearing in the expression of `h(t)`. This time corresponds to the maximum of the time function: `h(t0) = amp`.

`beta`

The beta value appearing in the expression `h(t)`. It governs the exponential decay of the time function.

`sx, sy, sz`

Components of the slipping vector.

`nx, ny, nz`

Components of the normal vector. If omitted, the normal direction is assumed coincident with the slipping vector.

`x, y, z`

Coordinates of the ipocenter.

`vrup`

Velocity of propagation of loading (by default, this is the speed of transverse wave propagation).

`NOEU /LECT/`

Nodal points in which the loading acts. Unlike in the `PLAN` case, the code requires that the given nodes actually lie on a line or a plane (3D).

Comments:

The present model has been borrowed from the ELSE code of CRS4 and is mesh-dependent in that the applied loadings depend on mesh size. A slightly modified, mesh-indepenedent implementation is also available in EUROPLEXUS, and is activated by choosing a negative value for `VRUP`.

10.7 NEW CONSTANT LOADS

Object:

This directive allows to introduce constant forces or moments during the whole computation. The loads may be applied either to the nodes of a deformable body, or to the centroid of a rigid body.

Syntax:

```
FCTE  $[ NODE ; RIGI ]$ /LECT/
      $[ FORC f ; MOME m ]$ VECT x y z
```

`NODE`

The loads will be applied at the following specified nodes.

`RIGI`

The loads will be applied at the following specified rigid bodies.

`/LECT/`

Concerned nodes or concerned rigid bodies (see directive `COMP RIGI`).

`f`

Force modulus.

`m`

Moment modulus.

`x y z`

Components of the vector or moment-vector. See comments below for the meaning of each component.

Comments:

Three vector components must be specified, even in 2-D calculations. The vector is used to determine the direction of the applied force or moment. It does not need to be unitary, since it is automatically normalized immediately after reading.

The applied forces or moments must be expressed in the global reference frame X, Y, Z (for rigid bodies, the rotational values are then converted internally to the local reference frame, as appropriate). The meaning of the vector components (`VECT x y z`) is as follows:

1. For an applied force (`FORC`):

- In 2D calculations, `x` is component X, `y` is component Y and `z` must be 0 (component Z).
- In 3D calculations, `x` is component X, `y` is component Y and `z` is component Z.

2. For an applied moment (`MOME`):

- In 2D calculations, `x` is component X and must be 0, `y` is component Y and must be 0, and `z` is component Z.
- In 3D calculations, `x` is component X, `y` is component Y and `z` is component Z.

10.8 IMPOSED TIME-DEPENDENT LOADS

Object:

This directive allows to introduce time-dependent forces or moments during the transient computation. The loads may be applied either to the nodes of a deformable body, or to the centroid of a rigid body. The time-dependency of the load is specified by a function (see directive `FONC` on page E.15 and following ones).

Syntax:

```
FIMP  $[ NODE ; RIGI ]$ /LECT/
      $[ FORC f ; MOME m ]$ VECT x y z NUFO nf
```

`NODE`

The loads will be applied at the following specified nodes.

`RIGI`

The loads will be applied at the following specified rigid bodies.

`/LECT/`

Concerned nodes or concerned rigid bodies (see directive `COMP RIGI`).

`f`

Force modulus (base value, to be multiplied by the time function).

`m`

Moment modulus (base value, to be multiplied by the time function).

`x y z`

Components of the vector or moment-vector. See comments below for the meaning of each component.

`nf`

Number of the function defining the time-dependency of the imposed load.

Comments:

Three vector components must be specified, even in 2-D calculations. The vector is used to determine the direction of the applied force or moment. It does not need to be unitary, since it is automatically normalized immediately after reading.

The applied forces or moments must be expressed in the global reference frame X, Y, Z (for rigid bodies, the rotational values are then converted internally to the local reference frame, as appropriate). The meaning of the vector components (`VECT x y z`) is as follows:

1. For an applied force (`FORC`):
   - In 2D calculations, `x` is component X, `y` is component Y and `z` must be 0 (component Z).
   - In 3D calculations, `x` is component X, `y` is component Y and `z` is component Z.
2. For an applied moment (`MOME`):
   - In 2D calculations, `x` is component X and must be 0, `y` is component Y and must be 0, and `z` is component Z.
   - In 3D calculations, `x` is component X, `y` is component Y and `z` is component Z.

The defined load A is multiplied by a coefficient C(t) which varies in time and is interpolated from the specified table:

$$\mathrm{Q(t) = A * C(t)}$$

10.9 DYNALPY LOADS

Object:

This directive allows to introduce time-dependent dynalpy loads in 1-D elements of type TUBE or TUYA.

Syntax:

```
FDYN  NODE /LECT/ PZER p0 COEF c VECT x y z ELEM e
```

`/LECT/`

Concerned node. Only one single node is possible to define.

`p0`

Reference pressure.

`c`

Coefficient.

`x y z`

Components of the vector or moment-vector.

`e`

Number of the concerned element.

Comments:

Three vector components must be specified, even in 2-D calculations. The vector is used to determine the direction of the applied load. It does not need to be unitary, since it is automatically normalized immediately after reading.

These loads are only related to 1-D elements of type TUBE or TUYA and are defined as:

$$\underline{F} = c(p - p_0)\underline{v}$$

where p is the current pressure in the specified element.

10.10 AIR BLAST (AIRB) LOADING

Object:

This directive allows to apply air blast loading directly to a set of strucural elements (continuum, shells) without using specialized CLxx elements with an associated `IMPE AIRB` material. This simplifies the treatment of element erosion and mesh adaptivity.

Syntax:

```
AIRB  |[ "X" x "Y" y <"Z" z> ; "NODE" /LEC1/ ]|
            "MASS" m $[ "TINT" t ; "TAUT" ]$ <"OPOS">
            <"ANGL">
            <"CUBE">
            <"COEF" cf>
            <"CONF" c>
            <"DECA" d>
            <"PMAX" pmax "TD" td "B" b>
            <"SHAD" /LECS/>
            /LECT/
```

`X x`

X-coordinate of the explosive source.

`Y y`

Y-coordinate of the explosive source.

`Z z`

Z-coordinate of the explosive source. This is 0 by default.

`NODE /LEC1/`

Introduces the node where the explosive charge is located. Typically, a `PMAT` element may be located at the charge position, so as to be able to visualize it.

`MASS m`

Mass of the explosive in Kilograms.

`TINT t`

Starting time of the explosion. By default it is equal to the initial time of the calculation.

`TAUT`

Indicates that the starting time is calculated automatically by the code, in such a way that the air blast wave reaches the first loaded element shortly after the starting of the calculation. This is to avoid an “idle” calculation at the beginning of the transient.

`OPOS`

Indicates that only the part with the positive pressure (overpressure) is regarded. After the time of duration of the positive phase the pressure is set to 0.

`ANGL`

Indicates that the angle of incidence between the charge and the structural element is considered.

`CUBE`

Indicates that the cubic approach will be used for the calculation of the negative phase. By default the bilinear approach is used.

`COEF cf`

The user can input a value to calibrate the decay coefficient of the air blast load. The calculated decay coefficient is multiplied by the inserted value in order to produce a load closer to experimental data.

`CONF c`

Choice between different available explosion models, see the References below. By default it is 1 (unconfined, reflected, Kingery). The term "unconfined" below means that the explosion takes place in an unconfined space, as opposed to "half-confined" where the charge is placed close to a rigid ground and so the wave propagation occurs in a half-space (experimentally, the measured pressure is somewhat lower in this case because some of the energy is absorbed by the ground). The term "reflected" hereafter means that the model accounts for the pressure increase due to (first) wave reflection at a rigid wall as it is typically measured in experiments. The pressure value in this case may be between 2 and 8 times the incident pressure in the "non-reflected" case, i.e. without taking into account this first reflection.

1. unconfined (full space), reflected (Kingery)
2. unconfined (full space), not reflected (Kingery)
3. unconfined (full space), not reflected (Kinney)
4. half-confined (half space), reflected (Kingery)
5. half-confined (half space), not reflected (Kingery)
6. Blast parameters will be directly specified next

`CONF 6` indicates that the blast parameters $p_{\max}$, t_d and b appearing in the so-called modified Friedlander equation (see below) will be directly specified next and should not be calculated automatically by the code. In this case, no other parameters (except `CONF` of course) are accepted, only the positive pressure (overpressure) is considered and the pressure-time function is identical in each element. The **modified Friedlander equation** reads:

$$p(t) = p_0 + p_{\max}(1 - \frac{t}{t_d})^{-\frac{bt}{t_d}}$$

and expresses the pressure p as a function of time t, with p_0 the initial (normally the atmospheric) pressure, $p_{\max}$ the maximum overpressure (peak overpressure), t_d the duration of the positive pressure phase and b the decay parameter, which defines how rapidly the pressure decays.

`DECA d`

Choice between different available decay coefficient equation models. Each equation is defined according to the explosion model chosen before (incident, reflected - spherical, hemispherical). The equations based on the Kingery-Bulmash data have been calculated by iteratively solving the Friedlander equation with the set of positive blast parameters proposed by Kingery-Bulmash. There are different equations for reflected or not reflected (incident) cases of unconfined (spherical) and half-confined (hemi-spherical) blast waves. An additional equation for the blast coefficient is available which is based on the Kinney and Baker data. The default blast decay equation is based on the Kingery-Bulmash data. The explosion model, that has already been defined by the parameter c, shows which of the blast wave decay equations (incident, reflected, spherical or hemispherical) will be used.

1. Blast wave decay equation based on Kinney data
2. Blast wave decay equation based on Kingery-Bulmash data (default)

`PMAX pmax`

Maximum overpressure $p_{\max}$ appearing in the modified Friedlander equation. This should only be given when `CONF 6` has been specified.

`TD td`

Duration of the positive pressure phase t_d appearing in the modified Friedlander equation. This should only be given when `CONF 6` has been specified.

`B b`

Decay parameter b appearing in the modified Friedlander equation. This should only be given when `CONF 6` has been specified.

`SHAD /LECS/`

This directive is still implemented in a non-optimized way. Its CPU cost in medium-large simulations might be important. Check for shadowing: an element is not loaded by AIRB pressure if it is "shadowed" by another element belonging to the set specified by the `/LECS/` list (which may or may not coincide with the `/LECT/` set of elements subjected to the AIRB loading).

`/LECT/`

Elements concerned. These must be of type continuum or shell.

Comments:

This model requires that the user adopts the standard Unit system, i.e. metres, Kilograms, seconds.

The equations of Kingery are only usable up to a scaled distance of Z=40. Above this distance, diagrams of Baker are used (linearised in the double logarithmic scale).

References:

For more information on the physical models, consult the following references:

- Kingery, Charles N., Bulmash, Gerald: *Airblast Parameters from TNT Spherical Air Burst and Hemispherical Surface Burst*, Defense Technical Information Center, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, 1984.
- Baker, Wilfrid E.: *Explosions in the Air.* University of Texas Pr., Austin, 1973.
- Kinney, G.F., Graham, K.J.: *Explosive Shocks in Air.* Springer, Berlin, 1985.

11 GROUP G—PRINTOUT AND STORAGE OF RESULTS

Object:

The `ECRITURE` directive enables the user to specify the requested printouts and data storages during a computation (including data saving for successive restart).

The `REGION` directive enables to define certain "regions" of the mesh, on which the printout of results will then be performed.

The `MEASURE` directive enables to request the printout of various "measurements" on the current geometrical mesh.

Syntax:

```
< ECRITURE  . . .  /CTIM/
      <  NOPO  ;  POIN  /LECTURE/  >
      <  NOEL  ;  ELEM  /LECTURE/  >
      <  FICH . . .                > >

< REGION  ( 'nom region'  . . .  )   >

< MEASURE ...                        >
```

Comments:

The keyword `ECRI` must only appear once in an input sequence. It allows to specify the values to be printed on the listing file, and the nodes and elements for which these values must be printed.

Furthermore, the directive allows to define which results files should be produced, in view of a subsequent post-processing.

If the keyword `ECRI` is absent, a printout is performed for all the time steps, all the nodes and all the elements of the mesh.

In the following subsections, first a general description of the `ECRI` directive is given. Then, all the optional keywords (`NOPO` ...) and optional sub-directives (`FICH` ...) are described below. Output regions created by the directive `REGI` are described on page G.100. Finally, the `MEAS` directive is described on page G.105.

11.1 SELECTIVE PRINTOUTS (”ECRITURE”)

Object:

The ”ECRITURE” directive can be used to select specific quantities to be printed out in the output listing at user-chosen times. It allows also to choose the nodes and elements for which the quantities will be printed.

The various quantities are associated to nodes or elements as described on page G.30 and following ones.

Syntax:

```
"ECRITURE"
            < "COOR" > < "DEPL" > < "VITE" > < "ACCE" >
            < "FINT" > < "FEXT" > < "FLIA" > < "FDEC" >
            < "MASN" > < "CONT" > < "EPST" > < "ECRO" >
            < "ENER" > < "MCVA" > < "MCVC" > < "MCVS" >
            < "FAIL" > < "VFCC" >
```

`COOR`

Printout of nodal coordinates.

`DEPL`

Printout of nodal displacements.

`VITE`

Printout of nodal velocities. In ALE cases, both fluid and grid velocities are printed out.

`ACCE`

Printout of nodal accelerations.

`FINT`

Printout of nodal internal forces.

`FEXT`

Printout of (total) nodal external forces.

`FLIA`

Printout of nodal forces due to liaisons (coupled links: LINK COUP).

`FDEC`

Printout of nodal forces due to decoupled links: LINK DECO.

`MASN`

Printout of assembled nodal masses.

`CONT`

Printout of element stresses.

`EPST`

Printout of element total strains.

`ECRO`

Printout of element material parameters (hardening for solids, pressure and density for fluids, etc.).

`ENER`

Printout of energies.

`MCVA`

Printout of nodal quantities related to multicomponent fluids: pressure, density, temperature, sound speed and mass fractions. Note that this type of printout is incompatible with `MCVC` and `MCVS`.

`MCVC`

Printout of conserved variables (nodal quantities) related to multicomponent fluids: partial densities (ρ_i) of the various components i, momentum ($\rho \underline{u}$) (each spatial component separately), energy (ρE). Note that this type of printout is incompatible with `MCVA`.

`MCVS`

Printout of secondary variables (nodal quantities) related to multicomponent fluids: total density (ρ), total pressure p, sound speed c, pressure derivative ($\frac{\partial p}{\partial(\rho e)}$), absolute temperature (T), pressure derivative ($\frac{\partial p}{\partial(\rho_i)}$) for each component, mass fraction (μ_i) for each component. Note that this type of printout is incompatible with `MCVA`.

`MCFL`

Printout of MC numerical fluxes: partial densities (first two components), momentum (each spatial component separately) and total energy. In case of FLSR fluid-structure interaction, print out also the list of blocked MC fluxes (in the form of node couples).

`MCEF`

Printout of MC numerical "external" fluxes: partial densities (first two components), momentum (each spatial component separately) and total energy.

`MCMU`

Printout of MC "MUSCL" conserved variables (2nd order in space and time): partial densities (first two components), momentum (each spatial component separately) and total energy.

`MCVM`

Printout of MC volumes (at n, n+1/2 and n+1) and masses (at n+1/2, n+1 and n+3/2).

`FAIL`

Printout of reached failure level of the elements. This is only available if the element erosion model has been activated by means of the `EROS` keyword in the problem type declaration, see page A.30. A value of 0 indicates a virgin element, a value of 100 indicates a completely failed element, an intermediate value indicates the ratio (in per cent) between the number of failed Gauss points and the total number of Gauss points in the element.

`VFCC`

Printout at each selected output time of “element” quantities related to cell-centred Finite Volumes: various volume-related quantities and conserved variables.

Comments

The keyword ”ECRITURE” should only appear once in an input data sequence. Keywords ”COOR”, ”DEPL”, etc. should immediately follow the ”ECRI” keyword.

Warning:

If none of the preceding keywods is specified, nothing will be printed.

In a standard calculation (not a restart), EUROPLEXUS always prints the last computed time step.

Take care when choosing output frequencies, because the size of listing files may grow very fast.

Note that the results file of type ”ALICE” allows to re-construct a listing. You may therefore choose to print out the bare minimum. Later on, if additional results need to be printed, you may do so by re-reding the ”ALICE” file (which must have been specified, of course).

11.2 PRINTABLE QUANTITIES

11.2.1 NODE-RELATED QUANTITIES

For each chosen node, one may ask to print:

- current coordinates;
- displacements;
- velocities;
- accelerations;
- internal forces;
- total external forces;
- external reaction (coupled link) forces for the nodes sujected to “coupled” conditions (see LINK COUP);
- external reaction (decoupled link) forces for the nodes sujected to “decoupled” conditions (see LINK DECO);
- multi-component flow-related data (finite volumes).

Coordinates For each chosen node, the code prints X,Y or R,Z o X,Y,Z.

Displacements, velocities, accelerations and forces The chosen nodes are grouped by increasing number of degrees of freedom (d.o.f.). First all the nodes with 1 d.o.f. are printed, then those with 2 d.o.f.s, etc.

11.2.2 ELEMENT-RELATED QUANTITIES

For each chosen element and each integration point one may ask to print:

- the stress components (SIG);
- the deformation (EPST);
- the hardening parameters (ECR).

Stresses and material parameters The stress tensor and the total deformation tensor are related to the element, and independent from the material.

The material parameters, contained in the ECR table, sre independent of the element, and are only function of the material.

The choices done in EUROPLEXUS for these two quantities are detailed in the following pages.

11.3 STRESSES AND DEFORMATIONS

For a given element type, the stress components have always the same meaning, for whatever material is assigned to the element. On the contrary, the hardening values (ECR) are strictly related to the chosen material, and do not depend upon the element type.

The stress tensor is stored and printed in vector form, and is printed for each integration point of the element.

Remark 1:

In 2D, it will be necessary to distinguish the axisymmetric case (AXIS) from the plane strain (DPLA) and plane stress (CPLA) cases.

Remark 2:

For continuum-like elements, the stresses are written in the global reference frame, while for the other types of elements (shells, beams, bars) they are expressed in a local frame attached to the element.

Remark 3:

Instead of computing a bending moment, one computes a "bending stress" (sigf), that may be directly compared with the membrane stresses. This bending stress is related to the bending moment as follows:

```
Moment = E * I * Khi              Khi : curvature

sigf   = E * (h/2) * Khi          h   : thickness

Hence:     Moment = 2 * ( I / h ) * sigf

For a shell:    Moment = ( h * h / 6 ) * sigf
```

2D ELEMENTS

BARR and PONC

These elements may only work in traction and compression. There is just one stress component (scalar).

COQU

This element works in membrane and bending. There are 4 stress components per element, expressed in a local reference frame.

The first direction of the local frame is along the element from node 1 to node 2. The second, located in the mesh plane, is normal to the first. The third direction is such that the reference (u, v, w) be right-handed.

```
sig(1) : membrane (u)          sig(3) : bending (v)
sig(2) : membrane (w)          sig(4) : bending (w)
```

COQC

Also this element works in membrane and bending. But besides the 4 preceding stress components, there is a fifth one for the shear, which is treated elastically.

```
sig(1) : membrane (u)          sig(3) : bending (v)
sig(2) : membrane (w)          sig(4) : bending (w)
                 sig(5) : shear
```

CONTINUUM ELEMENTS

The stress components are expressed in the global frame. For a calculation in plane stress, there are three stresses expressed in the (x, y) frame. For an axisymmetric calculation or a plane strain calculation there are 4 stress components, expressed in the frame (x, y, z). The z direction is the normal to the mesh plane, and such that (x, y, z) be right-handed.

```
1) CPLA:

             ( SIG(1)  SIG(3) )
    (sig) =  (                )
             ( SIG(3)  SIG(2) )

2) AXIS or DPLA:

             ( SIG(1)  SIG(3)    0    )
             (                        )
    (sig) =  ( SIG(3)  SIG(2)    0    )
             (                        )
             (   0       0     SIG(4) )
```

3D ELEMENTS

BR3D

Like for the BARR and PONC elements in 2D, these elements may only work in traction and compression. The stress tensor has just one component.

POUT

This element works in traction, torsion and bending. There are always 4 stresses per Gauss point, expressed in the local frame.

The first direction of the local frame (u) is along the element, from node 1 to node 2. The second (v) is in the plane defined by u and the local vector V, on the same side as V. The third one (w) is deduced from the others.

Here, due to beam assumptions, the bending stresses are expressed in the frames (u, v) and (u, w):

```
sig(1) : traction (u)          sig(3) : bending (u,v)
sig(2) : torsion  (u)          sig(4) : bending (u,w)
```

Important:

In order to determine the local state of the beam, only the moments and the deformation have a sense! It is therefore mandatory to estimate the moments starting from the stresses, by the following relation:

$$M = \sigma \frac{I}{h}$$

The value of σ is read on the listing, I and h are specified in the input data set (see Chapter C1). The deformations are read directly from the listing.

For an elastic calculation ONLY, it is then possible to compute the stresses in any point of the cross-section.

COQ3 and COQ4

These elements work in membrane and bending. There are always 6 stress components per Gauss point, expressed in a local frame.

For the triangular elements COQ3, the first direction of the local frame (u) is along the first side of the element, from node 1 to node 2. The second (v) lies on the element plane, such that node 3 is on the positive side.

Because of shell hypotheses, the stresses are expressed in the (u, v) frame.

The quadrangular elements COQ4 are composed by 4 triangles:

1-2-3 3-4-1 1-2-4 3-4-2

Each of these triangles has a local reference frame as defined above. If the quadrangle is a parallelogram, the 4 local frames are identical.

The 4 Gauss points of element COQ4 are at the centers of the triangles mentioned above. If the element has an irregular shape, the stresses at the various Gauss points will not be directly comparable.

```
sig(1) : membrane (u)          sig(4) : bending (u)
sig(2) : membrane (v)          sig(5) : bending (v)
sig(3) : membrane (uv)         sig(6) : bending (uv)
```

Continuuum elements

The stresses are expressed in the global frame (x, y, z).

```
          ( SIG(1)  SIG(4)  SIG(6) )
          (                        )
(sig) =   ( SIG(4)  SIG(2)  SIG(5) )
          (                        )
          ( SIG(6)  SIG(5)  SIG(3) )
```

11.3.1 TOTAL DEFORMATIONS

The tensor of total deformations is the dual of the stress tensor. Its structure is therefore the same as that of the stresses (see the previous Section).

11.4 MATERIAL PARAMETERS (”ECROU”)

All internal variables pertaining to the different materials are stored in the ECR table. Initially reserved only for the hardening parameters, this table has been considerably enlarged, as more complex materials have been implemented in EUROPLEXUS.

Only the simplest materials use just the first hardening quantities. For the others, the meaning of the ECR components are described within each material law description (see page C.100 and following ones).

```
ECR     |      shells       | continua (solids) | continua (fluids)
--------+-------------------+-------------------+------------------
ECR(1)  |   V.M. membrane   |      Pressure     |      Pressure
ECR(2)  | V.M. memb. + bend.|      Von Mises    |      Density
ECR(3)  |   plast. deform.  |   plast. deform.  |         -
```

Remarks:

The equivalent plastic deformation (ECR(3)) is only printed for elasto-plastic calculations.

The Von Mises criterion for the shells is expressed as:

```
sig(*) = SQRT( sig(m)*sig(m) + (alpha**2)*sig(f)*sig(f))
```

with `sig(m)` and `sig(f)` Von Mises stresses in membrane and bending and `alpha = 2/3` by default.

The Von Mises criterion for the beams is expresses as:

```
sig(*) = SQRT( ap * press*press + am * sig(1)*sig(1) +
               at * sig(2)*sig(2) +
               af * (sig(3)*sig(3) + sig(4)*sig(4)) )
```

The `sig(i)` are defined above, and `press` is the internal pressure, if the beam is a pipe. The coefficients `ap` (pressure), `am` (membrane), `at` (torsion) and `af` (bending) are computed by EUROPLEXUS according to the type of beam, of the existence or not of a curvature, etc.

11.5 TIME CHOICE (PROCEDURE /CTIME/) FOR THE PRINTOUTS

Object:

The /CTIME/ procedure, described in the introduction (see page INT.57) is used to specify when printouts should take place during a computation.

Comments:

If nothing is specified, the printouts are performed for all time steps.

If the keyword "NUPA" is used, do not forget to dimension adequately by means of the word "MNTI" as described on page A.100.

If the keyword "TIME" is used, do not forget to dimension adequately by means of the word "MTTI" as described on page A.100.

Be aware that printout times specified via "TFRE" or "TIME" are rounded to the closest time unit, that can be chosen via the "OPTI TION" directive.

Warning:

Be careful in the choice of your printouts if you do not want to produce unnecessarily large listings. In general, it is advisable to use graphics post-processing in order to analyse the results, instead of reading values on a listing.

It is useful to know that the output file of the results ("FICH" "ALICE"), enables to print selected results on a listing after completion of a calculation. Therefore it is advisable to print only the bare minimum, although it will be necessary to read the results file again, in order to output interesting things after a calculation has been completed.

11.6 NODES OR ELEMENTS TO BE PRINTED

Object:

The user can choose the nodes and/or elements where he wants to print the results.

Syntax:

```
$["NOPOINT"  ;  "POINT"  /LECTURE/  ]$
$["NOELEM"   ;  "ELEM"   /LECTURE/  ]$
```

`"NOPOINT"`

No point is printed.

`"POINT"`

Selection of the points which have to be printed.

`"NOELEM"`

No element is printed.

`"ELEMENT"`

Selection of the elements which have to be printed.

`/LECTURE/`

List of the points or elements for which the results are printed.

Comments:

The two options "POINT" and "NOPOINT" are mutually exclusive, and the same is true for the two options "ELEMENT" and "NOELEM".

If none of the two options is specified, the results are printed for all nodes and for all elements.

11.7 RESULT FILES

Object:

This directive is aimed at creating files for the post-processing of the computation results or a saving file to restart the calculation. The following file types are available:

```
-  SAUVER file               (saving file for successive restart)
-  ALICE file                (postprocessor: EUROPLEXUS)
-  ALIT (ALICE TEMP) file    (postprocessor: EUROPLEXUS)
-  PVTK file                 (postprocessor: PARAVIEW VTK format)
-  TABL file                 (a simple formatted table)
-  POCH file                 (for Pochhammer-Chree post-treatment by EPX)
-  MAPB file                 (to store a blast wave for later mapping)
-  MED file                  (compatible with many softwares)
-  MAPP file                 (to store a solution for later mapping
                              onto a different model)
-  GMAP file                 (GMAP mapping solution file)
-  SNAP file                 (to store a snapshot of of some fields at
                              given times)
-  EPP (full) file           (postprocessor: EUROPLEXUS)
-  EPT (reduced) file        (postprocessor: EUROPLEXUS)
```

The following file types are also available but are not being further developed:

```
-  SPTAB file                (postpr.: SUPERTAB (old I-DEAS interface))
-  TPLOT file                (postprocessor: TPLOT)
-  XPLOT file                (postprocessor: TPLOT)
-  K2000 file                (postprocessor: CAST3M)
-  AVS file                  (postprocessor: AVS and old ParaView)
-  PLOT-MTV file             (postprocessor: PLOT-MTV)
-  UNIV file                 (postprocessor: I-DEAS)
```

The SAUVER file is used to restart the calculation. It is described in detail on GBG_0110.

CAST3M is the product of CEA (see http://www-cast3m.cea.fr), SUPERTAB is a commercial software by SDRC, TPLOT is a software by JRC, AVS is a commercial product by Advanced Visual Systems, PLOT-MTV is a public utility (2D plotting only), I-DEAS is a commercial software by SDRC. The MED format is a format co-developed by the CEA and EDF which is compatible with many softwares. PARAVIEW is an open-source multi-platform application designed to visualize data sets of size varying from small to very large (see http://www.paraview.org).

Note that, besides the I-DEAS interface (`UNIV` keyword) described hereafter, another version is available, that had been independently developed by the CESI (formerly ENEL) group, and which is described on GBG_0072.

The EPP and EPT files are used to store data for post-processing via EPX itself. They are meant to gradually replace the ALIC and ALIT files, respectively, by offering a more flexible and more efficient (in terms of disk space) type of data storage.

Syntax:

```
< FICH
  |[ "SAUV" <ndsauv> <"PROT" 'maclef'> <"LAST"> </CTIM/> ;

     "ALIC" <"FORM"> <"SPLI"> <ndgrap> /CTIM/ ;

     "ALIT" <"FORM"> <ndalic> /CTIM/  ...
        ... < "POIN" /LECT/ > ...
        ... < "ELEM" /LECT/ > ...
        ... < ("POSP" /LEC1/ $[x y <z> ; "FOLL" dx dy <dz> /LECF/]$ ...
        ...           "OBJE" /LEC2/) > ...
        ... < ("POSE" /LEC1/ $[x y <z> ; "FOLL" dx dy <dz> /LECF/]$ ...
        ...           "OBJE" /LEC2/) > ;

     "EPP"  <"FORM"> <ndepp> /CTIM/ ;

     "EPT"  <"FORM"> <ndept> /CTIM/ ...
        ... < "POIN" /LECT/ > ...
        ... < "ELEM" /LECT/ > ...
        ... < ("POSP" /LEC1/ $[x y <z> ; "FOLL" dx dy <dz> /LECF/]$ ...
        ...           "OBJE" /LEC2/) > ...
        ... < ("POSE" /LEC1/ $[x y <z> ; "FOLL" dx dy <dz> /LECF/]$ ...
        ...           "OBJE" /LEC2/) > ;

     "PVTK" < $["FORM" ; "FOLD"]$ > <ndpara> /CTIM/ ...
        ... <"PINB"> <"MPI"> <"FLSW"> <"SL3D"> ...
        ... <"VOXB"> <"LCOH"> <"OCOH"> ...
        ... <"GROU" |[ "AUTO" ; nobj*("OBJE" <'groupname'> ...
        ...         $[ "GAUS" ngaus ; "GAUZ" ngauz ]$ /LECT/) ]| > ...
        ... <"VARI" <"DEPL"> <"VITE"> <"ACCE"> <"FEXT"> ...
        ...         <"FINT"> <"FLIA"> <"MCXX"> <"SIGN"> ...
        ...         <"ECRN"> <"RISK"> <"FAIL"> <"VCVI"> ...
        ...         <"CONT"> <"EPST"> <"ECRO"> <"XLVL"> ...
        ...         <"DTST"> <"EPAI"> <"PCLD"> <"PL2T"> ...
        ...         <"VFLU"> <"EFSI" efsi_params> > ...
        ... <"ECRC" /LECT/> ...
        ... <"SHEL" $[vx vy vz ; "ORTS"]$ /LECT/ >  ;

     "TABL" <ndtabl> /CTIM/ ...
        ...  "VARI" <"NUGR"> nv * ( ...
        ...       |[ "COOR" "COMP" ic "NOEU" /LECT/ ; ...
        ...          "DEPL" "COMP" ic "NOEU" /LECT/ ; ...
        ...          "VITE" "COMP" ic "NOEU" /LECT/ ; ...
        ...          "ACCE" "COMP" ic "NOEU" /LECT/ ; ...
        ...          "FINT" "COMP" ic "NOEU" /LECT/ ; ...
        ...          "FEXT" "COMP" ic "NOEU" /LECT/ ; ...
        ...          "CONT" "COMP" ic "GAUS" gp "ELEM" /LECT/ ; ...
        ...          "ECRO" "COMP" ic "GAUS" gp "ELEM" /LECT/ ; ...
        ...          "EPST" "COMP" ic "GAUS" gp "ELEM" /LECT/ ; ...
        ...          "VCVI" "COMP" ic "ELEM" /LECT/ ; ...
        ...          "FONC" ifon                            ]| ) ;
```

```
"POCH" <"FORM"> <"SPLI"> <ndpoch> /CTIM/ ...
   ...  "NLIN" nl * ( /LECT/ ) ...
   ...  "VARI" $[ "DEPL" ;"VITE" ; "ACCE" ]$ ;

"MAPB" | "MSPA" ; "MTIM" | "DIPR" dipr "PCHE" pche /CTIM/ ;

"MAPP" <"FORM"> <nmapp> "OBJE" /LECT/
       $[ /CTIM/ ;
          TRIG |[ CONT icon ; ECRO iecr ; EPST ieps ;
                DEPL idep ; VITE ivit ; ACCE iacc ; VCVI ivcv ]|
                <TSTO> TVAL tval /LECT/ ]$ ;

"GMAP" <"FORM">
       $[
          < "PRES" pthres "COOR" x y <z> > ;
          < "TSAV" /CTIM/ >;
       ]$ ;

"SNAP" /CTIM/ <"ELEM" /LECT/> <"POIN" /LECT/> ...
      <"VARI" <"ECRO"> <"DEPL"> <"VITE"> ...
              <"ACCE"> <"FEXT"> <"FINT"> > ...
      <"ECRC" /LECT/> ;
"SPTA" <ndspta> /CTIM/ ;

"TPLO" <"FORM"> <ndtplo> /CTIM/ "DESC" 'dddddd' ...
      ... < "POIN" /LECT/ > ...
      ... < "ELEM" /LECT/ > ;

"XPLO" <"FORM"> <ndxplo> /CTIM/ "DESC" 'dddddd' ...
      ... < "POIN" /LECT/ > ;

"K200" < $["FORM";"XDR";"BINA"]$ > <"SPLI"> <ndcast> /CTIM/ ...
   ... < "POIN" /LECT/ > ...
   ... < "ELEM" /LECT/ > ...
   ... <"SHEL" $[vx vy vz ; "ORTS"]$ /LECT/ > ...
   ... <"CHAM"> ...
   ... <"VARI" <"DEPL"> <"VITE"> <"FEXT"> <"ACCE"> <"MCXX"> ...
   ...         <"SIGN"> <"ECRN"> <"CONT"> <"EPST"> <"ECRO"> ...
   ...         <"ECRC" /LECT/> > ;

"AVS" "FORM" <"PRVW"> <ndavs> /CTIM/ ...
   ... <"VARI" <"DEPL"> <"VITE"> <"FEXT"> <"ACCE"> <"MCXX"> ...
   ...         <"CONT"> <"EPST"> <"ECRO"> <"XLVL"> ...
   ...         <"ECRC" /LECT/> > ;

"PMTV" "FORM" <npmtv> /CTIM/ ...
   ... <"VARI" <"DEPL"> <"VITE"> <"SIGN"> <"ECRN"> > ;

"UNIV" <FORM> $["CURR";"OBSO"]$ <nuniv> /CTIM/ ;

"MED" /CTIM/ ...
```

```
        ... < "POIN" /LECT/ > ...
        ... < "ELEM" /LECT/ > ...
        ... <"SHEL" $[vx vy vz ; "ORTS"]$ /LECT/ >  ;
  ]| >
```

`FORMAT`

If this keyword is present, the file will be formatted, otherwise it will be unformatted ("BINA") (but only where both possibilities exist).

`XDR`

Only for K2000 file if this keyword is present, the K2000 file will be independent of hardware and operating systems. This is the default option for K2000 file.

`ALICE`

A file of results is written in the standard ALICE format. This file can be read again by the EUROPLEXUS or ALICE programs.

`SPLI`

Split the ALICE or K2000 (formatted file only) or Pochhammer-Chree results into several files, one for each time instant, instead of producing just a single, big file. Useful e.g. to produce animations of results, which require typically many tens or even a few hundred time instants and to overcome the file size limitations that hold under some operating systems (e.g., under 32 bit MS-Windows maximum file size is 2 GB).

`ALIT`

A file of results is written in the ALICE format as a function of time. This file will only contain the results at the nodal points and elements defined with the keywords `POIN` and `ELEM`. This file can be read again by the EUROPLEXUS or ALICE programs.

`POIN /LECT/`

List of nodes to be stored on the ALIC TEMP (or ALIT) file.

`ELEM /LECT/`

List of elements to be stored on the ALIC TEMP (or ALIT) file.

`POSP /LEC1/`

Introduces a position (or an offset) in space. The results at the node currently closest to the given position will be stored in the node specified in /LEC1/ (which must contain only one node), denoted in the following the *placeholder* node. This may be useful e.g. in case of mesh adaptivity, since the numbering of (descendant) nodes continuously changes in general, in order to get the value of a quantity at a chosen position in space. The values will be available as the ones associated with node /LEC1/ for the post-processing. For consistency, the node specified in /LEC1/ may not also appear in the list of regular nodes to be stored in the POIN /LECT/ directive above. Another restriction is that the placeholder node should have the same nature as the nodes in the object OBJE: for example, if the object is composed of shell elements (whose nodes admit both translations and rotations) then the placeholder node should also belong to a shell since if it would belong to a continuum it would lack the rotational degrees of freedom. The responsibility of satisfying this requirement is left to the user, since the code does not check it.

`x y <z>`

Position (fixed) of the desired sampling point in space. The third coordinate is mandatory in 3D while specifying it in 2D is an error.

`FOLL dx dy <dz> /LECF/`

Instead of using a fixed sampling position in space, search the node currently closest to the (single) node in /LECF/ at an offset dx, dy (and dz in 3D) from it. The sampling node "follows" the position of the node specified in /LECF/.

`OBJE /LEC2/`

Specifies the object (list of elements /LEC2/) among which the node currently closest to the chosen position must be sought.

`POSE /LEC1/`

Introduces a position (or an offset) in space. The results at the element currently closest to the given position will be stored in the element specified in /LEC1/ (which must contain only one element), denoted in the following as the *placeholder* element. The element centroid is used as a representation of an element's position. This may be useful e.g. in case of mesh adaptivity, in order to capture a local value in a descendant element rather than the (averaged) value in the corresponding base element, since the numbering of (descendant) elements continuously changes in general, in order to get the value of a quantity at a chosen position in space. The values will be available as the ones associated with element /LEC1/ for the post-processing. For consistency, the element specified in /LEC1/ may not also appear in the list of regular elements to be stored in the ELEM /LECT/ directive above. Another restriction is that the placeholder element should be of the same type and have the same material as the elements in the object OBJE: for example, if the object is composed of fluid CCFV finite volumes (say, CUVF) with a perfect gas material (GAZP) then the placeholder element should also be a CUVF with GAZP material, so that the size and meaning of the ECR components be the same. The responsibility of satisfying this requirement is left to the user, since the code does not check it.

`x y <z>`

Position (fixed) of the desired sampling element (centroid) in space. The third coordinate is mandatory in 3D while specifying it in 2D is an error.

`FOLL dx dy <dz> /LECF/`

Instead of using a fixed sampling position in space, search the element currently closest to the (single) node in /LECF/ at an offset dx, dy (and dz in 3D) from it. The sample element "follows" the position of the node specified in /LECF/.

`OBJE /LEC2/`

Specifies the object (list of elements /LEC2/) among which the (descendant) element currently closest to the chosen position must be sought.

`EPP`

A file of results is written in the EPP (EPX Post-Processing full) format. This file is a more modern version of the ALICE format and the syntax of the command is the same. This file can be read back by EPX.

`EPT`

A file of results is written in the EPT (EPX Post-Processing reduced) format. This file is a more modern version of the ALICE TEMPS format and the syntax of the command is the same. This file can be read back by EPX.

`SPTAB`

An output results file in the SUPERTAB universal file format is produced (old I-DEAS version).

`TPLOT`

A file of results is written in the standard TPLOT format. This file can be further processed by the TPLOT program.

`XPLOT`

A file of results is written in the XPLOT format. This file can be further processed by the TPLOT program.

`K2000`

A file of results is written in the CAST3M format. The default mode of K2000 output is **XDR**. It can be read by CAST3M by using the keyword `RESTITUER`. The file format is the standard format of a CAST3M file obtained with the `SAUVER` directive. It is mandatory in this case to indicate the list of the nodes for which the results have to be stored (possibly `TOUS`). The directive `CHAMELEM` is optional. The values defined on the elements (stresses, hardening quantities, strains) are only stored if this keyword is specified. Note that these element values are averaged on the element GPs (or on the GPs of a specific fibre of the element: see `K2FB` option) and are affected either to the nodes or to the barycentre of the element (see `K2CH` option).

`CHAM`

This keyword introduces the the definition of “chamelems” in the K2000 results file. If it is omitted, the latter will only contain the selected “champoints”, defined on the nodes chosen by directive `POIN` above.

`VARI`

Alternatively to `CHAM`, one can use the directive `VARI` which allows finer-grain control over the quantities effectively stored. Each nodal quantity (`DEPL`, `VITE`, `FEXT`, `ACCE`, `MCXX` in case of multicomponent gases, `SIGN` + `ECRN` in case of spectral elements, `VCVI` in case of finite volumes) and each element quantity (`CONT`, `ECRO`, `EPST`) may be specified separately. Furthermore, one may specify exactly which components of the ECR vector are to be stored, via the `ECRC /LECT/` directive. Up to a maximum of 40 different components can be selected via the /LECT/ directive. This mechanism allows to greatly reduce the size of output files in large complex 3D calculations.

`DEPL`

Nodal displacements.

`VITE`

Nodal velocities.

`FEXT`

Nodal external forces (including reactions).

`FINT`

Nodal internal forces.

`ACCE`

Nodal accelerations.

`MCXX`

Nodal variables for multicomponent fluids (pressure, density, temperature, sound speed and component mass fractions).

`SIGN`

Nodal stress components (only for spectral elements).

`ECRN`

Nodal hardening variables (only for spectral elements).

`VCVI`

Velocity in the centre of finite volumes (CEA formulation, only available for `PVTK`).

`VFLU`

Fluid velocity (in 3D) at the nodes of 1D FE pipe elements (`TUBE` and `TUYA`) (only available for `PVTK`).

`EFSI`

EFSI (Extract embedded FSI fields) field extracted from the fluid. The `EFSI` keyword must be followed by the EFSI parameters, which are described in the `EFSI` "interactive" command on Page O.10 (15.1). This keyword is only available for `PVTK` output.

`FLSW`

Face or volume blocked by FLSW (only available for `PVTK`).

`RISK`

Risk limit for eardrum failure and death. In addition, the maximum pressure and the total impulse are written to the result file. The risk types can also be split by using the SPLI command when the risk is defined (see A.30). (only available for `PVTK`).

`FAIL`

Failure level. Not active debris get a failure level of -1.0. (only available for `PVTK`).

`XLVL`

Level set of XFEM (only available for `PVTK`).

`FLIA`

Nodal forces due to liaisons (links) (only available for `PVTK`).

`DTST`

Stable time step (only available for `PVTK`).

`EPAI`

Thickness (and other `COMP` parameters) (only available for `PVTK`).

`PCLD`

Outputs related to point cloud adaptivity: point could index, distance to point could, adaptivity level (only available for `PVTK`).

`PL2T`

Treat mesh adaptivity in the visualization by converting elements with hanging nodes to triangles or tetrahedra to achieve correct visualization of sharp corners and other artefacts (only available for `PVTK`).

`SHEL`

Option which enables to print in the K2000 output file, the PVTK output file or the MED output file the stress (`CONT`) and strain (`EPST`) of shells according to specific axes rather than local axes (default). vx vy vz are the coordinates of the vector which is projected onto the shells read in `/LECTURE/` in order to define the first direction of the posttreatment axes. There is also the keyword ORTS that can be given in place of a vector, see details below. The third posttreatment direction is identical with the third one in local axes. This definition of the posttreatment axes is made in the initial configuration and is not updated ; that means this option is only relevant for small strains. This command may be repeated as many times as needed. This option is available only for DST3, DKT3, T3GS and Q4GS shells.

`ORTS`

For shells with orthotropic materials, the orthotropic axes are given using the directive COMP ORTS. In this case (only), the keyword ORTS allows to use these orthotropic directions to define the posttreatment axes.

`AVS`

A set of result files (see note below) are written in the AVS format. For the moment, only a formatted output is available for AVS, so the `FORM` option is actually mandatory in this case.

`PRVW`

The AVS files are modified to be imported into PARAVIEW software (see note below). This is only compatible with older versions of ParaView (less than 2.9 or so). For newer versions, use the `PVTK` type of output, which produces files in the VTK format.

`UNIV`

A results file in “universal” (I-DEAS) format is to be written. This file may be of two types: “current” or “obsolete”. By default it is of “current” type.

`CURR`

The universal results file will be of type “current”. This is the default.

`OBSO`

The universal results file will be of type “obsolete”.

`PVTK`

A set of result files (see note below) are written in the PARAVIEW format (`.pvd` and `.vtu` files). This is the VTK format, compatible with the newer versions of ParaView. By default, use is made of the library LIB_VTK_IO, written by Stefano Zaghi (see http://stefano.zaghi.googlepages.com/lib_vtk_io), which allows to produce either ASCII or binary output formats. However, if the (obsolete) keyword `FOLD` is specified in place of `FORM`, then formatted output is produced without making use of the LIB_VTK_IO library (note that in this case only ASCII format, not binary format, is possible).

`PINB`

The geometry of the pinballs are written in a separate vtu-file.

`MPI`

MPI calculations only. One set of vtu-files is written for each subdomain, to avoid centralizing data from all subdomains on one thread before writing. Groups must be defined at least via `GROU AUTO`

`FLSW`

FLSW links are written in a separate vtu-file.

`SL3D`

GLIS sliding surfaces are written in a separate vtu-file.

`VOXB`

VOXB faces are written in a separate vtu-file.

`LCOH`

Cohesive links between ELDI are written in a separate vtu-file.

`OCOH`

Old cohesive links between ELDI are written in a separate vtu-file.

`GROU`

Groups can be defined automatically (using keyword `AUTO`) or manually by entering `nobj` objects defined with the `OBJE` keyword (which must be repeated exactly `nobj` times). A name can be optionally given to each manually defined group. Automatic groups were generated for each material definition and for each element class (not element type). Each separate group is written as output files (see comments below for syntax). For manually defined groups, the number of the Gauss point `ngaus` or the number of the layer `ngauz`, which is used for output, can be defined for each group with `GAUS` or `GAUZ` respectively. The logic of the VTK format is not the same as the one of CAST3M and EUROPLEXUS. If an element is contained in several groups, the element will be written to the output files several times. This element is also repeated in the output of ParaView. If present, only the elements (and nodes) defined by the `GROU` keyword are written to the output.

`MSPA`

Introduces the writing of a blast field into a map file for one specific time step over a certain geometry.

`MTIM`

Introduces the writing of a blast field into a map file for one specific distance over the given time.

`DIPR`

For `MSPA`: Distance in which the pressure is checked and the output is written when the pressure reaches a certain value.
For `MTIM`: distance where the pressure history is saved.

`PCHE`

Pressure value which is used for the check to write the map file. For the `MTIM` option this is the start point of the output. The `CTIME` parameter should be set small in order to check the limits often.

`MAPP`

Activate creation of one or more so-called map file(s), where the solution of the current simulation (limitedly to a specified object part of the mesh) is stored, for successive mapping as initial conditions on a (possibly) different mesh. See directive `INIT MAPP` on page GBE_0260 for a description of how to read back the map file and use it to initialize the solution in a subsequent calculation. If only one map file is created (according to the /CTIM/ specified), such file is automatically named `<basename>_01.map`, where `<basename>` is the base name of the input file. If several map files are created (according to the /CTIM/ specified), such files are automatically named `<basename>_01.map`, `<basename>_02.map` etc., where `<basename>` is the base name of the input file.

`FORM`

Create formatted (ASCII) map file(s), instead of the default unformatted (binary) map file(s).

`nmapp`

Number of the logical unit of the map file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is `.MAP`.

`OBJE`

Introduces the list of elements (specified by the following `/LECT/`) whose solution must be stored on the map file for subsequent mapping on a different (or identical) mesh.

`/CTIM/`

Choice of the time station(s) at which the mapping file should be produced (see Page INT.57). In alternative to specifying explicitly the map time(s), a trigger mechanism can be set, see the `TRIG` sub-directive below.

`TRIG`

Introduces a “trigger” which activates thr writing of the map file when a certain variable reaches a given value at a given location. With this syntax, only one map file is produced. If a results file of type ALIC (full) is specified in the simulation, then an ALIC storage is automatically generated at the MAPP trigger time, in addition to the other storages specified in the EPX input file.

`CONT icon`

Set the trigger on stress component `icon`.

`ECRO iecr`

Set the trigger on hardening component `iecr`.

`EPST ieps`

Set the trigger on total strain component `ieps`.

`DEPL idep`

Set the trigger on displacement component `idep`. If one specifies 0 for `idep`, then the displacement norm of the first `IDIM` components is used.

`VITE ivit`

Set the trigger on velocity component `ivit`. If one specifies 0 for `ivit`, then the velocity norm of the first `IDIM` components is used.

`ACCE iacc`

Set the trigger on acceleration component `iacc`. If one specifies 0 for `iacc`, then the acceleration norm of the first `IDIM` components is used.

`VCVI ivcv`

Set the trigger on cell-centered velocity component `ivcv`. If one specifies 0 for `ivcv`, then the cell-centered velocity norm of the first `IDIM` components is used.

`TSTO`

If `TSTO` is specified, the simulation stops immediately after writing the map file.

`TVAL tval`

Set the value which activates the trigger. The trigger is activated when the value of the monitored quantity exceeds `tval`. Once activated, the trigger remains active for the rest of the computation.

`/LECT/`

Specify the (single) element or the (single) node at which the specified variable is monitored.

`GMAP`

Similarly to `MAPP`, activate creation of a `.gmap` file, where the solution of the current simulation is stored, if the latter have some prerequisities. In particular, calculations can be dumped according to a pressure-based criteria `PRES` at a given location `COOR`, or a time-based criteria `TSAV`. Meanwhile, see directive `INIT GMAP` on page GBE_0270 for a description of how to read back the map file and use it to initialize the solution in a subsequent calculation.

Current assumptions:

- Only finite-volume-based data is to be dumped and mapped;
- Material consistency between the first and the second simulation;
- `"JWL"`-like materials (to be improved);
- Mesh dimension of the second calculation must be **equal or higher** than the first one.

`SNAP`

Activate creation of a so-called snapshot file (with extension ".snp"), where snapshots of some given fields (limitedly to a specified object part of the mesh) are stored at given times of the calculation. For nodal and elementary fields, the user has to specify which nodes or elements to consider with the keywords `POIN` and `ELEM` respectively. At this time, the only elementary field allowed for this snapshot output is `ECRO`. If the field `ECRO` is queried, the keyword `CERC` is mandatory to specify which `ECRO` components to output.

`ndgrap`

Number of the logical unit of the ALICE file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is `.ALI`. For the special case of split ALICE files, see comments below.

`ndalic`

Number of the logical unit of the ALICE TEMPS file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is `.ALT`. If the `SPLI` keyword is specified, potentially many ALIC results files are produced. To place all these files in a results sub-directory (in order to unclutter the currect directory) one can use the technique explained on Page A.28.

`ndspta`

Number of the logical unit of the SPTAB file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is `.SPT`.

`ndtplo`

Number of the logical unit of the TPLOT file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is `.TPL`.

`ndxplo`

Number of the logical unit of the XPLOT file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is `.XPL`.

`ndcast`

Number of the logical unit of the CAST3M file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is `.K20`. For the special case of split CAST3M files, see comments below.

`ndavs`

Number of the logical unit of the AVS file(s) or file name in quotes. If omitted, the program chooses a (base) file name by default (see page A.27). The default extension is `.AVS`. Split files are generated for this type of output. See comments below.

`ndpara`

Number of the logical unit of the PARAVIEW file(s) or file name in quotes. If omitted, the program chooses a (base) file name by default (see page A.27). The default extension is `.pvd`. This file contains links to files with the data (vtu-format, extension `.vtu`). See comments below. To place all these files in a results sub-directory (in order to unclutter the currect directory) one can use the technique explained on Page A.28.

`npmtv`

Number of the logical unit of the PLOT-MTV file or file name in quotes. If omitted, the program chooses a (base) file name by default (see page A.27). Split files are generated for this type of output. The default extension is `.MTV`. See comments below.

`nuniv`

Number of the logical unit of the universal file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is `.UNV`.

`ndtabl`

Number of the logical unit of the table file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is `.TAB`.

`/CTIM/`

This procedure is described in the introduction (page INT.57). If the keywords `NUPA` or `TIME` are used, do not forget to dimension adequately by means of keywords `MNTI`, `MTTI` (see also page A.100).

`DESC 'dddddd'`

Six-character descriptor to identify the run for the TPLOT (or XPLOT) data-base. Note that this item is in text format, therefore it must be enclosed in quotes. When loading data on the TPLOT database, a prefix `PL` is automatically placed in front of this descriptor. Thus, the full descriptor on the database will be `PLdddddd`. For XPLOT, the prefix is `XL`, so the full descriptor will be `XLdddddd`.

`POIN /LECTURE/`

List of nodes for which the results have to be stored for successive treatment by TPLOT or XPLOT.

`ELEM /LECTURE/`

List of elements for which the results have to be stored for successive treatment by TPLOT.

`MED`

A file of results is written in the MED format. This file will only contain the results based on the nodes and the elements selected with the keywords `POIN` and `ELEM`. For the selected nodes, nodal displacements, nodal velocities, grid velocities (in ALE only), nodal accelerations, nodal external forces (including reactions), nodal internal forces are stored. For selected elements, stresses, strains, internal variables and VCVI field (on VFCC element) are stored. Do not forget to create the MED file before with the keyword `MEDE` (see page A.30).

`TABL`

A file of results is written in a simple text file in tabular form. This type of output is meant to monitor just a few variables, say a nodal displacement and an element stress component, but with great precision. Results are always written formatted, and with full double precision (16 significant digits). The table contains one line per storage station (typically, each time step). The first two columns of the table always contain the current time step (`npas`) ad the current time (`t`). The following columns contain the chosen variables. Obviously, no more than just a few variables can be specified, in practice, else the length of the table line would become excessive. The keyword `VARI` introduces the chosen variables. Their number is given by `nv` and thereafter exactly `nv` variable specifications must be given, chosen among the following possibilities: `COOR` for nodal coordinates, `DEPL` for nodal displacements, `VITE` for nodal velocities, `ACCE` for nodal accelerations, `FINT` for nodal internal forces, `FEXT` for nodal external forces, `CONT` for elemental stresses, `ECRO` for elemental hardening quantities, `EPST` for elemental total strains, `FONC` for the value of a specified function. The keyword `COMP` introduces the component, `GAUS` the Gauss point, `NOEU` the node and `ELEM` the element. Note that the `/LECT/` directives must specify one single node or element. The value `ifon` after `FONC` specifies the function identifier (see the `FONCTION` directive).

`NUGR`

Optional variable allowing, if present, the output (in the listing file) of the correspondence between the nodes or elements indicated in the header of the ".tab" file with the name (node, element, group, ..) entered by the user in the Europlexus file.

`ndpoch`

Number of the logical unit of the Pochhammer-Chree file(s) or file name in quotes. If omitted, the program chooses a (base) file name by default (see page A.27). The default extension is `.poc`.

`NLIN`

Introduces the number of "lines" along which the results will be sampled for the successive Pochhammer-Chree post-treatment. Each line is formed by an ordered sequence of nodes and is defined by the following `/LECT/`.

Comments:

The keyword `FICHIER` is not compulsory. If it is used, the last step is systematically saved.

Do not forget to define the logical unit(s) of the file(s), on the control cards. As an alternative, EUROPLEXUS accepts the name of the file enclosed in quotes.

If one does not pay attention, result files may become very bulky, because the total number of computed time steps is often very large. It is then advisable to estimate the total number of steps from the stability step computed by the program, and then choose a reasonable number of storages on the ALICE file. It is also possible to obtain a smaller results file by using the `ALICE TEMPS` (`ALIT`) directive: in this case only the variables relative to the nodes and elements given in directives `POIN` and `ELEM` will be stored.

It is rare that one needs more than a dozen of time stations to plot the deformed shapes of the mesh — in this case the `ALICE` directive will be used. It is also infrequent that one needs more than a few hundred points to plot curves as a function of time — it is suggested to use the directive `ALIT` which allows to obtain a file reduced to just the selected points. Therefore it is possible to specify a much larger number of saving stations on an `ALIT` file than on an `ALIC` one.

For ALICE, the `SPLI` option allows to split the results into many small files, one for each stored time instant, rather than producing just one big file. This option is useful for very large computations and/or for producing animations, which typically require many saved instants. In this case, `ndgrap` is just the base name of the output files. The single file names are automatically given progressive numbers (`_0001`, `_0002`, etc.) appended to the name, which identify the storage index. A file with suffix `_0000` is also produced, which contains the initial mesh topology.

In order to post-treat these split results with EUROPLEXUS, proceed exactly as if the results would be in a single file, but remember to specify the `SPLIT` keyword in the `RESU ALIC` directive, see page ED.20.

XPLOT storage is intended to perform pseudo-1D visualization of data in a 2D or 3D run. A curvilinear abscissa is built up passing through the nodes defined in `POIN /LECT/`. Then, nodal and element quantities are stored as a function of this abscissa. By using the TPLOT program, the relevant quantities can then be plotted along the curvilinear abscissa (either initial or current). Note that nodal quantities (displacements, velocities, etc.) are stored without modification at the specified nodes. Element quantities, however, (such as stresses and hardening parameters), that are usually defined only at points internal to the elements, are first extrapolated to the nodes, then stored. Currently, the extrapolation consists of simply: 1/ averaging each quantity over each element (by using the values at the different Gauss points), 2/ averaging all neighbour element contributions to obtain nodal values. Neighbour elements to a node are those elements that contain that node.

Note also that, in the extrapolation process, only certain types of elements are considered. For example, shell or beam elements are rejected, because the mean value of the stress components on all the Gauss points is likely to be meaningless for such elements. Only the following element types are considered: TRIA(2), CAR1(8), CAR4(9), CUBE(11), CUB6(13), PR6 (20), TETR(21), PRIS(27), FLU1(52), FLU3(53), FL23(64), FL24(65), FL34(66), FL35(67), FL36(68), FL38(69), Q41 (71), Q42 (72), Q41N(73), Q42N(74).

In order to read with CAST3M a file written by EUROPLEXUS, use the following CAST3M commands:

1/ Formatted file:

```
OPTI REST FORM 'file';
```

```
REST FORM;
. . . (post-treatment commands)
```

2/ Unformatted file:

```
OPTI REST BINA 'file';
REST BINA;
. . . (post-treatment commands)
```

3/ XDR file:

```
OPTI REST 'file';
REST ;
. . . (post-treatment commands)
```

For K2000, note that two syntaxes are possible. With the 'old' syntax (the keyword `VARI` does not appear), all nodal quantities are always stored. Furthermore, all element quantities are stored if `CHAM` appears. The components of the ECR table which are stored depends in this case from the material: they are the same components of ECR that are printed on the listing.

With the new syntax (the keyword `VARI` appears) only the specified nodal quantities, element quantities and ECR table components are actually stored.

Note that, strictly speaking, it is only possible to produce an output file for K2000 when the input mesh has also been produced (and read into EUROPLEXUS) in this format. However, if this is not the case but you still desire to postprocess your EUROPLEXUS calculation with K2000, consider transforming your mesh in K2000 by the option `K2MS` (see Section H, output options). Beware, however, that this may require some manual intervention and in any case the obtained mesh will be less flexible to use than a "real" K2000 mesh.

In the case of standard AVS storage, a set of files is written, one for each stored variable. The files basename is given by ndavs. If ndavs as given by the user contains the extension `.avs` or `.AVS`, this extension is removed by the program. An extension of the form `.VARI.N.inp` is then automatically provided by EUROPLEXUS. Here `VARI` is the variable type (`DEPL`, `VITE` , ...) and `N` an integer counter which is automatically incremented by 1 at each successive storage in time.

Recall that AVS storage can also be requested interactively, i.e. during an interactive execution of EUROPLEXUS (See Group A, Interactive (Foreground) Execution).

In the case of AVS storage modified for usage with PARAVIEW, elements are split into groups with same element topology and same material law. One file is stored for each group of elements at each successive storage in time. This file contains geometry and both nodal fields and elemental fields required by the user. It is named from the name given by ndavs, with its extension removed. An extension of the form `_N1_N2.inp` is is then added to the name. `N1` is the number of the element group and `N2` is an integer counter as for standard AVS files. If `ndavs` is not defined, the base of the EUROPLEXUS input file name is used to build AVS-PARAVIEW file names.

If a directory name is provided for AVS-PARAVIEW files with the `OPNF` directive, files are written in this directory, excepted if `ndavs` represents a name with full path. In this latter case, the above given directory is ignored.

The AVS-PARAVIEW format is only readable with older versions of PARAVIEW (less than 2.9). For newer versions of PARAVIEW, the PARAVIEW output (see `PVTK`) with a `.pvd` and `.vtu` files is recommended.

Automatic group definition for PARAVIEW output (with keyword `GROU AUTO`) consists in the same splitting of elements as described above for the AVS-PARAVIEW output.

The PLOT-MTV output is only available in 2D and for spectral elements. the program will only include spectral elements and nodes in these files. A separate file with the extension `.mtv` is produced for each nodal quantity and at each selected storage time.

The `SIGN` keyword produces storage of 4 nodal stress (6 in 3D) components (`SGXX`, `SGYY`, `SGZZ`, `SGXY`, `SGYZ`, `SGZX`). The `ECRN` keyword produces storage of 2 nodal hardening quantities: the hydrostatic stress (`HYDR`) and the Von Mises stress (`VMIS`).

When using SPTAB output format, a file named `sptab.param` must exist in the current directory, containing the following key-words useful to declare the variables to print out: `DISP`, `VELO`, `ACCE`, `INTF`, `EXTF`, `MCVAR`, `MCVEL`, `MCMFR`, `FLVAR`, `SCUB8`, `ECOQI`.

For CAST3M , the `SPLI` option allows to split the results into many small files, one for each stored time instant, rather than producing just one big file. In this case, the chosen output type MUST be formatted (`FORM`). This option is useful for very large computations and/or for producing animations, which typically require many saved instants. In this case, ndcast is just the base name of the output files. The single file names are automatically given progressive numbers (_0001, _0002, etc.) appended to the name, which identify the storage index. A file with suffix _0000 is also produced, which contains the initial mesh topology.

In order to post-treat one of these split results with CAST3M, proceed as follows: choose the instant to be treated, say number 3 i.e. the third storage performed; then, produce a file by concatenating the 'zero' file (_0000) and the file for the chosen instant; finally, read and post-process the resulting file with CAST3M. In this example:

```
cat mytest_0000.k20 mytest_0003.k20 >out.k20

K2000

opti rest form 'out.k20'; rest form; ...
```

Warning :

Be careful: output files may become very large, because the total number of the time steps computed is often large. Therefore it is better to estimate that number from the stability step computed by the program. Then, the user can choose a reasonable number of writings on the output files.

The user seldom needs more than a dozen storage stations ('cases') to draw deformed structures and no more than fifty points to draw time functions.

11.8 POST-PROCESSING BY I-DEAS MASTER SERIES

Object:

This is aimed at creating files for the post-processing of computation results by I-DEAS master series.

This model is part of the models developed by the CESI team (formerly at ENEL, Milano) in collaboration with JRC.

I-DEAS is a commercial software by SDRC.

Syntax:

```
 <  "FICHIER" <FORMAT> "IDEA" ndidea   /CTIME/
                                ... < "POINT" /LECTURE/ > ...
                                ... < "ELEM"  /LECTURE/ > ...
             < "VARI" < "DEPL" "VITE" "FEXT" "ACCE" "MCXX" >
                      < "CONT" "MESH" "MCVA" "MCVE" "MCMF" >
                      < "FLVA" "ECOQ" >             >        >
```

`"FORMAT"`

If present, the file is formatted, otherwise it is unformatted.

`"IDEA"`

An output results file in the I-DEAS universal file format is produced (new version).

`ndidea`

File name in quotes of the universal output file for I-DEAS.

`"POIN" /LECT/`

Same meaning as for the other result files, see page G.70.

`"ELEM" /LECT/`

Same meaning as for the other result files, see page G.70.

`"CTIM" ..  "CONT"`

Same meaning as for the other result files, see page G.70.

`"VARI"`

Introduces the list of variables to be stored.

`"DEPL"`

The I-DEAS universal file in output will contain the displacements.

"VITE"

The I-DEAS universal file in output will contain the velocities.

"FEXT"

The I-DEAS universal file in output will contain the external forces.

"ACCE"

The I-DEAS universal file in output will contain the accelerations.

"MCXX"

The I-DEAS universal file in output will contain the MC variables.

"CONT"

The I-DEAS universal file in output will contain the stresses.

"MESH"

The I-DEAS universal file in output will contain the mesh data (only node and element datasets).

"MCVA"

The I-DEAS universal file in output will contain the MC conserved variables: pressure, density, internal energy, maximum pressure, minimum pressure, temperature.

"MCVE"

The I-DEAS universal file in output will contain the MC velocities: x, y, z velocity components, velocity modulus, sound speed and Mach number.

"MCMF"

The I-DEAS universal file in output will contain the MC mass fractions.

"FLVA"

The I-DEAS universal file in output will contain the fluid finite elements variables (FLxx family with FLUT material): pressure, density, internal energy, max pressure, min pressure, sound speed.

"ECOQ"

The I-DEAS universal file in output will contain the COQI element ECR variables: hydrostatic pressure, Von Mises, plasticity flag, current yield stress.

Comments:

The general comments of page G.70 apply to the I-DEAS results file as well.

When using "IDEA" output format, the default options for the selection of the results are: whole geometry (i.e. all nodes/elements are treated if "POIN", "ELEM" are omitted), no variable (i.e. only the variables specified in the "VARI" option are stored).

Element output in I-deas universal file format is only available for FLxx, MCxx, CUB8, COQI, CQD3, CQD4 elements at the moment.

11.9 OUTPUT REGIONS

Object:

This directive enables the printing of physical values within a given region.

A region is defined by the list of the elements which compose it. The region could correspond to a GIBI object.

Syntax:

```
 "REGION"  ( 'nom region'
      $[ "RMAS" ; "VOLU" ; "BARY" ; "DIMX" ; "DIMN" ;
         "DMOY" ; "VEMX" ; "VEMN" ; "VMOY" ; "ACMX" ;
         "ACMN" ; "AMOY" ; "IMPU" ; "ECIN" ; "WINT" ;
         "WEXT" ; "PDV"  ; "WINJ" ; "RESU" ; "IRES" ;
         "ECRG" ; "ECRM" ; "EMAS" ; "FLIR" ; "RISK" ;
         "EROD" ; "ENDO" ; "CLAS' ; "EPSM" ; "TOUT" ]$
       < "DIRX" rx "DIRY" ry "DIRZ" rz >
      |[     /LECTURE/     ;
         "POIN" /LECTURE/  ]| )
```

`nom region`

Name of the region given by the user (in apostrophes).

`RMAS`

Mass (components, computed via XMEL).

`VOLU`

Volume.

`BARY`

Center of gravity (barycentre) of the region.

`DIMX`

Maximum displacement (absolute) of the region (vector), only components 1 to 3.

`DIMN`

Minimum displacement (absolute) of the region (vector), only components 1 to 3.

`DMOY`

Average displacements (components).

`VEMX`

Maximum velocity (absolute) of the region (vector), only components 1 to 3.

`VEMN`

Minimum velocity (absolute) of the region (vector), only components 1 to 3.

`VMOY`

Average velocity (components).

`ACMX`

Maximum acceleration (absolute) of the region (vector), only components 1 to 3.

`ACMN`

Minimum acceleration (absolute) of the region (vector), only components 1 to 3.

`AMOY`

Average acceleration (components).

`IMPU`

Impulse (components).

`ECIN`

Kinetic energy (norm and components).

`WINT`

Internal energy.

`WEXT`

Work of external forces applied to the nodes of the region.

`PDV`

Work of pressure forces in ALE for a stand-alone domain.

`WINJ`

Injected energy (only for material EAU).

`RESU`

Resultant of the external forces applied at the nodes.

`IRES`

Impulse corresponding to the above resultant.

`ECRG`

For each component of ECR (in fact, for the first 10 components), sum of the values on the Gauss points of the region.

`ECRM`

Average of the ECR over the region.

`EMAS`

Mass (scalar, computed via the element's mass XM0).

`FLIR`

Resultant of the force due to LINK/LIAI applied at the nodes.

`RISK`

Global risk (average).

`EROD`

Number of eroded elements.

`ENDO`

Number of damaged elements (A damaged element contains a least a Gauss point which is not broken.) - (See A.30 : EROS ldam)

`CLAS`

Number of eroded classes and number of damaged classes - A class is eroded as soon as an element of this class is eroded - A class is damaged if the class is not eroded and if the class contains at least a damaged element.

`EPSM`

Average of the EPST (strain variables) over the region.

`TOUT`

All possible physical values are required.

`DIRX, DIRY, DIRZ`

Components of the direction vector specifying the user-defined frame. Definition of the local frame (x,y,z) with respect to the global frame (X,Y,Z):

- Local x-axis is collinear with the sliding direction specified by the user through the triplet DIRX, DIRY, and DIRZ.
- Local z-axis is orthogonal to x-axis and it is situated in the plane described by the axes x and Z. Positive projection on Z is used.
- Local y-axis completes the direct orthogonal axis system.

If the slider direction is vertical, the local x-axis is collinear with the sliding direction, the y-axis is collinear with Y-axis, and z-axis completes the direct orthogonal axis system.

Only the following quantities can be written in this frame: MASS, ECIN, AMOY, ACMX, ACMN, VMOY, VEMX, VEMN, DMOY, DIMX, DIMN, BARY, IMPU, QMVT, RESU, ECRG, FLIR

`LECTURE`

List of the elements composing the region.

`POIN /LECTURE/`

List of the nodes composing the region.

Comments:

The computation takes place within the elements.

It is possible to have elements which belong to several regions.

If the region is only known by its nodes (it has not been defined in the directive "GEOM"), the only possible balances are WEXT, RESU and IRES. In this case, it is mandatory to use the keyword "POIN" before the /LECTURE/ procedure, to avoid confusion between nodes and elements.

If the region is nothing else but the whole structure, the values of WINT and ECIN are the same as those printed in the energy balance.

The physical values of the regions are computed during the printing.

Important: restart calculation (see page ED.10)

There is no problem if the computed quantity does not depend on masses (WINT). If the physical values are dependant on the masses (ECIN BARY VMOY IMPU RMAS VOL PDV), the computation will be correct only if the masses are constant during the EUROPLEXUS computation. In fact, in order to lighten the file of the results (FICHIER ALICE), only the initial masses are copied out. There is no problem concerning a Langrangian computation. For an Eulerian or A.L.E computation, the masses change. Therefore, the physical values will not be correct.

All this happens during a restart; if the physical values are computed during a normal (non restart) EUROPLEXUS run, all the results are correct.

11.10 MEASUREMENTS AND MESH QUALITY

Object:

This directive enables: 1) the printout of various types of simple **measurements** taken on the current geometrical mesh; 2) the verification of **mesh quality** (`MQUA`) on the initial configuration as well as at chosen later times during the simulation by choosing appropriate criteria; 3) the use of such mesh quality criteria to get rid of heavily distorted elements via the element **erosion** mechanism.

Normally, it is called from the input file and the requested measurements are then printed on the listing. However, the same directive (same syntax) is available also from the command line during an interactive execution (see pages A.25 and O.10). For this reason, the present directive **must** be terminated by the keyword `TERM`, as shown below in the syntax. In case of interactive use, the requested measurements are printed on the console window, not on the listing.

Syntax:

```
MEASURE   $[ ELEM e ;
             NODE n ;
             OBJE /LECT/ ;
             EMIN /LECT/ ;
             EMAX /LECT/ ;
             DIST <POIN> /LEC1/ <POIN> /LEC2/ ;
             MQUA nmq <mesh quality assessment commands> ]$
          TERM
```

`ELEM e`

Returns information about the chosen element `e`: its type, the associated nodes (with their coordinates), its size, its mass and the list of objects or groups to which it belongs.

`NODE n`

Returns information about the chosen node `n`: its coordinates, its mass, the list of elements to which it belongs and the list of objects or groups to which it belongs.

`OBJE /LECT/`

Returns information about the chosen object `/LECT/`: the associated elements, the associated nodes, its size and its mass.

`EMIN /LECT/`

Returns information (see `ELEM` above) about the “smallest” element among those belonging to the object specified in the following `/LECT/`. Use `LECT tous TERM` to get the smallest element in the whole mesh. As smallest element, we consider the one having the shortest (non-zero) intra-nodal distance among its nodes (and thus most likely the shortest element characteristic length as far as stability is concerned).

`EMAX /LECT/`

Returns information (see `ELEM` above) about the "largest" element among those belonging to the object specified in the following `/LECT/`. Use `LECT tous TERM` to get the largest element in the whole mesh. As largest element, we consider the one having the largest intra-nodal distance among its nodes (and thus most likely the longest element characteristic length as far as stability is concerned).

`DIST <POIN> /LEC1/ <POIN> /LEC2/`

Returns the minimum (intra-nodal) distance between the two objects defined in `/LEC1/` and `/LEC2/`. Normally the two objects are interpested as a set of elements. The nodes of such elements are automatically extracted and used to compute the minimum (intra-nodal) distance. However, one may want to specify an object composed only of points (nodes). This can be done by adding the optional `POIN` keyword just before the `/LECT/` of the concerned object(s).

`MQUA ...`

Introduces the commands to activate mesh quality assessment. See below for a complete description of all such commands.

`TERM`

Indicates the termination of measurements. This keyword is necessary so that the present directive may be used also in interactive mode.

