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Proceedings of a Course on

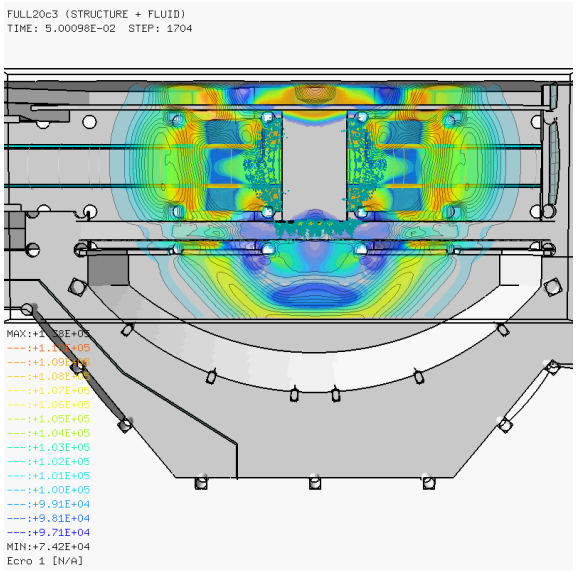
Numerical Simulation of Fast Transient Dynamic Phenomena in Fluid-Structure Systems

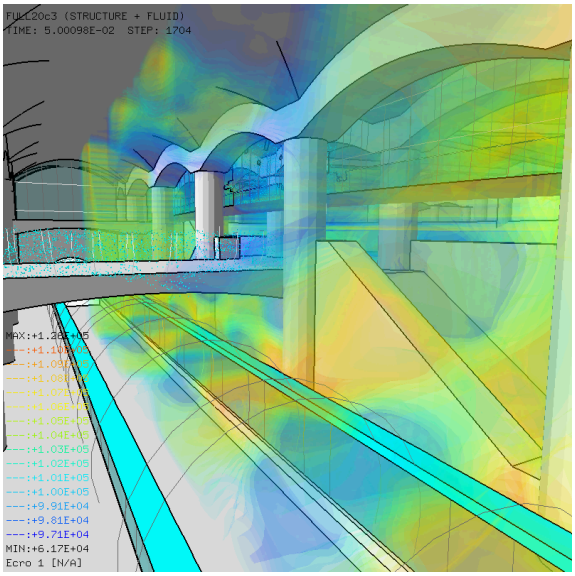
Presentation slides and traces of proposed exercises / examples

Course given at Universitat Politècnica de Catalunya, Barcelona, April 15–19, 2013

Folco Casadei
George Solomos
Georgios Valsamos

2013





Joint Research Centre

European Commission
Joint Research Centre
Institute for the Protection and Security of the Citizen

Contact information
George Solomos
Address: Joint Research Centre, Via Enrico Fermi 2749, TP 480, 21027 Ispra (VA), Italy
E-mail: george.solomos@jrc.ec.europa.eu
Tel.: +39 0332 78 9916
Fax: +39 0332 78 9049

http://ipsc.jrc.ec.europa.eu/
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Proceedings of a Course on:

Numerical Simulation of Fast Transient Dynamic Phenomena in Fluid-Structure Systems

(Presentation slides and trace of proposed exercises/examples)

A Short Course given by:

F. Casadei

at

Universitat Politècnica de Catalunya, Barcelona, April 15–19, 2013

The present document contains the presentation slides and the traces of proposed exercises/examples related to the Course: Numerical Simulation of Fast Transient Dynamic Phenomena in Fluid-Structure Systems, given by F. Casadei at the Universitat Politècnica de Catalunya, Barcelona, April 15–19, 2013.

This is the tenth, completely revised edition of the document:

"Proceedings of a Course on: Numerical Simulation of Fast Transient Dynamic Phenomena in Fluid-Structure Systems, Presentation Slides and Trace of Proposed Exercises/Examples"

(1st Edition): JRC — Ispra, 11-15 April 2005", JRC Special Publication N. S.P.I.05.93, 2005.

(2nd Edition): Universitat Politècnica de Catalunya, Barcelona, May 17-20, 2005, JRC Special Publication N. I.05.139, June 2005.

(3rd Edition): Universitat Politècnica de Catalunya, Barcelona, May 15-18, 2006, and Royal Military Academy, Brussels, June 26-30, 2006, JRC Special Publication N. PB/2006/IPSC/1956, June 2006.

(4th Edition): Universitat Politècnica de Catalunya, Barcelona, May 14-17, 2007, PUBSY No. 007357, June 2007.

(5th Edition): Universitat Politècnica de Catalunya, Barcelona, May 19-23, 2008, PUBSY No. JRC45967, June 2008.

(6th Edition): Universitat Politècnica de Catalunya, Barcelona, May 11-15, 2009, PUBSY No. JRC52299, June 2009.

(7th Edition): Universitat Politècnica de Catalunya, Barcelona, May 31 – June 4, 2010, PUBSY No. JRC59017, June 2010.

(8th Edition): Universitat Politècnica de Catalunya, Barcelona, May 9 – 13, 2011, PUBSY No. JRC65139, June 2011.

(9th Edition): Universitat Politècnica de Catalunya, Barcelona, May 9 – 13, 2011, PUBSY No. JRC71459, June 2012.

Numerous corrections and ameliorations have been carried out in the presentation slides and a number of new proposed practical exercises and examples have been added.

Universitat Politècnica de Catalunya, Barcelona, 15–19 April 2013

Numerical Simulation of Fast Transient Dynamic Phenomena in Fluid-Structure Systems

A Short Course by F. Casadei

The objective of the Course is to provide participants with a good understanding of state-of-the-art techniques for the numerical simulation of fast transient dynamic phenomena, which occur in many safety-related applications.

These are typically explosions, crashes, impacts etc., both due to natural phenomena and to malicious actions such as terrorist attacks.

The Course covers in some depth structural aspects, since the primary focus is on structural behavior and collapse simulation. The modeling of fluids via an ALE formulation and the coupling between the two domains (Fluid-Structure Interaction) are also considered, as they play an important role in these analyses.

An important part of the Course are the practical exercises. These are mainly hands-on interactive computer sessions, in which the participants use the EUROPLEXUS code (developed jointly by JRC and CEA) to solve both some academic problems, in order to consolidate the theoretical knowledge, and some typical medium-sized applications.

Final Programme:

Date/Time	Topics
Monday April 15, (10:00–12:00) Room B1-005	**1. Introduction (Solids)** a. Introductory example of a FSI problem i. Application spectrum and goals b. Modeling the structural domain i. Equilibrium equations ii. Explicit time integration scheme c. Treatment of essential boundary conditions i. The Lagrange multipliers method ii. Solving the linear system
Afternoon (14:00–16:00)	• Practical exercises (Room D1-101)
Tuesday April 16, (10:00–12:00) Room B1-005	**2. ALE formulation (Fluids)** a. Modeling the fluid domain i. Euler equations ii. Finite Element discretization iii. Finite Volume discretization (N-C, C-C) b. Mesh rezoning algorithms i. Motivation ii. Mean-based algorithms iii. Giuliani's algorithm c. Free surface modeling
Afternoon (14:00–16:00)	• Practical exercises (Room D1-101)

Wednesday April 17, (10:00–12:00) Room B1-005	**3. Classical Fluid-Structure Interaction** a. Motivation b. A classification of FSI algorithms c. Geometrical methods i. The FSA/FSR method d. Equilibrium-based methods i. The Uniform Pressure (UP) method e. A combined method i. The FSCR method f. Application to Finite Volumes i. Weak FSI for NCFV ii. Weak FSI for CCFV (conforming) g. Non-conforming FSI i. For FE / NCFV (strong approach) ii. For CCFV (weak approach) h. Some special FSI techniques/applications i. Modeling of perforated structures ii. Sloshing problems
Afternoon (14:00–16:00)	• Practical exercises (Room D1-101)
Thursday April 18, (10:00–12:00) Room B1-005	**4. Advanced FSI (with Failure/Fragmentation)** a. Structural failure and element erosion b. Fragmentation and flying debris i. Modeling of glass c. Treatment of failure with CCFV (conforming, weak FSI) d. Embedded FSI models i. The FLSR method (strong approach) ii. The FLSW method (weak approach) e. Advanced FSI example: structural vulnerability i. Scenarios ii. Geometry reconstruction iii. Simplified building vulnerability study iv. Accounting for dead (static) weight v. Modeling the explosive charge (AIRB, BUBB, JWLS) vi. Risk evaluation vii. Case studies. 1: Railway Station; 2: Metro Station; 3: Metro Carriage viii. Complete Metro / Railway Station Simulation
Afternoon (14:00–16:00)	• Practical exercises (Room D1-101)
Friday April 19, (10:00–12:00) Room B1-005	**5. Further topics and applications** a. ALE description of structures b. Lagrangian contact i. Classical methods ii. Pinballs iii. SPH (for fluid-like materials) c. Meshless methods i. SPH for structures ii. DEM d. Spectral elements e. Spatial time step partitioning f. Domain decomposition g. Mesh adaptivity i. Application to solids ii. Application to fluids iii. FSI
Afternoon (14:00–16:00)	• Explanation of Questionnaires (Room D1-101)

Universitat Politècnica de Catalunya, Barcelona, 15 – 19 April 2013

Numerical Simulation of Fast Transient Phenomena in Fluid-Structure Systems

A Short Course by F. Casadei
Retired from European Commission, Joint Research Centre
Institute for the Protection and Security of the Citizen
T.P. 480, I-21027 Ispra (VA), Italy.
E-mail: casadeifolco@gmail.com

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The Joint Research Centre **(JRC)**

7 Institutes in 5 Member States:



IRMM – Geel, Belgium
- Institute for Reference Materials and Measurements



IE – Petten, The Netherlands
- Institute for Energy



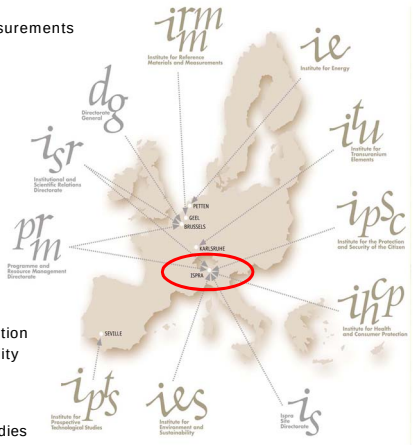
ITU – Karlsruhe, Germany
- Institute for Transuranium elements



IPSC - IHCP - IES – Ispra, Italy
- **Institute for the Protection and Security of the Citizen**
- Institute for Health and Consumer Protection
- Institute for Environment and Sustainability



IPTS – Seville, Spain
- Institute for Prospective Technological Studies



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The European Laboratory for Structural Assessment **(ELSA)**





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ELSA Facilities:



Reaction Wall ("**Slow**" Dynamics)

Large Hopkinson Bar ("**Fast**" Dynamics)



“Slow” dynamics: earthquake …



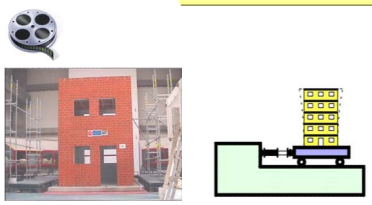
Kobe (Japan) earthquake. January 17, 1995 (6,300 fatalities)

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Earthquake testing of structures:

two complementary methods

Shaking Table



- Dynamic test (real time)
- Small-scale models

Reaction Wall



- Pseudo-dynamic test (expanded time scale)
- Full-scale models

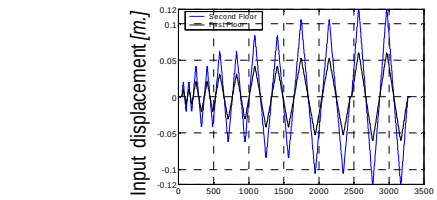
(ELSA)

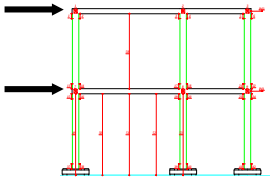
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Imposed motion

Shaking Table
Base motion

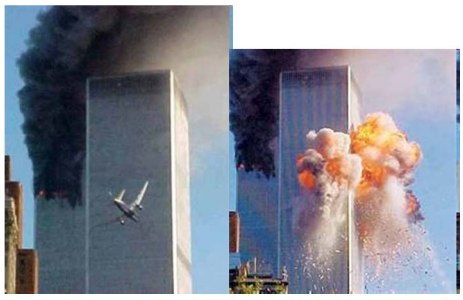
Reaction Wall
Floors motion





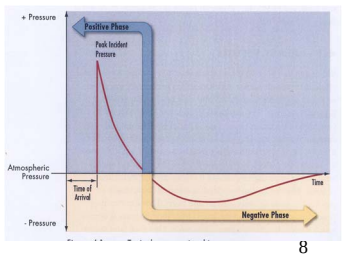
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"Fast" dynamics: impact, explosion …



Twin towers. September 11, 2001
(2,967 fatalities)





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Progressive Collapse: a “slow” phenomenon often initiated by a “fast” transient



Twin towers.

Structure collapse



Murrah Building, Oklahoma City. April 19, 1995 (168 fatalities)



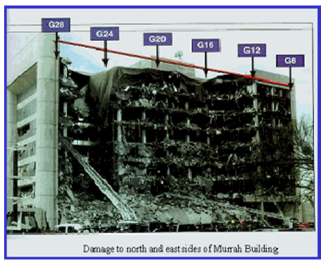
Aladdin Hotel, Las Vegas. April 27, 1998 (controlled demolition)

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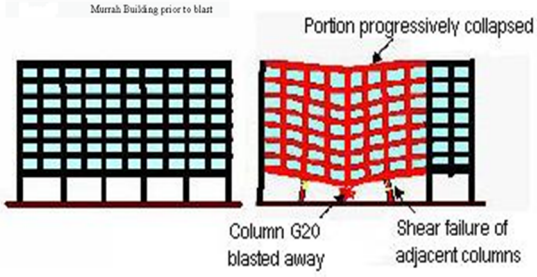
Example of Progressive Collapse due to terrorist attack



Murrah Building prior to blast

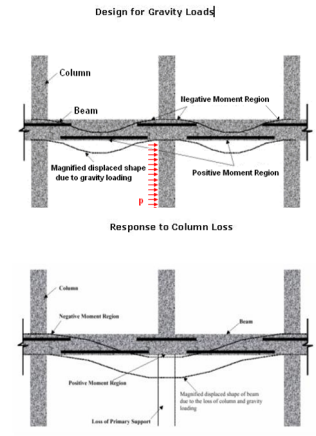


Damage to north and east sides of Murrah Building



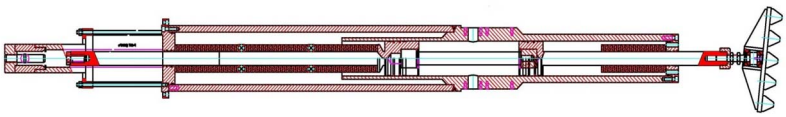
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Blast Simulator (Under construction)





(Courtesy of San Diego University)



Actuator prototype design (JRC)

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Contents

- I – Introduction (Structures)
- II – ALE formulation (Fluids)
- III – Classical Fluid-Structure Interaction
- IV – Advanced FSI (Failure/Fragmentation)
- V – Further topics and applications

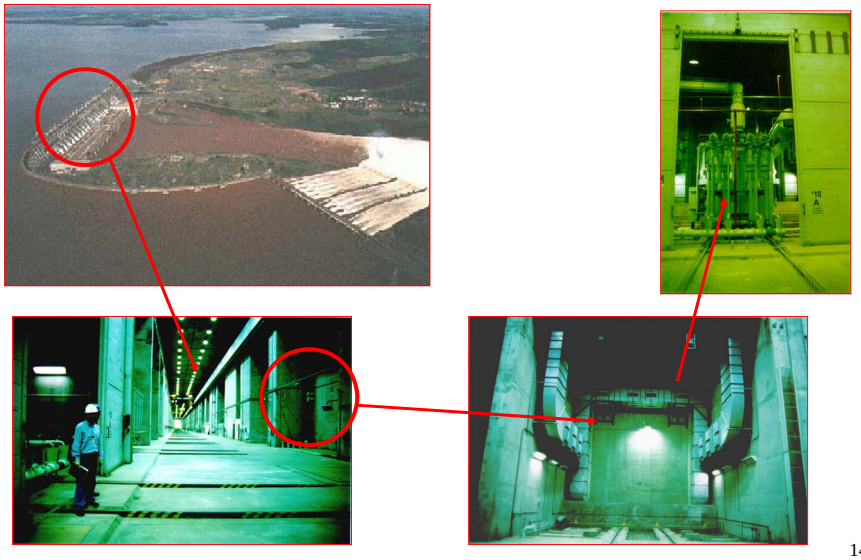
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Credits & Acknowledgments

- Structural Dynamics team at JRC Ispra (70's – to date):
  - J. Donea, J.P. Halleux, S. Giuliani, F. Casadei, M. Larcher, G. Solomos, G. Giannopoulos, G. Valsamos, N. Leconte …
- Structural Dynamics team at CEA Saclay (70's – to date):
  - H. Bung, P. Galon, M. Lepareux, V. Faucher, A. Beccantini …
- Contributions from research/academic bodies and industry:
  - UPC (A. Huerta, P. Diez, F. Verdugo), Cachan, CRS4, Lyon, …
  - EDF, Onera, ENEL, Snecma, SamTech …
- Three decades of code develompent:
  - EURDYN, Castem-PLEXUS / PLEXIS-3C, EUROPLEXUS …
  - Commercial / Academic versions now available from CEA

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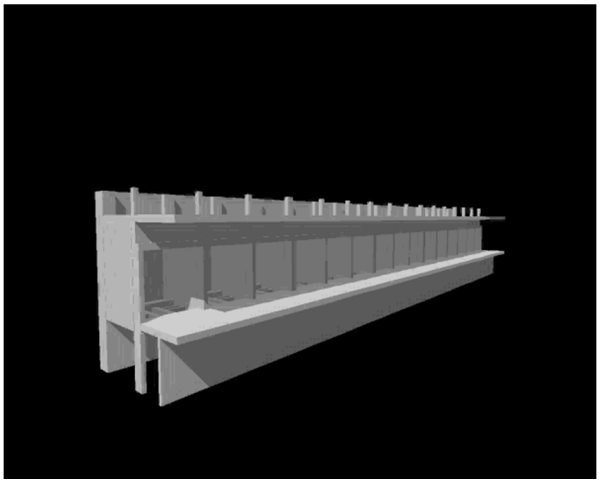
Introductory Example (Courtesy of ENEL-Hydro)