Comments

An example of this directive (to achieve simple measurements) is as follows:

```
MEASURE
  ELEM 123
  NODE 74
  ELEM 1
  OBJE LECT toto TERM
  EMIN LECT tous TERM
  EMAX LECT 1 2 4 TERM
  DIST LECT toto TERM LECT tata TERM ! min distance between two
                                     ! objects made of elements
  DIST POIN LECT p1 TERM LECT tata TERM ! min dist. between a point
                                        ! (node) and an object made
                                        ! of elements
  DIST POIN LECT p1 TERM POIN LECT p2 TERM ! distance between two
                                           ! points (two nodes)
TERM
```

When used interactively, the code pauses for input after each sub-command, waiting for the next sub-command. To exit from the `MEAS` directive, give the final `TERM` command.

11.10.1 Mesh Quality assessment

Syntax:

```
MEAS ... MQUA nmq
     ( $[ ASPE ; SKEW ; WARP ; TAPE ;
          SYMM PX px PY py PZ pz
               NX nx NY ny NZ nz TOL tol ]$ < /LECT/ >
        < EROS eros > < PRIN > )
       < EVAL /CTIM/ >
```

`MQUA nmq`

Introduces the commands to activate mesh quality assessment. The `nmq` quantity is the number of mesh quality assessment criteria that will be defined next.

`ASPE`

Compute aspect ratio of the elements.

`SKEW`

Compute skewness of the elements.

`WARP`

Compute warping of the elements.

`TAPE`

Compute tapering of the elements.

`SYMM`

Compute symmetry of the chosen mesh with respect to a plane passing through a given point and of given normal. A value of 0.0 is assigned both to elements having a symmetric companion and to elements whose centroid lies on the symmetry plane. A value of 1.0 is assigned to elements not having a symmetric companion and whose centroid does not lie on the symmetry plane.

`PX px`

Defines the x-coordinate of the point.

`PY py`

Defines the y-coordinate of the point.

`PZ pz`

Defines the z-coordinate of the point.

`NX nx`

Defines the x-component of the normal. The normal needs not be unitary, since it is normalized to 1.0 internally.

`NY ny`

Defines the y-component of the normal.

`NZ nz`

Defines the z-component of the normal.

`TOL tol`

Defines the tolerance (absolute distance) to decide whether two points (nodes or element centroids) are coincident or whether a point (element centroid) lies on the symmetry plane.

`/LECT/`

Optional list of all elements for which the current quality criterion must be evaluated. By default (if omitted), the evaluation is done for all elements in the mesh (when applicable).

`EROS eros`

Optional keyword that produces the following effect: if the computed criterion exceeds the given value `eros` for an element, then the element is eroded (removed from the computation). If this keyword is omitted for a criterion, then no elements are eroded according to that criterion.

`PRIN`

Printout the evaluated criterion values on the listing each time they are evaluated. By default, i.e. without specifying the `PRIN` optional keyword, the evaluated values are not printed. Beware that the list of values may be long, since there is one value for each element in the mesh.

`EVAL /CTIM/`

Reading procedure (see page INT.57) of the chosen time steps or time instants at which the evaluation of the above defined mesh quality criteria should be performed. If omitted, the evaluation is performed *at every time step*. However, note that this may be very expensive so that in large applications it is strongly advised to perform the evaluation (and the optional element erosion) only at a certain chosen frequency in time.

Comments

The parentheses `( ... )` in the above syntax signify that more than one criterion can be chosen at the same time, by simply repeating the parenthesized context. The total number of declared criteria **must** be equal to the number `nmq` declared just after the `MQUA` keyword.

The results of the chosen quality criteria evaluations become available for visualization at the time steps or time instants specified in the `/CTIM/` directive.

Each time an `MQUA` directive is entered (either in the input data set or from the command line, in case of interactive execution), any pre-existing mesh quality assessment criteria are wiped out and are replaced by the newly declared criteria.

An example of this directive is as follows:

```
MEAS MQUA 3
     ASPE LECT plate TERM EROS 2.5
     WARP EROS 5.0 ! Erode if warping angle > 5 degrees
     SKEW
     EVAL TFRE 1.0E-3 NUPA LECT 5000 7500 TERM
TERM
```

This means that the following three quality criteria will be evaluated:

- Element aspect ratio, limitedly to the elements of the `plate` object. Such elements will be eroded if the evaluated criterion exceeds the value 2.5.
- Element warping, for the whole mesh. Elements will be eroded if their warping (angle) exceeds 5 degrees.
- Skewing. This criterion will be evaluated for all elements. However, it will generate no element erosion (it is only computed to be visualized).

The above mentioned evaluations (and the associated element erosions, if any) are performed every millisecond of physical time and, in addition, also at steps 5000 and 7500. At any of these chosen time instants the user will be able to visualize the computed quality criterion fields (one field for each active criterion).

11.11 SAVING FILE FOR SUCCESSIVE RESTART

Object:

This keyword creates a saving file and, in conjunction with the keyword `REPR` (to be used in a subsequent run), allows splitting a computation in two or more parts.

This directive replaces the old (deprecated and obsolescent) directive `SAUV` (group A, see page SR.20).

The results are saved on a file (saving file) at times specified by the user. Each saving corresponds to a number or position on the file (1, 2, 3 etc.), from which a restart of the computation can be carried out in a successive run (see directive `REPR` on page SR.30).

Syntax:

```
FICH  SAUV <ndsauv>  <PROT 'maclef'>  <LAST>  </CTIM/>
```

`nbansav`

Number of the saving file or name of the file in quotes. If completely omitted, the code will assume the default file name `<basename>.sau` where `<basename>` is the root of the input file name (i.e. without extension `.epx`).

`PROT`

Keyword entering a protection on the saving file.

`'maclef'`

Key of up to 8 characters, enclosed in apostrophes. In order to restart the computation from that file, the instruction `REPR` must contain the keyword `PROT` with an identical key.

`LAST`

This keyword indicates that the saving file should contain just one saving station, corresponding to the last saved time station in the present calculation. In other words, each new saving station replaces the former one, if any. This allows to obtain a saving file of the smallest possible size. However, restarting from an intermediate time is obviously not possible in this case: the only possibility to restart the calculation will be `REPR` ... `POSI 1` (see page SR.30).

`/CTIM/`

The `/CTIM/` procedure (see page INT.57) is used to specify the saving times via a step frequency (`FREQ`), a time frequency (`TFRE`), a list of steps (`NUPA`) or a list of times (`TIME`). If `NUPA` or `TIME` are used, do not forget to dimension accordingly using `MTTI` or `MNTI`, respectively, see page A.100. Note that the code always saves the last step of the calculation (if the run is terminated normally), irrespective of the frequency chosen. Therefore, if one is only interested in getting the possibility to continue the calculation further on, simply omit the `/CTIM/` procedure.

Comments:

The keyword `PROT` is not compulsory. If it is not used, there is no protection (this is equivalent to a key of 8 blanks).

If a unit number is used for `nbansav`, the saving file and its number must have been defined before on the control cards.

A first saving station (position number 1) containing some header data is always produced at the initial time (step 0 of the calculation). Of course, it is normally meaningless to restart from this time station, unless the `LAST` keyword has been specified (see above), because it would be the same as starting the calculation anew from the initial time. On the contrary, if `LAST` has been specified, the only possibility for restart is to use the first time station which, in this case, will contain the data of the last saving performed (not the first one in general).

Examples:

Assume a calculation performs 4994 time steps to arrive at its final time. The following saving directives are accepted:

- `FICH SAUV 'myfile.sau' FREQ 1000` saves data for restart on the indicated file every 1000 steps. The following six saving stations are produced: 1 (step 0), 2 (step 1000), 3 (step 2000), 4 (step 3000), 5 (step 4000) and 6 (step 4994, i.e. the last step).
- `FICH SAUV FREQ 1000`: same as above but the saving file has the default name `<basename>.sau`.
- `FICH SAUV 'myfile.sau' LAST FREQ 1000` saves data for restart on the indicated file every 1000 steps, by always re-writing the previous saving. Only one saving station is thus present on the saving file (assuming that the run terminates normally): 1 (step 4994, i.e. the last step). If the run would fail, say, at step 2500, the saving file would also contain one station (step 2000).
- `FICH SAUV FREQ 10000`: the saving file has the default name `<basename>.sau`. Only one saving station is produced (assuming that the run terminates normally): 1 (step 4994, i.e. the last step). If the run would fail, say, at step 2500, no (useful) saving time station would be available (there is still one saving station, but it is at step 0).
- `FICH SAUV LAST`: the saving file has the default name `<basename>.sau`. Only one saving station is produced (assuming that the run terminates normally): 1 (step 4994, i.e. the last step). If the run would fail, say, at step 2500, no (useful) saving time station would be available (there is still one saving station, but it is at step 0).
- `FICH SAUV`: the saving file has the default name `<basename>.sau`. Two saving stations are produced (assuming that the run terminates normally): 1 (step 0) and 2 (step 4994, i.e. the last step). If the run would fail, say, at step 2500, no (useful) saving time station would be available (there is still one saving station, but it is at step 0).

12 GROUP H—OPTIONS

Object:

These keywords give the additional options of the computation. They can be grouped as:

- options associated with time-steps;
- options associated with dampings;
- options for finite elements;
- output options;
- returning to default options;
- options for an advection-diffusion computation;
- options for ALE computations in structures;
- options for debugging purposes;
- options to declare FANTOME certain elements;
- options to define classes of elements within a list of elements;
- options related to the treatment of shocks and impacts;
- options for FSA (fluid-structure interactions of the ALE type);
- options for node-centered finite volumes;
- options for multiphase, multicomponent fluid flows;
- options for the automatic rezoning in ALE computations;
- options for cell-centred finite volumes;
- options for "LIAISONS"/LINKS (connections);
- options for graphical rendering;
- options for mesh-adaptive computations;
- options for strain rate filtering;
- options for parallel computing;
- computational options of the elastic gradient damage model.

Syntax:

```
"OPTION"
```

`OPTION`

Announces that one or several options will be specified.

Comments:

The keyword "OPTION" may appear more than once in the EUROPLEXUS data.

The following sub-instructions may appear in any order.

The different options are described on the following pages.

12.1 OPTIONS RELATED TO THE TIME-STEP

Object:

Additional options are given to provide optimum time stepping.

Syntax:

```
 < |[ "PAS" |[ "UTILISATEUR" ; "AUTOMATIQUE" ]| ;
      "PARTITION" $["PLIN" ; "PNOL"]$ <PLOG> ]| >
 < "DTVAR"  dtvar      >
 < |[ "NOTEST" ; "TEST" ]| >
 < "STABILITE"           >    < "STEL" >
(< "NOCRITIC" < $ "UPTO" t ; "TRIG" $ > /LECTURE/ >)
 < "CSTAB"      cstab    >
 < "CSVF"       csvf     >
 < "PASMINI"    pasmi    >
 < "DTFORCE"    dtfor    >
 < |[ "STEP" "IO" ; "STEP" "IOT" ; "STEP" "LIBR" ]| >
 < "TION"       tionor   >
 < "DTML"                >
 < "DTBE"       kdtbe    >
 < "TMCO"                >
 < "DIVG"       divg     >
 < "DTDR"       dtdrop   >
 < "CMDF"  <"NPAS"  npas > <  "CPUT"  cput > >
```

PAS UTILISATEUR

The time step is prescribed by the user (see also keyword CALCUL). Note that this option cannot be chosen in the case of impacts (the time increment may be limited by the program in case of an impact).

PAS AUTOMATIQUE

The time-step is determined by the program (see also keyword CALCUL). This is the default, i.e. if neither PAS UTIL nor PAR are specified the time step is automatically computed by the code.

PARTITION

The computation step is partitioned automatically in space (and the step also varies with time), according to the stability step of each element (see also keyword CALCUL). PARTITION is not available for MPI calculations.

PLIN

In the space partitioning procedure, dofs subjected to any links are treated according to the lowest level among the ones that are linked together. This works only with the `LINK` directive, while conditions imposed by the `LIAI` directive are not treated. The option has no effect in cases without space partitioning.

`PNOL`

In the space partitioning procedure, dofs subjected to any liaisons or any links (but only of the permanent type) are put in the lowest partition level. This is the default, so this option should not be used, except for changing back from a previously issued `OPTI PLIN`. The option has no effect in cases without space partitioning.

`PLOG`

In case of space partitioning, a special log file is written `<basename>.plog`. This file contains an output line for each sub-cycle, in contrast to the normal log file, which contains one line for each macro step. The extra information may be quite long but is sometimes useful for debugging. By default no such log file is written.

`dtvar`

Maximum growth factor of the time step among two subsequent steps in `PAS AUTO`. Default is 2.0.

`NOTEST`

The energy check and related information is not printed at each step, but only when general printouts are required (see `ECRI`).

`TEST`

The energy check and related information is printed at each step. This is the default.

`STABILITE`

The energy check and related informations is printed only if EUROPLEXUS reduces the time step.

`STEL`

At each step for which a printout is produced, the stability steps Δt_{stab} for all elements are printed out. The *stability step* is the *critical step* Δt_{crit} estimated by the code (roughly the element length L divided by the speed of sound c in the element material) multiplied by the *safety coefficient* ϕ (`CSTA`, by default 0.8): $\Delta t_{\mathrm{stab}} = \phi \Delta t_{\mathrm{crit}} \approx \phi \frac{L}{c}$. For a Cell-Centred Finite Volume, the value obtained is further multiplied by an additional safety coefficient C_s^{CCVF} (`CSVF`). By default, $C_s^{\mathrm{CCVF}} = 1.0$.

`NOCRITIC`

The elements defined in the following `/LECTURE/` will not be considered in the calculation of the critical time step by EUROPLEXUS. In practice, they will be assigned a very large critical step. Optionally (see next keywords) this behaviour can be imposed only until a certain time or event. Note that the `NOCR` keyword (with its optional sub-keywords) can be repeated as many times as needed to set different criticality limits for the various elements in the mesh, if needed. Each element retains the last criticality limit that has been set for it (if any).

`UPTO t`

The above mentioned elements are not considered in the calculation of the critical step only until time `t` is reached. Thereafter, they are treated just like any other elements.

`TRIG`

The above mentioned elements are not considered in the calculation of the critical step only until a trigger is activated. The trigger refers to the `TRIG` keyword which activates mesh refinement in some adaptivity models, see `OPTI ADAP TRIG` on Page H.180. Thereafter, they are treated just like any other elements.

`cstab`

Safety coefficient assumed over the estimated stability (i.e., critical) time step for each element. Default value is 0.8. It is only effective for `PAS AUTO` or `PART`. See also the comments below.

`CSVF csvf`

Additional safety stability coefficient C_s^{CCVF} for CCVF elements. For such elements it is: $\Delta t_{\mathrm{stab}} = \phi C_s^{\mathrm{CCVF}} \Delta t_{\mathrm{crit}}$. By default, it is $C_s^{\mathrm{CCVF}} = 1.0$. In an FSI simulation, specifying $C_s^{\mathrm{CCVF}} < 1.0$ allows to use a stricter stability for the CCFV (as required typically in 3D) without at the same time penalizing the structure.

`PASMINI`

The calculation will stop if the time increment becomes less than `dtmax` $\times$ `pasmi`.

`DTFORCE`

The stability step of the more stringent elements is forced to assume tha value `dtfor` by increasing their mass. This option is dangerous: see the comments below.

`STEP IO`

During the computation, the time step will be adjusted to exactly fit chosen times for output events such as printouts (see `ECRI`), storage of data for post-processing (`FICH ALIC` but not `FICH TPLO` nor `FICH ALIC TEMP` nor `FICH TABL`!), or storage of data for restart (`FICH SAUV`). Note that `TPLOT`, `ALICE TEMPS` and `TABL` data storages are not included (use `STEP IOT` instead). This choice is justified by the fact that `TPLOT`, `ALICE TEMPS` and `TABL` storage times are usually much more numerous than (normal) `ALICE` storages, but include only a limited number of nodes and elements. Note that this option has only effect in `PAS AUTO` or `PART`, but obviously it has no effect in `PAS UTIL`.

`STEP IOT`

Same as `STEP IO`, but now output events considered for time step adjustment include also `TPLOT`, `ALICE TEMPS` and `TABL` storages. Note that this option has only effect in `PAS AUTO` or `PART`, but obviously it has no effect in `PAS UTIL`.

`STEP LIBR`

During the computation, the step will be varied only according to stability limits. No adjusting to output times for printing, etc., will be performed. In this case, if the user chooses a given printout or storage time, the program will perform the action at the first step in which the time is equal or greater that the specified value. In general, the error on time is small since it is of the order of one time increment. This is the default (as opposed to `STEP IO`).

`tionor`

Important: to be effective, this option must be specified **before** the `ECRI` directive. This quantity represents the value of time units used for the normalization of selected times and time frequencies for printing and storage (in particular see the `ECRI` directive and its sub-directives for the different types of output files). It is only relevant to the `STEP IO` or `STEP IOT` options described above. The default value is 1 picosecond (1.D-12 s). Since at least 18 digits are available in an INTEGER(8), the final time of a calculation can be up to 1.D6 s with the standard value of `tionor`. Be aware that the normalization process may only take place if time values are less than `1.E18*tionor`. An error is produced otherwise. This precision should be largely sufficient in practical cases. In fact, this allows to specify a precision of e.g. 1.E-6 times the typical time step, for a computation with up to 1.E12 steps.

`DTML`

This option chooses a different rule from the standard one to estimate the critical time step of JRC's FLxx fluid elements. The standard rule for FLxx, originating from EURDYN, was quite complex and was documented in the report "Implementation of Compressible Fluid Models in PLEXIS-3C", Technical Note No. I.93.86. This rule was found to be inaccurate in some cases. The new rule activated with the present option uses the minimum intra-nodal distance as the characteristic length and the sound speed plus the maximum nodal $(w - v)$ value (mesh velocity minus fluid velocity) as the characteristic speed. This is in accordance with the rule used in CEA's fluid elements. The `DTML` option can also be invoked to use the minimum intra-nodal distance for calculation of the stability of C27 elements in 3D (by default these elements use an estimation of the element's stretch and shear to compute the element's characteristic length).

`DTBE`

This option chooses a different rule from the standard one to estimate the critical time step for the `POUT` element. Three different values can be chosen: kdtbe = 0 indicates the default version (considering both axial and flexural critical time steps, see also option `MDIA` in GBC_0050); kdtbe = 1 uses an optimized time step (formula for `ED01` elements); kdtbe = 2 considers only the length of the element and disregards the cross section. The default time step used for the `POUT` element seems to be very conservative. Larger time steps result using the formula for `ED01` elements, which is as follows. If the element length L is larger than $\sqrt{(3)}h$, where h is the element thickness, then the normal expression is used: $\Delta t = L/c$, where c is the sound speed. Otherwise, the element length is corrected: $L_{corr} = L^2/\sqrt{3}h$ and then $\Delta t = L_{corr}/c$.

`TMCO`

The `TMCO` option chooses a different rule from the standard one proposed in T.J.R. Hughes, M. Cohen, & M. Haroun (Reduced and selective integration techniques in the finite element analysis of plates. Nuclear Engineering and Design, 1978, 46(1), 203-222.) for the estimation of the rotational terms in the lumped mass matrix for shell elements.

When the option is chosen, the terms in $e^2/12$ corresponding to the rotational inertia for a plate is neglected. This option is only available for the following shell elements:

- the 4-node shell elements: `QPPS`(35), `Q4G4`(90), `Q4GR`(111), `Q4GS`(112) and `Q4MC`(138),
- the 3-node shell elements: `TR3D`(12), `T3GS`(51), `DST3`(83), `DKT3`(84) and `TM3C`(139)

`divg`

This options give the possibility to define a value that the energy balance can not exceed. The default is 0.

`dtdrop`

Define the coefficient `dtdrop`. A warning message is printed on the listing each time the stability is imposed by a finite element and the ratio $\Delta t_2/\Delta t_1$ is smaller than `dtdrop`. The default is 0.3. Some special materials (such as e.g. the `JWLS` material) used to represent very violent explosions and wave propagations may abruptly reduce the time step in order to preserve stability. In such cases, it may be useful to re-define `dtdrop` to values smaller than the default (e.g., 0.005) in order to avoid too many warning messages on the listing.

`npas`

Define the number of time steps after which the existence of the command file "command.epx" is checked.

`cput`

Define the CPU time after which the existence of the command file "command.epx" is checked. More information about the command file can be found in 17.

Comments:

Options by default : `PAS AUTOMATIQUE TEST STEP LIBR`.

The calculation stops if the time step becomes too small. The limit value is proportional to dtmax (directive `CALCUL`). By default, `pasmi=0.001`, i.e. the calculation will stop whenever the time step becomes less than `0.001` $\times$ `dtmax`. This option is only active when the old syntax of the `CALCUL` directive is used. With the new syntax, `pasmin` is redundant because `DTMIN` directly gives the minimum step (see I.20).

The energy check deals with the energy balance. The value of the stability time step is also printed.

The option `PARTITION` is especially useful when the mesh contains a few very small elements among a large number of bigger ones. In this case, the small elements are paid more attention, without carrying out useless computations on the big ones. This option could be inefficient if used when all elements have nearly the same size, or if there are only a few large elements in the mesh.

Like all explicit programs, EUROPLEXUS requires a sufficiently small time increment in order to ensure the stability of calculations. By default, EUROPLEXUS uses the CFL time step (Courant-Friedrichs-Lévy condition), multiplied by a safety coefficient `CSTAB` = 0.8. However, for very fast phenomena this condition may be insufficient. It is then possible to ensure stability by assuming for `CSTAB` a value smaller than 0.8.

The option `DTFORCE` affects only Lagrangian elements. In an ALE calculation, only the Lagrangian elements (if any) will be considered, and the others will be ignored. Since the mass of elements is modified, it is necessary yo check that such modifications do not affect too much the physics of the problem.

To this end, some indications are available on the listing:

- The mass by zones before and after modification;
- The list of the 20 most constraining elements, with the old and the new time step;
- A message `ATTENTION` also appears if the mass of a zone increases more than 10 %.

12.2 OPTIONS RELATED TO THE DAMPINGS

Object:

To enter the dampings.

Syntax :

```
 |[   "QUASI" "STATIQUE"  fsys  beta <"FROM" t1> <"UPTO" t2> ;
      "AMORT" "LINE"  betal                                 ;
      "AMORT" "AXIA"  betal                                 ;
      "AMORT" "QUAD"  a2                                    ;
    $[ "HOURG" <"ASSE"> ; "VISC"  hvis ; "RIGI" hrig ; "NOHOURG" ]$ ]|
```

`QUASI STATIQUE`

Quasi static computation. A linear damping with a given cut-off frequency is applied.

`fsys`

Frequency f of the first system mode to be cut off.

`beta`

Reduced damping coefficient β.

`t1`

Initial time t_1 at wich the quasi-static option starts to operate. By default, this coincides with the initial time of the calculation. See comments below for the use of t_1 and t_2 to define a closed interval or two open intervals.

`t2`

Final time t_2 until wich the quasi-static option operates. By default, this coincides with the final time of the calculation. See comments below for the use of t_1 and t_2 to define a closed interval or two open intervals.

`AMORT LINE`

Computation with linear damping of high frequencies (artificial viscosity). This damping is advisable in FE calculations (CEA model: CAR1, CUBE etc.) involving a **liquid**, but it can also safely be added in calculations involving gases. The value to be used is betwen 0.05 and 0.20 in general. Note that this damping has no effect on calculations with cell-centred finite volumes (VFCC). In fact, the scheme with limiters used in that case is built in such a way that it does not need any damping. Note also that linear damping in FE models for fluids from JRC (FLxx elements) is activated by the keyword `CL` of the `FLUT` material, see Page C.520.

`AMORT AXIA`

Computation with linear damping of high frequencies, but only for the elements on the symmetry axis (for 2D axisymmetric problems only).

`betal`

Reduced damping coefficient β_l for linear damping (of type `LINE` or `AXIA`).

`AMORT QUAD`

Computation with quadratic damping (artificial viscosity). This damping is advisable in FE calculations (CEA model: CAR1, CUBE etc.) involving a **gas**, but it can also safely be added in FE calculations involving liquids. The value to be used is betwen 2.0 and 4.0 in general. Note that this damping has no effect on calculations with cell-centred finite volumes (VFCC). In fact, the scheme with limiters used in that case is built in such a way that it does not need any damping. Note also that quadratic damping in FE models for fluids from JRC (FLxx elements) is activated by the keyword `CQ` of the `FLUT` material, see Page C.520.

`a2`

Coefficient a_2 for the quadratic damping (shock waves).

`HOUR ASSE`

Anti-hourglass damping for assumed-strain elements (IHOURG=3).

`VISC`

Anti-hourglass damping on viscous terms (IHOURG=1).

`hvis`

Reduced damping for anti-hourglass $h_{\rm vis}$ ($h_{\rm vis} = 0.5$ is suggested).

`RIGI`

Anti-hourglass damping based on artificial stiffness (IHOURG=2).

`hrig`

Reduced damping for anti-hourglass.

`NOHOURG`

Allows to eliminate the anti-hourglass damping.

Comments :

In the case of the `QUASI STATIQUE` option, $\beta = 1$ corresponds to the critical damping for the frequency f. In fact, one adds an external force F_i^{QS} proportional to the mass M_i and to the particle velocity v_i for each degree of freedom i:

$$F_i^{QS} = -4\pi\beta f M_i v_i = -2\beta\omega M_i v_i$$

where $\omega = 2\pi f$.

In practice, only the product βf is relevant.

Linear damping of high frequencies is only possible for elements of type CAR1, CAR4, TRIA, TUBE, FUN2 and FUN3. This damping allows to eliminate the high-frequency oscillations related to the finite element discretization. In order to obtain the critical damping of a free-free oscillation for each element, take $\beta_l = 1$.

When t_1 is less than t_2 (be these values specified or not) the quasi-static damping acts in the closed time interval $t_1 \leq t \leq t_2$, i.e. in the central part of the transient calculation. However, it is also possible to specify t_1 greater than t_2: in this case the critical damping acts in the open time interval $t \leq t_2$ (i.e. at the beginning of the calculation) and in the open time interval $t_1 \leq t$ (i.e. at the end of the calculation). This second form of the directive may be useful when one wants to model a structure initially subjected only to gravity loads (with quasi static option so as to rapidly reach the initial static deformed configuration), followed by a dynamic event such as an explosion (without quasi static option), and finally by a stabilization phase (again with quasi static option) so as to rapidly compute the final static deformation. Thus this form of the directive allows to perform the complete analysis of the three phases in just one run of the code, instead of running three separate calculations (each one starting from the results of the previous one) via e.g. the directive `INIT ALIC` (see page E.140).

For the quadratic damping, it is suggested to take $a_2 = 4$.

Quadratic damping is only possible for elements of types CAR1, CAR4, CUBE, PRIS, TRIA and TUBE.

The present linear and quadratic damping models are distinct from the selective damping model (`AMOR`) described on page C.106, which applies to selected dofs and nodes of a zone specified by the user.

The anti-hourglass damping is currently available only for the elements CAR1 et CUBE. By default, an anti-hourglass damping with $h_{\text{vis}} = 0.5$ is affected to a calculation. If the user wants to do a calculation without anti-hourglass damping, he must use the option `NOHOURG`.

Warnings :

In case of restart, the `QUASI STATIQUE` damping remains active; to eliminate it, one must specify $\beta = 0$.

Linear damping should be used with care, since it may considerably perturbate the solution. It is advisable not to exceed the value $\beta_l = 0.05$. In case of axisymmetric linear damping, since the concerned elements are usually a few and with a small mass, on may go up to $\beta_l = 0.5$.

12.3 OPTIONS FOR FINITE ELEMENTS AND GEOMETRIC ISSUES

Object:

To introduce optional parameters related to finite elements and geometric issues.

Syntax:

```
<   "DECENT"  |[ "TOTAL" ; "CALC"       ;
                 "IMPOSE" "DCEN" de "DCMA" dm  ]| >
<   "ROLIM"  rholim                             >
<   "JAUMAN"                                    >
<   "CODG" <"REFE" zbar> <SMAL>                 >
<   "EDSS"                                      >
<   "LFUN"                                      >
<   "P2X2"                                      >
<   $ "NF34" ; "OF34" $                         >
<   "MOMT" kmtran                               >
<   "TOLC" tolc                                 >
<   "HGQ4" hgq4ro                               >
<   "CLMT" <"FARF" farf> <"ABSI" absi>          >
<   "LMST"                                      >
<   "NTSM"                                      >
<   "RIGB" <"VERS" vers> <"TOLE" tole>
                         <"NITM" nitm>          >
                         <"JTOL" jtol>          >
```

`DECENT CALC`

A.L.E. only. Upwinding computed by EUROPLEXUS according to the volume covered in one time step with respect to the total volume.

`DECENT TOTAL`

A.L.E. only. Total upwinding for the mass.

`DECENT IMPOSE`

A.L.E. only. Prescribed upwinding.

`de`

Upwinding concerning transport terms.

`dm`

Upwinding concerning mass fluxes.

`ROLIM rholim`

ALE/Eulerian only: if the donor element has a density less than `rholim`, the mass and energy fluxes are not considered for this element.

`JAUMAN`

Large strain computation with JAUMAN's stress tensor.

`CODG`

Introduces options for calculations with degenerated shell elements (CQDx).

`zbar`

Parameter defining the position of the reference surface for degenerated shell elements: -1 indicates the lower element surface, 0 the mean surface, +1 the upper surface. By default, zbar = 0.

`SMAL`

Specifies that a small strain model of membrane deformation has to be used for degenerated shell elements, so the thickness of these elements stays constant. By default, a large membrane deformation is assumed and the element thickness is varied accordingly. This option is only useful to compare a solution with an old run done by JRC's SHELL3D.

`EDSS`

Specifies that certain elements (ED01, FUN2, FUN3) will adopt a small strain, large displacements, large rotations formulation instead of the large strain formulation that is used by default.

`LFUN`

Specifies that certain elements (FUN2, FUN3) will adopt a fully linear, small strain model: element cross section stays constant and also length stays constant for the calculation of critical time step (which is therefore constant). This option should only be used for debugging purposes and for the study of time integration algorithms (to compare analytical and simplified numerical solutions).

`P2X2`

This option activates a spatial integration rule for pressure forces in CEA's fluid elements (CUBE, PRIS, TETR) which is equivalent to a 2x2x2 Gauss rule, and is therefore exact also for distorted geometry (e.g. non-planar faces). The standard rule uses a single-point scheme which is under-integrating the function in the presence of distortions. The resulting inaccuracy of pressure force computation leads to the effect that fluid nodes internal to the fluid domain and completely surrounded by a fluid at uniform pressure are not in perfect equilibrium when the surrounding mesh is irregular. Spurious resultant pressure forces cause spurious velocities in the fluid which are non-physical. Although these velocities were usually found to remain relatively small with respect to physical ones in typical applications (explosions etc.), it is generally preferable to avoid them altogether by using the present option, although it is of course slightly more computationally expensive. The standard rule (single-point) is left as a default for compatibility with old input files and applications.

`NF34`

Use new (2007) implementation for FL34 JRC's tetrahedral 4-node fluid element. The new implementation is described in reference [235]. From April 2014 this is the default, so it should be rarely necessary to specify this option.

`OF34`

Use old (before 2007) implementation for FL34 JRC's tetrahedral 4-node fluid element.

`MOMT`

This option allows choosing the degree of precision for the spatial integration rule used in the computation of momentum transport forces in Eulerian or ALE calculations using JRC's FL3x fluid elements. The `kmtran` parameter may assume the values 0 (no momentum transport forces at all), 1 (corresponding to single-point integration), 2 (for 2x2x2 spatial integration) or 3 (3x3x3 spatial integration). For distorted geometries only the 3x3x3 rule is exact. The default rule (as used in EURDYN) is the single-point one which is of course the most economical, but unfortunately may lead to spurious mechanisms (appearance of spurious fluid velocities) in some cases, typically when the geometry of the elements is irregular or distorted (e.g., non-planar faces). The mechanisms may rapidly grow and in some cases they completely destroy the numerical computation. In all practical cases investigated so far it was found that a 2x2x2 rule (MOMT 2) is accurate enough and sufficient to prevent the appearance of mechanisms. The cost of this is of the order of 20% to 30% overhead compared with the default, (MOMT 1) option. The MOMT 3 option is exact, but may cause a 100% overhead in computer time. Finally, note that the MOMT 0 option is only to be used for debugging purposes, since computations without momentum transport forces are of course largely inaccurate.

`TOLC`

This option allows to change the tolerance `tolc` that is used to automatically search for node correspondence, see page C.92. The default behaviour (no OPTI TOLC) is that two nodes are considered to match if their initial positions differ, along each one of the global coordinate axes, by less than 1.E-4 times the "mean" size of the mesh. This mean size is defined as the sum of the sizes of the mesh along each one of the global axes, divided by the space dimension. If `tolc` is explicitly specified, it is retained as the maximum distance (in absolute terms, not relative to the mesh size) between two coincident nodes along the global axes. In this case therefore, the above mentioned mean mesh size is not computed: `tolc` is used directly. Note that, in order to be effective, this option must be specified *before* the directives that might use it, in particular before the LIAI FSA directive.

`hgq4ro`

Adjusting coefficient for the anti-hourglass rotation stiffness of the Q4GR shell element. The default value of hgq4ro is 0.018.

`CLMT`

This keyword introduces options for the treatment of momentum transport forces in fluid Finite Elements (JRC formulation, i.e. FLxx family of elements). It applies to the CL22, CL2S, CL3I, CL3Q and CL3S element types, associated with either a FLUT material (for far-field conditions) or an IMPE ABSI material (for absorbing boundary conditions).

`FARF farf`

Use `FARF` 1 to activate momentum transport forces in CLxx due to far-field conditions, or `FARF 0` to de-activate them. The default is 0, i.e. no momentum transport forces.

`ABSI absi`

Use `ABSI` 1 to activate momentum transport forces in CLxx due to absorbing (IMPE ABSI) conditions, or `ABSI 0` to de-activate them. The default is 0, i.e. no momentum transport forces.

`LMST`

The `LMST` option (for Large Membrane STrains) is used to activate the update of the thickness of some shell elements (from CEA) due to large membrane strains. The affected elements are Q4GS and T3GS. Note, however, that the thickness update is activated only if such elements possess a non-linear material (i.e. *other* than `LINE` or `GLRC`). By default, the thickness of such elements is not updated even if large membrane strains occur. Note also that the thickness of other shell elements from CEA (namely Q4GR, QPPS, DST3, DKT3, T3MC) is also *never* updated and the present option will have no effect on such shell elements.

`NTSM`

The `NTSM` option deactivates the smoothing of the pressures of tetrahedrals. Tetrahedral elements show a pressure locking in particular for non-linear materials. A very strong locking can be identified in impact calculations. A smoothing of the pressures over the neighbour elements solves that problem. This option is activated by default. The keyword `NTSM` deactivates that option.

`RIGB`

Introduces options related to the formulation of rigid bodies as a whole (see the references at the end of this Page).

`VERS`

Optional specification of the rigid model's version. By choosing version 1, the old formulation is used, in which the rotational equations of motion are expressed in the local reference frame of the rigid body, which is aligned along the principal axes of inertia of the body. The (principal) moments of inertia are constant (do not change) in this reference and need not be updated. The corresponding model is described in reference 1. below. By choosing version 2 (which is the default), the alternative formulation described in reference 2. below is chosen. All equations of motion (both translational and rotational) are expressed in the global reference frame. The calculation of the pricipal directions of inertia is not necessary but it is still performed at step 0 for the User's convenience.

`TOLE`

Convergence tolerance for the procedure of iterative determination of the new omega_dot (angular acceleration) and omega (angular velocity). By default it is 1.E-6.

`NITM`

MAximum number of iterations for the procedure of iterative determination of the new omega_dot (angular acceleration) and omega (angular velocity). By default it is 20.

`JTOL`

A principal moment J is considered vanishing if $J/J_{\max} < j_{\mathrm{tol}}$, where $J_{\max}$ is the maximum of principal moments. The code adopts suitable corrections in order to avoid numerical problems with vanishing moments. By default, it is $j_{\mathrm{tol}} = 1.0 \times 10^{-3}$.

Comments:

A large strain calculation with the JAUMAN tensor is only possible at the moment with elements "CAR1", "CAR4" and "TRIA".

The upwinding is only effective for a computation with a non-Lagrangian formulation (keyword "ALE" or "EULER" in the type of problem to deal with , see page A.30).

By default, EUROPLEXUS uses the total upwinding (`dm` = 1 and `de` = 0).

References

More information on the formulation of the rigid body model (JRC formulation) may be found in the following references:

1. Casadei, F., Valsamos, G., Larcher, M.: *Formulation and implementation of a new model of rigid bodies in EUROPLEXUS.*, JRC Techical Report JRC117293, 2019.

2. Casadei, F., Valsamos, G., Larcher, M.: *Further development of the new model of rigid bodies in EUROPLEXUS.*, JRC Techical Report JRC117294, 2019.

12.4 OPTIONS FOR FLYING DEBRIS

Object:

To introduce optional parameters related to the flying debris model, described on Page C.66.

Syntax:

```
< "DEBR" <"NTRA" ntra> <STTR> <MAC1 ; MACN> >
```

`DEBR`

Starts the specification of debris-related options.

`NTRA ntra`

Number of points `ntra` for flying debris trajectories. The points are equi-spaced in time betwee the initial time and the final time of the calculation given in the `CALC` directive. The actual number of points will be `ntra + 1`, since also the initial position (initial time) is stored. The default value of `ntra` is 100 points (i.e., 101, if one counts also the initial point).

`STTR`

Store the flying debris trajectories on the ALIC file. This will allow visualizing the trajectories when reading back the results (`RESU`). If this option is not set, the trajectories are not stored in the `ALIC` file (because these data may be huge, if there are many particles), and in this case the trajectories can only be visualized during the main calculation (**not** when reading back the results).

`MAC1`

Associate only one marker (for the evaluation of macro debris risk) with each element. This is the default, so the keyword is only useful to erase the effect of the `MACN` keyword presented next.

`MACN`

Associate more than one marker (for the evaluation of macro debris risk) with each element. The actual number depends on the element type and on the `PLEV` specified in the `DEBR FILL` directive shown on Page C.66. This option is only useful for debugging purposes. It may be used to reproduce old solutions obtained with EPX versions until 2016, which adopted a different strategy for the markers.

12.5 OUTPUT OPTIONS

Object:

These options enable the output format to be chosen.

Syntax:

```
< $[ "NOPR" ;
     "PRIN" < "PMES" > < "PCAS" > < "PCOM" >
            < "PGRI" > < "PLOA" > < "PLIN" >
            < "PRES" > < "PLAW" > < "PMED" >
            < "PE2M" > < "PINI" > < "PDOM" >
            < "PKFI" >                   ]$ >
<   "DPMA"               >
< $[ "NWAL" ; "WALI" ]$ >
< $[ "NWSA" ; "WSAU" ]$ >
< $[ "NWTP" ; "WTPL" ]$ >
< $[ "NWXP" ; "WXPL" ]$ >
< $[ "NWAT" ; "WATP" ]$ >
< $[ "NWK2" ; "WK2O" ]$ >
< $[ "NWST" ; "WSTB" ]$ >
< $[ "NOEC" ; "ECHO" ]$ >
<   "LOG" nlog           >
<   "K2FB" k2fibe        >
< $[ "K2CH" ; "K2GP" ]$ >
<   "K2MS" |[ "MANU" ; "READ" ; "SAUV" ]| >
<   "DYMS" nobj*("OBJE" /LECT/) >
<   "PRGR" >
```

NOPR/PRIN

This option allows to suppress or re-activate a part of the printouts of the following directives.

If one of the keywords PRIN/NOPR is followed by one or more parameters, only the corresponding parts of the listing are activated (or deactivated)

"PMESH" : mesh (nodal coordinates and elements topology)
"PCAST" : detail of the CASTEM objects
"PKFIL" : detail of the k-file mesh
"PCOMP" : geometrical complements
"PGRID" : parameters of the ALE rezoning
"PLOAD" : details of the charges
"PLINK" : details of the liaisons/links
"PRESU" : details of the results files
"PLAW" : details of the material laws
"PMED" : detail of the MED objects
"PE2M" : table of MED element number associated to each EPX element
"PINI" : initial conditions for CCFV "PDOM" : Recursive Orthogonal Bisection (ROB) automatic partitioning

See also the comments below.

`"DPMA"`

Prints nodal and element masses with each general printout. This can be useful to check masses in problems where the mass varies, such as ALE calculations.

`NWAL`

No printout on the listing of information about each storage of data for ALICE (see "FICH ALIC").

`WALI`

A line of information containing the time, step number, etc. will be printed on the output listing at each storage of data on the ALICE file (see "FICH ALIC"). This is the default option.

`NWSA`

No printout on the listing of information about each storage of data for restart (see "SAUV").

`WSAU`

A line of information containing the time, step number, etc. will be printed on the output listing at each storage of data on the restart file (see "SAUV"). This is the default option.

`NWTP`

No printout on the listing of information about each storage of data for TPLOT (see "FICH TPLO"). This is the default option, since usually many storages are requested for TPLOT.

`WTPL`

A line of information containing the time, step number, etc. will be printed on the output listing at each storage of data on the TPLOT file (see "FICH TPLO").

`NWXP`

No printout on the listing of information about each storage of data for XPLOT (see "FICH XPLO").

`WXPL`

A line of information containing the time, step number, etc. will be printed on the output listing at each storage of data on the XPLOT file (see "FICH XPLO"). This is the default option.

`NWAT`

No printout on the listing of information about each storage of data for ALICE TEMPS (see "FICH ALIC TEMPS"). This is the default option, since usually many storages are requested for ALICE TEMPS.

`WATP`

A line of information containing the time, step number, etc. will be printed on the output listing at each storage of data on the ALICE TEMPS file (see "FICH ALIC TEMPS").

`NWK2`

No printout on the listing of information about each storage of data for K2000 (see "FICH K2000").

`WK20`

A line of information containing the time, step number, etc. will be printed on the output listing at each storage of data on the K2000 file (see "FICH K2000"). This is the default option.

`NWST`

No printout on the listing of information about each storage of data for SUPERTAB (see "FICH SPTAB").

`WSTB`

A line of information containing the time, step number, etc. will be printed on the output listing at each storage of data on the SUPERTAB file (see "FICH SPTAB"). This is the default option.

`NOEC/ECHO`

This option allows to suppress or re-activate input data echo in the EUROPLEXUS window.

`LOG`

Causes a one-line information to be written to standard error file each 'nlog' time steps. The information includes current step number, time, CPU time, critical step, critical element, energy check and mass check. This is useful e.g. to monitor the execution of very long and CPU-intensive runs. Usually, the standard error information will be redirected to a file, e.g. with the Unix command '2>file'. The colums of the log files (S standard calculation, P calculation using partitioning) are described in the table below.

	Description	S	P
STEP	Time step number (main step for Partitioning)	X	X
TIME	Time	X	X
CPU(S)	CPU time used	X	X
DTCRIT	Critical time step used	X	
ELCR	Element with the smallest time step	X	
DELMIN	Time step of the smallest substep		X
MINS	Minimum level factor		X
DE/E	Energy balance per element	X	X
DM/M(NOD)	Mass balance per node	X	X
DM/M(ELE)	Mass balance per element	X	X
DTMX	Maximum time step	X	
EL	Element of the maximum time step	X	
DELMAX	Time step of the main step		X
MAXS	Maximum level factor		X
VITMAX	Maximum velocity	X	X
NODE	Node of the maximum velocity	X	X
ISUBTO	Total number of substeps		X
MAXSTO	Total number of substeps		X
ELSTEP	Number of callings of element routines	X	X

`K2FB`

Indicates the index of the Gauss Point, along each fiber, for which variables are stored for subsequent K2000 postprocessing. For example, if there are 5 GPs along fibers in the shell elements used in a calculation, then `k2fibe` = 1 indicates the GPs closest to one face of the structure, `k2fibe` = 5 indicates the GPs closest to the opposite face of the structure, `k2fibe` = 3 indicates the GPs on the midsurface of the strucure, and so on. Note that this parameter has only effect for shell elements of types ED01, ED41, COQI and CQDx. The default value is `k2fibe` = 1.

`K2CH`

With this option, the output chamelems for K2000 will be defined for each element at the element nodes, rather than at the element barycenter (default) or at the Gauss points (`K2GP` option). Note, however, that the computation of values is crude: an average on all GPs is computed, and this value is affected to all nodes of the element (although the contributions to the same node from different elements may be different). The default (without the `K2CH` option) is to compute an average on all GPs and affect this value to the barycenter of the element.

`K2GP`

With this option, the output chamelems for K2000 will be defined for each element at the Gauss points, rather than at the element barycenter (default) or at the element nodes (`K2CH` option). The exact value is affected at each GPs of the element. In case of multilayer plates (CEA-plates: DKT3, Q4GS...) an average on the GPs in the thickness is computed, and each of these values is affected to the corresponding GP on the surface of the element. The default (without the `K2GP` option) is to compute an average on all GPs and affect this value to the barycenter of the element.

`K2MS`

With this option, the code will produce a file containing a series of GIBIANE instructions that, when processed by CASTEM2000, will produce the current mesh in CASTEM2000 format. This option is only useful when the mesh has been produced by a pre-processor different from CASTEM2000 (see also comments below).

`MANU`

The CASTEM2000 mesh generation commands will use the CASTEM2000 operator MANU. The name of the generated file is pxtok200.dgibi on the current directory

`READ`

The data for CASTEM2000 will be written on file pxtok200.inp on the current directory. These data are suitable to be read by CASTEM2000 via the READ operator (see also comments below).

`SAUV`

With this option, the code will produce a file containing the mesh in Cast3m's GIBI format, similar to what would be obtained by producing the mesh by Cast3m and saving it with Cast3m's `SAUV` command. The file produced has the fixed name PXTOK200.SAUV. The named element groups will be available but no relationships (dependencies) between the sub-objects will be created. To read back the file in Cast3m, use the commands: OPTI REST FORM 'PXTOK200.SAUV'; REST FORM;.

`DYMS`

With this option, the code will produce an input file for LS-DYNA. For each of the `nobj` objects defined by the `OBJE` keyword (which must be repeated exactly `nobj` times), the nodes and elements are written in this file. No material and load definitions are exported.

`PRGR`

Print named element and node groups on the listing in a format that can be directly included in a .EPX file (on 72 columns and using LECT ... PAS ... TERM syntax). This printout is made *in addition* to the normal printout of named groups on the listing. To find the group of lines search for `COMP GROU` and for `COMP NGRO` in the listing. Note that in order to be effective, this option **must** be set **before** the definition of the named groups.

Comments:

The presence of `OPTI NOPR` immediately after the dimensioning in the input file minimizes the listing file. On the contrary, `OPTI PRIN` maximizes the listing file. It is possible to activate or deactivate the various printouts selectively. For example:

```
OPTI  NOPR  PMESH  PCAST  PLINK
```

will deactivate the printouts relative to the mesh, the CASTEM objects and the liaisons/links. This allows to avoid repeating the commands `NOPR` and `PRIN` within the input file.

In case of re-reading the results file (file ALICE or ALICE TEMPS) the option `NOPR` is taken by default. To have complete printouts, it is sufficient to add `OPTI PRIN` after the keyword `TERM` of directive `DIME`.

The K2MS option can be very useful in the case that an input file for EUROPLEXUS uses a mesh defined in a format different from CASTEM2000, but the user wants to do the post-processing of the calculation by CASTEM2000 (or to manipulate the mesh in CASTEM2000 before running the actual EPX calculation). This option will produce a file containing data that can be used by CASTEM2000 to generate the desired mesh.

Typically, in such cases one would perform the following steps:

1. - Run the EUROPLEXUS input file with the non-CASTEM mesh, including option K2MS. The calculation can be stopped at step 0 (use VERI or CONV TEKT and then the stop interactive command). This will produce a file of data for CASTEM2000 in either file `pxtok200.dgibi` or file `pxtok200.inp` on the current directory.

2. - Run CASTEM2000 on the above mentioned file, to produce a mesh in CASTEM2000 format. See below for examples and details.

3. - Finally, run again EUROPLEXUS by specifying that the input geometrical data are from CASTEM2000 (CASTEM directive). Now, a CASTEM2000 post-processing file can be produced by EUROPLEXUS, because the input is indeed in CASTEM2000 format.

Note, however, that the CASTEM2000 mesh produced by this method will be somewhat special. The global mesh will be accessible as on bject named `MESH`. In addition, *but only if the* `K2MS MANU` *option is used*, then also all named element groups and all named node groups present in the original EPX input file will be available in the automatically generated CASTEM2000 mesh. However, no other *sub-objects* (in the sense of CASTEM2000 mesh generation building blocks) will be available.

When the K2MS MANU option is used, the file produced (`pxtok200.dgibi`) will contain a line for each node, of the form:

```
Pxxxxx = xcoor ycoor [zcoor];
```

where `xxxxx` is the node number (e.g., 00025 for node 25), `xcoor`, `ycoor` (and `zcoor` in 3D) are its coordinates.

For example:

```
P00332 =   1.000000000000D+01  1.000000000000D+01 ;
```

Then, for each element there will be a line of the form:

```
Eyyyyy = manu elem node1 node2 ... ;
```

where `yyyyy` is the element number, `elem` is the element type according to CASTEM2000 (e.g., QUA4 for 4-node quadrilaterals) and `node1`, `node2` etc. are its nodes. For example:

```
E00002=manu QUA4 P00004 P00006 P00005 P00003;
```

The global object will be called `MESH`. If you need to define sub-objects (in addition to the EPX named groups), use appropriate GIBIANE instructions.

A typical CASTEM2000 command file using `pxtok200.dgibi` is as follows:

```
(pxtok200.dgibi as produced by EUROPLEXUS) ...

mesh3 = mesh ELEM 'TRI3';
mesh4 = mesh ELEM 'QUA4';
...
opti sauv 'file';
sauv mesh;
```

In addition to file `pxtok200.dgibi`, another CASTEM2000 input file `pxrest.dgibi` is also automatically produced in this case. By running CASTEM2000 on `pxtok200.dgibi` first, the CASTEM2000 mesh is produced and saved in SAUV format. Then, by running CASTEM2000 on `pxrest.dgibi`, the CASTEM2000 mesh is read back (just for checking) from the SAUV file.

Unfortunately, it has been noted that CASTEM2000 changes the numbering of elements in a mesh generated in this way. The other method (using the READ option) can be used in cases this could cause trouble (which is typically the case if other input directives in the EUROPLEXUS input file use element numbers). Or, alternatively, try using the SORT operator instead of the SAUV operator to save the mesh, as detailed below.

When the K2MS READ option is used, the file produced (`pxtok200.inp`) contains a simple list of nodal coordinates and element topology (by zones). These data can be read by CASTEM2000 using the READ operator developed at JRC. No named element and node groups are translated into CASTEM2000 objects in this case.

To this end, use a command file of the form:

```
...
mesh = READ 'pxtok200.inp' MESH ELEM;
mesh3 = mesh ELEM 'TRI3';
mesh4 = mesh ELEM 'QUA4';
...
opti sauv 'file';
sauv mesh;
```

From the tests performed, it seems that CASTEM2000 maintained the element numbering in this case, but only up to version 9 of the SAUV operator included. For higher versions of the SAUV operator, numbering is generally changed.

In order to try to avoid renumbering, use the CASTEM operator SORT instead of SAUV to save the mesh. The SORT operator is more limited than SAUV (it may only save meshes, for example), but has the advantage that it apparently does not change mesh numbering, and its implementation is somewhat "frozen" in the code, unlike the SAUV operator which evolves constantly.

Recall that a mesh saved with SORT must be read in EUROPLEXUS by the GIBI directive, not by the CAST directive (see page A.30), and that SORT files are formatted by default.

The command file will be in this case of the form:

```
...
mesh = READ 'pxtok200.inp' MESH ELEM;
mesh3 = mesh ELEM 'TRI3';
mesh4 = mesh ELEM 'QUA4';
...
opti sort 'file';
sort mesh;
```

In EUROPLEXUS, the mesh will be read as follows:

```
...
GIBI 'file' mesh
...
```

12.6 RETURNING TO DEFAULT OPTIONS

Object:

To set the options relative to a standart computation back to their default values.

Syntax:

```
<    "ZERO"                              >
```

`ZERO`

Discards any previous options, returning to default values.

Comments:

All the options which have been defined previously are discarded, and the options by default are assumed again.

12.7 OPTIONS FOR AN ADVECTION-DIFFUSION COMPUTATION

Object:

To provide options for an advection-diffusion computation.

Syntax:

```
<   "ADDF" < "GRAV" gravi  > < "PSYS" psyst  >
           < "ELEM" ielref > < "SORD" nsord  >
           < "NGAU" ngau   > < "ITER" nitef  >
           < "ITEP" niter  > < "TOLER" titer >
           < "ADTI" adtime > < "ERRO" errix  >
           < "NIMA" nimax  >                     >
```

`gravi`

Acceleration of gravity (default=0.0).

`psyst`

System pressure, used to remove the singularity of the pressure field solution matrix (default=0.0).

`ielref`

Index of element in which the pressure is equal to psyst. (default=1)

`nsord`

When 2, 3 or 4, a Taylor-Galerkin method is used of order 2, 3 or 4, respectively (default=2). When nsord=5, a Least-square, space-time method is used. When nsord=6, a Least-square, Crank-Nicolson method is used.

`ngau`

Number of Gauss points in each direction for the integration of advection terms, can be 1 or 2 (default=1).

`nitef`

Number of iterations in the factorization of the consistent mass matrix during the advection phase, can be 1 to 9. (default=3)

`niter`

Maximum number of iterations for the solution of the system of equations for the pressure phase. If set to null, a direct solution is performed (default=0).

`titer`

Convergence tolerance for the iterative solution of pressure phase equations (default=0.01).

`adtime`

Time step fraction.

`errix`

Tolerance of implicit resolution. Is only used with Least-square method (see nsord above).

`nimax`

Maximum number of iterations for implicit resolution. Is only used with Least-square method (see nsord above).

12.8 OPTIONS FOR ALE CALCULATIONS IN STRUCTURES

Object:

To provide options for an ALE calculation in structures.

Syntax:

```
<   "ALES"  |[ "KINT" kintm ; "UPWM" upwm ; "UPWS" upws ]| >
```

`kintm`

Integration type for momentum transport: 0 means 1x1 (not available for the moment!), 1 means 2x2 (exact for plane problems), 2 means 3x3 (exact for axisymmetric problems). Default is 1.

`upwm`

Upwind parameter for momentum transport, can be chosen between 0 and 1 (default is 1.0).

`upws`

Upwind parameter for stress transport, can be chosen between 0 and 1 (default is 1.0).

12.9 OPTIONS FOR DEBUGGING

Object:

To provide options to help in debugging the program (for developers only).

Syntax:

```
< $[ "DUMP" ; "NODU" ]$              >
<   "DPAS" /LECTURE/                 >
<   "DPEL" /LECTURE/                 >
<   "DPEM"                           >
<   "VIDA" /LECTURE/                 >
<   "DPGR"                           >
<   "OLDS"                           >
<   "DPCA"                           >
<   "DPLE"                           >
<   "DPLM"                           >
<   "DPSD"                           >
<   "DPAR"                           >
<   "DPAX"                           >
```

"DUMP"

Prints dump of variables as long as they are initialised in the various routines before starting time integration. Of course, this option tends to produce extremely large output files and is only useful for very small test cases, for program development.

"NODU"

Turns off dumping option.

"DPAS"

The following list enumerates the integration time steps for which extensive information has to be dumped out. A maximum of 200 step indexes can be specified (this dimension is fixed).

"DPEL"

The following list enumerates the elements for which extensive information has to be dumped out. A maximum of 20 element indexes can be specified (this dimension is fixed).

"DPEM"

Prints (on the log file!) tables of available elements and materials in a format suitable for rapid inclusion in this user's manual.

"VIDA"

The following list indicates the indexes of the variables to be dumped (these can range from 1 to the total number of variables, see include MAPORGA), a value of 0 indicates that the contents of the commons has also to be dumped. Note that the commons are dumped at the moment when the directive 'OPTI VIDA LECT 0 TERM' is encountered in the input file, therefore it is suggested to place this directive just before the 'CALC' directive, which starts the time-marching calculation.

`DPGR`

Prints a table containing the list of all nodes with their grid motion attributes: L for Lagrangian, E for Eulerian, AA for ALE, manually rezoned, AM for ALE, automatically rezoned, AS for ALE, rezoned by "FSS ALE", AZ for ALE, rezoned by "MEAN". The dump is performed after complete processing of the input, immediately before starting the time loop. This allows to check possible changes applied by the program to conditions imposed by the user through the "GRILLE" directive. This option is only active for Eulerian or ALE calculations.

`"OLDS"`

Specifies that an old model for the VM23 material has to be used in place of the most recent model. The old model was slightly less accurate in elastoplastic cases and was used in the EURDYN programs. This option should only be used for debugging purposes, if a very precise comparison with an old EURDYN calculation is desired.

`"DPCA"`

Prints on the listing tables of element and material characteristics. For the elements, the NCEL variables are listed in tabular form, for the materials the MATALE and LGEP variables are listed.

`"DPLE"`

Prints on the listing a table of element characteristics in LaTeX input format. This may then e.g. be edited for inclusion in the present User's Manual.

`"DPLM"`

Prints on the listing a table of material characteristics in LaTeX input format. This may then e.g. be edited for inclusion in the present User's Manual.

`"DPSD"`

In multi-domain calculations, dumps out extra information on the listing file. Furthermore, for each sub-domain a separate log file is produced that reports, at every time station, a line collecting information relevant to the sub-domain. The name of such files is `<base_name>_xxx.log`, where `xxx` is the index of the sub-domain (e.g. 012 for the twelfth sub-domain), and `base_name` is the base name of the test case (without the extension `.epx`). By examining these log files, one is able to follow precisely the time integration history of each sub-domain. At most 10 such log files are produced, therefore if the number of sub-domains is larger only the first 10 sub-domains will be dumped out.

`"DPAR"`

In calculations with space partitioning, dumps out extra information on the listing. All cycles, in addition to macro steps, are printed out.

`"DPAX"`

Dump out on the listing a list of all nodes on the axis of revolution i.e. nodes with $x = 0$. This option has only effect in 2D axisymmetric calculations, and must be issued **before** the `GEOM` directive.

Comments:

Another useful debugging tool is the ”ECHO” ”VERI” directive (see page A.20) that causes, among other things, the memory allocated to each variable to be printed out.

Concerning the `"DPSD"` option, note that the per-domain log files are automatically opened under the Windows platform. On non-windows platforms (e.g. Unix), it may be necessary to explicitly open these files by including in the input file appropriate `OPNF` directives (see page A.28). Here is an example:

```
(on non-Windows platform)

OPNF FORMAT 51 '/disk1/fauvin/SD_001.LOG'
OPNF FORMAT 52 '/disk1/fauvin/SD_002.LOG'
. . .
OPTI DPSD
. . .
STRUCTURE 2
 DOMA LECT ZON1 TERM
 DOMA LECT ZON2 TERM
. . .
```

In this example there are 2 sub-domains. Note that the unit numbers to be used are 51, 52, etc. up to 60 (max. 10 sub-domains). The names associated with the files are arbitrary, and the files are formatted. On some platforms, full-path names only are accepted as in the above example.

12.10 PHANTOM OPTION (Element erosion by time)

Object:

Elements are eroded when the time exceeds a given value.

Syntax:

```
"FANTOME"    t_fant   /LECTURE/
```

`t_fan`

Time starting from which the elements become eroded.

`/LECTURE/`

List of the concerned elements.

Comments:

This option may appear at most once. However, it is possible to declare as many sequences t_fant, /LECTURE/ as needed.

In order to use this option, do not forget to specify the `EROS` keyword in the problem type, see GBA_0030. The value of `ldam` after `EROS` must be also given, but it has no effect on the present option.

12.11 CLASS (For a post-treatment with the directive REGION)

Object:

This directive allows to create classes of elements within a list of elements. Each element of the list of elements may belong to one and only one class.

Syntax:

```
"CLASSE"    /LECTURE/
            nb_classes*(/LECTURE/)
```

`/LECTURE/`

List of elements.

`nb_classes`

Number of classes.

`/LECTURE/`

List of elements of each of the classes.

Comments:

This option may appear at most once.

This option must be associated with the directive REGION defined on the list of elements to obtain informations on the classes (see G.100).

12.12 SHOCK AND IMPACT OPTIONS

Object:

This option alows to define the energy restitution coefficients for the shocks and the impacts.

Syntax:

```
"CHOC"      coechoc
```

`coechoc`

Energy restitution coefficient for shocks and impacts.

Comments:

The restitution coefficient is between 0 (plastic shock) and 1 (perfectly elastic shock).

The default value (when the present option is not activated) is 0.5.

12.13 OPTIONS FOR FSA/FSR

Object:

To provide options for fluid-structure interactions of the ALE type for an either deformable (FSA) or rigid (FSR) structure.

Syntax:

```
< "FSA" "ALFO" alf0 >
< $[ "NFSC" ; "FSCR" < "INCL" /LEC1/ > < "EXCL" /LEC2/ > ]$  >
< "FSR" "MFSR" >
```

`alf0`

Maximum angle, in degrees, between two element faces for which a unique normal is computed. If the actual angle exceeds this value, then two distinct normals are generated. By default, alf0 = 60 degrees.

`NFSC`

Do NOT correct geometrically computed normals for the FSA and FSR fluid-structure interaction conditions. This is the default.

`FSCR`

After computing geometrically the normals for the FSA and FSR fluid-structure interaction conditions, apply a correction based on the direction of fictitious internal forces resulting from a uniform pressure field p =1. This correction can be useful e.g. in 3D cases when the element faces are warped (non-planar), or when the integration of the element's internal forces is done with an integration rule that does not exactly match the estimation of the normal to the surface computed by purely geometrical considerations from the surface data.

`INCL /LEC1/`

An optional list of nodes to which the `FSCR` option is applied. By default, the option is applied to all `FSA` and `FSR` nodes.

`EXCL /LEC2/`

An optional list of nodes to which the `FSCR` option is **not** applied. By default, the option is applied to all `FSA` and `FSR` nodes.

`MFSR`

Allow a manually rezoned (i.e., moving) node to be declared FSR at the same time. These two conditions are normally incompatible and therefore an error message is normally issued and the code stops. However, there are cases when this is not an error (but only the user can judge on this, it cannot be done automatically). An example is a node on a rigid plane which at the same time must be moved by some manual rezoning to avoid mesh entanglement. The node can be at the same time manually rezoned (along the plane) and FSR because the link coefficients stay constant even though the node moves. The option deactivates the error message: only one warning message is issued, for the first node concerned. Note that obviously, if this option is specified, it must be inserted in the input file *before* the `LIAI FSR` or the `LINK FSR` directive.

Remarks

In some special cases it may be useful to exclude some `FSA` or `FSR` nodes from the `FSCR` correction. For example, in the transition zone of a pipeline mesh between a 3D representation and a 1D representation by means of the `TUYM` (deformable structure) or `TUBM` (rigid structure) junction: all fluid nodes in the external circumference of the 3D pipe mesh shall be declared `FSA` or `FSR`, but we want to make sure that no `FSCR` correction is applied to them (while it may be desirable for the other nodes). So we may explicitly exclude them by means of the `EXCL /LEC2/` directive.

12.14 OPTIONS FOR NODE-CENTERED FINITE VOLUMES

Object:

To provide options for node-centered Finite Volumes (multicomponent fluid flows).

Syntax:

```
<  MC <ORDR ordr>
      <NUFL $[ ROE ; VANL ; STWA ]$ >
      <WBC>
      <SYNC sync>
>
```

`ORDR`

Introduces the order `ordr` of the numerical integration scheme. May be 1 (first order) or 2 (second order). By default, it is taken `ordr = 2`.

`NUFL`

Introduces the type of flux calculation in the bulk fluid; may be `ROE` (Roe flux), `VANL` (Van Leer flux) or `STWA` (Steger-Warming flux). It is only accepted in purely Eulerian calculations. Recall that the far-field flux type is chosen (independently from the bulk flux type) by directive `BDFO` in material `MCFF`. By default, it is taken `NUFL ROE` (Roe flux).

`WBC`

If specified, the boundary conditions are treated according to a weak formulation. It is only accepted in purely Eulerian calculations. In this case external forces at the boundaries are evaluated by imposing zero momentum flux across the solid boundaries, while in the default case (no `WBC` specified) these forces are evaluated by the method of Lagrange multipliers.

`SYNC`

Introduces the type of synchronization `sync` for the MC variables: 0 (the default) is the old procedure; 1 is the new procedure.

Remarks

The “new” synchronization algorithm (`SYNC 1`), introduced in April 2010, should be used systematically for new calculations. The old algorithm is left only for compatibility with old input files.

12.15 OPTIONS FOR MULTIPHASE MULTICOMPONENT FLUIDS

Object:

To provide options for multiphase multicomponent fluid flows.

Syntax:

```
<   "FLMP"  < "EPS1" eps1 > < "EPS2" eps2 > < "EPS3" eps3 >
            < "EPS4" eps4 > < "NIMA" nima > < "DUMP" dump >  >

< $[ "DPLG"   ;
     "VOFIRE" < "VSWP" > < "CORR" > < "RFCR" >
                         < "NOCR" > < "NORC" >
            < "SKIP" /LECTURE/ >            ]$ >
```

`eps1`

Tolerance for the determination of number of effective components (a component is effectively present if its mass fraction is >= eps1mp). Default is 1.E-7.

`eps2`

Tolerance for the convergence of Newton-Raphson iterations. Default is 1.E-6.

`eps3`

Relative density variation to determine initial conditions in FLMPPR (case LIQ + GAS). Default is 1.E-5.

`eps4`

Tolerance to find the cut-off density for liquids in FLMPRP. Default is 1.E-12.

`nima`

Max. number of iterations in the above mentioned procedures

`dump`

Dump (1) or do not dump (0) informations on N-R iterations.

`DPLG`

Activates Despres-Lagoutiere anti-dissipative algorithm for multi-component flows on structured mesh (see comment below).

`VOFIRE`

Activates VOFIRE anti-dissipative algorithm for multi-component flows on unstructured mesh (see comment below).

`VSWP`

If present, exact advected volume is computed for each element face. If not, volume is approximated through the sweep formula.

`CORR`

Enables the use of CEA improved version of the VOFIRE algorithm.

`RFCR`

Enables the use of improved algorithm for mixture's density.

`NOCR`

Disables the use of CEA improved version of the VOFIRE algorithm.

`NORC`

Disables the use of improved algorithm for mixture's density.

`SKIP`

Deactivates VOFIRE for the given fluid elements.

Comments:

Despres-Lagoutiere anti-dissipative algorithm and its extension to unstructured meshes called VOFIRE are used to prevent numerical spreading of the mixing zone of physically non-miscible components. This is still a development in progress and is only available when multi-component material ADCR or SGMP is used for the fluid in the model. With the SGMP material, VOFIRE is only applicable with two constituants.

Improved algorithms for geometric reconstruction and computation of mixture's density on elements faces are currently disabled by default.

12.16 OPTIONS FOR AUTOMATIC REZONING IN ALE COMPUTATIONS

Object:

To provide options for automatic rezoning algorithms in ALE computations.

Syntax:

```
< REZO < SPLI |[ GIUL ; MODI ; BOTH ]| >
       < MVRE |[ NONE ; MODU <VFAC vfac>; MOPR <GAMO gam0> ]| >
       < MEAN |[ POSI ; DEPL ]| >
       < DIRE RMAX rmaxrz >
       < NSTE rznste > < CSHE cshear > < CSTR cstret >
       < YOUN rezyo NU reznu RHO rezro >
       $[ VFLU ; LIAI ]$  >
```

SPLI

Use the splitting algorithm specified next in order to split up the mesh elements around each node and to form the node's influence domain. The available possibilities are: GIUL for Giuliani's original splitting rule, MODI for the modified rule, or BOTH to use a superposition of both methods. The default value is GIUL. This parameter applies only to Giuliani's (AUTO) rezoning model and to the mean (MEAN) rezoning model. For the former, this parameter applies only to 2D quadrilateral ALE finite elements and finite volumes. For the latter, it applies to all elements (2D and 3D), but with a slightly different meaning: the GIUL option considers as neighbours of the node under consideration only the nodes that are connected to it by a face side; the other two options (MODI or BOTH) are equivalent and consider as neighbours all nodes belonging to neighbour elements.

MVRE

Use the mesh velocity restriction algorithm specified next in order to limit the 'raw' optimal mesh rezoning velocity computed by a rezoning algorithm. As shown in the preceding Sections, since all implemented algorithms are explicit, they are unstable unless some limitation is introduced. The available possibilities are: NONE for no restriction (as said, this is likely to be unstable), MODU for the modulus-based rule, or MOPR to use the standard modulus plus projection rule that was adopted in the original Giuliani algorithm. The default value is MOPR. This parameter applies to all rezoning methods described above.

VFAC

The velocity factor to be used in conjunction with the MVRE MODU option. By default it is 2.0. This parameter applies to all rezoning methods described above.

GAMO

The velocity factor to be used in conjunction with the MVRE MOPR option. By default it is 0.2. The obsolete specification of this parameter in the GRIL directive should be avoided from now on. This parameter applies to all rezoning methods described above.

`MEAN`

Use the mean algorithm variant specified next. The available possibilities are: POSI for an algorithm based on (current) nodal positions, or DEPL for an algorithm based on (current) nodal displacements. The default value is POSI. This parameter applies to all ALE element types.

`RMAX`

The maximum aspect ratio to be used in conjunction with the DIRE rezoning algorithm. By default it is 5.0. Note, however, that this parameter applies only to 2D quadrilateral ALE finite elements and finite volumes.

`NSTE`

The number of steps in which rezoning is applied (repartition parameter). By default it is 1.0. This parameter applies to all rezoning methods described above.

`CSHE`

The shear weight coefficient. By default it is 1.0. Note, however, that this parameter applies only to: a) any elements rezoned by Giuliani's method (AUTO); b) 2D triangles and quadrilaterals rezoned by the SPEC method; c) 2D quadrilaterals rezoned by the QUAD method; d) 2D quadrilaterals rezoned by the MECA method.

`CSTR`

The stretch weight coefficient. By default it is 1.0. Note, however, that this parameter applies only to: a) any elements rezoned by Giuliani's method (AUTO); b) 2D triangles and quadrilaterals rezoned by the SPEC method; c) 2D quadrilaterals rezoned by the QUAD method; d) 2D quadrilaterals rezoned by the MECA method.

`YOUN`

The fictitious material Young's modulus to be used in conjunction with the MECA rezoning algorithm. By default it is 1.0. Note, however, that this parameter applies only to 2D quadrilateral ALE finite elements and finite volumes.

`NU`

The fictitious material Poisson's coefficient to be used in conjunction with the MECA rezoning algorithm,. By default it is 0.0. Note, however, that this parameter applies only to 2D quadrilateral ALE finite elements and finite volumes.

`RHO`

The fictitious material density to be used in conjunction with the MECA rezoning algorithm. By default it is 1.0. Note, however, that this parameter applies only to 2D quadrilateral ALE finite elements and finite volumes.

`VFLU`

Choose the 'old' method of dealing with rezoning of nodes that are subjected to liaisons,. The imposed direction(s) are determined indirectly, from the fluid velocity components. As discussed, in 3D cases this method may be too restrictive and prevent the rezoning algorithm from fulfilling its tasks.

`LIAI`

Choose the 'new' method of dealing with rezoning of nodes that are subjected to liaisons. The imposed direction(s) are determined directly from inspection of the liaison coefficients.

12.17 OPTIONS FOR CELL-CENTRED FINITE VOLUMES

Object:

To provide options for Cell-Centred Finite Volume (VFCC) computations.

Syntax:

```
< VFCC <DUMP>
       <FCON fcon>  <VISC visc>
       <ORDR ordr>
       <STPS stps>
       <RECO reco> <GRAD grad>
       <LMAS lmas>  <LQDM lqdm>  <LENE lene>  <LALP lalp>
       <LVEL lvel>  <LPRE lpre>  <LLAG llag>
       <KMAS kmas>  <KQDM kqdm>  <KENE kene>  <KBAR kbar>
       <RVIT rvit>
       <CENE>       <NTIL>
       <M0   m0>    <VINF vinf>
       <NCFS <NHIE> /LECT/>
       <FLSW flsw>
       <TGRA tgra>
       <PAS0 pas0>
       <ELAM elam>
     $ <VF1D> ; <FCON fcon> <ORDR ordr> <STPS stps> <RECO reco>
                <LMAS lmas> <LQDM lqdm> <LENE lene> <LALP lalp>
                <LVEL lvel> <LPRE lpre> <LLAG llag>
                <KMAS kmas> <KQDM kqdm> <KENE kene> <KBAR kbar> $
>
```

`VFCC`

Introduces the options for Cell-Centred Finite Volume computations.

`DUMP`

Dumps out on listing the data structures FACE_VFCC and SOLUTION_VFCC (only for debugging).

`fcon`

Solver for the calculation of numerical fluxes at interfaces between volumes. One of the following solvers can be chosen (**by default the code uses the HLLC solver**, number 6 in the following list):

1. Rusanov
2. Flux-centred with viscosity (see `VISC` below)
3. HLLE
4. Exact Riemann for perfect gas

5. Zha-Bilgen (Flux Vector Splitting)
6. HLLC **This is the default**.
7. Dominant Wave-Capturing
8. AUSM+ (Flux Vector Splitting)
9. Zha-Bilgen modified
10. LDFSS-2 (Flux Vector Splitting)
11. AUSM+ Low-Mach
12. AUSM+ -up- Low-Mach
13. HLLC Low-Mach

`visc`

Defines the viscosity for use with the Flux-centered solver (`FCON 2`). **By default there is no viscosity**.