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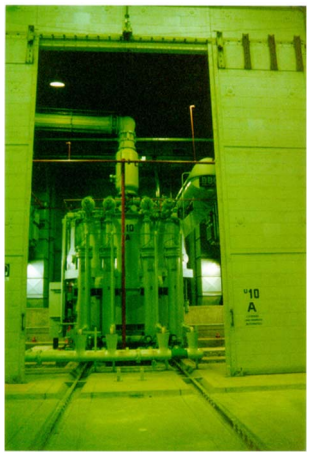
Introductory Example (2)

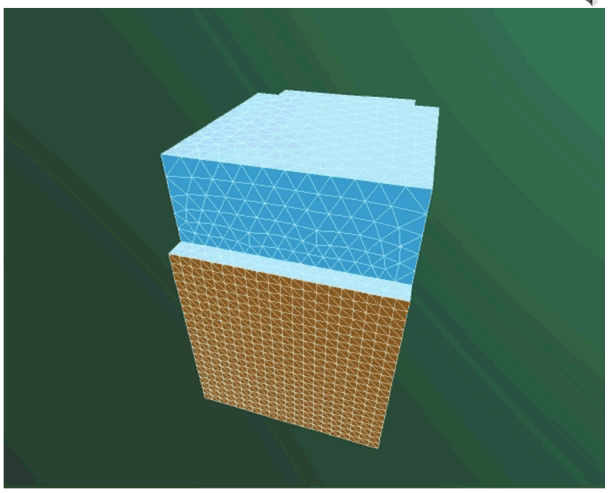




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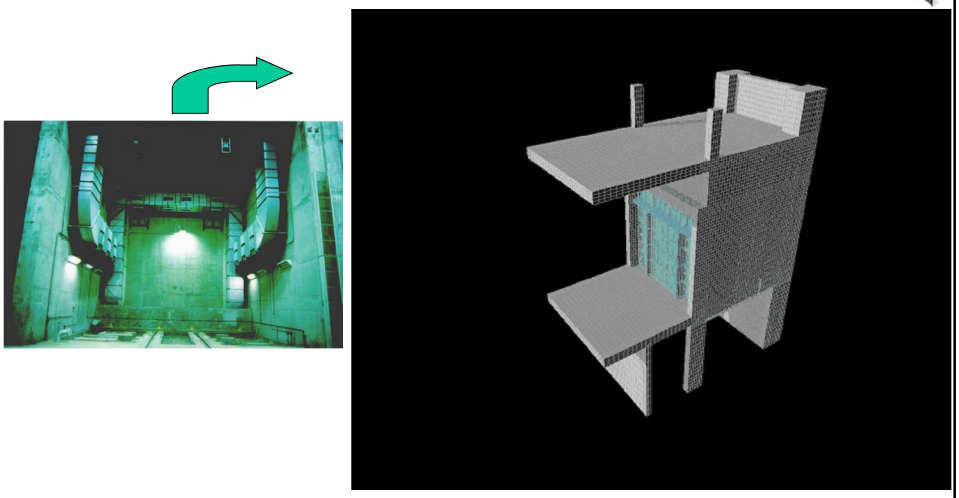
Introductory Example (3)





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Introductory Example (4)



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Application Spectrum

- Energy (safety issues): nuclear and fossil-fueled plants, electrical devices, chemical plants, pressure vessels, …
- Civil engineering: earthquakes, soil-structure interactions, building vulnerability to terrorist attacks …
- Marine/Offshore: ships and submarines, oil industry, pipelines, cables …
- Transportation: crash, road barriers, tunnels safety, trains/ metro stations and rolling stock…
- etc…

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Goals/Characteristics

- Simulate fast transient dynamic phenomena: explosions, crashes, impacts …
- Short time scale: (typically *ms* to a few *s*) with large frequencies spectrum
- Geometric and material non-linearities: large motions, large strains, plasticity, visco-plasticity, damage …
- Structures and fluids: heterogeneity, interaction phenomena, …
- For reliable solutions, simple and robust numerical methods are needed: direct time integration, explicit schemes …

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Detailed Contents of Part I

- Introductory example of FSI problem
  - ✓ Application spectrum and goals
- Modeling the structural domain
  - ✓ Equilibrium equations
  - ✓ Explicit time integration scheme
- Treatment of essential boundary conditions
  - ✓ The Lagrange multipliers method
  - ✓ Solving the linear system

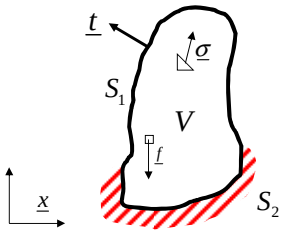
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Computational Framework

- Governing equation for structural domain: principle of virtual work (conservation of momentum, i.e. equilibrium in a dynamic sense)

$$\int_V \rho \ddot{\underline{x}} \delta \underline{x} dV + \int_V \underline{\sigma} D(\delta \underline{x}) dV - \int_V \rho \underline{f} \delta \underline{x} dV - \int_{S_1} \underline{t} \delta \underline{x} dS = 0$$

ρ mass density
V current domain
$\underline{x}$ current configuration
$\ddot{\underline{x}}$ accelerations



$\underline{\sigma}$ Cauchy stress
$D()$ spatial derivative operator
$\underline{f}$ volumetric forces per unit mass
$\underline{t}$ boundary surface tractions

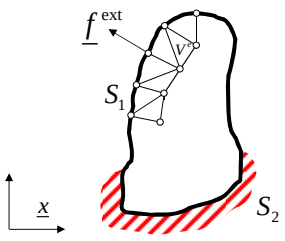
Must hold for all variations $\delta \underline{x}$ of configuration (virtual displacements) compatible with essential b.c.s on S_2 .

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Computational Framework (2)

- This integral form lends itself to direct application of F.E. method. Upon spatial discretization:

$$\underline{M}\ddot{\underline{u}} = \underline{f}^{\text{ext}} - \sum_e \int_{V^e} \underline{B}^T \underline{\sigma} dV$$



$\underline{M}$ Mass matrix
$\underline{u}$ nodal displacement vector
$\underline{f}^{\text{ext}}$ discrete external forces
$\sum_e$ standard F.E. assembly operator
V^e element (e) current volume
$\underline{B}$ matrix of shape functions derivatives

This set of discrete differential equations in time is decoupled by diagonalization (lumping) of mass matrix $\underline{M}$

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$$\underline{M}\ddot{\underline{u}} = \underline{f}^{\text{ext}} - \sum_e \int_{V^e} \underline{B}^T \underline{\sigma} dV$$

Computational Framework (3)

- Description is Lagrangian: nodes and G.P.s remain always associated with same material point (particle)
- Stress is "true": expressed in fixed reference (but corotational formulation can be useful for beams/plates/shells)
- All RHS terms are known ($\underline{f}^{\text{ext}}, \underline{B}$) or computable: stresses must be obtained via material constitutive law
- Diagonalization of $\underline{M}$ by lumping: $\underline{M}^e = \int_{V^e} \underline{N} \rho dV$ where $\underline{N}$ are the element shape functions
- We work on current configuration: no need to define a reference configuration and no use of (total) deformation

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$$\underline{M}\ddot{\underline{u}} = \underline{f}^{\text{ext}} - \sum_e \int_{V^e} \underline{B}^T \underline{\sigma} dV$$

Direct Time Integration

- Time integration is achieved via the Central Difference scheme, usually written as:

$$\dot{\underline{u}}^{n+1} = \dot{\underline{u}}^n + \frac{\Delta t}{2}(\ddot{\underline{u}}^n + \ddot{\underline{u}}^{n+1})$$

$$\underline{u}^{n+1} = \underline{u}^n + \Delta t(\dot{\underline{u}}^n + \frac{\Delta t}{2}\ddot{\underline{u}}^n)$$

n stays for time t^n

$n+1$ stays for $t^{n+1} = t^n + \Delta t$

Δt is the time increment

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$$\dot{\underline{u}}^{n+1} = \dot{\underline{u}}^{n} + \frac{\Delta t}{2}(\ddot{\underline{u}}^{n} + \ddot{\underline{u}}^{n+1})$$
$$\underline{u}^{n+1} = \underline{u}^{n} + \Delta t(\dot{\underline{u}}^{n} + \frac{\Delta t}{2}\ddot{\underline{u}}^{n})$$

Direct Time Integration (2)

- These formulas are a particularization of the well-known Newmark integration formulas:

$$\dot{\underline{u}}^{n+1} = \dot{\underline{u}}^{n} + \Delta t[(1-\gamma)\ddot{\underline{u}}^{n} + \gamma\ddot{\underline{u}}^{n+1}]$$

$$\underline{u}^{n+1} = \underline{u}^{n} + \Delta t\dot{\underline{u}}^{n} + \frac{\Delta t^2}{2}[(1-2\beta)\ddot{\underline{u}}^{n} + 2\beta\ddot{\underline{u}}^{n+1}]$$

  written for $\boxed{\gamma = 1/2}$ and $\boxed{\beta = 0}$.

$$\underline{M}\ddot{\underline{u}} = \underline{f}^{\text{ext}} - \underline{f}^{\text{int}}$$

- These two equations, plus the equilibrium, can be solved for $\underline{u}$, $\dot{\underline{u}}$, $\ddot{\underline{u}}$ upon step-by-step marching in time.
- This particular choice for β renders the scheme explicit, while the chosen γ ensures no numerical damping.

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$$\dot{\underline{u}}^{n+1} = \dot{\underline{u}}^{n} + \frac{\Delta t}{2}(\ddot{\underline{u}}^{n} + \ddot{\underline{u}}^{n+1})$$
$$\underline{u}^{n+1} = \underline{u}^{n} + \Delta t(\dot{\underline{u}}^{n} + \frac{\Delta t}{2}\ddot{\underline{u}}^{n})$$

Direct Time Integration (3)

How is the scheme used in practice?

- Introduce a mid-step velocity:

$$\underline{v}^{n+1/2} \doteq \dot{\underline{u}}^{n} + \frac{\Delta t}{2}\ddot{\underline{u}}^{n}$$

  which transforms configuration *n* into *n+1* over the step.
- The second equation becomes:

$$\underline{u}^{n+1} = \underline{u}^{n} + \Delta t \cdot \underline{v}^{n+1/2}$$

- Carry on mid-step velocities rather than full-step ones. The first equation becomes:

$$\underline{v}^{n+3/2} = \underline{v}^{n+1/2} + \Delta t \cdot \ddot{\underline{u}}^{n+1}$$

$$\underline{v}^{n+3/2} \doteq \dot{\underline{u}}^{n+1} + \frac{\Delta t}{2}\ddot{\underline{u}}^{n+1} = \dot{\underline{u}}^{n} + \frac{\Delta t}{2}\ddot{\underline{u}}^{n} + \frac{\Delta t}{2}\ddot{\underline{u}}^{n+1} + \frac{\Delta t}{2}\ddot{\underline{u}}^{n+1} = \underline{v}^{n+1/2} + \Delta t \cdot \ddot{\underline{u}}^{n+1}$$

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Direct Time Integration (4)

- The final algorithm reads:

$$\underline{u}^{n+1} = \underline{u}^{n} + \Delta t \cdot \underline{v}^{n+1/2}$$

$$\underline{\ddot{u}}^{n+1} = \underline{M}^{-1}(\underline{f}^{\text{ext}(n+1)} - \sum_e \int_{V^{e(n+1)}} \underline{B}^T \underline{\sigma}^{e(n+1)} dV)$$

$$\underline{v}^{n+3/2} = \underline{v}^{n+1/2} + \Delta t \cdot \underline{\ddot{u}}^{n+1}$$

How does one obtain $\underline{\sigma}^{e(n+1)}$? (see below)

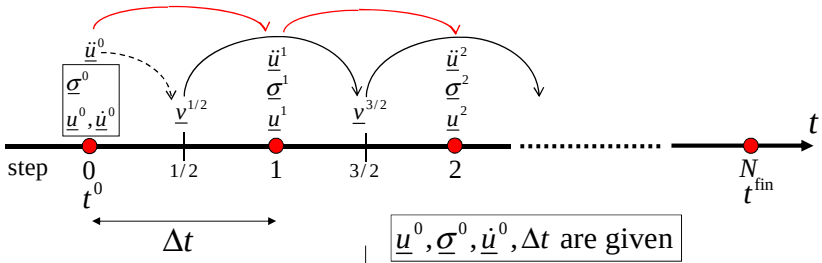
A new configuration is obtained first. On this known configuration, equilibrium is enforced. The new mid-step velocity is obtained last.

- This scheme is explicit.
- If Δt varies in time, the only change is in the third equation, which becomes:

$$\underline{v}^{n+3/2} = \underline{v}^{n+1/2} + \frac{\Delta t^{n} + \Delta t^{n+1}}{2} \cdot \underline{\ddot{u}}^{n+1} \qquad \textit{with:} \quad \Delta t^{n} \equiv t^{n+1} - t^{n}, \quad \Delta t^{n+1} \equiv t^{n+2} - t^{n+1}$$

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Scheme start-up and marching



$\underline{u}^0, \underline{\sigma}^0, \underline{\dot{u}}^0, \Delta t$ are given

$n = -1$

$\underline{\ddot{u}}^0 = \underline{M}^{-1}(\underline{f}^{\text{ext}} - \underline{f}^{\text{int}})^0$

$\underline{v}^{1/2} = \underline{\dot{u}}^0 + (\Delta t / 2) \cdot \underline{\ddot{u}}^0$

$n \leftarrow n+1$

$\underline{u}^1 = \underline{u}^0 + \Delta t \cdot \underline{v}^{1/2}$

$\underline{\ddot{u}}^1 = \underline{M}^{-1}(\underline{f}^{\text{ext}} - \underline{f}^{\text{int}})^1$

$\underline{v}^{3/2} = \underline{v}^{1/2} + \Delta t \cdot \underline{\ddot{u}}^1$

etc.

t

$$\underline{u}^{n+1} = \underline{u}^{n} + \Delta t \cdot \underline{v}^{n+1/2}$$

$$\underline{\ddot{u}}^{n+1} = \underline{M}^{-1}(\underline{f}^{\text{ext}} - \underline{f}^{\text{int}})^{n+1}$$

$$\underline{v}^{n+3/2} = \underline{v}^{n+1/2} + \Delta t \cdot \underline{\ddot{u}}^{n+1}$$

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Scheme start-up and marching (2)

- For practical reasons, the code also computes the full-step velocities:

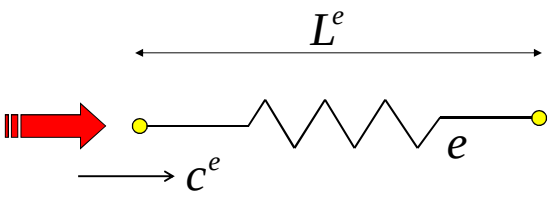
$$\underline{\dot{u}}^{n+1} = \underline{v}^{n+1/2} + \frac{\Delta t}{2}\underline{\ddot{u}}^{n+1}$$

- These are the velocities printed out in the listing and visualized in post-processing
- However, the fundamental quantity in the time integration scheme is the mid-step velocity!

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Integration Scheme Characteristics

- Central difference scheme is second-order accurate and introduces no numerical damping
- However, it is conditionally stable (Courant):



$$\Delta t^e_{\text{stab}} \approx L^e / c^e$$

$$\Delta t^e = \varphi \cdot \Delta t^e_{\text{stab}}$$

(with $\varphi < 1$)

- In highly non-linear cases, small steps are needed even with unconditionally stable schemes, to get good accuracy

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Integration Scheme Characteristics (2)

- Spectral analysis shows that the central difference scheme tends to produce frequencies slightly higher than physical ones. Same effect is obtained using a consistent mass matrix.
- However, use of a lumped mass matrix tends to reduce frequency values.
- Therefore, combination of CD time integrator with a lumped mass matrix gives optimal numerical precision.
- This is a remarkable result, since the final equations are completely decoupled: contrary to classical FE method, there are no matrices to assemble and no need for system solvers (except for treatment of essential BCs).

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Integration Scheme Characteristics (3)

- See: S.W.Key, "*Transient Response by Time Integration*".

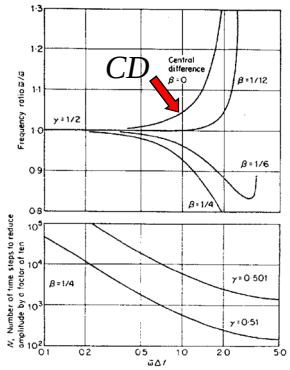


FIG. 6. The frequency response for $\gamma = 0{\cdot}5$ and damping for $\beta = 0{\cdot}25$ for the Newmark β time integrator.

Scheme effect on frequency

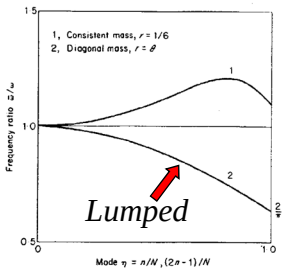


FIG. 2. The ratio of approximate frequency, $\bar{\omega}$, to true frequency, ω, versus non-dimensional wave number for a piecewise linear spatial approximation.

Mass matrix effect on frequency

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Stress Update

- To solve the equilibrium equation for the new accelerations:

$$\underline{\ddot{u}}^{n+1} = \underline{M}^{-1}(\underline{f}^{\text{ext}(n+1)} - \sum_e \int_{V^{e(n+1)}} \underline{B}^T \underline{\sigma}^{e(n+1)} dV)$$

  one needs the new stress $\underline{\sigma}^{e(n+1)}$.

- In general one can formally write:

$$\underline{\sigma}^{n+1} = \underline{\sigma}^n + \Delta\underline{\sigma}$$

$$\Delta\underline{\sigma} = H(\underline{\sigma}^n, \Delta\underline{\varepsilon}, \underline{p}, \underline{\dot{\varepsilon}}, \ldots) \quad \text{(Rate form)}$$

  H Constitutive law

  $\Delta\underline{\sigma}$ stress increment over the step — $\underline{p}$ hardening parameters (e.g. plasticity)

  $\Delta\underline{\varepsilon}$ strain increment over the step — $\underline{\dot{\varepsilon}}$ strain rate (e.g. viscous behaviour)

- Note that the total deformation $\underline{\varepsilon}$ does not appear anywhere and is not used in the process.