`ordr`

Order in space. Either first or second order is possible for 2D/3D VFCCs or 1D-VFCCs. **The default is** `ORDR 2` which, however, corresponds to real second order in space only if a so-called *reconstruction* (see `RECO` below for an explanation) is chosen (`RECO` > 0). Since by default `RECO` is 0 (see below), **the default scheme** (obtained by specifying neither `ORDR` nor `RECO`) **is first-order** in practice. *An old (obsolescent) implementation of first order in space scheme is also available in the code, but is still accepted only for backward compatibility and should not be used in new calculations since it will be removed soon. This is activated by choosing* `ORDR 1` *and no reconstruction (thus* `RECO` *is 0). However, be warned that the explicit choice of* `ORDR 1` *is incompatible with use of the* `FLSW` *fluid-structure interaction model.* See the comments at the end of this page for examples of use of the `ORDR` and `RECO` keywords.

`stps`

Scheme for time integration.

1. explicit Euler
2. Van Leer-Hancock predictor-corrector scheme (second order)
3. second order explicit Runge-Kutta (not available for 1D-VFCCs)

The default value is 1. `STPS` replaces the old options `OTPS` and `ERK2`.
We also notice the Van Leer-Hancock predictor-corrector scheme is not available for some multi-fluid materials like `CDEM` or `DEMS`.

`reco`

Activates the so-called reconstruction of the variables at the inter-volume interfaces starting from the values at the centroids and from the (spatial) gradients at the centroids. Since the spatial gradients are only computed when second-order in space is activated (`ORDR 2`), reconstruction only makes sense in this case. **The default value is 0 (no reconstruction)**. Option `RECO 1` stays for Green-Gauss reconstruction of the conservative variables (density, momentum and total energy per unit volume). Option `RECO 2` stays for Green-Gauss reconstruction of the primitive variables (density, velocity, internal energy per unit mass, mass fraction). Option `RECO 3` is only available for the CDEM or DEMS materials and stays for Green-Gauss reconstruction of the primitive variables, which in this case involves the pressure instead of the internal energy per unit mass.

`grad`

Type of gradient used for the reconstruction.

- grad 1 refers to the Gauss-Green reconstruction (**the default one**). The gradient of a variable ϕ at the center is computed according to the formula

$$\left(\vec{\nabla}\phi\right)_C = \frac{1}{\Omega}\sum_f S_f \phi_f \vec{n}_f$$

where Ω is the cell volume, S_f and $\vec{n}_f$ are the interface surface and normal. ϕ_f is an estimation of the variable ϕ at the center of the interface and is here obtained by a linear interpolation of the values at the two cell centers sharing this interface. It can be shown that the computed gradient is linear exact when the center of each interface is aligned with the cell centers sharing the interface itself. See for instance [937, formulae (1)-(6)] and details therein.

- grad 2 is based on the Modified Gauss-Green reconstruction of [937] and is linear-exact on irregular meshes, even if the center of each interface is not aligned with the cell centers sharing the interface itself.
The gradient of a variable ϕ is computed according to the formula

$$\left(\vec{\nabla}\phi\right)_C = \frac{1}{\Omega}\sum_f S_f \left(\left(\vec{\nabla}\phi\right)_f \cdot \vec{n}_f\right)\left(\vec{X}_f - \vec{X}_C\right).$$

where $\left(\vec{X}_f - \vec{X}_C\right)$ is the vector going from the cell center to the interface center. $\left(\vec{\nabla}\phi\right)_f$ is an estimation of the gradient at the interface center and is here computed by imposing that

$$\left(\vec{\nabla}\phi\right)_f \cdot \left(\vec{X}_{Cf} - \vec{X}_C\right) = \phi_{Cf} - \phi_C$$

Cf being the center of the neighbor sharing the interface, and

$$\left(\vec{\nabla}\phi\right)_f \cdot \vec{t} = \left(\vec{\nabla}\phi\right)_C \cdot \vec{t} \qquad \text{if} \qquad \vec{t}\cdot\left(\vec{X}_{Cf} - \vec{X}_C\right) = 0.$$

This generates, in each cell, a local implicit linear problem involving a square matrix (2x2 in 2D and 3x3 in 3D).
Before concluding we emphasize that the estimation of $\left(\vec{\nabla}\phi\right)_f$ in [937] is different (it is the same as here only along the direction $\left(\vec{X}_{Cf} - \vec{X}_C\right)$) and involves an iterative process which requires to store the gradient values at the interfaces and at the cells (see details therein).

`lmas, lqdm, lene, lalp, lvel, lpre, llag`

Limitation for the reconstruction (`RECO` > 0) of the various quantities: `lmas` for the density, `lqdm` for the momentum, `lene` for the total energy per unit volume, `lalp` for the volume fraction (only for CDEM or DEMS material), `lvel` for the velocity, `lpre` for the pressure, `llag` for the Lagrangian variables, i.e. the mass fractions prior to chemical reaction (only for CDEM material). A limiter typically is a number between 0.0 and 1.0, which multiplies the value of the gradient in order to ensure that the reconstructed values at the interfaces do not violate some conditions. The value of the limiter is automatically computed by the code in each Finite Volume (and typically varies from volume to volume, and also in time). The available types of limiter are: 0 indicates no limitation (limiter

equal to 1.0), 1 indicates a first-order limitation (this corresponds to limiter equal to 0.0 and in practice vanifies the effects of the reconstruction), 2 indicates the limitation of Barth and Jesperson, and 3 indicates the limitation of Dubois. **By default the code assumes the limitation of Dubois**.
Summarizing. For `RECO` equal 1 or 2 one should specify `lmas`, `lqdm`, `lene` and `llag`. For `RECO` equal 3 one should specify `lmas`, `lvel`, `lpre` and `llag`.

`kmas, kqdm, kene`

Parameter for the limitation of Dubois for the density (`LMAS` 3), for the momentum (`LQDM` 3) or for the total energy per unit volume (`LENE` 3). This parameter should be between 0.0 and 1.0. **The default value is 0.5**.

`kbar`

Parameter for the limitation of Barth and Jesperson, all variables (e.g. `LMAS` 2). The value 0 indicates the standard one (**this is the default**), while 1 indicates a modified one which is more robust for the calculation of shock waves. The value `kbar` 1 produces the strongest possible limitation.

`rvit`

Type of reconstruction of the fluid velocity field at VFCC nodes, starting from the velocity field at the VFCC volume centres. This is used to compute the automatic rezoning (mesh velocity) of ALE VFCC fluid nodes and the motion of Lagrangian VFCC fluid nodes. A value of 0 indicates no reconstruction, 1 (**default**) indicates the **arithmetic mean of the neighboring volumes**, 2 is the mean weighted by the element volumes, 3 is the mean weighted by the element masses, 4 is the mean weighted by the inverse of the element volumes, 5 is the mean weighted according to Roe.

`CENE`

This option adds a correction of the gradients such that the internal energy is always positive. This affects only second-order in space calculations with `RECO` 1 or 2, but not 3.

`m0`

Cut-off value for the Mach number for use with low-Mach solvers (i.e. `FCON` 11, 12 or 13). For the other solvers, it is ignored. **By default it is 0.5**.

`vinf`

Reference velocity for use with low-Mach solvers (i.e. `FCON` 11, 12 or 13). For the other solvers, it is ignored. **By default it is 0.0**.

`NTIL`

No "tilt" in the calculation (i.e. suppress error message and subsequent stop if the internal energy becomes negative). **The default is to stop (tilt) if the internal energy becomes negative**. This option has no effect on calculations with the CDEM or DEMS materials.

`NCFS`

Announces that a (nodally) non-conforming fluid-structure interaction exists between a structure (typically meshed by shell elements) and a fluid meshed by VFCC. The following `/LECT/` lists all fluid nodes (which must belong to the VFCC domain) which are located along the non-conforming F-S interface. The code automatically searches the facing structural element, which must be "superposed" (within a small tolerance) to the fluid volume face (such an element *must* exist, else an error message is issued).

`NHIE`

Optional sub-keyword, specifying that the F-S interface is not hierarchic, besides being non-conforming. Checks about the hierarchicity of the F-S interface are disabled, at the risk and peril of the user. Use of this option is discouraged, unless you know exactly what you are doing, because the use of a non-hierarchic interface will degrade the accuracy of the FSI algorithm. Good practice is that of using a hierarchic (non-conforming) F-S interface, obtained as follows. The structural side of the F-S interface is meshed first. Then, it is duplicated to obtain an identical fluid side of the F-S interface. Next, this fluid interface is refined, e.g. by dividing each fluid face in two faces (in 2D) or in 4 faces (in 3D). This ensures that the fluid mesh is hierarchic with respect to the structural mesh. Finally, the fluid volumetric mesh is built by using (and respecting) the hierarchic fluid surface mesh.

`flsw`

This option allows to choose the type of FLSW algorithm to be used for fluid-structure interaction modeling in conjunction with cell-centred finite volumes. The value 0 means that all numerical fluxes across interfaces near the structure are set to zero, except those related to momentum (which are the pressure forces). **The value 1 is the default** and means that all numerical fluxes across interfaces near the structure are computed by introducing fictitious "ghost" states corresponding to a rigid wall moving with the same speed as the structure.

`tgra`

By specifying `TGRA i` with $i > 0$ one activates the non-regression test for the gradient limiter for the perfect gas in the CDEM model: the gradient of the i-th variable is stored in the ECR table. **By default ($i = 0$) no gradient is stored**.

`pas0`

The initial time step is imposed to be `pas0`. **The default is 0.0**, which means that the code computes it **automatically**.

`ELAM elam`

Parameter λ_E (with $0 < \lambda_E \leq 1$) controlling the partial erosion of structural elements as far as the classical FSI coupling algorithm with a VFCC fluid is concerned, based on direct transmission of fluid pressure forces to the structure. The algorithm attempts to take into account structural erosion, and lets the fluid pass through eroded zones of the structure. A (base) structural element P coupled with the VFCC fluid is considered eroded, *as far as FSI is concerned*, if its erosion ratio ϕ_P reaches the limit λ_E , i.e. when $\phi_P \geq \lambda_E$. The erosion ratio is defined as the ratio between the eroded volume of the element V_E, given by the sum of the volumes of all its active descendents which are eroded, and the total volume V_P of the element: $\phi_P = V_E/V_P$, so that $0 \leq \phi_P \leq 1$. The default value of λ_E is 1.0, i.e. an element is considered eroded, as far as classical FSI is concerned, when it is *completely* eroded (i.e. when all its active descendents have been eroded). If specified, the value of λ_E must be such that $0 < \lambda_E \leq 1$. By specifying a negative value of λ_E the code uses its absolute value but the erosion ratio is computed differently. Instead of considering all active descendents of a continuum strucural element, only the descendents adjacent to the face coupled with the fluid are taken into account.

`VF1D`

Set options specifically related to 1D-VFCC elements.

Options set in the VFCC section are by default also applied to 1D-VFCC elements. This keyword is used to set different options for 1D-VFCC elements than 2D/3D VFCC : different solver, scheme order in time/space, reconstruction type or limiter. Compatible options are : `FCON, ORDR, OTPS, RECO`, as well as limiter options (type and Dubois coeff by variable). If set, this keyword ends the section. Other VFCC options must be all written before it.

Comments:

Below are some examples of use of the `ORDR` and `RECO` keywords. The effect of `RECO` > 1 is similar to `RECO 1`, only the type of reconstruction is different. Options set in this section are by default also considered for 1D-VFCC. Use `VF1D` options to set specific options for these.

`ORDR`	`RECO`	**Result**
none	none	First-order in space (default)
none	`0`	First-order in space (default)
none	`1`	Second-order in space
`2`	none	First-order in space (default)
`2`	`0`	First-order in space (default)
`2`	`1`	Second-order in space
`1`	none	Older version of first-order in space: **FLSW not available!**
`1`	`0`	Older version of first-order in space: **FLSW not available!**
`1`	`1`	**Input error: this combination is not available!**

12.18 OPTIONS FOR CONNECTIONS ("LIAISONS"/LINKS)

Object:

To provide options for the connections in general, for the LIAISON CONTACT directive and for the pinball impact model (either standard or generalized), see Section D.

Syntax:

```
< LIAJ <ALPH alph> >
< CONT |[ CONS ; VARI ]| >
< GLIS < NORM |[ ELEM < ANGM >; NOEU ]| >
       < GAP  |[ ELEM ; NOEU ]| > < DUMP >
       < $ ADAP ; NOAD $ > < $ SYME ; NOSY $ > >
< PINS < DUMP > < STAT > < VIDE > < DTPB < CSPB cspb > > < UPDR >
       < EQVL > < EQVD > < EQVF > < NEQV > < ERCE >
       < $[ FACE ; FACI ]$ < FNOR >                             >
       < CNOR < $[ MIDP ; NCOL < RCEL < $[ MASL ; MAS2 ]$ > > ]$ > >
       < SNOR > < REDU > < ASN > < NPSF >
       < $[ REB1 ; REB2 ; NORB ]$ >
       < $[ NOGR ; GRID <DGRI> <SORT>
                  $[ HGRI hgri ; NMAX nmax ; DPIN dpin ]$
                  < PACK ipac > ]$ >
       < ADJA <BODY> <SELF> > >
< GPNS < DUMP > < STAT > < DTPB < CSPB cspb > >
       <SLIM slim> <PHIR phir> <RCEL>
       < $[ REB0 ; REB1 ; REB2 ; NORB ]$ > < REBC >
       < $[ NOGR ; GRID <DGRI> <SORT>
                  $[ HGRI hgri ; NMAX nmax ; DPIN dpin ]$
         ]$ > >
< LNKS < STAT > < STAD > < DIAG > < DUMP > < VISU > <NOCU>
       < RIGI <DISP> <CMID> >                            >
< FLS <CUB8 c8> >
```

`LIAJ <ALPH alph>`

This option causes all constraints (imposed either via LIAI on via LINK COUP) on velocities to be expressed on the velocity at time $n+1+\alpha/2$, rather than at time $n+3/2$, which is the default in EUROPLEXUS (note that in this notation the current configuration is indicated by $n+1$). If the `ALPH` sub-keyword is omitted, the code assumes $\alpha = 1.0$ and so the constraints are expressed at the next mid-step (time $n+3/2$). If α is specified, it must be $0.0 \leq \alpha \leq 1.0$. The value $\alpha = 0.0$, corresponding to full-step velocity constraints (at time $n+1$), was used for example in PLEXIS-3C. Therefore, this option is mainly useful in order to perform fine-grain comparisons between results of PLEXIS-3C and EUROPLEXUS, for debugging purposes. Specifying intermediate values of α may be useful to fine-tune the properties of some types of constraints, e.g. contacts or impacts, while the value of α may be irrelevant for other types of constraints (e.g. blockages).

`CONT`

Introduces options related to geometric bilateral restraints (`LIAISON CONTACT`, see Page D.40 and following ones).

`CONS`

Constant coefficients will be used in the `LIAI CONT` directives of type `SPHE`, `CYLI`, `CONE` and `TORE`.

`VARI`

Variable coefficients will be used in the `LIAI CONT` directives of type `SPHE`, `CYLI`, `CONE` and `TORE`. Remember to dimension adequately by the `DIME VCON` directive.

`GLIS`

Introduces options to the `LIAI` or `LINK GLIS` (sliding surfaces) model.

`NORM`

Introduces options (ELEM, NOEU) to control the face normal computation.

`ELEM`

Exact face normals are computed (see Comments for details).

`ANGM`

Activates a blind spot detection for shell elements (with NORM ELEM only).

`NOEU`

Nodal normals are first computed as mean values from the faces surrounding each node. Face normals are then deduced by averaging the nodal normals at the centre of each face. Default method. See Comments for details.

`DUMP`

Dump out on the listing the data structure related to GLIS each time it is created or updated (e.g. in case of adaptivity). This option should be only used for debugging purposes since it will produce huge output. Note that, in order to get the printout of the data structures as they are first created, the option must be set *before* the directive `LINK GLIS`.

`GAP`

Options to control the way of considering the gap for contact between shell structures.

`ELEM`

Gap is considered on the master side, which means that the master facet is translated by the gap value in its normal direction before contact detection.

`NOEU`

Gap is considered on the slave side, which means that the slave node is translated by the opposite of the gap value in the direction normal to the master facet before contact detection. This is the default method (see comment below).

`ADAP`

Combine sliding surfaces (`GLIS`) with adaptivity. This means that the sliding surfaces data structure is updated whenever the mesh is adaptively refined or un-refined. The calculation becomes more CPU-expensive but the contact is likely to be treated better. This feature is under development and should ultimately become the default, but for the moment we leave it as an option.

`NOAD`

Do not combine sliding surfaces (`GLIS`) with adaptivity. This is currently the default. This means that the sliding surfaces data structure is not updated whenever the mesh is adaptively refined or un-refined. The calculation is less CPU-expensive but the contact is likely to be treated worse, since it "sees" only the *base* elements and nodes, and not the descendent ones in case of adaptivity. As already noted, `ADAP` (see above) should ultimately become the default, but for the moment we set `NOAD` as default in order not to break any older test cases.

`SYME`

Combine sliding surfaces (`GLIS`) with symmetries. This is currently implemented only in the coupled version of the links (`LINK COUP`). The combination prevents the appearance of unsymmetric contact forces (which could break the symmetry of the model), especially in case of friction.

`NOSY`

Do not combine sliding surfaces (`GLIS`) with symmetries. This is the default, in order not to modify the results of old input models.

`PINS`

Introduces options related to the `LIAI` or `LINK PINB` (pinball contact) model (see page D.480).

`DUMP`

Dumps out extensive pinballs information on the listing. Note that even further pinball-related dumps take place by activating the generic option `OPTI DUMP` in conjunction with the present pinball-specific option. Note also that this option should be activated *before* declaring the pinballs, i.e. before the `LINK PINB` directive, in order to get on the listing a detailed information on pinballs.

`STAT`

Dumps out statistics relative to pinballs on a special file `<basename>.pin`. At each time step are printed: the number of "raw" detected pinball contacts, the number of contacts remaining after the `CNOR` algorithm, the number after the `NCOL` algorithm, the number after the `RCEL` algorithm and the (final) number of contacts after the *a priori* rebound algorithm.

`VIDE`

Visualize all descendent pinballs generated by the hierarchic splitting process. This option should only be used for debugging purposes. When activated, all the descendent pinballs (of the highest level) generated during the splitting process are considered in contact, so that they may be visualized interactively e.g. by the `TRAC PINC` command (see pages A.25 and O.10). This allows to visualize the result of the splitting process. Beware that in complex cases a very large number of such pinballs may be generated. When the option is activated, pinball links are not generated, however, since the retained contacts are unphysical. In addition, the calculation is automatically stopped after time step 0, and the `PINS DUMP` (see above) option is automatically activated.

`DTPB`

Activate automatic limitation of the time increment Δt to account for contacts modelled by pinballs (irrespective of the specific model used, i.e. liaisons, coupled links, or uncoupled penalty). This option is ignored if the user pilots the time increment e.g. by specifying `PAS UTIL`. By default, i.e. without the present option, pinball contacts have no effect on time increments.

`CSPB`

Introduces the reading of the "stability" coefficient `cspb` to be used in conjunction with the `DTPB` option for the limitation of the time increment Δt due to pinballs. By default the code assumes `cspb=cstab` i.e. the same value as the stability coefficient used for the elements' stability (see `OPTI CSTA` on page H.20). This quantity should be less than 1.0, like for `CSTA`.

`UPDR`

Update the radius of parent (0-level) pinballs at every step. By default, the radius is computed only at the initial time. This option may be useful in problems with very large deformations.

`EQVL`

The radius of parent pinballs (i.e. at the 0-level) is computed in such a way that the pinball volume equals the initial volume of the associated element. By default, the radius is computed so as to encompass all element nodes in the initial configuration.

`EQVD`

Same as `EQVL` above, but concerning the descendent pinballs generated in hierarchic methods (and this at every level of the hierarchy). The sub-pinball radius is computed in such a way that its volume equals the initial volume of the associated element portion. By default, the radius is computed so as to encompass all element portion "nodes" in the current configuration.

`EQVF`

Same as `EQVD` above, but affects only the proper descendent (i.e. of level $L > 0$) pinballs generated in hierarchic methods **at the last (final) level** of the hierarchy. The parent (0-level) pinballs are not affected. The radius of a **final** proper sub-pinball is computed in such a way that its volume equals the initial volume of the associated element portion. By default, the radius is computed so as to encompass all element portion "nodes" in the current configuration. This option should be preferably used in most cases: the other options (`EQVL`, `EQVD` or `NEQV`) are in fact probably useful only in special cases, or for debugging purposes.

`NEQV`

No equivalent volume calculations. The radius of parent pinballs is computed so as to encompass all element nodes in the initial configuration. The radius of any proper descendent pinballs is computed so as to encompass all element portion "nodes" in the current configuration. This is currently the default. It may be used to restore the default behaviour after one of the other options (`EQVL`, `EQVD` or `EQVF`) has been specified.

`FACE`

The velocity constraint for a contact between parent pinballs is written at the centroids of the faces crossed by the line joining the pinball centers (it involves only the face nodes). By default, the velocity constraint is written at the pinball centers (which for 0-level pinballs corresponds with the element centroid) and thus involves all the nodes of the element. This option has no effect on contacts between sub-pinballs.

`FACI`

The velocity constraint for a contact between parent pinballs is written at the intersections of the faces crossed by the line joining the pinball centers (it involves only the face nodes). By default, the velocity constraint is written at the pinball centers (which for 0-level pinballs corresponds with the element centroid) and thus involves all the nodes of the element. This option has no effect on contacts between sub-pinballs.

`FNOR`

The velocity constraint for a contact between parent pinballs is written along a "mean" of the two face normals $n = (n_A - n_B)$. Note that this requires that either `OPTI PINS FACE` or `OPTI PINS FACI` be specified as well. By default, the velocity constraint is written along the direction of the line that joins the pinball centers.

`CNOR`

The velocity constraint for a contact between sub-pinballs is written along a "common" normal. One such normal is determined for each couple of contacting element faces. When multiple contacts between sub-pinballs occur (pinballs hierarchy at level > 0) in case of flat (face to face) contact, this common normal is an approximation of the normal to the contacting faces.

`MIDP`

The velocity constraint for a contact between sub-pinballs is written at "midpoints" along the lines that join the retained contacting sub-pinballs. This option is part of the common normal algorithm and therefore it requires that the `CNOR` option be specified as well (see above). This option is incompatible with the `NCOL` option described below. Note that this option has effect only on constraints between sub-pinballs that are part of a "sequence" of two or more contacts between the same couple of ancestors. Single or "isolated" contacts between two ancestors (to which the concept of common normal does not apply) sre not affected, and in such cases the constraint is written at the sub-pinball centers.

`NCOL`

Collapse onto the nearest node of the parent element the center of those descendent pinballs located at "corners". In addition, for the remaining (non-corner) descendent pinballs, collapse their center onto the element side or face. Note that the above mentioned collapse is performed only as far as the application point of contact reaction forces is concerned, i.e. when writing down the constraints, and it does not affect the position (center, radius) of the descendent pinball itself. By this option the form of the resulting constraints is simpler because they involve less dofs, and the constraints are more independent from one another. This option has only effect on contacts between sub-pinballs (not for contact between parent pinballs) and is incompatible with the `MIDP` option described above. It requires the `CNOR` option.

`RCEL`

Eliminate repeated constraints for contacts between sub-pinballs that may result after collapse (see option `NCOL` above). This option may help removing a priori from the system repeated constraints that occur e.g. in flat contact between adjacent elements. It requires that the `NCOL` option (and thus also the `CNOR` option) be specified as well. Normally to obtain the maximum benefits a user would specify the three options `CNOR NCOL RCEL`.

`MASL`

Apply master/slave rule in order to further simplify constraints in case of multiple flat contact between bodies. Constraints of type NP (node-to-point) whose associated node belongs to the “hardest” one of the two contacting bodies are rejected. Body “hardness’ is specified optionally in the `PINB BODY HARD` directive, see Page D.480. This option requires that `HARD` has actually been specified for both contacting bodies, and that the `RCEL` option described above has been specified as well. The result should be similar to the more traditional sliding lines (slave node / master surface) algorithm, and might lead to slight under-constraining (spurious penetration) in some cases (if this happens, try using the `MAS2` option below instead).

`MAS2`

Apply master/slave rule in order to further simplify constraints in case of multiple flat contact between bodies. Multiple constraints of type NP (node-to-point) whose associated node belongs to the “hardest” one of the two contacting bodies are rejected. Body “hardness’ is specified optionally in the `PINB BODY HARD` directive, see Page D.480. This option requires that `HARD` has actually been specified for both contacting bodies, and that the `RCEL` option described above has been specified as well. The result should be intermediate between a purely pinballs-based algorithm and the more traditional sliding lines (slave node / master surface) algorithm. It might lead to slight over-constraining (contact locking) in some cases (if this happens, try using the `MASL` option above instead).

`SNOR`

When a *single* contact occurs between sub-pinballs belonging to the same couple of element faces, and only one of the two sub-pinballs is a face sub-pinball, then the used normal is the normal to that face. This option may be used alone or combined with the `CNOR` option (which acts only upon *multiple* contacts).

`REDU`

Eliminate the redundant constraints which typically arise in flat contact with hierarchic pinballs, and which may lead to singularity of the links matrix. If $n > 1$ (raw) contacts are detected between (descendants of) a couple of parent pinballs A and B, replace them by a single *equivalent* contact obtained from the weighted average of the raw contacts. This option cannot be used together with (is an alternative to) options `FNOR`, `CNOR` (and its sub-options), or `SNOR`. However, it can be used in combination with `ASN`.

`ASN`

The so-called "assembled surface normal" (ASN) algorithm of Belytschko and Law (1985) is used to compute a unique (normalized) normal to each external node of the mesh portion subjected to contact, and a unique (normalized) normal to each pinball (parent or descendent). The penetration direction between contacting pinballs is then computed using the ASNs of the two pinballs according to a set of rules. This ameliorates the treatment of flat contact, especially in conjunction with a penalty formulation to compute the contact forces. This option cannot be used together with (is an alternative to) options `FNOR`, `CNOR` (and its sub-options), or `SNOR`. However, it can be used in combination with `REDU`.

`NPSF`

Add a scaling force factor for pseudo-nodal pinballs at an adaptivity level $L > 1$. If this option is specified, then the penalty force for newly created pseudo-nodal pinballs (i.e., pinballs associated with to a mass-less `PMAT` element attached at element nodes) are scaled down by multiplying the penalty force normally computed by a factor:

$$\phi = 1/(2^{L-1})) \tag{93}$$

where L is the hierarchy level in adaptivity of the node to which the pseudo-nodal pinball is attached (via the `PMAT` element). If the keyword is not specified, then $\phi = 1.0$ and the penalty force is not scaled. If specified, the option has effect only on pseudo-nodal pinballs using the `PENA` (penalty) method, it has no effect on element-based pinballs nor on pseudo-nodal pinballs using the Lagrange multipliers method.

`REB1`

The so-called *a priori* pinball contact rebound detection algorithm is used. This is the default contact rebound detection algorithm and therefore specifying this keyword is usually redundant. Rebound-related options are only used in the Lagrange Multipliers version of the pinball method. The penalty formulation does not use any special rebound treatment, so these options are ignored.

`REB2`

The so-called *a posteriori* pinball contact rebound detection algorithm is used instead of the default *a priori* contact rebound detection algorithm. This option is only intended for internal code testing and verification, because the default algorithm is normally superior to the other one. Rebound-related options are only used in the Lagrange Multipliers version of the pinball method. The penalty formulation does not use any special rebound treatment, so these options are ignored.

`NORB`

Do not apply any pinball contact rebound detection algorithm. Rebound between pinballs is not treated. Rebound-related options are only used in the Lagrange Multipliers version of the pinball method. The penalty formulation does not use any special rebound treatment, so these options are ignored. This option is therefore useful only (for debugging purposes) with pinball contacts treated by Lagrange multipliers (see `LINK COUP PINB`).

`NOGR`

Do not use a grid of cells to speed up search of neighbours for contact detection. This is the default.

`GRID`

Use a grid of cells (as in bucket sorting) to speed up search of neighbours for contact detection. The grid encompasses all elements containing parent pinballs and is built up either automatically (if no further options are specified) in the way specified below, or according to one of the following criteria.

`DGRI`

Dump out the grid of cells used for fast searching on the listing. For brevity, the print is done only the first time that the grid is computed.

`SORT`

Sort the list of contacts in growing order so they (should) become like in the case without grid. This option is only to be used for debugging, since it facilitates the comparison of results with and without grid.

`HGRI`

Specifies the size of the grid cell. Each cell has the same size in all spatial directions and is aligned with the global axes.

`NMAX`

Specifies the maximum number of cells along one of the global axes.

`DPIN`

Specifies the size of the grid cell as a multiple of the diameter of the largest parent pinball. For example, by setting `DPIN 4` the size of the cell is four times the diameter of the largest parent pinball. By default, i.e. if neither `HGRI`, nor `NMAX`, nor `DPIN` are specified, the code takes `DPIN 1.1`. Normally, the cost of searching decreases as one takes smaller values of `DPIN`. However, the memory used tends to increase because there will be more cells. In large cases, a trade-off must be found but it is difficult to say a priori what is the optimal value for `DPIN`. Note that values of `DPIN` at or below 1.0 are **unsafe**. Some contacts may be overlooked (but this depends on the case). To be sure that **all** contacts are detected, use `DPIN` (slightly) larger than 1.0, say 1.001.

`PACK`

This optional keyword allows to specify a packing size `ipac` for the fast search grid. The search is then done by partially overlapping cubic (square in 2D) "macro cells" each containing `ipac` search cells along each spatial direction. See below for comments.

`ADJA`

This optional keyword introduces some options relative to the treatment of "adjacent" elements in the pinball contact method. Two elements are considered adjacent if they share at least one common node. Normally, contact between adjacent elements is *not* activated, since the pinballs associated with an element may slightly protrude from the element itself and therefore interpenetrate with the pinballs associated with the adjacent elements.

`SELF`

By specifying the `ADJA SELF` keyword, self contact between adjacent elements is activated.

`BODY`

By specifying the `ADJA BODY` keyword, contact between adjacent elements belonging to two different bodies is activated. This is the case, for example, of a zone of elements being assigned *both* element-based (possibly hierarchic) pinballs *and* nodal-based (via PMAT) pinballs, declared as two different `BODY` directives. This is an alternative way of achieving self-contact (to the use of only one set of `SELF` element-based pinballs) which might be advantageous for example in the case of a very thin shell impacting a rigid obstacle and forming very narrow plies, each formed by only one row of elements.

`GPNS`

Introduces options related to the `GPIN` (generalized pinball contact) model (see page D.490).

`DUMP`

Dumps out extensive GPINs information on the listing. Note that even further GPIN-related dumps take place by activating the generic option `OPTI DUMP` in conjunction with the present GPIN-specific option.

`STAT`

Dumps out statistics relative to GPINs on a special file `<basename>.gpn`. At each time step are printed: the number of “raw” detected GPIN contacts, the (final) number of contacts after the *a priori* rebound algorithm, the maximum penetration at the current step, the maximum penetration so far, the maximum penetration rate at the current step and the maximum penetration rate so far.

`DTPB`

Activate automatic limitation of the time increment Δt to account for contacts modelled by GPINs (irrespective of the specific model used, i.e. coupled links, or uncoupled penalty). This option is ignored if the user pilots the time increment e.g. by specifying `PAS UTIL`. By default, i.e. without the present option, GPIN contacts have no effect on time increments.

`CSPB`

Introduces the reading of the “stability” coefficient `cspb` to be used in conjunction with the `DTPB` option for the limitation of the time increment Δt due to GPINs. By default the code assumes `cspb=cstab` i.e. the same value as the stability coefficient used for the elements’ stability (see `OPTI CSTA` on page H.20). This quantity should be less than 1.0, like for `CSTA`.

`SLIM`

Limit value s_{lim} of the scalar product between two normals: $s = \hat{\mathbf{n}}_1 \cdot \hat{\mathbf{n}}_2$ beyond which a single-sided structural GPIN should be treated as a two-sided GPIN. By default it is $s_{\text{lim}} = -\sqrt{2}/2$. See the report on generalized pinballs (GPIN) for more information.

`PHIR`

Value of the coefficient ϕ which multiplied by the GPIN radius defines the validity zone for penetration into an L-GPIN. It should be $0 \leq \phi \leq 1$. By default the code currently assumes $\phi = 0$ in order not to modify benchmarks evolved before the introduction of this parameter. However, in the future the default could be set to a more realistic value, e.g. $\phi = 0.7$. By setting `PHIR 0` the entire length of the L-GPIN is valid for penetration, but this may produce P-L contacts instead of P-P contacts, and L-L contacts instead of

P-L contacts (the effects on engineering results of such approximations should be small anyway). See the report on generalized pinballs (GPIN) for more information.

`RCEL`

Activate redundant constraints elimination. Unlike in the case of `PINB`, with `GPIN` this is done during the seatch of (raw) penetrations itself. For the moment, it is only implemented in 2D.

`REB0`

The so-called simplified *a priori* GPIN contact rebound detection algorithm is used. Rebound-related options are only used in the Lagrange Multipliers version of the generalized pinball method. The penalty formulation does not use any special rebound treatment, so these options are ignored. In this version of the *a priori* rebound algorithm the penetration rate is evaluated simply based upon the current velocities.

`REB1`

This is the default contact rebound detection algorithm for generalized pinballs and therefore specifying this keyword is usually redundant. This is a more elaborate version of the *a priori* GPIN rebound algorithm where the penetration rate is evaluated based upon the estimated "free" position of the GPINs at the next time step, in the absence of contact forces. It uses the accelerations (i.e. the forces and the masses) in addition to the velocities, similarly to what is done by default for standard pinballs (`PINB`). Rebound-related options are only used in the Lagrange Multipliers version of the generalized pinball method. The penalty formulation does not use any special rebound treatment, so these options are ignored.

`REB2`

The so-called *a posteriori* GPIN contact rebound detection algorithm is used instead of the default *a priori* contact rebound detection algorithm. This option is only intended for internal code testing and verification, because the default algorithm is normally superior to the other one. Rebound-related options are only used in the Lagrange Multipliers version of the pinball method. The penalty formulation does not use any special rebound treatment, so these options are ignored.

`NORB`

Do not apply any GPIN contact rebound detection algorithm. Rebound between pinballs is not treated. Rebound-related options are only used in the Lagrange Multipliers version of the pinball method. The penalty formulation does not use any special rebound treatment, so these options are ignored. This option is therefore useful only (for debugging purposes) with pinball contacts treated by Lagrange multipliers (see `LINK COUP GPIN`).

`REBC`

This option activates a *combined pre-post* form of a priori rebound. In other words, rebound is checked both a priori (before solving the constraints) and a posteriori (i.e. by checking the sign of the Lagrange multiplier in the algorithm that treats the friction). The option affects only the two types of a priori rebound described above, i.e. either the simplified a priori rebound (`REB0`) or the full a priori rebound (`REB1`).

`NOGR`

Do not use a grid of cells to speed up search of neighbours for contact detection. This is the default.

`GRID`

Use a grid of cells (as in bucket sorting) to speed up search of neighbours for contact detection. The grid encompasses all GPINs and is built up either automatically (if no further options are specified) in the way specified below, or according to one of the following criteria.

`DGRI`

Dump out the grid of cells used for fast searching on the listing. For brevity, the print is done only the first time that the grid is computed.

`SORT`

Sort the list of contacts in growing order so they (should) become like in the case without grid. This option is only to be used for debugging, since it facilitates the comparison of results with and without grid.

`HGRI`

Specifies the size of the grid cell. Each cell has the same size in all spatial directions and is aligned with the global axes.

`NMAX`

Specifies the maximum number of cells along one of the global axes.

`DPIN`

Specifies the size of the grid cell as a multiple of the diameter of the largest GPIN. For example, by setting `DPIN 4` the size of the cell is four times the diameter of the largest GPIN. By default, i.e. if neither `HGRI`, nor `NMAX`, nor `DPIN` are specified, the code takes `DPIN 1.1`. Normally, the cost of searching decreases as one takes smaller values of `DPIN`. However, the memory used tends to increase because there will be more cells. In large cases, a trade-off must be found but it is difficult to say a priori what is the optimal value for `DPIN`. Note that values of `DPIN` at or below 1.0 are **unsafe**. Some contacts may be overlooked (but this depends on the case). To be sure that **all** contacts are detected, use `DPIN` (slightly) larger than 1.0, say 1.001.

`LNKS`

This keyword introduces options which are specific of the links model. They are ignored by the "liaisons" model.

`STAT`

Dumps out statistics relative to *coupled* links (`LINK COUP`) on a special file `<basename>.lks`. At each time step are printed: the number of link groups (N_GPS), the total number of links (N_LKS), the total number of permanent links (N_PLKS), the total number of non-permanent links (N_NPLKS) and finally the number of links of each type (e.g., `BLOQ`, `RELA` etc.).

`STAD`

Print similar information to the statistics for coupled links, but relative to the decoupled links (`LINK DECO`), on file `<basename>.lkd`. Attention: the programming of this feature is under development. At the moment, statistics is available only for the following types of decoupled links: `PINB`.

`DIAG`

Dumps out additional diagnostics relative to current links (both permanent and non-permanent) on the listing, together with each normal printout (see directive `ECRI`. The information concerns the size of the links matrix, and its "fullness" (i.e. the relative number of non-zero entries). This information can be useful in view of the choice of the most appropriate solution strategy for the links problem.

`DUMP`

Dumps out all current links (both permanent and non-permanent) on the listing, together with each normal printout (see directive `ECRI`. The generated output can be huge, therefore this option should be used with great care (and for debugging purposes only).

`VISU`

Activate the possibility of visualizing the links in the built-in OpenGL graphical module.

`NOCU`

Do *not* check for unconnected nodes presence in links (coupled or decoupled). Unconnected nodes are nodes not belonging to any element. Having such nodes in links may be dangerous, especially in MPI calculations. By default, the code checks for the presence of such nodes and stops with an error message if any are found. In some particular cases (old models) such nodes are present but this is not harmful. In such cases, one may use this option (under his responsibility) to disable the check and to avoid the error (the error is converted into a warning). Note that, in order to be effective, the `NOCU` option **must be placed before** the `LINK` directive.

`RIGI`

Introduce options related to the treatment of links for rigid bodies (new JRC formulation).

`DISP`

Express the links for rigid bodies on the displacements rather than on the velocities.

`CMID`

Compute the links coefficients for rigid bodies at the new mid-step rather than at the current full step.

`FLS`

This keyword introduces options which are specific of the `FLSR` and `FLSW` fluid-structure interaction models.

`CUB8 c8`

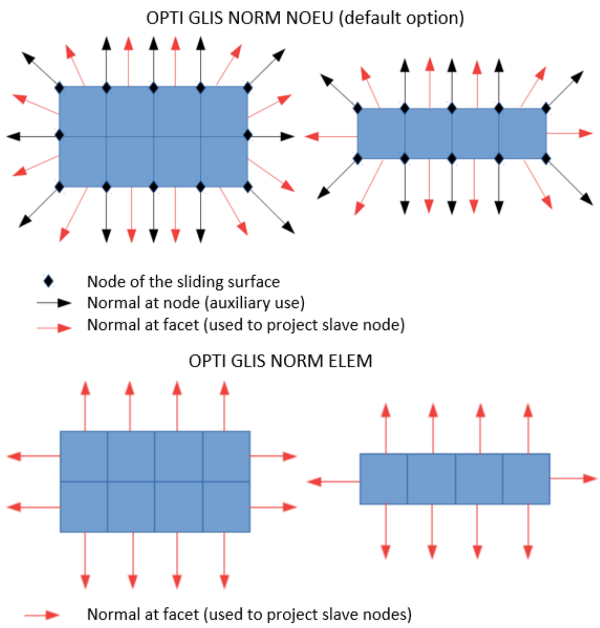
Sets the error level for inverse mapping in 8-node cube elements. By default it is 0, meaning that any error is treated as a real error. By setting it to 1, a lack of convergence in the inverse mapping procedure is not considered an error, but simply that the point considered lies outside the 8-noded cube. By setting it to 2, both a lack of convergence and a zero determinant are considered not as errors, but as an indication that the point considered lies outside the 8-noded cube. These options should be set only in problematic cases (and until the inverse mapping for the CUB8 shape is reformulated in a more robust way). Note that this option has effects only on the `FLSR` and `FLSW` models, in the tracking of flying debris embedded in a fluid, and in contact by pinballs, but not on other model which use CUB8 inverse mapping. Note also that this option has the same effect **also** upon inverse mapping in **3-node triangles in 3D**, but with the following meaning of the `c8` parameter: 1 means that $d_{\max} < \text{tol\_vol}$ is not considered as an error, while 2 means the above plus also $\text{abs(err)} > \text{tol\_dis}$ is not an error. Finally, this option has the same effect **also** upon inverse mapping in **4-node quadrilaterals in 3D** (which may be warped), but with the following meaning of the `c8` parameter: 1 means that performing too many iterations is not considered as an error, 2 means the above plus also that a 0 determinant is not an error, and 3 means all the above plus also the fact that the point does not lie on the quadrilateral surface is not considered an error. If you activate this optional switch, it is probably safer to use the value 2 (or 3, in the case of 3D quadrilaterals) anyway.

`ERCE`

Instead of an error message for not possible inverse mapping to get the centroid shape, the concerned element is eroded. This might be helpful to continue calculations with highly distorted elements and pinballs.

Comments:

Nodal or element methods can define the facet normals for contact detection and links generation. Both present advantages and drawbacks in different situations. Nodal approach produces smoother variations of the normal along the master side and may be useful for problems such as rolling bodies. In the case of strongly folded structures (for example, self-contact crashed bodies), element approach ensures better detection of contact between folds and should be preferred.



Considering the gap on slave side is the original way that was implemented in EUROPLEXUS. It has shown recently to potentially produce instabilities for strongly folded structures. In this case, considering the gap on master side has proved to be much more robust. The former approach remains the default until the latter is fully tested and validated.

Be sure to consult also the interactive commands for the visualization of pinballs and of contacts, see Pages A.25 and O.10.

When a fast search by cells grid is specified for the macro pinballs (or for the GPINs) in contact (`PINS|GPNS GRID ...`) and a large 3D problem is being solved with relatively few (but largely scattered) contacts, then one may easily generate an enormous number of cells and the memory required becomes prohibitive. In such cases, it may be convenient to do the search not as a unique scan but by several scans over contiguous "packs" (i.e. rectangular patches) of cells. Each pack or "macro cell" contains a number `ipac` of cells along each spatial direction. In addition, an extra cell is added along each boundary since the packs must be partially superposed for the algorithm to work. Thus in 2D the size of a pack will be (`ipac+2 * ipac+2`) and in 3D (`ipac+2 * ipac+2 * ipac+2`) cells. The search by packs is slightly slower than global search because of the increased number of operations and of the more complex algorithm, but the used memory might be much smaller (the user may reduce it by using a lower `ipac`).

12.19 OPTIONS FOR GRAPHICAL RENDERING

Object:

To provide options for the graphical rendering (OpenGL).

Syntax:

```
< REND < $[ FAST ; SAFE ]$ >
       < $[ NODU ; DUMP ]$ >
       < $[ NAVI ; NONA ]$ >
          <STAT>
          <FAC4 SPLI n TOLE eps>
          <SHAR <ANGL angl> <ABS>> >
```

`REND`

This keyword introduces the options related to rendering.

`FAST`

This option uses the fastest available algorithms for the in-software geometric calculations preliminary to geometric rendering operations (see `TRAC REND`). This is the default.

`SAFE`

This option uses straightforward (but inefficient) algorithms for the in-software geometric calculations preliminary to geometric rendering operations (see `TRAC REND`). It may be useful when one has doubts on the graphical results obtained with the fast version.

`NODU`

This option does not dump out data related to the in-software geometric calculations preliminary to geometric rendering operations (see `TRAC REND`). This is the default.

`DUMP`

This option dumps out on the listing data related to the in-software geometric calculations preliminary to geometric rendering operations (see `TRAC REND`). This may be useful for debugging purposes but it produces a big output file.

`NAVI`

This option declares that any changes in the following rendering operations will be due only to navigation (`NAVI`) around or inside a fixed (static) scene, so that use of `SAVE/REUS` becomes possible also in Lagrangian cases, see page O.0030. In this case the user is responsible for making sure that no geometrical data vary between a rendering and the next one(s): the mesh does not move, no elements are eroded, adaptivity does not modify the current mesh, etc. The option is useful in order to speed up preparation of an animation containing a navigation in a static scene containing Lagrangian nodes.

`NONA`

Disables the `NAVI` option set with a previous `NAVI` keyword so that the normal behaviour of the `SAVE/REUS` mechanism is restored, see page O.0030.

`STAT`

This option produces statistics on the allocations performed by the OpenGL graphics module on a special file `<basename>.ogl`. This is useful only for debugging purposes.

`FAC4`

This option introduces indications about how to render 4-node faces. By default each 4-node face is split into four triangles by generating an extra point at the face center. In this way the rendering of non-planar (warped) 4-node faces is best and does not depend upon face (or element) numbering. Also the representation of iso-values is best. However, a lot of memory is required. Memory can be saved, at the expense of a somewhat worse representation (and not completely numbering-independent), by treating them as a single quadrilateral.

`SPLI n`

The number of figures into which an almost-planar 4-node face is split. By default it is 4. It may be optionally set to 1. The value 2 was initially also foreseen, but it has still to be programmed and is not currently available.

`TOLE eps`

Tolerance ϵ to decide whether a 4-node face is planar or not. The face is considered planar if the scalar product between the two unit normals to triangles 1-2-3 and 1-3-4 obtained from the face is greater than $(1 - \epsilon)$.

`SHAR`

Introduces options related to the visualization of sharp corners.

`ANGL`

Sets the minimum angle α_0 (between two 3D faces with a common side) beyond which the side is considered to be a sharp corner. By default, this angle is 60 degrees. Let n_1 and n_2 be unit normals to the two faces. Then the scalar product $n_1 \cdot n_2 = \cos\alpha$ is equal to the cosine of α, the angle between the normals (which is also the angle between the faces). Thus the corner is sharp if $\cos\alpha < \cos 60°$, i.e. when $\alpha < 60°$.

`ABS`

Consider the absolute value of the above scalar product instead of the signed value. This has the following effect: when two faces have a common side and opposite (or nearly opposite) normals, the side is *not* considered sharp (while by default it would be). This option may be useful in the presence of complex 3D shell structures, because it is not always easy (and sometimes even impossible) to orient them consistently. With this option many "spurious" sharp corners disappear. Thus with this option the rule becomes: the corner is sharp when $|\alpha| < 60°$.

12.20 OPTIONS FOR MESH-ADAPTIVE COMPUTATIONS

Object:

To provide options for mesh-adaptive computations.

Syntax:

```
< ADAP < $[ NODU ; DUMP ]$ > <STAT> <CHEC> <RCON> <MAXL maxl> <NOPP>
       <RESE>
       < $[ PHAN CD cd <CV cv> ; DHAN < $[ DEPL ; VITE ]$ > ; WHAN ]$ >
       <PCLD $[ MODE imod ]$ $[ SMOO ]$ <DUMP> >
       <TRIG |[ CONT icon ; ECRO iecr ; EPST ieps ;
                DEPL idep ; VITE ivit ; ACCE iacc ; VCVI ivcv ]|
                TVAL tval /LECT/>
>
```

ADAP

This keyword introduces the options related to mesh-adaptive computations.

NODU

This option does not dump out data related to the mesh-adaptive computations. This is the default.

DUMP

This option dumps out on the listing data related to the mesh-adaptive computations. This may be useful for debugging purposes but it produces a big output file.

STAT

This option prints out on the listing some additional "statistical" data related to the mesh-adaptive computations. The increment in listing size is very small, but the calculation of these data requires some (small) computational effort, therefore they are not computed by default.

CHEC

This option performs some extra checks during mesh-adaptive computations. The CPU overhead is high, so the option should be used only for debugging. The checks are mainly of geometrical nature: consistency of neighbors and pseudo-neighbors, consistency of CCFV interfaces, etc. In case an inconsistency is detected, an extensive printout (dump) of the concerned data structure is made on the listing (which can become very big) and the code stops with an informative error message.

RCON

This option imposes a smooth refinement of the mesh, such that the difference in refinement level between two neighboring (or pseudo-neighboring) elements is at most 1.

MAXL

This option introduces an upper limit `maxl` to the level of refinement of the adptive mesh, for those types of adaptivity that do not allow to specify the maximum refinement level in their own syntax, e.g. `ADAP INDI` (see Page B.210). For the other types of adaptivity (e.g. `ADAP PCLD`), the maximum refinement level `MAXL` is specified directly in the corresponding `ADAP` directive, so the present option is still accepted with a warning message but it is ignored (it has no effect).

`NOPP`

Do not propagate MAXCURV and ERRIND to descendents upon elements split (only for debugging). By default they are propagated.

`RESE`

Upon un-splitting of a Q41L or Q42L element with a solid material (VM23 with linear elastic characteristics), recompute SIG and ECR from parent element nodal positions instead of doing averaging on child elements.

`PHAN`

Use penalty (decoupled) constraints on hanging nodes rather than Lagrange multipliers (fully coupled).

`CD cd`

Penalty coefficient on displacements.

`CV cv`

Penalty coefficient on velocities. This is zero by default.

`DHAN`

Use decoupled Lagrange-multiplier constraints on hanging nodes rather than fully coupled Lagrange multipliers.

`DEPL`

The decoupled Lagrange-multiplier constraints on hanging nodes are expressed on displacements. This is the default.

`VITE`

The decoupled Lagrange-multiplier constraints on hanging nodes are expressed on velocities rather than on displacements.

`WHAN`

Use “weak” decoupled constraints on hanging nodes rather than fully coupled Lagrange multipliers.

`imod`

Mode for mesh refinement using PCLD indicators. 1: refinement is homogeneous within one base cell (faster mesh adaptation, more cells, this is default), 2: refinement is heterogeneous with one base cell (slower mesh adaptation, fewer cells)

`SMOO`

Activates a smoothing step after mesh adaptation through PCLD criteria to avoid jumps of refinement levels between neighbor cells (option close to `ADAP RCON` option above for PCLD).

`DUMP`

Dumps out on the listing the PCLD internal data, but only in sequential calculations (it is ignored in MPI calculations). This option should only be used on small tests, for debugging purposes, since it will produce a huge output on the listing.

`TRIG`

Introduces a "trigger" which activates any forms of "automatic" mesh adaptivity present in the calculation only when a certain variable reaches a given value at a given location. The trigger affects following types of adaptivity models: `WAVE`, `INDI`, `PCLD`, `THRS` and `FLSR/FLSW`. The trigger has no effect on initial mesh adaptivity (`INIT ADAP`) or manually piloted adaptivity (`ADAP SPLI/USPL` interactive commands).

`CONT icon`

Set the trigger on stress component `icon`.

`ECRO iecr`

Set the trigger on hardening component `iecr`.

`EPST ieps`

Set the trigger on total strain component `ieps`.

`DEPL idep`

Set the trigger on displacement component `idep`. If one specifies 0 for `idep`, then the displacement norm of the first `IDIM` components is used.

`VITE ivit`

Set the trigger on velocity component `ivit`. If one specifies 0 for `ivit`, then the velocity norm of the first `IDIM` components is used.

`ACCE iacc`

Set the trigger on acceleration component `iacc`. If one specifies 0 for `iacc`, then the acceleration norm of the first `IDIM` components is used.

`VCVI ivcv`

Set the trigger on cell-centered velocity component `ivcv`. If one specifies 0 for `ivcv`, then the cell-centered velocity norm of the first `IDIM` components is used.

`TVAL tval`

Set the value which activates the trigger. The trigger is activated when the value of the monitored quantity exceeds `tval`. Once activated, the trigger remains active for the rest of the computation.

`/LECT/`

Specify the (single) element or the (single) node at which the specified variable is monitored.

12.21 STRAIN RATE FILTERING OPTION

Object:

The strain rate filtering option allows to damp high frequency vibrations wich are not physical and therefore to obtain more physical strain rate values.

Syntax:

```
"FVIT"      alpha
```

`alpha`

filter coefficient, must be of the order of the smallest element size.

Comments:

This option is still under development and testing and should therefore be used with great care. this option is available only for isotropic Von Mises material depending on strain rate (VMIS DYNA).

The default value when the present option is not activated is 1. (no filtering).

12.22 OPTIONS FOR PARALLEL COMPUTING

Object:

This section provides options for advanced parallel computing. This is still a work in progress and may be significantly modified in the future.

Syntax:

```
"DOMD" < "MANU" /CTIM/ >
       < "ADAP" >
```

`MANU`

Keyword used to enter a manual frequency for domain decomposition update

`ADAP`

Keyword used to trigger a domain decomposition each time the elements extension zones are exhausted (requires ADAP PCLD refinement indicators with OPTION ADAP PCLD MODE 2)

Comments:

Using `DOMD` keyword toggles the update of the domain decomposition (MPI only)using either a given frequency (MANU keyword) or the exhaustion of elements zones (ADAP keyword). It allows to take into account strong changes in the topology of the models (large displacements, failure and fragmentation or mesh adaptation for instance), making a static domain decomposition less and less efficient as the simulation progresses. Using DOMD ADAP allows avoiding to overdimension the extension zones (see ADAP directive in group A), for significantly improved computation and memory performance.

12.23 OPTIONS FOR GRADIENT DAMAGE MODELS

Object:

This section describes various numerical parameters for the gradient damage models `ENGR`, see 7.7.24. In particular, several options could be provided here for the parallel linear algebra library PETSc used to solve the structural scale damage evolution equation as a bound-constrained minimization problem.

Syntax:

```
< "ENGR"  < "MONI" >
          < "DEBG" >
          < "PROJ" >
          < "SAIJ" >
          < "PREC" >
          < "INIT" >
          < "EDOT" >
>
```

`MONI`

Activate the PETSc monitor which allows the user to obtain setting and convergence information of the specified solver via an additional log file `*_petsc.log`. On the top of this file are summarized the global Hessian matrix information (number of rows, of non-zeros, etc.) and the solver setting (minimization method, tolerances, underlying linear solver, underlying preconditioner used, etc.). Then the log file prints at every time step following information: `STEP`, the current time step, `ITER`, number of CG iterations, `FVAL`, value of the objective functional (quadratic function), `RNOM`, norm of the residual vector, and `REASON`, the convergence information. At the end of this file some profiling information is given through PETSc's `log_summary` command.

`DEBG`

This option provides various debugging information concerning for example nodes partitioning with PETSc convention.

`PROJ`

By default we prescribe the use of `GPCG` solver for such constrained minimization problems. It performs several gradient projections to identify the active (constrained by the bounds) nodes, and several subsequent conjugate gradient iterations to solve a reduced unconstrained minimization problem for all free (non-active) nodes. *This method is extremely efficient.*

However for comparison we also provide this option `PROJ` to use instead the conjugate gradient method for the unconstrained problem and then an *a posteriori* projection on the admissible space to satisfy irreversibility condition. Note however, that this method `PROJ` makes sense only when the damage constitutive law `AT` chosen by specifying `LAW 2` is used.

`SAIJ`

When this option is used, only the upper triangular portion of the Hessian matrix is stored by the classical CSR format in PETSc. The memory use is reduced, however in terms of computational efficiency/cost nothing is gained through comparison with the full storage format.

`PREC`

This option sets the tolerance norm type of the underlying CG linear solver to be `PRECONDITIONED`, *i.e.* using the inner product defined by the preconditioner matrix. This options has virtually no influence on the computational efficiency through tests.

`INIT`

This option is concerned with the initial condition of damage to model for example an initial crack along some given nodes. When the option `INIT` is activated, all neighboring nodes of the previous ones are also prescribed by the damage value. In case of an initial crack, all the nodes of an element along this crack are thus totally damaged. (Tensile-type) wave propagation is hence prohibited across the crack.

`EDOT`

This option activates strain-rate effects in the damage criterion.

13 GROUP I—TRANSIENT CALCULATION DEFINITION

Object:

The following directives define, run, verify (qualify) and stop the transient computation which has been defined with all directives given so far.

Furthermore, by means of a so-called "ED1D input deck" it is possible to perform a coupled 1-D/multi-D calculation, see also pages INT.80 and I.23.

Syntax :

```
<  "STRUCTURES"  . . .        >

<  "INTERFACES"  . . .        >

<  "XFEM"  ...                >

   "CALCUL"  . . .

<  "ED1D" {Eurdyn-1D input deck} "ED1D END" >

<  "PLAY" {interactive commands} "ENDPLAY" >

<  "QUALIFICATION"   . . .     >

$  "SUITE"  ;  "FIN"  $
```

These instructions are described in detail on the following pages.

13.1 STRUCTURES

Object :

This directive enables the use of the domain decomposition method that has been recently implemented in EUROPLEXUS. Therefore, only some of the elements are currently available, see the list below.

This directive is optional. However, when used it **MUST APPEAR BEFORE** the "CALCUL" directive.

Syntax :

```
"STRUCTURE" <"DTUN">
      |[ "AUTO" <"PMET"> <"ROB"> <"CINI"> ...
         ... <"WFIL" <ndwfil>> <"DACT" /LECDDL/> <"DPRE" ipre>
         ... <"REGU"> <"CART"> ;

            nbdo * (
            |[ "DOMA" /LECT/ <"IDEN" ndom> <$["DTMX" dtmx ; "DTFX" dtfx]$> ;
               "MODA" /LECT/ <"IDEN" ndom> ...
                     ... "FICHIER_VIBRATIONS" <FORMAT> <ndfich> ...
                     ... <"POST_TRAITEMENT" $["TOUS" ; "CHPO"]$ > ...
                     ... <"NOFO"> ]|
                    ) ]|
```

`DTUN`

Multiple time scales treatment (one per subdomain) is deactivated. Every subdomain has the same time scale (see comment below).

`AUTO`

MPI only. Automatic domain decomposition using available number of threads.

`PMET`

MPI only. ParMetis library is used to perform domain decomposition.

`ROB`

MPI only. Recursive Orthogonal Bisection algorithm is used to perform domain decomposition (see comment below).

`CINI`

MPI only. Automatic domain decomposition with ROB after a restart is performed using initial coordinates instead of current coordinates.

`WFIL`

MPI only. Use of an element weight file for automatic domain decomposition (see comment below).

`ndwfil`

MPI only. Number of the logical unit of the weight file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is .wgt.

`DACT`

MPI only. Selection of active directions (from 1 to 2 in 2D, from 1 to 3 in 3D) for automatic domain decomposition using ROB.

`ipre`

Number of the first cutting direction for automatic domain decomposition using ROB (see comment below).

`REGU`

MPI only. Activates a regularizaing step for ROB domain decomposition to avoid quasi-orphans (i.e. elements sharing a majority of their faces with elements from another sub-domain). The purpose is to optimize interfaces and to provide robustness for geometric operations associated with mesh adaptivity.

`NOOP`

MPI only. Activates an optimization step improving the splitting of elements located on located on a plane orthogonal to the actual cutting direction during ROB decomposition. Concerned grid cells are read through the LECTURE directive.

`nbdo`

Number of subdomains for fixed domain decomposition.

`/LECTURE/`

Indexes of the elements forming the current subdomain. Note that these must include also the indexes of the CLxx elements used to represent any *non-matching interfaces* belonging to the current subdomain (see directive `INTERFACE` below).

`DOMA`

This keyword introduces the definition of a subdomain.

`MODA`

This keyword introduces the definition of a subdomain represented by a modal basis.

`ndom`

Number to identify the subdomain when declaring the interfaces. If omitted, this number is the rank of the subdomain in the order of declaration of all the subdomains (including modal ones).

`dtmx`

Maximum time cycle imposed for the current subdomain (see comment below).

`dtfx`

Fixed (constant) time cycle imposed for the current subdomain (see comment below). This keyword is incompatible with the `dtmx` described above, and may be used only if the step is also user-driven (`OPTI PAS UTIL`). The given value `dtfx` should be an integer sub-multiple of the user-specified time step (typically `pasf`, see the `CALC` directive).

`ndfich`

Number of the logical unit of the file containing the modes and reduced matrices, or file name in quotes. If omitted, the program chooses a file name and unit number by default (see page A.27). The default extension is `.MSH` and the default unit number is 9, so that by default the modes are read from the same file that contains the CASTEM 2000 mesh (file <base_name>.msh).

`FORMAT`

If this keyword is present, the file is formatted, otherwise it is unformatted.

`TOUS`

Keyword meaning that all CHAMELEMS and CHAMPOINTS will be calculated within the modal subdomain.

`CHPO`

Keyword meaning that only CHAMPOINTS will be calculated within the modal subdomain (see comment below).

`NOFO`

Keyword meaning that no external forces will be calculated within modal subdomain in order to save computation time.

Comments :

The elements currently available for calculations with domain decomposition are:

`in 2D :`

```
COQU, TRIA, BARR, MEMB, CL2D, CAR1, CAR4, COQC, Q92 , Q93 , COQI,
ED01, CL2S, CL22, Q41L, Q42L, FUN2, T3VF, Q4VF
```

`in 3D :`

```
CUBE, COQ4, POUT, CL3D, BR3D, PR6,  TETR, PRIS, PMAT, CL3T, CUB8,
APPU, MECA, T3GS, FL38, DKT3, SHB8, FUN3, Q4G4, CL3Q, Q4GR, Q4GS,
ASHB, T3MC, TEVF, PYVF, PRVF, CUVF
```

The code initially performs the following checks:

1. The union of the defined subdomains must cover the entire domain.
2. The intersection of any two subdomains must be empty.

In a calculation by domain decomposition, the following terminology applies:

time cycle Is the time increment associated with a specific subdomain. It varies in general from subdomain to subdomain.

time step Is a (macroscopic) time increment common to all subdomains (global quantity). At the end of each one of these time steps, all subdomains are "synchronized" by solving the equilibrium equations without any interpolation. For this reason, time steps are also called **sync steps**. Printout and storage of results and in general any interaction with the user is only available at sync steps.

time stations An integer counter that counts the union (not the sum) of time cycles and time steps. It is incremented by 1 each time the code computes at least one subdomain.

It is important to note that users normally have limited control over time cycles, which are managed internally by the code according to the characteristics of each subdomain. All time-related quantities, such as for example those of the `CALCUL` directive (see page I.20) or the chosen instants for data printing and storage (see the `ECRITURE` directive, page G.70), concern time steps (i.e. sync steps) as defined above, and not time cycles.

The user may explicitly **control the sync step** in the following ways:

- By choosing the option `OPTI PAS UTIL` and by specifying a **constant** sync step in the `CALCUL` directive by means of `PASFIX pfix`. In this case, the sync step is constant and equal to `pfix`.
- By choosing the option `OPTI PAS UTIL` and by specifying a list of sync steps in the `CALCUL` directive by means of `HIST /PROG/`. In this case, the sync step evolves according to the specified time sequence given in `/PROG/`.
- By choosing the (default) option `OPTI PAS AUTO` and by optionally specifying a factor (see `SDFA sdfac` keyword in the `CALCUL` directive). The code computes the maximum of the stability times teps of the various subdomains, and multiplies this value by `sdfac` to obtain the sync step (by default, `sdfac` is 1.0). This calculation is performed at the end of each sync step, so the sync step generally varies in time. Note also that in this case the sync steps may be automatically adapted to match the chosen printing and storage times by specifying the option `OPTI STEP IO` (default) or `OPTI STEP IOT`, see page H.20. Furthermore, in this case the maximum sync step may be limited by specifying the `DTMA dtmax` keyword of the `CALCUL` directive.

The user may explicitly **control the cycles** in the following ways:

- By choosing the option `OPTI CSTA` that specifies the safety factor over the stability value. This factor applies to all elements, and therefore it equally affects all subdomains (global quantity).
- By specifying, for each subdomain, a limiting value of the associated time cycle, see the `DTMX dtmx` keyword above.
- By specifying, for each subdomain, a constant time cycle, see the `DTFX dtfx` keyword above.

Note, however, that within each time step the time cycles vary in general from subdomain to subdomain, and vary in time for a given subdomain, even in the case that the user chooses `OPTI PAS UTIL` and a fixed time step, except in the case that a fixed cycle value `dtfx` value is explicitly specified.

When the `DTUN` keyword is used, subdomains are forced to follow one unique time scale. According to options set in the `OPTION` directive and to stability conditions on all subdomains, one single time-step is computed at each cycle and given to each subdomain. Subdomains are thus always synchronized.

Since the behaviour of the present domain decomposition model as regards time stepping depends upon the corresponding user option (i.e. upon `PAS AUTO` or `PAS UTIL`), it is advised to specify the `STRUCTURE` directive **after** any options that set the time stepping mode (but **before** the `CALCUL` directive, as already noted).

When option `"POST" "CHPO"` is activated, the CHAMELEMS are to be computed out of EUROPLEXUS from the CHAMPOINTS with a linear elastic constitutive law, which is the only valid within a modal subdomain.

Example 1 :

```
   OPTION PAS AUTO STEP IO
...

   STRUCTURE 3
       DOMA LECT zone1 TERM IDEN 91
       DOMA LECT zone2 TERM IDEN 92 DTMX 5e-6
       MODA LECT zone3 TERM IDEN 93 FICH FORM POST TOUS
                            NOFO
   CALCUL TINI 0.0   DTMAX 40e-5  NMAX 80000 TFIN 350e-3
```

The computational domain consists of three subdomains. The stability time cycle of the first subdomain is computed automatically by the code. The stability cycle of the second subdomain is the minimum between the computed value and 5E-6. The third subdomain is replaced by a modal basis, with modes and matrices given in file '<base_name>.msh' (i.e. the same file that contains the CASTEM 2000 mesh). Both the CHAMELEMS the CHAMPOINTS but no external forces are computed within this subdomain. The sync step is automatically computed by the code as the minimum value between 40E-5 (`DTMAX`) and 1.0 times the maximum stability step over all subdomains (recall that by default `sdfac` equals 1.0). Furthermore, the selected printing and storage times will be precisely matched by adapting the sync step (`OPTI STEP IO`). The three subdomains are identified as `'91'`, `'92'` and `'93'` as far as interface declarations are concerned (see the `INTERFACES` directive next).

Example 2 :

```
   OPTION PAS UTIL
...

   STRUCTURE 3
       DOMA LECT zone1 TERM DTFX 1e-6
```

```
    DOMA LECT zone2 TERM DTMX 5e-6
    DOMA LECT zone3 TERM
CALCUL TINI 0.0   PASF 40e-5  NMAX 80000 TFIN 350e-3
```

The computational domain consists of three subdomains. The stability cycle of subdomain 1 is fixed to the constant value 1E-6. That of subdomain 2 is the minimum between its stability value and 5E-6. That of subdomain 3 is dictated only by local stability. The sync step is constant and has the value 40E-5. Printout and storage of results will occur at the sync steps whose times are greater than or equal to the chosen values. This is because the `OPTI STEP IO` or `OPTI STEP IOT` options may not be used in conjunction with `OPTI PAS UTIL`, i.e. the sync step (being constant) may not be adapted.

MPI calculations

With fixed domain decomposition, the number of parallel threads **must** be equal to the number of declared subdomains.

For automatic domain decomposition, an external file can be entered to provide elementary weights, in order to optimize load balancing. Each line of the weight file is composed of 2 integers: first the number of the concerned elementary entity (finite element, finite volume, SPH particle...), second the weight associated to it.

Classically, EUROPLEXUS is used to generate the weight file (see page I.20). To generate the file from scratch, elementary numbers can be found in the listing file of a previous run with the same model. Every elementary entity, except CL elements and debris elements, must be given a weight.

If no weight file is used, all weights are set to 1.

Automatic decomposition using **Recursive Orthogonal Bisection** consists in successive recursive splittings of the domain along available space directions with circular permutations among them. Some directions may be deactivated, either by the user (`DACT` keyword) or automatically by the program if the bounds of the model along these directions are too small.

By default, the first splitting direction is the one along which the spatial extension of the model is maximal. However, one specific starting direction can be forced using `DPRE` keyword.

Classically, each splitting involved in the algorithm consists in creating from 1 part of the model 2 subparts of equal weight, yielding that the number of used threads must be a power of 2. However, the proposed algorithm allows to use any number of threads, by adjusting the number of levels of the recursive decomposition and the number of subparts per part created at the last level, 2 subparts per part being created at every other levels.

For example, with 12 threads, 3 levels will be considered, with 3 subparts per part at the last level (2*2*3=12), whereas with 10 threads, 2 levels will be considered, with 5 subparts per part at the last level (2*5=10).

13.2 INTERFACES

Object:

This directive allows to set options for the treatment of connections between subdomains. It also allows the explicit declaration of interfaces between couples of sub-domains. These interfaces *may correspond to matching or non-matching meshes.*

In the case of matching meshes, interface declaration is optional, provided the interface nodes are the same (i.e., have the same index) for the two sub-domains. If only the geometric points are identical (i.e., coordinates are the same), but each subdomain has its own nodes (with different indexes), a compatible interface has to be declared (see the `COMP` keyword below).

In the case of non-matching meshes, this directive is **mandatory**.

The `STRUCTURE` directive must appear **before** this directive.

Syntax:

```
"INTERFACE" <"LINK"> < $[ "MULT" ; "NOMU" ]$ > <"NORE"> <"DUMP> ...

 ... < nbinterf * (
        |[ "COMP" ; "MORTAR" ; "OPTIMAL" ]| <"TOLE" tole>  ...

    ... "DOMAINE" ndom1 /LECTURE/  "DOMAINE" ndom2 /LECTURE/ ) >
```

`LINK`

Interface connections are coupled with other kinematic links declared with the `LINK` directive (not the `LIAI` directive). This option is mandatory if some declared links concern more than just one subdomain.

Using this option causes the option `DTUN` of the `STRUCTURE` directive to be activated (see comment below).

Note that by default, i.e. by *not* specifying `LINK`), interface connections are treated independently from any other kinematic links, which implies that no kinematic link involving more than one subdomain can be declared.

`MULT`

Every interface connections are treated by means of Lagrange multipliers. This is default.

`NOMU`

Interface connections with matching meshes and coincident nodes are treated directly with no Lagrange multipliers (faster solution). Non-matching meshes or matching meshes with duplicated nodes are still treated by means of Lagrange multipliers.

The optional keyword `LINK` must be specified if tt NOMU is specified.

Using this option causes the option `DTUN` of the `STRUCTURE` directive to be activated (see comment below).

`NORE`

Do *not* re-localize the nodes and the dofs of the links on the S/D to which they belong. By default, they are re-localized.

The optional keyword `LINK` must be specified if tt NORE is specified.

`DUMP`

Produce extensive dump on the listing (for debugging).

`nbinterf`

Number of interfaces.

`COMP`

Keyword declaring an interface with matching meshes.

`MORTAR`

Keyword declaring an interface with non-matching meshes, treated by the mortar method (see comment below).

`OPTIMAL`

Keyword declaring an interface with non-matching meshes, treated by the optimal method.

`tole`

Tolerance given to find matching nodes (default=1.E-3).

`ndom1`

Identification number of the first sub-domain (see `STRUCTURE` directive).

`ndom2`

Identification number of the second sub-domain.

`/LECTURE/`

In the case of matching meshes, indexes of the **nodes** forming the sub-domains interfaces.

In the case of non-matching meshes, indexes of the interface **elements** forming the sub-domains interfaces (see comment below).

Comments:

Handling multiple time scales in a multi-domain framework requires a special treatment of the interface connections using Lagrange multipliers. This treatment is not avalaible for generic kinematic links, so that multiple time scales option must be deactivated in order to couple interface connections to other kinematic links, which may thus involve more than one subdomain. This is done by automatically activating the `DTUN` option in the `STRUCTURE` directive. This is also the case when the treatment of connections between matching meshes with coincident nodes is accelerated by not using Lagrange multipliers. In those cases, multiple time scales in the model can still be taken into account by using the `PART` keyword in the `OPTION` directive.

When using the mortar method, the sub-domains whose mesh is used to discretize Lagrange multipliers has to be specified. It is the **second one** (`ndom2`) in the order of declaration of the sub-domains concerned by the interface.

When using interfaces with non-matching meshes, so-called `CLxx` elements (see pages INT.90 and INT.100) have to be affected to interface regions of each sub-domain. These elements **must** be given the "phantom" material (`MATE FANT`) with density equal to zero.

The treatment of non-matching meshes with 3D solid elements is restricted to hierarchical meshes. In this case, the mortar method and the optimal method are identical, and a mortar interface has to be declared, **with the second sub-domain corresponding to the finest mesh**.

The **mortar** method may be used with any element types in 2D, but only with shell element types in 3D. When using the **mortar** method with linear interfaces (2-noded element sides), there must be at least one geometrical point that has the same coordinates, within the tolerance `tole` defined above, in the two facing meshes. The node indexes (node numbers) of this point can be different in the two meshes. This is necessary because the interface model uses the point's coordinates internally in order to define a reference frame on the interface.

Example 1 :

```
   STRUCTURE 3
       DOMA LECT zone1 inte12 inte13 TERM IDEN 91
       DOMA LECT zone2 inte21 inte23 TERM IDEN 92
       MODA LECT zone3 inte31 inte32 TERM IDEN 93 FICH FORM 'fich.mrd'
                                          POST TOUS NOFO
...
   INTERFACE 3
       COMP TOLE 1.E-2
            DOMA 91 LECT inte12 TERM
            DOMA 92 LECT inte21 TERM
       MORTAR TOLE 1.E-2
            DOMA 92 LECT inte23 TERM
            DOMA 93 LECT inte32 TERM
       OPTIMAL
            DOMA 91 LECT inte13 TERM
            DOMA 93 LECT inte31 TERM
```

The computational domain consists of three sub-domains. Three interfaces are declared:

1. The first between sub-domain number `91` and sub-domain number `92` with matching meshes.

2. The second between sub-domain number `92` and sub-domain number `93` with non-matching meshes treated by the mortar method. The nodes of sub-domain number `93` are used to enforce kinematical continuity.