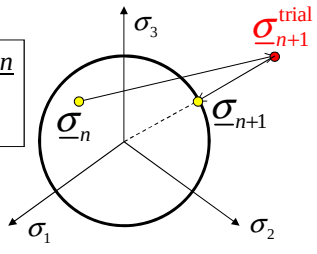
33

Elasto-plastic material

As an example of non-linear material behaviour consider the important case of metal plasticity:

- Rate-independent deviatoric plasticity model with Von Mises yield criterion:

Radial return method (Wilkins)



- "Trial" stress (elastic):

$$\underline{\sigma}^{\text{trial}}_{n+1} = \underline{\sigma}_n + \underline{\underline{C}} \cdot \Delta\underline{\varepsilon}$$

- If trial stress lies outside yield surface, perform radial return onto (current) yield surface. No iterations!

How does one compute $\Delta\underline{\varepsilon}$ from displacement increments (or velocities) in the presence of *geometrical non-linearities* (large strains and large motions, in particular large rotations?)

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Geometric non-linearities

A large-displacement large-strain formulation is adopted for full generality. For continuum-like FE:

- Compute spatial velocity gradient:

$$\underline{L} = \partial \dot{\underline{x}} / \partial \underline{x}$$

- Use additive decomposition to separate instantaneous deformation (symmetric) from rotation (antisymmetric part):

$$\underline{L} = \underline{D} + \underline{W}$$

$$\underline{D} = \frac{1}{2}(\underline{L} + \underline{L}^T) \quad (\textit{stretching} \text{ i.e. rate of deformation})$$

$$\underline{W} = \frac{1}{2}(\underline{L} - \underline{L}^T) \quad (\textit{spin} \text{ i.e. rate of rotation})$$

- We obtain then:

$$\boxed{\dot{\underline{\varepsilon}} = \underline{D} \qquad ; \qquad \Delta \underline{\varepsilon} = \underline{D} \cdot \Delta t}$$

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Geometric non-linearities (2)

For a continuum element the state of stress of interest to us, Cauchy stress $\underline{\sigma}$, is referred to a fixed frame in space. Consequently, its time derivative is not invariant with respect to rotation: $\dot{\underline{\sigma}}$ is *not objective*.

- An objective rate of stress $\hat{\underline{\sigma}}$ can be obtained under the form: $\hat{\underline{\sigma}} = \dot{\underline{\sigma}} - \underline{A}\underline{\sigma} + \underline{\sigma}\underline{A}$ where $\underline{A}$ is an appropriate vorticity matrix.

- In the Zaremba-Jaumann-Noll formulation: $\underline{A} \doteq \underline{W}$ (other choices are possible, e.g. Green-Naghdi).

- However, the above considerations are valid only in an infinitesimal sense, while we need to use finite increments.

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Geometric non-linearities (3)

Set up following incrementally objective scheme to update the Cauchy stress (2D case for simplicity) in three phases:

- Let α be the angle of rotation over Δt and let $\theta = \alpha / 2$

$$\tan\theta = (\Delta t / 2) \cdot W_{12}^{n+1/2}$$

1. Apply first half of the rotation increment:

$$\underline{\sigma}^{n^*} = \underline{R}\underline{\sigma}^{n}\underline{R}^{T} \quad \text{with} \quad \underline{R} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

2. Apply the constitutive equation:

$$\boxed{\underline{\sigma}^{(n+1)^*} = \underline{\sigma}^{n^*} + \underline{\underline{C}} \cdot \Delta t \cdot \underline{D}^{n+1/2}}$$

3. Apply second half of the rotation increment:

$$\underline{\sigma}^{n+1} = \underline{R}\underline{\sigma}^{(n+1)^*}\underline{R}^{T}$$

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Geometric non-linearities (4)

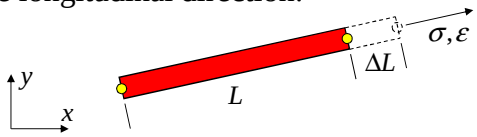
For structural elements (bars, beams, shells) use co-rotational formulation:

- The stress is measured in a reference frame that rotates with the element
- This greatly simplifies the stress increment procedure: the stress can be incremented directly by applying the constitutive law.

Example (bar element). In the longitudinal direction:

$$\Delta\varepsilon = \frac{\Delta L}{L} \quad \rightarrow \quad \Delta\sigma$$

$$\sum \Delta\varepsilon = \sum \frac{\Delta L}{L} \simeq \int_{L_0}^{L} \frac{dL}{L} = \ln\frac{L}{L_0}$$



(Natural or logarithmic strain)

A small-strain formulation would be:

$$\Delta\varepsilon = \frac{\Delta L}{L_0} \quad \rightarrow \quad \sum \Delta\varepsilon = \frac{L - L_0}{L_0}$$

(Engineering strain)

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Advantages of the Method

- Transient dynamic problem: find $\underline{\sigma}$ on new configuration $\underline{x}$ (known) from $\underline{\sigma}^{old}$ and deformation process between $\underline{x}^{old}$ and $\underline{x}$
- Compare <u>implicit</u> methods: find $\underline{\sigma}$ and $\underline{x}$ <u>simultaneously</u>, typically by iterative procedures and convergence criteria.
- The proposed method is particularly <u>simple</u> for complex non-linear problems, hence very <u>robust</u>.
- Direct application of virtual work principle plus second-order accurate time integration scheme, guarantee <u>high accuracy</u> of numerical results.

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Checking the Solution Quality

- The quality of the obtained solution can be checked globally by computing at each time step the <u>*energy balance*</u>.
- Initially, set: $W_0^{ext} \doteq E_0^{int} + E_0^{kin}$
- At any time, the balance error can be computed as:

$$\varepsilon = \frac{W^{ext} - (E^{int} + E^{kin})}{W^{ext}}$$ or perhaps better: $$\boxed{\varepsilon = \frac{W^{ext} - (E^{int} + E^{kin})}{\max\left(\left|W^{ext}\right|, \left|W_0^{ext}\right|\right)}}$$

- This error indicator is used *a posteriori* in order to check the previously obtained solution and must not be confused with convergence parameters typical of iterative approaches

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Essential Boundary Conditions

Essential conditions are imposed via Lagrange multipliers.

- Assume a linear set of constraints on the velocities:

$$\underline{C}\underline{v} = \underline{b}$$

- Both $\underline{C}$ and $\underline{b}$ are known, and can be function of time.
- The equilibrium equations for the subset of d.o.f.s concerned become, introducing unknown reactions $\underline{r}$:

$$\underline{m}\underline{a} = \underline{f}^{\mathrm{e}} - \underline{f}^{\mathrm{i}} + \underline{r}$$

- Without loss of generality, the unknown reactions can be expressed via a vector $\underline{\lambda}$ of Lagrange multipliers:

$$\underline{r} = \underline{C}^T \underline{\lambda}$$

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Finding the Lagrange Multipliers

- Replacing into the equilibrium equations yields:

$$\underline{m}\underline{a} = \underline{f}^{\mathrm{e}} - \underline{f}^{\mathrm{i}} + \underline{C}^T \underline{\lambda}$$

- Multiplying both members by $\underline{C}\underline{m}^{-1}$ gives:

$$\underline{C}\underline{a} = \underline{C}\underline{m}^{-1}(\underline{f}^{\mathrm{e}} - \underline{f}^{\mathrm{i}}) + \underbrace{\underline{C}\underline{m}^{-1}\underline{C}^T}_{\underline{B}^*}\underline{\lambda}$$

Matrix of connections

- The Lagrange multipliers are obtained symbolically from:

$$\underline{B}^*\underline{\lambda} = \underline{C}\underline{a} - \underline{C}\underline{m}^{-1}(\underline{f}^{\mathrm{e}} - \underline{f}^{\mathrm{i}})$$

- To obtain $\underline{\lambda}$, we must first express the term $\underline{C}\underline{a}$ as a function of known quantities, by using the constraint and the time integration scheme.

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Finding the Lagrange Multipliers (2)

- The CD scheme for the velocity and constant Δt is:
  $\underline{v}^{n+3/2} = \underline{v}^{n+1/2} + \Delta t \cdot \underline{a}^{n+1}$
- Substituting this into the constraint $\underline{C}\underline{v} = \underline{b}$ gives:
  $\underline{C}\underline{v}^{n+3/2} = \underline{C}\underline{v}^{n+1/2} + \Delta t \cdot \underline{C}\underline{a}^{n+1} = \underline{b}$
- From this we obtain:
  $\underline{C}\underline{a} = \frac{1}{\Delta t}(\underline{b} - \underline{C}\underline{v}^{n+1/2}) = \frac{1}{\bar{\gamma}}(\underline{b} - \underline{C}\underline{v}^{n+1/2})$ having posed: $\boxed{\bar{\gamma} = \Delta t}$
- For a variable Δt in time, one has simply:
  $\boxed{\bar{\gamma} = \frac{\Delta t^n + \Delta t^{n+1}}{2}}$

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Finding the Lagrange Multipliers (3)

- Summarizing, the Lagrange multipliers $\underline{\lambda}$ are obtained by solving the linear algebraic system:
  $\underline{B}^* \underline{\lambda} = \underline{w}$
  We obtain one multiplier for each imposed constraint
  where the known terms are given by:
  $\underline{B}^* \equiv \underline{C}\underline{m}^{-1}\underline{C}^T$ and $\underline{w} \equiv \frac{1}{\bar{\gamma}}(\underline{b} - \underline{C}\underline{v}^{n+1/2}) - \underline{C}\underline{m}^{-1}(\underline{f}^e - \underline{f}^i)$
  $\bar{\gamma} = \Delta t$ for constant Δt
  $\bar{\gamma} = (\Delta t^n + \Delta t^{n+1})/2$ for variable Δt in time
- Finally we compute the reactions:
  $\underline{r} = \underline{C}^T \underline{\lambda}$
  We obtain one reaction for each constrained dof
  and add them to the other known external forces.
- This is the only implicit part of the whole method.

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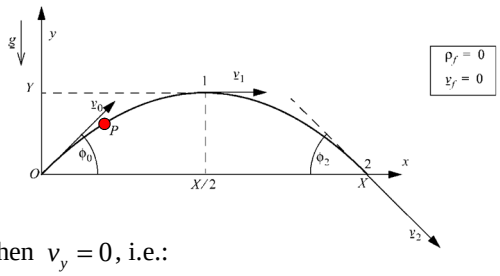
Exercise 0 – Ideal ballistics

- Motion in vacuum is analytical:

$$v_x = v_{0x} = v_0 \cos\phi_0$$
$$v_y = v_{0y} - gt = v_0 \sin\phi_0 - gt$$

- The trajectory is a parabola:

$$\phi_2 = \phi_0 \quad \text{and} \quad \|\underline{v}_2\| = \|\underline{v}_0\|$$



- Time to reach highest point is when $v_y = 0$, i.e.:

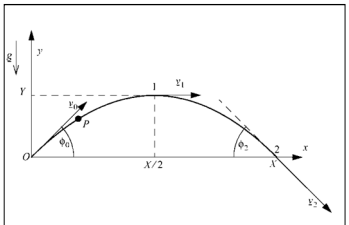
$$t_1 = \frac{v_{0y}}{g} = \frac{v_0}{g}\sin\phi_0$$

- By symmetry, time to impact is twice as long:

$$t_2 = 2t_1 = 2\frac{v_{0y}}{g} = 2\frac{v_0}{g}\sin\phi_0$$

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Exercise 0 – Ideal ballistics (2)



$$v_x = v_{0x} = v_0 \cos\phi_0$$
$$v_y = v_{0y} - gt = v_0 \sin\phi_0 - gt$$
$$t_1 = \frac{v_{0y}}{g} = \frac{v_0}{g}\sin\phi_0$$
$$t_2 = 2t_1 = 2\frac{v_{0y}}{g} = 2\frac{v_0}{g}\sin\phi_0$$

- The range is therefore:

$$X = v_x t_2 = 2v_{0x}\frac{v_{0y}}{g} = 2\frac{v_0^2}{g}\sin\phi_0\cos\phi_0 = \frac{v_0^2}{g}\sin(2\phi_0)$$

- Max range is when shooting at 45º:

$$X_{\max}(\phi_0) = \frac{v_0^2}{g} \quad \text{for} \quad \sin(2\phi_0) = 1 \Leftrightarrow \phi_0 = \pi/4$$

- The position at the generic time is:

$$x(t) = v_{0x}t = v_0 t\cos\phi_0$$
$$y(t) = v_{0y}t - g\frac{t^2}{2} = v_0 t\sin\phi_0 - g\frac{t^2}{2}$$

- Max elevation depends only on v_{0y}:

$$Y = y_{\max} = y(t_1) = \frac{v_{0y}^2}{g} - \frac{g}{2}\frac{v_{0y}^2}{g^2} = \frac{v_{0y}^2}{2g} = \frac{v_0^2}{2g}\sin^2\phi_0$$

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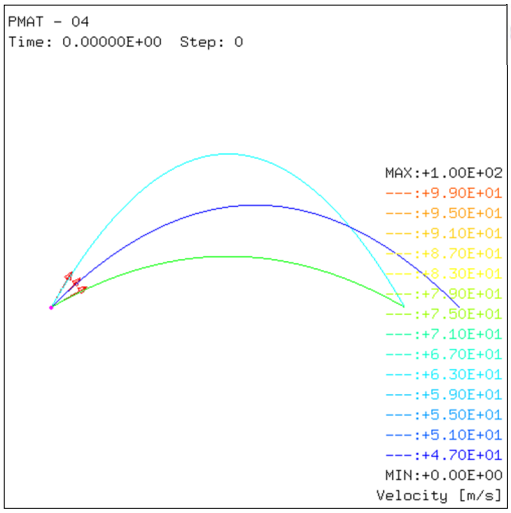
Exercise 0 – Ideal ballistics (3)

- Study motion of projectile as a function of the shooting angle:

  $v_0 = 100$

  $\phi_0 = 30°, 45°, 60°$

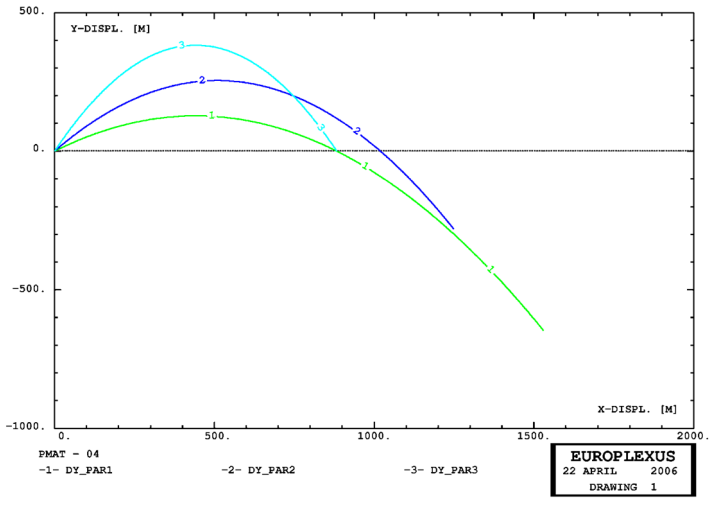
- Computed vs. analytical positions:



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Exercise 0 – Ideal ballistics (4)

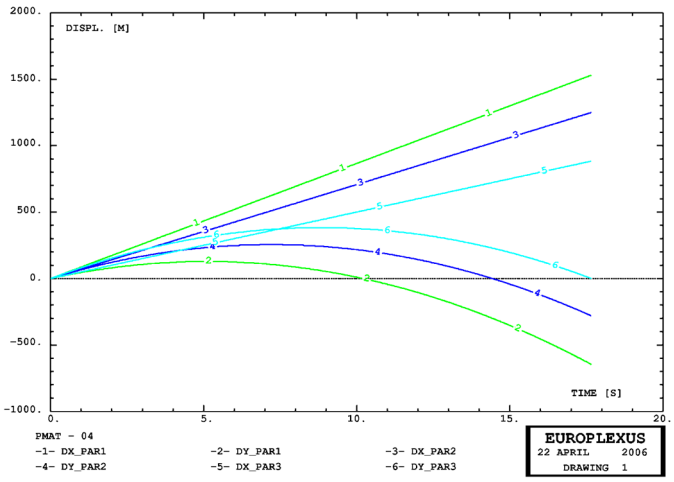
- Computed trajectories:



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Exercise 0 – Ideal ballistics (5)

- Computed displacement components:



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Exercise 0 – Ideal ballistics (6)

- Influence of time discretization:

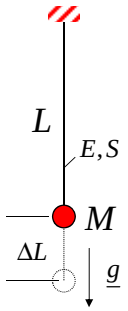
Case	Description	Flight time t_2	Range X	N. of steps
PMAT01	$\phi_0 = 30°$	10.197	883.1	1000
PMAT01B	$\phi_0 = 30°$	10.197	883.1	100
PMAT01C	$\phi_0 = 30°$	10.197	883.1	10
PMAT01D	$\phi_0 = 30°$	10.197	883.1	2
PMAT01E	$\phi_0 = 30°$	10.197	883.1	1
PMAT02	$\phi_0 = 45°$	14.421	1019.7	1000
PMAT03	$\phi_0 = 60°$	17.662	883.1	1000
PMAT04	$\phi_0 = 30°, 45°, 60°$	10.197, 14.421, 17.662	883.1, 1019.7	1000

- No stability restraints (no wave propagation)
- Analytical precision

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Exercise 1 – Suspended mass

- Single-element discrete model: check vs. (linear) analytical solution
- Explain possible reasons for observed discrepancies
- Try out different values: e.g. gravity 1000 times smaller
- Discuss multi-element discrete model

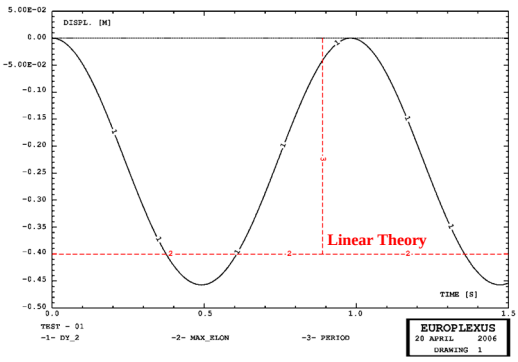


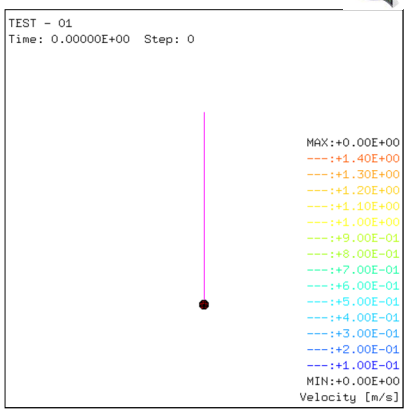
$L = 1$ m
$M = 100$ kg
$g = 10$ m/s^2
$S = 2.5\times10^{-8}$ m^2
$E = 2\times10^{11}$ Pa
$\rho = 8000$ kg/m^3
$\nu = 0$

- Replace gravity by initial velocity and discuss effects of structure modeling: A) as a bar, B) as a cable …

Exercise 1 – Suspended mass (2)

- **TEST01** : 1 element of type FUN2 (cable), no resistance to bending. Use FUNE material (no resistance to compression)





Exercise 1 – Suspended mass (3)

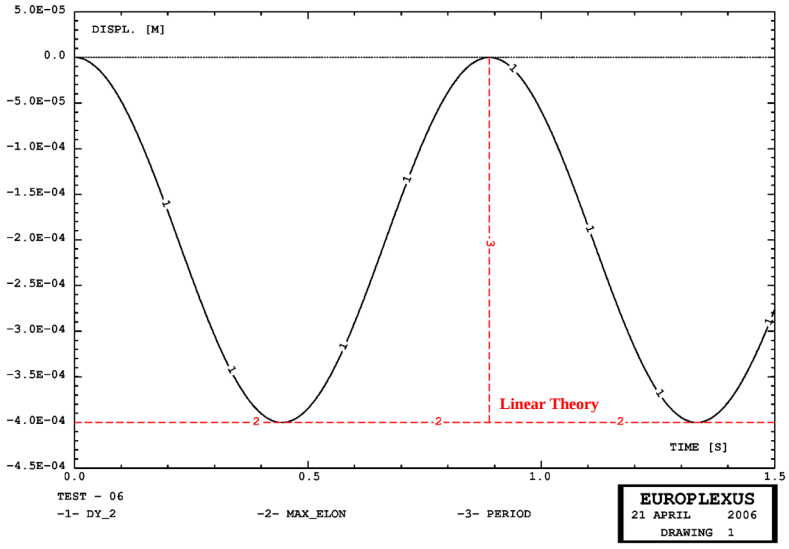
- EUROPLEXUS input file:

```
TEST - 01
*-------------------------------------------------------------
ECHO
*CONV win
*-----------------------------------------------------Problem type
CPLA LAGR
*-----------------------------------------------------Dimensioning
DIME
 PT2L 2 FUN2 1 PMAT 1 ZONE 2
 TABL 1 2
 FORC 1
TERM
*-----------------------------------------------------Geometry
GEOM LIBR POIN 2 FUN2 1 PMAT 1 TERM
 0 0  0 -1
 1 2
 2
*-----------------------------------------------Geometrical complements
COMP EPAI 2.5E-8 LECT 1 TERM
*-----------------------------------------------------Material data
MATE FUNE RO 8000. YOUN 2.0E11 NU 0.0 ELAS 2.0E11 ERUP 1.0E0
       TRAC 1 2.0E11 1.E0
       LECT 1 TERM
   MASS 100.0 LECT 2 TERM
*-----------------------------------------------Boundary conditions
LINK COUP
    BLOQ 2 LECT 1 TERM
*-----------------------------------------------------Applied loads
CHAR 1 FACT 2 FORC 2 -1.E3 LECT 2 TERM
    TABL 2 0.0 1.0 10.0 1.0
*-----------------------------------------------------Outputs
ECRI DEPL VITE CONT ECRO TFREQ 0.5
   FICH ALIC TEMP FREQ 20
         POIN LECT 1 2 TERM
         ELEM LECT 1 TERM
*-----------------------------------------------------Options
OPTI PAS UTIL NOTEST
*-----------------------------------------------Transient calculation
CALCUL TINI 0. TEND 1.5 PASF 0.1E-3
```

```
*=================================================
=======POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
*-----------------------------------------------Curve definitions
COUR 1 'dy_2'    DEPL COMP 2 NOEU LECT  2 TERM
COUR 2 'sg_1'    CONT COMP 1 ELEM LECT  1 TERM
COUR 3 'fe_2'    FORC COMP 2 NOEU LECT  2 TERM
COUR 4 'fe_1'    FORC COMP 2 NOEU LECT  1 TERM
DCOU 6 'Max_elon' 2
     0.0 -0.4
     1.5 -0.4
DCOU 7 'Period' 2
     0.889 0.0
     0.889 -0.4
*-----------------------------------------------------Plots
trac 1 6 7 axes 1.0 'DISPL. [M]' yzer
       colo noir roug roug
       dash 0   2   2
trac 2 axes 1.0 'CONTR. [PA]' yzer
trac 3 4 axes 1.0 'FORCE [N]' yzer
list 1 axes 1.0 'DISPL. [M]'
*-----------------------------------------------Results qualification
QUAL DEPL COMP 2 LECT   2 TERM REFE -4.53636E-1  TOLE 1.E-2
   CONT COMP 1 LECT   1 TERM REFE  7.48171E+10 TOLE 1.E-2
*=================================================
====================
FIN
```

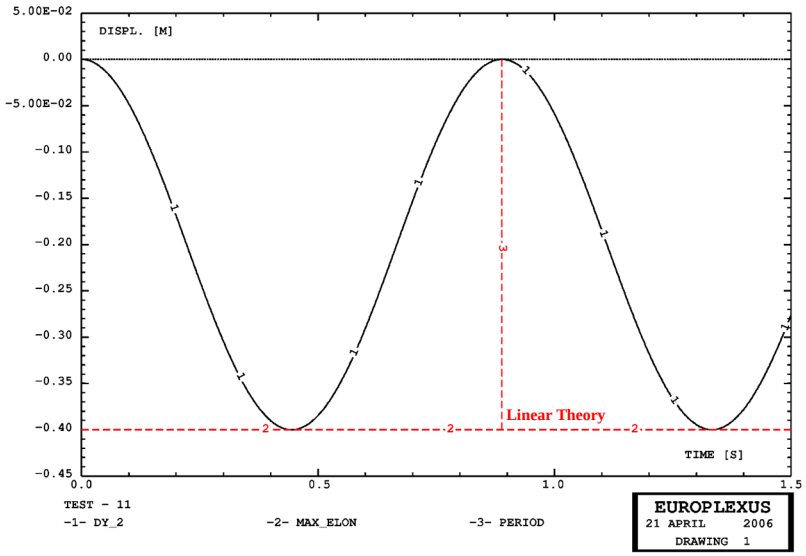

Exercise 1 – Suspended mass (4)

- **TEST06** : applied load 1000 times smaller (small-strain)



Exercise 1 – Suspended mass (5)

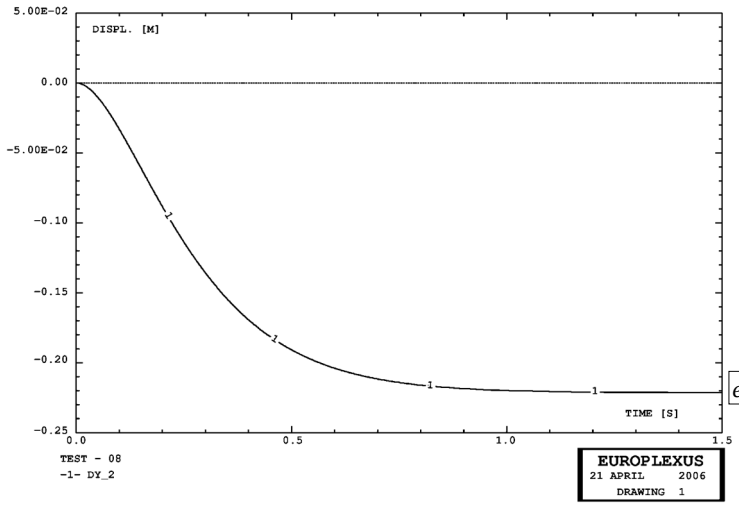
- **TEST11** : standard load but small-strain option (OPTI EDSS)



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Exercise 1 – Suspended mass (6)

- **TEST08** : "quasi-static" option (OPTI QUAS STAT …)

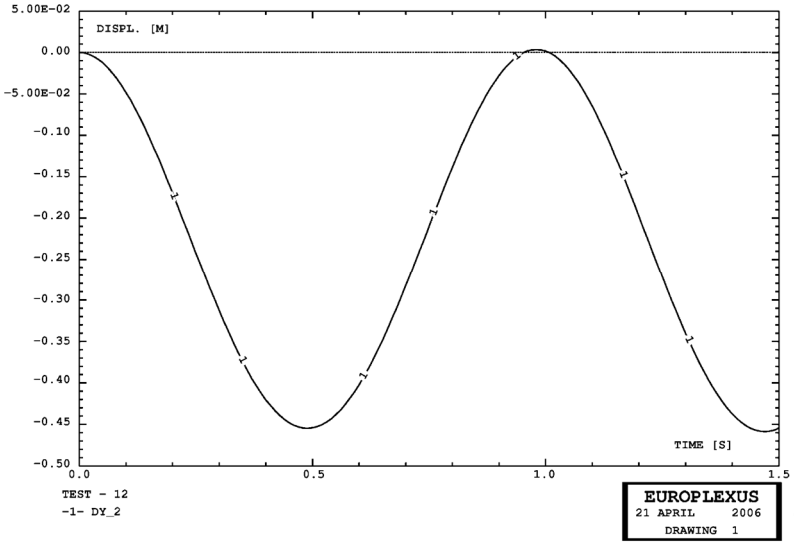


$e^{0.2} - 1 = 0.2214$

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Exercise 1 – Suspended mass (7)

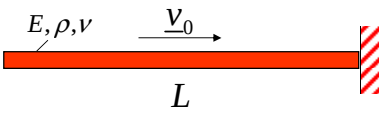
- **TEST12** : time increment 50 times the critical value



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Exercise 2 – Wave propagation

- Obtain 1D analytical solution
- Discuss numerical solution
- Why was cross-section not specified?
- Study effect of time increment
- Study effect of Poisson's ratio …

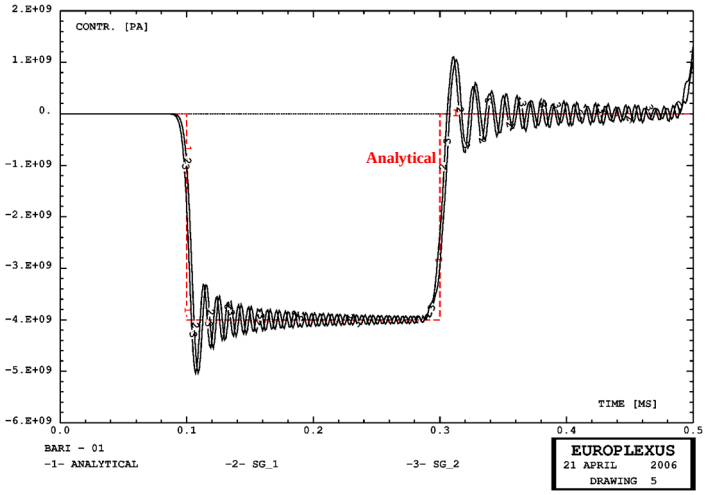


$L = 1$ m
$\underline{v}_0 = 100$ m/s
$E = 2 \times 10^{11}$ Pa
$\rho = 8000$ kg/m^3
$\nu = 0.3$

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Exercise 2 – Wave propagation (2)

- **BARI01** : 100 elements of type FUN2 (cable), VM23 material (traction/compression), small-strain option (OPTI EDSS)



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Exercise 2 – Wave propagation (3)

- EUROPLEXUS input file:

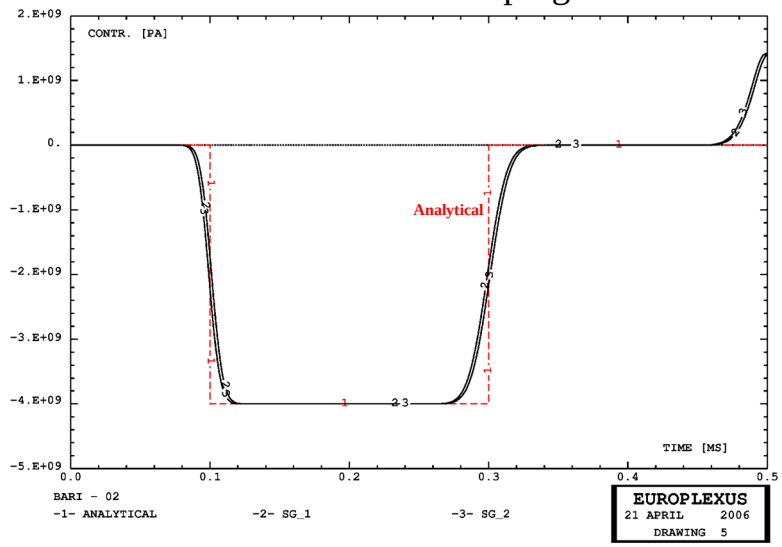
```
BARI - 01
*-------------------------------------------------------------------
ECHO
*CONV win
CAST mesh
*-----------------------------------------------------------Problem type
CPLA LAGR LAGC
*-----------------------------------------------------------Dimensioning
DIME
 PT2L 102 FUN2 100 PMAT 1 ZONE 2
 BLOQ 2
 TABL 1 2
 FORC 1
 IMPA 1 PSIM 1
TERM
*-------------------------------------------------------------Geometry
GEOM FUN2 bar PMAT obst TERM
*-----------------------------------------------Geometrical complements
COMP EPAI 2.5E-8 LECT bar TERM
*-----------------------------------------------------------Material data
MATE VM23 RO 8000. YOUN 2.0E11 NU 0.0 ELAS 2.0E11
      TRAC 1 2.0E11 1.E0
      LECT bar TERM
   MASS 1.0 LECT obst TERM
*-----------------------------------------------------Boundary conditions
LIAI FREQ 1
   BLOQ 12 LECT obst TERM
   IMPA DDL 1 COTE -1
      PROJ LECT obst TERM
      CIBL LECT p2  TERM
*-----------------------------------------------------Initial conditions
INIT VITE 1 100.0 LECT bar TERM
*-------------------------------------------------------------------Outputs
ECRI DEPL VITE CONT ECRO TFREQ 0.1E-3
   FICH ALIC TEMP FREQ 1
        POIN LECT p3 p2 TERM
        ELEM LECT e1 e2 TERM
*-----------------------------------------------------------Options
OPTI PAS UTIL NOTEST
   LOG 1
   EDSS
*-----------------------------------------------Transient calculation
CALCUL TINI 0. TEND 0.5E-3 PASF 0.1E-5
```

```
*================================================
=======POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------Curve definitions
COUR 1 'dx_2'   DEPL COMP 1 NOEU LECT p2 TERM
COUR 2 'dx_3'   DEPL COMP 1 NOEU LECT p3 TERM
COUR 3 'sg_1'   CONT COMP 1 ELEM LECT e1 TERM
COUR 4 'sg_2'   CONT COMP 1 ELEM LECT e2 TERM
DCOU 5 'Analytical' 6
     0.0   0.0
     0.1E-3 0.0
     0.1E-3 -4.E9
     0.3E-3 -4.E9
     0.3E-3 0.0
     0.5E-3 0.0
*-------------------------------------------------------------Plots
trac 1 axes 1.0 'DISPL. [M]'
trac 2 axes 1.0 'DISPL. [M]'
trac 3 axes 1.0 'CONTR. [PA]'
trac 4 axes 1.0 'CONTR. [PA]'
trac 5 3 4 axes 1.0 'CONTR. [PA]' yzer
       colo roug noir noir
       dash 2   0   0
*-----------------------------------------------Results qualification
QUAL DEPL COMP 1 LECT  p2 TERM REFE -9.76759E-3  TOLE 1.E-2
   DEPL COMP 1 LECT  p3 TERM REFE -9.86359E-3  TOLE 1.E-2
   CONT COMP 1 LECT  e1 TERM REFE  1.00128E+9  TOLE 1.E-2
   CONT COMP 1 LECT  e2 TERM REFE  1.31288E+9  TOLE 1.E-2
*================================================
=====================
FIN
```

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Exercise 2 – Wave propagation (4)

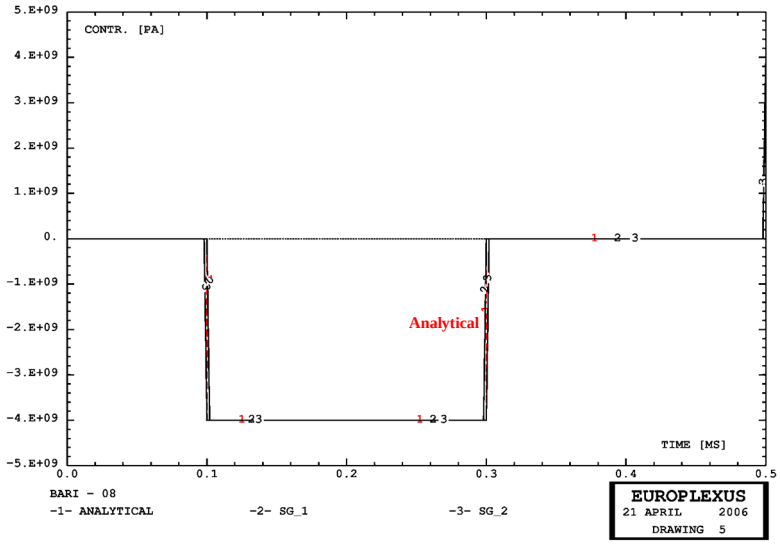
- **BARI02** : 10 % of critical damping added



61

Exercise 2 – Wave propagation (5)

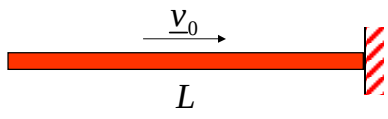
- **BARI08** : use critical time increment

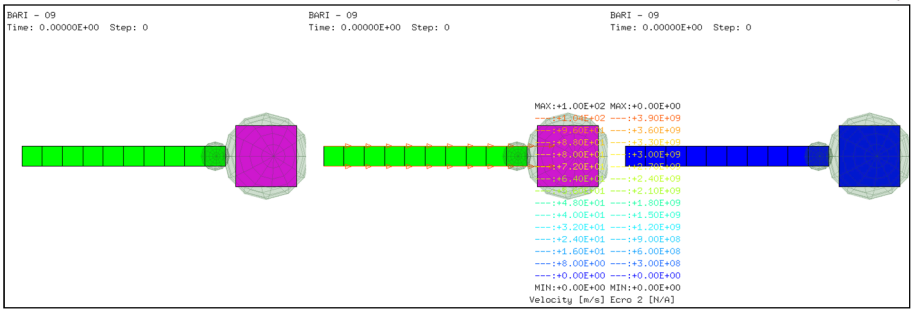


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Exercise 2 – Wave propagation (6)