3. The third between sub-domain number `91` and sub-domain number `93` with non-matching meshes treated by the optimal method.

Note that `inte12`, `inte21` are nodes groups, whereas `inte23`, `inte32`, `inte13`, `inte31` are elements groups.

13.3 XFEM

Object :

This directive enables the use of the eXtended Finite Element Method (X-FEM). It uses a specific Level-set mesh to describe the crack in space.

The formulation of X-FEM is given by a standard part and an enriched one as follow:

$$\bar{\mathbf{U}} = \sum_{i \in \mathcal{N}} N_i(\mathbf{x})\mathbf{U}_i + \sum_{j \in \mathcal{N}^e} N_j(\mathbf{x})H(\mathbf{x})\mathbf{U}_j^e \tag{94}$$

This formulation allows to take into account a displacement discontinuity in the mechanical mesh (a crack). And the characterization of propagation law makes the crack propagate through the mesh without remeshing at any time. But enriched element are used in order to describe the discontinuity with additionnal degrees of freedom. The corresponding available elements are XCAR and XCUB for 2D and 3D.

References

The model is described in reference [855], [859].

Syntax :

```
"XFEM"    "NI"    ni    "NJ"    nj    "DX"    dx    "DY"    dy
          "XZER"  xzer  "YZER"  yzer  "FISX"  fisx  "FISY"  fisy
          "FISC"  fisc  "PRBX"  prbx  "PRBY"  prby  "PRBC"  prbc
          "ORDR"  ordr  "KICR"  kicr  "RAYO"  rayo  "CHOI"  choi
          "CR"    cr
         <"NK"    nk    "DZ"    dz    "ZZER"  zzer  "FISZ"  fisz
          "PRBZ"  prbz  "RPLA"  rpla  "NCOU"  ncou >
          /LECTURE/
```

`ni`

Number of subgrids in x direction.

`nj`

Number of subgrids in y direction.

`nk`

Number of subgrids in z direction (Default 1).

`dx`

Discretization of subgrids in x direction.

`dy`

Discretization of subgrids in y direction.

`dz`

Discretization of subgrids in z direction (Default 0.).

`xzer`

Position x0 of left bottom point of the mesh of the level-set.

`yzer`

Position z0 of left bottom point of the mesh of the level-set.

`zzer`

Position z0 of left bottom point of the mesh of the level-set (Default 0.).

`fisx`

Equation of the planned crack surface.

`fisy`

Equation of the planned crack surface.

`fisz`

Equation of the planned crack surface (Default 0.).

`fisc`

Equation of the planned crack surface.

`prbx`

Equation of the planned crack front surface.

`prby`

Equation of the planned crack front surface.

`prbz`

Equation of the planned crack front surface (Default 0.).

`prbc`

Equation of the planned crack front surface.

`ordr`

Paramater for level set algorithms (reinitialization, orthogonalization, propagation, extension).

`kicr`

Critical value for crack propagation.

`rayo`

Length to characterize average or integral ”near crack tip”.

`choi`

Parameter to choose: 1 for stress intensity factors (only 2D), and 2 for non-local stress near crack tip (2D and 3D).

`cr`

Rayleigh wave velocity (maximum crack velocity).

`rpla`

Length parameter to subcut element (choose around 3 times rayo).

`ncou`

Number of layer in thickness (1 in 2D, and Default 1).

`LECTURE`

List of the elements concerned (XCAR in 2D or XCUB in 3D).

The localization of the initial crack is given by 2 plans. The first one defines the surface of the crack by: (level-set ϕ_1)

$$fisx \cdot X + fisy \cdot Y + fisz \cdot Z + fisc = 0 \tag{95}$$

The corresponding level-set is:

$$\phi_1(X,Y,Z) = \frac{fisx \cdot X + fisy \cdot Y + fisz \cdot Z + fisc}{\sqrt{fisx^2 + fisy^2 + fisz^2}} \tag{96}$$

And the second one defines the front of the crack: (level-set ϕ_2)

$$prbx \cdot X + prby \cdot Y + prbz \cdot Z + prbc = 0 \tag{97}$$

The corresponding level-set is:

$$\phi_2(X,Y,Z) = \frac{prbx \cdot X + prby \cdot Y + prbz \cdot Z + prbc}{\sqrt{prbx^2 + prby^2 + prbz^2}} \tag{98}$$

The crack is the isozero ϕ_1 and the negative part of ϕ_2. Both level-sets are exported in paraview output with the keyword XLVL. So the representation of the crack in possible in paraview by doing the negative part of PHI2 on isozero PHI1.

Example 1:

```
...
  ECRITURE
         ...
       FICHIER FORMAT AVS PRVW FREQ 10
               VARI DEPL XLVL ECRO ECRC LECT 2 TERM
...
  XFEM
       NI 300    NJ 200     NK 100
```

```
        DX 0.0005 DY 0.0005  DZ 0.00025
        XZER 0.03 YZER 0.01  ZZER -0.004
        FISX -0.2 FISY 1.    FISZ 0.     FISC -0.026
        PRBX 5.   PRBY 1.    PRBZ 0.     PRBC -0.416
        ORDR 8    KICR 12.E6 RAYO 0.001  CHOI 2
        CR 250.   RPLA 0.003 NCOU 7
        LECT MAILX
 ...
  CALCUL TINI 0.0   DTMAX 40e-5  NMAX 80000 TFIN 350e-3
```

Bibliography:

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Moës N., Dolbow J., Betlytschko T., "A finite element method for crack growth without remeshing", *International Journal for Numerical Methods in Engineering* (1999) **46**:131–150.

Moës N., Gravouil A., Belytschko T., "Non-planar 3D crack growth by the extended finite element and level sets - Part I: Mechanical model", *International Journal for Numerical Methods in Engineering* (2002) **53**:2549–2568.

Gravouil A., Moës N., Belytschko T., "Non-planar 3D crack growth by the extended finite element and level sets - Part II: Level set update", *International Journal for Numerical Methods in Engineering* (2002) **53**:2569–2586.

Menouillard T., Réthoré J., Combescure A. and Bung H., "Efficient explicit time stepping for the eXtended Finite Element Method (X-FEM)", *International Journal for Numerical Methods in Engineering* (2006) **68**:911–939.

Menouillard T., "Dynamique explicite pour la simulation numérique de propagation de fissure par la méthode des éléments finis étendus", Thèse de Doctorat INSA de Lyon 2007.

13.4 "CALCUL" DIRECTIVE

Object:

This directive starts the time solution of a given problem. The keyword `CALCUL` is compulsory and should appear after the data sets A, B, C, D, E, F, G and H.

The user can specify the initial and final times of the computation, the value of or constraints on the time step and the maximum number of computation steps.

Syntax:

```
"CALCUL"   "TINI" tini  "TEND" tend
           < "NMAX" nmax                    >
           < "DTMI" dtmin                   >
           < "DTMA" dtmax                   >
           < "TFAI" tfai                    >
           < $[ "HIST" /PROG/ ; "PASFIX" pfix ]$ >
           < "PAS1" pasone                  >
           < "SDFA" sdfac                   >
           < "LBMS" nfreq                   >
           < "LBNS" nstep                   >
           < "LBMD" mxdev                   >
           < "LBST"                         >
           < "LBPW" ndwfil                  >
           < "LBFT"                         >
```

`tini`

Initial time of the computation. In case of a restart run, this value is ignored (it may actually be left out), since the actual initial time is set to the value read from the restart file.

`tend`

Final time of the computation (the keyword `TFIN` is also accepted as a synonym of `TEND`).

`nmax`

Maximum number of computation steps (see comments below). Default is 1000000.

`dtmin`

Minimum value for the time step. Is only considered in a `PAS AUTO` or `PART` calculation. Default is 1.D-12 at JRC.

`dtmax`

Maximum value of the time step. Is only considered in a `PAS AUTO` or `PART` computation. Default is 1.D12.

`tfai`

Elements having a smaller stability time step than this value are eroded (failure). Note that the chosen value applies to *all* elements in the mesh. However, only those elements that possess an "erodible" material (see `EROS` directive on page A.30 for more information) are actually eroded. Whenever an element is eroded due to this criterion, the element characteristics at the moment of the erosion are written on the listing. This may allow to check *a posteriori* why the element's stability dropped below the specified value (e.g., excessive distortion of the element).

`HIST`

Can only be used in `PAS UTIL` cases. The following `/PROG/` procedure defines the actual 'time history' of the computation, i.e. all the times for which the solution will be computed. In this way, the user assumes complete control over the time step. No check on minimum or maximum values are performed. Time steps are computed as the difference between two successive specified times. The initial time of the computation should not be specified in the `/PROG/`.

`pfix`

This is a short-cut to assign a user defined time step that remains fixed in time. Can only be used in `PAS UTIL`.

`pasone`

This option allows to specify the value of the time increment used during step 0 and is only useful for `PAS AUTO` cases. In particular, it is mandatory to use it in the case of an advection-diffusion calculation, because in such a case the program does not compute the first time increment automatically. Another useful case is in the presence of energy injection in MC (multicomponent fluid) calculations, in order to use a smaller initial deltat than that automatically computed by the code. In order to let the time increment grow slowly, use can be made of the `DTVA` option (see Options related to the time step).

`sdfac`

Factor for subdomains computations. This optional keyword is only relevant in multi-domain calculations (see `STRUCTURE` directive on page I.15) that use automatic calculation of the time step (`OPTI PAS AUTO`). In this case, the sync step common to all subdomains is automatically chosen as `sdfac` times the **largest** stability step of the various subdomains. By default, `sdfac` equals 1.0.

`nfreq`

MPI only. Number of time-steps between two load-balancing measuring periods (see comment below).

`nstep`

MPI only. Number of time-steps within a load-balancing measuring period (see comment below).

`mxdev`

MPI only. Maximum standard deviation for load-balancing quality estimation (see comment below)..

`LBST`

MPI only. Stop calculation if previous maximum standard deviation is exceeded for elementary tasks balance (see comment below).

`LBPW`

MPI only. Print elementary weight file at the end of each load-balancing measuring period (see comment below)..

`ndwfil`

MPI only. Number of the logical unit of the weight file or file name in quotes. If omitted, the program chooses a file name by default (see page A.27). The default extension is .wgt.

`LBFT`

MPI only. Enable filtering of measured computational costs before writing weight file (see comment below).

Comments:

The word `CALCUL` is compulsory and should appear only once.

If a user does not have an idea of the stability step for a given problem, he can run the program with the

If a user specifies `PAS UTILISATEUR`, he is responsible for the stability of the computation, because EUROPLEXUS does not check the stability in this case. This option may therefore lead to instabilities in the calculation, and should only be used in special cases.

The maximum value of the time step enables the time step to be limited in the case of the option `PAS AUTOMATIQUE` or `PARTITION`.

For very long computations, when NMAX could exceed the value 999999999, the number of steps should be specified in a floating-point format. In such a case, the maximum value accepted is 2.E9. Note that the step number will no more be printed correctly being replaced by stars.

The computation stops when either the maximum number of steps or the final time is reached. A computation in `PAS AUTO` or `PART` also stops if the stability step becomes lower than the minimum value.

If `HIST` is used, remember to dimension adequately (see `TTHI` on page A.105).

Note that, in multi-domain computations, all time-related quantities in the `CALCUL` directive refer to sync steps and not to subdomains cycles (see directive `STRUCTURE` on page I.15).

Load-balance measuring for MPI calculations

This section is still under strong development.

Load-balance is a key point to achieve parallel performance. Load-balance measuring consists in measuring time taken by each thread to perform computational tasks within a given number of time steps.

The first measuring period starts at the first step of the simulation. After that, the number of time steps between the starting steps of two successive measuring periods is given using `LBMS` keyword. Measuring options are activated as soon as a positive integer is read after `LBMS keyword`.

The number of time steps within a measuring period is given using `LBNS` keyword, which should be smaller than the interval between two measuring periods to produce accurate results. Default value is 100.

Quality of load-balance is estimated through the value of the standard deviation of the quantity of interest. If the quantity is well distributed among the threads, standard deviation should be close to 0. 2 quantities are currently considered: first, the time needed to perform elementary computations, which is controlled by the quality of domain decomposition, second, the time needed to perform every computational tasks, including treatment of links. `LBMD` is used to enter a maximum authorized standard deviation for both quantities, generating a warning message if it is overcome at the end of a measuring period. The calculation can be forced to stop in the case of unauthorized standard deviation concerning elementary computations (`LBST` keyword), as it indicates that domain decomposition should be improved.

Using time measures during a period, the program is able to estimate the computational cost of elementary entities (finite elements, finite volumes, SPH particles...), as far as elementary operations only are concerned. A weight file can be written using `LBPW` keyword, to be used to improve automatic domain decomposition (see page I.15).

Measured weights can be filtered prior to file writing, to account for numerical noise in measures due to execution environment. Current filter consists in computing a global cost for groups of elements instead of individuals. Elements are grouped with respect to the couple of parameters (type of element, type of material). Group weight is then equally divided among concerned elements.

This can produce bad results and should be used with care. Raw weights and filtered weights can be visualized using PVTK output file.

13.5 ED1D INPUT DECK

Object:

This directive allows to specify a so-called "EURDYN-1D input deck", i.e. a set of input data to be read by the EURDYN-1D module (ED1D) that is now embedded within EUROPLEXUS. In this way it is possible to perform a coupled 1-D/multi-D calculation, as described on page I.80.

The ED1D input deck must be included within the normal EUROPLEXUS input file, immediately after the CALCUL directive and before any additional EUROPLEXUS directives (for example, QUALIFICATION).

The ED1D input deck must be immediately preceded by a line containing `ED1D` (capitals, starting in column 1, followed only by blanks if any) and be immediately followed by a line containing `ED1D END` (capitals, starting in column 1, followed only by blanks if any).

Syntax:

```
. . .
"CALC" . . . (see CALCUL directive, page I.20)
*
*=======================================================
ED1D
(as many ED1D data as needed to describe the 1D part of
the numerical model)
ED1D END
*=======================================================
*
<"PLAY" . . . or "QUAL" . . . or "SUIT" or "FIN">
```

Comments:

The keyword `ED1D` must appear as such and start in column 1. There must not be any other data on the same line.

The keywords `ED1D END` must appear as such and start in column 1. There must not be any other data on the same line.

The contents of the ED1D data deck proper (i.e. the lines contained between `ED1D START` and `ED1D END`) is described in the EURDYN-1D manual, listed in the References: ([33]).

By default, EUROPLEXUS reserves a memory of 50,000 REAL*4 for the ED1D data. If necessary the size of this memory can be increased by the `DIME ME1D` keyword, see Page A.67.

13.6 PLAY (interactive commands)

Object:

This directive allows to execute a set of "interactive" commands, i.e. any of the commands described on Pages A.25 and O.10, by reading them from a file (actually, from the regular EUROPLEXUS input file) rather than from the keyboard.

If present, this directive must immediately follow the `CALC` directive (and the optional `ED1D ... ED1D END` directive, if present).

Normally, interactive commands are typed by the user at the keyboard. With the present directive, it is possible to store such commands in the regular EUROPLEXUS input file, with the advantage that a given "interactive" calculation may be repeated identically as many times as needed.

This feature is especially useful for the automatic execution of calculations with intermediate visualizations (`TRAC`) and for the automatic generation of animations (`AVI`).

After reading the `PLAY` directive, the code continues to read the following commands from the regular EUROPLEXUS input file, but interprets them as interactive commands (i.e. like if they were typed at the keyboard), until the termination sequence `ENDPLAY` is encountered. Then, normal input file reading (again from the regular EUROPLEXUS input file) is restored.

Syntax:

```
. . .
"CALC" . . . (see CALCUL directive, page I.20)
*
<"ED1D" {Eurdyn-1D input deck} "ED1D END">
*
*==================================================================
PLAY
(as many 'interactive' commands (see Pages A.25 and O.10) as needed)
ENDPLAY
*==================================================================
*
<"QUAL" . . . or "SUIT" or "FIN">
```

Comments:

The keyword `PLAY` must appear as such and start in column 1. There must not be any other data on the same line.

The keyword `ENDPLAY` must appear as such and start in column 1. There must not be any other data on the same line.

The available interactive commands are listed on page A.25.

13.7 QUALIFICATIONS

Object :

This directive allows to verify (qualify) the results of a calculation by comparing them with given reference values.

The keyword `VALIDATION` is still accepted in place of `QUALIFICATION` for backward compatibility. However, new input files should always use the keyword `QUAL`.

The qualification is normally done at the final time of the transient calculation. However, when reading a results file it can also be done at an intermediate time by using the `SORT ARRE` commands, see comments below and Page ED.40.

Yet another possibility is that of doing a qualification *interactively*, i.e. on-the-fly (as the calculation is beig performed interactively) at the *current step*. See the interactive `QUAL` command on page O.10. Since the syntax of the `QUAL` directive is a bit complicated to be typed interactivey, this possibility is probably most useful from within a `PLAY ... ENDP` directive.

Syntax :

```
"QUAL" <"AUTO"> (  |[  "COOR" ; "DEPL" ; "VITE" ; "ACCE" ; "FEXT" ;
                       "MASN" ; "ADFT" ; "MCPR" ; "MCRO" ; "MCTE" ;
                       "MCVI" ; "MCMF" ; "SIGN" ; "ECRN" ; "FINT" ;
                       "FLIA" ; "FDEC" ; "PFSI" ; "PFMI" ; "PFMA" ;
                       "CONT" ; "EPST" ; "ECRO" ; "ENEL" ; "RHO"  ;
                       "MASE" ; "EPAI" ; "VCVI" ; "RISK" ; "DEBR" ;
                       "BILA" ; "WINT" ; "WEXT" ; "WCIN" ; "WECH" ;
                       "TIME" ; "WFIS" ;
                       "COUR" icourb <"AT" xval> >               ]|

                   $[ |[ "COMP" icomp ; "NORM" ]| <"GAUS" igaus>  ]$
                   ![ "REFE" valref    "TOLE" valtol  ]!

                        /LECTURE/  )
```

`AUTO`

Automatic qualification, see comments below. This keyword should be used only in very special cases.

`COOR ... PFMA`

Name of the nodal variable to be checked: `COOR` (coordinate), `DEPL` (displacement), `VITE` (velocity), `ACCE` (acceleration), `FEXT` (external force), `MASN` (nodal mass), `ADFT` (advection-diffusion temperature), `MCPR` (finite volume pressure), `MCRO` (finite volume density), `MCTE` (finite volume temperature), `MCVI` (finite volume velocity), `MCMF` (finite volume mass fraction), `SIGN` (spectral element stress at nodes), `ECRN` (spectral element internal variable at nodes), `FINT` (internal force), `FLIA` (force due to LIAI/LINK COUP), `FDEC` (force due to LINK DECO), `PFSI` overpressure due to FSI, `PFMI` minimum FSI overpressure in time, `PFMA` maximum FSI overpressure in time.

`CONT ... DEBR`

Name of the element variable to be checked: `CONT` (stress), `EPST` (total deformation), `ECRO` (internal variable), `ENEL` (internal energy), `RHO` (density), `MASE` (element mass), `EPAI` (thickness), `VCVI` (FV centroid velocity). `RISK` (Human risk model. COMP 1: Death; COMP 2: Eardrum rupture; COMP 3: Max. overpressure; COMP 4: Impulse). `DEBR` (Flying debris model. COMP 1: Current flying area for an active debris particle, current impact area for an inactive debris particle (marker); COMP 2: Current activity flag for a debris particle: -1 for an unused debris, 0 for an inactive debris (marker), $+1$ for an active debris (particle)).

`COMP icomp`

Number of the component concerned (for nodes or elements only).

`NORM`

For vectorial quantities, such as velocities, this causes the code to compute the norm of the first IDIM components (length of the vector). For other types of quantities requesting the norm may be illegal and in this case it raises an error.

`igaus`

Number of the Gauss point (integration point) concerned (for elements only). By default `igauss`=1.

`BILA ... WFIS`

Name of the global variable associated with the energy balance for the whole calculation, which allows to monitor the stability and the energy transfers: `BILA` energy balance, `WINT` internal energy, `WEXT` work of the external forces, `WCIN` kinetic energy, `WECH` energy exchanged with the external world, injected or lost, `TIME` physical time, `WFIS` fracture surface energy. For these parameters, the component and `/LECTURE/` are redundant.

`COUR icourb <AT xval>`

icourb is the number of the curve defined in GRAPH directive. For this parameter, the component and `/LECTURE/` are redundant. The optional `AT xval` parameter allows to define the x-value (usually the time) at which the y-value from the given curve should be extracted for the qualification. Linear interpolation and constant extrapolation (for x-values outside the range of definition of the curve) are used to compute the value from the curve. It is assumed that the x-values of the curve are monotonically increasing. This condition is satisfied for the most common types of curves (e.g. curves in time or in space), but it might be not satisfied for other more complex types of curves.

`valref`

Reference value expected.

`valtol`

Relative tolerance. If a **negative** value is specified, the qualification is ignored, i.e. it is always considered valid. This feature should only be used during the code evolution process, when it is necessary to temporarily disable a certain qualification, in view of forthcoming changes in the code source which will have an influence on the results.

`LECTURE`

Number of the node or element concerned.

Comments :

Only one node or element must be concerned by the validation.

The specification of a Gauss point makes sense only for parameters related to elements, such as: `CONTR`, `EPST` or `ECRO`.

It is possible to check as many values as needed, by repeating the name of the variable. The calculation will be considered correct if **all** checks are correct.

By default the qualification is done at the final time of the calculation. When reading a results file, it is possible to perform the qualification at a different time (not the final one), by using the `SORT ARRE` command, see Page ED.40. This can be useful in case the “signal” (monitored quantity) to be checked has either a very small value or a very large time derivative at the final time, while it has a more “stable” value (plateau) at a previous time.

It is sometimes tedious to prepare an input data set for a new test case or benchmark calculation, especially when many quantities must be verified. In some cases, the reference values are not well known a priori from physical considerations, analytical solutions or experimental data. Therefore, sometimes these values are computed by the code itself.

Although this is in some sense a misuse of the `QUAL` directive (because it is no longer a true qualification of results!), it may be useful e.g. to verify non-regression of code results during the development phase.

In such cases, the `AUTO` directive may speed up the process of preparing the input file, in the following way. First, write the qualification directives for the desired quantities, but by setting arbitrary reference values (e.g. all zero). Specify the `AUTO` directive immediately after `QUAL` and run the code.

In this way, qualification is computed normally, but for each verified quantity the code writes on the listing an extra line, introduced by the sequence `AQ:`, and containing the qualification directive with the 'correct' reference value (i.e. the one found by the code).

By searching all such lines in the listing, cutting them and pasting into the input file, it is possible to obtain a ‘correct’ input file much more rapidly (and with less errors) than by typing in the correct reference values by hand. Do not forget to remove the AUTO keyword once done the job.

Example of using the command `COUR`:

```
GRAPH
```

```
 COURBE 52 'RR-P2' distance lecture OO P2 term
...
QUALIF COURBE 52  REFE 1.2      TOLE 1e-4
```

Outputs :

The expected and obtained values are printed on the listing, together with the relative error, which is compared with the tolerance.

For each correct (respectively incorrect) check, the phrase: `==> VALIDATION : SUCCES` is printed on the listing (resp. `==> VALIDATION : ECHEC`).

At the end of the calculation, if all is fine the phrase: `==> LE CALCUL EST CORRECT !` is printed, else: `==> LE CALCUL EST FAUX !`.

13.8 "SUITE" OR "FIN"

Object :

The word "SUITE" written immediately after the instruction "CALCUL" enables the next data set to be read, and the corresponding case to be processed, immediately after the first (or current) computation.

Using the word "SUITE" placed after each data set, the user can enter as many data sets as he wants.

The last set must end with the word "FIN".

Syntax :

```
$[  "SUITE"  ;  "FIN"  ]$
```

Comments :

The word "SUITE" is the only word of the directive. It must immediately follow the instruction "CALCUL" .

The word "FIN" is compulsory at the end of the data.

14 GROUP ED—POST-TREATMENT BY EUROPLEXUS

Object:

To post-treat a results file containing the EUROPLEXUS results from a previously executed transient calculation.

Syntax :

```
 1/ General syntax :

   ... title ...

  <"ECHO">

  <"OPNF"  . . . >

   "RESUL"  . . .

  <"DIME"   . . .  "TERM">

   "SORT"     $   "ARRET"      . . .   $
              $                        $
              $   "FICHIER"    . . .   $
              $                        $
              $   "ECRITURE"   . . .   $
              $                        $
              $   "GRAPHIQUES" . . .   $
              $                        $
              $ ( "VISUALISER" . . . ) $

  <"QUAL" . . . >

   "FIN"
```

Comments:

These directives are described in detail on the following pages, except for the `QUAL` directive, which has been already presented on page I.25.

The following page shows a full synopsis of the EUROPLEXUS post-treatment directives.

```
 ... title ...
<ECHO> <OPNF  . . . >
 RESU <FORM>
      |<SPLI> ALIC;ALIC TEMP;UNIV <CURR>;UNIV OBSO|
      |nban;'nom_fich'| <GARD> <PSCR>
<DIME <TIMP nimp> TERM>
<FONC ..., see page E.15>
 SORT $ ARRE <TEMP time;NUPA npas;NSTO nsto>                          $
      $ FICH <FORM> nfic $FREQ nfre;TFRE tfre  $                      $
      $                  $NUPA /LECT/;PASM pasm$                      $
      $ ECRI <COOR> <DEPL> <VITE> <ACCE> <FINT> <FEXT>                $
      $      <CONT> <EPST> <ECRO> /CTIM/                              $
      $      <NOPO;POIN /LECT/> <NOEL;ELEM /LECT/>                    $
      $      <FICH <FORM> K200 ndca /CTIM/ POIN /LECT/ <CHAM>>        $
      $ GRAP AXTE coef 'nom_axe_Ox'                                   $
      $   <MINM> <FENE tmin tmax>                                     $
      $   <PERF 'nom_fic'> <PERK 'nom_fic'>                           $
      $   (COUR nuco <'nomcourbe'>                                    $
      $     $WINT;WEXT;WCIN;BILA;WSUM;DTMI;DTMA;MXSU$ <COMP ico>      $
      $     $COOR;DEPL;VITE;ACCE$                                     $
      $     $FORC;ADFT;MCPR;MCRO$                                     $
      $     $MCTE;MCMF;SIGN;ECRN$                                     $
      $     $LFNO;LFNV;ILNO;DTNO$ $COMP ico;NORM$ NOEU /LECT/         $
      $     $CONT;ECRO;EPST;ENEL$                                     $
      $     $WAUX;LFEL;LFEV;DTEL$ COMP ico <GAUS igau> ELEM /LECT/    $
      $     $VCVI$                $COMP ico;NORM$      ELEM /LECT/    $
      $     $SOMM nbrs*(courbe_i coef_i)$                             $
      $     $PROD pcoef nbrp*(courbe_k) $                             $
      $     $INTE courbe_i            $                               $
      $     $DIST /LECT/              $                               $
      $     $LIBR                     $                               $
      $     $MASS;VOLU;BARY;VMOY$                                     $
      $     $IMPU;ECIN;EINT;EEXT$                                     $
      $     $EPDV;EINJ;RESU;IRES$                                     $
      $     $ECRG;DT1           $ <COMP ico;NORM> <REGI nure>)        $
      $   (LCOU nuco <'nomcourbe'> <FICH 'nom_fich'>                  $
      $     $STEP;TCPU;DTCR;ELCR;DEE $                                $
      $     $DMMN;DMME;DTMX;ELMX;VMAX$                                $
      $     $NVMX;ELST;MEMO;MEMP$ <NMAX nmax>)                        $
      $   (SCOU nuco <'nomcourbe'> <$T t;NPAS npas;NSTO nsto$>        $
      $                         SAXE scoe 'nom_saxe' <INIT> /LECT/    $
      $     $COOR;DEPL;VITE;ACCE$                                     $
      $     $FORC;ADFT;MCPR;MCRO$                                     $
      $     $MCTE;MCMF;SIGN;ECRN$                                     $
      $     $LFNO;LFNV;ILNO;DTNO$ $COMP ico;NORM$                     $
      $     $CONT;ECRO;EPST;ENEL$                                     $
      $     $WAUX;LFEL;LFEV;DTEL$ COMP ico <GAUS igau>)               $
      $   (RCOU nuco  'nomcourbe'  FICH 'nom_fic'                     $
      $         <RENA 'new_name'> <FACX fx> <FACY fy>)                $
      $   (DCOU nuco <'nomcourbe'> $npt*(x y);FONC ifon$)             $
      $   ($TRAC;XMGR$                                                $
      $    $K200;LIST$ (nuco) <PS <TEXT>;MIF> AXES coef 'nom_axe_Oy'  $
      $                    <XAXE nxax coex 'nom_axe_Ox'>              $
      $                    <COLO (co)> <THIC (th)> <DASH (da)>        $
      $                    <XZER> <YZER> <XGRD> <YGRD> <XLOG> <YLOG>) $
      $ (VISU $T t;NPAS npas;NSTO nsto$                               $
      $   <PLAY>                                                      $
      $     <sequel of interactive commands, see pages A.25, O.10>    $
      $   <ENDPLAY>)                                                  $
<QUAL ..., see page I.25>
 FIN
```

14.1 TITLE AND CHOICE OF RESULTS FILE

Object:

The user gives a title and specifies the file (or files) from which the results to be edited will be read. The file(s) must have been produced during a previous execution of EUROPLEXUS (or during a previous phase of a composite execution, where the various phases are separated by the keyword `SUIT`).

Currently, results may be edited from any of the following file types:

- An ALICE file (either single or split);
- An ALICE TEMPS file;
- A file of type UNIVERSAL CURRENT;
- A file of type UNIVERSAL OBSOLETE.
- A file of type POCHHAMMER.

However, note that a file of type POCHHAMMER can only be read *in addition to* a file of the other types (usually an ALICE file). It cannot be read in by itself.

Syntax :

```
/TITLE/

<"ECHO">

<"OPNF"  < "FORMAT" >  nfic  'nom.fic'>

"RESUL" (<"FORMAT">
         |[ < "SPLI" > "ALIC" ; "ALIC" < "TEMP" > ;
              "ALIT" ; "POCH" ;
            "UNIV" <"CURR"> ; "UNIV" "OBSO" ]|
         $[ nban ; 'nom_fich' ]$
         <"GARDE">
         <"PSCR"> )
```

`"ECHO"`

Like for a normal calculation, this keyword indicates that the EUROPLEXUS input directives will be echoed in the execution window.

`"OPNF"`

This option may be used to open the chosen results file, like for a normal calculation. Refer to page A.28.

`"FORMAT"`

This keyword indicates that the chosen results file is a formatted file. By default, this file is unformatted.

`"SPLI"`

The chosen results file is a set of ALICE split files rather than a single file, produced by the directive `ECRI ... FICH SPLI ALIC ...`, see page G.70.

`"ALIC"`

The chosen results file is an ALICE file (this is the default).

`"ALIC TEMP"` **or** `"ALIT"`

The chosen results file is an ALICE TEMPS file.

`"POCH"`

The chosen results file is a POCHHAMMER file (which is being read in addition to another results file).

`"UNIV CURR"`

The chosen results file is a file of type UNIVERSAL CURRENT. The keyword `CURR` may be omitted in this case since this is the default for a file of type UNIVERSAL.

`"UNIV OBSO"`

The chosen results file is a file of type UNIVERSAL OBSOLETE.

`nban`

Number of the logical unit on which the results file is stored.

`nom_fich`

Name of the results file, enclosed in single quotes.

`"GARDE"`

This keyword allows to keep for the drawings the title read in the results file. Else, it is the title defined above.

`"PSCR"`

This keyword allows to produce the plots resulting from the `GRAP` directive in PostScript. Since 1995 it is the default, so that this keyword id redundant now.

Comments:

The word `RESULT` is compulsory.

When it is present, only an edition of results may be done and not a normal calculation.

14.2 DIMENSIONING

Object :

Allocation of memory for the post-treatment of a results file by means of EUROPLEXUS.

If one limits itself to graphical output, EUROPLEXUS automatically allocates the necessary space, so it is no longer necessary to give dimensions. This directive must therefore be omitted in that case.

Syntax:

```
"DIME"

  <    "TIMP"    nimp  >

"TERM"
```

`nimp`

Number of time steps for which printing on the listing is requested (see option `/CTIM/` of `ECRI` on page ED.50).

14.3 OUTPUTS

Object :

The following directive enables the types of output to be chosen.

Syntax:

```
"SORT"
   $   "ARRET"  <"TEMPS" time ; "NUPAS" npas ; "NSTO" nsto>  $
   $                                                         $
   $   "FICHIER"    . . .                                    $
   $                                                         $
   $   "ECRITURE"   . . .                                    $
   $                                                         $
   $   "GRAPHIQUES" . . .                                    $
   $                                                         $
   $ ( "VISUALISER" . . . )                                  $
```

`ARRET`

This directive allows to stop reading the results file at the time instant, at the time step or at the time station corresponding to values `time`, `npas` or `nsto`, respectively, specified in the directive, rather than reading the whole file. Note that a storage station is always produces at step 0 (beginning of the transient calculation): this storage station has the index `nsto=0`. This directive is only useful for the qualification of a calculation at intermediate times (and not at the final time as per default), since it may **not** be combined with the other directives `FICH`, `ECRI`, `GRAP` and `VISU`, as indicated in the syntax. For more details on the qualification, see directive `QUAL` on Page I.25. Note also that qualification (from a post-processing PostScript curve) at a user-defined time (not the final time) can also be obtained by the `QUAL COUR AT` command, see Page I.25 without using `ARRE`.

`FICHIER`

To extract from the chosen results file a certain number of computation steps, and to store them in a new results file which will typically contain less information (less storage stations).

`ECRI`

To print out results on the EUROPLEXUS listing.

`GRAP`

To produce graphic outputs. The curves of certain variables are drawn with respect to time or are printed on file(s) in a variety of possible formats.

`VISU`

To produce (a subset of) the visualizations that are possible during direct execution of the code (see Pages A.25 and O.10). These include graphical rendering either interactively in a window or in batch mode on a file and production of animations. Not all visualization types and features are available, though (see below for details).

Comments:

The keyword `SORT` should appear only once in an input data sequence. Note, however, that the `VISU` sub-directive may be repeated as many times as needed inside the `SORT` directive.

The directives `ARRE`, `ECRI`, `GRAP`, `FICH` and `VISU` are mutually exclusive.

In the case that a graphical output is requested (`GRAP ... TRAC`), the produced file is in the PostScript format (a product of Adobe Co.).

14.4 CREATING A REDUCED RESULTS FILE

Object:

To extract a certain number of computation steps from the chosen results file, in order to create a new results file which has the same structure as if it was created directly, but typically contains less information (less storage stations).

Syntax:

```
"FICHIER" < "FORMAT" >  nfic    |[  "FREQ"       nfreq        ;
                                    "TFREQ"      tfreq        ;
                                    "NUPAS"     /LECTURE/     ;
                                    "PASMAX"     pasmax       ]|
```

`FORMAT`

This keyword indicates that the new file created will be formatted. By default, it is unformatted.

`nfic`

Logical number of the new file.

`nfreq`

All the results whose step number is a multiple of `nfreq` are extracted from the results file.

`tfreq`

Time interval between two extracted results.

`/LECTURE/`

List of the step numbers to be taken.

`pasmax`

Maximum number of the time step to be copied.

Comments:

The options `FREQ`, `TFREQ`, `NUPAS` and `PASMAX` can be combined.

If the step number required is not stored in file `nfic`, EUROPLEXUS takes the step just above it.

The option `PASMAX` allows e.g. to “clean up” a results file that has become unusable due to a computation error. In fact, one may then create a new file containing the results of the steps from the beginning to a step `pasmax` prior to the encountered error.

Warning:

The logical unit number of the new file (`nfic`) must be different from that of the old one, `nban`, defined in the instruction `RESULT` (see page ED.20).

14.5 PRINTOUTS ON THE LISTING

Object :

To print data extracted from a chosen results file onto the EUROPLEXUS listing file or to produce a CASTEM 2000 file for further post-processing by CASTEM 2000.

Syntax :

```
"ECRITURE"
             <  "COOR"  >   <  "DEPL"  >  <  "VITE"  >  <  "ACCE"  >
             <  "FINT"  >   <  "FEXT"  >  <  "FLIA"  >
             <  "CONT"  >   <  "EPST"  >  <  "ECRO"  >
             <  "ENER"  >   <  "MCVA"  >  <  "MCVC"  >
             <  "MCVS"  >   <  "FAIL"  >  <  "VFCC"  >
             /CTIM/

$[  "NOPOINT"  ;  "POINT"  /LECTURE/  ]$
$[  "NOELEM"   ;  "ELEM"   /LECTURE/  ]$

<  "FICHIER" < FORMAT >   "K2000" ndcast   /CTIM/
                          "POINT" /LECTURE/
                       <  "CHAMELEM"  > >
```

"COOR"

Coordinates are printed on the EUROPLEXUS listing.

"DEPL"

Displacements are printed on the EUROPLEXUS listing.

"VITE"

Velocities are printed on the EUROPLEXUS listing.

"ACCE"

Accelerations are printed on the EUROPLEXUS listing.

"FINT"

Internal forces are printed on the EUROPLEXUS listing.

"FEXT"

Total external forces are printed on the EUROPLEXUS listing.

"CONT"

Stresses are printed on the EUROPLEXUS listing.

"EPST"

Total strains are printed on the EUROPLEXUS listing.

"ECRO"

Hardening parameters are printed on the EUROPLEXUS listing.

"ENER"

Energies are printed on the EUROPLEXUS listing.

"MCVA"

Printout of nodal quantities related to multicomponent fluids: pressure, density, temperature, sound speed and mass fractions. Note that this type of printout is incompatible with MCVC and MCVS.

MCVC

Printout of conserved variables (nodal quantities) related to multicomponent fluids: partial densities (ρ_i) of the various components i, momentum ($\rho \underline{u}$) (each spatial component separately), energy (ρE). Note that this type of printout is incompatible with MCVA.

MCVS

Printout of secondary variables (nodal quantities) related to multicomponent fluids: total density (ρ), total pressure p, sound speed c, pressure derivative ($\frac{\partial p}{\partial(\rho e)}$), absolute temperature (T), pressure derivative ($\frac{\partial p}{\partial(\rho_i)}$) for each component, mass fraction (μ_i) for each component. Note that this type of printout is incompatible with MCVA.

"FAIL"

Failure values are printed on the EUROPLEXUS listing.

VFCC

Printout at each selected output time of "element" quantities related to cell-centred Finite Volumes: various volume-related quantities and conserved variables.

/CTIM/

Reading procedure of the chosen time instants at which the results have to be printed on the listing. See page INT.57.

"NOPOINT"

Do not print any nodal variables. By default the chosen nodal variables are printed for all nodes stored in the results file.

"POINT /LECTURE/"

Print the chosen nodal variables only for the nodes defined in the /LECT/ (provided they are stored in the results file).

"NOELEM"

Do not print any element variables. By default the chosen element variables are printed for all elements stored in the results file.

`"ELEM /LECTURE/"`

Print the chosen element variables only for the elements defined in the `/LECT/` (provided they are stored in the results file).

`"FICH"`

Produce a CASTEM 2000 results file from the EUROPLEXUS results file.

`"FORMAT"`

If this keyword is present, the CASTEM 2000 results file is formatted; else, it is unformatted (binary).

`ndcast`

Logical unit number of the CASTEM 2000 file; the results file is written with the standard `SAUVER` format of CASTEM 2000. It may be read by CASTEM 2000 by using the command `RESTITUER`. It is mandatory to specify the list of points for which results have to be included in the file, and if necessary also the word `CHAMELEM`.

`/CTIM/`

Reading procedure of the chosen time instants at which the results have to be stored. See page INT.57.

`"POIN" /LECTURE/`

List of the nodes for which the results are stored for a subsequent post-processing by CASTEM 2000. This directive is mandatory for a file of type "K2000".

`"CHAMELEM"`

This keyword causes the CHAMELEMS to be included in the CASTEM 2000 file. If it is omitted, the latter will only contain the selected CHAMPOINTS, on the nodes identified by the previous directive `POINT`.

Comments :

The syntax is the same as for directive `ECRI`. For more details see page G.10 and following ones.

14.6 GRAPHIC OUTPUTS

Object :

To produce drawings or lists on files (in a variety of formats) of different quantities in the form of curves with respect to time, or with respect to a curvilinear abscissa, or combined plots (e.g. sigma/epsilon graphs).

Syntax:

```
"GRAP"  "AXTEMP"  coef  'nom_axe_Ox'
        < "MINMAX" >
        < "PERFO"    'nom_fic'   >
        < "PERK"     'nom_fic'   >
        < "FENETRE"  tmin  tmax  >
        ( "COURBE"   . . .  )
        ( "SCOURBE"  . . .  )
        ( "RCOURBE"  . . .  )
        ( "DCOURBE"  . . .  )
        ( "PCOURBE"  . . .  )
        ( "TRACE"    . . .  )
        ( "XMGR"     . . .  )
        ( "K2000"    . . .  )
        ( "LISTE"    . . .  )
        ( "FVAL"     . . .  )
```

`coef`

The time values are multiplied by `coef` (this e.g. enables the unit of measure to be changed).

`'nom_axe_Ox'`

Name of the time axis (at most 16 characters), enclosed in apostrophes.

`MINMAX`

Print on the EUROPLEXUS listing the minimum and the maximum values for each curve.

`PERFO`

The value tables specified in the following `LISTE` directive will be output on an auxiliary file, whose name by default is `<base>.PUN`, where `<base>` is the base name of the current calculation. This directive allows to change the default name into the following `'nom_fic'`.

`PERK`

The value tables specified in the following `K2000` directive will be output on an auxiliary file, whose name by default is `<base>.PUK`, where `<base>` is the base name of the current calculation. This directive allows to change the default name into the following `'nom_fic'`.

`FENETRE`

Only the results in a given time interval (time window) are considered.

`tmin`

Minimum time (beginning of the time window).

`tmax`

Maximum time (end of the time window).

`COURBE`

Define a curve representing the evolution **in time** of a certain variable in the current transient calculation. See below for the full details of this directive.

`SCOURBE`

Define a curve representing the evolution **in space** of a certain variable in the current transient calculation. The space is a curvilinear abscissa (s) defined by a sequence of nodes. The curve is by default built at the final time of the current calculation. To select a different time, use the `ARRET` directive described on page ED.40. See below for the full details of this directive.

`RCOURBE`

Read in a curve representing the evolution **in time or in space** of a certain variable in a previously executed EUROPLEXUS calculation. The data are read in from a "punch" file produced by EUROPLEXUS via the `SORT LIST` directive, to be described below. In this way, results from different EUROPLEXUS runs may be compared on the same plot. See below for the full details of this directive.

`DCOURBE`

Define a curve in the form of a table of (x, y) values. This allows e.g. to build a piecewise analytical solution to be compared with numerical results. It may even be used to input experimental results to be used as a reference solution. See below for the full details of this directive.

`PCOURBE`

Define a *set of curves* for Pochhammer-Chree post-processing. See below for the full details of this directive.

`TRACE`

Produce a graph containing one or more of the curves defined above, plotted either versus time, or versus space (curvilinear abscissa), or as a function of another curve (e.g. σ-ϵ type of plot). The graph is produced in the PostScript language on a file.

`XMGR`

Same as `TRACE` but the graph data are stored on a file which may then be read by the XMGR program (a publicly available software) to produce the actual drawing.

`K2000`

Same as `TRACE` but the graph data are stored on a file which may then be read by the CASTEM 2000 program to produce the actual drawing.

`LISTE`

Same as `TRACE` but the graph data are stored on a file which may then be read by a generic external tool to produce the actual drawing. The file format is very simple. This command also allows to store a curve in a certain EUROPLEXUS run and read it in (by the `RCOURBE` directive described above) in a subsequent EUROPLEXUS run, thus opening the way to the production of graphs containing comparisons of results from different EUROPLEXUS calculations, and even analytical curves or experimental data.

`FVAL`

Find values (abscissas) x of a curve for which the curve assumes a given value v, i.e. for which $y(x) = v$. Linear interpolation is used.

Comments:

- The time axis is the same for all drawings produced as a function of time.

- The time window is the same for all drawings produced as a function of time.

Example :

```
"GRAP"  "AXTEMP"  1000.  'TEMPS (MS)'
"FENETRE"   0.   10E-3   MINMAX
. . .
```

14.6.1 Post-processing in adaptivity

The post-processing of results in mesh adaptive computations may be somewhat different from the case of normal computations with a constant mesh connectivity. Some care is required in the interpretation of mesh adaptive results, especially as concerns time curves in selected nodes or elements.

The visualization of maps of values at a fixed time, e.g. a pressure field in the form of iso-values or a velocity field in the form of vectors, is similar to the case of non-adaptive calculations. The only thing to keep in mind is that, if a zone or part of the mesh must be selected for visualization, then the user should normally provide the list of the **base** elements. The code will then automatically replace these elements by the set of their active descendants at the chosen time. This mechanism is transparent to the user since object names and element group names always contain the indexes of the base elements concerned. Therefore, if no element indexes are explicitly given, the procedure from the user's viewpoint is exactly like in the case of non-adaptive computations.

The production of time curves in adaptive computations requires some more attention, since an element or node at which the results are to be extracted must be specified and this can be either a base item or a descendant item. Furthermore, the element or node can be active only during part of the time transient. The following rules are applied:

Rule 1: in an adaptive calculation, a **node-related** quantity

- represents the value belonging to the node itself, if the node is currently used. Note that in adaptivity nodes can be either used or unused. A used node is also active. An unused node is inactive. Base nodes are always used and therefore they are always active.
- is undefined (and is typically set to 0.0) if the node is currently not used.

Rule 2: in an adaptive calculation, an **element-related** quantity

- represents the value belonging to the element itself, if the element is currently active.
- represents the weighted average value of all its current active descendants, if the element is currently used but inactive. Note that, in particular, base elements (unlike base nodes) can become inactive, although they are always used.
- is undefined (and is typically set to 0.0) if the element is currently not used.

Rule 3: in an adaptive calculation, a **list of elements** or the name of an **object** or **group** made of elements

- represents the listed elements themselves, if such elements are currently active.
- represents the set of all current active descendants of the elements listed, if the elements are currently used but inactive.
- is illegal if the elements listed are currently not used.

14.6.2 Curve (Nodal Variables)

Object:

Definition of the variables **relative to nodes** to be drawn or listed.

Syntax :

```
"COURBE" nuco < 'nomcourbe' >

        |[ "COOR" ; "DEPL" ; "VITE" ; "ACCE" ; "FINT" ; "FEXT" ;
           "FLIA" ; "ADFT" ; "MCPR" ; "MCRO" ; "MCTE" ; "MCMF" ;
           "MCUX" ; "MCUY" ; "MCUZ" ; "SIGN" ; "ECRN" ; "LFNO" ;
           "LFNV" ; "ILNO" ; "DTNO" ; "VITG" ; "NTLE" ; "MASN" ;
           "FDEC" ; "PFSI" ; "PFMI" ; "PFMA" ; "FORC" ; "QUAT" ;
           "QSQO" ]|

        |[ "COMP" icomp ; "NORME" ]|

        $[ "NOEU" /LECTURE/ ;
           "NODE" /LECTURE/ ;
           "ZONE" /LECTURE/ ;
           "POSI" $[ x y <z> ;
                     "FOLL" dx dy <dz> /LECT1/ ]$
                  "OBJE" /LECT2/                   ]$
```

`nuco`

Identifier of the curve (reference for `TRAC`, `XMGR`, `K2000` or `LISTE`). A (unique) integer number, freely chosen by the user, by which the curve may be successively referred to when needed.

`'nomcourbe'`

Name of the curve (reference for the user). This will appear on plots, etc.

`COOR`

Coordinate.

`DEPL`

Displacement.

`VITE`

Velocity.

`ACCE`

Acceleration.

`FINT`

Internal force.

`FEXT`

Total external force.

`FLIA`

External force due to coupled links (LINK COUP).

`ADFT`

Advection-diffusion temperature.

`MCPR`

Finite volume (MC) pressure.

`MCRO`

Finite volume (MC) density.

`MCTE`

Finite volume (MC) temperature.

`MCMF`

Finite volume (MC) component mass fraction.

`MCUX`

Finite volume (MC) fluid velocity along X computed from the conserved variable ($u_x = (\rho u_x)/\rho$)).

`MCUY`

Finite volume (MC) fluid velocity along Y computed from the conserved variable ($u_y = (\rho u_y)/\rho$)).

`MCUZ`

Finite volume (MC) fluid velocity along Z computed from the conserved variable ($u_z = (\rho u_z)/\rho$)).

`SIGN`

Spectral element stress.

`ECRN`

Spectral element internal variable.

`LFNO`

Logarithm in base 2 of the level factor associated with a node in the spatial time step partitioning algorithm.

`LFNV`

Logarithm in base 2 of the level factor associated with a node, including the neighbours in the spatial time step partitioning algorithm.

`ILNO`

Flag indicating whether a node is (1) or is not (0) subjected to a link condition, used in the spatial time step partitioning algorithm.

`DTNO`

Stability time step associated with a node, used in the spatial time step partitioning algorithm.

`VITG`

Grid velocity (ALE only).

`NTLE`

Node tree level (only in adaptivity).

`MASN`

Nodal mass.

`FDEC`

External force due to decoupled links (LINK DECO).

`PFSI`

Overpressure due to FSI in the nodes of CLxx elements associated with an `IMPE VISU` material (see Page C.885) and with either `COUP` or `DECO` specified. These CLxx elements, used only for results visualization purposes, must be attached to structural elements (typically shells) embedded in a fluid and subjected to either `FLSR` or `FLSW` model of FSI.

`PFMI`

Minimum FSI overpressure in time at the node (see `PFSI` above.

`PFMA`

Maximum FSI overpressure in time at the node (see `PFSI` above.

`FORC`

Total external force. This is an obsolescent alias of `FEXT`, still used in some old benchmarks. Use `FEXT` in new inputs.

`QUAT`

Quaternion representing the current angular orientation of a rigid body (see `COMP RIGI`). This quantity is available only if the chosen node (see `NOEU` below) is the "lumped" node associated with a rigid body. Such nodes (one per rigid body) are automatically generated by EPX when declaring rigid bodies in the input file and may be easily accessed via the special group names `_RIGI001`, `_RIGI002`, etc. Note that in this case the sub-directives `ZONE` or `POSI` cannot be used. One may choose to draw one component of the quaternion (`COMP` followed by an index from 1 to 4), or its norm (`NORM`).

QSQ0

Ratio between current quaternion $\hat{q}$ and initial quaternion $\hat{q_0}$, Representing the current angular orientation with respect to the initial angular orientation of the body.

COMP

Introduces the chosen component.

icomp

Component number. Default value is 1.

NORM

The norm of the considered vector (where applicable) is drawn.

NOEU /LECTURE/ **or** NODE /LECTURE/

Number of the node. The procedure /LECTURE/ allows if necessary to read a GIBI object, of which only the first node will be retained.

ZONE /LECTURE/

Set of nodal numbers defining a zone. The contributions of all these nodes are added together. This probably makes sense only for some types of variables (e.g. forces, masses etc.). This can be useful to plot e.g. the total (resultant) force acting on a set of nodes, or the total mass of such nodes. It is an alternative to the use of the REGI directive. The difference is that with REGI the region must be defined in the main calculation, and it cannot be defined when reading the results file (e.g. an Alice file). The present ZONE directive, on the contrary, can be defined "on the fly" when reading any results file (provided this file contains the results of all concerned nodes).

POSI

The nodal values should be extracted at the nearest node to the position specified next. Note that the nearest node may vary in time, either due to motion of the mesh or to mesh adaptivity. The position can either be specified by its coordinates (and in this case it is fixed in time), or by an offset to the position of a node in the mesh. In the latter case, if the specified node moves in time, then the position moves as well by "following" the specified node. This may be useful to track, say, the fluid velocity at a position slightly upstream of a deformable plate.

x y <z>

Coordinates of the position (fixed in time).

FOLL /LECT1/

The position should follow the node specified in the /LECT1/.

dx dy <dz>

Offset of the position with respect to the node.

OBJE /LECT2/

Object (list of **elements**) whose nodes are candidates for the search of the nearest node. If more than one node has the minimum distance from the position specified, then the first such node is retained. Note that although the variable to be drawn is relative to nodes, the object must be defined in term of (base) elements. The code then extracts automatically the nodes belonging to such elements (or to their active descendants, in case of adaptivity). In case of the use of a k-file, the node numbers relate to the original node numbers in the k-file and not the ones internally used.

Comments :

The directive `COURBE` can be repeated as many times as desired, but each time with a different identifier.

Curve identifiers may be freely chosen by the user, and the order in which they are given is irrelevant.

The keyword `FORC` is accepted as a synonym of `FEXT` for backward compatibility, but is obsolescent and should not be used in new input files.

For an introduction to post-processing, and in particular to time curves production in mesh adaptive calculations, see page ED.65.

14.6.3 Curve (Element Variables)

Object:

Definition of the variables **relative to elements** to be drawn or listed.

Syntax:

```
"COURBE"  nuco  < 'nomcourbe' >

  |[
     |[ "CONT" ; "ECRO" ; "EPST" ; "ENEL" ; "WAUX" ; "LFEL" ;
        "LFEV" ; "DTEL" ; "ELCE" ; "FAIL" ; "RISK" ; "CERR" ;
        "MAXC" ; "ERRI" ; "CLEN" ; "ILEN" ; "ETLE" ; "MASE" ]|

        "COMP" icomp $[ "GAUS" igaus ; "GAUZ" igauz ]$  ;

     "VCVI" |[ "COMP" icomp ; "NORM" ]|
  ]|

  $[ "ELEM" /LECTURE/ ;
     "ZONE" /LECTURE/ ;
     "POSI" $[ x y <z> ;
               "FOLL" dx dy <dz> /LECT1/ ]$
            "OBJE" /LECT2/                   ]$
```

`nuco`

Identifier of the curve (reference for `TRAC`, `XMGR`, `K2000` or `LISTE`). A (unique) integer number, freely chosen by the user, by which the curve may be successively referred to when needed.

`'nomcourbe'`

Name of the curve (reference for the user). This will appear on plots, etc.

`CONT`

Stress tensor.

`ECRO`

Hardening quantity.

`EPST`

Total deformation tensor.

`ENEL`

Internal energy.

`WAUX`

Auxiliary energy terms for the element (see details below).

`LFEL`

Logarithm in base 2 of the level factor associated with an element in the spatial time step partitioning algorithm.

`LFEV`

Logarithm in base 2 of the level factor associated with an element including its neighbours in the spatial time step partitioning algorithm.

`DTEL`

Stability time step Δt_{stab} associated with the element. The *stability step* is the *critical step* Δt_{crit} estimated by the code (roughly the element length L divided by the speed of sound c in the element material) multiplied by the *safety coefficient* ϕ (`CSTA`, by default 0.8): $\Delta t_{\mathrm{stab}} = \phi \Delta t_{\mathrm{crit}} \approx \phi \frac{L}{c}$.

`ELCE`

Coordinates of the barycentre of the element.

`FAIL`

Failure level of the element.

`RISK`

Risk level of the element (only if risk is activated). `COMP` must be given to define the kind of risk: `COMP`=1 chooses the risk of eardrum rupture, `COMP`=2 chooses the risk of death. Be aware that when reading results from an Alice file (produced by a previous calculation with risk activation), it is mandatory to (re-)specify the whole `RISK` directive (in particular as concerns the `PROB` ... and `LUNG` ... sub directives, see page A.30), because the risk is computed with the current values of the optional parameters.

`CERR`

Constant used in element error indicator calculation (adaptivity), see the `CERR` input keyword of the `ADAP` directive on page B.210.

`MAXC`

Maximum principal curvature of least-squares fitting function, used for element error indicator calculation (adaptivity).

`ERRI`

Element error indicator (adaptivity).

`CLEN`

Current characteristic element length used in element error indicator calculation (adaptivity).

`ILEN`

Optimal (indicated) characteristic element length resulting from error indicator calculations (adaptivity).

`ETLE`

Element tree level (adaptivity).

`MASE`

Element mass.

`VCVI`

Material or particle velocity (first idim components) in Finite Volumes Cell Centered model. Note that these vectors are not represented at the nodes but at the "elements" (i.e. Finite Volumes) centroids.

`COMP`

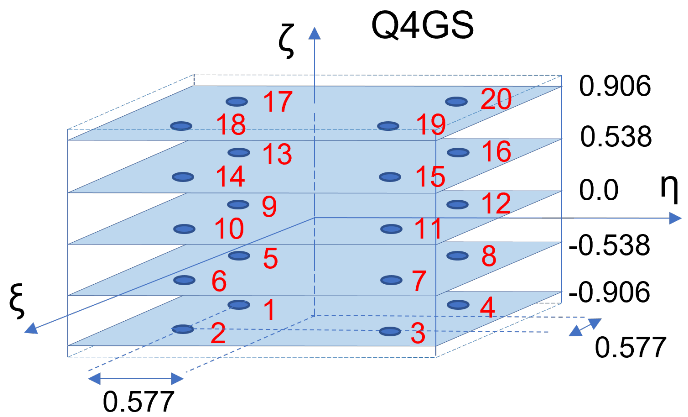
Introduces the component (unused for `ENEL`, `LFEL`, `LFEV` and `DTEL`).

`icomp`

Number of the component.

`GAUS`

Allows to choose a specific Gauss point index (only for the quantities `CONT`, `EPST` and `ECRO`). For example, for the Q4GS shell element using a non-linear material integrated through the thickness the following points may be addressed:



`igaus`

Number of the Gauss point chosen. The special value 0 means that the average over all Gauss points in the element is taken. The default value is 1, i.e. if neither `GAUS` nor `GAUZ` is specified then the first Gauss Point of the specified element is taken. Note that this default is different from the default in rendering via OpenGL, where 0 (average over all Gauss Points) is assumed.

`GAUZ`

Allows to choose a specific “lamina” of the (shell) element. The value is the index of the lamina through the thickness (only for the quantities `CONT`, `EPST` and `ECRO`). In this case, the code takes the average value of all Gauss Points belonging to the specified lamina.

`igauz`

Number of Gauss point through the thickness (i.e. index of the chosen lamina).

`NORM`

The norm of the VCVI vector is drawn.

`ELEM /LECTURE/`

Number of the element. The procedure `/LECTURE/` allows if necessary to read a GIBI object, of which only the first element will be retained. In case of the use of a k-file, the element numbers relate to the original element numbers in the k-file and not the ones internally used.

`ZONE /LECTURE/`

Set of element numbers defining a zone. The contributions of all these elements are added together. This probably makes sense only for some types of variables (e.g. masses). This can be useful to plot e.g. the total (resultant) mass of a set of elements. It is an alternative to the use of the `REGI` directive. The difference is that with `REGI` the region must be defined in the main calculation, and it cannot be defined when reading the results file (e.g. an Alice file). The present `ZONE` directive, on the contrary, can be defined “on the fly” when reading any results file (provided this file contains the results of all concerned elements).

`POSI`

The element values should be extracted at the nearest element (centroid) to the position specified next. Note that the nearest element may vary in time, either due to motion of the mesh or to mesh adaptivity. The position can either be specified by its coordinates (and in this case it is fixed in time), or by an offset to the position of a node in the mesh. In the latter case, if the specified node moves in time, then the position moves as well by “following” the specified node. This may be useful to track, say, the fluid pressure at a position slightly upstream of a deformable plate.

`x y <z>`

Coordinates of the position (fixed in time).

`FOLL /LECT1/`

The position should follow the node specified in the /LECT1/.

`dx dy <dz>`

Offset of the position with respect to the node.

`OBJE /LECT2/`

Object (list of **elements**) whose elements are candidates for the search of the nearest element. If more than one element has the minimum (centroid) distance from the position specified, then the first such element is retained. Note that the object must be defined in term of (base) elements. The code then extracts automatically the list of their active descendants, in case of adaptivity.

Comments:

The directive COURBE can be repeated as many times as desired, but each time with a different identifier.

Curve identifiers may be freely chosen by the user, and the order in which they are given is irrelevant.

If the keyword GAUSS is omitted, the first integration point is considered. If GAUSS is set to 0, the average over all integration points is used.

As concerns the auxiliary energy terms for the element (WAUX), the following components are available at the moment:

- WAUX 1 ⇒ Energy dissipated by artificial viscosity (WARD)
- WAUX 2 ⇒ Pressure work for fluids $-PdV$ (W_PDV)
- WAUX 3 ⇒ Energy injected or lost at the walls (W_INJ)
- WAUX 4 ⇒ Kinetic energy for CCFV Elements on X axis
- WAUX 5 ⇒ Kinetic energy for CCFV Elements on Y axis
- WAUX 6 ⇒ Kinetic energy for CCFV Elements on Z axis
- WAUX 7 ⇒ Total Energy for CCFV Elements
- WAUX 8 ⇒ Used for saving initial injected energy
- WAUX 9 ⇒ Total energy of the liquid phase (Only ADCR/ADCJ Model)
- WAUX 10 ⇒ Total energy of the bubble (Only ADCR/ADCJ Model)
- WAUX 11 ⇒ Total energy of the cover gas (Only ADCR/ADCJ Model)
- WAUX 12 ⇒ Kinetic energy of the liquid phase (Only ADCR/ADCJ Model)
- WAUX 13 ⇒ Kinetic energy of the bubble (Only ADCR/ADCJ Model)
- WAUX 14 ⇒ Kinetic energy of the cover gas (Only ADCR/ADCJ Model)
- WAUX 15 ⇒ Internal energy of the liquid phase (Only ADCR/ADCJ Model)
- WAUX 16 ⇒ Internal energy of the bubble (Only ADCR/ADCJ Model)
- WAUX 17 ⇒ Internal energy of the cover gas (Only ADCR/ADCJ Model)

Quantities 4 to 17 were added to account for auxiliary energies needed in FV cases. Contrary to FE, Total and kinetic energy FV contributions have to be computed at elements and not at nodes. Quantities 9 to 17 are only relevant for the ADCR/ADCJ Model, it will return 0 in other cases.

Note:

All printed energy quantities are equivalent in FE and FV cases, except for**W_PDV** : In FE, the contribution of pressure work W_PDV on the variation of kinetic energy is neglected in relation to the internal energy variation, which is relevant for smooth solutions. In FV, W_PDV is computed as the variation of total energy, which is always the work of pressure forces for a stand-alone domain.

For an introduction to post-processing, and in particular to time curves production in mesh adaptive calculations, see page ED.65.

14.6.4 Curve (Combinations)

Object:

Definition of **combinations** of the previously defined curves, to be drawn or listed.

Syntax:

```
"COURBE"  nuco  < 'nomcourbe' >

      |[   "SOMME"       nbrs*( courbe_i  coef_i )           ;
           "PRODUIT"     pcoef   nbrp*( courbe_k )           ;
           "INTEGRALE"   courbe_i                            ;
           "DISTANCE"         /LECTURE/                      ;
           "LIBR"                                            ;
           "ADDC"  icou val       ;    "SUBC"  icou val      ;
           "MULC"  icou val       ;    "DIVC"  icou val      ;
           "EXPC"  icou val       ;    "CEXP"  icou val      ;
           "SHIFT" icou val       ;    "MOVE"  icou ival     ;
           "ADD"   icou jcou      ;    "SUB"   icou jcou     ;
           "MUL"   icou jcou      ;    "DIV"   icou jcou     ;
           "EXPF"  icou jcou      ;    "DUP"   icou jcou     ;
           "ABS"   icou           ;    "SEGN"  icou          ;
           "SQRT"  icou           ;    "INV"   icou          ;
           "EXP"   icou           ;    "LN"    icou          ;
           "LOG10" icou           ;    "SIN"   icou          ;
           "COS"   icou           ;    "ASIN"  icou          ;
           "ACOS"  icou           ;    "DIFF"  icou          ;
           "INT"   icou           ;    "AVER"  icou          ;
           "MAX"   icou           ;    "MIN"   icou          ;
           "FLIP"  icou           ;
           "MEAN"  nc*(icou)      ;    "SMAX"  nc*(icou)     ;
           "SMIN"  nc*(icou)      ;    "JOIN"  nc*(icou)     ;
           "FILT"  "MOYG"  icou nval                         ]|
```

`nuco`

Identifier of the curve (reference for `TRAC`, `XMGR`, `K2000` or `LISTE`). A (unique) integer number, freely chosen by the user, by which the curve may be successively referred to when needed.

`'nomcourbe'`

Name of the curve (reference for the user). This will appear on plots, etc.

`SOMME`

The current curve results from the linear combination of `nbrs` curves, among those already defined.

```
result = coef\_1*courbe\_1 ... + coef\_i*courbe\_i + ...
```

`PRODUIT`

The current curve results from the product of `nbrp` curves, among those already defined.

```
result = pcoef * courbe\_1 ... *courbe\_k * ...
```

`INTEGRALE`

Each point of this curve is the value at time t of the integral between 0 and t of curve number `courbe_i`, supposed already defined.

`DISTANCE`

The current curve results from the calculation of the distance between the two nodes specified by the following directive `/LECTURE/`.

`LIBR`

The variable concerned by this curve is computed by the subroutine GRLIBR, written by the user.

`ADDC`

Add to curve `icou` a constant value `val`.

`SUBC`

Subtract from curve `icou` a constant value `val`.

`MULC`

Multiply curve `icou` by a constant value `val`.

`DIVC`

Divide curve `icou` by a constant value `val`.

`EXPC`

Raise curve `icou` to a constant power `val`.

`CEXP`

Raise constant `val` to power values in curve `icou` (powers of a constant).

`SHIFT`

Translate of curve `icou` in its abscissa by a value `val`. Undefined values are set to zero. The abscissa of the generated curve is the same as that of curve `icou`.

`MOVE`

Translate of curve `icou` in its abscissa by a value `val`. The abscissa of the generated curve is no longer the same as that of curve `icou`, but it is shifted by the chosen amount `val`.

`ADD`

Add curve `jcou` to curve `icou`.

`SUB`

Subtract curve `jcou` from curve `icou`.

`MUL`

Multiply curve `icou` by curve `jcou`.

`DIV`

Divide curve `icou` by curve `jcou`.

`EXPF`

Raise curve `icou` to power values contained in curve `jcou`.

`DUP`

Copy of curve `icou` having the abscissa of curve `jcou`. The result is set at zero in the non-overlapping abscissa zones.

`ABS`

Absolute value of curve `icou`.

`SEGN`

Sign (unit) function of curve `icou`.

`SQRT`

Square root of curve `icou`.

`INV`

Inverse of curve `icou`.

`EXP`

Exponential of curve `icou`.

`LN`

Natural logarithm of curve `icou`.

`LOG10`

Decimal logarithm of curve `icou`.

`SIN`

Sine of curve `icou`.

`COS`

Cosine of curve `icou`.

`ASIN`

Arc sine of curve `icou`.

`ACOS`

Arc cosine of curve `icou`.

`DIFF`

Derivative of curve `icou` with respect to its abscissa (usually time).

`INT`

Integral of curve `icou` with respect to its abscissa (usually time).

`AVER`

Average value of curve `icou`. This results in a single value, repeated over the whole abscissa.

`MAX`

Maximum value of a curve `icou`. This results in a single value, repeated over the whole abscissa.

`MIN`

Minimum value of a curve `icou`. This results in a single value, repeated over the whole abscissa.

`FLIP`

Flip of a curve `icou` in time (or in space, for a space curve). The curve is flipped (symmetrized with respect to the first point in abscissa). The obtained curve is the specular symmetric of the original curve with respect to the origin. To obtain the union of the original curve and of its symmetric, use the `JOIN` operator.

`MEAN`

Arithmetic mean of a set of `nc` curves `icou`.

`SMAX`

Upper bound of a set of `nc` curves `icou`.

`SMIN`

Lower bound of a set of `nc` curves `icou`.

`JOIN`

Union of a set of `nc` curves `icou`. The values from each curve are merged together to form a new curve. This especially makes sense for "curves" consisting of just one point each, or for curves whose definition domains are disjoint.

`FILT MOYG`

Mobile average on `nval` consecutive values of curve `icou` .

Comments:

The directive `COURBE` can be repeated as many times as desired, but each time with a different identifier.

Curve identifiers may be freely chosen by the user, and the order in which they are given is irrelevant.

For `SOMME` and `PRODUIT`, the curves starting from which the sum (resp. product) is computed must have identifiers lower than that of the current curve and must have been already defined.

Commands `ADDC` to `SMIN` have been inspired from similar ones present in the TPLOT data management system, developed at JRC since the 1970's. For these commands, the curves identified by `icou`, `jcou`, etc., must have been already defined. Note also that for any of these commands that involve two or more curves `icou`, `jcou`, etc., with the notable exception of the `DUP` command, the abscissas (i.e. the discrete x-values) of all such curves must be identical, otherwise the combination may not be computed. Note also that, with respect to TPLOT, the meanings of `MIN`, `SMIN` and of `MAX`, `SMAX` have been interchanged. Moreover, `MIN` and `MAX` now produce a (uniform-valued) curve rather than the printout of a single value.

The subroutine GRLIBR allows to compute a quantity as a function of other quantities defined previously by a directive `COURBE`.

An example of such subroutine is:

Programming example for GRLIBR:

```
      SUBROUTINE GRLIBR(TT,VAL,NT,NTEMAX)
C-----------------------------------------------------------------------
C
C    CALCUL LIBRE DE GRANDEURS A TRACER EN FONCTION DU TEMPS
C
C-----------------------------------------------------------------------
C            TT   = TABLEAU DES TEMPS (BANDE ALICE)
C            IT   = NUMERO DU PAS DE TEMPS
C            NT   = NOMBRE DE PAS DE TEMPS TOTAL (BANDE ALICE)
C            ICO  = NUMERO D'UNE COURBE
C     VAL(IT,ICO)  = TABLEAU DES GRANDEURS DEFINIES PAR UNE COURBE
C          NTEMAX  = NOMBRE MAXIMAL DE POINTS
C
      REAL TT, VAL
      DIMENSION TT(NTEMAX),VAL(NTEMAX,*)
C
C----  EXEMPLE : A = B * C
C     DO 10 IT=1,NT
C  10 VAL(IT,5)=VAL(IT,1)*VAL(IT,3)
C
C----  EXEMPLE d'INTEGRATION :
C     VAL(1,40)=0.
C     NT1=NT-1
C     DO 10 IT=1,NT1
C  10 VAL(IT+1,40)=VAL(IT,40)+0.5*(VAL(IT+1,22)+VAL(IT,22))
C    *      *(TT(IT+1)-TT(IT))
      RETURN
      END
```

Warning: the tables `TT` and `VAL` must be in simple precision (`R*4`).

14.6.5 Curve (Regional Balances)

Object:

Definition of **quantities related to regions** to be drawn or listed. Erosion is taken is account if active.

Syntax:

```
"COURBE"  nuco  < 'nomcourbe' >
    |[ "MASS" ; "VOLU" ; "BARY" ; "VMOY" ; "VEMX" ; "VEMN" ; "DMOY" ;
       "DIMX" ; "DIMN" ; "AMOY" ; "ACMX" ; "ACMN" ; "IMPU" ; "ECIN" ;
       "EINT" ; "EEXT" ; "EPDV" ; "EINJ" ; "RESU" ; "IRES" ; "ECRG" ;
       "ECRM" ; "EMAS" ; "FLIR" ; "RRIS" ; "EPSM" ; "NERO" ; "NEND" ;
       "CERO" ; "CEND"]|

    $[ "COMP" icomp ; "NORM" ]$

    "REGION" nureg
```

`nuco`

Identifier of the curve (reference for `TRAC`, `XMGR`, `K2000` or `LISTE`). A (unique) integer number, freely chosen by the user, by which the curve may be successively referred to when needed.

`'nomcourbe'`

Name of the curve (reference for the user). This will appear on plots, etc.

`MASS`

Mass of the region (scalar, computed via XMEL).

`VOLU`

Volume of the region (scalar).

`BARY`

Barycenter of the region (vector).

`VMOY`

Mean velocity of the region (vector).

`VEMX`

Maximum velocity (absolute) of the region (vector), only components 1 to 3.

`VEMN`

Minimum velocity (absolute) of the region (vector), only components 1 to 3.

`DMOY`

Mean displacement of the region (vector).

`DIMX`

Maximum displacement (absolute) of the region (vector), only components 1 to 3.

`DIMN`

Minimum displacement (absolute) of the region (vector), only components 1 to 3.

`AMOY`

Mean acceleration of the region (vector).

`ACMX`

Maximum acceleration (absolute) of the region (vector), only components 1 to 3.

`ACMN`

Minimum acceleration (absolute) of the region (vector), only components 1 to 3.

`IMPU`

Impulse (momentum) of the region (vector).

`ECIN`

Kinetic energy of the region (vector).

`EINT`

Internal energy of the region (scalar).

`EEXT`

Work of external forces applied to the region (scalar).

`EPDV`

Work of pressure forces (PdV) for the region (scalar).

`EINJ`

Energy injected in the region (scalar).

`RESU`

Resultant of the external forces applied to the region (vector).

`IRES`

Impulse due to external forces applied to the region (vector).

`ECRG`

Sum of the values of ECR on the Gauss points of the region (vector without norm).

`ECRM`

Average of the ECR over the region.

`EMAS`

Mass of the region (scalar, computed via the element masses XM0).

`FLIR`

Resultant of the force due to LINK/LIAI applied at the nodes.

`RRIS`

Average of the RISK over the region.

`EPSM`

Average of the EPST over the region.

`NERO`

Number of eroded elements over the region (See G.100).

`NEND`

Number of damaged elements over the region (See G.100).

`CERO`

Number of eroded classes over the region (See G.100).

`CEND`

Number of damaged classes over the region (See G.100).

`COMP`

Introduces the component.

`icomp`

Index of the component.

`NORME`

The norm of the chosen vector will be plotted.

`nureg`

Number of the concerned region in the order of definition.

Comments:

The directive COURBE can be repeated as many times as desired, but each time with a different identifier.

Curve identifiers may be freely chosen by the user, and the order in which they are given is irrelevant.

The directives COMP and NORM make sense only for vectors: they are possible with BARY, DIMX, DIMN, VMOY, VEMX, VEMN, IMPU, ECIN, RESU, and IRES. Furthermore, NORM does not make sense for ECRG, ECRM, EPSM and RRIS (only COMP is possible).

The directives COMP and NORM make no sense for scalars: MASS, VOLU, EINT, EEXT, EPDV, EINJ, EMAS, NERO, NEND, CERO and CEND.

If the keyword COMP is absent, it is the first component that is taken in the case of vectors.

The directive EPDV makes sense only for a stand-alone system, for example the fluid within a reservoir. In the remaining cases, it is suggested to use EEXT, which gives the work of the applied external forces.

Note:

In FE, the contribution of pressure work W_PDV on the variation of kinetic energy is neglected in relation to the internal energy variation, which is relevant for smooth solutions. In FV, W_PDV is computed as the variation of total energy, which is always the work of pressure forces for a stand-alone domain.

The directive EINJ is only valid for material EAU.

14.6.6 Curve (Global Quantities)

Object:

Definition of some **global quantities** to be drawn or listed, e.g. relative to energy balance or spatial time step partitioning.

Syntax:

```
"COURBE"  nuco  < 'nomcourbe' >

       |[          "WINT"                  ;
                   "WEXT"                  ;
                   "WCIN"                  ;
                   "WTOT"                  ;
                   "WIMP"                  ;
                   "WSYS"                  ;
                   "BILAN"                 ;
                   "WSUM"   <COMP icomp>   ;
                   "DTMI"                  ;
                   "DTMA"                  ;
                   "MXSU"                  ;
                   "DT1"                   ;
                   "NSPL"                  ;
                   "NUSP"                  ;
                   "NSPT"                  ;
                   "NUSE"                  ;
                   "NACT"                  ;
                   "NUSN"                  ;
                   "LMAX"                  ;
                   "LMIN"                  ]|
```

`nuco`

Identifier of the curve (reference for `TRAC`, `XMGR`, `K2000` or `LISTE`). A (unique) integer number, freely chosen by the user, by which the curve may be successively referred to when needed.

`'nomcourbe'`

Name of the curve (reference for the user). This will appear on plots, etc.

`WINT`

Internal energy.

`WEXT`

External work.

`WCIN`

Kinetic energy.

`WTOT`

Sum of all external energies (see comments below).

`WIMP`

Energy dissipated during contact/impact calculations.

`WSYS`

Total energy of the system (see comments below).

`BILAN`

Energy balance.

`WSUM`

Sum of the auxiliary energy terms, see below (vector).

`DTMI`

Minimum time increment in the time spatial step partitioning algorithm. This quantity is available only in calculations with partitioning (`OPTI PART`, see Page H.20).

`DTMA`

Maximum time increment in the time spatial step partitioning algorithm. This quantity is available only in calculations with partitioning (`OPTI PART`, see Page H.20).

`MXSU`

Logarithm in base 2 of the maximum depth of the time spatial step partitioning algorithm. This quantity is available only in calculations with partitioning (`OPTI PART`, see Page H.20).

`DT1`

Time integration step (scalar). This is the time increment that has led to the current time. However, at the initial time of the calculation (step 0, i.e. `NPAS=0`) this quantity does not make sense, so we take `DT2` instead, i.e. the time increment that will lead to the following time.

`NSPL`

Number of elements which have been split during the current time step.

`NUSP`

Number of elements which have been unsplit during the current time step.

`NSPT`

Total number of elements which have been split during the calculation.

`NUST`

Total number of elements which have been unsplit during the calculation.

`NUSE`

Number of used elements (active or inactive) at the current time step.

`NACT`

Number of active elements at the current time step.

`NUSN`

Number of used (and also of active) nodes at the current time step.

`LMAX`

Maximum element level among all currently active elements at the current time step.

`LMIN`

Minimum element level among all currently active elements at the current time step. Level 0 (unused elements) is not considered in computing this quantity. Also currently used but inactive elements are excluded.

`icomp`

Index of the chosen component (only for vector quantities).

Comments:

The directive `COUR` can be repeated as many times as desired, but each time with a different identifier.

Curve identifiers may be freely chosen by the user, and the order in which they are given is irrelevant.

`WTOT` is the sum of all the "external" energies of the system: the work of external forces, the injected energy, the energy due to oil pyrolisis, etc. `WTOT` is used in the calculation of the energy balance.

`WIMP` is the energy dissipated due to contact-impact phenomena. This dissipation may come from the impact model used (soft impact, hard impact) in conjunction with the temporal discretization of the problem.

`WSYS` is the energy of the system, defined as: `WSYS` = `WTOT` + `WIMP`.
In a closed system, `WSYS` must be conserved.

As concerns the global auxiliary energy terms (`WSUM`), the following components are available at the moment:

- `WSUM 1` ⇒ Energy dissipated by artificial viscosity (WARD)
- `WSUM 2` ⇒ Pressure work for fluids $-PdV$ (W_PDV)

- `WSUM 3` ⇒ Energy injected or lost at the walls (W_INJ)
- `WSUM 4` ⇒ Kinetic energy for CCFV Elements on X axis
- `WSUM 5` ⇒ Kinetic energy for CCFV Elements on Y axis
- `WSUM 6` ⇒ Kinetic energy for CCFV Elements on Z axis
- `WSUM 7` ⇒ Total Energy for CCFV Elements
- `WSUM 8` ⇒ Used for saving initial injected energy
- `WSUM 9` ⇒ Total energy of the liquid phase (Only ADCR/ADCJ Model)
- `WSUM 10` ⇒ Total energy of the bubble (Only ADCR/ADCJ Model)
- `WSUM 11` ⇒ Total energy of the cover gas (Only ADCR/ADCJ Model)
- `WSUM 12` ⇒ Kinetic energy of the liquid phase (Only ADCR/ADCJ Model)
- `WSUM 13` ⇒ Kinetic energy of the bubble (Only ADCR/ADCJ Model)
- `WSUM 14` ⇒ Kinetic energy of the cover gas (Only ADCR/ADCJ Model)
- `WSUM 15` ⇒ Internal energy of the liquid phase (Only ADCR/ADCJ Model)
- `WSUM 16` ⇒ Internal energy of the bubble (Only ADCR/ADCJ Model)
- `WSUM 17` ⇒ Internal energy of the cover gas (Only ADCR/ADCJ Model)

Quantities 4 to 17 were added to account for auxiliary energies needed in FV cases. Contrary to FE, Total and kinetic energy FV contributions have to be computed at elements and not at nodes. Quantities 9 to 17 are only relevant for the ADCR/ADCJ Model, it will return 0 in other cases.

Note:

All printed energy quantities are equivalent in FE and FV cases, except for**W_PDV** : In FE, the contribution of pressure work W_PDV on the variation of kinetic energy is neglected in relation to the internal energy variation, which is relevant for smooth solutions. In FV, W_PDV is computed as the variation of total energy, which is always the work of pressure forces for a stand-alone domain.

Note that the global quantities `NSPL` to `LMIN` in the above list are available only in calculations with adaptivity and with STAT option activated (`OPTI ADAP STAT`, see Page H.180).

14.6.7 Curve (Quantities from LOG file)

Object:

Definition of some quantities to be extracted from the LOG file, then drawn or listed.

Syntax:

```
LCOU  nuco  < 'nomcourbe' >
      < FICH 'nom_fich' >
      $ STEP ; TCPU ; DTCR ; ELCR ; DEE  ;
        DMMN ; DMME ; DTMX ; ELMX ; VMAX ;
        NVMX ; ELST ; MEMO ; MEMP $
      < NMAX nmax >
```

`nuco`

Identifier of the curve (reference for `TRAC`, `XMGR`, `K2000` or `LISTE`). A (unique) integer number, freely chosen by the user, by which the curve may be successively referred to when needed.

`'nomcourbe'`

Name of the curve (reference for the user). This will appear on plots, etc.

`FICH 'nom_fich'`

Name of the log file from which data should be extracted. If omitted, the file `basename.log` is used, where `basename` is the base name of the current input file.

`STEP`

Step number.

`TCPU`

CPU time (in s).

`DTCR`

Critical time step.

`ELCR`

Critical element index.

`DEE`

Energy balance.

`DMMN`

Mass balance based on nodes.

`DMME`

Mass balance based on elements.

`DTMX`

Maximum elemental time step.

`ELMX`

Element index having the maximum elemental time step.

`VMAX`

Maximum velocity norm.

`NVMX`

Node (if > 0) or Finite Volume (if < 0) where the maximum velocity occurs.

`ELST`

Number of elements * steps computed so far.

`MEMO`

Memory required.

`MEMP`

Memory peak so far.

`NMAX`

Maximum number of data points retained. If omitted, all data points present in the LOG file are retained.

14.6.8 Curve in space (Nodal Variables)

Object:

Definition of the variables **relative to nodes** to be drawn or listed **as a function of space** and not of time (as by default). The space is here represented by a curvilinear abscissa, which is built up starting by the definition of a sequence of nodes.

Syntax :

```
"SCOURBE"  nuco  < 'nomcourbe' >
           $[ "T" t ; "NPAS" npas ; "NSTO" nsto ]$
           "SAXE" scoe 'nom_saxe' <"INIT"> /LECTURE/
           < "SUPP" /LECT_ELEM/ >

           |[ "COOR" ; "DEPL" ; "VITE" ; "ACCE" ; "FINT" ; "FEXT" ;
              "FLIA" ; "ADFT" ; "MCPR" ; "MCRO" ; "MCTE" ; "MCMF" ;
              "MCUX" ; "MCUY" ; "MCUZ" ; "SIGN" ; "ECRN" ; "LFNO" ;
              "LFNV" ; "ILNO" ; "DTNO" ; "VITG" ; "MASN" ]|

           |[ "COMP" icomp ; "NORME" ]|
```

`nuco`

Identifier of the curve (reference for `TRAC`, `XMGR`, `K2000` or `LISTE`). A (unique) integer number, freely chosen by the user, by which the curve may be successively referred to when needed.

`'nomcourbe'`

Name of the curve (reference for the user). This will appear on plots, etc.

`t`

Time of the desired storage station from which results have to be read in. If option `STEP IO` is active, then the code looks for the precise time `t` specified (within a small tolerance) among all stored time stations and, if no such time is found, an error message is issued. If option `STEP LIBR` is active, the code takes the first stored time station (if any) at a time equal to or greater than the specified time. Again, if no such time is found then an error message is issued.

`npas`

Time step number of the desired storage station from which results have to be read in.

`nsto`

Storage index number of the desired storage station from which results have to be read in.

`SAXE`

Introduces the definition of the curvilinear abscissa to be used as x-axis for the curve.

`scoe`

Multiplicative coefficient for the values of the curvilinear abscissa used as x-axis for the curve. By default, the abscissa is built up according to the distance between nodes, in the order they are defined in the following `/LECTURE/`.

`'nom_saxe'`

Name of the curvilinear abscissa. This will appear on plots, etc.

`INIT`

Build up curvilinear abscissa by using the *initial* nodal positions and not the *current* ones.

`/LECTURE/`

List of nodes defining the curvilinear abscissa. They are taken in the order given by the user (not re-ordered).

`SUPP /LECT_ELEM/`

The optional keyword `SUPP` allows to specify, via the following `/LECT_ELEM/` directive, the geometrical support (list of the elements) to be considered for the search of the concerned descendant nodes between to base nodes of the curvilinear abscissa. By default, all nodes in the mesh are considered as possible candidates. If the mesh contains superposed (or contiguous) objects this can lead to ambiguities as to which nodes should be actually retained. The use of `SUPP` allows to avoid such ambiguities in the formation of the curvilinear abscissa. in particular in adaptivity where thw curvilinear abscissa is built starting from the base nodes, which are the only ones declared by the user.

`COOR`

Coordinate.

`DEPL`

Displacement.

`VITE`

Velocity.

`ACCE`

Acceleration.

`FINT`

Internal force.

`FEXT`

Total external force.

`FLIA`

External force due to liaisons (links).

`ADFT`

Advection-diffusion temperature.

`MCPR`

Finite volume (MC) pressure.

`MCRO`

Finite volume (MC) density.

`MCTE`

Finite volume (MC) temperature.

`MCMF`

Finite volume (MC) component mass fraction.

`MCUX`

Finite volume (MC) fluid velocity along X computed from the conserved variable ($u_x = (\rho u_x)/\rho$)).

`MCUY`

Finite volume (MC) fluid velocity along Y computed from the conserved variable ($u_y = (\rho u_y)/\rho$)).

`MCUZ`

Finite volume (MC) fluid velocity along Z computed from the conserved variable ($u_z = (\rho u_z)/\rho$)).

`SIGN`

Spectral element stress.

`ECRN`

Spectral element internal variable.

`LFNO`

Logarithm in base 2 of the level factor associated with a node in the spatial time step partitioning algorithm.

`LFNV`

Logarithm in base 2 of the level factor associated with a node, including the neighbours in the spatial time step partitioning algorithm.

`ILNO`

Flag indicating whether a node is (1) or is not (0) subjected to a link condition, used in the spatial time step partitioning algorithm.

`DTNO`

Stability time step associated with a node, used in the spatial time step partitioning algorithm.

`VITG`

Grid velocity (ALE only).

`MASN`

Nodal mass.

`COMP`

Introduces the chosen component.

`icomp`

Component number.

`NORM`

The norm of the considered vector (where applicable) is drawn.

Comments :

The directive `SCOURBE` can be repeated as many times as desired, but each time with a different identifier. Identifiers should of course also be different from those of curves defined by the other curve-definition directives (`COURBE`, `RCOURBE`, `DCOURBE`).

Curve identifiers may be freely chosen by the user, and the order in which they are given is irrelevant.

If neither `T` nor `NPAS` nor NSTO are specified, then the last storage station is taken by default.

The keyword `FORC` is accepted as a synonym of `FEXT` for backward compatibility, but is obsolescent and should not be used in new input files.

14.6.9 Curve in space (Element Variables)

Object:

Definition of the variables **relative to elements** to be drawn or listed **as a function of space** and not of time (as by default). The space is here represented by a curvilinear abscissa, which is built up starting by the definition of a sequence of nodes.

Syntax :

```
"SCOURBE"  nuco  < 'nomcourbe' >
           $[ "T" t ; "NPAS" npas ; "NSTO" nsto ]$
           "SAXE" scoe 'nom_saxe' <"INIT"> /LECTURE/
           < "SUPP" /LECT_ELEM/ >

           |[ "CONT" ; "ECRO" ; "EPST" ; "ENEL" ; "WAUX" ; "LFEL" ;
              "LFEV" ; "DTEL" ; "CERR" ; "MAXC" ; "ERRI" ; "CLEN" ;
              "ILEN" ; "MASE" ]|

           "COMP" icomp |[ "GAUS" igaus ; "GAUZ" igauz ]|

           "VCVI" |[ "COMP" icomp ; "NORM" ]|
```

`nuco`

Identifier of the curve (reference for `TRAC`, `XMGR`, `K2000` or `LISTE`). A (unique) integer number, freely chosen by the user, by which the curve may be successively referred to when needed.

`'nomcourbe'`

Name of the curve (reference for the user). This will appear on plots, etc.

`t`

Time of the desired storage station from which results have to be read in. By default, the last storage station is taken.

`npas`

Time step number of the desired storage station from which results have to be read in. By default, the last storage station is taken.

`nsto`

Storage index number of the desired storage station from which results have to be read in. By default, the last storage station is taken.

`SAXE`

Introduces the definition of the curvilinear abscissa to be used as x-axis for the curve.

`scoe`

Multiplicative coefficient for the values of the curvilinear abscissa used as x-axis for the curve. By default, the abscissa is built up according to the distance between nodes, in the order they are defined in the following `/LECTURE/`.

`'nom_saxe'`

Name of the curvilinear abscissa. This will appear on plots, etc.

`INIT`

Build up curvilinear abscissa by using the *initial* nodal positions and not the *current* ones.

`/LECTURE/`

List of nodes defining the curvilinear abscissa. They are taken in the order given by the user (not re-ordered).

`SUPP /LECT_ELEM/`

The optional keyword `SUPP` allows to specify, via the following `/LECT_ELEM/` directive, the geometrical support (list of the elements) to be considered for the projection onto nodes of the chosen element variable. By default, all elements of continuum, shell or beam type present in the mesh are considered. However, the default behaviour may lead to wrong results, for example in the case of shells whose nodes are merged with continuum fluid elements. If one traces, say, the pressure in the fluid, then also the (unrelated) value in the shell would be considered by default. To avoid the problem, specify `SUPP LECT fluid TERM`, where `fluid` is an object containing only the fluid elements. The `SUPP` directive should also be used in *adaptivity* for the definition of space curves (`SCOU`) involving elemental quantities, even in the absence of merged nodes. This allows to avoid ambiguities in the formation of the curvilinear abscissa starting from the base nodes, which are the only ones declared by the user.

`CONT`

Stress tensor.

`ECRO`

Hardening quantity.

`EPST`

Total deformation tensor.

`ENEL`

Internal energy.

`WAUX`

Auxiliary energy terms for the element (see details below).

`LFEL`

Logarithm in base 2 of the level factor associated with an element in the spatial time step partitioning algorithm.

`LFEV`

Logarithm in base 2 of the level factor associated with an element including its neighbours in the spatial time step partitioning algorithm.

`DTEL`

Stability time step Δt_{stab} associated with the element. The *stability step* is the *critical step* Δt_{crit} estimated by the code (roughly the element length L divided by the speed of sound c in the element material) multiplied by the *safety coefficient* ϕ (`CSTA`, by default 0.8): $\Delta t_{\text{stab}} = \phi \Delta t_{\text{crit}} \approx \phi \frac{L}{c}$.

`CERR`

Constant used in element error indicator calculation (adaptivity), see the `CERR` input keyword of the `ADAP` directive on page B.210.

`MAXC`

Maximum principal curvature of least-squares fitting function, used for element error indicator calculation (adaptivity).

`ERRI`

Element error indicator (adaptivity).

`CLEN`

Current characteristic element length used in element error indicator calculation (adaptivity).

`ILEN`

Optimal (indicated) characteristic element length resulting from error indicator calculations (adaptivity).

`MASE`

Element mass.

`VCVI`

Material or particle velocity (first idim components) in Finite Volumes Cell Centred model. Note that these vectors are not represented at the nodes but at the “elements” (i.e. Finite Volumes) centroids.

`COMP`

Introduces the component (unused for `ENEL`, `LFEL`, `LFEV` and `DTEL`).

`icomp`

Number of the component.

`GAUSS`

Introduces the Gauss point (only for the quantities `CONT`, `EPST` and `ECRO`).

`igau`

Number of Gauss point chosen.

`GAUZ`

Introduces the Gauss point through the thickness (only for the quantities `CONT`, `EPST` and `ECRO`).

`igau`

Number of Gauss point through the thickness.

`NORM`

The norm of the VCVI vector is drawn.

Comments :

The directive `SCOURBE` can be repeated as many times as desired, but each time with a different identifier. Identifiers should of course also be different from those of curves defined by the other curve-definition directives (`COURBE`, `RCOURBE`, `DCOURBE`).

Curve identifiers may be freely chosen by the user, and the order in which they are given is irrelevant.

If the keyword `GAUSS` is omitted, the first integration point is considered. If `GAUSS` is set to 0, the average over all integration points is used.

As concerns the auxiliary energy terms for the element (`WAUX`), the following components are avaliable at the moment:

- `WAUX 1` ⇒ Energy dissipated by artificial viscosity (WARD)
- `WAUX 2` ⇒ Pressure work for fluids $-PdV$ (W_PDV)
- `WAUX 3` ⇒ Energy injected or lost at the walls (W_INJ)
- `WAUX 4` ⇒ Kinetic energy for CCFV Elements on X axis
- `WAUX 5` ⇒ Kinetic energy for CCFV Elements on Y axis
- `WAUX 6` ⇒ Kinetic energy for CCFV Elements on Z axis
- `WAUX 7` ⇒ Total Energy for CCFV Elements
- `WAUX 8` ⇒ Used for saving initial injected energy
- `WAUX 9` ⇒ Total energy of the liquid phase (Only ADCR/ADCJ Model)
- `WAUX 10` ⇒ Total energy of the bubble (Only ADCR/ADCJ Model)
- `WAUX 11` ⇒ Total energy of the cover gas (Only ADCR/ADCJ Model)

- `WAUX 12` ⇒ Kinetic energy of the liquid phase (Only ADCR/ADCJ Model)
- `WAUX 13` ⇒ Kinetic energy of the bubble (Only ADCR/ADCJ Model)
- `WAUX 14` ⇒ Kinetic energy of the cover gas (Only ADCR/ADCJ Model)
- `WAUX 15` ⇒ Internal energy of the liquid phase (Only ADCR/ADCJ Model)
- `WAUX 16` ⇒ Internal energy of the bubble (Only ADCR/ADCJ Model)
- `WAUX 17` ⇒ Internal energy of the cover gas (Only ADCR/ADCJ Model)

Quantities 4 to 17 were added to account for auxiliary energies needed in FV cases. Contrary to FE, Total and kinetic energy FV contributions have to be computed at elements and not at nodes. Quantities 9 to 17 are only relevant for the ADCR/ADCJ Model, it will return 0 in other cases.

Note:

All printed energy quantities are equivalent in FE and FV cases, except for**W_PDV** : In FE, the contribution of pressure work W_PDV on the variation of kinetic energy is neglected in relation to the internal energy variation, which is relevant for smooth solutions. In FV, W_PDV is computed as the variation of total energy, which is always the work of pressure forces for a stand-alone domain.

14.6.10 Curve Read In from a File

Object:

Definition of curves to be read in from a file. The file must have been previously produced by EUROPLEXUS itself by means of the `SORT LIST` command, and is a file of type "PUNCH", see page ED.125.

Syntax :

```
"RCOURBE"  nuco    'nomcourbe'    FICH 'nom_fic'
        <"RENAME" 'new_name'>  <"FACX" fx>  <"FACY" fy>
```

`nuco`

Identifier of the curve (reference for `TRAC`, `XMGR`, `K2000` or `LISTE`). A (unique) integer number, freely chosen by the user, by which the curve may be successively referred to when needed.

`'nomcourbe'`

Name of the curve (reference for the user). This will appear on plots, etc. Unlike for the other curve definitions, this name is mandatory here and must exactly match the name by which the curve has been stored on the punch file during a previous EUROPLEXUS run.

`nom_fich`

Name of the punch file enclosed in apostrophes.

`RENA`

Allows to change the name of the curve if so desired.

`new_name`

New name of the curve enclosed in apostrophes.

`FACX`

Allows to change the x-scale of the curve if so desired.

`fx`

Multiplicative factor for the x-values.

`FACY`

Allows to change the y-scale of the curve if so desired.

`fy`

Multiplicative factor for the y-values.

Comments :

The directive `RCOURBE` can be repeated as many times as desired, but each time with a different identifier. Identifiers should of course also be different from those of curves defined by the other curve-definition directives (`COURBE`, `SCOURBE`, `DCOURBE`).

Curve identifiers may be freely chosen by the user, and the order in which they are given is irrelevant.

This directive allows to retrieve curves from different calculations and to compare them by plotting them on the same graph. The time scales and the number of points of the various curves are different in general. The program automatically takes this into account.

Warning :

A certain care should be taken concerning the units of measurement of curves stored and later retrieved for plotting. Note that curves are stored with exactly the x-values and the y-values as they would appear on a drawing. In particular, if the coefficients `AXTE coef`, see page ED.60 and `AXES coef`, see page ED.125, are not unitary, the stored values are multiplied by these coefficients.

When the data are subsequently read in by `RCOU`, the scaling is already included. So, plotting them by re-specifying again `AXTE coef` and/or `AXES coef` would probably not have the desired effect, since the coefficients would be applied twice! The results may be particularly confusing if the curves read from file are plotted together with “normal” curves (for which the coefficients are only applied once).

There is a simple way of avoiding this type of problem: when defining curves to be stored on file for subsequent plottings or comparisons, it is advisable to always specify `AXTE 1.0` and `AXES 1.0`. In this way all curves are saved with their “native” units of measurement. Any scale coefficients may be applied later, during the actual plotting phase.

In case of need, it is possible to assign a new name to a read-in curve by means of the `RENA` directive. This is the name that will appear on the plot legend. However, do not confuse this with the original name of the curve (`nomcourbe`) which must in any case exactly match the name stored in the file in order to select the desired curve.

A mechanism for changing the scales of a read-in curve both in x and in y is offered by means of the `FACX` and `FACY` directives. This is another way of overcoming the difficulties mentioned above concerning the scale factors. However, their use should be avoided whenever possible. The method outlined above of using unit factors at storage is cleaner and much preferable.

Comments about the .pun file format:

In case that the pun file should be used for external data the following format restrictions must be followed:

- The file starts with the word "VALUES".

- The number of stored values is given between the character 7 and 12 of the first line.
- Characters 18:27 are the word COMPONENTS.
- Character 28 and 29 of the first line define the number of components.
- The next line consists from the name of the axe X (6:21) and axe Y (23:38).
- The next line contains the name of the curves (curve X 6:21 and curve Y 23:38). The last part is important since that is the name of the curve that must be defined in the RCOU command.
- After that, all values are defined by two fields of a length of 17 characters (2E17.6). Each couple must be written in a separate line.

14.6.11 Curve Defined By The User

Object:

Definition of curves in the form of tables containing a sequence of (x-y) values. These curves may represent a (piecewise) analytical solution, or even an experimental result, to be compared with numerical solutions by EUROPLEXUS.

The table containing the couples of values may be specified directly within the present directive, or refer to a function previously defined by the directive FONCTION, see page E.15, or represent an analytical solution to a perfect gas shock tube problem, or represent the air blast over-pressure obtained from the AIRB model (modified Friedlander equation) at a given position. The second possibility allows to plot and to visually check the functions which are defined and used in the calculation.

Syntax :

```
"DCOURBE"  nuco  < 'nomcourbe' >
          |[ npt*(x y) ;
             "FONC" ifonc ;
             "SHTU" "GAMM" gamm "ROM" rom "ROP" rop
                    "EINT" eint "LENM" lenm "LENP" lenp "TIME" time
                    "NRAR" nrar "VARI" vari ;
             "AIRB" |[ "X" x "Y" y <"Z" z> ; "NODE" /LEC1/ ]|
                    "MASS" m $[ "TINT" t ; "TAUT" ]$ <"OPOS">
                    <"ANGL">
                    <"CUBE">
                    <"COEF" cf>
                    <"CONF" c>
                    <"DECA" d>
                    <"PMAX" pmax "TD" td "B" b>
                    |[ "PX" px "PY" py <"PZ" pz> ; "PNOD" /LEC2/ ]|
                   <"NX" nx "NY" ny <"NZ" nz>>
                    "TINI" tini "TEND" tend "DT" dt
                                                                     ]|
```

`nuco`

Identifier of the curve (reference for TRAC, XMGR, K2000 or LISTE). A (unique) integer number, freely chosen by the user, by which the curve may be successively referred to when needed.

`'nomcourbe'`

Name of the curve (reference for the user). This will appear on plots, etc.

`npt`

Number of (x-y) couples defining the curve (i.e. number of points). In this case the values table is specified directly.

`x`

Value of the abscissa.

`y`

Corresponding value of the ordinate.

`ifonc`

Index of a function previously defined by the directive `FONCTION`, see page E.15.

`SHTU`

Introduces the parameters of the perfect gas shock tube problem for which the analytical solution (space curve of a chosen variable along the tube length) has to be generated. The high-pressure zone is assumed to be in the left part of the tube, of length `lenm`. The low-pressure zone is assumed to be in the right part of the tube, of length `lenp`. The initial specific energy (and hence the initial temperature) is the same in both parts. The initial density, and hence the initial pressure, is higher in the left part than in the right part of the tube.

`gamm`

Ratio γ between the specific heat C_p at constant pressure and the specific heat C_v at constant volume of the perfect gas.

`rom`

Initial density ρ_m in the left part of the tube (high-pressure zone).

`rop`

Initial density ρ_p in the right part of the tube (low-pressure zone).

`eint`

Initial specific energy i_0 of the perfect gas.

`lenm`

Length l_m of the left part of the tube (high-pressure zone).

`lenp`

Length l_p of the right part of the tube (low-pressure zone).

`time`

Time t at which the analytical solution should be produced.

`nrar`

Number of spatial intervals n_r at which the analytical solution has to be computed in the rarefaction zone.

`vari`

Desired output variable for the analytical solution: 1 means pressure, 2 means density, 3 means specific internal energy, 4 means sound speed, 5 means velocity.

`AIRB`

Introduces the parameters of the AIRB model defining the air blast characteristics (see Page ED.118), plus some parameters indicating the location at which the over-pressure should be evaluated.

`X x Y y <Z z>`

Coordinates of the explosive source. If `z` is omitted, the code takes $z = 0$.

`NODE /LEC1/`

Introduces the node where the explosive charge is located. Typically, a `PMAT` element may be located at the charge position, so as to be able to visualize it.

`MASS m`

Mass of the explosive in Kilograms.

`TINT t`

Starting time of the explosion. By default it is equal to the initial time of the calculation.

`TAUT`

For the `IMPE AIRB` model, this indicates that the detonation time is calculated automatically by the code, in such a way that the air blast wave reaches the first CLxx element shortly after the starting time of the calculation. This is to avoid an "idle" calculation at the beginning of the transient. In the present `DCOU AIRB` directive, however, no CLxx elements are involved. Their role, as concerns `TAUT`, is played by the sampling point (`PX`, `PY`, `PZ`) or sampling node (`PNOD`) defined below. So the detonation time for the current AIRB curve is calculated automatically by the code, in such a way that the air blast wave reaches the sampling entity shortly after the starting time of the calculation.

`OPOS`

Indicates that only the part with the positive pressure (overpressure) is regarded. After the time of duration of the positive phase the pressure is set to 0.

`ANGL`

Indicates that the angle of incidence between the charge and the structural element is considered. In the `IMPE AIRB` model, the normal to the structural element, used to compute the angle of incidence), coincides with the normal to the CLxx element attached to the structural element and having the `IMPE AIRB` material. In the present `DCOU AIRB` model, no CLxx element is present and therefore the normal must be given by the user via the `NX`, `NY`, `NZ` parameters described below, if `ANGL` is activated.

`CUBE`

Indicates that the cubic approach will be used for the calculation of the negative phase. By default the bilinear approach is used.

`COEF cf`

The user can input a value to calibrate the decay coefficient of the air blast load. The calculated decay coefficient is multiplied by the inserted value in order to produce a load closer to experimental data.

`CONF c`

Choice between different available explosion models, see the References at the end of this Page. By default it is 1 (unconfined, reflected, Kingery). The term "unconfined" below means that the explosion takes place in an unconfined space, as opposed to "half-confined" where the charge is placed close to a rigid ground and so the wave propagation occurs in a half-space (experimentally, the measured pressure is somewhat lower in this case because some of the energy is absorbed by the ground). The term "reflected" hereafter means that the model accounts for the pressure increase due to (first) wave reflection at a rigid wall as it is typically measured in experiments. The pressure value in this case may be between 2 and 8 times the incident pressure in the "non-reflected" case, i.e. without taking into account this first reflection.

1. Unconfined (full space), reflected (Kingery)
2. Unconfined (full space), not reflected (Kingery)
3. Unconfined (full space), not reflected (Kinney)
4. Half-confined (half space), reflected (Kingery)
5. Half-confined (half space), not reflected (Kingery)
6. Blast parameters will be directly specified next

`CONF 6` indicates that the blast parameters $p_{\max}$, t_d and b appearing in the so-called modified Friedlander equation (see below) will be directly specified next and should not be calculated automatically by the code. In this case, no other parameters (except `CONF` of course) are accepted, only the positive pressure (overpressure) is considered and the pressure-time function is identical in each element. The **modified Friedlander equation** reads:

$$p(t) = p_0 + p_{\max}(1 - \frac{t}{t_d})^{-\frac{bt}{t_d}}$$

and expresses the pressure p as a function of time t, with p_0 the initial (normally the atmospheric) pressure, $p_{\max}$ the maximum overpressure (peak overpressure), t_d the duration of the positive pressure phase and b the decay parameter, which defines how rapidly the pressure decays.

`DECA d`

Choice between different available decay coefficient equation models. Each equation is defined according to the explosion model chosen before (incident, reflected - spherical, hemispherical). The equations based on the Kingery-Bulmash data have been calculated by iteratively solving the Friedlander equation with the set of positive blast parameters proposed by Kingery-Bulmash. There are different equations for reflected or not reflected (incident) cases of unconfined (spherical) and half-confined (hemi-spherical) blast waves. An additional equation for the blast coefficient is available which is based on the Kinney and Baker data. The default blast decay equation is based on the Kingery-Bulmash data. The explosion model, that has already been defined by the parameter c, shows which of the blast wave decay equations (incident, reflected, spherical or hemispherical) will be used.

1. Blast wave decay equation based on Kinney data
2. Blast wave decay equation based on Kingery-Bulmash data (default)

`PMAX pmax`

Maximum overpressure $p_{\max}$ appearing in the modified Friedlander equation. This should only be given when `CONF 6` has been specified.

`TD td`

Duration of the positive pressure phase t_d appearing in the modified Friedlander equation. This should only be given when `CONF 6` has been specified.

`B b`

Decay parameter b appearing in the modified Friedlander equation. This should only be given when `CONF 6` has been specified.

`PX px`

X-coordinate of the sampling point for the over-pressure.

`PY py`

Y-coordinate of the sampling point for the over-pressure.

`PZ pz`

Z-coordinate of the sampling point for the over-pressure. This is 0 by default.

`PNOD /LEC2/`

Introduces the node where the over-pressure should be sampled. Typically, a `PMAT` element may be located at the charge position, so as to be able to visualize it.

`NX nx NY ny NZ nz`

Components of the normal (not necessarily unitary) to the surface on which the sampling point is located. This corresponds to the normal to the CLxx element in the IMPE AIRB model and must point **away from** the AIRB charge. The normal is only used when the `ANGL` keyword has been specified (and is mandatory in that case). If `ANGL` has not been specified, the normal (if given) is simply ignored.

`TINI tini`

Initial time of the user-defined curve to be generated. Typically this coincides with the initial time of the simulation.

`TEND tend`

Final time of the user-defined curve to be generated. Typically this coincides with the final time of the simulation.

`DT dt`

Time increment Δt with which the over-pressure is sampled in the decaying exponential part of the modified Friedlander curve. The sampling occurs between the initial time and the final time specified in the calculation. The code sets the first point of the user curve at (TINI, 0) where TINI is the initial time. The second point is set at (TARR,0) where TARR is the arrival time of the wave at the sampling point (evaluated automatically). The third point is set at (TARR,PMAX) where PMAX is the maximum overpressure. This allows to make sure that the maximum over-pressure is exactly represented in the user-defined curve. Thereafter, additional points are computed and added to the curve at a regular time distance Δt until the final time is reached.

Comments :

The directive `DCOURBE` can be repeated as many times as desired, but each time with a different identifier. Identifiers should of course also be different from those of curves defined by the other curve-definition directives (`COURBE`, `SCOURBE`, `RCOURBE`).

Curve identifiers may be freely chosen by the user, and the order in which they are given is irrelevant.

This directive allows to define arbitrary curves and to compare them with curves built up from EUROPLEXUS results by plotting them on the same graph. The time scales (or more generally the abscissas) and the number of points of the various curves are different in general. The program automatically takes this into account.

If a curve is specified by means of a function previously defined by the directive `FONCTION`, then:

- If the function is of type `TABL`, then the (x-y) values of the table function are directly used for the curve.
- If the function is of type `ROUT` (see user routine `TABANA`) or of type `LSQU` (least-squares fitting), then the x-values are not specified in the function. The code will try to use the stored time values for the current calculation as the x-values and to compute the corresponding y-values by calling the specified function.
- Other types of functions are not accepted at the moment and an error message is issued.

References:

For more information on the AIRB physical models, consult the following references:

- Kingery, Charles N., Bulmash, Gerald: *Airblast Parameters from TNT Spherical Air Burst and Hemispherical Surface Burst*, Defense Technical Information Center, Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, 1984.
- Baker, Wilfrid E.: *Explosions in the Air.* University of Texas Pr., Austin, 1973.
- Kinney, G.F., Graham, K.J.: *Explosive Shocks in Air.* Springer, Berlin, 1985.

14.6.12 Set of Pochhammer-Chree curves

Object:

Automatic generation of a *set of* curves for Pochhammer-Chree equation verification. The user must have previously read in results from a `.POC` file by means of the `RESU` directive, in addition to reading (global) results from an ordinary results file (typically an ALICE file).

Syntax :

```
"PCOURBE" "YOUN" youn "NU" nu "RHO" rho "R" r
          "NM" nm "IDOF" idof
         <"DHAR" dhar "TOL" tol "STEP" step "N1" n1 "AXTE" axte "FREQ" freq "M" m>
```

`youn`

Young's modulus of the bar material.

`nu`

Poisson's coefficient of the bar material.

`rho`

Density of the bar material.

`r`

Radius of the cylindrical bar.

`nm`

Number of the dispersive modes that will be calculated.

`idof`

Global dof along which the chosen variable is considered: 1 means radial direction, 2 means axial direction. A 2D axisymmetric calculation (with the bar axis directed vertically along the y-axis) is assumed.

`dhar`

Number of harmonics (or frequencies) that participate in the solution. In the case of the single harmonic excitation it should be 1. By default, 250 harmonics are taken.

`tol`

Relative error between an analytical and numerical solution. By default, it is 0.05.

`step`

Number of increments that will be used in the area of the relative error in order to identify a solution. By default, it is 200.

`n1`

Identifier (number) of the first generated curve. By default, it is 1.

`axte`

The name of the x-axis that will be used in the plotting of the curves. By default, it is 'RAD/WAVELENGTH'.

`freq`

The frequency of the excitation load (used only for the case of the single harmonic load).

`m`

The m ratio between the thickness of the shell and the mean radius of the hollow cylinder (in the case of hollow cylinder). By default, it is 0.

Comments :

The directive `PCOURBE` **automatically** generates three sets of curves. The first set (ranging from `n1` to `n1 + nm - 1`) contains the analytical solutions, one for each chosen mode. These curves have the following names: `Mode_1`, `Mode_2` etc. The second set (ranging from `n1 + nm` to `n1 + 2*nm - 1`) contains the numerical solutions, one for each chosen mode. These curves have the following names: `Nume_1`, `Nume_2` etc. The third set (ranging from `n1 + 2*nm` to `n1 + 2*nm + nlines*dhar - 1`) contains the wavenumber spectrum for all the frequencies of interest for all the lines (parallel to the axis of the rod) of the calculation. The peaks on the wavenumber spectrum indicates the specific mode wavenumber for each frequency. These curves have the following name: `LINE_1`, `LINE_2` etc.

Note that any pre-existing curves with the same identifiers will be erased.

The phenomenon of dispersion is the reason why waves with different wavelengths will travel at different speed in the same material. The new module is dealing with the propagation of compressional waves in isotropic cylinders. It calculates the dispersion curves corresponding to each mode of propagation. The dispersion curves for each mode of propagation show the relationship between the phase velocity and the wavelength of a specific material. The procedure of defining those curves is described below in 7 steps

- An axial step function load is imposed in the circular face of the bar.
- Velocity versus time data are calculated and stored at equally spaced points along a predefined line in the axial direction of the bar.
- An FFT analysis is performed for each set of these time data in order to obtain the frequency spectrum for each point. This spectrum data are calculated and stored in order to be used in the next step.
- For each frequency, a history in the space domain across the predefined line is calculated and stored. This history can be calculated if the value of spectrum data is used for every point of the line for the desired frequency.

- By performing an FFT analysis on the space domain history across the predefined line, a wavenumber spectrum can be obtained for each frequency. These results corresponds to the third set of curves produced under `PCOURBE` directive.

- Each peak of the wavenumber spectrum corresponds to specific mode wavenumber for each frequency. The identification of the peaks for each frequency, leads to one point on the dispersion curves for each mode (for the modes that appeared in the desired frequency). Each peak indicates a wave number for the desired frequency and from this pair of values (wavenumber and frequency) the phase velocity and the wavelength of the mode can be defined. Lower modes peaks are located in higher wavenumbers.

- Finally the numerical results are compared with the analytical results of Pochhammer-Cree solution.

In the case where the m directive is defined, the hollow cylinder case is considered for the calculation of the analytical solution. The Mirksy-Herrman frequency equation is used in the case of the hollow cylinder. Also the user is encouraged to use the hole directive in order to define the inner radius of the hollow cylinder.

14.6.13 Drawings (TRACE)

Object:

This instruction is aimed at defining the drawings to be produced.

Syntax:

```
"TRACE"  (  nuco  )  $["PS" ; <"TEXT"> ; "MIF" ]$
                      "AXES"     coef 'nom_axe_Oy'
                     <"XAXE" nxax coex 'nom_axe_Ox'>
                     <"COLO" (co)>
                     <"THIC" (th)>
                     <"DASH" (da)>
                     < $[ "NOLI" ; "LINE" (li) ]$ >
                     <"SYMB" <(sy)>> <"SYSC" sysc>
                     <"NOXL" (nx)>
                     <"NOYL" (ny)>
                     <"XZER"> <"YZER">
                     <"XGRD"> <"YGRD">
                     <"XLOG"> <"YLOG">
                     <"XMIN" xmin "XMAX" xmax $[ "DX" dx ; "NX" nx ]$>
                     <"YMIN" ymin "YMAX" ymax $[ "DY" dy ; "NY" ny ]$>
```

`nuco`

Identifiers of the curves to be drawn (at most 12 curves).

`PS`

Draw on a PostScript file (this is the default).

`TEXT`

In addition to drawing on a PostScript file, also produce a list of the drawn data in tabular form (x-value, y-value) on a text file. The name of this file is `<base>.txt`, where `<base>` is the base name of the current calculation.

`MIF`

Draw on a MIF file. MIF is Adobe FrameMaker's language and may be suited to embed the graphics in a FrameMaker document. The drawing remains fully editable in FrameMaker (line style, colors, fonts etc.).

`coef`

Multiplying coefficient to change the units of the `Oy` axis.

`'nom_axe_Oy'`

Name of the `Oy` axis (at most 16 characters).

`nxax`

Optional identifier of a curve to be used for the x-axis. By default, the drawing of the specified curves is done vs. time. However, by specifying the `XAXE` sub-directive, it is possible to produce a combined graph in which one or more quantities are plotted vs. another quantity rather than vs. time. For example, a σ-ϵ graph may be produced.

`coex`

Multiplying coefficient to change the units of the `Ox` axis.

`'nom_axe_Ox'`

Name of the `Ox` axis (at most 16 characters).

`COLO`

Optional keyword that introduces the colors to be used for the various curves. If omitted, all curves are drawn in black.

`co`

Name of the color for the curve, (**not** enclosed in quotes). This must be repeated exactly as many times as there are curves in the drawing (see `nuco` above). The valid names are those of Cast3m, i.e. `bleu`, `roug`, `rose`, `vert`, `turq`, `jaun`, `blan` or `noir`.

`THIC`

Optional keyword that introduces the line thicknesses to be used for the various curves, in points. If omitted, all curves are drawn with a line thickness of 0.1 points.

`th`

Line thickness for the curve, in points. This must be repeated exactly as many times as there are curves in the drawing (see `nuco` above).

`DASH`

Optional keyword that introduces the dash patterns to be used for the various curves. If omitted, all curves are drawn as solid lines.

`da`

Code for the curve dash pattern. This must be repeated exactly as many times as there are curves in the drawing (see `nuco` above). Valid dash pattern codes are: 0 for a solid line, 1 for long dashes, 2 for medium dashes, 3 for short dashes, 4 for extra-short dashes, and 5 for long-short dashes.

`NOLI`

Do not draw any lines connecting points on (all) the curves.

`LINE`

Choose which curve(s) should be drawn as lines or not.

`li`

Code for the line connecting the curve points. This must be repeated exactly as many times as there are curves in the drawing (see `nuco` above). Valid line codes are: 0 means no line, 1 means line (with the chosen color, thickness and dash pattern, if any).

`SYMB`

Draw a symbol at each data point on each of the curves. The symbol is drawn *in addition* to the curve line. To remove the line (leaving only the symbols), use the `NOLI` or the `LINE (li)` keywords described above. To selectively choose which curves will get symbols, and/or the symbol used for each curve, specify the following (optional) sequence `(sy)`. By default (no `(sy)` specified), symbol types 1 to 12 (see below) are used for curves 1 to 12.

`sy`

Code for the symbol drawn on each curve data point. If present, this must be repeated exactly as many times as there are curves in the drawing (see `nuco` above). Symbols are drawn with the same color and thickness as the associated curve. Valid symbol codes are: 0 no symbol, 1 plus, 2 cross, 3 square, 4 octagon, 5 triangle north, 6 triangle south, 7 triangle east, 8 triangle west, 9 hourglass, 10 hourglass horizontal, 11 diamond, 12 Y, 13 Z.

`SYSC`

Introduce a symbol scaling factor `sysc`. By default, the factor is 1.0.

`NOXL`

Optional keyword that introduces the definition of whether or not the various curves participate in the definition of the x-axis (automatic search of the limits and of the major and minor subdivisions). If omitted, all curves participate in the definition of the x-axis.

`nx`

Code for the curve participation in the definition of the x-axis. This must be repeated exactly as many times as there are curves in the drawing (see `nuco` above). Valid codes are: 0 means that the curve participates in the definition of the axis, 1 means that the curve is ignored in definition of the axis.

`NOYL`

Optional keyword that introduces the definition of whether or not the various curves participate in the definition of the y-axis (automatic search of the limits and of the major and minor subdivisions). If omitted, all curves participate in the definition of the y-axis.

`ny`

Code for the curve participation in the definition of the y-axis. This must be repeated exactly as many times as there are curves in the drawing (see `nuco` above). Valid codes are: 0 means that the curve participates in the definition of the axis, 1 means that the curve is ignored in definition of the axis.

`XZER`

Draw a vertical dotted line in correspondence of the abscissa $x = 0$.

`YZER`

Draw a horizontal dotted line in correspondence of the ordinate $y = 0$.

`XGRD`

Draw vertical grid lines at every major axis tick.

`YGRD`

Draw horizontal grid lines at every major axis tick.

`XLOG`

Use a logarithmic (10-base) scale for the x-axis instead of a linear scale. Obviously, all x-values must be strictly positive.

`YLOG`

Use a logarithmic (10-base) scale for the y-axis instead of a linear scale. Obviously, all y-values must be strictly positive.

`XMIN`

Use the specified lower limit for the x-axis instead of computing it automatically.

`XMAX`

Use the specified upper limit for the x-axis instead of computing it automatically.

`DX`

Use the specified scale increment for the x-axis instead of computing it automatically.

`NX`

Use the specified number of increments for the x-axis instead of computing it automatically.

`YMIN`

Use the specified lower limit for the y-axis instead of computing it automatically.

`YMAX`

Use the specified upper limit for the y-axis instead of computing it automatically.

`DY`

Use the specified scale increment for the y-axis instead of computing it automatically.

`NY`

Use the specified number of increments for the y-axis instead of computing it automatically.

Comments:

The instruction `TRAC` may be repeated as many times as desired.

It is possible to use the same curve (same identifier) for several drawings.

Normally the axes scales are computed automatically. However, the user may take full control of this process by specifying `XMAX ...` and / or `YMAX ...`. When specifying a lower bound also the corresponding upper bound and either the increment or the number of increments must be specified as well.

Examples:

```
"TRAC"   1 4 2  "AXES"  1.  'PRESSION (PA) '
"TRAC"     1 2  "AXES" 1E-6 'PRESSION (MPA)'
"TRAC" 6 "AXES" 1E-6 'STRESS (MPA)' "XAXE" 5 1.0 'STRAIN'
```

14.6.14 Output on file (XMGR)

Object:

Definition of the variables to be printed on the auxiliary files directly readable by the XMGR software (Copyright Paul J. Turner). See also the directive `PERK` on page ED.60, which allows to change the default name of the output file.

Syntax:

```
"XMGR"   (  nuco  )   "AXES"      coef 'nom_axe_Oy'
                     <"XAXE" nxax coex 'nom_axe_Ox'>
```

`nuco`

Identifiers of the curves to be printed (at most 12 curves).

`coef`

Multiplying coefficient to change the units of the `Oy` axis.

`'nom_axe_Oy'`

Name of the `Oy` axis (at most 16 characters).

`nxax`

Optional identifier of a curve to be used for the x-axis. By default, the drawing of the specified curves is done vs. time. However, by specifying the `XAXE` sub-directive, it is possible to produce a combined graph in which one or more quantities are plotted vs. another quantity rather than vs. time. For example, a σ-ϵ graph may be produced.

`coex`

Multiplying coefficient to change the units of the `Ox` axis.

`'nom_axe_Ox'`

Name of the `Ox` axis (at most 16 characters).

Comments:

The `XMGR` directive may be repeated as many times as needed.

The use of this directive is identical to that of directive `TRACE`. It is possible to combine them by using the same curves:

Example:

```
"TRACE"    1 4 2  "AXES"  1.  'PRESSION (Pa)'
"XMGR"       4 2  "AXES"  1.  'PRESSION (Pa)'
```

The files created for XMGR have names of the form: `<base_xxx>.MGR`, where `<base>` is the base name of the current calculation and `xxx` is a counter. A separate file is produced for each `XMGR` directive. If no base name is available, then the file name becomes `TRACXMGR_xxx.MGR`.

It is possible to use the same curve (same identifier) for more than one list.

Examples:

```
"XMGR"    1 4 2  "AXES"  1.  'PRESSION (Pa)'
"XMGR"      1 2  "AXES" 1E-6 'PRESSION (MPa)'
"XMGR" 6 "AXES" 1E-6 'STRESS (MPA)' "XAXE" 5 1.0 'STRAIN'
```

14.6.15 Output on file (K2000)

Object:

Definition of the variables to be printed on an auxiliary file directly readable by the CASTEM 2000 software. See also the directive `PERF` on page ED.60, which allows to change the default name of the output file.

Syntax:

```
"K2000"   (  nuco  )   "AXES"      coef 'nom_axe_Oy'
                     <"XAXE" nxax coex 'nom_axe_Ox'>
```

`nuco`

Identifiers of the curves to be printed (at most 12 curves).

`coef`

Multiplying coefficient to change the units of the `Oy` axis.

`'nom_axe_Oy'`

Name of the `Oy` axis (at most 16 characters).

`nxax`

Optional identifier of a curve to be used for the x-axis. By default, the drawing of the specified curves is done vs. time. However, by specifying the `XAXE` sub-directive, it is possible to produce a combined graph in which one or more quantities are plotted vs. another quantity rather than vs. time. For example, a σ-ϵ graph may be produced.

`coex`

Multiplying coefficient to change the units of the `Ox` axis.

`'nom_axe_Ox'`

Name of the `Ox` axis (at most 16 characters).

Comments:

The `K2000` directive may be repeated as many times as needed.

The use of this directive is identical to that of directive `TRACE`. It is possible to combine them by using the same curves:

Example:

```
"TRACE"    1 4 2  "AXES"  1.  'PRESSION (Pa)'
"K2000"      4 2  "AXES"  1.  'PRESSION (Pa)'
```

The formatted file may be directly inserted in the input data for CASTEM 2000. The contained objects are of type "LISTREEL", and the names are "L_TEMPS" for the time and "L_number" for the curves (number is the curve identifier).

It is possible to use the same curve (same identifier) for more than one list.

Examples:

```
"K2000"    1 4 2  "AXES"  1.  'PRESSION (Pa)'
"K2000"      1 2  "AXES" 1E-6 'PRESSION (MPa)'
"K2000" 6 "AXES" 1E-6 'STRESS (MPA)' "XAXE" 5 1.0 'STRAIN'
```

14.6.16 Output on file (LIST)

Object:

Definition of the variables to be printed on an auxiliary file of type "PUNCH" (see also the directive PERF).

Syntax:

```
"LISTE"   (  nuco  )   "AXES"      coef 'nom_axe_Oy'
                      <"XAXE" nxax coex 'nom_axe_Ox'>
```

nuco

Identifiers of the curves to be printed (at most 12 curves).

coef

Multiplying coefficient to change the units of the Oy axis.

'nom_axe_Oy'

Name of the Oy axis (at most 16 characters).

nxax

Optional identifier of a curve to be used for the x-axis. By default, the drawing of the specified curves is done vs. time. However, by specifying the XAXE sub-directive, it is possible to produce a combined graph in which one or more quantities are plotted vs. another quantity rather than vs. time. For example, a σ-ϵ graph may be produced.

coex

Multiplying coefficient to change the units of the Ox axis.

'nom_axe_Ox'

Name of the Ox axis (at most 16 characters).

Comments:

The LISTE directive may be repeated as many times as needed.

The use of this directive is identical to that of directive TRACE. It is possible to combine them by using the same curves:

Example:

```
"TRACE"    1 4 2  "AXES"  1.  'PRESSION (Pa)'
"LISTE"      4 2  "AXES"  1.  'PRESSION (Pa)'
```

The tables come out as `nbco` blocks of NT lines with two numbers (x-y values) each each The first value is the abscissa (by default the time), and the second value is the corresponding ordinate (y-value). Each block therefore fully describes one curve. Blocks are given in the same order as they appear in directive `LISTE`.

To facilitate the subsequent reading of these tables, each block is proceeded by three description lines:

- On the first line, after the word `VALEURS` there is `NT`, the number of lines of the block, that is also the number of x-y couples. Then comes the word `COMPOSANTES`, followed by the number of y-value columns (this number is always 1).
- On the second line, which starts by `*`, are given the names of the `Ox` axis and of the `Oy` axis (string `nom_axe_Oy` of directive `AXES`).
- On the third line, which also starts by `*`, are given the names of the curves (`nomcourbe`) defined in `COURBE`.

It is possible to use the same curve (same identifier) for more than one list.

Examples:

```
"LISTE"    1 4 2  "AXES"  1.  'PRESSION (Pa)'
"LISTE"      1 2  "AXES" 1E-6 'PRESSION (MPa)'
"LISTE" 6 "AXES" 1E-6 'STRESS (MPA)' "XAXE" 5 1.0 'STRAIN'
```

Warning :

A certain care should be taken concerning the units of measurement of curves stored and later retrieved for plotting. Note that curves are stored with exactly the x-values and the y-values as they would appear on a drawing. In particular, if the coefficients `AXTE coef`, see page ED.60 and `AXES coef`, see above, are not unitary, the stored values are multiplied by these coefficients.

When the data are subsequently read in by `RCOU`, the scaling is already included. So, plotting them by re-specifying again `AXTE coef` and/or `AXES coef` would probably not have the desired effect, since the coefficients would be applied twice! The results may be particularly confusing if the curves read from file are plotted together with “normal” curves (for which the coefficients are only applied once).

There is a simple way of avoiding this type of problem: when defining curves to be stored on file for subsequent plottings or comparisons, it is advisable to always specify `AXTE 1.0` and `AXES 1.0`. In this way all curves are saved with their “native” units of measurement. Any scale coefficients may be applied later, during the actual plotting phase.

14.6.17 Find value on a curve (FVAL)

Object:

Find values (abscissas) x of a curve for which the curve assumes a given value v, i.e. for which $y(x) = v$. Linear interpolation is used. All found values of x are printed on the listing.

If $y(x_n) \leq v \leq y(x_{n+1})$, or $y(x_n) \geq v \geq y(x_{n+1})$, then the value of x in the interval from x_n to x_{n+1} is interpolated linearly by the expression:

$$x = x_n + (x_{n+1} - x_n)\,\frac{v - y_n}{y_{n+1} - y_n} \tag{99}$$

Syntax:

```
"FVAL" nuco val
```

`nuco`

Identifier of the curves to be examined.

`val`

Value to be sought on the curve.

Comments:

Note that, like in the case of minimum and maximum values (`MINM`) of curves, the found values (if any) are printed on the listing only when the corresponding curve is drawn via the `TRAC` command.

Therefore, in order to get the desired values actually printed make sure to first use the `FVAL` directive for the desired curve(s) and then let the curve number appear in at least one `TRAC` directive. For example:

```
SORT GRAP ...
. . .
COUR 1 ...
COUR 3 ...
COUR 23 ...
. . .
FVAL 1 3.14  ! search value 3.14 on curve #1
FVAL 23 -1.0 ! search value -1.0 on curce #23
. . .
TRAC 23 ...
FIN
```

In the above example, the value search for -1.0 in curve 23 is printed on the listing, but the search for value 3.14 in curve 1 is not printed.

14.7 VISUALIZATIONS

Object:

To produce, by reading results stored in the results file, (a subset of) the visualizations that are possible during direct execution of the code (see Pages A.25 and O.10). These include graphical rendering interactively in a window or in batch mode on file and production of animations. Not all visualization types and features are available, though (see below for details).

Syntax:

```
( "VISU" $ "T" t ; "NPAS" npas ; "NSTO" nsto $
      <PLAY>
      <sequel of interactive commands, see pages A.25 and O.10>
      <ENDPLAY>
)
```

`t`

Time of the desired (initial) storage station from which results have to be read in. Subsequent time stations may then be reached by suitable commands (e.g. `GO` and `FREQ`) in the `PLAY` ... `ENDPLAY` sequence.

`npas`

Time step number of the desired (initial) storage station from which results have to be read in. Subsequent time stations may then be reached by suitable commands (e.g. `GO` and `FREQ`) in the `PLAY` ... `ENDPLAY` sequence.

`nsto`

Storage index number of the desired (initial) storage station from which results have to be read in. Subsequent time stations may then be reached by suitable commands (e.g. `GO` and `FREQ`) in the `PLAY` ... `ENDPLAY` sequence.

`PLAY`

Introduces a sequel of "interactive" commands (see pages A.25 and O.10) that are read subsequently from the input file rather than from the keyboard.

`ENDP`

Terminates the sequel of "interactive" commands (see pages A.25 and O.10) that are read subsequently from the input file rather than from the keyboard.

Comments:

As indicated by the parentheses in the above syntax, the `VISU` sub-directive may be repeated as many times as needed within the `SORT` directive (see Page ED.40). However, only one `SORT` directive is allowed within each input data set.

Repetition of the `VISU` sub-directive (without repeating `SORT`) may be useful e.g. to **step back** in the ALICE file, i.e. to go to a previously saved time step. To **step forth** in the ALICE file, simply use the `GO` and `FREQ` commands in the `PLAY` ... `ENDPLAY` sequence, as mentioned above.

The options `T`, `NPAS` and `NSTO` are mutually exclusive. Exactly one of them must be specified, in order to position the read cursor of the storage file at the initial storage position of interest. Following storage positions may then be accessed by the "interactive" commands if so desired (e.g. to produce an animation).

So-called "interactive" commands such as `TRAC` may then be issued from the keyboard. Alternatively, they may be embedded in the input file by enclosing them in the pair of keywords `PLAY ... ENDPLAY`.

The read cursor may be advanced by means of the `GO` command. In this case, however, the frequency `FREQ` counts the storage stations rather than the time steps. To terminate the execution of interactive commands (when typing them actually at the keyboard) and to return control to the input file, use the `ENDP` command.

Warnings:

Note that not all the visualization features described in pages A.25 and O.10 for direct execution of the code are available when visualizing results from a results file. Most restrictions come from the fact that the results file (typically an ALICE file) does not contain all the information that is available during direct execution.

For example, the following features will not work:

- Visualization of thicknesses.
- Visualization of material-related data.
- Etc. etc.

Note also that, although the `RESU` directive allows to read data from several types of results files, not all of them are suitable for visualizations. For example, an `ALIC TEMP` results file typically contains only very limited information (just a few nodes and elements) and therefore it is suitable for the productiuon of graphs (time curves) but not of visualizations involving the whole mesh.

15 GROUP O—INTERACTIVE COMMANDS

Object

This Section describes all the interactive commands which can be issued during a foreground (interactive) execution of the code. To launch EUROPLEXUS in interactive mode, include the `CONV` keyword at the beginning of the input file, as described in Section 4.2 (Page A.25).

When interactive execution is chosen, EUROPLEXUS reads the input data-set as usual, performs step 0 to initialise the computation, then prompts the user for commands from the keyboard with the phrase: `COMMANDE ?`.

The user can then issue various commands and subcommands **typically from the keyboard** in order to pilot the computation. For example, he can ask the program to perform a certain number of steps, then to pause again for further commands. Each time the calculation is paused, the current computational model can be visualized (e.g. by means of the built-in OpenGL-based visualization module) and information concerning the computation (time step, CPU time, etc.) can be printed. Furthermore, the current time step can be varied by the user.

As an alternative to typing commands by hand from the keyboard, such commands may be included in the regular EUROPLEXUS input file by enclosing them into a special directive `PLAY` ... `ENDPLAY` as described in Section 13.6 (Page I.24) and in Section 14.7 (Page ED.140). For example, this may be useful when the "interactive" command have to be saved for later re-execution, or when the command sequence is particularly complex, e.g. for the production of an animated visualization sequence.

COMMANDS

The following Sections list all the available "interactive" commands:

- Section 15.1 lists all primary interactive commands;
- Section 15.2 lists all the keystrokes and mouse events which are interpreted as commands in the built-in OpenGL-based graphical visualizer;
- Section 15.3 lists all `CALCUL` commands, used to pilot the current time increment;
- Section 15.4 lists all `TRACE` commands, used to visualize the current results;
- Section 15.5 lists all `MAVI` commands, used to produce an animation AVI file from a sequence of images previously produced by EUROPLEXUS itself;
- Section 15.6 lists all `GOTRAC` commands, used to activate a simple looping mechanism, useful e.g. in animation production;
- Section 15.7 lists all `CAMERA` commands, used to set the camera used for visualization;
- Section 15.8 lists all `SLERP` commands, used to set the motion of the camera used for visualization;
- Section 15.9 lists all `SCENE` commands, used to set all the details of a visualization;
- Section 15.10 lists all `TITLES` commands, used to insert titles in an animation.

15.1 Primary interactive commands

Object

To pilot a calculation interactively. Note, however, that it is also possible to store such commands within the regular EUROPLEXUS input file (rather than typing them at the keyboard) and then to execute them by means of the `PLAY` directive, described on Page I.24. In this way, the unique functionalities offered by the "interactive" commands become available also for unattended code execution, allowing e.g. to automatize the production of graphics or animated sequences.

Syntax

Here is the syntax of interactive commands and subcommands:

```
$ "?"                                                          $
$ "GO"                                                         $
$ "STOP"                                                       $
$ "INFO"                                                       $
$ "FREQ" npas                                                  $
$ "TFRE" tfreq                                                 $
$ <$ HPIN ; NOHP $>                                            $
$ "CALC" $ "?"       $                                         $
$        $ "AUTO"    $                                         $
$        $ "UTIL"    $                                         $
$        $ "DT" tstep $                                        $
$        $ "R"       $                                         $
$ "TRAC" $ "?"                                               $ $
$        $ "NORM"                                            $ $
$        $ "ELEM" i1 i2                                      $ $
$        $ "ZOOM" $ "?"                        $             $ $
$        $        $ "POIN" xmin ymin xmax ymax $             $ $
$        $        $ "RETI"                     $             $ $
$        $        $ "R"                        $             $ $
$        $ "OEIL" xoeil yoeil zoeil                          $ $
$        $ "CULL"                                            $ $
$        $ "NOCU"                                            $ $
$        $ "NUME" $ "NOEU" $                                 $ $
$        $        $ "ELEM" $                                 $ $
$        $ "NONU"                                            $ $
$        $ "R"                                               $ $
$        $ "CDEP"                                            $ $
$        $ "CDNO"                                            $ $
$        $ <$ "FAIL" ; "NFAI" ; "FANF" $>                    $ $
$        $ "OBJE" /LECT/ <SURF ; FSIN /LECT/>                $ $
$        $ "NOOB" "NOGR" "OMEM"                              $ $
$        $ "PINB"                                            $ $
$        $ "PINC"                                            $ $
```

```
$        $ "DEFO"                                                $ $
$        $ "AMPD" ampd                                           $ $
$        $ "VITE"                                                $ $
$        $ "VITG"                                                $ $
$        $ "AMPV" ampv                                           $ $
$        $ "FEXT"                                                $ $
$        $ "FINT"                                                $ $
$        $ "AMPF" ampf                                           $ $
$        $ "DASH" idsh                                           $ $
$        $ "AVS" | "DEPL" "VITE" "FEXT" "ACCE" "MCXX"            $ $
$        $         "VITG" "FINT" "CONT" "EPST" "ECRO"            $ $
$        $         "ECRC" /LECT/                               | $ $
$        $ "PS"                                                  $ $
$        $ "MIF"                                                 $ $
$        $ "POVR"                                                $ $
$        $ "P10"                                                 $ $
$        $ < <"OFFS" <"SIZE" w h> <$ "RPOV" ; "BPOV"$>           $ $
$        $           <"ZIP"> <"FICH" $ "BMP"       $             $ $
$        $                           $ "PPM"       $             $ $
$        $                           $ "PPMA"      $             $ $
$        $                           $ "TGA"       $             $ $
$        $                           $ "EPS"       $             $ $
$        $                           $ "EPSB"      $             $ $
$        $                           $ "PRAY"      $             $ $
$        $                           $ "AVI" <pars> $ <'base'> >  $ $
$        $   <"SYMX"> <"SYMY"> <"EXTZ nz dz>                     $ $
$        $   <"AXIS" na ang> <"NOSY">                            $ $
$        $   <"SAVE"> <"REUS">                           "REND" > $ $
$ <Keystrokes and mouse events (OpenGL visualizer): see Page O.15>  $
$ "MAVI" <"DUMP"> <"FROM" 'base'> <"UZIP"> <"RZIP"> <"TO" 'to'>     $
$        <"FIRS" firs> <"LAST" last> <"STEP" step"> <pars> "REND"   $
$ "CAME" icam < "EYE" ex ey ez >                                    $
$        < $ "Q" qr qx qy qz                          $             $
$          $ "VIEW" vz vy vz "RIGH" rx ry rz "UP" ux uy uz $ >      $
$        < FOV fovy >                                               $
$ "LCAM"                                                            $
$ "SLER" "CAM1" ic1 <"CAM2" ic2> <"NFRA" nfra>                      $
$        <INTE /PROG/> <CENT cx cy cz>                              $
$ "LSLE"                                                            $
$ "SCEN" <spars>                                                    $
$ "TITL" <tpars>                                                    $
$ "GOTR" <"LOOP" n> <trac_options> trac_terminator                  $
$ "R"                                                               $
$ "TIME"                                                            $
$ "BENS"                                                            $
$ "NOBE"                                                            $
$ "QMS"                                                             $
$ "COPY"                                                            $
$ "MEAS" <measurement commands> TERM                                $
$ "ADAP" ($ <"RECU"> $ "SPLI" ; "USPL" $ $ iel ; "OBJE" /LECT/ $ $  $
$         $ "UHAN" nod                                            $) $
```

```
$       TERM                                                $
$ "EROD" /LECT/                                             $
$ "QUAL" ... (see syntax on Page I.25)                      $
$ "EFSI" "STRU" /LECTS/ "FLUI" /LECTF/                      $
$       "VARI" $ "PRES" ; "DENS" ; "PMAX" ;                 $
$                "PMIN" ; "POVR" ; "IMPL" $ "DIST" d        $
$       <"SLOW">                                            $
```

`?`

Lists the available primary interactive commands.

`GO`

Advances the computation of npas time steps.

`STOP`

Stops the computation.

`INFO`

Prints information: current time and step number of the computation, time step increment, stability step and critical time step.

`FREQ`

In a direct calculation, this specifies the interval (in time steps) between two successive interruptions of the calculation. Initial value is 1. The computation will halt every `npas` steps (counted from step 0!) and prompt for commands. This command may be combined with `TFRE`, see below. Note that in a post-treatment calculation (`RESU` keyword, which reads previously stored data from a results file, typically an ALIC file) the meaning of `npas` is different: it indicates the storage stations and not the time step numbers. Furthermore, in this case the `FREQ` and `TFRE` commands may not be combined (i.e., either `npas` or `tfreq` *must* be 0).

`npas`

Computation interval in time steps (or in storage stations).

`TFRE`

In a direct calculation, this specifies the interval (in time) between two successive interruptions of the calculation. Initial value is 0.0. The computation will halt every `tfreq` time units (counted from the initial time!) and prompt for commands. This command may be combined with `FREQ`, see above. Note that in a post-treatment calculation (`RESU` keyword, which reads previously stored data from a results file, typically an ALIC file) the `FREQ` and `TFRE` commands may not be combined (i.e., either `npas` or `tfreq` *must* be 0).

`tfreq`

Computation interval in time units.

`HPIN`

Halt interactive execution whenever pinball contacts are established (passing from a situation of zero contacts to one or more contacts) or completely disappear (passing from one or more contacts to zero contacts), so that the user may e.g. visualize the contacts. This switch has a toggling behaviour (see comments and sample usage below).

`NOHP`

Do not halt interactive execution whenever pinball contacts appear or disappear. This is the default so normally it does not need to be specified explicitly. However, the keyword is useful to restore the default behaviour after the optional keyword `HPIN` has been specified.

`CALC`

Allows to change the current time step increment. See options below.

`TRAC`

Displays (on graphics screens) or plots (on plotting devices) the current, deformed mesh shape. By default the entire mesh is visualized. See options below.

`Keystrokes and mouse commands`

When using the OpenGL built-in visualizer interactively, some keystrokes and mouse events are interpreted as commands. A complete list of these commands is given in Page O.15.

`MAVI`

Make an animation file (.AVI) starting from a sequence of bitmap images. At the moment, this functionality is available only starting from bitmap files of type BMP. See syntax and options below.

`CAME`

Defines a camera for OpenGL rendering. See below for the various options.

`LCAM`

List all the cameras defined so far. Note that on EUROPLEXUS versions implemented on a non-OpenGL platform, this directive is simply ignored. This enhances portability of benchmark tests on the various platforms.

`SLER`

Defines a spherical linear interpolation (slerp) for OpenGL rendering. See below for the various options.

`LSLE`

List the currently valid slerp. Note that on EUROPLEXUS versions implemented on a non-OpenGL platform, this directive is simply ignored. This enhances portability of benchmark tests on the various platforms.

`SCEN`

Define the current scene parameters `<spars>` to be used for OpenGL rendering. See below for the various parameters.

`TITL`

Define the titles (`<tpars>`) to be used for the production of a titles frame (or AVI sequence) in off-screen OpenGL rendering. See below for the various parameters.

`GOTR`

Performs a `GO` followed by a `TRAC`. The sequence may be automatically repeated `n` times by using the `LOOP` sub-keyword. This command is useful, among other things, for the automatic preparation of image sequences or animations. See below for a complete description.

`R`

Repeat the last command issued (this works also if the preceding command was a `GOTR`).

`TIME`

Prints the current physical and CPU time.

`BENS`

Activates Benson plotter graphics output instead of screen output.

`NOBE`

Deactivates Benson plotter output; subsequent graphics are visualized on the screen.

`QMS`

Pilots a QMS laser printer directly connected to a graphics terminal (Tektronix emulation) to obtain a copy of the graphics appearing on the screen. This command was formerly used at JRC and is now obsolete.

`COPY`

Used at JRC to redirect Tektronix graphics output from the screen to a file, defined as logical unit number 17. The typical command sequence is "COPY TRAC NORM", by which the current mesh plot is added to the contents of the file connected to unit 17 (initially void). This can be later visualized again (under UNIX, by the 'cat file_name' command) and/or printed.

`MEAS ... TERM`

Introduces some measurement commands, see the full syntax on page G.105.

`ADAP ... TERM`

Introduces interactive adaptivity commands. These commands may be repeated any number of times. The end of this directive is marked by the `TERM` keyword.

`RECU`

Treat the element(s) specified next recursively, not literally. See the comments below for a detailed explanation of the use of the `RECU` optional keyword and for an example of its use.

`SPLI iel`

Split element `iel`.

`SPLI OBJE /LECT/`

Split the object defined by `/LECT/`.

`USPL iel`

Unsplit element `iel`.

`USPL OBJE /LECT/`

Unsplit the object defined by `/LECT/`.

`UHAN nod`

Un-hang the hanging node `nod`. This command should be used only for debugging purposes and never in a normal calculation. Normally, hanging nodes become non-hanging automatically (if appropriate) as a consequence of element splitting or un-splitting in adaptivity.

`EROD /LECT/`

Erode immediately the object defined by `/LECT/`. The keyword `EROS` (see GBA_0030) must be present at the beginning of the input file (before DIME and GEOM) to activate the erosion mechanism.