- **BARI09** : 2-D geometry (Q42L) and pinballs for contacts:

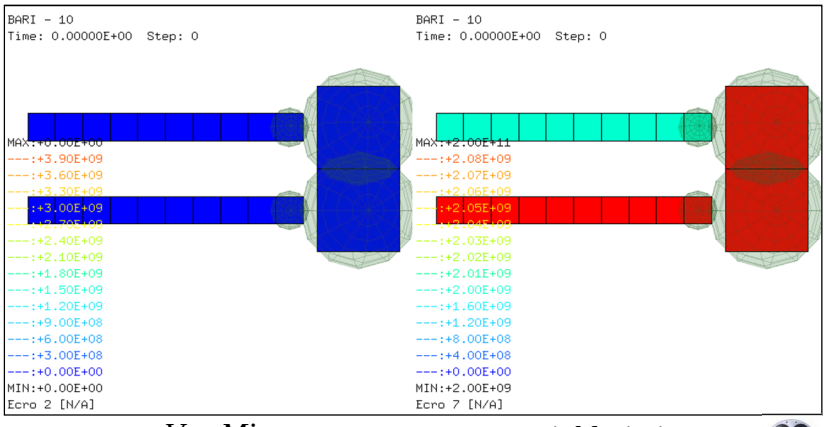




Geometry *Velocities* *Von Mises*

Exercise 2 – Wave propagation (7)

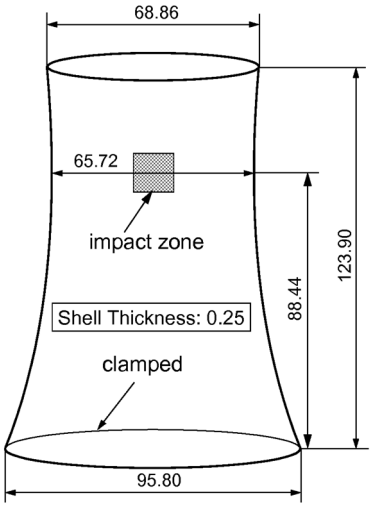
- **BARI10** : Compare elastic (bottom) and <u>elasto-plastic</u> (top) solutions:



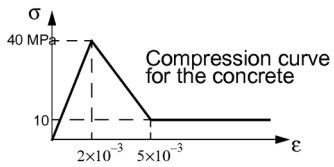
Von Mises *Yield Limit*

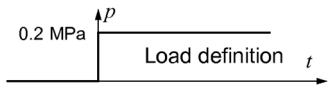
Exercise 3 – Impact on Cooling Tower

- Problem definition:



Layer N.	φ_L	Material
1	0.1	concrete
2	0.0025	steel
3	0.795	concrete
4	0.0025	steel
5	0.1	concrete

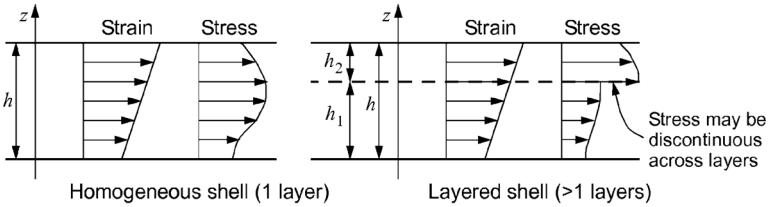




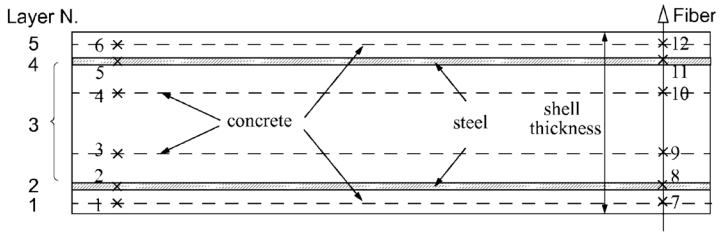
65

Exercise 3 – Impact on Cooling Tower (2)

- Shell model:



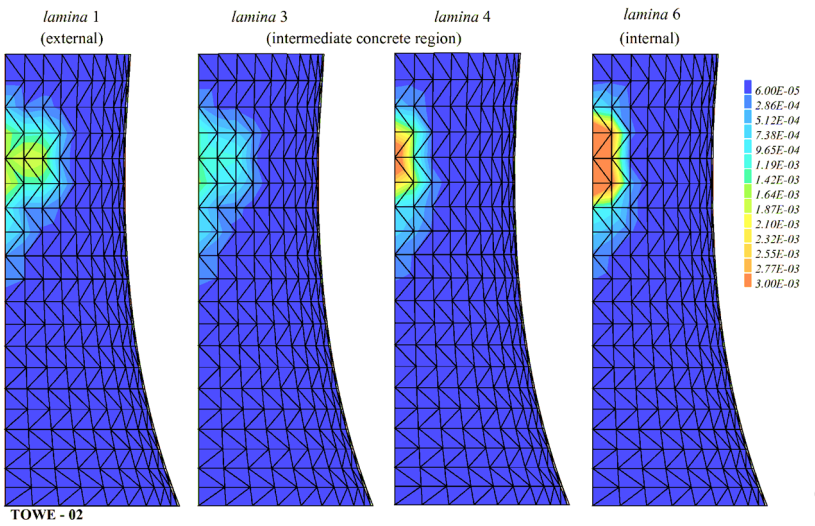
- Layers:



66

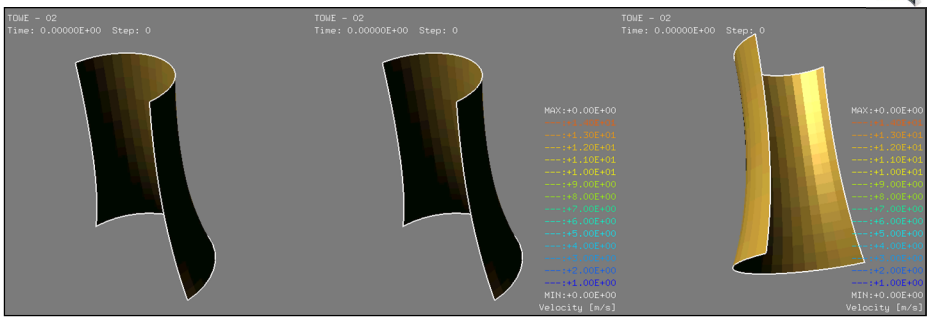
Exercise 3 – Impact on Cooling Tower (3)

- Results - equivalent plastic strain for the 4 concrete laminae at 100 ms:



67

Exercise 3 – Impact on Cooling Tower (4)



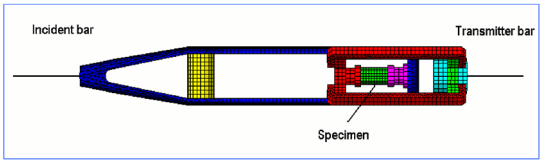
Deformation *Velocities* *Velocities (2)*

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Exercise 4 – Hopkinson Bar



JRC Large Dynamic Test Facility (HopLab)

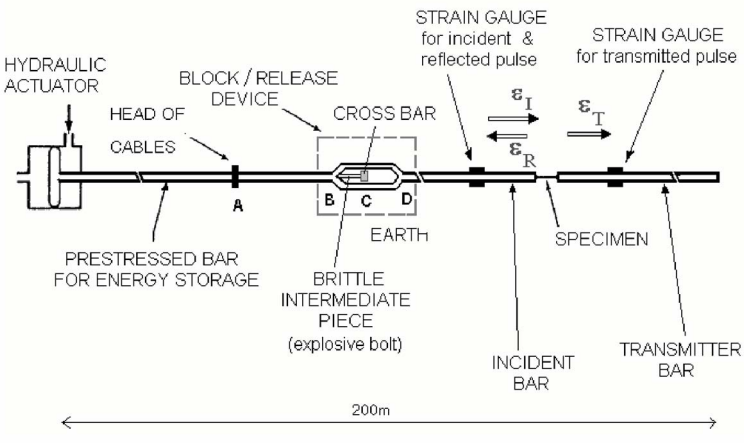


Fast Compression Test on Ductile Metallic Specimen

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Exercise 4 – Hopkinson Bar (2)

Functioning Principle (Hopkinson):



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Exercise 4 – Hopkinson Bar (3)

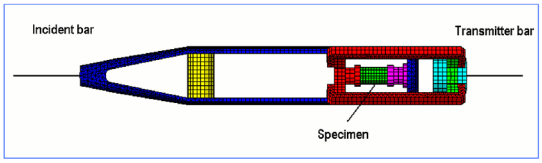


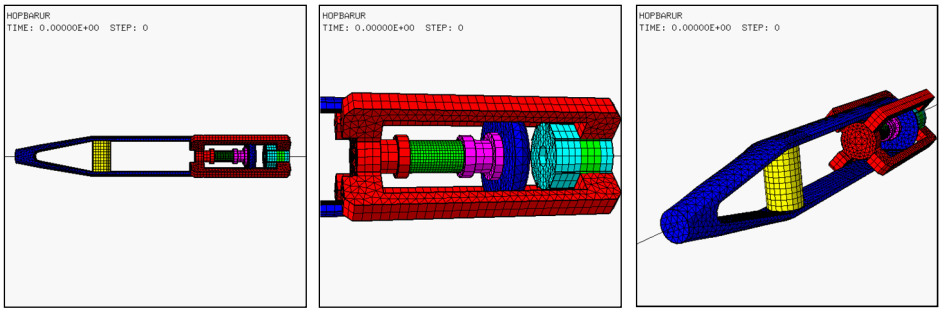


Figure 2: Incident and transmitter inversion cages

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Exercise 4 – Hopkinson Bar (4)

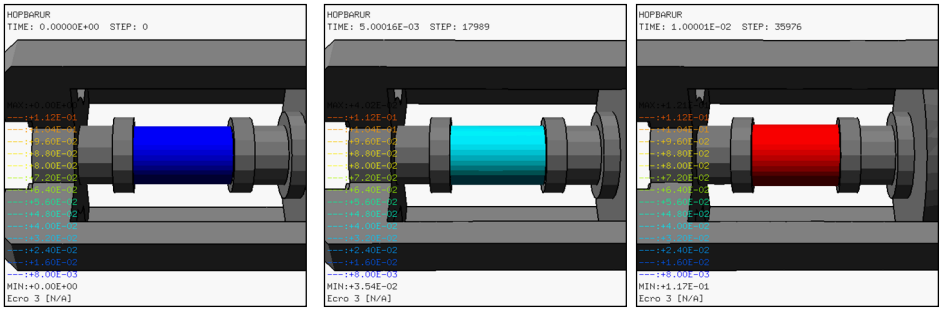
Numerical simulation : geometrical model



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Exercise 4 – Hopkinson Bar (5)

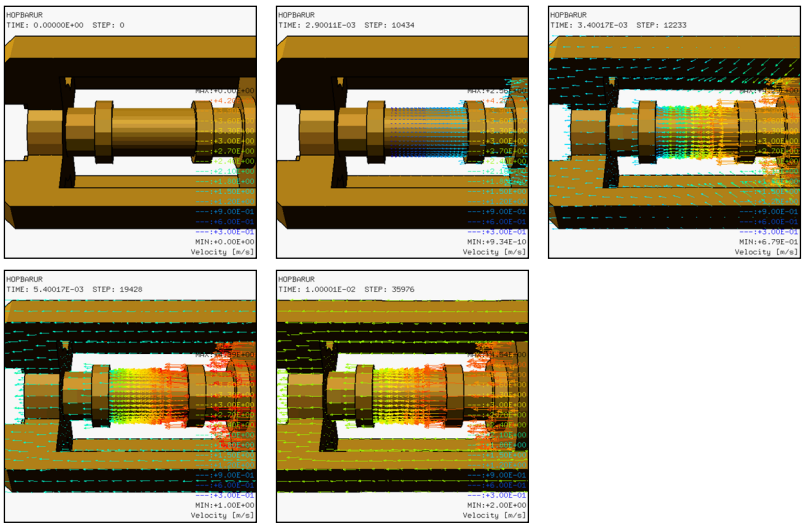
Numerical simulation : specimen plastification



73

Exercise 4 – Hopkinson Bar (6)

Numerical simulation : velocities



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Exercise 4 – Hopkinson Bar (7)

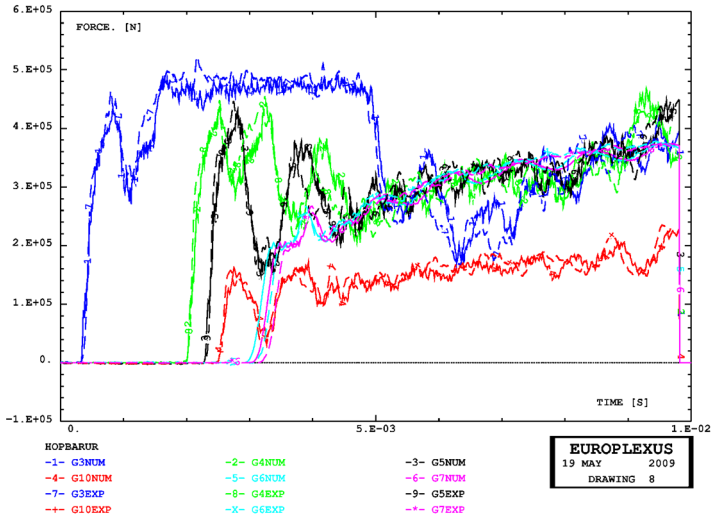
Numerical simulation : results animation



75

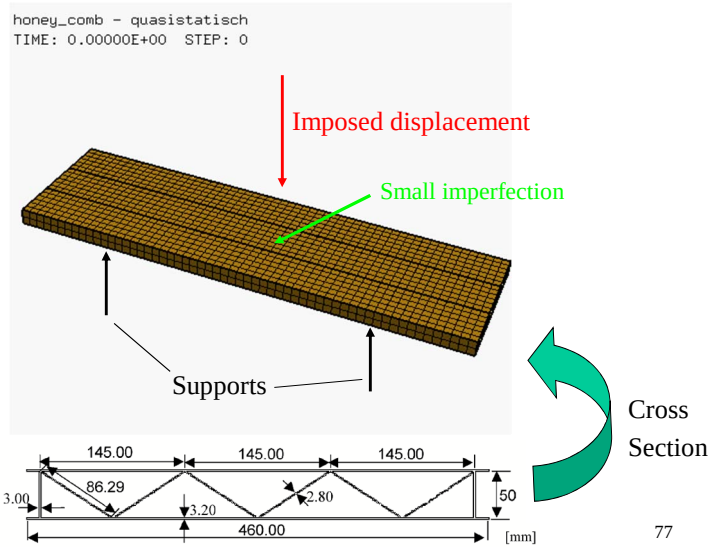
Exercise 4 – Hopkinson Bar (8)

Comparison experiment vs. calculation :



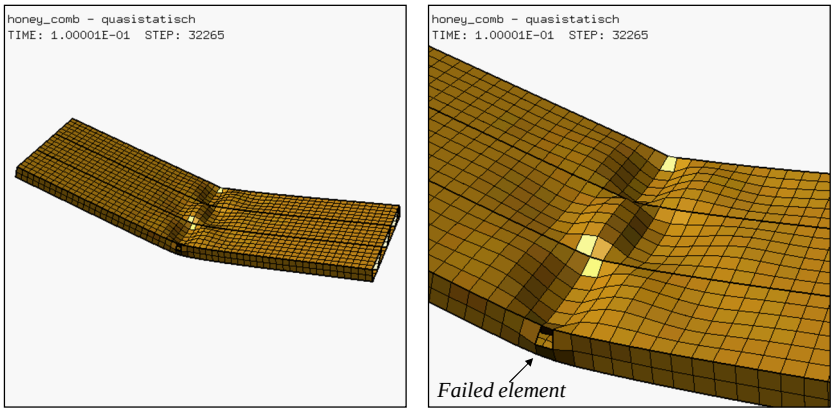
76

Exercise 5 – Honeycomb buckling



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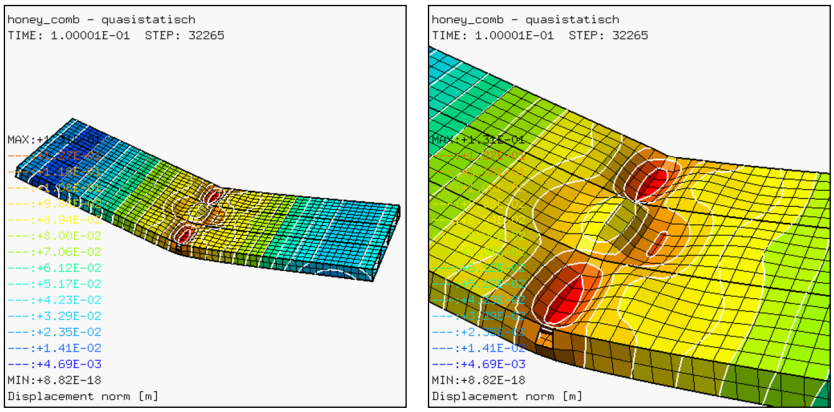
Exercise 5 – Honeycomb buckling (2)



Final deformed shape

78

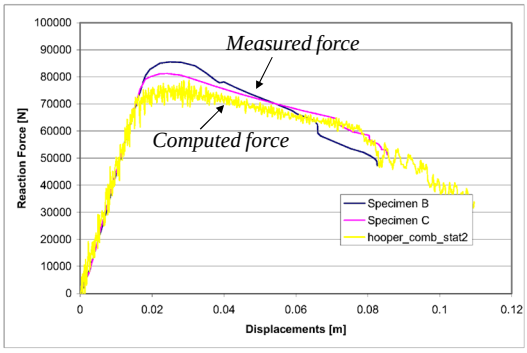
Exercise 5 – Honeycomb buckling (3)



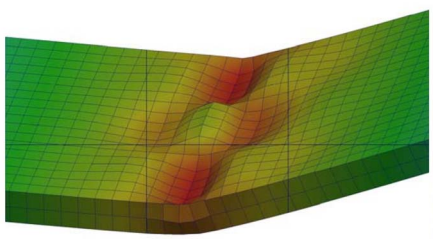
Final displacement norm (buckling mode)

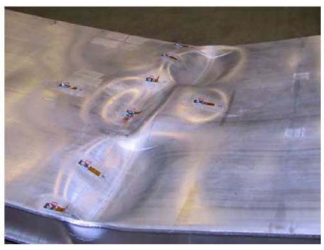
79

Exercise 5 – Honeycomb buckling (4)



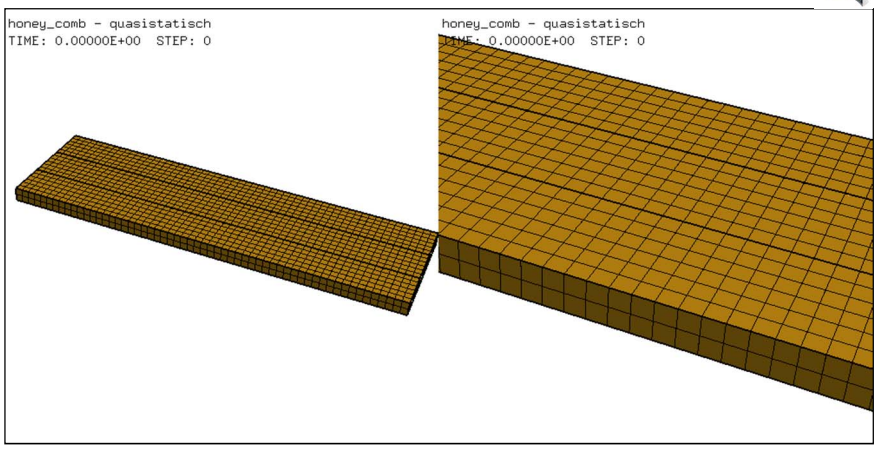
Comparison experiment / calculation





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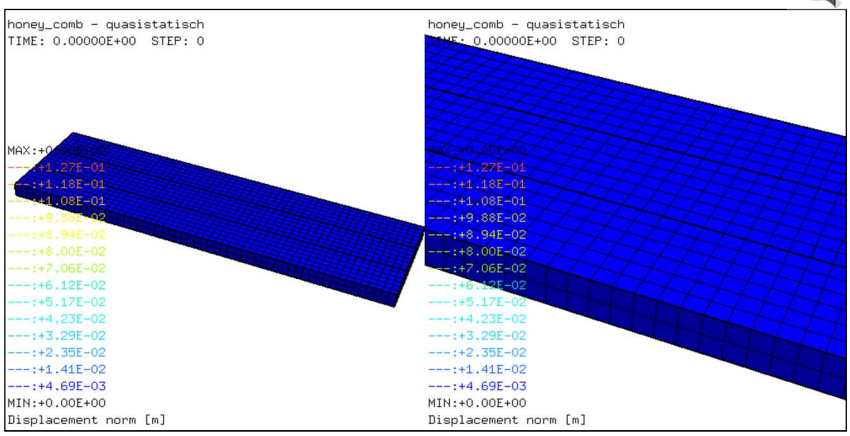
Exercise 5 – Honeycomb buckling (5)



Deformation

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Exercise 5 – Honeycomb buckling (6)



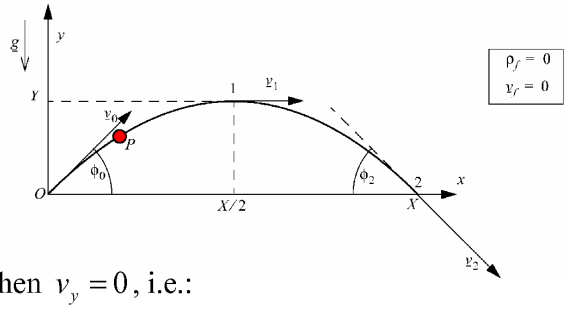
Displacement

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Exercise 0 – Ideal ballistics

- Motion in vacuum is analytical:

$$v_x = v_{0x} = v_0 \cos\phi_0$$
$$v_y = v_{0y} - gt = v_0 \sin\phi_0 - gt$$



- The trajectory is a parabola:

$$\phi_2 = \phi_0 \quad \text{and} \quad \|\underline{v}_2\| = \|\underline{v}_0\|$$

- Time to reach highest point is when $v_y = 0$, i.e.:

$$t_1 = \frac{v_{0y}}{g} = \frac{v_0}{g}\sin\phi_0$$

- By symmetry, time to impact is twice as long:

$$t_2 = 2t_1 = 2\frac{v_{0y}}{g} = 2\frac{v_0}{g}\sin\phi_0$$

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TITLE:
PMAT04: motion of projectiles.

PROBLEM:
We want to study the motion of a projectile in vacuum, subjected to the gravity force. The initial velocity is given and has a value of 100 m/s, however the shooting angle may vary.

MESH:
The model is 2D and uses three elements of type PMAT to represent three projectiles which are shot at different initial angles: 30°, 45° and 60°, respectively.
The mesh includes also 3000 elements of type FUNE (2-noded bars) which, however, are only used to represent the analytical trajectories of the three projectiles. This allows to visually compare, at each time instant, the numerical and analytical positions.

MATERIALS:
The projectiles use a material of type MASS (concentrated mass), while the auxiliary FUNE elements used to visualize the trajectories are associated with a FANT material (phantom) and thus do not intervene in any way in the calculation.

INITIAL CONDITIONS:
The three projectiles have the same initial velocity in modulus, but different shooting angles.

LOADING:
A standard gravity load is applied to the three projectiles by means of the CHAR CONS GRAV directive.

CALCULATION:
The calculation is performed up to 17.7 s over 1000 time steps of fixed length. At the final time, the third projectile has reached the ground.
RESULTS:
Results are in perfect agreement with the analytical solutions.

POST-TREATMENT
An animation of the computed results from this calculation is made.

Numerical Solutions

PMAT04

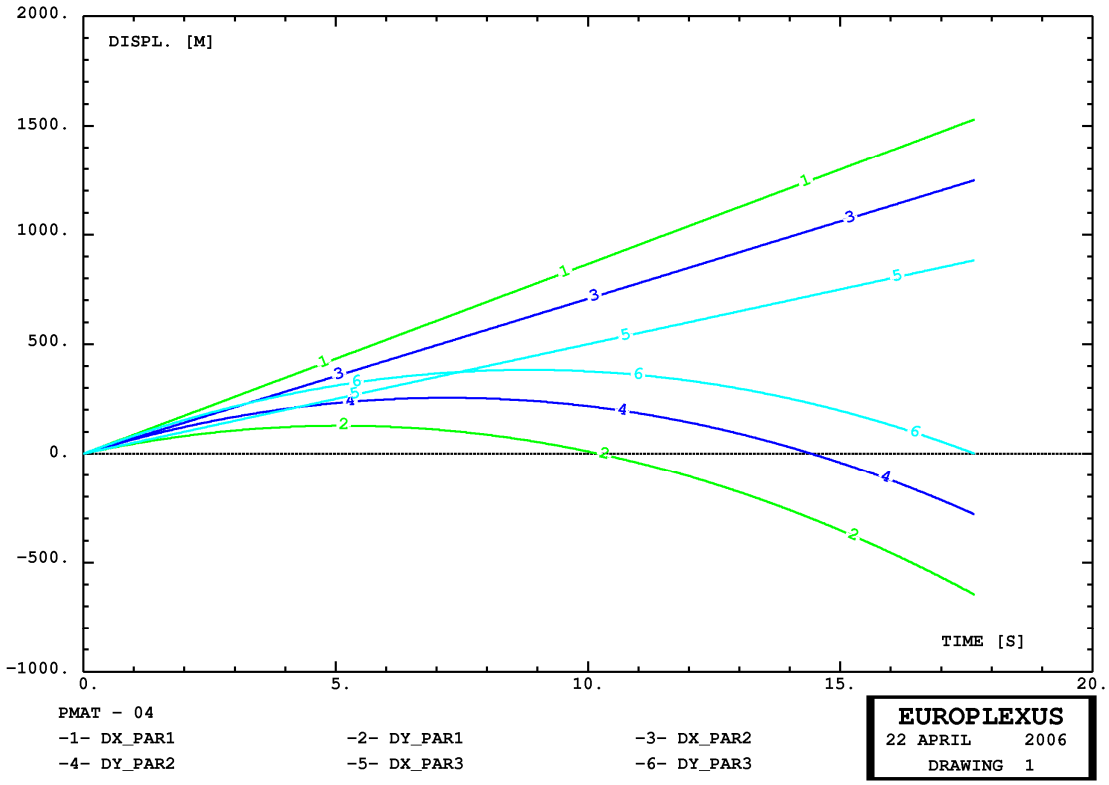
The mesh generation file (K2000):

```
*%siz 100
opti echo 1;
*
opti titr 'PMAT - 04';
opti dime 2 elem qua4;
opti trac psc;
opti ftra 'pmat04_mesh.ps';
*
p0=0 0;
g = 9.80665d0;
v0 = 100.;
n = 1000;
*
* First projectile
*
phi0 = 30.d0;
sinp = sin phi0;
cosp = cos phi0;
tfin = 2.d0 * v0 * sinp / g;
dt = tfin / n;
*
par1 = manu poi1 (p0 plus (0 0));
*
x y = coor p0;
t = 0.0;
i = 0;
p2 = p0 plus (0 0);
repe loop1 n;
 i = i + 1;
 t = t + dt;
 x = v0 * t * cosp;
 y = v0 * t * sinp - (0.5d0 * g * t * t);
 p1 = p2;
 p2 = x y;
 ele = manu seg2 p1 p2;
 si (i ega 1);
   tra1 = ele;
 sinon;
   tra1 = tra1 et ele;
 finsi;
fin loop1;
*
* Second projectile
*
phi0 = 45.d0;
sinp = sin phi0;
cosp = cos phi0;
tfin = 2.d0 * v0 * sinp / g;
dt = tfin / n;
*
par2 = manu poi1 (p0 plus (0 0));
*
x y = coor p0;
t = 0.0;
i = 0;
p2 = p0 plus (0 0);
repe loop2 n;
 i = i + 1;
 t = t + dt;
 x = v0 * t * cosp;
 y = v0 * t * sinp - (0.5d0 * g * t * t);
 p1 = p2;
 p2 = x y;
 ele = manu seg2 p1 p2;
 si (i ega 1);
   tra2 = ele;
 sinon;
   tra2 = tra2 et ele;
 finsi;
fin loop2;
*
* Third projectile
*
phi0 = 60.d0;
sinp = sin phi0;
cosp = cos phi0;
tfin = 2.d0 * v0 * sinp / g;
dt = tfin / n;
*
par3 = manu poi1 (p0 plus (0 0));
*
x y = coor p0;
t = 0.0;
i = 0;
p2 = p0 plus (0 0);
repe loop3 n;
 i = i + 1;
 t = t + dt;
 x = v0 * t * cosp;
 y = v0 * t * sinp - (0.5d0 * g * t * t);
 p1 = p2;
 p2 = x y;
 ele = manu seg2 p1 p2;
 si (i ega 1);
   tra3 = ele;
 sinon;
   tra3 = tra3 et ele;
 finsi;
fin loop3;
*
mesh=par1 et par2 et par3 et tra1 et tra2 et tra3;
*
tass mesh;
trac qual mesh;
*
opti sauv form 'pmat04.msh';
sauv form mesh;
*
opti trac mif;
trac tra2;
fin;
```

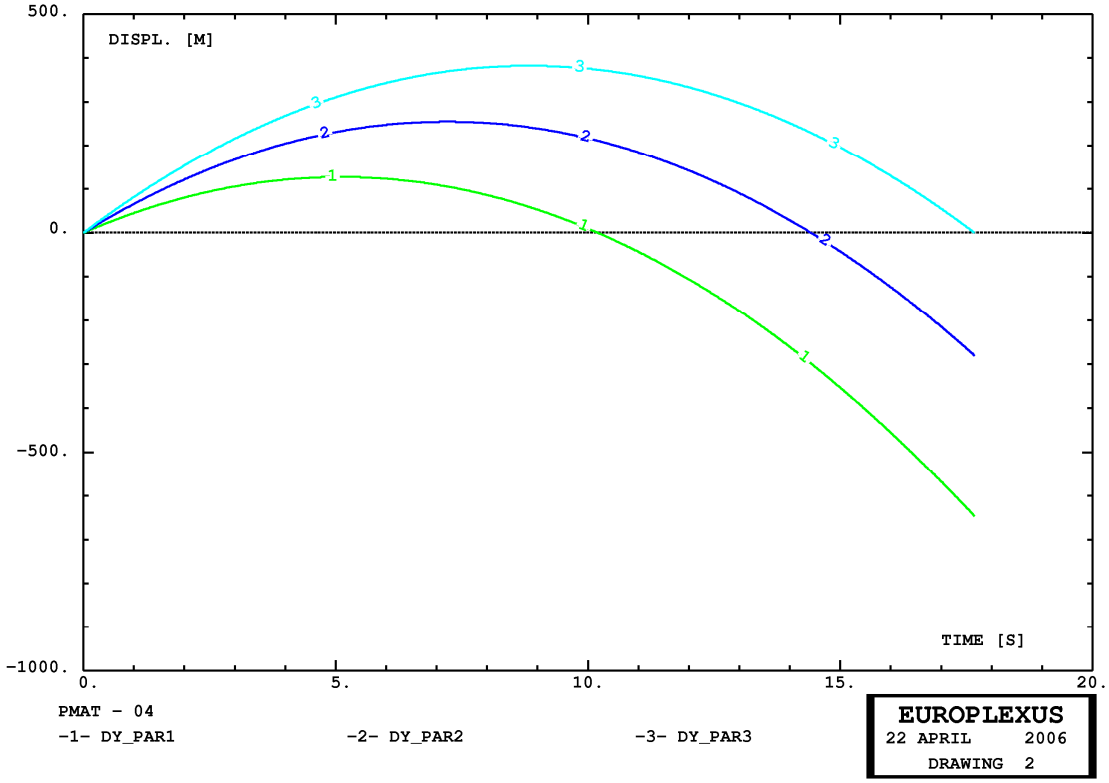
The EUROPLEXUS input file is:

```
PMAT - 04
ECHO
 CONV win
CPLA LAGR
CAST MESH
DIME
  PT2L 3006 PMAT 3 FUN2 3000 ZONE 2
TERM
GEOM PMAT par1 par2 par3 FUN2 tra1 tra2 tra3 TERM
COMP EPAI 10.0 LECT par1 par2 par3 TERM
          1.0 LECT tra1 tra2 tra3 TERM
     COUL roug LECT par1 TERM
          jaun LECT par2 TERM
          rose LECT par3 TERM
          vert LECT tra1 TERM
          bleu LECT tra2 TERM
          turq LECT tra3 TERM
MATE FANT 1.0 LECT tra1 tra2 tra3 TERM
     MASS 1.0 LECT par1 par2 par3 TERM
INIT VITE 1 86.6025404D0 LECT par1 TERM
     VITE 2 50.0000000D0 LECT par1 TERM
     VITE 1 70.7106781D0 LECT par2 TERM
     VITE 2 70.7106781D0 LECT par2 TERM
     VITE 1 50.0000000D0 LECT par3 TERM
     VITE 2 86.6025404D0 LECT par3 TERM
CHAR CONST GRAV 0 -9.80665D0 LECT par1 par2 par3 TERM
ECRI DEPL VITE FREQ 100
          POIN LECT par1 par2 par3 TERM
     FICH ALIC TEMP FREQ 1
               POIN LECT par1 par2 par3 TERM
     FICH ALIC FREQ 250
OPTI NOTE PAS UTIL
 log 1
CALCUL TINI 0. TEND 17.66200291D0 PASF 17.66200291E-3 NMAX 1000
*=====================================================================
PLAY
CAME   1 EYE   5.09858E+02  1.27465E+02  2.62775E+03
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.68819E+01
SCEN GEOM NAVI FREE
          LINE HEOU
          POIN SPHP
     COLO PAPE
     VECT SCCO FIEL VITE SCAL USER PROG 47 PAS 4 99 TERM
     TEXT VSCA
SLER CAM1 1 NFRA 1
FREQ 10
TRAC OFFS FICH AVI NOCL NFTO 101 FPS 15 KFRE 10 COMP -1 REND
GOTR LOOP 99 OFFS FICH AVI CONT NOCL REND
GO
TRAC OFFS FICH AVI CONT REND
ENDPLAY
*=====================================================================
SUIT
Post-treatment
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dx_par1' DEPL COMP 1 NOEU LECT par1 TERM
COUR  2 'dy_par1' DEPL COMP 2 NOEU LECT par1 TERM
COUR  3 'dx_par2' DEPL COMP 1 NOEU LECT par2 TERM
COUR  4 'dy_par2' DEPL COMP 2 NOEU LECT par2 TERM
COUR  5 'dx_par3' DEPL COMP 1 NOEU LECT par3 TERM
COUR  6 'dy_par3' DEPL COMP 2 NOEU LECT par3 TERM
*
trac 1 2 3 4 5 6 axes 1.0 'DISPL. [M]' yzer
     COLO vert vert bleu bleu turq turq
trac   2   4   6 axes 1.0 'DISPL. [M]' yzer
     COLO      vert      bleu      turq
trac 2 axes 1.0 'Y-DISPL. [M]' xaxe 1 1.0 'X-DISPL. [M]' yzer
     COLO vert
trac 4 axes 1.0 'Y-DISPL. [M]' xaxe 3 1.0 'X-DISPL. [M]' yzer
     COLO bleu
trac 6 axes 1.0 'Y-DISPL. [M]' xaxe 5 1.0 'X-DISPL. [M]' yzer
     COLO turq
list 2 axes 1.0 'Y-DISPL. [M]' xaxe 1 1.0 'X-DISPL. [M]'
list 4 axes 1.0 'Y-DISPL. [M]' xaxe 3 1.0 'X-DISPL. [M]'
list 6 axes 1.0 'Y-DISPL. [M]' xaxe 5 1.0 'X-DISPL. [M]'
*
QUAL DEPL COMP 1 LECT par3 TERM REFE 8.831001451D+2 TOLE 1.E-6
     DEPL COMP 2 LECT par3 TERM REFE 0.000000000D+0 TOLE 1.E-6
*=====================================================================
SUIT
Post-treatment (rendering on bitmap file)
ECHO
*
RESU ALIC GARD PSCR
*
SORT VISU NSTO 1
*
*=====================================================================
PLAY
CAME   1 EYE   5.09858E+02  1.27465E+02  2.62775E+03
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.68819E+01
SCEN GEOM NAVI FREE
          LINE HEOU
          POIN SPHP
     COLO PAPE
     VECT SCCO FIEL VITE SCAL USER PROG 47 PAS 4 99 TERM
     TEXT VSCA
SLER CAM1 1 NFRA 1
FREQ 1
TRAC OFFS FICH BMP REND
GOTR LOOP 3 OFFS FICH BMP REND
GO
TRAC OFFS FICH BMP REND
ENDPLAY
*=====================================================================
FIN
```