`QUAL ...`

Qualify the results interactively (on the fly, i.e. at the current step). The complete syntax of the `QUAL` directive is given on page I.25. This is probably most useful within a `PLAY ... ENDP` directive.

EFSI commands

`EFSI ...`

Introduces commands to Extract embedded FSI fields (EFSI). These are fluid fields (pressure, density etc.) that can be visualized on a structure used as geometrical support. They are useful in conjunction with FSI algorithms of the embedded type (`FLSR`, `FLSW`).

`STRU /LECTS/`

List of the (base) structural elements (typically shells) forming the geometrical support on which the extracted fluid field will be visualized.

`FLUI /LECTF/`

List of the (base) fluid elements from which the field will be extracted.

`VARI ...`

Selects the physical variable(s) to be extracted: `PRES` is the pressure, `DENS` the density, `PMAX` the maximum pressure ever experienced, `PMIN` the minimum pressure ever experienced, `POVR` the risk-related overpressure and `IMPL` the risk-related impulse. In case of PVTK output more than one variable can be chosen while for the interactive mode, only one variable is possible.

`DIST d`

Explicitly sets the distance d from each structural element at which the fluid data should be extracted. Positive values of d indicate that data should be extracted from the positive direction of the oriented normal to the structure, negative values of d indicate that data should be extracted from the negative (opposite) direction of the oriented normal to the structure. For the resulting visualization to be meaningful, it is **fundamental** that the structure (shells) be oriented consistently. In 3D, this can be verified by simply drawing the (geometry of the) structure in the OpenGL built-in visualizer: the front faces of the structure will appear as colored while the back faces will appear as empty (since the default is to fill the front faces but not the back faces).

`SLOW`

Optional keyword that activate the brute force search of candidate fluid elements for the extraction of the EFSI flied, instead of the fast search used by default. To be used only for debugging purposes since the search becomes very slow in medium/large applications.

Comments

An example of use of the `HPIN` and `NOHP` keywords is as follows. Suppose a user wants to visualize contact details in a calculation using pinballs. Normally it is difficult to exactly foresee when a contact will be established and/or it will disappear. Use the following interactive commands:

```
FREQ 1000000
HPIN
GO
```

In this way, the code will halt when the first pinball contact is detected and the user will have the possibility of visualizing the contact conditions. Then, type again:

```
GO
```

The execution will continue and will halt again when there are no more pinball contacts (toggling behaviour). This is useful because normally a contact remains for a number of successive time steps after it has first occurred. Then, type again:

```
GO
```

The calculation will halt when a new contact is detected, and so on.

Note that the `HPIN` keyword is automatically combined with the effects of `FREQ`, `TFRE` etc. The first of the specified conditions which occurs determines code halting.

To disable this behaviour and restore the normal behaviour, use the `NOHP` command.

Example of interactive adaptivity

To pilot adaptivity interactively, proceed as follows (this is useful mainly for debugging purposes). Assume we have a base mesh of quadrilaterals with ten elements. We want to split elements 1 and 3 at step 1, generating descendent elements 11 to 18. Then at step 2 we want to further split element 15. Finally, at step 3 we want to unsplit element 1. At each step we want to dump out the whole adaptivity data structure for debugging, and also plot the adapted mesh.

We can do this either interactively or in batch mode (via the `PLAY ... ENDPLAY` command).

In the second case, the input would be as follows.

```
Title of test
CONV win
<normal input of a test case with adaptivity>
ECRI ... FREQ 1
OPTI ADAP DUMP ! to dump out adaptivity data structure at printouts
CALC ...
PLAY
  TRAC REND               ! draw base mesh at step 0
  ADAP SPLI 1 SPLI 2 TERM ! split elements 1 and 2
  GO                      ! compute step 1
  TRAC REND               ! draw adapted mesh at step 1
  ADAP SPLI 15 TERM       ! further split element 15
  GO                      ! compute step 2
  TRAC REND               ! draw adapted mesh at step 2
  ADAP USPL 1 TERM        ! unsplit element 1
  GO                      ! compute step 3
  TRAC REND               ! draw adapted mesh at step 3
  STOP                    ! terminate calculation
ENDPLAY
```

Obviously, the same interactive commands can also be typed from the keyboard, if one removes the `PLAY ... ENDPLAY` block from the input file.

Note that the first time station at which adaptivity commands can be prescribed is step 1 (not step 0), because step 0 is always computed by the code before asking for interactive commands for the first time.

Use of the optional RECU keyword in interactive adaptivity

The optional `RECU` keyword can be used in conjunction with the `SPLI` and `UNSPL` commands that perform interactive user-driven adaptivity.

If the `RECU` keyword is not specified, the following element number (`iel`) or numbers (`LECT`) are meant literally. It is the user's responsibility to ensure that each mentioned element can be actually split (being a leaf) or unsplit (being a branch whose children are all leaves).

If the `RECU` keyword is specified, the following element number (`iel`) or numbers (`LECT`) are recursively inspected for descendents:

- With `RECU SPLI` the active descendents of each mentioned element are split. If the mentioned element is a leaf (having no descendents) then the element itself is split.
- With `RECU USPL` we first build up the set of active proper descendents of each mentioned element. If the mentioned element is a leaf (having no descendents) then the element is skipped and we move on to the next element, if any. Next, for each element in the set we extract its parent, thus obtaining the set of parents. Multiple element indexes are eliminated from the set of parents. Finally, each element in the set of (unique) parents is unsplit.

By using the `RECU` keyword one can perform some particular types of splitting and unsplitting which are not possible (or more complicated) with the standard syntax. For example, assume that we want to refine a given object `obj` up to level 4. This can be achieved by the command:

```
PLAY
  ADAP RECU SPLI OBJE LECT obj TERM
       RECU SPLI OBJE LECT obj TERM
       RECU SPLI OBJE LECT obj TERM
  TERM
ENDPLAY
```

The `RECU` keyword could be omitted in the first of the `SPLI` commands above, if none of the elements of the `obj` has been previously split (i.e., if they are all base elements). Without the `RECU` keywords, in order to perform the second and third split operation in the above example one would have to identify (and explicitly list) the indexes of the (descendent) elements generated by the previous split operation.

15.2 Keystrokes and mouse events in the OpenGL graphical visualizer

Object

When using the built-in OpenGL graphical visualizer interactively, some keystrokes and mouse events are interpreted as navigation commands.

Keystrokes

A list of the available keystrokes is given in the following Table.

Key	Action	Amount	`CTRL-`	`CTRL/SHIFT-`	`SHIFT-`
`0` (zero)	Reset default view	—	—	—	—
Up arrow	Rotate camera "up"	5°	1°	10°	30°
Down arrow	Rotate camera "down"	5°	1°	10°	30°
Left arrow	Rotate camera "left"	5°	1°	10°	30°
Right arrow	Rotate camera "right"	5°	1°	10°	30°
`PgUp`	Rotate camera anticlockwise	5°	1°	10°	30°
`Ins`	Rotate camera clockwise	5°	1°	10°	30°
`b`	Translate camera backwards	$R/2$	$R/10$	R	$3R$
`f`	Translate camera forwards	$R/2$	$R/10$	R	$3R$
`i`	Zoom camera in (without moving)	×1.2	×1.1	×1.5	×2.0
`o`	Zoom camera out (without moving)	×1.2	×1.1	×1.5	×2.0
`r`	Move camera rightwards (free mode only)	$R/2$	$R/10$	R	$3R$
`l`	Move camera leftwards (free mode only)	$R/2$	$R/10$	R	$3R$
`u`	Move camera upwards (free mode only)	$R/2$	$R/10$	R	$3R$
`d`	Move camera downwards (free mode only)	$R/2$	$R/10$	R	$3R$

Table 19: Available keystrokes.

The keystrokes are *not* case sensitive: for example, `b` has the same effect as `B`. Some keystrokes (`r`, `l`, `u` and `d`) have effect only when the camera is set in "free navigation" mode (not in "rotating" mode). In order to change the camera navigation mode interactively, press the right mouse button in order to bring up the interactive menu and then use the Geometry → Navigation sub-menu.

The description of motions refers to the "camera" model, i.e. to the ideal observer. If preferred, the user may think of the same motion as applied to the object that is being viewed, by just inverting the "sign" of the motion. For example, the "Left arrow" key rotates the observer to the left or, alternatively, the object to the right.

Each motion has pre-defined amounts: 5 degrees for rotations, 1/2 of the object radius for translations, 20% magnification/reduction for zooming. Smaller amounts may in some cases be obtained by pressing the Control key (`CTRL`), larger ones by the Control-Shift keys (`CTRL-SHIFT`), and even larger amounts by the Shift key (`SHIFT`) in conjunction with any of the above described keys. For example, the keys combination `CTRL-PgUp` turns the camera by 1 degree, `CTRL/SHIFT-PgUp` turns it by 10 degrees and `SHIFT-PgUp` turns it by 30 degrees.

Mouse events

A simple and intuitive way of moving the model (or the observer) which is alternative to the keyboard commands described above is by means of the mouse.

With the navigation mode set in “rotating” camera mode, by pressing the left mouse button while the pointer is inside the graphical window, a sort of “virtual trackball” is activated. The object “follows” any subsequent motions of the mouse by rotating around its centerpoint in the corresponding direction.

The effects that may be obtained with the left mouse button are summarized below.

Action	Effect
Press left button	The object starts “following” the mouse cursor by rotating around its centerpoint
Release button while not moving	The object stops rotating, in the final position reached during the previous motion
Move button while pressed	The object follows the mouse motion
Release button while moving	The object continues to “spin” around its centerpoint along the last rotation axis that was active immediately before releasing the button (sort of continuous animation)
Release button while not moving	The object stops rotating, in the final position reached during the previous motion

Table 20: Available mouse events.

Some experimentation will make readily clear what the above somewhat complicated verbal descriptions mean.

A situation which may arise with inexperienced users is that, after using the mouse to rotate the body, it does not stop but it continues “forever” its rotation. This happens when the mouse button is released while still moving (though slowly) the mouse. To stop a rotating object, the following technique may be used: just give a single, quick “click” of the mouse in the window (i.e. press and then immediately release the button) by making sure that you do not move the mouse meanwhile.

15.3 CALCUL options

Object

To pilot current time step.

Syntax:

```
"CALC"    $ "?"        $
          $ "AUTO"     $
          $ "UTIL"     $
          $ "DT" tstep $
          $ "R"        $
```

`?`

Lists available subcommands

`AUTO`

Sets automatic time step calculation (see ”OPTI PAS AUTO”).

`UTIL`

Sets fixed time step (see ”OPTI PAS UTIL”)

`DT`

Set fixed time step to following value.

`tstep`

Time step value.

`R`

Return to primary commands.

15.4 TRACE options

Object

To set options for successive mesh visualizations.

Syntax

```
"TRAC" $ "?"                                               $
       $ "NORM"                                            $
       $ "ELEM" i1 i2                                      $
       $ "ZOOM" $ "?"                        $             $
       $        $ "POIN" xmin ymin xmax ymax $             $
       $        $ "RETI"                     $             $
       $        $ "R"                        $             $
       $ "OEIL" xoeil yoeil zoeil                          $
       $ "CULL"                                            $
       $ "NOCU"                                            $
       $ "NUME" $ "NOEU" $                                 $
       $        $ "ELEM" $                                 $
       $ "NONU"                                            $
       $ "R"                                               $
       $ "CDEP"                                            $
       $ "CDNO"                                            $
       $ <$ "FANF" ; "NFAI" ; "FAIL" $>                    $
       $ "OBJE" /LECT/ <SURF ; FSIN /LECT/>                $
       $ <"NOEL"> "OBJN" /LECT/                            $
       $ "NOOB" "NOGR" "OMEM" "NOIS"                       $
       $ "PINB"                                            $
       $ "PINC"                                            $
       $ "DEFO"                                            $
       $ "AMPD" ampd                                       $
       $ "VITE"                                            $
       $ "VITG"                                            $
       $ "AMPV" ampv                                       $
       $ "FEXT"                                            $
       $ "FINT"                                            $
       $ "AMPF" ampf                                       $
       $ "DASH" idsh                                       $
       $ "AVS" | "DEPL" "VITE" "FEXT" "ACCE" "MCXX"        $
       $         "VITG" "FINT" "CONT" "EPST" "ECRO"        $
       $         "ECRC" /LECT/                       |     $
       $ "PS"                                              $
       $ "MIF"                                             $
       $ "POVR"                                            $
       $ "P10"                                             $
       $ < <"OFFS" <"SIZE" w h> <$ "RPOV" ; "BPOV"$>       $
       $           <"ZIP"> <"FICH" $ "BMP"       $         $
```

```
      $                          $ "PPM"      $          $
      $                          $ "PPMA"     $          $
      $                          $ "TGA"      $          $
      $                          $ "EPS"      $          $
      $                          $ "EPSB"     $          $
      $                          $ "PRAY"     $          $
      $                          $ "AVI" <pars> $ <'base'> >$
      $   <"SYMX"> <"SYMY"> <"EXTZ" nz dz>               $
      $   <"SYXY"> <"SYYZ"> <"SYXZ">                     $
      $   < $ "AXIS" ; "AXOL" $ na ang> <"TOLS" tols>    $
      $   <"NOSY">                                       $
      $   <"SAVE"> <"REUS">                              $
      $   <$ "ADAV" ; "ADAP" ; "NOAD" $>   "REND" >      $
```

`?`

Lists available subcommands.

`NORM`

Displays current mesh according to current options.

`ELEM i1 i2`

Chooses elements `i1` to `i2` for display. To select a non-contiguous set of elements use the `OBJE` directive, see below.

`ZOOM`

Activates zoom display mode.

`OEIL x y z`

Sets position of viewpoint (3D only) for parallel projection.

`CULL`

Activates backfacing polygon culling (3D only).

`NOCU`

Deactivates backface polygon culling (default).

`NUME`

Activates number visualization for nodes and/or elements.

`NONU`

Deactivates number visualization (default).

`R`

Returns to primary commands.

`CDEP`

Represents 3D degenerated shells of type CQDx with their physical thickness (the topological thickness of these elements is zero). All other element types are automatically hidden in the plot.

`CDNO`

Represents 3D degenerated shells of type CQDx with their topological (zero) thickness. This is the default.

`FANF`

Allows to choose for display both the failed and the non-failed elements. So, all the elements (including all DEBR elements possibly present, irrespective of their activity state), are visualized. This is the default, so this keyword is normally redundant.

`NFAI`

Allows to choose for display only the non-failed elements. By default, all elements (both failed and non-failed) are chosen for display. Note that failed elements have a tendency to assume strange forms due to excessive deformation. This is not a problem for the numerical simulation itself, since they are excluded from the calculation after failure. But with the present keyword they are (also) removed from the visualization, thus avoiding possible cluttering of the scene. Note also that for elements of type DEBR (flying debris particle), this keyword has a special meaning. It visualizes: i) the *active* debris particles, i.e. those resulting from the fragmentation of a previously failed element (which is not shown, since it is failed), and ii) any *markers*, i.e. any used but inactive particles, possibly present in the model.

`FAIL`

Allows to choose for display only the failed elements. By default, all elements (both failed and non-failed) are chosen for display. Note that failed elements have a tendency to assume strange forms due to excessive deformation. This is not a problem for the numerical simulation itself, since they are excluded from the calculation after failure. However, beware that they might somewhat clutter the scene when visualized. Note also that for elements of type DEBR (flying debris particle), this keyword has a special meaning: it visualizes only the *unused* debris particles. This means that both markers and active particles are excluded from the scene.

`OBJE`

Allows to choose non-consecutive elements for display. The list of elements is given in the following `/LECT/` and may be in the form of one or more CASTEM2000 objects. This directive is alternative to the `ELEM` directive, which only allows to specify a range of consecutive elements. To draw a set of nodes instead of (or in addition to) a set of elements, see the `OBJN` directive below and the techniques described in the comments at the end of this Section (see “Drawing nodes alone or in conjunction with elements”).

`SURF`

Allows to choose only the external surface of the chosen object. This greatly reduces the amount of information to treat in the graphical module with respect to the full 3D case in large and complicated models (but of course it prevents the possibility of visualizing results in the internal parts of the model). This visualization mode makes sense only in 3D and requires the presence of continuum-like fluid elements. This option is only available for the OpenGL-based visualizer (`TRAC ... REND`) and, if specified, it must immediately follow the `OBJE /LECT/` directive (so it is mutually exclusive with the `FSIN` keyword described below).

`FSIN`

Allows to visualize only the fluid-structure interface portions of the fluid part of the chosen object. These appear as fluid element faces "sticking" onto the matching structural parts, if any are specified as well. For optimal visualization in the OpenGL renderer, it is suggested to turn on backface rendering and to apply some shrinking, e.g. by the directive (see the `SCEN` directive below): `SCEN ... GEOM SHRI 0.98 ISOL FACE SBAC ....` The following `/LECT/` lists the concerned fluid *nodes*, i.e. the fluid nodes that lie on the fluid-structure interface: in simple cases these are just the same nodes used in the `FSA` and/or `FSR` directives. A fluid face is drawn if and only if all its nodes belong to the given `/LECT/`. This visualization mode makes sense only in 3D and requires the presence of continuum-like fluid elements. This option is only available for the OpenGL-based visualizer (`TRAC ... REND`) and, if specified, it must immediately follow the `OBJE /LECT/` directive (so it is mutually exclusive with the `SURF` keyword described above).

`NOEL`

Do not show any elements in the visualization. This should probably be used in combination with the following `OBJN` directive.

`OBJN`

Choose a set of nodes (specified in the following `/LECT/`) for visualization, rather than a set of elements. If the following `/LECT/` contains elements (e.g. via a Cast3m object name), the nodes of the object (not the elements) are chosen for visualization (as a cloud of thick points). To visualize **only** a set of nodes, say `p1` and `fsan`, the command is `TRAC NOEL OBJN LECT p1 fsan TERM REND`. To visualize **both** a set of elements, say `flui`, and a set of nodes the command is `TRAC OBJE LECT flui TERM OBJN LECT p1 fsan TERM REND`. To visualize **all** elements with a set of nodes highlighted as thick points the command is `TRAC OBJN LECT p1 fsan TERM REND`.
Other techniques that can be used to visualize a set of nodes alone or in addition to a set of elements are described below in the comments at the end of this Section (see "Drawing nodes alone or in conjunction with elements").

`NOOB`

Do not make available object names (either defined by CAST3M or by I-DEAS) in the graphical rendering module. This option may be useful to speed up the rendering operations since the number of defined objects is sometimes very large. By default, object names are made available in on-screen rendering, because the user may decide interactively to use them. In off-screen rendering, they are made available only if they are needed for the visualization of the specified scene.

`NOGR`

Do not make available element group names (defined by the `GROU` directive, see page C.61) nor node group names (defined by the `NGRO` directive, see page C.62) in the graphical rendering module. By default, group names are made available in on-screen rendering, because the user may decide interactively to use them. In off-screen rendering, they are made available only if they are needed for the visualization of the specified scene.

`OMEM`

Optimize memory during the graphical rendering, at the expense of some (or may be a lot) more CPU time. This optional keyword should only be activated in extreme cases where the size of the geometrical model is so large that the memory is not sufficient to render it (the graphics-related arrays are too big). In this way the code tries to save memory by computing some big arrays "on the fly" rather than storing them in memory. An example is the representation of iso-surfaces in very large fluid volumes. This is only useful in off-screen rendering, since in on-screen rendering any manipulation of the mesh (e.g. rotation, zoom etc.) would be extremely slow. Furthermore, if there is memory shortage, then off-screen rendering is by far preferable since only the strictly necessary tables are allocated, in contrast to on-screen (interactive) rendering. Another way of saving some memory is to specify also the `NOOB` and `NOGR` keywords described above, if objects/groups are not needed.

`NOIS`

Do not make available the "true" element fields for visualization in iso form in the graphical rendering module. This option may be useful to speed up the rendering operations since the number of data for the true element fields (stresses, hardening components, etc.) is sometimes very large. By default, all element fields are made available in on-screen rendering when no `SCEN` is specified, so that the user can decide interactively to show any of them. In off-screen rendering (or in on-screen rendering with a specified `SCEN`), only the element field (if any) needed for the visualization of the specified scene is made available. Recall for completeness that all *nodal* fields are always made availavble for visualization under iso-value form, in on-screen rendering.

`PINB`

Draw the pinballs declared by the LIAI PINB directive. These are represented by circles. If this directive is combined with the TRAC DEFO directive, then the displacement amplification facor (AMPD) must be 1.0.

`PINC`

Draw the contacting (sub-)pinballs. These are represented by circles. A straight line joins the centers of each couple of contacting (sub-)pinballs. If this directive is combined with the TRAC DEFO directive, then the displacement amplification facor (AMPD) must be 1.0.

`DEFO`

This directive produces a plot of the initial, undeformed geometry of the model, superposed to the deformed one, which is plotted by default. The initial geometry is traced using a dashed line style (see directive DASH below) in order to distinguish it better from the current one. If this directive is combined with the TRAC PINB or TRAC PINC directive, then the amplification factor AMPD must be set at 1.0.

`AMPD`

Sets the amplification factor for displacements used to draw the deformed geometry. By default it is 1.0. If this directive is combined with the TRAC PINB or TRAC PINC directive, then the amplification factor must be 1.0.

`VITE`

This directive produces a plot of the material velocity vectors, superposed to the deformed mesh.

`VITG`

This directive produces a plot of the grid (mesh) velocity vectors, superposed to the deformed mesh.

`AMPV`

Sets the amplification factor for velocity vectors. By default it is 1.0.

`FEXT`

This directive produces a plot of the external force vectors, superposed to the deformed mesh.

`FINT`

This directive produces a plot of the internal force vectors, superposed to the deformed mesh.

`AMPF`

Sets the amplification factor for force vectors. By default it is 1.0.

`DASH`

Sets the line type for plotting the initial geometry, when "DEFO" is specified. There are 4 different styles, so idsh should be from 1 to 4. By default, idsh=3.

`AVS`

Produce a storage for AVS postprocessing. The variable(s) to be stored (each one on a separate file) are specified next. Before listing the variables, one may optionally specify a deformation factor (1.0 by default) via the DEFO directive and an object via the OBJE directive (by default the entire mesh is stored). Note that output results for AVS may also be produced (in "batch" modality) by means of the ECRI FICH AVS directive, see page G.70.

`DEPL`

Store displacements for AVS post-processing. In this case the geometry stored is the initial one and displacements are also stored as a nodal field. For all other variables, the stored geometry is the current (deformed) one.

`VITE`

Store particle velocity for AVS post-processing.

`FEXT`

Store external forces (including reactions) for AVS post-processing.

`ACCE`

Store particle acceleration for AVS post-processing.

`MCXX`

Store multicomponent fluid variables for AVS post-processing.

`VITG`

Store grid velocity for AVS post-processing.

`FINT`

Store internal forces for AVS post-processing.

`CONT`

Store stresses for AVS post-processing.

`EPST`

Store total strains (still to be implemented for AVS post-processing.

`ECRO`

Store hardening quantities for AVS post-processing. The relevant components are chosed by ECRC.

`ECRC`

Select ECR components to be chosen (/LECT/).

`PS`

Produce output on PostScript file instead of screen.

`MIF`

Produce output on MIF (FrameMaker) file instead of screen.

`POVR`

Produce output in the form of a POV-Ray (Persistence of Vision Ray tracer) file instead of screen. Only the geometry is stored.

`P10`

Produce PLOT-10 (Tektronix) output on file instead of screen (available also on MS-Windows).

`<OFFS ...> REND`

Start OpenGL rendering (currently available only under MS-Windows or Linux). The rendering process may take place either on-screen (the default) or off-screen (in a file), as specified by the `OFFS` sub-directive (see full description below) which, if present, must precede the `REND` keyword. Note that on EUROPLEXUS versions implemented on a non-OpenGL platform, the `TRAC ... REND` directive is simply (and entirely) ignored. This enhances portability of benchmark tests on the various platforms.

`SYMX`

Perform a symmetry with respect to the X-axis before rendering. (This option is still under development).

`SYMY`

Perform a symmetry with respect to the Y-axis before rendering. (This option is still under development).

`EXTZ nz dz`

Perform an extrusion with respect to the Z-plane before rendering. The extrusion amount is `dz`, subdivided into `nz` increments. (This option is still under development).

`SYXY`

Perform a symmetry with respect to the XY-plane before rendering. (This option is still under development).

`SYYZ`

Perform a symmetry with respect to the YZ-plane before rendering. (This option is still under development).

`SYXZ`

Perform a symmetry with respect to the XZ-plane before rendering. (This option is still under development).

`AXIS na ang`

Perform an axial symmetry around the Y-axis before rendering. The total angle of symmetry is `ang`, subdivided into `na` increments. If necessary, a small hole is generated along the axis of symmetry of the symmetrized mesh in order to simplify the generation of symmetrized elements. This command supersedes an older version of the command that is still available via the `AXOL` command, see below. This new strategy is compatible with the use of `SUPP`.

`AXOL na ang`

Same as `AXIS` described above, but by using an older strategy for axisymmetric symmetrization. Any quadrangular element with only one point on the axis of revolution produces two new elements instead of just one. This version of the procedure does not need to generate a small hole in the symmetrized mesh along the axis of symmetry, but it is likely to be incompatible with `SUPP`.

`TOLS tols`

Set tolerance used for nodes relative positions in symmetries. For example, when asking for symmetrization with respect to plane XY, all nodes must either have $z \leq 0$ or $z \geq 0$. The absolute nodal positions are divided by the maximum size of the visualized object along the coordinate axes in order to obtain relative values. Default value of `tols` is 1.E-5. One may try to slightly increase this value in case an error is printed by the code (this happens when some nodes lie "slightly" on the wrong half-space for symmetrization).

`NOSY`

Disable any symmetries previously defined by the `SYMX`, `SYMY`, `EXTZ`, `SYXY`, `SYYZ`, `SYXZ` and `AXIS` directives. Also, the symmetrization tolerance `TOLS` is reset to its default value (see above). Beware that when performing a visualization with symmetrization, the code *remembers* the symmetrization settings for the next visualizations. Therefore, the `NOSY` command can be used to reset all symmetrization parameters to their default (no symmetrization) and then use a different set of parameters, if needed.

`SAVE`

Save for the next rendering action(s) all geometrical quantities computed in the rendering process. Since the computation of these quantities is very CPU time consuming, this option may allow to considerably shorten the time required to produce animations composed by long sequences of frames in which the geometrical quantities stay constant and only the iso field or vector field change from frame to frame. The default is not to save the computed quantities. A typical use of `SAVE/REUS` would be in an Eulerian calculation, to show the time evolution of pressure field and velocity vectors in the fluid domain. The chosen domain (fluid) is always the same in all frames (although possibly the viewpoint may change) and the nodes do not move since they are Eulerian. The same optimization may be obtained also in an ALE calculation, if one visualizes only a completely Eulerian sub-domain: typical is the case of a fluid-structure interaction calculation with the `FLSR` model, where the fluid domain is typically completely Eulerian. For safety, the code verifies that all nodes to be visualized be Eulerian. If this rule is not respected, the geometrical quantities are re-computed and so no (or little) optimization takes place. This verification may be skipped by activating the `OPTI REND NAVI` option, see page H.170. With this option, the user declares that any changes in the following rendering operations will be due only to navigation (`NAVI`) around or inside a fixed (static) scene, so that use of `SAVE/REUS` becomes possible also in Lagrangian cases. In this case the user is responsible for making sure that no geometrical data vary between a rendering and the next one(s): the mesh does not move, no elements are eroded, adaptivity does not modify the current mesh, etc.

`REUS`

Re-use the geometrical quantities computed and saved in a preceding rendering process (by the `SAVE` option described above) rather than spend CPU time to recompute them. The default is to re-compute these quantities anew each time. Note that `REUS` is not compatible with symmetry commands, i.e. with the `SYMX`, `SYMY`, `EXTZ` and `AXIS` directives.

`ADAV`

Take into account adaptivity in the visualization. An adapted mesh is usually non-conforming: so-called hanging nodes are present along locally non-conforming element-to-element interfaces. This produces locally incorrect visualization of internal faces, sharp corners and free edges. When this option is set, the computational mesh is replaced by a newly built visualization mesh. This is a pseudo-conforming mesh built up and passed to the graphical visualizer in place of the computational mesh, in order to allow correct visualization of internal faces, sharp corners and free edges. The strategy used is similar to that of the `PL2T` option (see Page G.70), but the latter option applies to the ParaView output (`PVTK`), while the present one applies to the OpenGL-based graphical module. Note, however, that this strategy has some serious limitations. For example, it works for mesh visualization but not for vector fields or iso fields. Therefore, it should only be used for debugging purposes and the `ADAP` keyword should be used instead.

`ADAP`

The strategy activated by this keywod is similar to the one of the `ADAV` keyword described above, but the visualization mesh is built up and passed to the OpenGL module *in addition* to the computational mesh, and is used *exclusively* to compute and visualize the free edges and the sharp corners. This strategy has no known limitations and should be preferred to the `ADAV` keyword in practical applications.

`NOAD`

Do not take into account adaptivity in the visualization. This is currently the default, so using this keyword should be unnecessary.

Comments

The `CULL` otion performs a very basic hidden surface removal. All element faces (polygons) whose outward normal points away from the observer are eliminated from the plot. This results in hidden surface removal for very simple, basic shapes, but is imperfect for complex, arbitrary geometries.

At each required AVS storage (see AVS above), one file is produced for each variable, with the name `avs.<VARI>.N.inp`, where `<VARI>` stands for the variable (i.e., `DEPL`, `VITE` etc.), and `N` is an integer counter which is automatically incremented by one each time storage is requested. Such files may be postprocessed interactively by AVS while EUROPLEXUS is running.

At each required POV-Ray storage (see POVR above), one file is produced containing the current geometry of the model. The file names are `povray.GEOM.N.pov` where `N` is an integer counter starting at 0 and incremented by one each time storage is requested. Such files may be postprocessed interactively by POV-Ray while EUROPLEXUS is running.

Symmetries

Note that these options are still under development.

The `SYMX`, `SYMY`, `EXTZ` and `AXIS` directives are only available in conjunction with OpenGL-based rendering (`REND`).

They may be combined, but the following combinations are invalid:

- `EXTZ` and `AXIS` are mutually exclusive.
- `SYMY` and `AXIS` are mutually exclusive.

Furthermore, the following restrictions apply:

- All nodes of the original mesh must have $z = 0$.
- `SYMX` requires that all nodes of the original mesh have $y \geq 0$.
- `SYMY` requires that all nodes of the original mesh have $x \geq 0$.
- `AXIS` requires that all nodes of the original mesh have $x \geq 0$.

Off-screen rendering

The `REND` directive admits an optional `OFFS` sub-directive that allows to produce OpenGL rendered images off-screen and to prepare animations of the results. By default, when the `OFFS` keyword is specified alone, each frame of the scene is recorded in a bitmap file, having the name `base_nnnn.<ext>`, where `base` is the base name of the run, `nnnn` is a four-digit integer counter that starts at 0001 and is incremented automatically by the program, and `<ext>` is the file extension which depends upon the chosen file type.

The following bitmap file types are currently supported:

- `BMP` indicates a MS Windows bitmap (binary) file, with the extension `.bmp`.
- `PPM` indicates a Portable Pixmap (binary) file, with the extension `.ppm`.
- `PPMA` indicates a Portable Pixmap (ASCII) file, with the extension `.ppm`.
- `TGA` indicates a Targa (binary) file, with the extension `.tga`.
- `EPS` indicates an Encapsulated PostScript file in color, with the extension `.eps`.
- `EPSB` indicates an Encapsulated PostScript file in black and white, with the extension `.eps`.
- `PRAY` indicates a POV-Ray scene description file, with the extension `.pov`. Note that this is *not* a bitmap file, but a text (Ascii) file which, interpreted by the POV-Ray program, can generate a bitmap rendering of the scene. POV-Ray can be launched directly from EPX by adding the optional `RPOV` or `BPOV` keyword, as explained below.

Such files are uncompressed by default and may therefore require a large disk space. To save space, the optional `ZIP` keyword may be specified, which automatically compresses the bitmap file after its generation.

In the case of a POV-Ray file, the optional `RPOV` keyword can be used to launch POV-Ray on the generated `.pov` file *immediately* after its creation (and before zipping it, if the `ZIP` keyword is specified as well). This will generate a `.bmp` file ready for use as an illustration or for preparation of an animation in EPX via the `MAVI` command. This of course requires that POV-Ray is installed on the platform where EPX is being run. Note that under Windows POV-Ray always opens a window even when it is launched from the command line (as it occurs with the `RPOV` or `BPOV` keywords). This may be slightly annoying, although the window is automatically closed when the execution of POV-Ray terminates.

As an alternative to `RPOV` keyword, one may use the `BPOV` keyword (for Batch POV-Ray execution), which will launch POV-Ray *only at the end* of the EPX job, and will process all the previously produced `.pov` files in a single execution of POV-Ray. This considerably speeds up the process of conversion from POV-Ray to bitmap files since POV-Ray is launched only once and processes all the files in a single execution. Also, only one POV-Ray window is created (and finally destroyed) on screen.

Note that in case of POV-Ray output the `SAVE/REUS` keywords described previously have a special meaning. The `SAVE/REUS` mechanism (combined with the `OPTI REND NAVI` option described on page H.170, if necessary) can be used in order to speed up and also to drastically reduce the disk storage needed when preparing a POV-Ray based animation. In such a case the geometrical data, which occupy a lot of space on disk, are written only once, when the first POV-Ray file is produced, in a "geometry" file named `<base>_geom.pov`. This file is then included in all following regular POV-Ray files `<base>_0001.pov`, `<base>_0002.pov`, etc., which will only contain the scene data that vary from frame to frame. The `OPTI REND NAVI` option is necessary if any of the nodes to be rendered with the `SAVE/REUS` mechanism are Lagrangian.

By specifying the optional keyword `FICH`, users may change the base name mentioned above: for example the sequence `TRAC OFFS FICH BMP 'toto' REND` would produce frame files `toto_0001.bmp`, `toto_0002.bmp`, etc.

In addition (or in alternative), the user may request the production of an AVI animated sequence from the single frames. For example, the directive `TRAC OFFS FICH AVI 'anim' REND` would produce an animation file `anim_01.avi` but no BMP frame files. To produce both the BMP frames and the AVI file, specify both options. The default name of the animation file (i.e. if `'base'` is omitted in the above syntax) is `base_nn.avi` where `base` is the base name of the run and `nn` is a two-digit integer counter that starts at 01 and is incremented automatically by the program.

By default, the size of off-screen generated (`OFFS`) bitmap and AVI files is of 500 pixels (width) by 500 pixels (height). To produce a different size, use the `SIZE w h` sub-directive where `w` is the width in pixels and `h` is the height in pixels. Both these quantities should be multiples of 4.

For on-screen generated images, the *initial* size as the window is popped up is of 500 pixels (width) by 500 pixels (height). This may then be changed interactively by the user.

The production of AVI files may be piloted by a sequence of parameters `<pars>` that are described below.

ZOOM suboptions

Syntax:

```
"ZOOM" $ "?"                      $
       $ "POIN" xmin ymin xmax ymax $
       $ "RETI"                   $
       $ "R"                      $
```

`?`

Lists available subsubcommands.

`POIN`

Sets zoom window using coordinates of lower left and upper right corner.

`xmin ymin`

Coordinates of lower left window corner.

`xmax ymax`

Coordinates of upper right window corner.

`RETI`

Activates crosshair cursor for the definition of zoom window. Position the cursor with direction keys on lower left corner, then type <CR>, repeat for upper right corner.

`R`

Return to primary commands.

NUME suboptions

Syntax:

```
"NUME" $ "NOEU" $
       $ "ELEM" $
```

`NOEU`

Activates node number display.

`ELEM`

Activates element number display.

Direct AVI file generation

Object

To generate directly an animated AVI file without using an external utility program that generates the AVI starting from a sequence of still frames (bitmaps).

A serious drawback for the use of this command, in particular during the (direct) calculation of a transient solution, is that the total number of frames in the animation (see `NFTO` below) must be set exactly. If for some reason the application stops before having written all the frames and having closed properly the AVI file, this file is unusable. The problem may be circumvented by producing bitmaps (frames) during the direct calculation, and then by making the AVI file separately starting from the frames sequence, as described in the `MAVI` directive below. In fact, in that case the program is able to determine the total number of frames automatically, if needed, because all the frames are available when the animation production is started. At the moment, the `MAVI` command is only available for bitmap images of type BMP.

Note that this functionality is based upon the Microsoft Video for Windows library and therefore it is currently available only on MS-Windows based platforms. If the following commands are issued on a different platform, they are simply ignored by EUROPLEXUS.

Syntax:

```
TRAC   <OFFS <FICH AVI <pars> $ <'base'> > > REND
```

where `<pars>` represents the following syntax:

```
<CONT> <NOCL>
<NFTO nfto>
<FPS fps> <COMP comp> <KFRE kfre> <CQUA cqua>
```

`CONT`

The AVI scene is a continuation of the AVI file created with a previous `TRAC OFFS FICH AVI` command *during the same EUROPLEXUS run.* This optional keyword allows to build up a complex animation as a series of simple sequences (scenes), each one produced by a separate command. By default (i.e. in the absence of the `CONT` keyword) a new AVI file is started. Note that, if present, the keywords `CONT` and/or `NOCL` must immediately follow the keyword `AVI` and come before the other optional keywords.

`NOCL`

Do not close the AVI file after writing the current scene. This allows to add further scenes by subsequent commands. By default, i.e. in the absence of the `NOCL` keyword, the AVI file is closed after writing the current scene. Note that, if present, the keywords `CONT` and/or `NOCL` must immediately follow the keyword `AVI` and come before the other optional keywords.

`nfto`

The total number of frames forming the AVI file animated sequence. Note that, unlike the following ones, this parameter is mandatory but only when the scene being defined is the first one of a multi-scene AVI file, i.e. when the `CONT` keyword is not present but the `NOCL` keyword is specified. When both `CONT` and `NOCL` are omitted, then the AVI file contains just one scene (the current one) and the (total) number of frames needs not be specified, since it may be obtained as the value given for the currently valid slerp (see `SLER` below).

`nfto`

The total number of frames forming the AVI file animated sequence. Note that, unlike the following ones, this parameter is mandatory.

`fps`

Number of frames per second for the visualization of the AVI file. If omitted, the default value of 5 frames per second is used.

`comp`

Compression type of the produced AVI file. The value `-1` indicates that the Microsoft Video 1 codec has to be used. This codec is somewhat obsolete for realistic films, but perfectly adequate for the type of technical graphics produced by EUROPLEXUS, and has the advantage of being present on virtually any MS-Windows based computer. The value 1 produces a popup dialog box that allows the user to interactively choose (and somewhat configure) the desired codec from the list of those available on his platform. Obviously, this is adequate only for interactive execution of EUROPLEXUS (while the previous value `-1` is the normal choice for unattended AVI file creation, i.e. batch execution). If omitted, the default value of 0 (no compression) is used. Note, however, that without compression the produced AVI file size grows very rapidly since it is simply the sum of the size of its (uncompressed) frames. An advantage of this choice is that the AVI file may be compressed *a posteriori* by means of an external utility (e.g. Virtualdub).

`kfre`

Key frame frequency. This parameter is only used when the Microsoft Video 1 codec is chosen (see `comp` above). The default value is 0, meaning that every frame is a key frame. This somewhat increases the file size but it simplifies navigation through it during playback.

`cqua`

Compression quality in %. This parameter is only used when the Microsoft Video 1 codec is chosen (see `comp` above). The default value is 100, meaning full (loss-less) quality.

Drawing nodes alone or in conjunction with elements

Normally EUROPLEXUS draws an object composed of **elements**, and the nodes belonging to such elements are drawn as a consequence of elements visualization.

A user may sometimes want to visualize a set of **nodes** *independently* from the elements to which they belong, or *in addition* to the elements to which they belong (by highlighting the chosen nodes in some manner so that they stand out). Below are summarized some techniques to obtain such effects.

1. Drawing nodes only.
   Assume that we have an object `mynodes` composed only of nodes. This may come from a mesh generator such as Cast3m, it can be the result of an `NGRO` nodes group definition, or be simply a list of node indexes. To visualize just these nodes, the command is:

   ```
   TRAC NOOB OBJN LECT mynodes TERM REND
   ```

   Note that the view will be set up automatically to fit only the drawn nodes. This technique can be used either in interactive or in batch mode.

2. Drawing nodes in addition to elements in interactive mode.
   A possible approach is the following: first draw the whole mesh (or a sub-mesh of elements containing all the nodes that should be visualized):

   ```
   TRAC REND
   ```

   Then unselect all elements by right-clicking on Objects → Hide All.
   Finally, select the group of nodes `mynodes` by right-clicking on Objects → Select Groups. Note that the `mynodes` group has 0 elements and $N > 0$ nodes. In this way, only the selected nodes will remain visible (no elements).
   The appearance of the nodes can be set by right-clicking on the Geometry → Points menu. Note that with this technique the view will be set up automatically to fit the initially drawn mesh, and not only the drawn nodes. Sometimes this may be inappropriate.

3. Drawing nodes in addition to elements in batch mode.
   A possible approach is the following:

   ```
   PLAY
   CAME ... ! set up the chosen camera, e.g. encompassing
            ! only the chosen nodes
   SCEN OBJE USLM LECT tous TERM    ! unselect all elements
             SELP LECT mynodes TERM ! select the wanted nodes
        GEOM NAVI FREE
             POIN SPHE 2 ! for example ...
        COLO PAPE
   SLER CAM1 1 NFRA 1
   TRAC REND ! to show on screen. use OFFS to draw offscreen
   ENDPLAY
   ```

   In this way, only the selected nodes will be visible (no elements).
   Note that with this technique the view is set up by the user via the `CAME` directive. This gives complete freedom, but is more laborious.

15.5 AVI file generation from a sequence of bitmaps (MAVI)

Object

To generate an animated AVI file starting from a sequence of still frames (bitmaps). At the moment, the only type of bitmap images that are recognized by the `MAVI` command are BMP images.

Note that this functionality is based upon the Microsoft Video for Windows library and therefore it is currently available only on MS-Windows based platforms. If the following commands are issued on a different platform, they are simply ignored by EUROPLEXUS.

Syntax:

```
MAVI <DUMP> <FROM 'base'> <UZIP> <RZIP> <TO 'to'>
     <FIRS firs> <LAST last> <STEP step> <pars> REND
```

`DUMP`

Dump out verbose information about the bitmaps that are being read in during the AVI file generation (only for debugging).

`'base'`

Base name of the sequence of bitmap images, in quotes. If omitted, the base name of the test case is used. For example, by specifying `FROM 'toto'` the program looks for files of the form `toto_0001.bmp`, `toto_0002.bmp` etc. in the current directory, if uncompressed bipmats (as by default) are used. If compressed bitmaps are used (see the next keyword `UZIP`), then the expected file names are `toto_0001.bmp.gz`, `toto_0002.bm.gz` etc. in the current directory.

`UZIP`

Unzip (decompress) the bitmap files before using them to produce the AVI file. The bitmap files have either been compressed by hand, or they have been produced by the `TRAC OFFS ZIP ...` directive as explained above. By default, uncompressed bitmaps are expected.

`RZIP`

Re-zip (re-compress) the bitmap files after using them to produce the AVI file. This saves a lot of disk space. By default, the bitmap files are left uncompressed after use.

`'to'`

Base name of the AVI file to be produced, in quotes. If omitted, the base name of the test case is used. For example, by specifying `TO 'tata'` the program generates AVI file(s) of the form `tata_01.avi`, `tata_02.avi` etc. in the current directory.

`FIRS`

Index of the first bitmap file (frame) to be used for the animation. By default, the first found file in alphabetical order is used.

`LAST`

Index of the last bitmap file (frame) to be used for the animation. By default, the last found file in alphabetical order is used, so the total number of frames in the animation is in this case determined automatically by the program.

`STEP`

Increment in the index of the bitmap file (frame) to be used for the animation. By default, all files are used, in alphabetical order.

`REND`

This keyword terminates the `MAVI` sequence and triggers its execution. If omitted, no animation file is produced!

In the above `MAVI` directive, the sequence `<pars>` represents the following syntax (similar to the one already described above for the direct AVI file creation):

```
<FPS fps> <COMP comp> <KFRE kfre> <CQUA cqua>
```

`fps`

Number of frames per second for the visualization of the AVI file. If omitted, the default value of 5 frames per second is used.

`comp`

Compression type of the produced AVI file. The value `-1` indicates that the Microsoft Video 1 codec has to be used. This codec is somewhat obsolete for realistic films, but perfectly adequate for the type of technical graphics produced by EUROPLEXUS, and has the advantage of being present on virtually any MS-Windows based computer. The value 1 produces a popup dialog box that allows the user to interactively choose (and somewhat configure) the desired codec from the list of those available on his platform. Obviously, this is adequate only for interactive execution of EUROPLEXUS (while the previous value `-1` is the normal choice for unattended AVI file creation, i.e. batch execution). If omitted, the default value of 0 (no compression) is used. Note, however, that without compression the produced AVI file size grows very rapidly since it is simply the sum of the size of its (uncompressed) frames. An advantage of this choice is that the AVI file may be compressed *a posteriori* by means of an external utility (e.g. Virtualdub).

`kfre`

Key frame frequency. This parameter is only used when the Microsoft Video 1 codec is chosen (see `comp` above). The default value is 0, meaning that every frame is a key frame. This somewhat increases the file size but it simplifies navigation through it during playback.

`cqua`

Compression quality in %. This parameter is only used when the Microsoft Video 1 codec is chosen (see `comp` above). The default value is 100, meaning full (loss-less) quality.

15.6 GOTRAC: a simple looping mechanism

Object

To perform a GO in order to advance the solution to the next desired time step or time value, directly followed by a TRAC operation to display the results. This sequence may be automatically repeated a given number of times, if so desired.

Syntax:

```
"GOTR" <"LOOP" n> <trac_options> trac_terminator
```

n

An integer used to specify the number of times the GOTRAC sequence has to be repeated. By default, the sequence is executed just once.

trac_options

Any valid sequence of sub-commands of the TRAC command, see above.

trac_terminator

A valid terminator of the TRAC command, which actually produces the drawing or visualization. The possible values are NORM for vector-graphics based (on-screen or on file) drawing or REND for OpenGL-based rendering. See the above description of the TRAC command for further details.

15.7 CAMERA parameters and options

Object

To define a camera for OpenGL rendering. Repeat this command any number of times to define as many cameras as needed (with different identifiers `icam`, see below). The orientation of the camera in space may be defined in two alternative ways: either via a quaternion, or via a triplet of versors defining a right-handed reference frame.

Note that on EUROPLEXUS versions implemented on a non-OpenGL platform, this directive is simply (and entirely) ignored. This enhances portability of benchmark tests on the various platforms.

Syntax:

```
 CAME icam < EYE ex ey ez >
           < $ Q qr qx qy qz                              $
             $ VIEW vz vy vz RIGH rx ry rz UP ux uy uz     $ >
           < FOV fovy >
```

`icam`

An integer used to identify the camera later on. It must be a positive number and it is mandatory (no default value is provided). Typically, use 1, 2, 3, etc. Best efficiency is obtained by starting the definition of cameras with the highest index. By repeating the definition of an existing camera (same index), the old one is replaced by the new one and is no longer available.

`EYE`

Position of the camera in space, i.e. position of the observer's eye. If omitted, the program assumes the position (0,0,1).

`Q`

Quaternion defining the orientation of the camera in space. Here `qr` is the real part while `qx`, `qy`, `qz` are the components of the imaginary part. Its norm must be unitary, so that the quaternion represents a rigid-body rotation in space, with respect to a default orientation. This default orientation is assumed such that the x-axis points to the right of the picture, the y-axis points upwards and the negative z-axis points "inside". The default value of this parameter is the identity quaternion (1,0,0,0).

`VIEW RIGH UP`

Triplet of unit versors that may be used, in alternative to the quaternion form described above, to define the orientation in space of the camera. The `VIEW` vector points from the camera position (`EYE`) to the observed object. The `RIGHT` vector defines the right-hand orientation (horizontally in the picture) and the `UP` vector defines the upright direction (vertically in the picture). These vectors must be unitary in length and be mutually orthogonal so as to define a left-handed reference frame. The vector product of `RIGH` times `VIEW` must equal `UP` (and cyclic permutations thereof). The default values are: (0,0,-1) for `VIEW`, (1,0,0) for `RIGH` and (0,1,0) for `UP`.

`FOV`

Angle representing the field of view of the camera, in degrees. Smaller angles produce a zoom-in effect while larger ones produce a zoom-out effect. The default value is 60 degrees.

15.8 SLERP parameters and options

Object

To define a slerp (spherical linear interpolation) of camera positions for OpenGL rendering.

Note that on EUROPLEXUS versions implemented on a non-OpenGL platform, this directive is simply (and entirely) ignored. This enhances portability of benchmark tests on the various platforms.

Syntax:

```
 SLER  CAM1 ic1 <CAM2 ic2> <NFRA nfra>
       <INTE /PROG/> <CENT cx cy cz>
```

`CAM1`

Identifier of the first (initial) camera for the slerp. This camera must of course have been previously defined by the `CAME` directive. This value is mandatory, and thus no default value is provided.

`CAM2`

Identifier of the second (final) camera for the slerp. This camera must of course have been previously defined by the `CAME` directive. This value may be omitted, and in that case 0 is assumed. This means that the scene is still: the first camera defined above is used for the whole sequence.

`NFRA`

Number of frames of the slerp sequence. If omitted, 1 is assumed: the scene consists of a single frame, produced by `CAM1`. If greater than 1, then there are two cases: if `CAM2` is not defined, then all frames are produced with the first camera (`CAM1`), i.e. the sequence is still. If `CAM2 is defined`, then the camera is interpolated between `CAM1` and `CAM2`. Note, however, that in the case of linear interpolation (missing `INTE`, see below) the first interpolated value is **not** `CAM1` but the first non-zero value going from `CAM1` to `CAM2`. The last interpolated camera, however, coincides with `CAM2`. This convention allows to chain successive sequences one after the other without obtaining double (repeated) frames at the intermediate camera values.

`INTE`

Interpolation values for the calculation of parameters for the intermediate frames. If omitted, linear equidistant values are used. Linear interpolation is applied to the camera `FOV` while slerp interpolation is used for the camera orientation (`Q` or `VIEW`, `RIGH`, `UP`). The camera `EYE` is interpolated as described below (see `CENT`).

`CENT`

Centre of rotation for the interpolation of the camera eye positions. If omitted, or if its position coincides with the eye position for the first camera (`CAM1`), the eye position is interpolated linearly between the initial and final (if relevant) specified positions. Thus, the observer moves along a straight line (while at the same time possibly rotating around the eye). When present and different from the eye position for the first camera (`CAM1`), it represents the centre of a circle along which the camera eye moves. The circle passes through the initial and final camera eye positions. Therefore, the given point must be equidistant from these two points (but of course not aligned between them, so that the three points define a unique plane).

15.9 SCENE options

Object

To define a set of parameters (globally indicated above as `<spars>`) for the definition of the characteristics of the current scene, to be used during OpenGL rendering.

These parameters parallel as closely as possible the menu items that are available for interactive OpenGL visualization. For more details on the parameters and options, see the reference manual of the interactive OpenGL renderer.

Once defined by a SCEN directive, a set of scene parameters (the **current scene**) remains active for any following TRAC directive(s), until a new set of parameters is defined by a new SCEN directive.

If no SCEN directive is given, some reasonable default values are assumed.

In order to restore the default scene values during a calculation *after* a scene has been defined, use an empty SCEN directive, i.e. SCEN followed by no other sub-keywords or parameters.

Note that on EUROPLEXUS versions implemented on a non-OpenGL platform, this directive is simply (and entirely) ignored. This enhances portability of benchmark tests on the various platforms.

Syntax:

```
SCEN
   <OBJE ( <SELM /LECT/> <USLM /LECT/>
           <SELG /LECT/> <USLG /LECT/>
           <SELP /LECT/> <USLP /LECT/> )
           <SELV | FLSR ; FLSW ; HANG ; BHAN | >
         <DHAS $ OUTL ; CGLA ; BGLA ; GGLA ; GLAS ; FADE ffac $> >
   <GEOM <NAVI FREE>
         <NPTO npto>
         <PROJ ORTH>
         <REFE <FRAM> <BBOX> <CENT> >
         <FACE <HFRO> <SBAC> <SINT> <HBIS> <SHOW /LECT/> >
         <LINE <HEOU> <SSHA> <SFRE> <SPER> <SISO> <ANTI> <SBOU> <SIOU> >
         <POIN $ DOT dsiz ; SPHE ssiz ; SPHP <FACT fact> $>
         <SHRI sh <GROU> <NOUT> <ISOL> <HFAC> <PINS> <NODE> >
         <PINB <PARE> <CDES> <CPOI> <NORM> <JOIN> <NASN> <PASN> <DASN>
               <$ SOLI ; TRAN $> >
         <GPIN <DOMA> <SPHE> <CONE> <PRIS> <HEXA> <CDOM>
               <PENE> <PDOT> <CPOI> <NORM> <JOIN> <PASN>
               <$ ALEN afac ; ASFA asfa $>
               <$ NLEN nfac ; NSFA nsfa $> >
         <INIT $ ASIS ; CGLA ; WIRE ; OUTL $ >
         <DEBR $ TRAJ ; TRCO $ >
```

```
      <FLSR <DOMA> <SPHE> <CONE> <PRIS> <HEXA> <NORM> <COUP> <BLOQ> >
      <FLSW <DOMA> <SPHE> <CONE> <PRIS> <HEXA> <NORM> <COUP> <BLOQ> >
      <PCLD <POIN> <SEGM> <CLOU /LECT/> <COPO> <COSE>>
      <GLIS (SURF /LECT/ <MAST> <SLAV> <MNOD> <SNOD> <MFAC>
                         <NORM> <$ LENG fac ; SFAC sfac $> )>
      <LNKS <SHOW <$ ALL ; (link_type)>>
            <HIDE <$ ALL ; (link_type)>>
            <$ LENG fac ; SFAC sfac $>
            <JOIN> >
<VECT $ SCAV ; COLO ; SCCO $
      <vec_field> <SUPP /LECT/>
      <SCAL $ A6 ; A14 ; USER /PROG/ $>
      <$ LENG fac ; SFAC sfac $>
      <COSC $ COLS ; GRAY ; ICOL ; IGRA $ >
      <SIVE>                                >
<ISO  $ LINE ; FILL ; FILI ; FELE <$ AVE ; MAX ; MIN ; AMAX $>;
        SMOO ; SMLI ;        SMEL <$ AVE ; MAX ; MIN ; AMAX $>;
        SURF ; SULI $
      <SHIN> <FADE ffac>
      <iso_field> <SUPP /LECT/>  <GAUS igaus | GAUZ igauz>
      <SCAL $ A1 ; A6 ; A14 ; USER /PROG/ $>
      <COSC $ COLS ; GRAY ; ICOL ; IGRA $ >      >
<TEXT <NODE> <ELEM> <OBJE> <$VSCA ; NVSC$> <$ISCA ; NISC$>
      <HINF> <CAME> <DEBU> <PCON> >
<COLO ( SELE $ RED  ; GREE ; BLUE ; CYAN ; MAGE ;
               YELL ; BLAC ; WHIT ; GR05 ; GR10 ;
               GR15 ; GR20 ; GR25 ; GR30 ; GR35 ;
               GR40 ; GR45 ; GR50 ; GR55 ; GR60 ;
               GR65 ; GR70 ; GR75 ; GR80 ; GR85 ;
               GR90 ; GR95                      $
        APPL $ BGRN ; CENT ; BBOX ; IFAC ; ELOU ;
               SHAR ; FRED ; PERP ; VECT ; ISOE ;
               ISOL ; POIN ; NNUM ; ENUM ; ONAM ;
               TEXT ; INWI ; INOU ; TRAJ ; ISOD $ )
      <$ PAPE ; SCRN $> >
<LIMA <ON>
      <LIGX ligx> <LIGY ligy> <LIGZ ligz>
      <LAMB $ LOW ; MEDI ; HIGH >
      <LDIF $ LOW ; MEDI ; HIGH >
      <LSPE $ LOW ; MEDI ; HIGH >
      <LSHI $ LOW ; MEDI ; HIGH >
      <LMAM $ LOW ; MEDI ; HIGH >
      ( SELE $ BRAS ; BRON ; PBRO ; CHRO ; COPP ;
               PCOP ; GOLD ; GOL2 ; PGOL ; PEWT ;
               SILV ; PSIL ; EMER ; JADE ; OBSI ;
               PEAR ; RUBY ; TURQ ; BLAP ; CYAP ;
               GREP ; REDP ; WHIP ; YELP ; BLAR ;
               BLR2 ; CYAR ; GRER ; REDR ; WHIR ;
               YELR $
        APPL $ MESH ; SELO ; /LECT/ $ ) >
<POVR <GLOB <GAMM gamm> <MTRC mtrc> >
```

```
<DEFA <FINI <AMBI ambi> <DIFF diff> > >
<LIGH ( <light_definition> ) >
<TXTR ( $ SELE 'texture_identifier' ; DEFI <texture_definition> $
          APPL $ MESH ; SELO ; /LECT/ $ ) > >
```

15.9.1 Objects Menu Parameters

`OBJE`

Introduces the parameters relative to the **Objects** menu.

`SELM`

Choice of the elements (objects of mesh type) to be visualized.

`USLM`

Choice of the elements (objects of mesh type) to be hidden.

`SELG`

Choice of the groups (of elements) to be visualized.

`USLG`

Choice of the groups (of elements) to be hidden.

`SELP`

Choice of the points (objects of points type) to be visualized.

`USLP`

Choice of the points (objects of points type) to be hidden.

`SELV`

Select some "variable" objects, i.e. objects (of elements or of points type) whose composition varies in time rather than being topologically constant. At the moment, only the keywords `FLSR`, `FLSW`, `HANG` and `BHAN` are available. This directive is useful only in the generation of graphics in 'batch' mode. In fact, when using the graphics interactively one may access the same objects from the `SELG` or `SELP` menus. For example, the fluid nodes currently subjected to `FLSR` coupling conditions are available interactively in a special node group named "`_FLSR`".

`FLSR`

Select for visualization the fluid nodes currently subjected to `FLSR` coupling conditions. These nodes are drawn according to the selected drawing mode for points (see `GEOM POIN` directive).

`FLSW`

Select for visualization the fluid elements currently subjected to `FLSW` coupling conditions.

`HANG`

Select for visualization the currently hanging nodes in adaptivity. These nodes are drawn according to the selected drawing mode for points (see `GEOM POIN` directive).

`BHAN`

Select for visualization the currently boundary-hanging nodes in adaptivity. These nodes are drawn according to the selected drawing mode for points (see `GEOM POIN` directive).

`DHAS`

Allows to choose the way to draw the hidden (non-visualized) portions of the mash. If omitted, they are ‘drawn’ as hidden (i.e., not drawn at all).

`OUTL`

Draw hideen mesh portions as element outlines (wireframe representation).

`CGLA`

Draw hideen mesh portions as colored glass.

`BGLA`

Draw hideen mesh portions as blue glass.

`GGLA`

Draw hidden mesh portions as green glass.

`GLAS`

Draw hidden mesh portions as colored glass (variation of `CGLA` that produces better results in some circumstances).

`FADE`

Draw hidden mesh portions as fading out objects.

`ffac`

Fading out factor (between 1.0 i.e. fully visible and 0.0 i.e. fully hidden).

15.9.2 Geometry Menu Parameters

GEOM

Introduces the parameters relative to the **Geometry** menu.

NAVI

Introduces the parameters relative to the *Navigation* sub-menu.

FREE

Choose the free camera navigation mode. By default, the rotating camera navigation mode is used.

NPTO

Introduces the parameters relative to the *Near Plane Tolerance* sub-menu.

npto

Near plane tolerance. By default, a value of 1.E-4 is used. During navigation inside bodies, it may be useful to increase this value (e.g. to 1.E-2).

PROJ

Introduces the parameters relative to the *Projection* sub-menu.

ORTH

Choose the orthogonal projection. By default, the perspective projection is used.

REFE

Introduces the parameters relative to the *References* sub-menu.

FRAM

Show the global reference frame.

BBOX

Show the bounding box.

CENT

Show the centre.

FACE

Introduces the parameters relative to the *Faces* sub-menu.

HFRO

Hide the front faces.

SBAC

Show the back faces.

SINT

Show the internal faces.

`HBIS`

Hide the back iso surfaces.

`SHOW /LECT/`

Force visualization of front and back faces belonging to the elements specified in the following `/LECT/`. This may be useful e. g. in a calculation with both a fluid (volumetric mesh) and a structure when the user wants to display both the structure and some iso-surfaces in the fluid. When `ISO SURF` or `ISO SULI` is selected, the code automatically disables the view of front faces (as a global setting), therefore the structure would not be drawn. By specifying `SHOW LECT stru TERM` the structural faces (both front and back faces) are forced to be drawn, thus obtaining the desired effect.

`LINE`

Introduces the parameters relative to the *Lines* sub-menu.

`HEOU`

Hide element outlines.

`SSHA`

Show sharp corners.

`SFRE`

Show free edges.

`SPER`

Show perpendicular contours.

`SISO`

Show iso surface outlines.

`ANTI`

Antialias lines.

`SBOU`

Show backface outlines (even when backfaces are not shown).

`SIOU`

Show internal face outlines (even when internal faces are not shown). This is a way to show the internal part of the mesh in wireframe representation.

`POIN`

Introduces the parameters relative to the *Points* sub-menu.

`DOT`

Render points as dots of size `psiz`. By default, points are rendered as dots of size 2.

`SPHE`

Render points as spheres of size `ssiz`.

`SPHP`

Render points as spheres of "physical" size (it must be possible to determine this size from some physical parameter associated with the point, e.g. the radius of a material particle).

`FACT`

Optional factor by which the physical radius of each sphere is multiplied for visualization purposes. By default it is 1.0.

`SHRI`

Introduces the parameters relative to the *Shrinkage* sub-menu.

`sh`

Shrink by a factor `sh`. This parameter is mandatory and must immediately follow the `SHRI` keyword.

`GROU`

Shrinkage will occur by element groups (which must have been defined), rather than element-by-element. If a group-related centerpoint has been specified in the `GROU` directive (see page C.61), then it is used for the shrinkage operation, otherwise shrinkage occurs around the average (unweighted) of the center points of the elements contained in the group. If a group-related shrink factor has been specified (see page C.61), it overriodes the scene's generic `sh` factor. Finally, if a group-related shift has been specified (see page C.61), it is applied as well during rendering.

`NOUT`

Do not shrink outlines (they are shrunken by default if some shrinkage is activated).

`ISOL`

Shrink isolines.

`HFAC`

Shrink hidden faces.

`PINS`

Shrink pinballs and gpinballs.

`NODE`

Shrink node numbers.

`PINB`

Introduces the parameters relative to the *Pinballs* sub-menu.

`PARE`

Show parent pinballs.

`CDES`

Show contacting descendents.

`CPOI`

Show contact points.

`NORM`

Show contact normals.

`JOIN`

Show contact joints.

`NASN`

Show nodal ASNs (assembled surface normals).

`PASN`

Show pinball ASNs (assembled surface normals) for the parent pinballs.

`DASN`

Show pinball ASNs (assembled surface normals) for the contacting descendent pinballs.

`SOLI`

Show pinballs as solid spheres.

`TRAN`

Show pinballs as semi-transparent spheres (this is the default).

`GPIN`

Introduces the parameters relative to the *Gpinballs* sub-menu.

`DOMA`

Render *all* the GPIN domains types (i.e. spheres, cones, prisms and hexahedra).

`SPHE`

Render the spherical GPIN domains.

`CONE`

Render the conical GPIN domains.

`PRIS`

Render the prisms GPIN domains.

`HEXA`

Render the hexahedra GPIN domains.

`CDOM`

Show the contacting GPIN domains.

`PENE`

Show the penetrations. By convention, and for representation clarity, each penetration is represented by two (equal and mutually opposite) arrows. The length of each arrow is equal to the amount of penetration in the geometric scale of the drawing. The arrows are located externally to the segment 12 that joins the two contacting points and in contact with each extremity of the segment. If the penetration is positive (real), then the arrows point towards each other and have their heads on the extremities of the segment. If the penetration is negative (fictitiuos), then the arrows point away from each other and have their tails on the extremities of the contact segment.

`PDOT`

Show the penetration rates. We use the same type of representation (by two mutually opposite arrows) as for the penetrations (see above). Each arrow representing the penetration rate has the same length as the penetration. In fact, it is not possible to take it equal (or proportional) to the penetration rate, since the range of the rate is arbitrary, unlike that of the penetration. The two arrows are pointing towards each other if the penetration rate is positive, otherwise they are pointing away from each other. Be aware that only the direction, and not the amplitude, of the arrows makes sense in this case!

`CPOI`

Show contact points. The "first" contact point (of each pcontact) is drawn in red, the "second" is drawn in green.

`NORM`

Show contact normals.

`JOIN`

Show contact joints.

`PASN`

Show gpinball ASNs (assembled surface normals) for the gpinballs.

`ALEN`

Introduces the parameters relative to the *ASN length* sub-menu.

`afac`

Scaling factor with respect to the default length of ASN vectors, which is 10% of the geometric model size.

`ASFA`

May be use in alternative to the `ALEN` directive to set the absolute length or the maximum length of the drawn ASN vectors. This is useful e.g. in animations when the size of the geometric model may vary considerably during a transient calculation.

`asfa`

Draw ASN vectors as arrows of uniform length (non-scaled), `asfa` represents the length of the drawn vectors.

`NLEN`

Introduces the parameters relative to the *Contact normal Length* sub-menu.

`nfac`

Scaling factor with respect to the default length of contact normal vectors, which is 10% of the geometric model size.

`NSFA`

May be use in alternative to the `NLEN` directive to set the absolute length or the maximum length of the drawn Contact normal vectors. This is useful e.g. in animations when the size of the geometric model may vary considerably during a transient calculation.

`nsfa`

Draw contact normal vectors as arrows of uniform length (non-scaled), `nsfa` represents the length of the drawn vectors.

`INIT`

Render the initial geometry of the model besides the current one.

`ASIS`

Render the initial geometry in the same way as the current one.

`CGLA`

Render the initial geometry as colored glass.

`WIRE`

Render the initial geometry as wireframe.

`OUTL`

Render the initial geometry as outline.

`DEBR`

Render the flying debris besides the current geometry.

`TRAJ`

Render the flying debris trajectories.

`TRCO`

Render the flying debris trajectories in shades of color. The color is related to the local debris velocity.

`FLSR`

Introduce rendering of quantities related to FLSR domains besides the current geometry.

`DOMA`

Render *all* the FLSR domains themselves (i.e. spheres, cones, prisms and hexahedra).

`SPHE`

Render the spherical FLSR domains.

`CONE`

Render the conical FLSR domains.

`PRIS`

Render the prisms FLSR domains.

`HEXA`

Render the hexahedra FLSR domains.

`NORM`

Render the FLSR domain normal(s). First normals are rendered in blue, second normals (if any) in green and third normals (if any) in red.

`COUP`

Render the FLSR couplings.

`BLOQ`

Render the FLSR blocked MC fluxes.

`FLSW`

Introduce rendering of quantities related to FLSW domains besides the current geometry.

`DOMA`

Render *all* the FLSW domains themselves (i.e. spheres, cones, prisms and hexahedra).

`SPHE`

Render the spherical FLSW domains.

`CONE`

Render the conical FLSW domains.

`PRIS`

Render the prisms FLSW domains.

`HEXA`

Render the hexahedra FLSW domains.

`NORM`

Render the FLSW domain normal(s). First normals are rendered in blue, second normals (if any) in green and third normals (if any) in red.

`COUP`

Render the FLSW couplings.

`BLOQ`

Render the FLSW blocked MC fluxes.

`PCLD`

Render the point clouds according to the following sub-keywords.

`POIN`

Render the cloud points. If this keyword is specified, all the points are rendered by default, irrespective of their cloud index. If you want to restrict the visualized clouds, use the `CLOU` keyword described next.

`SEGM`

Render the cloud segments. If this keyword is specified, all the segments are rendered by default, irrespective of their cloud index. If you want to restrict the visualized clouds, use the `CLOU` keyword described next.

`CLOU /LECT/`

Render only the points/segments belonging to the cloud indexes (e. g. 1, 2, etc.) listed in the following /LECT/.

`COPO`

Color the cloud points according to their cloud index: red for the first cloud, green for the second cloud etc. By default cloud points are shown in black or white depending on the choice of the default color scheme (for paper or for screen, respectively).

`COSE`

Color the cloud segments according to their cloud index: red for the first cloud, green for the second cloud etc. By default cloud segments are shown in black or white depending on the choice of the default color scheme (for paper or for screen, respectively).

`GLIS`

Render the GLIS sliding surfaces according to the following sub-keywords.

`SURF /LECT/`

Select the surface indexes (e. g. 1, 2, etc.) listed in the following /LECT/. The following commands will be applied only to the selected surfaces.

`MAST`

Render the master elements of the selected surfaces.

`SLAV`

Render the slave elements of the selected surfaces.

`MNOD`

Render the master nodes of the selected surfaces.

`SNOD`

Render the slave nodes of the selected surfaces.

`MFAC`

Render the master faces of the selected surfaces.

`NORM`

Render the contact normals at the currently penetrating slave nodes of the selected surfaces. In case of friction, render also the tangent(s) at such nodes.

`LENG fac`

Scaling factor with respect to the default length of normal vectors, which is 10% of the geometric model size.

`SFAC sfac`

May be used in alternative to the `LENG` directive to set the absolute length or the maximum length of the drawn normal vectors. This is useful e.g. in animations when the size of the geometric model may vary considerably during a transient calculation. Since normal vectors are of uniform length (non-scaled), `sfac` represents the length of the drawn vectors.

`LNKS`

Render the links. All links are rendered by default, i.e. if no further keywords such as `SHOW` or `HIDE` are specified after the `LNKS` keyword.

`SHOW`

Set all links as hidden and then introduce selection of which links have to be shown.

`ALL`

All links are shown (this is the default).

`link_type`

Specify one or more link types. Only the links of the selected type(s) will be shown. The list of available link types is given below (see also module M_LIAISORGA).

`HIDE`

Set all links as shown and then introduce selection of which links have to be hidden.

`ALL`

All links are hidden.

`link_type`

Specify one or more link types. The links of the selected type(s) will be hidden. The list of available link types is given below (see also module M_LIAISORGA).

`LENG`

Introduces the parameters relative to the *Length* sub-menu.

`fac`

Scaling factor with respect to the default length of links vectors, which is 10% of the geometric model size.

`SFAC`

May be used in alternative to the `LENG` directive to set the absolute length or the maximum length of the drawn links vectors. This is useful e.g. in animations when the size of the geometric model may vary considerably during a transient calculation.

`sfac`

Since links vectors are of uniform length (non-scaled), `sfac` represents the length of the drawn vectors.

`JOIN`

Show link joints (lines connecting all the nodes linked by a link).

Link types

The available link types are:

```
RELA,COQM,FS  ,BLOQ,NAVI,SOLI,BIFU,IMPA,
CONT,ACCE,VITE,DEPL,DRIT,FLST,FSA ,FSTG,
COLL,FLSR,GLIS,IMPA,FSR ,TUYM,TUYA,SH3D,
MENS,PINB,MAP2,MAP3,MAP4,MAP5,MAP6,MAP7,
FESE,SH3D,MOY4,MOY5,FLSW,PELM,GPIN,EDEF,
SPEF,TBLO,TMEN,FLSS,FLSX,MEC1,MEC2,MEC3,
MEC4,MEC5,RIC ,RIIL,RIIS,ADHE,HANG
```

15.9.3 Vectors Menu Parameters

`VECT`

Introduces the parameters relative to the **Vectors** menu.

`SCAV`

Show scaled vectors.

`COLO`

Show colored vectors.

`SCCO`

Show scaled colored vectors.

`SUPP`

Define, by means of the following `/LECT/`, the list of the nodes that form the geometric support of the vector field. By default, the support is the entire mesh.

<vec_field>

Choose the vector field to be represented (see below).

`SCAL`

Introduces the parameters relative to the *Scale* sub-menu.

`A6`

Use an automatic scale with 6 values. By default, an automatic scale with 14 values is used.

`A14`

Use an automatic scale with 14 values. This is the default.

`USER`

Use the fixed, user-specified scale given by `/PROG/`.

`LENG`

Introduces the parameters relative to the *Length* sub-menu.

`fac`

Scaling factor with respect to the default vector length, which is 10% of the geometric model size.

`SFAC`

May be use in alternative to the `LENG` directive to set the absolute length or the maximum length of the drawn vectors. This is useful e.g. in animations when the size of the geometric model may vary considerably during a transient calculation.

`sfac`

The meaning of this value depends upon the chosen vector type representation. For scaled vectors (colored or not) `sfac` is the scale factor by which the physical vector norm is multiplied to obtain the length of the drawn vector. Thus, the length of a drawn vector may be associated with a physical value of the represented quantity, independently from the geometric model size and its variations, and on the chosen scale. For colored vectors of uniform length (non-scaled) `sfac` represents the length of the drawn vectors.

`COSC`

Introduces the color scheme to be used for the visualization of vectors.

`COLS`

Use colors (this is the default).

`GRAY`

Use a scale of grays.

`ICOL`

Use colors but invert the colors set (blue indicates the maximum value insted of minimum value).

`IGRA`

Use a scale of grays but invert the colors set (dark gray indicates the maximum value insted of minimum value).