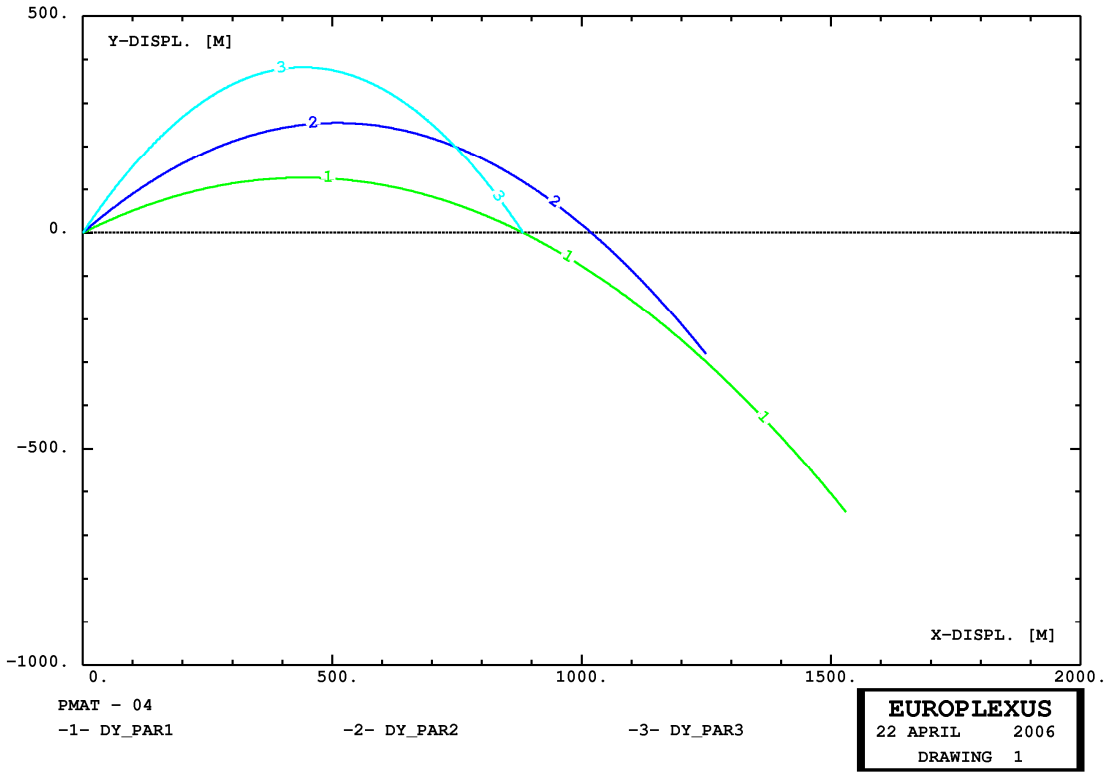
Some results: horizontal and vertical displacement components as a function of time (note that motion is uniform in the horizontal direction since there is no air resistance in the modelled case):



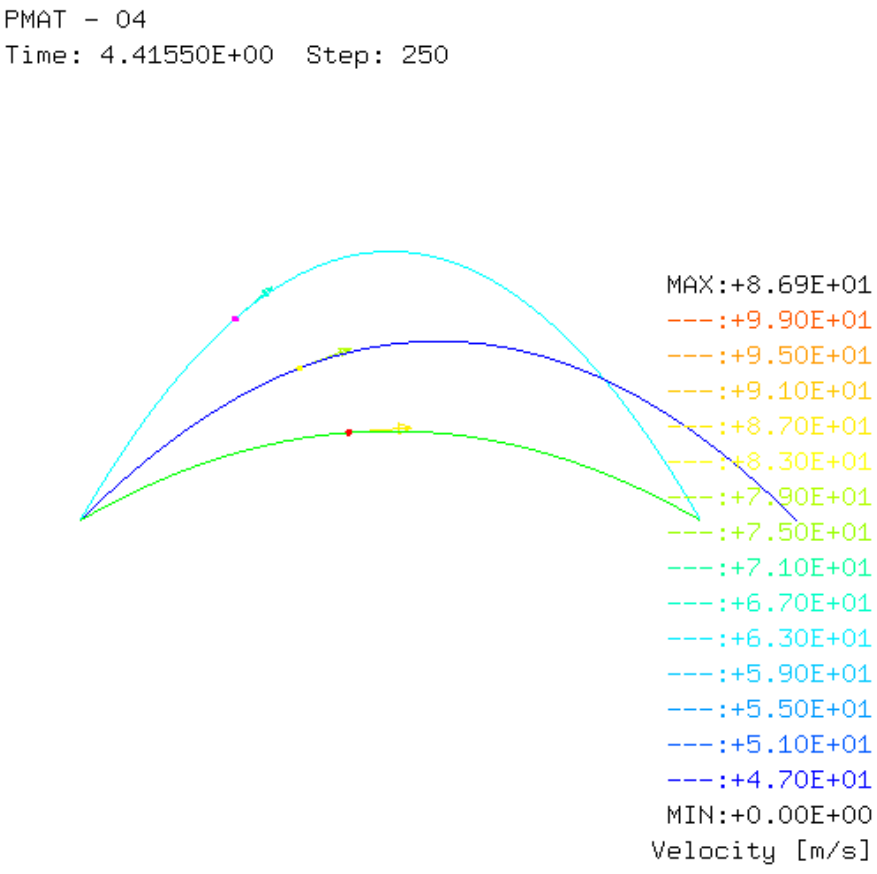
Vertical displacement components as a function of time:



Trajectories:



These results are in perfect agreement with the analytical results. An animation of the motion allows to visually compare the computed positions with the analytical ones:



PMAT01E

This test is similar to PMAT04 but uses only one projectile (the one at 30°) and just one time step to compute the final position of the projectile as it hits the ground.

The solution is in perfect agreement with the analytical one. This should not be surprising, since:

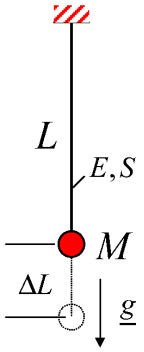
- In this problem there are no deformable structures, and therefore no wave propagation phenomena. Consequently, the usual stability requirements (Courant) of explicit time integration methods do not hold in the present case and one may use an arbitrarily large time increment (as far as stability is concerned).
- As concerns accuracy, the central difference scheme is second-order accurate and therefore it reproduces exactly the analytical solution which, in this case, is a second-degree polynomial (parabola).

A summary of solutions computed with different time increments is given in the following Table:

Case	Description	Flight time t_2	Range X	N. of steps
PMAT01	$\phi_0 = 30°$	10.197	883.1	1000
PMAT01B	$\phi_0 = 30°$	10.197	883.1	100
PMAT01C	$\phi_0 = 30°$	10.197	883.1	10
PMAT01D	$\phi_0 = 30°$	10.197	883.1	2
PMAT01E	$\phi_0 = 30°$	10.197	883.1	1
PMAT02	$\phi_0 = 45°$	14.421	1019.7	1000
PMAT03	$\phi_0 = 60°$	17.662	883.1	1000
PMAT04	$\phi_0 = 30°, 45°, 60°$	10.197, 14.421, 17.662	883.1, 1019.7	1000

Exercise 1 – Suspended mass

- Single-element discrete model: check vs. analytical solution
- Explain possible reasons for observed discrepancies
- Try out different values: e.g. gravity 1000 times smaller
- Discuss multi-element discrete model
- Replace gravity by initial velocity and discuss effects of structure modeling: A) as a bar, B) as a cable …



$L = 1$ m
$M = 100$ kg
$g = 10$ m/s^2
$S = 2.5\times10^{-8}$ m^2
$E = 2\times10^{11}$ Pa
$\rho = 8000$ kg/m^3
$\nu = 0$

41

Linear static analysis

The applied force is:

$$F = mg = 1000 \text{ N}$$

and the stress:

$$\sigma = F / S = 1000 / 2.5\times10^{-8} = 4\times10^{10} \text{ Pa}$$

This induces a strain:

$$\varepsilon = \sigma / E = 4\times10^{10} / 2\times10^{11} = 0.2$$

The elongation is:

$$\Delta L = L\varepsilon = 0.2 \text{ m}$$

Linear dynamic analysis

The cable mass is:

$$m = \rho V = \rho LS = 8000 \bullet 1 \bullet 2.5\times10^{-8} \ll M$$

and is therefore negligible with respect to the concentrated mass M.

By schematizing this system as a single-d.o.f. oscillator, the pulsation of the oscillation would be:

$$\omega = 2\pi f = \sqrt{K / M}$$

where f indicates the frequency and K the stiffness. The latter is given by:

$$K = \frac{F}{\Delta L} = \frac{\sigma S}{\Delta L} = \frac{E\varepsilon S}{\Delta L} = \frac{E\Delta L}{L\Delta L} S = \frac{ES}{L}$$

Hence:

$$\omega = \sqrt{\frac{ES}{LM}} = \sqrt{\frac{2\times10^{11}\cdot 2.5\times10^{-8}}{1\cdot 100}} = 7.071\ \mathrm{s}^{-1}$$

or, in terms of frequency:

$$f = \frac{\omega}{2\pi} = 1.125\ \mathrm{Hz}$$

The period is:

$$T = 1/f = 0.889\ \mathrm{s}$$

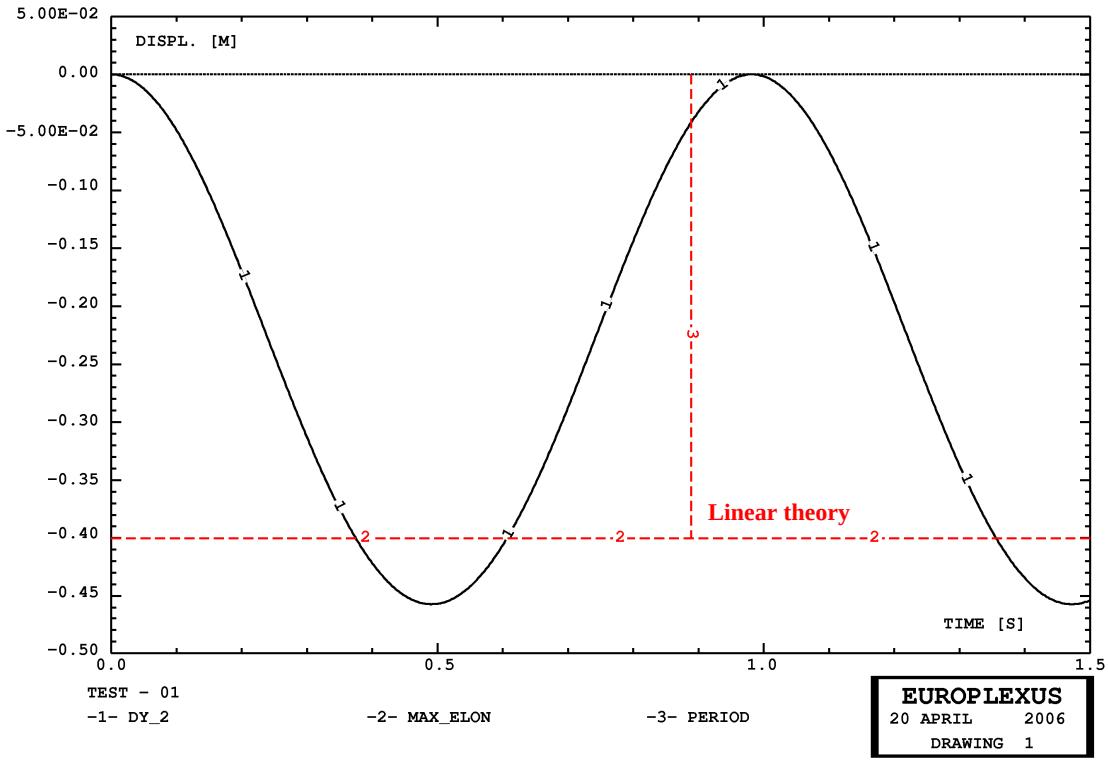
The expected behaviour is a sinusoidal oscillation around the static deflection value. The maximum dynamic deflection is twice the static value:

$$\Delta L^{\mathrm{dyn}} = 2\cdot\Delta L^{\mathrm{sta}} = 0.4\ \mathrm{m}$$

Numerical simulation

TEST01

Discretize the system by just one Finite Element of the "cable" type (FUN2). These elements do not offer any resistance to bending. In addition, the assumed material (of type FUNE) is linear elastic but with no resistance to compression (only to traction) and the formulation is large-strain as concerns axial deformations. The result is:



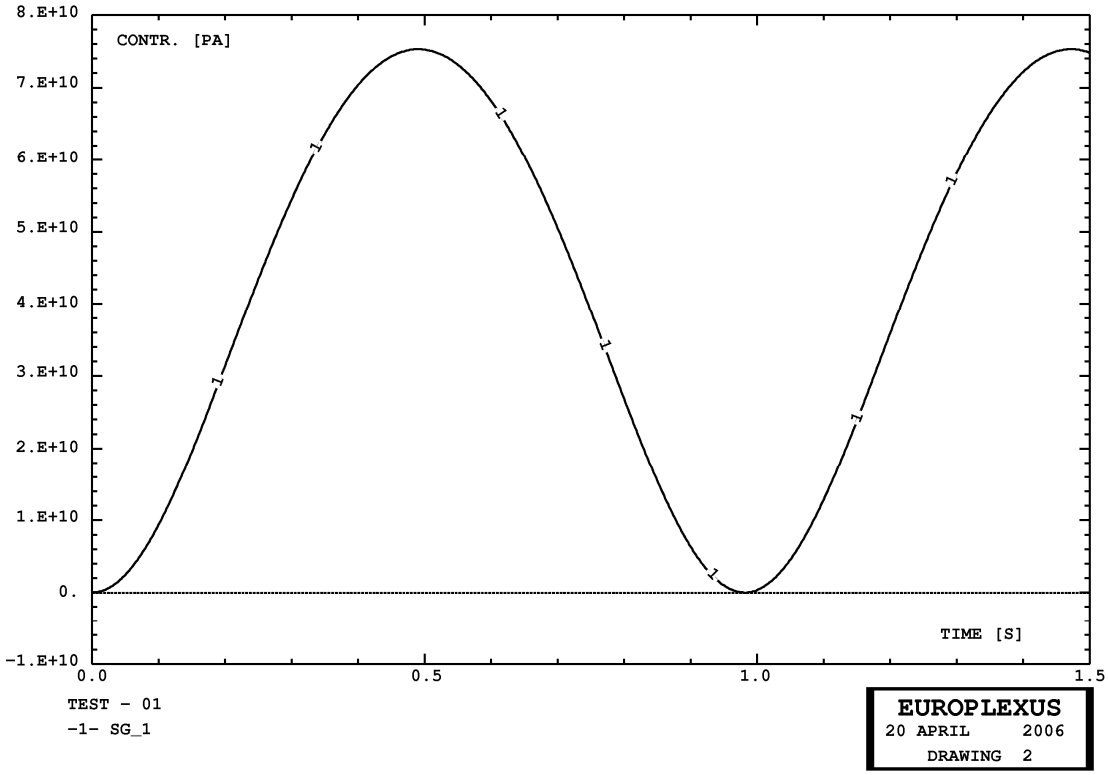
The obtained displacement resembles the expected one. However:

- The obtained maximum elongation is larger than the expected value (~0.45 instead of 0.40)
- The oscillation period is longer than expected (~0.98 instead of 0.89).