`SIVE`

Show internal vectors in 3D models. By default, vectors are only traced on the visible faces, i.e. typically just on the envelope of 3D models.

15.9.4 Choice of a vector field

Object

To select the vector field to be represented by the `VECT` directive described above.

Syntax:

```
VECT . . .  <FIEL $ VITE ; VITG ; ACCE ; DEPL ; FINT ; FEXT ; FLIA ;
                    MASS ; VCVI ; FDEC $> . . .
```

`VITE`

Material or particle velocity (first `idim` components). This is the vector field represented by default, if the `FIEL` directive is omitted.

`VITG`

Mesh velocity in an ALE calculation (first `idim` components).

`ACCE`

Material or particle acceleration (first `idim` components).

`DEPL`

Displacement (first `idim` components).

`FINT`

Internal force (first `idim` components).

`FEXT`

Total external force (first `idim` components).

`FLIA`

External force due to liaisons (coupled links) (first `idim` components).

`MASS`

Nodal mass (first `idim` components).

`VCVI`

Material or particle velocity (first `idim` components) in Finite Volumes Cell Centred model. Note that these vectors are not represented at the nodes but at the "elements" (i.e., Finite Volumes) centroids.

`FDEC`

External force due to decoupled links (first `idim` components).

15.9.5 Iso Menu Parameters

`ISO`

Introduces the parameters relative to the **Iso** menu.

`LINE`

Show iso lines.

`FILL`

Show iso fill.

`FILI`

Show iso fill lines.

`FELE`

Show iso fill elements. By default, the average over all Gauss points is shown for each element. Other possible types of representations are the maximum value, the minimum value or the absolute maximum value over all Gauss points for each element. See the following optional keywords.

`AVE`

Choose the average value over all Gauss points of the element to fill the element. This is the default so this keyword may be omitted for brevity.

`MAX`

Choose the maximum value over all Gauss points of the element to fill the element.

`MIN`

Choose the minimum value over all Gauss points of the element to fill the element.

`AMAX`

Choose the absolute maximum value over all Gauss points of the element to fill the element.

`SMOO`

Show iso smooth.

`SMLI`

Show iso smooth lines.

`SMEL`

Show iso smooth elements. By default, the average over all Gauss points is shown for each element. Other possible types of representations are the maximum value, the minimum value or the absolute maximum value over all Gauss points for each element. See the following optional keywords.

`AVE`

Choose the average value over all Gauss points of the element to fill the element. This is the default so this keyword may be omitted for brevity.

`MAX`

Choose the maximum value over all Gauss points of the element to fill the element.

`MIN`

Choose the minimum value over all Gauss points of the element to fill the element.

`AMAX`

Choose the absolute maximum value over all Gauss points of the element to fill the element.

`SURF`

Show iso surfaces.

`SULI`

Show iso surfaces lines.

`SHIN`

Render iso surfaces as shiny surfaces. By default, iso surfaces are rendered as dull surfaces.

`FADE`

Draw iso surfaces as fading out objects (this is only applicable to `SURF` or `SULI`. Useful to see “through” the iso surfaces, e.g. in case of pressure waves in a blast.

`ffac`

Fading out factor (between 1.0 i.e. fully visible and 0.0 i.e. fully hidden).

`SUPP`

Define, by means of the following `/LECT/`, the list of the elements that form the geometric support of the iso field. By default, the support is the entire mesh.

`GAUS`

Allows to choose a specific Gauss point index (only for the quantities `CONT`, `EPST` and `ECRO`).

`igaus`

Number of the Gauss point chosen. The special value 0 means that the average over all Gauss points in the element is taken. This is the default, i.e. if neither `GAUS` nor `GAUZ` is specified. Note that this default is different from the default in curve plotting (Page ED.80) where 1 is assumed, i.e. the first Gauss Point is plotted.

`GAUZ`

Allows to choose a specific “lamina” of the (shell) element. The value is the index of the lamina through the thickness (only for the quantities `CONT`, `EPST` and `ECRO`). In this case, the code takes the average value of all Gauss Points belonging to the specified lamina.

`igauz`

Number of Gauss point through the thickness (i.e. index of the chosen lamina).

<iso_field>

Choose the iso field to be represented (see below).

`SCAL`

Introduces the parameters relative to the *Scale* sub-menu.

`A1`

Use an automatic scale with just one value. This value is the average of the data extremes. By default, an automatic scale with 6 values is used.

`A6`

Use an automatic scale with 6 values. This is the default.

`A14`

Use an automatic scale with 14 values. By default, an automatic scale with 6 values is used.

`USER`

Use the fixed, user-specified scale given by `/PROG/`.

`COSC`

Introduces the color scheme to be used for the visualization of iso values.

`COLS`

Use colors (this is the default).

`GRAY`

Use a scale of grays.

`ICOL`

Use colors but invert the colors set (blue indicates the maximum value insted of minimum value).

`IGRA`

Use a scale of grays but invert the colors set (dark gray indicates the maximum value insted of minimum value).

15.9.6 Choice of an iso field

Object

To select the iso field to be represented by the `ISO` directive described above.

Syntax:

```
 ISO . . .  <FIEL $ CONT icon ; EPST ieps; ECRO iecr ; DTEL ;
                    VITE <icom> ; VITG <icom> ; ACCE <icom> ;
                    DEPL <icom> ; FINT <icom> ; FEXT <icom> ;
                    MASS <icom> ; FLIA <icom> ; FDEC <icom> ;
                    MCPR ; MCRO ; MCTE ; MCCS ; MCMF icom ;
                    MCP1 ; MCP2 ; PFSI ; PFMI ; PFMA ; EFSI ;
                    SIGN isig ; ECRN iecr ;
                    ADFT ;
                    FAIL ;
                    RISK irsk ;
                    LFEL ; LFEV ;
                    LFNO ; LFNV ; ILNO ; DTNO ;
                    VCVI <icom> ;
                    CERR ; MAXC ; ERRI ; CLEN ; ILEN           $> . . .
```

`CONT icon`

The `icon`-th component of the stress tensor.

`EPST ieps`

The `ieps`-th component of the cumulated strain.

`ECRO iecr`

The `iecr`-th component of the hardening parameters.

`DTEL`

Stability time step Δt_{stab} associated with the element. The *stability step* is the *critical step* Δt_{crit} estimated by the code (roughly the element length L divided by the speed of sound c in the element material) multiplied by the *safety coefficient* ϕ (`CSTA`, by default 0.8): $\Delta t_{\mathrm{stab}} = \phi \Delta t_{\mathrm{crit}} \approx \phi \frac{L}{c}$.

`VITE <icom>`

Material or particle velocity: `icom`-th component if specified, else norm of the first `idim` components. This is the iso field represented by default, if the `FIEL` directive is omitted.

`VITG <icom>`

Mesh velocity in an ALE calculation: `icom`-th component if specified, else norm of the first `idim` components.

`ACCE <icom>`

Material or particle acceleration: `icom`-th component if specified, else norm of the first `idim` components.

`DEPL <icom>`

Displacement: `icom`-th component if specified, else norm of the first `idim` components.

`FINT <icom>`

Internal force: `icom`-th component if specified, else norm of the first `idim` components.

`FEXT <icom>`

External force: `icom`-th component if specified, else norm of the first `idim` components.

`MASS <icom>`

Nodal mass: `icom`-th component if specified, else norm of the first `idim` components.

`FLIA <icom>`

Liaison (coupled links) force: `icom`-th component if specified, else norm of the first `idim` components.

`FDEC <icom>`

Decoupled links force: `icom`-th component if specified, else norm of the first `idim` components.

`MCPR`

Finite volumes pressure (defined at nodes).

`MCRO`

Finite volumes density (defined at nodes).

`MCTE`

Finite volumes temperature (defined at nodes).

`MCCS`

Finite volumes sound speed (defined at nodes).

`MCMF icom`

Finite volumes mass fraction of the `icom`-th component. (defined at nodes).

`MCP1`

Finite volumes minimum pressure during the transient (defined at nodes).

`MCP2`

Finite volumes maximum pressure during the transient (defined at nodes).

`PFSI`

Overpressure due to FSI in the nodes of CLxx elements associated with an `IMPE VISU` material (see Page C.885) and with either `COUP` or `DECO` specified. These CLxx elements, used only for results visualization purposes, must be attached to structural elements (typically shells) embedded in a fluid and subjectd to either `FLSR` or `FLSW` model of FSI.

`PFMI`

Minimum FSI overpressure in time at the node (see `PFSI` above).

`PFMA`

Maximum FSI overpressure in time at the node (see `PFSI` above).

`EFSI`

Extracted FSI fluid quantity to be visualized on the structure used as geometrical support (see `EFSI` sub-directive in the Primary interactive commands section above, 15.1).

`SIGN isig`

Stress (`isig`-th component) in spectral elements (defined at nodes).

`ECRN iecr`

Hardening parameter (`iecr`-th component) in spectral elements (defined at nodes).

`ADFT`

Advection-diffusion temperature (defined at nodes).

`FAIL`

Failure level of the element which has been reached: 0 means virgin element, 1 means completely failed element and an intermediate values indicates a partially failed element.

`RISK irsk`

Risk due to the effects of an explosion. Risk values go from 0 (no risk) to 1 (full risk). Risk is estimated in the fluid field, and at the moment, it is only computed in JRC's FLxx elements and the cell centred finite volumes (VFCC). To activate this calculation, it is necessary to specify the `RISK` keyword in the calculation type (see page A.30). The `irsk` parameter indicates the "component" (i.e. the type) of risk considered: 1 means eardrum rupture risk, 2 means death risk. Be aware that when reading results from an Alice file (produced by a previous calculation with risk activation), it is mandatory to (re-)specify the whole `RISK` directive (in particular as concerns the `PROB` ... and `LUNG` ... subdirectives, see page A.30), because the risk is computed with the current values of the optional parameters.

`LFEL`

Logarithm in base 2 of the level factor associated with elements in the spatial time step partitioning algorithm.

`LFEV`

Logarithm in base 2 of the level factor associated with elements including the neighbours in the spatial time step partitioning algorithm.

`LFNO`

Logarithm in base 2 of the level factor associated with nodes in the spatial time step partitioning algorithm (defined at nodes).

`LFNV`

Logarithm in base 2 of the level factor associated with nodes including the neighbours in the spatial time step partitioning algorithm (defined at nodes).

`ILNO`

Flag indicating whether a node is (1) or is not (0) subjected to a link condition, used in the spatial time step partitioning algorithm (defined at nodes).

`DTNO`

Stability time step associated with nodes, used in the spatial time step partitioning algorithm (defined at nodes).

`VCVI <icom>`

Material or particle velocity in Finite Volumes Cell Centred model: `icom`-th component if specified, else norm of the first `idim` components.

`CERR`

Constant used in element error indicator calculation (adaptivity), see the `CERR` input keyword of the `ADAP` directive on page B.210.

`MAXC`

Maximum principal curvature of least-squares fitting function, used for element error indicator calculation (adaptivity).

`ERRI`

Element error indicator (adaptivity),

`CLEN`

Current characteristic element length used in error indicator calculations.

`ILEN`

Optimal (indicated) characteristic element length resulting from error indicator calculations.

The `MCPR`, `MCRO`, `MCTE`, `MCVI` and `MCMF` keywords are available only in calculations with finite volumes.

The `SIGN` and `ECRN` keywords are available only in calculations with spectral elements.

The `ADFT` keyword is available only in calculations with advection-diffusion.

The `FAIL` keyword is available only in calculations with the element erosion algorithm, see Page A.30.

The LFEL, LFEV, LFNO, LFNV, ILNO and DTNO keywords are available only in calculations with spatial time step partitioning (OPTI PART, see Page H.20).

The CERR, MAXC, ERRI, CLEN, ILEN keywords are available only in calculations with "true" adaptivity (see the ADAP directive on page B.210).

15.9.7 Text Menu Parameters

`TEXT`

Introduces the parameters relative to the **Text** menu.

`NODE`

Show node numbers.

`ELEM`

Show element numbers.

`OBJE`

Show object names.

`VSCA`

Show vectors scale. Note that the scale is automatically shown when vectors are visualized.

`NVSC`

Do not show vectors scale. This can be used to disable the automatic visualization of the vectors scale when vectors are rendered.

`ISCA`

Show iso scale. Note that the scale is automatically shown when isovalues are visualized.

`NISC`

Do not show iso scale. This can be used to disable the automatic visualization of the iso scale when isovalues are rendered.

`HINF`

Hide info.

`CAME`

Show camera values.

`DEBU`

Show debug info.

`PCON`

Show pinball contact indexes (in yellow) and gpinball contact indexes (in magenta).

15.9.8 Colors Menu Parameters

`COLO`

Introduces the parameters relative to the **Colors** menu. This menu allows to choose the colors of many graphical elements of the rendered scene, such as the background, the element outlines etc. To apply special colors to the model itself, or to parts of it, see the parameters relative to the **Lights/Mats** menu below. To apply a color, first it is selected by means of the `SELE` keyword, then it is applied to the desired graphical element by means of the `APPL` keyword. This sequence may be repeated as many times as necessary.

`SELE`

Introduces the selection of a color by means of the *Select color* sub-menu. The available colors are listed in the following Table. For greys, the number indicates the luminosity, i.e. `GR05` is almost black, while `GR95` is almost white.

Name	**Color**	**Name**	**Color**	**Name**	**Color**
`RED`	Red	`GREE`	Green	`BLUE`	Blue
`CYAN`	Cyan	`MAGE`	Magenta	`YELL`	Yellow
`BLAC`	Black	`WHIT`	White	`GR05`	Grey 05%
`GR10`	Grey 10%	`GR15`	Grey 15%	`GR20`	Grey 20%
`GR25`	Grey 25%	`GR30`	Grey 30%	`GR35`	Grey 35%
`GR40`	Grey 40%	`GR45`	Grey 45%	`GR50`	Grey 50%
`GR55`	Grey 55%	`GR60`	Grey 60%	`GR65`	Grey 65%
`GR70`	Grey 70%	`GR75`	Grey 75%	`GR80`	Grey 80%
`GR85`	Grey 85%	`GR90`	Grey 90%	`GR95`	Grey 95%

`APPL`

Introduces the application of the selected color by means of the *Apply it to* sub-menu. The available items to which a color may be applied are listed in the following Table.

Name	**Item**	**Name**	**Item**	**Name**	**Item**
`BGRN`	Background	`CENT`	Centre	`BBOX`	Bounding box
`IFAC`	Internal faces	`ELOU`	Element outlines	`SHAR`	Sharp corners
`FRED`	Free edges	`PERP`	Perpendicular contours	`VECT`	Vectors
`ISOE`	Iso surface edges	`ISOL`	Iso surface outlines	`POIN`	Points
`NNUM`	Node numbers	`ENUM`	Element numbers	`ONAM`	Object names
`TEXT`	Text	`INWI`	Initial wireframe	`INOU`	Initial outline
`TRAJ`	Debris trajectories	`ISOD`	Iso default color		

`ISOD`

Introduces the default color for isovalues. When iso-values are drawn and the user has selected only part of the mesh by the `SUPP` directive, the non-selected parts of the mesh are drawn in this color. The default value of this color is `GR50` (i.e. 50% grey).

`PAPE`

Select colors suited for paper. This is the default. The scene background is white and the element outlines are black.

`SCRN`

Select colors suited for screen. The background becomes black and element outlines become white, in contrast with the `PAPE` (default) option where the background is white and the element outlines are black.

15.9.9 Lights and Materials Menu Parameters

`LIMA`

Introduces the parameters relative to the **Lights/Mats** menu. This menu allows to switch the light on, to choose some parameters relative to the lighting model and to apply special materials (colors) to the model, or to parts of it. To apply a material, first it is selected by means of the `SELE` keyword, then it is applied to the desired object by means of the `APPL` keyword. This sequence may be repeated as many times as necessary.

`ON`

Switches the light on. The light must be on to see the special material effects properly.

`LIGX`

Introduces the x-position of the light `ligx`. By default, `ligx=-1`, i.e. the light comes from the left.

`LIGY`

Introduces the y-position of the light `ligy`. By default, `ligy=1`, i.e. the light comes from the top.

`LIGZ`

Introduces the z-position of the light `ligz`. By default, `ligz=1`, i.e. the light comes from the front.

`LAMB`

Introduces the ambient light, which may be `LOW`, `MEDIUM` or `HIGH`. By default, the ambient light is `MEDIUM` for dull surfaces, `LOW` for shiny surfaces. The values for dull or shiny surfaces are somewhat different.

`LDIF`

Introduces the diffuse light, which may be `LOW`, `MEDIUM` or `HIGH`. By default, the diffuse light is `HIGH` for dull surfaces, `HIGH` for shiny surfaces. The values for dull or shiny surfaces are somewhat different.

`LSPE`

Introduces the specular light, which may be `LOW`, `MEDIUM` or `HIGH`. By default, the specular light is `LOW` for dull surfaces, `HIGH` for shiny surfaces. The values for dull or shiny surfaces are somewhat different.

`LSHI`

Introduces the light shininess, which may be `LOW`, `MEDIUM` or `HIGH`. By default, the light shininess is `LOW` for dull surfaces. This quantity is unused for shiny surfaces.

`LMAM`

Introduces the model ambient light, which may be `LOW`, `MEDIUM` or `HIGH`. By default, the model ambient light is `MEDIUM` for shiny surfaces. This quantity is unused for dull surfaces.

`SELE`

Introduces the selection of a material by means of the *Select material* sub-menu. The available materials are listed in the following Table.

Name	Material	Name	Material	Name	Material
BRAS	Brass	BRON	Bronze	PBRO	Polished bronze
CHRO	Chrome	COPP	Copper	PCOP	Polished copper
GOLD	Gold	GOL2	Gold 2	PGOL	Polished gold
PEWT	Pewter	SILV	Silver	PSIL	Polished silver
EMER	Emerald	JADE	Jade	OBSI	Obsidian
PEAR	Pearl	RUBY	Ruby	TURQ	Turquoise
BLAP	Black plastic	CYAP	Cyan plastic	GREP	Green plastic
REDP	Red plastic	WHIP	White plastic	YELP	Yellow plastic
BLAR	Black rubber	BLR2	Black rubber 2	CYAR	Cyan rubber
GRER	Green rubber	REDR	Red rubber	WHIR	White rubber
YELR	Yellow rubber				

APPL

Introduces the application of the selected material by means of the *Apply it to* sub-menu.

MESH

Apply the selected material to the whole mesh.

SELO

Apply the selected material to the currently selected objects.

/LECT/

Apply the selected material to the specified objects.

15.9.10 POV-Ray Menu Parameters

Notice: the present set of commands is experimental and still under development. Some of the described commands might not be implemented yet.

`POVR`

Introduces the parameters relative to the **POV-Ray** menu. These contain settings to be passed to the POV-Ray ray-tracing software via the generated `.pov` scene description file(s), when choosing a POV-Ray type of output.

`GLOB`

Introduces some global parameters to be set in POV-Ray's `global_settings` statement.

`GAMM`

This is POV-Ray's `assumed_gamma` parameter. By default it is set to 2.2, which is the advised value for Intel-based computed (according to Lohmueller).

`MTRC`

This is POV-Ray's `max_trace_level` parameter. By default it is set to 5.

`DEFA FINI`

Introduces some global POV-Ray parameters to be set in an inital `#default finish` statement.

`AMBI`

Ambient component of POV-Ray's default `finish`. By default it is set to 0.5.

`DIFF`

Diffuse component of POV-Ray's default `finish`. By default it is set to 0.5.

`LIGH`

Introduces the definition of light sources (if any) to be used in POV-Ray's scene. If no specific POV-Ray light sources are declared, then EPX's light source is tentatively translated to POV-Ray syntax. See *Defining POV-Ray lights* below for the syntax to define POV-Ray lights (<light_definition>).

`TXTR`

Introduces the definition of surface textures (if any) to be used in POV-Ray's scene. If no specific POV-Ray surface textures are declared, then EPX's (uniform) color for each element is tentatively translated to POV-Ray syntax.

`SELE`

Select a pre-defined POV-Ray texture by its identifier, i.e. by specifying the texture's name in quotes. For example: `SELE 'White_Marble'`, where the identifier `White_Marble` is defined in POV-Ray's `textures.inc` include file. This file is included automatically in the header of the generated `.pov` files. Note that POV-Ray identifiers are case-sensitive and must be encoded exactly, by respecting the letter case.

DEFI

Define a (new) POV-Ray texture by specifying its components, see `<texture_definition>` below. Only so-called plain textures may be defined via this input mechanism (not the more complex patterned or layered textures which are also available in POV-Ray). Typical components of a texture are a `pigment`, a `normal` and a `finish`. All components are optional and default values are used if they are not specified. In addition, a modifier such as `scale`, `rotate` and `translate` can be applied to a texture. See *Defining POV-Ray textures* below for the syntax to define POV-Ray textures (`<texture_definition>`).

APPL

Introduces the application of the selected or defined texture by means of the *Apply it to* sub-menu.

MESH

Apply the texture to the whole mesh.

SELO

Apply the texture to the currently selected objects.

/LECT/

Apply the texture to the specified objects.

Defining POV-Ray lights

A POV-Ray light may be defined by the syntax given below.

Defining POV-Ray textures

A (plain) POV-Ray texture may be defined by the syntax given below, by specifying the associated pigment, normal and finish (all of which are optional) and an optional scaling, rotation and translation.

Syntax:

```
  DEFI < PIGM $ SELE 'pigment_identifier' ;
              COLO $ 'color_identifier' ;
                     <R r> <G g> <B b> <T t> $ $ >
       < NORM ...                                >
       < FINI ...                                >
       < SCAL scal >
       < ROTA <RX rx> <RY ry> <RZ rz>            >
       < TRAN <TX tx> <TY Ty> <TZ tz>            >
```

`DEFI`

Introduces the definition of a plain POV-Ray texture.

`PIGM`

Introduces the definition of the texture's pigment.

`SELE 'pigment_identifier'`

Select a pre-defined POV-Ray pigment by its identifier, i.e. by specifying the pigment's name in quotes.

`COLO`

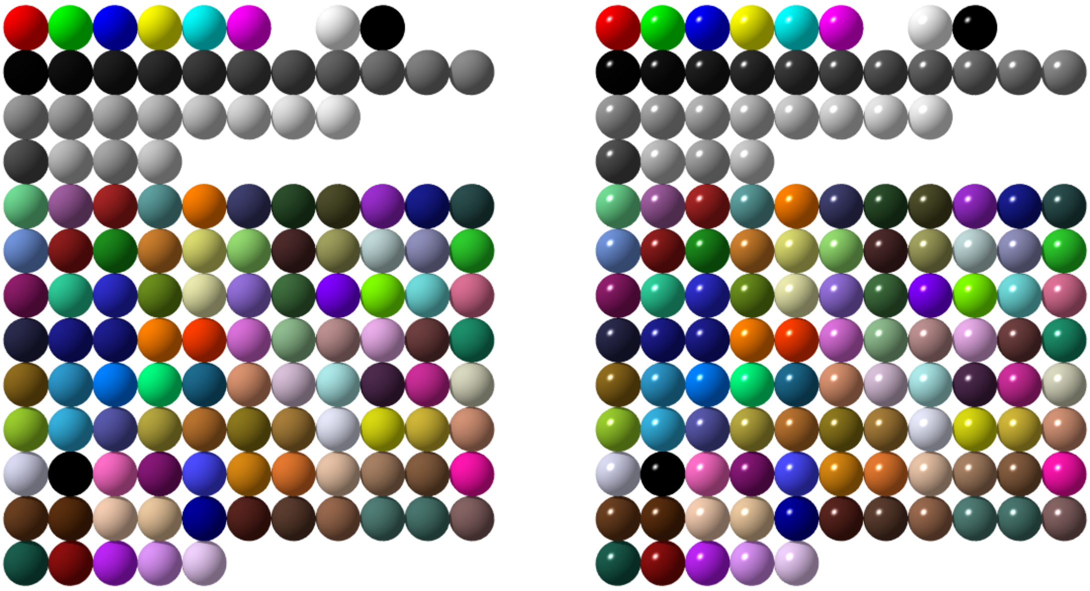
Introduces the definition of the pigment's color.

`'color_identifier'`

Select a pre-defined POV-Ray color by its identifier, i.e. by specifying the color's name in quotes. The colors defined in POV-Ray's include file `colors.inc` are shown below and are listed in the following Table.

Color	R	G	B
`Red`	1.000000	0.000000	0.000000
`Green`	0.000000	1.000000	0.000000
`Blue`	0.000000	0.000000	1.000000
`Yellow`	1.000000	1.000000	0.000000
`Cyan`	0.000000	1.000000	1.000000
`Magenta`	1.000000	0.000000	1.000000
`Clear`	1.000000	1.000000	1.000000
`White`	1.000000	1.000000	1.000000
`Black`	0.000000	0.000000	0.000000

Table 21: Definition of POV-Ray's default colors (from `colors.inc`).



(a) Dull colors (b) Shiny colors

Figure 9: POV-Ray's default colors with a dull or shiny finish.

`R`

Color's red component in the RGB color system ($0 \le R \le 1$). Default is 0.

`G`

Color's green component in the RGB color system ($0 \le G \le 1$). Default is 0.

`B`

Color's blue component in the RGB color system ($0 \le B \le 1$). Default is 0.

`T`

Color's transparency ($0 \le T \le 1$). Default is 0 (fully opaque), 1 means completely transparent (invisible).

`NORM`

Introduces the definition of the texture's normal.

`FINI`

Introduces the definition of the texture's finish.

`SCAL`

Introduces the definition of the texture's scaling. Default scaling is 1.0.

`ROTA`

Introduces the definition of the texture's rotation.

`RX`

Texture's rotation angle in degrees around the *global* X-axis. Defaults is 0. Note that POV-Ray's rotation follow the left-hand rule.

`RY`

Texture's rotation angle in degrees around the *global* Y-axis. Defaults is 0. Note that POV-Ray's rotation follow the left-hand rule.

`RZ`

Texture's rotation angle in degrees around the *global* Z-axis. Defaults is 0. Note that POV-Ray's rotation follow the left-hand rule and that the Z-axis points towards the screen interior (left-handed reference) in POV-Ray.

`TRAN`

Introduces the definition of the texture's translation.

`TX`

Texture's translation along the *global* X-axis. Defaults is 0.

`TY`

Texture's translation along the *global* Y-axis. Defaults is 0.

`TZ`

Texture's translation along the *global* Z-axis. Defaults is 0. Note that the Z-axis points towards the screen interior (left-handed reference) in POV-Ray.

15.10 TITLES options

Object

To define a set of parameters (globally indicated above as `<tpars>`) for the definition of a frame or AVI sequence containing titles, to be used during OpenGL rendering.

Once defined by a `TITL` directive, the first following `TRAC` directive will produce a titles frame (or AVI sequence) instead of the normal rendering of geometrical objects.

The color of the background and of the text used for the titles may be set by means of the `SCEN` directive described above (background color and text color, respectively).

Note that on EUROPLEXUS versions implemented on a non-OpenGL platform, this directive is simply (and entirely) ignored. This enhances portability of benchmark tests on the various platforms.

Syntax:

```
TITL
   <TIT1 'text1'>
   <TIT2 'text2'>
   <TIT3 'text3'>
```

`TIT1`

Introduces the text of the first title (`text1`), enclosed in quotes. This text appears centered in the upper part of the frame or sequence.

`TIT2`

Introduces the text of the second title (`text2`), enclosed in quotes. This text appears centered in the central part of the frame or sequence, and is therefore the "main" title.

`TIT3`

Introduces the text of the third title (`text3`), enclosed in quotes. This text appears centered in the lower part of the frame or sequence.

Comments:

If none of the titles is given, the `TITL` directive desactivates the production of title frames (i.e. the next `TRAC` directive will produce regular geometry rendering).

Any omitted title is not represented in the titles frame.

16 GROUP V—The built-in OpenGL Graphical Visualizer

Object

This Section describes the built-in OpenGL-based graphical visualizer. Note that *at the moment this tool is only available in the MS-Windows version* of EPX. Under Linux, an implementation of the visualizer may or may not be available depending on the version, but in any case the functionality is somewhat restricted with respect to the MS-Windoes version. For example, the direct production of animations in the form of AVI files is not available under Linux because some of the necessary graphical libraries are not available.

The graphical visualizer can be used in two modes:

- **Interactive mode**. The tool allows to obtain a graphical representation of the computational model (mesh) and of computed results, e.g. in the form of vectors or iso-values. Such visualizations can be obtained at any moment during the numerical simulation by making use of the interactive code piloting commands described in Section O.10, in particular the `FREQ`, `TFRE` and `GO` commands in order to advance the solution up to the desired time or time step. In this mode, the user interacts with the visualizer by means of a set of menus, keastrokes or mouse events.

- **Batch mode**. All visualizations that can be obtained interactively can also be obtained in "batch" (non-interactive) mode, by means of the commands described in Sections O.60 (`CAME` for piloting the camera), O.70 (`SLER` for camera interpolation) and 0.80 (`SCEN` to set the scen parameters and options). The commands should be enclosed in a `PLAY` ... `ENDPLAY` environment, as described in Section I.24. This is very handy in order to produce automatically a set of visualizations (raster images and/or animations) of the computed results, since the graphical commands may be embedded in the normal .EPX input file and executed in unattended mode whenever necessary.

It should always be kept in mind that the scope of the built-in graphical visualizer is not to rival the full-fledged powerful post-processors that can be used with EPX. For industrial use the ParaView software (or the Salome platform) are the obvious choice. However, during the development of the EPX code it may be handy to have access to a rapidly-programmable built-in visualizer that can be readily customized in order to obtain the exact desired graphical representation of some new features or model being developed, so as to help in the development and testing/debugging processes. Also, occasional users or students dealing with small academic examples may find it useful to exploit the embedded graphical visualizer, since it avoids the need of installing any additional software besides EPX itself.

An introduction to (an early version of) the graphical visualizer is given in reference [208]. A list of all menus and commands is also provided below with short explanations of each functionality.

16.1 Preparing to use the built-in graphical visualizer

In order to have access to interactive graphics capabilities, EPX must (at least formally) be run in "interactive' mode. This is accomplished by inserting in the input file (which has an extension .EPX) the following directive:

```
CONV WIN
```

where the keyword `CONV` stays for "conversationnel" (the French word for interactive) and the following one designates the type of graphical platform.

Historically, various platforms have been supported such as `TEKT` (Tektronix-like or PLOT-10 terminal) and `WIN` (MS-Windows graphics, originally implemented via QuickWin). For the purpose of the current discussion on 3D rendering, the choice is rather irrelevant since the OpenGL-based module operates separately and independently from the previous old-fashioned graphical routines, so users may want to just use `WIN` as shown above. The above directive must be inserted immediately after the problem title in the input file, i.e. before the "problem dimensioning" section of the file. For full details, see page A.25.

16.2 Interactive code execution

When interactive execution is chosen, EPX reads the input data-set as usual, performs step 0 to initialise the computation, then prompts the user for commands from the keyboard with the phrase:

```
COMMANDE ?
```

The user can then issue various commands and subcommands from the keyboard in order to pilot the computation. For example, he can ask the program to perform a certain number of steps, then to halt again for further commands. Each time the calculation is halted, the current mesh can be visualized and information concerning the computation (time step, CPU time, etc.) can be printed. To activate the 3D rendering, just type the command:

```
trac rend
```

(note that both input directives and interactive commands are case-insensitive in EPX). This should open a graphical OpenGL window visualizing the mesh in the current configuration. The default initial position of the "observer" is along the positive z-axis, and it looks towards the geometric centre of the model.

As long as the graphical window stays open, all input is "grabbed" by it. In particular, text typed at the keyboard is interpreted as graphic commands and does not go to the "normal" EPX console window as usual. To return control to the main EPX application, and to continue the calculation, close the graphical window by clicking on the "cross" in the top right corner of the border (or by using the pop-up Menu, see below). In the current implementation, just one graphical window may be open at any given time.

The initial size of the graphical window is 500 by 500 pixels. The window may be resized, and the shown object will resize accordingly.

By default, the viewing model is such that the observer always points its view towards the geometrical centre of the object. This is called the "rotating camera" model. Upon motion, the user may imagine that either the observer rotates around the model, or that the observer is fixed and the model is rotated, whatever seems most natural to him/her.

Rotation and other changes in the view parameters may be obtained in two ways: with keyboard command or by means of menu commands. We first list all the available keyboard commands, then we describe the menus.

16.3 Keyboard commands

The complete list of available keyboard command (at the moment of writing) is given in the following Table (see also Section O.15).

Key	Action	Amount	`CTRL-`	`CTRL/SHIFT-`	`SHIFT-`
`0` (zero)	Reset default view	—	—	—	—
Up arrow	Rotate camera “up”	5°	1°	10°	30°
Down arrow	Rotate camera “down”	5°	1°	10°	30°
Left arrow	Rotate camera “left”	5°	1°	10°	30°
Right arrow	Rotate camera “right”	5°	1°	10°	30°
`PgUp`	Rotate camera anticlockwise	5°	1°	10°	30°
`Ins`	Rotate camera clockwise	5°	1°	10°	30°
`b`	Translate camera backwards	$R/2$	$R/10$	R	$3R$
`f`	Translate camera forwards	$R/2$	$R/10$	R	$3R$
`i`	Zoom camera in (without moving)	$\times 1.2$	$\times 1.1$	$\times 1.5$	$\times 2.0$
`o`	Zoom camera out (without moving)	$\times 1.2$	$\times 1.1$	$\times 1.5$	$\times 2.0$
`r`	Move camera rightwards (free mode only)	$R/2$	$R/10$	R	$3R$
`l`	Move camera leftwards (free mode only)	$R/2$	$R/10$	R	$3R$
`u`	Move camera upwards (free mode only)	$R/2$	$R/10$	R	$3R$
`d`	Move camera downwards (free mode only)	$R/2$	$R/10$	R	$3R$

Table 22: Available keystrokes.

The keystrokes are *not* case sensitive: for example, `b` has the same effect as `B`. Some keystrokes (`r`, `l`, `u` and `d`) have effect only when the camera is set in “free navigation” mode (not in “rotating” mode). In order to change the camera navigation mode interactively, press the right mouse button in order to bring up the interactive menu and then use the Geometry → Navigation sub-menu.

The description of motions refers to the “camera” model, i.e. to the ideal observer. If preferred, the user may think of the same motion as applied to the object that is being viewed, by just inverting the “sign” of the motion. For example, the “Left arrow” key rotates the observer to the left or, alternatively, the object to the right.

Each motion has pre-defined amounts: 5 degrees for rotations, 1/2 of the object radius for translations, 20% magnification/reduction for zooming. Smaller amounts may in some cases be obtained by pressing the Control key (`CTRL`), larger ones by the Control-Shift keys (`CTRL-SHIFT`), and even larger amounts by the Shift key (`SHIFT`) in conjunction with any of the above described keys. For example, the keys combination `CTRL-PgUp` turns the camera by 1 degree, `CTRL/SHIFT-PgUp` turns it by 10 degrees and `SHIFT-PgUp` turns it by 30 degrees.

16.4 Mouse-driven motions

A simple and intuitive way of moving the model (or the observer) which is alternative to the keyboard commands described above is by means of the mouse (see also Section O.15).

With the navigation mode set in “rotating” camera mode, by pressing the left mouse button while the pointer is inside the graphical window, a sort of “virtual trackball” is activated. The object “follows” any subsequent motions of the mouse by rotating around its centerpoint in the corresponding direction.

The effects that may be obtained with the left mouse button are summarized below.

Action	Effect
Press left button	The object starts “following” the mouse cursor by rotating around its centerpoint
Release button while not moving	The object stops rotating, in the final position reached during the previous motion
Move button while pressed	The object follows the mouse motion
Release button while moving	The object continues to “spin” around its centerpoint along the last rotation axis that was active immediately before releasing the button (sort of continuous animation)
Release button while not moving	The object stops rotating, in the final position reached during the previous motion

Table 23: Available mouse events.

Some experimentation will make readily clear what the above somewhat complicated verbal descriptions mean.

A situation which may arise with inexperienced users is that, after using the mouse to rotate the body, it does not stop but it continues “forever” its rotation. This happens when the mouse button is released while still moving (though slowly) the mouse. To stop a rotating object, the following technique may be used: just give a single, quick “click” of the mouse in the window (i.e. press and then immediately release the button) by making sure that you do not move the mouse meanwhile.

16.5 The Main menu

The bulk of the user interface of the built-in graphics module is represented by a pop-up menu system that is activated by pressing the right mouse button while the pointer is inside the graphical window.

This stems from one of the fundamental choices that have been done during the design of the module, i.e. that of ensuring as wide as possible portability over different platforms. To achieve portability, use is made of the standard package GLUT (OpenGL Utility Toolkit). The only GUI features offered by this package is a hierarchy of pop-up menus. Other features that are common in many graphical environments such as a menu bar, buttons, labels, dials etc. are not supported. Although this is a serious limitation, it is believed that a quite usable interface has been realized, thanks to a careful choice of the arrangement of commands in the menus.

Each menu entry may represent either a command, or the "root" of a lower-level (or sub-) menu. In the latter case, a right-pointing arrow appears after the menu label.

Syntax:

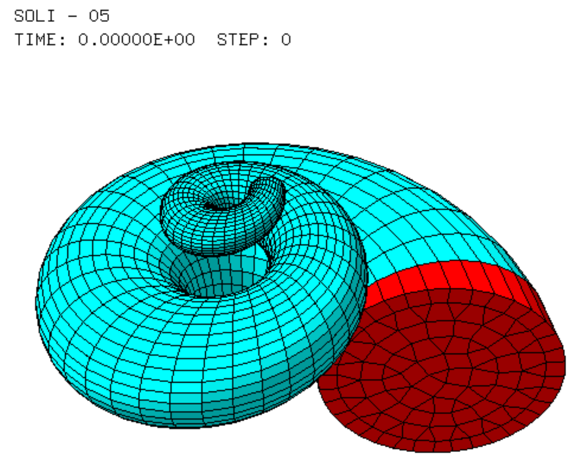
```
Objects     --> ...
Geometry    --> ...
Vectors     --> ...
Isovalues   --> ...
Text        --> ...
Colors      --> ...
Lights/Mats --> ...
Win/Copy    --> ...
Quit
```

In the following, menus and sub-menus are highlighted in bold for clarity, e.g. **Objects**, while commands are emphasized, e.g. *Quit*. The entries of the main menu are:

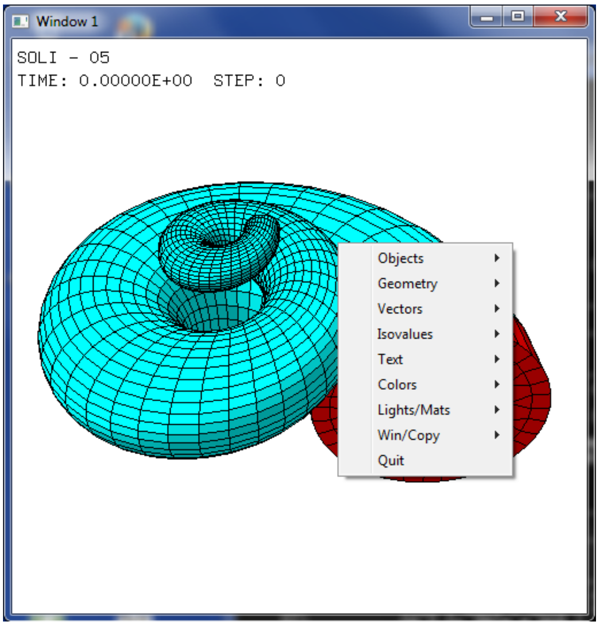
- **Objects**. Allows to select or unselect parts of the mesh.
- **Geometry**. Allows to choose details of the geometrical representation of the mesh: surfaces, lines, points, etc.
- **Vectors**. Allows to present some results in the form of vectors (arrows) on the mesh.
- **Isovalues**. Allows to present some results in the form of iso-lines or iso-surfaces on the mesh.
- **Text**. Allows to choose some text to be displayed such as node numbers, element numbers or object names.
- **Colors**. Allows to choose the colors used to represent various parts of the scene.
- **Lights/Mats**. Allows to add lighting and materials to the geometrical representation of the mesh.
- **Win/Copy**. Allows to set the graphical window size to some pre-determined values and to produce a bitmap copy of the graphical window in various raster formats. Note that the graphical window can also be resized by hand, maximized, minimized etc. with the normal window resizing techniques.

- *Quit.* Quits gracefully the graphical visualizer and returns control to the EPX program proper. It is equivalent to clicking on the "cross" in the upper right border of the window, but more stable. Caution should be taken not to close the graphical window while a menu is displayed, else the application may crash (blame GLUT for that).

The contents and functionality of each sub-menu is shortly described and illustrated in the following Sections.



(a) Standard view



(b) Right-Click shows the Main menu

Figure 10: The interactive graphical window.

16.6 The Objects menu

Object:

This menu allows to choose the objects to be visualized. Basically, objects are named lists of nodes and elements. They are optionally defined in the data structure that interfaces the OpenGL visualization module with the EPX program proper. If no objects are specified in the data interface, then the whole mesh is visualized and the user cannot select or unselect parts of the mesh. If some objects are specified, then the whole mesh is still visualized *by default*, but the user may choose to select or unselect some of these objects. The available sub-menus are:

Syntax:

```
Objects --> Show all
            Hide all
            Select meshes   --> <list of mesh objects>
            Unselect meshes --> <list of mesh objects>
            Select groups   --> <list of group objects>
            Unselect groups --> <list of group objects>
            Select points   --> <list of points objects>
            Unselect points --> <list of points objects>
            Draw hidden as  --> Hidden
                                Outlines
                                Colored glass
                                Blue glass
                                Green glass
                                Glass
                                Fading
```

- *Show all* (the default). This may be used explicitly to return to full mesh visualization after a partial visualization.
- *Hide all*. This deselects all objects (nothing is visualized). This allows to clear up (re-initialize) the object selection process.
- **Select meshes**. This opens a sub-menu containing a list of all the objects of mesh type that are available for selection. An object of mesh type is one that is composed by elements, besides nodes. To select an object, just click on the corresponding menu entry. Note that this menu appears only when there are objects of mesh type.
- **Unselect meshes**. This opens a sub-menu containing a list of all the objects of mesh type that are available for un-selection. An object of mesh type is one that is composed by elements, besides nodes. To un-select an object, just click on the corresponding menu entry. Note that this menu appears only when there are objects of mesh type.
- **Select groups**. This opens a sub-menu containing a list of all the "named element groups" and/or "named node groups" that are available for selection. A user can define such named groups directly in EPX by means of the `COMP GROU` and `COMP NGRO` directives, see page C.61 and C.62, respectively. To select a group, just click on the corresponding menu entry. Note that this menu appears only when there are named element or node groups.

- **Unselect groups**. This opens a sub-menu containing a list of all the "named element groups" and/or "named node groups" that are available for un-selection. A user can define such named groups directly in EPX by means of the `COMP GROU` and `COMP NGRO` directives, see page C.61 and C.62, respectively. To un-select a group, just click on the corresponding menu entry. Note that this menu appears only when there are named element or node groups.

- **Select points**. This opens a sub-menu containing a list of all the objects of points type that are available for selection. An object of points type is one that is composed just by nodes (no elements). To select an object, just click on the corresponding menu entry. Note that this menu appears only when there are objects of points type.

- **Unselect points**. This opens a sub-menu containing a list of all the objects of points type that are available for un-selection. An object of points type is one that is composed just by nodes (no elements). To un-select an object, just click on the corresponding menu entry. Note that this menu appears only when there are objects of points type.

- **Draw hidden as**. This opens a sub-menu that allows to specify how the hidden objects (of mesh type), i.e. those not currently selected, are to be drawn.

Note that individual objects may not be de-selected once they have been selected. This is due to the fact that objects are not necessarily disjoint. To deselect an object among a group of selected objects, first deselect all objects (Hide all) and then select the other members of the group.

16.6.1 The Draw hidden as menu

Syntax:

```
Objects --> Draw hidden as  --> Hidden
                                Outlines
                                Colored glass
                                Blue glass
                                Green glass
                                Glass
                                Fading
```

This sub-menu allows to specify how the hidden objects (of mesh type), i.e. those not currently selected, are to be drawn.

- *Hidden* (the default). Unselected parts of the mesh are hidden, i.e. not drawn.

- *Outlines*. Only the elements outlines (not the faces) are drawn, i.e. a wireframe representation of the mesh is drawn.

- *Colored glass*. The element faces are drawn as partially transparent with a glass-like appearance that maintains the original color of the element.

- *Blue glass*. The element faces are drawn as partially transparent with a bluish glass-like appearance.

- *Green glass*. The element faces are drawn as partially transparent with a greenish glass-like appearance.

- *Glass.* The element faces are drawn as partially transparent with a glass-like appearance.
- *Fading.* The element faces are drawn as fading away.

To draw just the edges (sharp corners, free edges, perpendicular contours) of the hidden parts of the mesh use the corresponding switches in the **Geometry** → **Lines** menu, described in Section V.70.

16.7 The Geometry menu

Object:

The Geometry menu allows to choose the way in which the geometrical appearance of the model is represented. By default, the body is rendered as a solid (opaque) surface composed by elements (subdivided into facets) with the border (outline) of each element highlighted.

Note incidentally that each command of the type *Show xxx* is of the toggle type. By activating the command, the menu entry changes into *Hide xxx* (the next time the menu is shown), and reciprocally. The available sub-menus are described hereafter.

Syntax:

```
Geometry --> Navigation           --> ...
             Near Plane Tolerance --> ...
             Projection           --> ...
             References           --> ...
             Faces                --> ...
             Lines                --> ...
             Points               --> ...
             Shrinkage            --> ...
             Pinballs             --> ...
             Initial geometry     --> ...
             Flying debris        --> ...
             FLSR domains         --> ...
             FLSW domains         --> ...
             Gpinballs            --> ...
             Links (coupled)      --> ...
             PCLD point clouds    --> ...
             GLIS surfaces        --> ...
```

- **Navigation**. This allows to specify details of the navigation model.
- **Near plane tolerance**. This allows to choose the tolerance used for the near clipping plane.
- **Projection**. This allows to choose the type of geometrical projection.
- **References**. This allows to visualize the reference frame, the bounding box and other visual hints together with the geometrical model.
- **Faces**. This allows to choose how to visualize the various faces of the model.
- **Lines**. This allows to choose how to visualize the various lines of the model.
- **Points**. This allows to choose how to visualize the various points of the model.
- **Shrinkage**. This allows to activate element shrinkage: each element is drawn as “shrunken” by a chosen amount around its centroid, so that the different elements of the mesh can be seen individually.
- **Pinballs**. This sub-menu appears only if there are pinballs in the computational model, and it allows to visualize the pinballs used for contact.

- **Initial geometry**. This sub-menu appears only if the user has given the DEFO optional keyword in the TRAC directive used to open the graphical window (TRAC ... DEFO ... REND). It allows to visualize the initial (undeformed) configuration of the computational model, in addition to the current (deformed) configuration which is drawn by default.
- **Flying debris**. This sub-menu appears only if there are flying debris in the computational model, and it allows to visualize the debris in the form of particles.
- **FLSR domains**. This sub-menu appears only if the FLSR model of FSI is used in the computational model. It allows to visualize the geometrical domains used in order to detect fluid-structure interaction by the FLSR model.
- **FLSW domains**. This sub-menu appears only if the FLSW model of FSI is used in the computational model. It allows to visualize the geometrical domains used in order to detect fluid-structure interaction by the FLSW model.
- **Gpinballs**. This sub-menu appears only if there are generalized pinballs (see the GPIN directive) in the computational model, and it allows to visualize the generalized pinballs used for contact.
- **Links (coupled)**. This sub-menu appears only if there are coupled links in the computational model and if the user has activated the OPTI LINK VISU option. It allows to visualize the link directions and to visually connect the linked nodes.
- **PCLD point clouds**. This sub-menu appears only if there are point clouds in the computational model (see PCLD keyword). It allows to visualize some geometrical aspects of eacj point cloud data structure.
- **GLIS surfaces**. This sub-menu appears only if there are contact sliding surfaces of the GLIS type in the computational model. It allows to visualize some geometrical aspects of each contact sliding surface.

The various sub-menus are described next.

16.7.1 The Navigation menu

Syntax:

```
Geometry --> Navigation --> Rotating camera
                            Free camera
                            Write camera
                            Update cameras list
                            Select camera       --> <list of camera files>
                            Focus on            --> ...
```

This sub-menu allows to specify details of the navigation model.

- *Rotating camera* (the default). In this navigation mode, the computational model is bound to rotate around its centroid. In other words, the observer's view vector always points towards the model centroid. This is the “safest” navigation mode because some parts of the mesh will always be visible, irrespective of the navigation commands that the User may give.

- *Free camera*. In this navigation mode, the camera motion is completely free. The User must be aware that, if the view vector points away from the model, nothing will be shown in the graphical window.
- *Write camera*. This command writes on the current directory a small text file `epx_cam_n.txt`, where `n` is an integer starting at 1 in each EPX session and being increased each time the command is issued. The file contains the commands that would be needed in EPX to set the viewing camera at the exact position currently displayed in the graphical window (see the `CAME` directive, which can be quite complex). This feature is very handy in order to "store" the camera position(s) most suited to represent a given computational model. The user may then include the text in the EPX command file in order to obtain again the desired view.
- *Update cameras list*. This command reads from the current directory any text files `epx_cam_n.txt` present, and stores the corresponding cameras in a list. The user may then select one of the available cameras from the list.
- **Select camera**. This command opens a sub-menu containing the list of available cameras stored in the current directory (the camera files are typically produced previously by the *Write camera* command). The list must have been previously built by the `Update cameras list` command.
- **Focus on**. This command causes the focus, i.e. the point onto which the observer's view vector is pointing, to be changed from the default (which is the centroid of the mesh). The focus can be set on a named part of the mesh such as an object, group or point.

The Focus on menu

Syntax:

```
Geometry --> Navigation --> Focus on --> All
                                         Meshes --> <list of mesh objects>
                                         Groups --> <list of group objects>
                                         Points --> <list of points objects>
```

This sub-menu allows to specify the part of the geometrical model on which focus should be set. It can be useful in case the User wants to concentrate attention on small details of the mesh which would be difficult to localize in the default view of the model, which is focused on the (whole) model's centroid.

- *All* (the default). Focus goes on the centroid of the whole mesh. This command can be useful to re-set the default focus after the focus has been previously moved to a specific part of the model.
- **Meshes**. This opens a sub-menu containing a list of all the objects of mesh type that are available for selection. An object of mesh type is one that is composed by elements, besides nodes. To select an object, just click on the corresponding menu entry. The focus will be set on the centroid of the chosen object. Note that this menu appears only when there are objects of mesh type.

- **Groups**. This opens a sub-menu containing a list of all the "named element groups" that are available for selection. A named element group is one that is composed by elements, besides nodes. To select a group, just click on the corresponding menu entry. The focus will be set on the centroid of the chosen group. Note that this menu appears only when there are named element groups in the model.
- **Points**. This opens a sub-menu containing a list of all the "named node groups" that are available for selection. A named node group is one that is composed by nodes (no elements). To select a group, just click on the corresponding menu entry. The focus will be set on the centroid of the chosen group. Note that this menu appears only when there are named node groups in the model.

16.7.2 The Near plane tolerance menu

Syntax:

```
Geometry --> Near plane tolerance --> 1.E-2
                                      1.E-3
                                      1.E-4
                                      1.E-5
```

This sub-menu allows to choose the tolerance for the near clipping plane among one of the values proposed. Changing the value may sometimes help in ameliorating some views.

16.7.3 The Projection menu

Syntax:

```
Geometry --> Projection --> Perspective
                            Orthogonal
```

This sub-menu allows to choose the type of geometrical projection used in the rendering process.

- *Perspective* (the default). A perspective projection is adopted. This is the most realistic projection.
- *Orthogonal*. An orthogonal projection is adopted, in which parallel lines always remain parallel. This type of projection can be sometimes useful to check some features of the geometrical model, but it is less natural than the Perspective projection. Note also that zooming is not available under Orthogonal projection.

16.7.4 The References menu

Syntax:

```
Geometry --> References --> Show reference frame
                            Show bounding box
                            Show center
```

The References menu may be used to visualize some geometrical elements that help understanding the positioning of the object in space.

- *Show reference frame.* This activates the visualization of the global reference frame in which all coordinates are expressed, represented by three colored axes: red for the x-axis, green for the y-axis and blue for the z-axis.
- *Show bounding box.* This visualizes the bounding box of the body, i.e. a parallelepiped aligned with the global reference planes which exactly contains the body.
- *Show center.* This visualizes the geometric center of the body, in the form of a small cube. All rotations of the model described in Section V.30 occur around this point. The center can be changed by the **Focus on** menu.

16.7.5 The Faces menu

Syntax:

```
Geometry --> Faces --> Hide front faces
                       Show back faces
                       Show internal faces
                       Hide back iso surfaces
```

The Faces menu allows to choose the way in which the element faces are rendered.

- *Hide front faces.* This disables external face filling and thus produces a wireframe representation of the body. By default, front faces are rendered as filled surfaces.
- *Show back faces.* This enables back face filling. By default, back faces are not rendered (they appear as fully transparent surfaces).
- *Show internal faces.* This has as an effect that not only the external surface of the body, but also the internal element faces, are shown. To actually see the difference with respect to the standard representation, for example a wireframe representation may be chosen, as explained above. This type of representation may be useful to highlight the internals of the body (e.g. by making the surface partially transparent, and in some particular iso-values or vectors representations. **Hide back iso surfaces**. This enables culling of back-facing iso surfaces. By default, these surfaces are not culled, unlike the other surfaces (element faces, for example).

16.7.6 The Lines menu

Syntax:

```
Geometry --> Lines --> Hide element outlines
                       Show sharp corners
                       Show free edges
                       Show perp contours
                       Show iso surface outlines
                       Antialias lines
                       Show backface outlines
                       Show internal outlines
```

The Lines menu allows to choose the way in which various types of lines are rendered.

- *Hide element outlines.* This represents the surface without highlighting the subdivision into finite elements. Note, however, that if in addition front face filling has been disabled by the **Faces** → *Hide front faces* command, then the body will totally disappear, which is probably not the desired effect.
- *Show sharp corners.* This highlights any "sharp corners" in the model. A sharp corner is a segment common to two external faces whose normals form an angle greater than a predefined value (60° by default). Sharp corners are only computed in 3D.
- *Show free edges.* This highlights any "free edges" in the model. A free edge is a segment on the border of an external face that has no adjacent faces. In 2D it is just the perimeter of the model. In 3D it may be useful to visualize the borders of flat surfaces (shells, for example).
- *Show perp contours.* This highlights any "perpendicular contours" in the model. A perpendicular contour is a segment common to two external faces, of which one is visible and the other is not visible in the current view. This depends on the current view and therefore it must be recomputed as the model rotates, so it is quite expensive.
- *Show iso surface outlines.* This enables visualization of the outlines of the elementary polygons (triangles and quadrilaterals) that form the iso surfaces.
- *Antialias lines.* This activates line anti-aliasing (smoothing) for the representation of lines such as element outlines, sharp corners, free edges, and isolines. This reduces the jagged appearance of these lines, but at the expense of using thicker lines, so the effect appears of dubious utility.
- *Show backface outlines.* This activates rendering of the outlines of backfaces.
- *Show internal outlines.* This activates rendering of the outlines of internal faces. If in addition the front faces are hidden by the **Faces** → *Hide front faces* command, then the body is rendered as a wireframe including the "internal" wires.

16.7.7 The Points menu

Syntax:

```
Geometry --> Points --> Dots 1
                        Dots 2
                        Dots 4
                        Dots 8
                        Spheres 1
                        Spheres 2
                        Spheres 4
                        Spheres 8
                        Spheres physical
```

The Points menu allows to choose the way in which various types of points are rendered. These include material points but also SPH particles, for example. Two basic representations are possible: by means of dots or by means of spheres. A dot is just a square block of color while a sphere is a full-fledged sphere rendered as a mesh of facets, with their own outlines (if element outlines are activated in the scene). Dot sizes vary from 1 to 8 in pixel units. Sphere sizes also vary from 1 to 8, but in an arbitrary unit which corresponds to 1/128 of the model size. By default, points are rendered as dots of size 4. There is also the possibility to represent spheres by their "physical" size: in this case the radius of the sphere corresponds to the physical value it has in the model. For example, in the case of SPH particles, this is the value assigned in the `CBIL RAYO` directive.

- *Dots 1.* This represents the dots as square dots of size 1 (the smallest possible).
- *Dots 2.* This represents the dots as square dots of size 2.
- *Dots 4.* This represents the dots as square dots of size 4.
- *Dots 8.* This represents the dots as square dots of size 8 (the largest possible).
- *Spheres 1.* This represents the dots as spheres of size 1 (the smallest possible).
- *Spheres 2.* This represents the dots as spheres of size 2.
- *Spheres 4.* This represents the dots as spheres of size 4.
- *Spheres 8.* This represents the dots as spheres of size 8 (the largest possible).
- *Spheres physical.* This represents the dots as spheres of size equal to the diameter of the dot. In the case of material points this is the diameter which has been assigned to the corresponding elements by the `COMP EPAI` directive. In the case of SPH particles, this is the value assigned in the `CBIL RAYO` directive.

16.7.8 The Shrinkage menu

Syntax:

```
Geometry --> Shrinkage --> No shrinkage
                           Shrink by groups
                           Shrink 99%
                           Shrink 80%
                           Shrink 60%
                           Shrink 40%
                           Shrink outlines
                           Shrink isolines
                           Shrink hidden faces
                           Shrink pinballs
                           Shrink node numbers
```

The Shrinkage menu allows to apply some "shrinkage" to each element rendered. The element is "shrunken" by the chosen amount with respect to its centroid. This produces an effect like if the mesh had "exploded" and allows to distinguish the various elements forming the mesh. This may be useful to see the "internals" of the mesh or to distinguish between superposed elements (e.g. a flat shell structure attached to a continuum fluid element). A toggle button *Shrink outlines* allows to shrink the element's outline like the element face, or not. Another toggle button *Shrink isolines* does the same for isolines. Finally, a toggle button *Shrink hidden faces* shrinks the faces of hidden objects (in case they are shown as translucent).

- *No shrinkage.* This is the default. No shrinkage is applied. The command may be useful to restore the default appearance after some shrinkage has been previously set.
- *Shrink by groups.* The chosen shrinkage amount (1.0 by default) is applied to each group of elements separately (i.e. with respect to the centroid of the group) rather than to each element separately. This might be useful to obtain an "exploded" view of a mesh subdivided into its (macroscopic) components, rather than in all its single elements.
- *Shrink 99%.* The shrinkage factor is set to 99%. This value is too close to 1.0 to produce a real "exploded" view of the mesh. However, it may be useful in some cases to obtain a clearer view of the mesh, since the element faces are drawn just slightly displaced towards the element centroid. For example, in case of two superposed faces, say a continuum element face and a flat element face such as a CLXX, of different colors, the color in which the resulting face points are rendered is sort of random because the two face points have the same coordinates. Setting a small shrinkage amount can avoid this problem, showing the face in the color that the user would expect (i.e. the CLXX color, if the body is looked at from the "outside" of the continuum element volume). (Note incidentally that this particular type of representation may require to turn on the rendering of internal faces since the CLXX face and the continuum face may have opposite normals and may therefore be considered as internal faces.)
- *Shrink 80%.* The shrinkage factor is set to 80%.
- *Shrink 60%.* The shrinkage factor is set to 60%.
- *Shrink 40%.* The shrinkage factor is set to 40%.
- *Shrink outlines.* Shrink the element outlines in addition to the element faces. This becomes the default, as soon as some shrinkage is applied (so that the menu entry changes to *Dont shrink outlines*. In order *not* to shrink the element outlines (only the element faces), select *Dont shrink outlines*.
- *Shrink isolines.* Shrink the isolines (iso-value lines) in addition to the element faces. The default is *not* to shrink the isolines, even when some shrinking is selected.
- *Shrink hidden faces.* Shrink the "hidden" element faces (i.e. the faces of hidden objects being rendered as translucent, see the **Objects** menu) in addition to the visible element faces.
- *Shrink pinballs.* Shrink the pinballs used to detect contact in addition to the element faces.
- *Shrink node numbers.* Shrink the node numbers in addition to the element faces.

16.7.9 The Pinballs menu

Syntax:

```
Geometry --> Pinballs --> Show parents
                          Show nodal ASNs
                          Show parent ASNs
                          Show contacting descendents
                          Show contact points
                          Show contact normals
```

```
Show contact joints
Show descendent ASNs
Show pinballs as solid
```

The Pinballs menu allows to visualize pinballs used in EPX to model contact between bodies. This menu appears only when pinballs are present in the current calculation. Pinballs are visually represented by semi-transparent spheres, and contacts can be highlighted in the form of red lines joining the centres of each pair of contacting pinballs. In addition, various types of normals can be visualized.

- *Show parents.* Visualize the parent (zero-level) pinballs (whether or not they are in contact with one another). A parent pinball is usually embedded in each element which may undergo contact by the `PINB` directive. This command can be useful to visually check where the contact-detecting pinballs have been placed in the model.
- *Show nodal ASNs.* Visualize the Assembled Surface Normals (ASNs) at nodes. These are only available is the `ASN` model is enabled.
- *Show parent ASNs.* Visualize the Assembled Surface Normals (ASNs) at parent pinballs. These are only available is the `ASN` model is enabled.
- *Show contacting descendents.* Visualize the descendent pinballs which are found to be in contact. This is useful to visually check at which locations of the model the pinball method is actually detecting contact.
- *Show contact points.* Highlight the centres of the (descendent) pinballs which are found to be in contact. These correspond approximately to the points which are found to be in contact, on the current contacting surfaces.
- *Show contact normals.* At each contacting descendent pinball centre, show the contact normal, i.e. the direction along which interpenetration of the pinballs is being detected. This is also the direction along which the contact force acts (in the absence of friction).
- *Show contact joints.* Join the centres of each couple of contacting descendent pinballs by a red line, symbolizing the contact condition.
- *Show descendent ASNs.* Visualize the Assembled Surface Normals (ASNs) at contacting descendent pinballs. These are only available is the `ASN` model is enabled.
- *Show pinballs as solid.* Visualize the pinballs as solid spheres. By default, pinballs are rendered as translucent spheres.

16.7.10 The Initial geometry menu

Syntax:

```
Geometry --> Initial geometry --> No initial geometry
                                  As current geometry
                                  Colored glass
                                  Wireframe
                                  Outline
```

The Initial geometry menu allows to visualize the initial (undeformed) configuration of the computational model in a variety of ways, in addition to the current (deformed) configuration. This menu appears only if the user has specified the `DEFO` optional keyword in the `TRAC` directive. An additional `AMPD ampd` keyword allows to choose an optional magnification factor `ampd` of the displacements (by default, `ampd` is 1.0).

- *No initial geometry.* Do not visualize the initial geometry (only the current one). This is the default. However, this command may be used to disable the visualization of the initial geometry, previously set by one of the following commands.
- *As current geometry.* Visualize the initial geometry with exactly the same appearance as the currently chosen appearance for the current geometry.
- *Colored glass.* Visualize the initial geometry as colored glass. Each initial-configuration element is rendered as partially translucent, with the same color as the current-configuration element.
- *Wireframe.* Visualize the initial geometry as wireframe. Only the element outlines are drawn (not the faces) for the initial-configuration elements.
- *Outline.* Visualize the initial geometry as an outline (free edges) only.

16.7.11 The Flying debris menu

Syntax:

```
Geometry --> Flying debris --> No trajectories
                               Trajectories
                               Colored trajectories
```

The Flying debris menu allows to visualize the trajectories of flying debris particles. The flying debris particles themselves are drawn as material points, with the corresponding options and settings (see the **Points** menu described above). The Flying debris menu appears only if there are flying debris (see `DEBR`) in the model and if the user has chosen to save the trajectories (which can lead to huge output).

- *No trajectories.* Do not visualize the flying debris trajectories. This is the default. However, this command may be used to disable the visualization of the trajectories, previously set by one of the following commands.
- *Trajectories.* Visualize the flying debris trajectories as thick lines of uniform color.
- *Colored trajectories.* Visualize the flying debris trajectories as thick lines of variable color. The color is "proportional" to the modulus of the particle velocity at each point of a trajectory.

16.7.12 The FLSR domains menu

Syntax:

```
Geometry --> FLSR domains --> Show all domains
                              Show spheres
                              Show cones
                              Show prisms
                              Show hexahedra
                              Show normals
                              Show couplings
                              Show blocked fluxes
```

The FLSR domains menu allows to visualize the Fluid-Structure Interaction (FSI) domains used by the FLSR model (see `FLSR`) in order to detect the interacting entities. In addition, one may visualize the normal directions used for the interaction relationships, the couplings and the blocked numerical fluxes.

- *Show all domains.* Show all the FLSR domains (spheres, cones etc.). Sometimes, this may produce a somewhat cluttered picture. Therefore, commands are available to select the domains type by type.
- *Show spheres.* Show the spherical domains at the (structure) nodes.
- *Show cones.* Show the truncated cone domains along the (structure) edges. Each cone connects the spheres at the two nodes of the edge.
- *Show prisms.* Show the prism domains along the (structure) triangular faces (3D only).
- *Show hexahedra.* Show the hexahedra domains along the (structure) quadrilateral faces (3D only).
- *Show normals.* Show the normal(s) associated with each domain.
- *Show couplings.* Show the coupling by means of thick red lines connecting each couple of interacting entities.
- *Show blocked fluxes.* Show the blocked numerical by means of thick green lines connecting the controids of couples of neighboring fluid elements between which the numerical fluxes are blocked.

16.7.13 The FLSW domains menu

Syntax:

```
Geometry --> FLSW domains --> Show all domains
                              Show spheres
                              Show cones
                              Show prisms
                              Show hexahedra
                              Show normals
                              Show couplings
                              Show blocked fluxes
```

The FLSW domains menu allows to visualize the Fluid-Structure Interaction (FSI) domains used by the FLSW model (see `FLSW`) in order to detect the interacting entities. In addition, one may visualize the normal directions used for the interaction relationships, the couplings and the blocked numerical fluxes. This menu is similar to the FLSR domains menu but it applies to Cell-Centred Finite Volume (VFCC) discretizations rather than to Finite-Element (FE) discretizations of the fluid sub-domain.

- *Show all domains.* Show all the FLSW domains (spheres, cones etc.). Sometimes, this may produce a somewhat cluttered picture. Therefore, commands are available to select the domains type by type.
- *Show spheres.* Show the spherical domains at the (structure) nodes.
- *Show cones.* Show the truncated cone domains along the (structure) edges. Each cone connects the spheres at the two nodes of the edge.
- *Show prisms.* Show the prism domains along the (structure) triangular faces (3D only).
- *Show hexahedra.* Show the hexahedra domains along the (structure) quadrilateral faces (3D only).
- *Show normals.* Show the normal(s) associated with each domain.
- *Show couplings.* Show the coupling by means of thick red lines connecting each couple of interacting entities.
- *Show blocked fluxes.* Show the blocked numerical by means of thick green lines connecting the centroids of couples of neighboring fluid volumes between which the numerical fluxes are blocked.

16.7.14 The Gpinballs menu

Syntax:

```
Geometry --> Gpinballs --> Show all domains
                           Show spheres
                           Show cones
                           Show prisms
                           Show hexahedra
                           Show contacting domains
                           Show domain ASNs
                           Show penetrations
                           Show penetration rates
                           Show contact points
                           Show contact normals
                           Show contact joints
                           ASN length              --> ...
                           Contact normal length   --> ...
```

Caution: The `GPIN` *model is still under development, so some of these features may have limited functionality.*

The Gpinballs menu allows to visualize the generalized pinballs (GPINs) used in EPX to model contact between bodies. This menu appears only when generalized pinballs (see `GPIN`) are present in the current calculation. Gpinballs are visually represented by semi-transparent spheres, cones, prisms and hexahedra. The penetrations and penetration rates are optionally visualized. Contacts can be highlighted in the form of red lines joining the contact points of each pair of contacting gpinballs. In addition, the contact normals and the contact points can be visualized.

- *Show all domains.* Show all the GPIN domains (spheres, cones etc.). Sometimes, this may produce a somewhat cluttered picture. Therefore, commands are available to select the domains type by type.
- *Show spheres.* Show the spherical domains at the nodes.
- *Show cones.* Show the truncated cone domains along the edges. Each cone connects the spheres at the two nodes of the edge.
- *Show prisms.* Show the prism domains along the triangular faces (3D only).
- *Show hexahedra.* Show the hexahedra domains along the quadrilateral faces (3D only).
- *Show contacting domains.* Show the contacting domains.
- *Show domain ASNs.* Visualize the Assembled Surface Normals (ASNs) at the gpinballs. Note that the GPINs model is not hierarchic (in contrast with the classical pinball model PINB), so taht in a sense all GPINs are parent GPINs.
- *Show penetrations.* Visualize the penetrations between GPINs.
- *Show penetration rates.* Visualize the penetration rates between GPINs.
- *Show contact points.* Highlight the centres of the gpinballs which are found to be in contact. These correspond approximately to the points which are found to be in contact, on the current contacting surfaces.
- *Show contact normals.* At each contacting gpinball centre, show the contact normal, i.e. the direction aling which interpenetration of the gpinballs is being detected. This is also the direction along which the contact force acts (in the absence of friction).
- *Show contact joints.* Join the centres of each couple of contacting gpinballs by a red line, symbolizing the contact condition.
- **ASN length**. Open a sub-menu which allows to adjust the length of the ASN arrows (see below).
- **Contact normal length**. Open a sub-menu which allows to adjust the length of the contact normal arrows (see below).

The ASN length menu

Syntax:

```
Geometry --> Gpinballs --> ASN length --> Double
                                          Half
                                          Default
```

This sub-menu allows to adjust the length of the ASN arrows. The *Double* and *Half* commands can be issued repeatedly in order to achieve (almost) any desired length of the arrows.

- *Double*. Double the length of the ASN arrows which, by default, amounts to 1/10 of the model diameter.
- **Half**. Halve the length of the ASN arrows.
- **Default**. Restore the default length of the ASN arrows.

The Contact normal length menu

Syntax:

```
Geometry --> Gpinballs --> Contact normal length --> Double
                                                     Half
                                                     Default
```

This sub-menu allows to adjust the length of the contact normal arrows. The *Double* and *Half* commands can be issued repeatedly in order to achieve (almost) any desired length of the arrows.

- *Double*. Double the length of the contact normal arrows which, by default, amounts to 1/10 of the model diameter.
- **Half**. Halve the length of the contact normal arrows.
- **Default**. Restore the default length of the contact normal arrows.

16.7.15 The Links (coupled) menu

Syntax:

```
Geometry --> Links (coupled) --> Show all links
                                 Length          --> ...
                                 Show link joints
                                 Show            --> <list of links by type>
                                 Hide            --> <list of links by type>
```

The Links (coupled) menu allows to visualize the coupled links present in the current model. This menu is only available if there are coupled links (see `LINK COUP`) and if the user has activated the `OPTI LNKS VISU` option in the input data file. A link is represented by a set of arrows, attached to each of the nodes that are connected by the link itself. The length of the arrows is arbitrary (by default, 1/10 of the model diameter) and can be adjusted by the **Length** sub-menu. The direction of the arrow is the direction along which the link constraint is acting.

- *Show all links*. Show all the coupled links. In some cases the figure can be cluttered. It is possible to select only certain types of links by the following sub-menus.
- **Length**. Open a sub-menu which allows to adjust the length of the link arrows (see below).
- *Show link joints*. In addition to the arrows, draw thick red lines joining each couple of linked nodes.

- **Show**. Open a sub-menu which allows to select which types of links should be visualized. The menu contains a list of all types of links currently present in the model (the number of such links is shown next to the type).
- **Hide**. Open a sub-menu which allows to select which types of links should be hidden. The menu contains a list of all types of links currently present in the model (the number of such links is shown next to the type).

The Length menu

Syntax:

```
Geometry --> Links (coupled) --> Length --> Double
                                            Half
                                            Default
```

This sub-menu allows to adjust the length of the links arrows. The *Double* and *Half* commands can be issued repeatedly in order to achieve (almost) any desired length of the arrows.

- *Double*. Double the length of the links arrows which, by default, amounts to 1/10 of the model diameter.
- **Half**. Halve the length of the links arrows.
- **Default**. Restore the default length of the links arrows.

16.7.16 The PCLD point clouds menu

Syntax:

```
Geometry --> PCLD point clouds --> Show selected cloud points
                                   Show selected cloud segments
                                   Select cloud    ---> ...
                                   Unselect cloud  ---> ...
                                   Color points by cloud
                                   Color segments by cloud
```

The PCLD point clouds menu allows to visualize some geometrical aspects of the point clouds (see `PCLD` keyword) present in the current numerical model. This menu is only available if there are point clouds in the model.

- *Show selected cloud points*. Show all the selected cloud points. In some cases the figure can be cluttered. It is possible to select only certain cloud points by the following sub-menus.
- *Show selected cloud segments*. Show all the selected cloud segments. In some cases the figure can be cluttered. It is possible to select only certain cloud segments by the following sub-menus.
- **Select cloud**. Open a sub-menu which allows to select clouds for visualization.
- **Unselect cloud**. Open a sub-menu which allows to un-select clouds for visualization.

- *Color points by cloud.* Assign a different color to each point according to the cloud it belongs to.
- *Color segments by cloud.* Assign a different color to each segment according to the cloud it belongs to.

The Select cloud menu

Syntax:

```
Geometry --> PCLD point clouds --> Select cloud --> All
                                                    <list of clouds>
```

This sub-menu allows to select clouds for visualization.

- *All.* Select all point clouds.
- ⟨*list of clouds*⟩. Select a specific cloud.

The Select cloud menu

Syntax:

```
Geometry --> PCLD point clouds --> Unselect cloud --> All
                                                      <list of clouds>
```

This sub-menu allows to un-select clouds for visualization.

- *All.* Unselect all point clouds.
- ⟨*list of clouds*⟩. Unselect a specific cloud.

16.7.17 The GLIS surfaces menu

Syntax:

```
Geometry --> GLIS surfaces --> Show masters
                               Show slaves
                               Show master nodes
                               Show slave nodes
                               Show master faces
                               Show normals
                               Current surface --> <list of surfaces>
```

The GLIS surfaces menu allows to visualize some geometrical aspects of each contact sliding surface using the `GLIS` model. This menu is only available if there are sliding surfaces in the model.

- *Show masters.* Show the master elements of the currently selected sliding surface.

- *Show slaves*. Show the slave elements of the currently selected sliding surface.
- *Show master nodes*. Show the master nodes of the currently selected sliding surface.
- *Show slave nodes*. Show the slave nodes of the currently selected sliding surface.
- *Show master faces*. Show the master faces of the currently selected sliding surface.
- *Show normals*. Show the normals at each penetrating slave node of the currently selected sliding surface. If there is friction, show also the two tangents at each penetrating slave node of the currently selected sliding surface.
- **Current surface**. Open a sub-menu which allows to select the current sliding surface for visualization (by defaukt the first sliding surface is selected).

16.8 The Vectors menu

Object:

The Vectors menu allows to visualize a vectorial field on the body geometry in the form of vectors (arrows). The vector field can be expressed at nodes (most commonly) or at the element centroids (e.g. in the case of Cell-Centred Finite Volumes).

Syntax:

```
Vectors --> No vectors
            Scaled vectors
            Colored vectors
            Scaled colored vectors
            Field                  --> <list of available fields>
            Scale                  --> ...
            Length                 --> ...
            Color scheme           --> ...
            Options                --> ...
```

- *No vectors*. This is the default. It may be used explicitly to switch off vectors representation when no longer required.
- *Scaled vectors*. This activates vectors rendering with a uniform (green) color. The length of the arrow is proportional to the local intensity (norm) of the vector field.
- *Colored vectors*. This activates vectors rendering with a uniform length. The color is proportional to the local intensity (norm) of the vector field.
- *Scaled colored vectors*. This activates vectors rendering with both the length and the color proportional to the local intensity (norm) of the vector field.
- **Field**. This opens a sub-menu which allows choosing the (vector) field to be visualized. By default, the velocity field is rendered. A list of the vector fields available in the present calculation is automatically buit up. The user can select any field by clicking on the corresponding entry in the sub-menu.
- **Scale**. This opens a sub-menu which allows choosing the scale for the vector field rendering.
- **Length**. This opens a sub-menu which allows to adjust the length of the arrows representing the vector field (without changing the scale steps).
- **Color scheme**. This opens a sub-menu which allows to select the colors scheme for the vector field rendering.
- **Options**. This opens a sub-menu which allows to select some generic options for the vector field rendering.

The various sub-menus are described next.

16.8.1 The Scale menu

Syntax:

```
Vectors --> Scale --> Auto 6
                      Auto 14
                      User
```

This sub-menu allows to choose the scale for the vector field.

- *Auto 6.* A 6-color (linear) scale is chosen which automatically encompasses the range of vector intensities (lengths) of the field to be rendered.
- *Auto 14.* This is the default. A 14-color (linear) scale is chosen which automatically encompasses the range of vector intensities (lengths) of the field to be rendered.
- *User.* The user-specified scale is selected. This scale must have been specified by the user in the `SCEN` directive before giving the `TRAC REND` command (else this entry does not appear in the menu). In this case, this scale is used by default so it should not be necessary to use this command explicitly. However, if the user wants to try interactively an automatic scale (with either 6 or 14 colors), the present command may be useful to return to the user-defined scale.

Note that from January 2016 the 14-color scale has become the default for colored vectors rendering, and not the 6-color scale. Furthermore, the vectors scale is automatically popped up as soon as some vectors representation is activated, and popped down when no vectors are shown.

16.8.2 The Length menu

Syntax:

```
Vectors --> Length --> Double
                       Half
                       Default
```

This sub-menu allows to modify the length of the vector arrows in the current drawing, *without* modifying the vectors scale. The commands may be used repeatedly in order to obtain (almost) any desired length of the arrows.

- *Double.* This command doubles the length of the arrows without modifying the vectors scale in use nor the vectors colors (if any).
- *Half.* This command halves the length of the arrows without modifying the vectors scale in use nor the vectors colors (if any).
- *Default.* This command restores the default length of the arrows without modifying the vectors scale in use nor the vectors colors (if any).

16.8.3 The Color scheme menu

Syntax:

```
Vectors --> Color scheme --> Colors
                             Grayscale
                             Inverted colors
                             Inverted grayscale
```

This sub-menu allows to choose the color scheme of the vector arrows, if any (i.e., unless the vectors are rendered in the *Scaled vectors* mode).

- *Colors.* This is the default. Vectors are drawn using a scale of 6 or 14 colors depending on the chosen scale option.
- *Grayscale.* This replaces the colors by a scale of grey tones.
- *Inverted colors.* The color scale is used but the red color corresponds to the lowest value rather than to the highest value.
- *Inverted grayscale.* The grayscale scale is used but the darkest gray color corresponds to the lowest value rather than to the highest value.

16.8.4 The Options menu

Syntax:

```
Vectors --> Options --> Show internal vectors
```

This sub-menu allows to choose some options related to the visualization of vector fields.

- *Show internal vectors.* This visualizes the vector arrows also at "internal" nodes (or element centroids) rather than only at nodes on the surface of the body, in 3D models. Beware that, by default, in 3D models only the vectors at nodes located on the surface of the body are drawn.

16.9 The Isovalues menu

Object:

The Isovalues menu allows to visualize a vectorial field on the body geometry in the form of vectors (arrows). The vector field can be expressed at nodes (most commonly) or at the element centroids (e.g. in the case of Cell-Centred Finite Volumes).

The Isovalues menu allows to represent a scalar field on the body geometry, in the form of iso values. The scalar field can be expressed either at the element centroids or at the nodes. Various types of representation are possible.

Syntax:

```
Isovalues --> No iso
              Iso lines
              Iso fill
              Iso fill lines
              Iso fill elements   --> <list of available representations>
              Iso smooth
              Iso smooth lines
              Iso smooth elements --> <list of available representations>
              Iso surfaces
              Iso surfaces lines
              Shiny iso surfaces
              Field               --> <list of available fields>
              Component           --> <list of available components>
              Scale               --> ...
              Color scheme        --> ...
```

- *No iso.* This is the default. It may be used explicitly to switch off isovalues representation when no longer required.
- *Iso lines.* This activates iso lines (think of “level curves” on a normal 2D geographical map) representation of the scalar field.
- *Iso fill.* This activates iso values representation by filling the spaces between the ideal iso lines (see previous options) by a uniform color.
- *Iso fill lines.* This is the combination of the two previous iso value representation modes (color filling plus lines).
- **Iso fill elements**. This corresponds to filling each element by a uniform color corresponding to the local value of the scalar field. The result is an arlequin-like representation of the field. This opens a sub-menu. The local value of the scalar field can be either the average over all Gauss points of the element, or the maximum, or the minimum, see the sub-menu that lists the various possible types of representations.
- *Iso smooth.* This activates iso values representation by first interpolating the filed value at the nodes (if necessary) and then filling the element faces by a graded color filling using the values at the nodes.

- *Iso smooth lines*. This is a combination of the smooth rendering mode described above and of iso lines.
- *Iso smooth elements*. This is similar to the arlequin mode described above (each element is filled by a uniform color), but the color is interpolated continuously on the colors scale (like in the smooth color filling mode) rather than choosing the nearest fixed scale color. This opens a sub-menu. The local value of the scalar field can be either the average over all Gauss points of the element, or the maximum, or the minimum, see the sub-menu that lists the various possible types of representations.
- *Iso surfaces*. This activates iso surfaces (think of "level surfaces") representation of the scalar field. It makes sense only in 3D models, Rendering of the model outer faces is automatically disabled o that one can se the iso surfaces in the interior of the body
- *Iso surfaces lines*. This is a combination of the iso surfaces rendering mode described above and of iso lines.
- *Shiny iso surfaces*. This renders the iso surfaces with a "shiny" appearance. For this to actually work, the light must be switched on, see the **Lights/Mats** menu below. This switch is a toggle, When activated, it changes to *Dull iso surfaces*, which allows to return to the default visualization of iso surfaces.
- **Field**. This opens a sub-menu which allows choosing the (scalar) field to be visualized. By default, the stress field (component 1) is rendered. A list of the scalar fields available in the present calculation is automatically built up. The user can select any field by clicking on the corresponding entry in the sub-menu. Note that the list does not include only the classical fields at element Gauss Points such as stress, total strain or hardening parameters, but also the nodal fields (velocity, force, etc.) which are typically considered as vector fields (see the **Vectors** menu in a previous Section. For the latter to be representable as iso-values, one must of course select just one component (or the norm of the vector field), see next sub-menu.
- **Component**. This opens a sub-menu which allows choosing the component of the field to be visualized. By default, the first component of the currently selected field is rendered. A list of the scalar field components available in the present calculation for the currently selected field is automatically built up, and the norm of all components is also added. The user can select any component (or the norm) by clicking on the corresponding entry in the sub-menu.
- **Scale**. This opens a sub-menu which allows choosing the scale for the isovalue field rendering.
- **Color scheme**. This opens a sub-menu which allows to select the colors scheme for the isovalue field rendering.

The various sub-menus are described next.

16.9.1 The Fill elements representations menu

Syntax:

```
Isovalues --> Iso fill elements --> Average over the GPs
                                     Maximum over the GPs
                                     Minimum over the GPs
                                     ABS MAX over the GPs
```

This sub-menu allows to choose the type of representation for the “Iso fill elements” or the ”Iso smooth elements” isovalues field.

- *Average over the GPs.* The code builds up the average of the iso-field over all GPs of each element and then uses that (scalar) value to decide the (uniform) color by which each element is filled.
- *Maximum over the GPs.* The code takes the maximum of the iso-field over all GPs of each element and then uses that (scalar) value to decide the (uniform) color by which each element is filled.
- *Minimum over the GPs.* The code takes the minimum of the iso-field over all GPs of each element and then uses that (scalar) value to decide the (uniform) color by which each element is filled.
- *ABS MAX over the GPs.* The code takes the maximum in absolute value of the iso-field over all GPs of each element and then uses that (scalar) value to decide the (uniform) color by which each element is filled.

16.9.2 The Scale menu

Syntax:

```
Isovalues --> Scale --> Auto 6
                        Auto 14
                        User
                        Auto 1
```

This sub-menu allows to choose the scale for the isovalues field.

- *Auto 6.* A 6-color (linear) scale is chosen which automatically encompasses the range of intensities of the field and component to be rendered.
- *Auto 14.* This is the default. A 14-color (linear) scale is chosen whichg automatically encompasses the range of intensities of the field and component to be rendered.
- *User.* The user-specified scale is selected. This scale must have been specified by the user in the `SCEN` directive before giving the `TRAC REND` command. In this case, this scale is used by default so it is not necessary to use this command explicitly. However, if the user wants to try interactively an automatic scale (with either 6 or 14 colors), the present command may be useful to return to the user-defined scale.
- *Auto 1.* A single-value scale is chosen. This allows to divide the model into two zones: one where the field values are below and one where they are above the chosen value. By default the automatically chosen value is the mean value between the minimum and the maximum values of the chosen field/component. The user can precisely set this value by choosing a user scale with just one value (instead of 6 or 14 values).

Note that from January 2016 the 14-color scale has become the default for colored iso rendering, and not the 6-color scale. Furthermore, the iso scale is automatically popped up as soon as some iso representation is activated, and popped down when no iso are shown.

16.9.3 The Color scheme menu

Syntax:

```
Isovalues --> Color scheme --> Colors
                               Grayscale
                               Inverted colors
                               Inverted grayscale
```

This sub-menu allows to choose the color scheme of the iso values representation.

- *Colors*. This is the default. A scale of 6 or 14 colors is used depending on the chosen scale option.
- *Grayscale*. This replaces the colors by a scale of grey tones.
- *Inverted colors*. The color scale is used but the red color corresponds to the lowest value rather than to the highest value.
- *Inverted grayscale*. The grayscale scale is used but the darkest gray color corresponds to the lowest value rather than to the highest value.

16.10 The Text menu

Object:

The Text menu may be used to visualize some textual information, such as node numbers, object names etc., in addition or in alternative to the problem title, time value and time step, which appear by default in the top left corner of the graphical window.

Syntax:

```
Text --> Show node numbers
         Show element numbers
         Show object names
         Show vectors scale
         Show iso scale
         Hide info
         Show camera values
         Show debug info
         Show pinball contacts
```

- *Show node numbers.* This activates the visualization of node numbers. Note that the text is represented in 3D such as any other geometrical element, therefore it may be obscured by other geometrical entities, such as element faces. To read the numbers, it may be useful to turn the body, or to switch off the face filling as described above in the **Geometry** menu.
- *Show element numbers.* This activates the visualization of element numbers. If faces are filled, then the element number is repeated at the center of each one of its faces (to maximize the probability that it becomes visible), else it is represented just once, at the geometric center of the element.
- *Show object names.* This activates the visualization of object names. Geometrical objects are inherited from pre-processors or mesh generators (such as Cast3m). They can also be generated in EPX as named element groups.
- *Show vectors scale.* This visualizes a legend for the vectors representation. This text is "fixed" in the sense that it does not rotate with the body, and should be always visible "on top" of the geometrical object.
- *Show iso scale.* This visualizes a legend for the iso-values representation (fixed text).
- *Hide info.* This hides the visualization of the problem title, time value and time step, which appear by default in the top left corner of the graphical window.
- *Show camera values.* This activates the visualization of the current value of the camera parameters (fixed text).
- *Show debug info.* This activates the visualization of debug-related information.
- *Show pinball contacts.* This activates the visualization of pinball contacts numbering. The text is only visualized if **Geometry** → **Pinballs** → *Show contact points* or **Geometry** → **Pinballs** → *Show contact joints* is selected.

16.11 The Colors menu

Object:

The Colors menu allows to change the colors that are assigned by default to those components of the scene which are rendered in a fixed color. This is accomplished in two steps:

1. First, a color is selected from the **Colors** → **1) Select color** menu. The available choices are listed below.
2. Then, the component to which the color must be applied is selected from the **Colors** → **2) Apply it to** menu. The available choices are listed below.

Syntax:

```
Colors --> 1) Select color --> <list of available colors>
           2) Apply it to  --> <list of colorized scene components>
           Default for screen
           Default for paper
```

- **Select color**. This activates a sub-menu which lists the available colors. To select a color, click on the corresponding entry.
- **Apply it to**. This activates a sub-menu which lists the colorized scene components, i.e. the scene items which are drawn in a pre-determined color. To select a component, click on the corresponding entry. The previously selected color is immediately applied to the selected component.
- *Default for screen*. This switch may be used to select a color scheme suitable for an on-screen representation (black background, white lines etc.). Note, however, that this color scheme is probably not suited for obtaining hard copies of the scene to be inserted in documents.
- *Default for paper*. This is the default (even for on-screen visualization). The switch may be used to restore the default values of colors, which are suitable for an on-paper representation (white background, black lines etc.), after the color scheme has been previously altered.

Note that from January 2016 the paper-suited color scheme has become the default scheme even for on-screen rendering (while the screen scheme was the default previously). This is because when hard-copies of the graphical window are produced, the paper color scheme is probably more suitable for inclusion of figures into paper (or even on-line) documentation.

The various sub-menus are described next.

16.11.1 The 1) Select color menu

```
Colors --> 1) Select color --> Red
                               Green
                               Blue
                               Cyan
                               Magenta
                               Yellow
```

```
Black
White
Grey05
Grey10
Grey15
Grey20
Grey25
Grey30
Grey35
Grey40
Grey45
Grey50
Grey55
Grey60
Grey65
Grey70
Grey75
Grey80
Grey85
Grey90
Grey95
```

The color names from `Red` to `White` are self-explaining. As concerns the greys, they range from nearly black (`Grey05`) to nearly white (`Grey95`).

16.11.2 The 2) Apply it to menu

```
Colors --> 2) Apply it to --> Background
                              Center
                              Bounding box
                              Internal faces
                              Element outlines
                              Sharp corners
                              Free edges
                              Perp contours
                              Vectors
                              Iso surface edges
                              Iso surface outlines
                              Points
                              Node numbers
                              Element numbers
                              Object names
                              Text
                              Initial wireframe
                              Initial outline
                              Debris trajectories
                              Iso default color
```

- **Background**. Apply the previously chosen color to the scene background.
- **Center**. Apply the previously chosen color to the model center. (See the **Geometry** menu.)

- **Bounding box**. Apply the previously chosen color to the model bounding box. (See the **Geometry** menu.)
- **Internal faces**. Apply the previously chosen color to the internal faces. (See the **Geometry** menu.)
- **Element outlines**. Apply the previously chosen color to the element outlines. (See the **Geometry** menu.)
- **Sharp corners**. Apply the previously chosen color to the sharp corners. (See the **Geometry** menu.)
- **Free edges**. Apply the previously chosen color to the free edges. (See the **Geometry** menu.)
- **Perp contours**. Apply the previously chosen color to the perpendicular contours. (See the **Geometry** menu.)
- **Vectors**. Apply the previously chosen color to vectors drawn as scaled vectors (not as colored or as scaled colored vectors). (See the **Vectors** menu.)
- **Iso surface edges**. Apply the previously chosen color to the edges of iso surfaces (3D only). (See the **Isovalues** menu.)
- **Iso surface outlines**. Apply the previously chosen color to the outlines of iso surfaces (3D only). (See the **Isovalues** menu.)
- **Points**. Apply the previously chosen color to the points (material points etc.). (See the **Geometry** menu.)
- **Node numbers**. Apply the previously chosen color to the node numbers. (See the **Text** menu.)
- **Element numbers**. Apply the previously chosen color to the element numbers. (See the **Text** menu.)
- **Object names**. Apply the previously chosen color to the object names. (See the **Text** menu.)
- **Text**. Apply the previously chosen color to the displayed text. (See the **Text** menu.)
- **Initial wireframe**. Apply the previously chosen color to the wireframe of the initial geometry, if any. (See the **Geometry** menu.)
- **Initial outline**. Apply the previously chosen color to the outline of the initial geometry, if any. (See the **Geometry** menu.)
- **Debris trajectories**. Apply the previously chosen color to the debris trajectories rendered as a uniform color, if any. (See the **Geometry** menu.)
- **Iso default color**. Apply the previously chosen color as filling color in iso-maps for any parts of the model which are excluded from the iso-values representation. (See keyword `ISO` ... `SUPP` in the `SCEN` directive on Page O.80.)

16.12 The Lights/Mats menu

Object:

The Lights/Mats menu allows to switch on or off the light and to assign an appearance ("material") to the whole mesh or to selected portions of it (objects). Lighting affects rendering of the scene and adds a touch of realism. The choice of materials takes place in two steps:

1. First, a material is selected from the **Lights/Mats** → **1) Select material** menu. The available choices are listed below.
2. Then, the object to which the material must be applied is selected from the **Lights/Mats** → **2) Apply it to** menu. The available choices are listed below.

Syntax:

```
Lights/Mats --> Switch light on
                Light X             --> ...
                Light Y             --> ...
                Light Z             --> ...
                Light ambient       --> ...
                Light diffuse       --> ...
                Light specular      --> ...
                Light shininess     --> ...
                Light model ambient --> ...
                Reset lights
                1) Select material  --> <list of available materials>
                2) Apply it to      --> ...
                Reset materials
```

- *Switch light on*. This switches the light on, i.e. it activates the lighting model.
- **Light X**. This opens a sub-menu which allows to define the position of the directional lighting source along the X axis. This light source always points towards the centroid of the model.
- **Light Y**. This opens a sub-menu which allows to define the position of the directional lighting source along the Y axis. This light source always points towards the centroid of the model.
- **Light Z**. This opens a sub-menu which allows to define the position of the directional lighting source along the Z axis. This light source always points towards the centroid of the model.
- **Light ambient**. This opens a sub-menu which allows to choose the intensity of the ambient light.
- **Light diffuse**. This opens a sub-menu which allows to choose the intensity of the diffuse light.
- **Light specular**. This opens a sub-menu which allows to choose the intensity of the specularity of surfaces subjected to lighting.

- **Light shininess**. This opens a sub-menu which allows to choose the intensity of the shininess of surfaces subjected to lighting.
- **Light model ambient**. This opens a sub-menu which allows to choose the intensity of the model ambient light.
- *Reset lights*. This resets the lights to their default values.
- **1) Select material**. This opens a sub-menu which allows to choose a material among a list of available materials.
- **Apply it to**. This opens a sub-menu which allows to select to which parts of the model to associate the previosly chosen material as far as the lighting model is concerned.
- *Reset materials*. This resets the materials to their default values.

The various sub-menus are described next.

16.12.1 The Light X menu

```
Lights/Mats --> Light X --> Left
                            Centre
                            Right
```

- *Left*. Set the directional lighting source to come from the "left" (i.e. from the negative part of the X axis).
- *Centre*. Set the directional lighting source to come from the "centre" (i.e. from the central part of the X axis).
- *Right*. Set the directional lighting source to come from the "right" (i.e. from the positive part of the X axis).

16.12.2 The Light Y menu

```
Lights/Mats --> Light Y --> Bottom
                            Centre
                            Top
```

- *Bottom*. Set the directional lighting source to come from the "bottom" (i.e. from the negative part of the Y axis).
- *Centre*. Set the directional lighting source to come from the "centre" (i.e. from the central part of the Y axis).
- *Right*. Set the directional lighting source to come from the "top" (i.e. from the positive part of the Y axis).

16.12.3 The Light Z menu

```
Lights/Mats --> Light Z --> Front
                            Centre
                            Back
```

- *Front*. Set the directional lighting source to come from the "front" (i.e. from the positive part of the Z axis).

- *Centre*. Set the directional lighting source to come from the "centre" (i.e. from the central part of the Z axis).
- *Back*. Set the directional lighting source to come from the "back" (i.e. from the negative part of the Z axis).

16.12.4 The Light ambient menu

```
Lights/Mats --> Light ambient --> Low
                                  Medium
                                  High
```

- *Low*. Set the ambient light to a low level of intensity.
- *Medium*. Set the ambient light to a medium level of intensity.
- *High*. Set the ambient light to a high level of intensity.

16.12.5 The Light diffuse menu

```
Lights/Mats --> Light diffuse --> Low
                                  Medium
                                  High
```

- *Low*. Set the diffuse light to a low level of intensity.
- *Medium*. Set the diffuse light to a medium level of intensity.
- *High*. Set the diffuse light to a high level of intensity.

16.12.6 The Light specular menu

```
Lights/Mats --> Light specular --> Low
                                   Medium
                                   High
```

- *Low*. Set the light specularity to a low level of intensity.
- *Medium*. Set the light specularity to a medium level of intensity.
- *High*. Set the light specularity to a high level of intensity.

16.12.7 The Light shininess menu

```
Lights/Mats --> Light shininess --> Low
                                    Medium
                                    High
```

- *Low*. Set the light shininess to a low level of intensity.
- *Medium*. Set the light shininess to a medium level of intensity.
- *High*. Set the light shininess to a high level of intensity.

16.12.8 The Light model ambient menu

```
Lights/Mats --> Light model ambient --> Low
                                        Medium
                                        High
```

- *Low.* Set the model ambient light to a low level of intensity.
- *Medium.* Set the model ambient light to a medium level of intensity.
- *High.* Set the model ambient light to a high level of intensity.

16.12.9 The 1) Select material menu

```
Lights/Mats --> 1) Select material --> Brass
                                       Bronze
                                       Polished bronze
                                       Chrome
                                       Copper
                                       Polished copper
                                       Gold
                                       Gold2
                                       Polished gold
                                       Pewter
                                       Silver
                                       Polished silver
                                       Emerald
                                       Jade
                                       Obsidian
                                       Pearl
                                       Ruby
                                       Turquoise
                                       Black plastic
                                       Cyan plastic
                                       Green plastic
                                       Red plastic
                                       White plastic
                                       Yellow plastic
                                       Black rubber
                                       Black rubber2
                                       Cyan rubber
                                       Green rubber
                                       Red rubber
                                       White rubber
                                       Yellow rubber
```

The material names are self-explaining. Of course these are not real materials but are only used to set the surface appearance for the rendering process.

16.12.10 The 2) Apply it to menu

```
Lights/Mats --> 2) Apply it to --> Whole mesh
                                   Selected objects
```

- **Whole mesh**. Apply the previously chosen material to the whole mesh (all elements).
- **Selected objects**. Apply the previously material to the currently selected objects only. (See the **Objects** → **Select objects** menu.) The mechanism of objects selection, followed by material selection and finally by material application allows to assign different materials interactively to the various components of the mesh.

16.13 The Win/Copy menu

Object:

The Win/Copy menu allows to resize the window to precise predefined sizes and to produce a copy on file of the current scene. The copy is not a simple dump of the graphical window, but a separate rendering in memory, which is successively dumped on a file in the well-known .BMP format (or in a number of other available formats, see below). Such images are then easily inserted in publications or may be used to produce animated sequences. Several options are available, as described below.

Note also that, of course, it is also possible to resize the graphical window interactively at any moment by means of the usual Windows techniques. However, it is generally difficult in that way to achieve a precise size of the graphicsl window. The default size of the graphical window is 500×500 pixels.

Syntax:

```
Win/Copy --> Window 320*240
             Window 600*600
             Window 640*480
             Window 800*600
             Window 1024*768
             Window 1200*1200
             Window 1280*1024
             Bitmap format    --> <available bitmap formats>
             Copy as is
             Copy public. (1600*1200)
             Copy poster (1800*1800)
```

- *Window 320*240.* This sets the graphical window size to 320×240 pixels.
- *Window 600*600.* This sets the graphical window size to 600×600 pixels.
- *Window 640*480.* This sets the graphical window size to 640×480 pixels.
- *Window 800*600.* This sets the graphical window size to 800×600 pixels.
- *Window 1024*768.* This sets the graphical window size to 1024×768 pixels.
- *Window 1200*1200.* This sets the graphical window size to 1200×1200 pixels.
- *Window 1280*1024.* This sets the graphical window size to 1280×1024 pixels.
- **Bitmap format** This opens a sub-menu which allows to choose the format in which a copy of the rendered scene will be saved.
- *Copy as is* Produce a copy of the current scene in the current window size on a file on the current directory, in the currently chosen format (.BMP format by default). A small approximation of the image size may come by the fact that the pixel size is rounded to the nearest multiple of 4, to avoid problems in the successive utilization of the file (e.g. when including it in a document or using it to produce an animation). For example, an image of 600*600 pixels has a size of about 1 MB (uncompressed) in the BMP format.

- *Copy public. (1600*1200)* Produce a publication-ready copy of the current scene with an image size of 1600 × 1200 pixels on a file on the current directory, in the currently chosen format (.BMP format by default). The graphical window is *not* resized. Each image has a size of about 5.6 MB (uncompressed) in the BMP format.

- *Copy poster (1800*1800)* Produce a poster-ready copy of the current scene with an image size of 1800 × 1800 pixels on a file on the current directory, in the currently chosen format (.BMP format by default). The graphical window is *not* resized. Each image has a size of about 9.5 MB (uncompressed) in the BMP format.

It is important to note that when planning to use the bitmap for producing an animation all the “frames” must be of the same size. To obtain bitmaps of sizes other than “publication” (1600*1200) or “poster” (1800*1800), first resize the window either by hand or, preferably, by one of the above Window www*hhh commands, and then use the *Copy as is* command.

The various sub-menus are described next.

16.13.1 The Bitmap format menu

```
Win/Copy --> Bitmap format --> BMP
                               PPM (binary)
                               PPM (Ascii)
                               TGA
                               EPS (color)
                               EPS (b&w)
                               POV-Ray
```

- *BMP*. This is the default. The format is known as device-independent bitmap format and is widely used on MS-Windows platforms. The image copy will be produced in the BMP format. This command might be useful to restore the default format after other format(s) were previously selected.

- *PPM (binary)*. The image copy will be produced in the PPM binary format. This format is known as the Portable Pixmap format (binary version), and is popular in the Unix world.

- *PPM (Ascii)*. The image copy will be produced in the PPM Ascii (pure text) format. This file is larger than the binary one, but probably much more portable.

- *TGA*. The image copy will be produced in the TGA (Targa) format.

- *EPS (color)*. The image copy will be produced in the Encapsulated Postscript (EPS) format in color. This is a purely ASCII file, and therefore very portable. It may be used e.g. to insert illustrations in LaTeXdocuments.

- *EPS (b&w)*. The image copy will be produced in the Encapsulated Postscript (EPS) format in black and white (i.e., by using shades of grey). The grey levels are obtained from the color version by means of the so-called NTSC color conversion algorithm:

  $$\lambda = 0.30R + 0.59G + 0.11B$$

  where R, G, B are the red, green and blue components of the pixel color (each one ranging from 0 to 1) and λ is the resulting luminosity value (a grey level from 0 to 1).

- *POV-Ray*. This is not a bitmap format, but an ASCII file containing scene description commands. An input file for the POV-Ray ray-tracer will be generated (`.pov`).

17 GROUP SR—SAVING AND RESTART

The following directives allow to save the data during a computation and to the successive restart of the computation.

17.1 SAVING

17.1.1 DEFINING SAVING IN THE INPUT CODE

Object:

To produce a saving file for successive restart, the directive `ECRI FICH SAUV` has to be inserted in group G of the EUROPLEXUS input data (as part of the `ECRI` directive). See page G.110 for details on the `SAUV` directive.

17.1.2 SAVING VIA COMMAND FILE

The code checks the existance of a file called ”command.epx” regularly. The intervals can be defined via `"OPTI" "CMDF" "NPAS"` nn `"CPUT"` nn. When the file exists, it is read and the containing command are performed. The following commands are possible:

Syntax:

```
< "SAVE">
< "STOP">
< "PVTK">
  "END"
```

`SAVE`

The model is saved at the currend time step.

`STOP`

The calculation is stoppped after the current time step.

`END`

End of command file.

`PVTK`

A PVTK output is written for the current time step.

17.2 RESTART

Object:

The REPR keyword, to be inserted in group A, enables to restart a computation which was previously saved. Not available in MPI.

Syntax:

```
... title ...

 "REPRISE"  nbanrep    "POSI" numer     < "PROT"  'maclef' >

... Instructions of the groups C,D,E,F,G that are modified ...
... (in particular, if a further saving is desired, repeat
    the ECRI FICH SAUV directive :)                         ...

 < ECRI ... FICH  SAUV <ndsauv>  <PROT 'maclef'>  <LAST>  </CTIM/> >

... Instructions of the group H that are modified ...

 "CALCUL"  . . .

 "FIN"
```

The REPR instruction is described in detail below, Page SR.30.

Warning:

During a restart the structure of the data is very different. In general, only the instructions of the groups C,D,E,F,G,H which are modified have to be repeated. However, note that the directive ECRITURE must be repeated even if it is not changed. All other instructions are useless. Especially, the geometry must NEVER be repeated.

During a restart run, the directive FICH ALIC reads the file produced during the previous run and adds the new results like if a single calculation would have been performed.

Comments:

The various possibilities are described in the following pages.

During the first run, the directive ECRI FICH SAUV FREQ n causes data to be saved once every n time steps, on the default saving file.

During a restart run, the directive `REPR 'myfile.sau' j` reads the previously created saving file and re-starts the calculation from the `j`-th saved data station.

If saving is requested during a restart run, be aware that a saving is not performed at the restart time itself.

During a restart run, all frequencies `nf` or `tf` in directives of the type:

```
- ECRI FICH SAUV iu FREQ nf
- ECRI FREQ nf
- ECRI TFRE tf
- ECRI FICH ALIC ju FREQ nf
- ECRI FICH ALIC ju TFRE tf
- ...
```

are considered starting from the initial time (or the initial step) of the first run, not of the restart run.

During a restart, if a directive similar to `CALC` ... `NMAX nsteps` ... is used, be aware that `nsteps` is the total number of time steps, not the number of steps during the restart run.

Files:

The listing file is always produced anew during a restart, beginning at the restart time.

The saving file is specified by the instruction `ECRI FICH SAUV`.

The restart one is specified by the directive `REPRISE`.

For postprocessing files, see the description of `REPRISE` below.

17.3 DIRECTIVE "SAUVE" (OBSOLETE FORM)

This is the obsolete form of the `SAUVER` directive, which produces a saving file for subsequent restart of the calculation. It is only included here for compatibility with old input files. For new input files, please use the `ECRI` ... `FICH SAUV` directive, described on page G.110.

Object:

This keyword creates a saving file and, in conjunction with the keyword `REPR` (to be used in a subsequent run), allows splitting a computation in two or more parts.

The results are saved on a file (saving file) at times specified by the user. Each saving corresponds to a number or position on the file (1, 2, 3 etc.), from which a restart of the computation can be carried out (see directive `REPR` on page SR.30.

Syntax:

```
SAUV nbansav   < FREQ > ifreq  < DER >  < PROT 'maclef' >
```

`nbansav`

Number of the saving file or name of the file in quotes. If completely omitted, the code will assume the default file name `<basename>.sau` where `<basename>` is the root of the input file name (i.e. without extension `.epx`). However, note that in this case the following keyword `FREQ` becomes mandatory to introduce the frequency.

`ifreq`

Frequency of the savings, in time steps. The results are saved each `ifreq` computation steps. Note that the code always saves the last step of the calculation (if the run is terminated normally), irrespective of the frequency chosen. Therefore, if one is only interested in getting the possibility to continue the calculation further on, a very large frequency may be chosen, larger than the total number of steps expected in the present run.

`DER`

This keyword indicates that the saving file should contain just one saving station, corresponding to the last saved time station in the present calculation. In other words, each new saving station replaces the former one, if any. This allows to obtain a saving file of the smallest possible size. However, restarting from an intermediate time is obviously not possible in this case: the only possibility to restart the calculation will be `REPR` ... `POSI 1` (see page SR.30).

`PROT`

Keyword entering a protection on the saving file.

`'maclef'`

Key of up to 8 characters, enclosed in apostrophes. In order to restart the computation from that file, the instruction `REPR` must contain the keyword `PROT` with an identical key.

Comments:

The keyword `FREQ` introduces a fixed frequency in time steps and has been maintained for backward compatibility (also, if `FREQ` is missing, and a number is read instead, the program assumes that it indicates a step frequency `ifreq`). This form of the directive (e.g. `SAUV 30 1000`) is still accepted for backwards compatibility only but is deprecated.

The keyword `PROT` is not compulsory. If it is not used, there is no protection (this is equivalent to a key of 8 blanks). If specified, the keyword `PROT` must be at the end of the `SAUV` directive (i.e., after `DER`, if any).

If a unit number is used for `nbansav`, the saving file and its number must have been defined before on the control cards.

A first saving station (position number 1) containing some header data is always produced at the initial time (step 0 of the calculation). Of course, it is normally meaningless to restart from this time station, unless the `DER` keyword has been specified (see above), because it would be the same as starting the calculation anew from the initial time. On the contrary, if `DER` has been specified, the only possibility for restart is to use the first time station which, in this case, will contain the data of the last saving performed (not the first one in general).

Examples:

Assume a calculation performs 4994 time steps to arrive at its final time. The following saving directives are accepted:

- `SAUV 'myfile.sau' FREQ 1000` saves data for restart on the indicated file every 1000 steps. The following six saving stations are produced: 1 (step 0), 2 (step 1000), 3 (step 2000), 4 (step 3000), 5 (step 4000) and 6 (step 4994, i.e. the last step).
- `SAUV FREQ 1000`: same as above but the saving file has the default name `<basename>.sau`.
- `SAUV 'myfile.sau' FREQ 1000 DER` saves data for restart on the indicated file every 1000 steps, by always re-writing the previous saving. Only one saving station is thus present on the saving file (assuming that the run terminates normally): 1 (step 4994, i.e. the last step). If the run would fail, say, at step 2500, the saving file would also contain one station (step 2000).
- `SAUV FREQ 10000`: the saving file has the default name `<basename>.sau`. Only one saving station is produced (assuming that the run terminates normally): 1 (step 4994, i.e. the last step). If the run would fail, say, at step 2500, no (useful) saving time station would be available (there is still one saving station, but it is at step 0).

The following saving directives are still accepted for backwards compatibility but are strongly deprecated:

- `SAUV 30 1000` saves data for restart on unit 30. Under Windows, this produces a file named `fort.30` on the current directory. The saving frequency is 1000, so the following six saving stations are produced: 1 (step 0), 2 (step 1000), 3 (step 2000), 4 (step 3000), 5 (step 4000) and 6 (step 4994, i.e. the last step).

17.4 DIRECTIVE "REPRISE"

Object:

This option enables a computation to be restarted from a time which was previously saved on a 'saving' file. This file now becomes the restart file and contains, besides the computed values at the saved time stations, a certain amount of data of the preceding computation which **must not** be defined again in the restart input file (see page SR.40).

Syntax:

```
REPR  nbanrep  POSI numer  < PROT 'maclef' >
```

`nbanrep`

Number of the restart unit, or name of the restart file in quotes.

`numer`

Number of the saving station which determines the restart (1, 2, 3 etc.). The restart will occur from the `numer`-th saved time station. If the keyword `LAST` was used for writing the restart file, `numer` must be 1.

`PROT`

Compulsory keyword if there is a protection on the saving file.

`'maclef'`

Key protecting the saving file.

Comments:

If a unit number is used for `nbanrep`, the restart file and its unit number must have been defined first in the control cards. The restart file corresponds to the former saving file (i.e., it has the same file name).

During a restart, the user can save data for a further restart. In this case, the logical numbers of the saving and restart files must be different.

As far as data storage for postprocessing purposes (FICH ALIC, TPLOT, XPLOT, K2000 etc.) is concerned, two strategies may be followed during a restart. The first one consists in producing a single results file that after the restart corresponds to the file which would have been produced by a single run. To obtain this behaviour, during the restart use the same storage file which was defined in the previous run. The program will read the previous results file, position the pointer at the correct time (restart time) and then continue writing the data on the file.

The second possibility is that of splitting the results file in several pieces, one for the first run, another for the first restart, and so on. This may be useful e.g. in very large computations, to keep the file size acceptable. To obtain this behaviour, simply change the name of the results file each time you restart the calculations. The program will then produce a new data set containing also the necessary header information (e.g., geometry, etc.).

In case of the ParaView pvtk output the files are already split into several .vtu-files. They are combined later on in ParaView using the file .pvtk. For a restart the vtu files must not be present but the pvtk file. This file will be read by the routine and the new result files will be added.

Examples of both techniques are available in the example files.

17.5 DATA NECESSARY FOR RESTARTS

Warning:

The data structure for restarts is different from that of a normal run.

All the EUROPLEXUS data relative to the preceeding computation are written on the restart file.

By explicitly re-defining a directive, the former one is cancelled and replaced. The user can also add some new directives.

The following directives must be repeated:

- Title card;
- Dimension (or keyword `TERM`);
- Directives `CALCUL` and `FIN`.

The following directive is NOT repeated:

- Geometry (with mesh).

The following directives may be defined again:

- Dimensions;
- Masses;
- Thicknesses;
- Materials;
- Connections;
- Loads;
- Printouts;
- Options.

Comments:

DIMENSIONS: they can be larger (if for example loads are added), or smaller (if too much space had been provided) than the dimension of the preceeding computation. If it is not modified, the word `TERM` at least must be used.

MATERIALS: the density of the material and the stress-strain law can be changed, but the value of the initial stresses and strains (final value of the saving computation) must be compatible with the new law for all elements.

CONNECTIONS: the user can for example add or suppress a blocked displacement; in this case, do not forget to define again the whole instruction. If he wants to cancel all the connections of the preceeding computation, only the keyword `LIAISON` is necessary, without any other sub-instruction.

LOADS: the loads may be completely re-defined. Sometimes this is necessary, if the final time defined in the arrays becomes lower than the final time of the instruction `CALCUL`.

COMPUTATION: the start time corresponds to the time of restart. If it does not, EUROPLEXUS uses the time written on the restart file. The number of time steps takes the preceeding computation into account. If the user stops after 1000 steps, but wants to continue for a further 500 steps, the total number of time steps will be 1500.

18 GROUP RM—CHANGE OF TOPOLOGY (”REMAILLAGE”)

Object:

This directive enables “remeshing”, i.e. changing the topology of a part of the mesh previously defined by directive ”GEOM”.

Note that this is very different from mesh “rezoning”, i.e. prescribing the motion of a fluid grid in ALE computations. In fact, rezoning operations just move the nodes, without changing the topology (number of nodes and elements, composition of the elements).

For remeshing, two options are possible:

- automatic;
- manual.

With the option ”AUTOMATIQUE”, the user has to supply only the boundary points of the zone submitted to remeshing, then EUROPLEXUS builds a new and more regular mesh based on the boundary.

With the option ”MANUEL”, the user must enumerate all the elements which are to be eliminated and supply the new mesh.

At the present time, only 3-noded triangles (”TRIA”) can be taken into account.

Syntax:

```
"REMAILLAGE"
     $   "AUTOMATIQUE"   . . .   $
     $   "MANUEL"        . . .   $
```

Comments:

The suppressed elements must belong to the same zone (defined by the instruction ”GEOMETRIE”).

18.1 AUTOMATIC REMESHING

Object:

The new sub-mesh is created by EUROPLEXUS. Therefore, only the boundary points are necessary. As a matter of fact, these points should be common to the old and the new mesh.

Syntax:

```
"AUTOMATIQUE"   "CONTOUR"   /LECTURE/
                "AJOUTER"   npts*( xi , yi )
                < "ELEM"  ideb ifin >  < "ZONE"  nzone >
                < "MAIL"  < nmail > >  < "STOP" >
```

`/LECTURE/`

Numbers of the existing points making up the boundary.

`npts`

Number of points to be added.

`xi , yi`

Coordinates of the added points (abscissa then ordinate for each of the npts points).

`ideb,ifin`

The numbers of the elements of the zone concerned are lying between ideb and ifin.

`nzone`

The elements of the zone to be remeshed belong to the zone number nzone.

`nmail`

Number of the logical unit (by default nmail = 7), where the data set available for the procedure "LECTURE" of "COCO" is stored.

Comments:

If the boundary point is an existing node, it is defined by its number.

If it is an added point, it is defined by a negative number. In this case, at the end to the procedure /LECTURE/, the user must enter the coordinates of these points in the same order as they are mentioned in the procedure, by the means of the instruction "AJOUTER".

The directives "ELEM" and "ZONE" enable the elements submitted for remeshing to be limited.

By means of the directive "MAIL", the user can obtain a data set for "COCO" in order to plot the results of the remeshing.

The key-word "STOP" stops EUROPLEXUS when the mesh is created and enables the user to check his mesh.

18.2 MANUAL REMESHING

Object:

This option enables a new partial mesh to be explicitly entered.

Syntax :

```
"MANUEL"   izone   nelim   nelaj   npaj
        "ANCIEN"   /LECTURE/
        "NOUVEAU"

          . . .    COCO data set . . .

        "IDENTIFIER"   npts*( numl  numg )
```

`izone`

Number of the zone of elements which must be eliminated.

`nelim`

Total number of the elements to be eliminated.

`nelaj`

Total number of the elements to be added and belonging to the new sub-mesh.

`npaj`

Total number of points belonging to the new sub-mesh.

`ANCIEN`

Keyword defining the old sub-mesh.

`LECTURE`

List of the elements belonging to the sub-mesh to be eliminated.

`NOUVEAU`

Keyword introducing the "COCO" data set of the new sub-mesh.

`npts`

Number of pairs (local number, global number) to be identified.

`numl`

Local number of the node in the sub-mesh `numg`

Number of that same node in the global mesh.

Comments:

The "COCO" data set with its title is composed of the coordinates of the new sub-mesh (in format 6E12.5) and of the numbers of the mesh elements (in format 18I4).

The key-word "IDENTIFIER" enables the integration of the new sub-mesh into the global mesh to be defined.

18.3 CHECKING THE REMESHING

Object:

To edit (verify) the result of a remeshing operation.

Syntax:

```
< "PERFO" nuperf >  < "TRACE" nutrac >  < "SAUVE" nusauv >
```

During a restart the user can save data for another restart.

`nuperf`

Number of the logical unit which will contain the "COCO" data necessary to plot a new sub-mesh.

`nutrac`

Necessary to write the results on the file "TRACE" number nutrac.

`nusauv`

To save the results on the file nusauv, so as to enable a further restart.

Comments:

The user is advised to use these commands, because the numbers of certain elements may have changed after a remeshing. That is why it is necessary to save that time step (considered by EUROPLEXUS as step zero). Do not forget to check that the new mesh is correct before the computation continues by means of a restart ("REPRISE").

19 GROUP EX—EXAMPLES

On the following pages the user may find some examples of input files. The examples are purely indicative of the 'flavour' of the program. Much more examples could be found as benchmarks of the EUROPLEXUS consortium.

In addition, the user can find many actual EUROPLEXUS examples (including input, pre-treatment and post-treatment files) in some of the publications listed in the bibliography at the end of the present manual.

Unless it is specified otherwise, the mesh is created by means of GIBI. The GIBI data is given so as to define the objects without any ambiguity.

19.1 BENDING OF A BEAM

This example is part of the EUROPLEXUS benchmarks and has the name bm_manex_01.

Object:

This is a 2D elastic computation.

A beam is subjected to an uniform stress (pressure).

Geometry and meshing :

L = 24.0 mm : half length of the beam;

e = 1.0 mm : thickness;

The mesh is entered in free format;

There are 12 "COQU" shell elements.

Physical properties:

rho = 8000 kg/m^3 : density;

nu = 0.3 : Poisson's ratio;

E = 200 GPa : Young's modulus.

Boundary conditions:

- The pressure increases from 0 to 2 MPa in 0.1 millisecond, then remains constant.

Clamped boundary and symmetry conditions are applied at the centre.

Computation:

The step is automatic and the computation ends at 0.01 s.

In order to visualize the results more easily, the computation is followed by the drawing of the time dependant displacement of the centre of the beam.

List of the input file:

```
VIBRATION   !Title - must be given!
!ECHO       !Output in the console
DPLA        !Two-dimensional plane strain computation
!
! Geometry
!
GEOM LIBR POIN 13 COQU 12 TERM           !Input of the geometry in free format
 0 0  2 0  4 0  6 0  8 0 10 0 12 0
14 0 16 0 18 0 20 0 22 0 24 0
1 2 2 3 3 4 4 5 5 6 6 7 7 8 8 9 9 10 10 11 11 12 12 13
COMP EPAI 1. LECT TOUS TERM              !Thickness of the shell elements
!
! Materials
!
MATE LINE RO 8E-9 YOUN 2E5 NU 0.3 LECT TOUS TERM
!
! Boundary Conditions
!
LINK COUP BLOQ 23 LECT  1 TERM
               13 LECT 13 TERM
CHAR 1 FACT 2 PRES COQU -2. LECT TOUS TERM  !Loading with a pressure
       TABL 3 0 0 1E-4 1 1 1                !Time depended variable for the pressure
!
! Outputs
!
ECRI VITE CONT ECRO TFRE 1.E-3            !Output into the listing
          POIN LECT 1 TERM
          ELEM LECT 1 TERM
     FICH ALIC TFRE 1E-4                  !Output into the alice file
     FICH PVTK TFRE 1E-4                  !Output into the ParaView file
               VARI ECRO CONT DEPL
!
! Options
!
OPTI NOTE
     LOG 1                                !log file is written for each time step
                                          !should not be done for MPI!
!
! Calculation Parameters
!
CALC TINI 0 TEND 10E-3                    !End of calculation at 10e-3 s
*=================================================================
SUIT
Post-Processing                           !Title
*
RESU ALIC GARD PSCR
SORT GRAP
*
AXTE 1E3 'TIME (MS)'
*
```

```
COUR 1 'COQU' DEPLA COMP 2 NOEU LECT 13 TERM
DESS 1 1 AXES 1. 'DEFLECTION (MM)'
*=================================================================
FIN
```

19.2 IMPACT ON A CIRCULAR PLATE

This example is part of the EUROPLEXUS benchmarks and has the name bm_manex_02.

Object:

This is a 2D plastic computation.

A clamped plate is submitted to the impact of a rigid missile.

Geometry and meshing :

D = 465 mm : diameter of the plate

e = 6 mm : thickness

The missile is a flat nose cylinder, 90 mm in diameter. It falls straight in the middle of the plate.

The user wants to follow the displacements of point P1 to P4 whose location has been imposed.

GIBI data:

```
TITRE 'IMPACT SUR DES PLAQUES CIRCULAIRES' ;
OPTIO DIME 2 ELEM SEG2 ;
DPROJ=90; RPROJ=DPROJ / 2;
DENS 7;
CENTR= 0 0 ; BORD=RPROJ 0 ; BORD2=DPROJ 0 ; ENCAS=233.5 0 ;
   P1=60 0 ;    P2=80 0    ;    P3=120 0   ;    P4=160 0   ;
   P0= 0 0 ;
LIG1=CENTR DROIT BORD  ; LIG1=LIG1 COUL ROUG ;
LIG2=BORD  D  P1  D  P2  D  BORD2  D  P3  D  P4  D  ENCAS ;
LIG2=LIG2 COUL VERT ;
PLAQ=LIG1 ET LIG2 ;
PROJ=MANUEL POI1 P0;
MESH=PROJ ET PLAQ;
SORTIE MESH;
TASS MESH;
OPTI sauv form 'bm_manex_02.msh';
sauv form MESH;
FIN;
```

Physical properties:

rho = 7800 kg/m3 : density;

nu = 0.3 : Poisson's ratio;

E = 230 GPa : Young's modulus;

Y = 188 MPa : elastic limit.

Boundary conditions:

The missile has a mass of 257 kg, it falls at a speed of 11.38 m/s (be careful, the axisymmetric computation concerns ONE radian).

- Clamped boundary and symmetry conditions.

Computation:

The step is automatic and the computation concerns the first 12 milliseconds.

In order to visualize the results more easily, the computation is followed by three drawings:

- impulse of the missile
- displacements of the missile and the nodes submitted to the impact
- displacements of the center and the remarkable points

List of the input file:

```
--- IMPACT SUR DES PLAQUES CIRCULAIRES (E=6 D=90 M=257 VI=11.38)
ECHO
CAST MESH
AXIS
GEOM COQU PLAQ PMAT PROJ TERM
COMP
     EPAI   6 LECT PLAQ TERM
MATE VMIS ISOT RO 7.8E-9 YOUN 230E3 NU .3 ELAS 188
     TRAC 13  188   .0817E-2
              261   .2000E-2
              288   .3000E-2
              318   .4900E-2
              339   .7500E-2
              354  1.07E-2
              377  1.94E-2
              423  4.75E-2
              497  9.54E-2
              585 18.20E-2
              649 26.20E-2
              693 33.70E-2
              710 37.20E-2
     LECT PLAQ TERM
     MASS 40.903E-3    LECT PROJ TERM
INIT VITE 2 -11380 LECT PROJ TERM
LIAI BLOQ 123 LECT ENCAS TERM
          13 LECT CENTR TERM
      IMPACT DDL 2 COTE -1 PROJ  LECT PROJ TERM
                           CIBLE LECT LIG1 TERM
```

```
ECRI VITE CONT ECRO TFRE 1.E-3            !Output into the listing
          POIN LECT 1 TERM
          ELEM LECT 1 TERM
     FICH ALIC TFRE 1E-3                  !Output into the alice file
     FICH ALIT TFRE 1E-4 POIN LECT 11 16 21 23 25 31 32 TERM
OPTION NOTEST
CALCUL TINI 0 TEND 12.01E-3
SUIT
IMPACT SUR DES PLAQUES CIRCULAIRES (E=6 D=90 M=257 VI=11.38)
RESU ALIC GARD PSCR
SORT GRAP
AXTEMPS 1000 'TEMPS (MS)'
COURBE  1 'IMPULSION'  ECROU COMP 1 ELEM 31
     DESSIN 1  1                AXES   1. 'IMPUL. (N*S)'
COURBE  2 'D-PROJ'     DEPLA COMP 2 NOEU 32
COURBE  3 'D-CENTRE'   DEPLA COMP 2 NOEU 31
COURBE  4 'D-BORD'     DEPLA COMP 2 NOEU 25
COURBE  5 'D-60 (J1)'  DEPLA COMP 2 NOEU 23
COURBE  6 'D-80 (D1)'  DEPLA COMP 2 NOEU 21
COURBE  7 'D-120 (D2)' DEPLA COMP 2 NOEU 16
COURBE  8 'D-160 (D3)' DEPLA COMP 2 NOEU 11
     DESSIN 3  2 3 4            AXES   1. 'DEPLA (MM)'
     DESSIN 6  3 4 5 6 7 8      AXES   1. 'DEPLA (MM)'
FIN
```

19.3 EXPLOSION IN A TANK

Object:

This is a 2-D computation in A.L.E.

A cylindrical tank is filled with water. At its center a micro charge of T.N.T. explodes. the development of a gas bubble (supposed perfect),and deformations of the cylinder may be observed.

Geometry and meshing:

Only one quarter of the tank is meshed. Water and gas are modelled by quadrilaterals and the cylinder by thin shell elements. There are also elements of fluid-structure interactions.

R = 0.19 m : radius of the cylinder;

H = 0.19 m : half height;

r = 0.299 m : initial radius of the bubble.

GIBI data:

```
TITRE 'MAILLAGE MANON';
OPTION DIME 2 ELEM QUA4;
RBUL=0.029947;RAY=0.19;
CB=0 0 ; FBR=RBUL 0; FLR=RAY 0;
FBZ=0 RBUL; FLZ=0 RAY;TOP=RAY RAY;
LBR=CB D 5 FBR;LLR=FBR D 12 FLR;
LBZ=CB D 5 FBZ;LLZ=FBZ D 12 FLZ;
AUX=RBUL*(SIN 45);P45=AUX AUX;
FB1=C 5 FBR CB P45;FB2=C 5 P45 CB FBZ;
FBUL=FB1 ET FB2;
BULLE=LBR FB1 FB2 LBZ DALLER PLAN;
TOIT=FLZ D 5 TOP;
SUR =FLR D 5 TOP;
SEP =P45 D 12 TOP;
LIQ1 =LLR SUR SEP FB1 DALLER PLAN;
LIQ2 =SEP TOIT LLZ FB2 DALLER PLAN;
EAU = LIQ1 ET LIQ2;
VA=0 0;CQ1=FLR PLUS VA;CQ2=TOP PLUS VA;
COQ=CQ1 D 5 CQ2;
RAC=RACCOR 0.001 SUR COQ;
PBUL=BULLE CHANGE POI1;
PBUL=PBUL DIFF ((FBUL CHANG POI1) ET CB);
PLIQ1=LIQ1 CHANGE POI1;
PLIQ1=PLIQ1 DIFF ((FB1 ET SEP ET SUR) CHANG POI1);
PLIQ2=LIQ2 CHANGE POI1;
PLIQ2=PLIQ2 DIFF (((FB2 ET SEP) CHANG POI1) ET FLZ);
```

```
PSEP=(SEP CHANG POI1) DIFF (TOP ET P45);
ZALE=PBUL ET PLIQ1 ET PLIQ2 ET PSEP;
TOUT=BULLE ET EAU ET RAC ET COQ ET ZALE;
SORTIE TOUT;
FIN;
```

Physical properties:

Water:

rho = 1000 Kg/m3 : density;

c = 1500 m/s : velocity of sound.

Bubble:

rho = 482 Kg/m3 : density;

pini = 288 MPa : initial pressure;

gamma = 1.535 : Cp/Cv ratio.

Cylinder:

rho = 7900 Kg/m3 : density;

E = 190 GPa : Young's modulus;

nu = 0.3 : Poisson's ratio;

elas = 265 MPa : elastic limit.

Boundary conditions:

- The upper part of the tank is very rigid, therefore displacements have been embedded along z.

Computation :

The step is automatic and the computation is done during the first two milliseconds.

In order to visualize the results more easily, the computation is followed by the drawing of the time dependant displacements of the generating line of the cylinder.

List of the input file:

```
TEST MANON 11 (1/4) ( IN A.L.E. WITH CAR4 ) !titre

echo
GIBI 9 TOUT
$TRAC
AXIS ALE
DIME
   BLOQ 50 RELA 1 2 NALE 200
TERM

GEOM CAR4 BULLE EAU COQU COQ FS2D RAC TERM

COMPL
   EPAIS 1.25E-3 LECT COQ TERM
GRILLE
   LAGRANGE LECT COQ FBUL TERM
   ALE      LECT BULLE EAU TERM
$ POUR LE CONTACT "FS"
       FS     LECT RAC TERM
$ POUR L'EAU
       LIGNE BASE LECT CQ2 P45 TERM
              LIST LECT PSEP TERM
       PLAN   BASE LECT CQ1 CQ2 P45 FBR TERM
              LIST LECT PLIQ1 TERM
       PLAN   BASE LECT CQ2 FLZ FBZ P45 TERM
              LIST LECT PLIQ2 TERM
$ POUR LA BULLE
       PLAN   BASE LECT CB FBR P45 FBZ TERM
              LIST LECT PBUL TERM

MATERIAUX
   VMIS ISOT RO 7900. YOUNG 190E9 NU .3 ELAS 265E6
        TRAC 5 265E6     .00139
                352E6    .0202
                481E6    .105
                559E6    .2214
                600E6    .349
        LECT COQ TERM
   FLUI RO 1000. C 1500. PINI 1E5 PREF 1E5 PMIN 0
        LECT EAU TERM
    GAZP RO 482. GAMMA 1.535 PINI 2.88E8 PREF 1E5
         LECT BULLE TERM
LINK RENUM
    BLOQ   1 LECT LBZ LLZ CQ2 TERM
           2 LECT TOIT LBR LLR TERM
          23 LECT CQ1 CQ2 TERM
ECRITURE
  TFREQ .25E-3     TRACE ALICE 10 TFREQ .5E-4
OPTION AUTO
        NOTEST
CALCUL tini 0  nmax  1000 tfin 1.005E-3
```

```
SUITE
TEST MANON 11 (1/4) ( EN A.L.E. AVEC CAR4 )
RESULT 10
TEMPS 100 COURBE 5 TERM
SORTIE GRAPHIQUE
AXTEMPS 1E3 'T (MILLISEC.)'
COURBE 1 'DR-00 '       DEPLA COMP 1 NOEUD 5
COURBE 2 'DR-38 '       DEPLA COMP 1 NOEUD 6
COURBE 3 'DR-76 '       DEPLA COMP 1 NOEUD 4
COURBE 4 'DR-114 '       DEPLA COMP 1 NOEUD 3
COURBE 5 'DR-152 '       DEPLA COMP 1 NOEUD 2
DESSIN 5       1 2 3 4 5    AXES 1000 'DR-COQUE (MM)'
FIN
```

19.4 MODELLING OF PERFORATED PLATES

Object:

This is a 2-D computation in A.L.E.

A plane wave is propagating in a cylindrical tube. It meets a perforated plate that generates partial reflections and head losses. The walls of the cylinder are supposed rigid and the plate flexible.

Geometry and meshing:

Only the fluid in the tube is meshed. Elements with absorbant boundary conditions shall avoid reflected waves. At one end, a range of CL2D elements enables pressure source to be input in the form of a slope. These elements are superimposed to the absorbant elements.

The clamped plate is meshed with shell elements. The fluid is meshed in a continuous way to make it pass through the plate. The connecting elements of the fluid-structure junction ensure the coupling between the plate and the neighbouring nodes of the fluid. Another range of CL2D elements enables the characteristics of the grid to be input for the computation of the head losses.

R = 500 mm : radius of the cylinder;

H = 1000 mm : half height.

GIBI data:

```
TITRE 'MAILLAGE D'UNE PLAQUE PERFOREES';
OPTI DIME 2 ELEM QUA4 NIVEAU 1;
PA=0 0    ; PB=500 0   ; PC=500 2000 ; PD=0 2000;
PE=0 1000 ; PF=500 1000;
ENT=PA D 5 PB ; SOR=PC D 5 PD ;
GRI=PF D 5 PE ; ENT2=ENT ;
LBF=PB D 10 PF ; LFC=PF D 10 PC ;
LDE=PD D 10 PE ; LEA=PE D 10 PA ;
LIQ1=ENT LBF GRI LEA DALLER PLAN ;
LIQ2=(INVE GRI) LFC SOR LDE DALLER PLAN ;
LIQ=LIQ1 ET LIQ2 ;
PCE=0 1000 ; PCF=500 1000 ;
COQ=PCF D 5 PCE;
FSE=RACC 0.00001 LIQ1 COQ ;
PLIQ=LIQ CHAN POI1;
PLIQ=PLIQ DIFF (GRI CHAN POI1);
AXE=LDE ET LEA ET PCE ;
BOR=LBF ET LFC ET PCF ;
LIQ=LIQ COUL BLEU;COQ=COQ COUL ROUG;
FSE=FSE COUL TURQ;ENT2=ENT2 COUL VERT;
```

```
TOUT=LIQ ET COQ ET FSE ET PLIQ ET AXE ET BOR ET ENT2;
SORT TOUT;
fin;
```

Physical properties:

Fluid:

rho = 1000 Kg/m3 : density

c = 1000 m/s : velocity of sound

Plate:

rho = 7800 Kg/m3 : density

E = 190 GPa : Young's modulus

nu = 0.3 : Poisson's ratio

Computation:

The step is automatic and the computation is carried out for the first 6 milliseconds.

In order to visualize the results more easily, the computation is followed by two drawings. The first one describes the evolution of the pressures upstream and downstream, and the second describes the displacement of the center of the plate

List of the input file:

```
PLAQUE PERFOREE SOUPLE (EULER) ALP=1 TAU=0 E=15
ECHO
GIBI 9 TOUT
AXIS EULER
DIMENSION
     BLOQ 60 NALE 100
     TERM
GEOM CAR1 LIQ CL2D ENT SOR GRI ENT2 COQU COQ FS2D FSE TERM
GRIL LAGR LECT COQ TERM
     ALE  LECT LIQ TERM
     FS   LECT FSE TERM
COMPLEMENT EPAIS 15 LECT COQ TERM
MATE LINE RO 7.8E-9 YOUNG 190E3 NU 0.3
          LECT COQ TERM
     FLUI RO 1E-9 C 1E6
          LECT LIQ  TERM
     IMPE PIMP RO 1E-9  PRES -0.02
          TABP 3  0 0    0.002  1     1 1
```

```
          LECT ENT  TERM
     IMPE ABSO RO 1E-9 C 1E6
          LECT SOR ENT2 TERM
     IMPE GRIL RO 1E-9 C 1E6 ALP 1 TAU 0
          LECT GRI  TERM
LIAI RENUM
     BLOQ 1   LECT AXE  TERM
          1   LECT BOR  TERM
          2   LECT PCF  TERM
          3   LECT PCE PCF TERM
     FS LECT FSE TERM
IMPR FREQ 500
     TRAC ALIC 10  10
OPTI PAS AUTO
     NOTEST
CALCUL 0. 1E-5   1E-4   500   6E-3
SUITE
PLAQUE PERFOREE SOUPLE (EULER) ALP=1 TAU=0 E=15
RESULT 10
TEMPS 60 COURBE 7 TERM
SORTIE GRAPHIQUE
AXTEMPS 1E3 'T (MILLISEC.)'
COURBE  1 'P-3    '   ECROU COMP 1 ELEM  3
COURBE  2 'P-28   '   ECROU COMP 1 ELEM  28
COURBE  3 'P-48   '   ECROU COMP 1 ELEM  48
COURBE  4 'P-53   '   ECROU COMP 1 ELEM  53
COURBE  5 'P-73   '   ECROU COMP 1 ELEM  73
COURBE  6 'P-98   '   ECROU COMP 1 ELEM  98
COURBE  7 'DZ-64  '   DEPLA COMP 2 NOEU  64
DESSIN 6  1 2 3 4 5 6     AXES 10   'PRES. (BARS)'
DESSIN 1  7               AXES 1.   'DEPLA. (MM)'
FIN
```

20 DEVELOPMENT NOTES

20.1 PROGRAMMING GUIDELINES

The present document (User's Manual) deals primarily with a detailed description of all the input commands of the EUROPLEXUS code, in the order in which they appear in a typical input file. It is meant to be an exhaustive *reference* for Users of the code, but it is *not a tutorial*.

Some short indications are given in this Section, which might be useful to EUROPLEXUS code *developers* (i.e. to *programmers*), in the form of simple programming guidelines. Developers are assumed to have access to the EUROPLEXUS Consortium web site, which contains among other things all the available technical documentation.

Only an overview is presented here for brevity. Reference is made to several reports and other documents, listed in the bibliography and available on-line on the Consortium web site, which contain all the details.

20.1.1 Programming Language

EUROPLEXUS is entirely written in the Fortran language. For historical reasons some parts of the code (the oldest ones) are still coded in Fortran 77 (F77). All new developments from 1999 onwards use the Fortran 90 (F90) language, mainly based upon F90 Modules.

A great effort of converting F77 parts to F90 is being performed, but the process is not yet complete. An example of successful conversion is the materials data structure, which has been completely ported to F90.

20.1.2 F77 Programming

An introduction to F77 programming style in EUROPLEXUS is given in reference [150].

20.1.3 F90 Programming

An introduction to F90 programming style and some tentative guidelines for the development of EUROPLEXUS are given in reference [175].

20.1.4 Code Profiling

A code profiler is **not** readily available under Windows. A simple mechanism is set up to profile selected parts of the code (in a platform-independent way) by using the standard system routine `CPU_TIME`, which returns the job's CPU time in seconds.

This profiling cannot be totally automatic as e.g. under Linux, but it is is set up in such a way:

- to have **virtually no impact** on the code standard version, i.e. when no profiling is activated.
- to require only a **very small** intervention on routines (or any code parts) to be profiled.

The mechanism is very simple. Assume we want to profile a routine `SUB1`. Then the following standard code is inserted at the beginning of the routine (before the first executable statement) and at the end of the routine (before the `RETURN` or the `END SUBROUTINE`):

```
SUBROUTINE SUB1
...
USE M_PROFILE
...

 ... routine body (executable statements)

END SUBROUTINE SUB1
```

Note that the two code portions to be inserted can be just copied (e.g. from `LOOPELM.FF`) and pasted as such. Only the name of the subroutine (`SUB1`) in the `CALL GET_PROFILE_INDEX` has to be changed.

To activate profiling of the routine, compile it with the `PROFILE` keyword activated for filtering. Under Windows the command is:

```
epx_cmp -o -k PROFILE
```

Then link normally and run the code normally. At the end of the listing the profile table is printed, reporting the CPU time spent in each profiled portion of the code (both in absolute terms and in % of total CPU time), and the number of calls of each profiled routine.

in the routines, since they have no impact on normal code efficiency thanks to the standard EUROPLEXUS filtering mechanism.

Obviously, this type of profiling is not only limited to entire subroutines. The same mechanism can also be used to profile other code parts, e.g. a suspect DO loop. The name passed to `GET_PROFILE_INDEX` can be freely chosen by the user, it is not necessarily a subroutine name (maximum length is 32 characters, including any inter-word blanks).

Profiling instructions (filtered) will be gradually inserted in at least the most important routines of the code (CELEM, LOOPELM etc.) so that first-attempt profiling can become as simple es the following commands (under Windows):

```
epx_modtree M_PROFILE    (search routines already containing M_PROFILE)
epx_get_users            (copy all such routines in current directory)
<possibly add some other routines for profiling>
epx_cmp -o -k PROFILE    (compile all local routines for profiling)
epx_lk -o                (link to produce a local executable epx.exe)
epx_bench -e epx.exe ... (run tests and obtain profile)
```

Based on the results of this first-level profiling, other routines can then be added to the list for a refinement of profiling results.

The implementation uses a very small module `M_PROFILE` containing some very small **static** tables (no allocation / dealloction), with space for up to `NPROFMAX` (currently 100) routines to be profiled.

A permanent (unfiltered) profiling based upon the above mechanism has been added in the time loop routines: `CALCUL` for the normal case or `TLOOPP` for the case with spatial partitioning. Thus, by default the following main "blocks" of code are profiled:

- VFCC (cell-centred Finite Volumes)
- Finite Elements
- External Forces
- Coupled links (LINK COUP)

- Coupled links by the old “liaison” implementation (LINK LIAI)
- Decoupled links (LINK DECO)
- Outputs

This should give a first-level (and fully automatic) overview of where in the code the majority of CPU time is spent, for a given application. Then, refinement of the profiling can be performed if necessary by the technique explained above on the affected code portion.

20.2 PRECOMPILER KEYWORDS

Several precompiler keywords are used before the compilation, shown in the table below. Concerning the versions, 'X' indicates that it is used, '(X)' means that it is used in some cases and '-' that it is never used.

Keyword	Description	Versions	
		Win Ispra	L64 CEA
CADNA	Version CADNA	-	(X)
CHECK_DATA	SALOME: check only syntax validity of epx file	-	-
CYGWIN	Windows version with CYGWIN	-	-
ER_LIGHT_VERSION	Filtering for the research light version	-	(X)
ER_VERSION	Filtering for the research version	-	(X)
EPX2XML	Version EPX2ML DATA for Salome	-	(X)
FRANCAIS	Output: French version, otherwise English version	-	X
GFORTRAN	GFORTRAN Compiler	-	(X)
KAAPI	Need library KAAPI	-	X
MED	Need library MED	-	X
MFFT	Need library MFFT	X	X
MFRONT	Need library MFRONT	-	(X)
MKL	Need library MKL (MKL is part of the Intel compiler)	X	X
MPI	Version MPI	(X)	X
NCOCO	Need library NCOCO	X	(X)
OGL	OpenGL (Windows)	X	-
ONLYF90	Fortran 90 pur, no extension Fortran 2000, 2003, etc....	-	X
PETSC	Use of PETSc (EDF)	-	(X)
PROD_VERSION	Filtering for the production version	-	(X)
PROFILE	Performance profile calculation	-	-
QWIN	Quick Win	-	-
SOFA	Need library SOFA	-	-
T_LINUX	Version OGL for Linux	-	(X)
UNIX32	Not windows version	-	X
W32	Windows 32 bit	(X)	-
W64	Windows 64 bit	X	-
WIN	Windows (32 and 64 bit)	X	-
XLF	XLF (IBM/AIX) compiler	-	X

Keywords for the manual

Keyword	Description	Versions	
		HTML	PDF
FIGURES	Including the figues	X	X
HEVEA	HAVEA version	X	-
LATEX1	?		
PDFLATEX	PDFLATEX version	-	X
SALOME	Special treatment for SALOME menus	-	-
TTH	TTH	Z	-

20.3 MANUAL CREATION

This documentation is produced starting from a LaTeX source file that is continuously updated and maintained. A formatted version of the manual, such as the present one, can be obtained for on-line consulting either via PDF or via HTML.

A table of contents and an index can be found at the beginning and at the end of this documentation, respectively, and may help to rapidly retrieve information.

20.3.1 PAGE NUMBERING CONVENTIONS

Each page of the present manual contains information in both an header (at the page top) and a footer (at the page bottom).

The header contains in its middle part a 'page identification' used to identify each page or sequence of pages dealing with a specific topic. This is composed by a letter or group of letters, indicating a 'section' of the manual, and a number. The same information is also repeated in the left part of the footer. The number is not the actual page number (this is given in the right part of the footer, instead), since this is subject to frequent changes as text is added or reformatting is performed. Cross references in the text are generally done by referring to the page identification.

The numbers appearing in the page identification are not incremented by 1, but have larger increments (usually 10) in order to leave space for future pages.

The page header contains in its right part a date indicating when a certain page has been inserted or modified in the manual.

The date in the centre of the footer corresponds to the manual edition date.

20.4 ACKNOWLEDGEMENTS, LICENSES

Several libraries are used in the EUROPLEXUS code.

20.4.1 lib_vtk_io

This library is used to write the vtk-files that are used in order to allow an output for ParaView. The library is written by Stefano Zaghi and can be find here:
https://github.com/szaghi/Lib_VTK_IO.

20.4.2 Blas, Lapack

The packages can be obtained from http://www.netlib.org/blas and http://www.netlib.org/lapack.

20.4.3 OpenMPI

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20.4.4 Glut

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20.4.5 f90gl, f90glu, f90glut

The package can be taken from here http://math.nist.gov/f90gl/.

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21 BIBLIOGRAPHY

This section provides a list of the bibliography related to EUROPLEXUS (from December 1999 on) and its ancestors: PLEXIS-3C (including its own ancestors, the codes of the EURDYN series), and CASTEM-PLEXUS.

The section is subdivided into six sub-sections:

- Some selected references of the EURDYN series of codes,
- References pertaining to PLEXIS-3C and EUROPLEXUS development performed at JRC,
- References pertaining to CASTEM-PLEXUS and EUROPLEXUS developments performed at CEA,
- References pertaining to PLEXUS and EUROPLEXUS developments performed at Samtech.
- References pertaining to CASTEM-PLEXUS and EUROPLEXUS developments performed at EDF,
- References pertaining to EUROPLEXUS developments performed at ONERA.

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It is also recalled that an updated on-line version of the EUROPLEXUS User manual is available on the Internet and may be consulted interactively from a workstation or terminal.

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22 Keywords Index

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