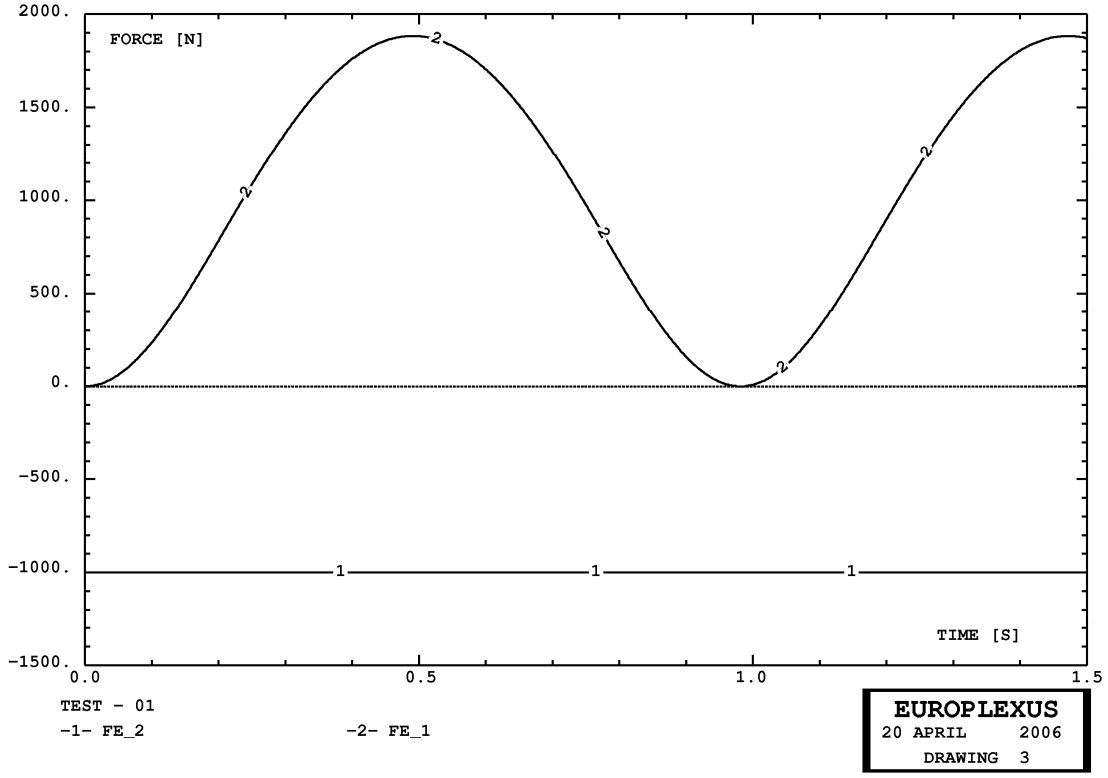
The EUROPLEXUS input file for this problem is:

```
TEST - 01
*-----------------------------------------------------------------------
ECHO
*CONV win
*-------------------------------------------------------------Problem type
CPLA NONL LAGR
*-----------------------------------------------------------Dimensioning
DIME
  PT2L 2 FUN2 1 PMAT 1 ZONE 2
  TABL 1 2
  FORC 1
TERM
*--------------------------------------------------------------------Geometry
GEOM LIBR POIN 2 FUN2 1 PMAT 1 TERM
 0 0  0 -1
 1 2
 2
*-------------------------------------------------Geometrical complements
COMP EPAI 2.5E-8 LECT 1 TERM
*-----------------------------------------------------------Material data
MATE FUNE RO 8000. YOUN 2.0E11 NU 0.0 ELAS 2.0E11 ERUP 1.0E0
          TRAC 1 2.0E11 1.E0
          LECT 1 TERM
     MASS 100.0 LECT 2 TERM
*-----------------------------------------------Boundary conditions
LINK COUP
     BLOQ 2 LECT 1 TERM
*-------------------------------------------------------------Applied loads
CHAR 1 FACT 2 FORC 2 -1.E3 LECT 2 TERM
       TABL 2 0.0 1.0 10.0 1.0
*-----------------------------------------------------------------------Outputs
ECRI DEPL VITE CONT ECRO TFREQ 0.5
     FICH ALIC TEMP FREQ 20
               POIN LECT 1 2 TERM
               ELEM LECT 1 TERM
*-----------------------------------------------------------------------Options
OPTI PAS UTIL NOTEST
*-------------------------------------------------Transient calculation
CALCUL TINI 0. TEND 1.5 PASF 0.1E-3
*=============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
*-----------------------------------------------------Curve definitions
COUR 1 'dy_2'     DEPL COMP 2 NOEU LECT  2 TERM
COUR 2 'sg_1'     CONT COMP 1 ELEM LECT  1 TERM
COUR 3 'fe_2'     FORC COMP 2 NOEU LECT  2 TERM
COUR 4 'fe_1'     FORC COMP 2 NOEU LECT  1 TERM
DCOU 6 'Max_elon' 2
       0.0 -0.4
       1.5 -0.4
DCOU 7 'Period' 2
       0.889 0.0
       0.889 -0.4
*-----------------------------------------------------------------------Plots
trac 1 6 7 axes 1.0 'DISPL. [M]' yzer
           colo noir roug roug
           dash 0    2    2
trac 2 axes 1.0 'CONTR. [PA]' yzer
trac 3 4 axes 1.0 'FORCE [N]' yzer
list 1 axes 1.0 'DISPL. [M]'
*-------------------------------------------------Results qualification
QUAL DEPL COMP 2 LECT   2 TERM REFE -4.53636E-1  TOLE 1.E-2
     CONT COMP 1 LECT   1 TERM REFE  7.48171E+10 TOLE 1.E-2
*=======================================================================
FIN
```

The stress history is:



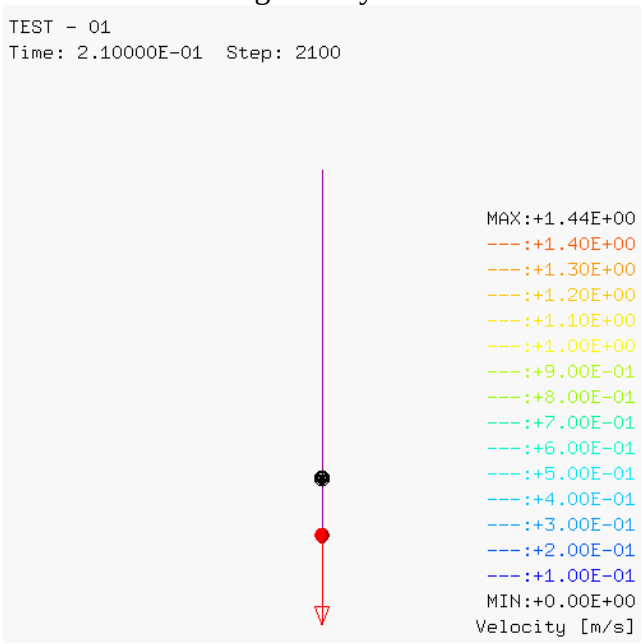
Note that the maximum stress is slightly lower than twice the static value ($\sim 7.5\times10^{10}$ Pa instead of 8.0×10^{10} Pa). The external forces at the two extremities are:



Again, the maximum reaction force at the fixed extremity is slightly lower than twice the applied force (~1900 N instead of 2000 N).

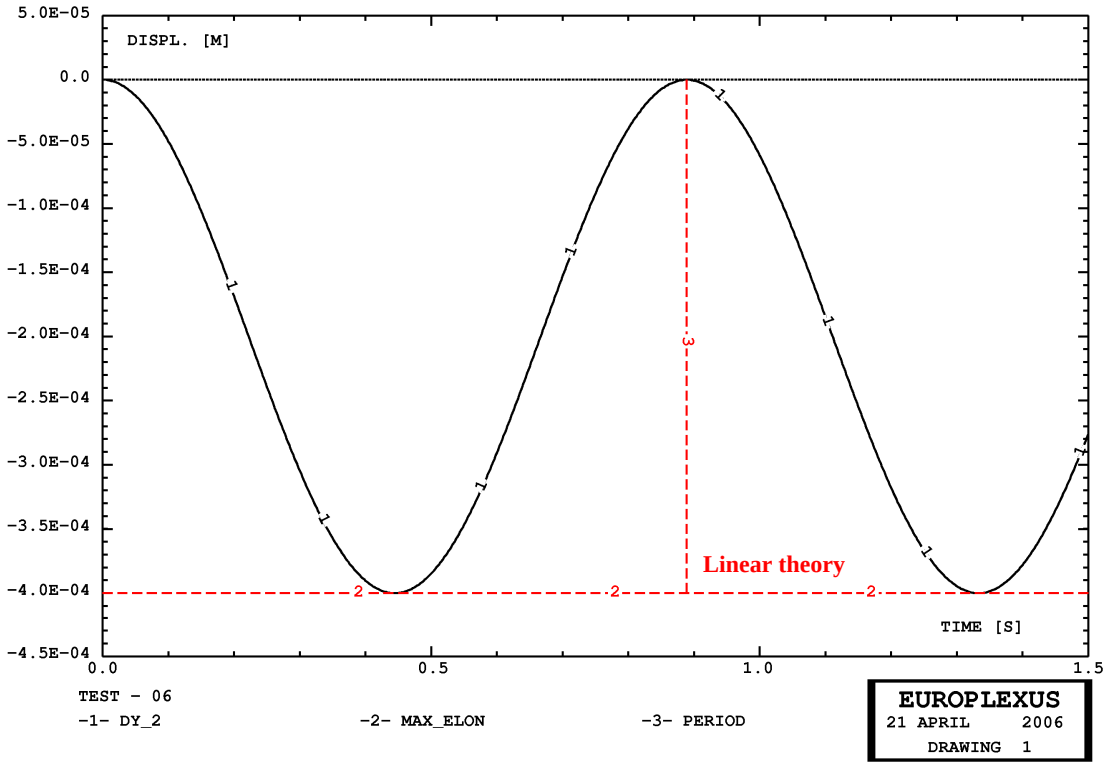
These discrepancies are due to the fact that the code uses a large-strain formulation for the cable element, and that for the chosen values of the parameters the obtained deformations are indeed quite large.

Here is an animation of the deformed geometry:

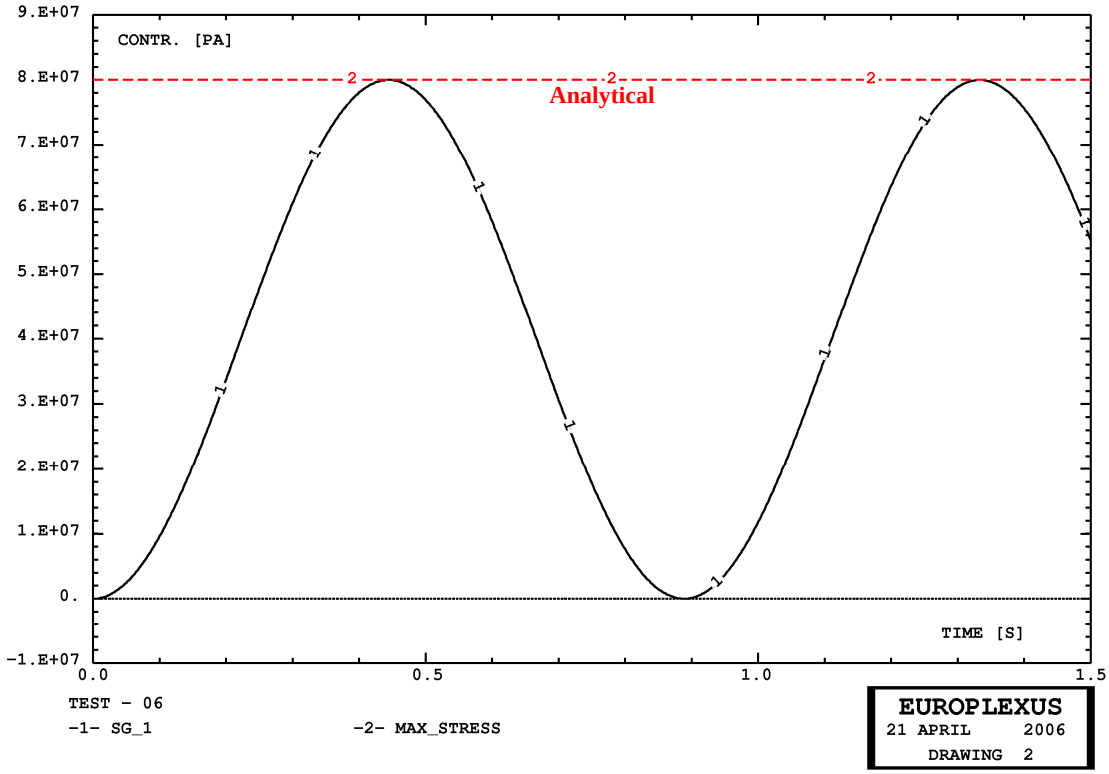


TEST06

Same as TEST01 but uses an applied load 1000 times smaller, so as to remain in the small-strain range. The results are in good agreement with the linear analysis. The maximum deflection is 4×10^{-4} :



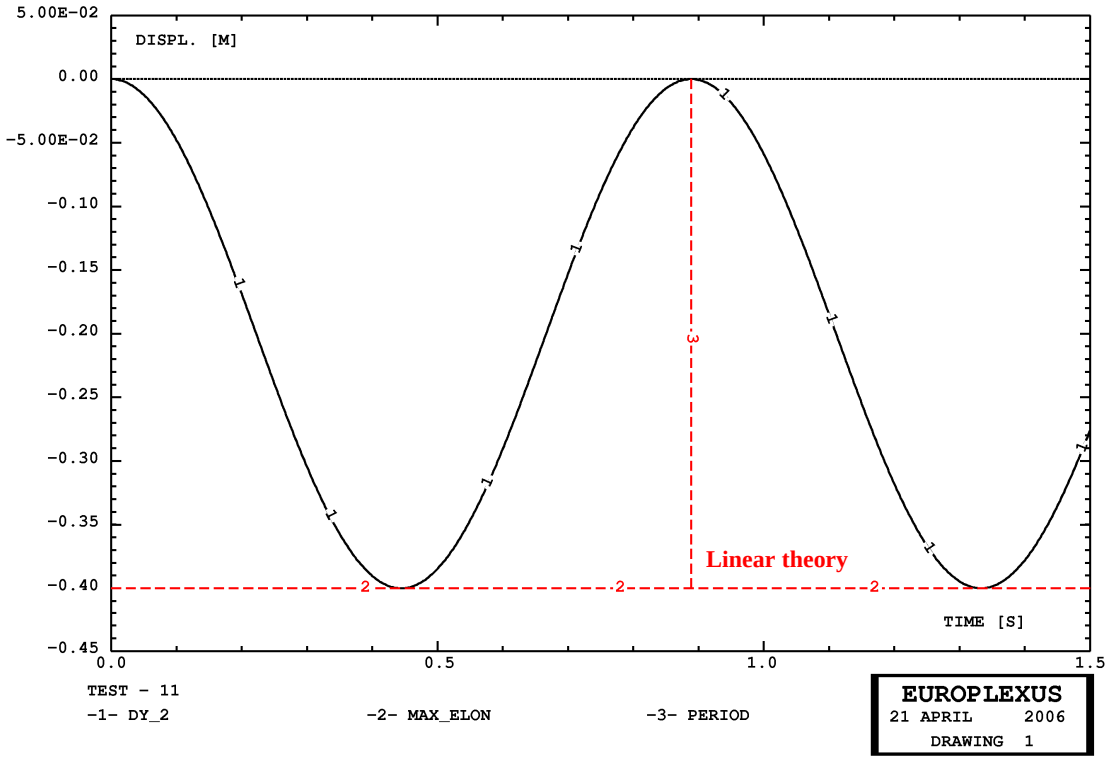
and the oscillation period is very close to the analytical value of 0.889 s. The maximum stress is 8×10^{7} :



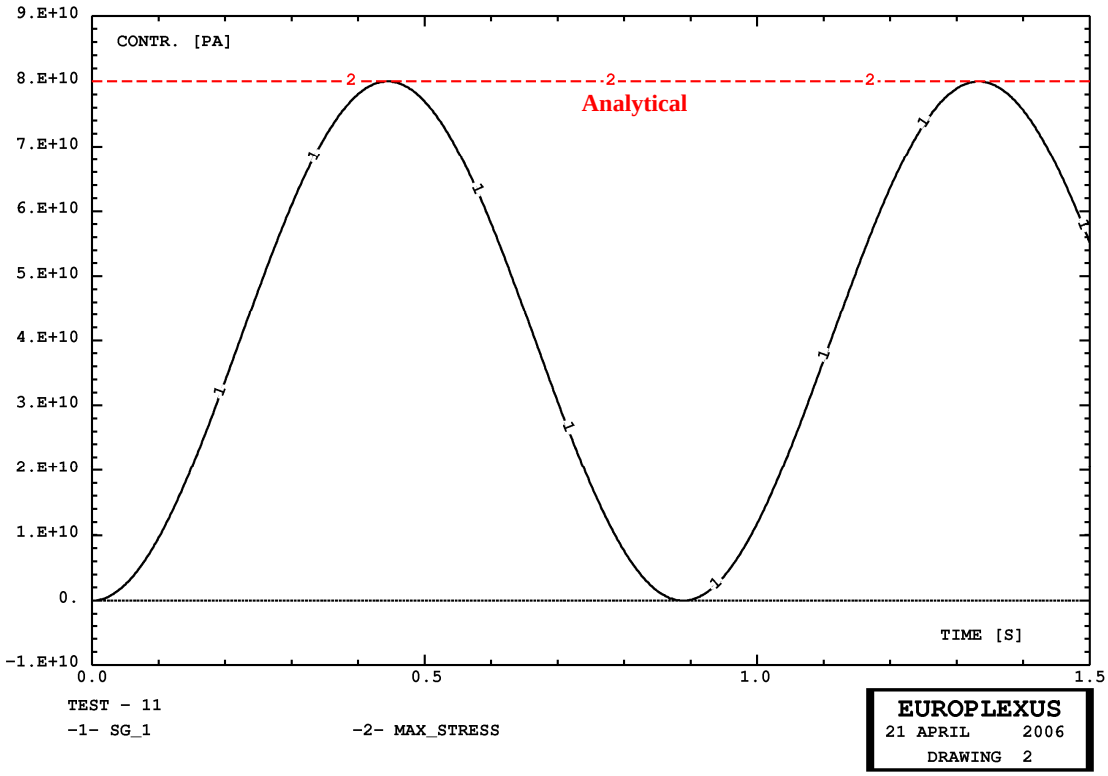
TEST11

Same as TEST01 but use a special option (`OPTI EDSS`) that causes the cable element to use a small-strain formulation instead of the default large-strain formulation. The only difference is in the calculation of the axial strain increment, which reads $\Delta\varepsilon = \Delta L / L_0$ instead of $\Delta\varepsilon = \Delta L / L$.

The results are in good agreement with the linear analysis. The maximum deflection is 0.4 and the period is 0.889 s:



The maximum stress is 8×10^{10} :



TEST08

Same as TEST01 but uses a special option to obtain a "quasi-static" calculation (`OPTI QUAS STAT FSYS beta`). The code adds a linear damping represented by an external force proportional to the mass for each degree of freedom:

$$F_{qs} = -4\pi\beta f_{sys} m v$$

where m is the mass and v the velocity. In practice, only the product βf_{sys} is relevant. The case $\beta = 1$ corresponds to critical damping for the frequency f_{sys}. Here we use $\beta = 1$ and $f_{sys} = 1$ Hz, because in the large-strain case we saw in calculation TEST01 that the obtained period is 0.98 so the frequency is $1/0.98 \approx 1$.

The resulting displacement at 1.5 s is 0.221345, which is already very close to the expected value of 0.221403 (i.e. $\exp(0.2)-1$) that would result from a large-strain static analysis (see below).

Explanation: since $\nu = 0$ there is no cross-section variation as long as the material remains linear elastic (as assumed here). The Cauchy stress is therefore:
$\sigma = F / S_0 = 1000 \text{ N} / 2.5\times10^{-8} \text{ m}^2 = 4\times10^{10} \text{ Pa}$.
This induces a strain (natural): $e = \sigma / E = 4\times10^{10} \text{ Pa} / 2\times10^{11} \text{ Pa} = 0.2$. But we have $e = \ln(L/L_0)$ so that $L/L_0 = \exp(e)$ and $L = L_0 \exp(e)$.
The elongation (or the displacement) is therefore: $\Delta L = L - L_0 = L_0 \exp(e) - L_0$. Since $L_0 = 1$ in this example, we get finally:

$$\Delta L = \exp(0.2) - 1 = 0.221403$$

Comparison of natural vs. engineering strain

1) Engineering stress is defined as:

$$\sigma \doteq F / S_0$$

and engineering strain as:

$$\varepsilon \doteq \int_{L_0}^{L} \frac{1}{L_0} dl = \frac{\Delta L}{L_0} = \frac{L - L_0}{L_0} = \frac{L}{L_0} - 1$$

2) Natural (Cauchy) stress is defined as:

$$s \doteq F / S$$

and natural strain as:

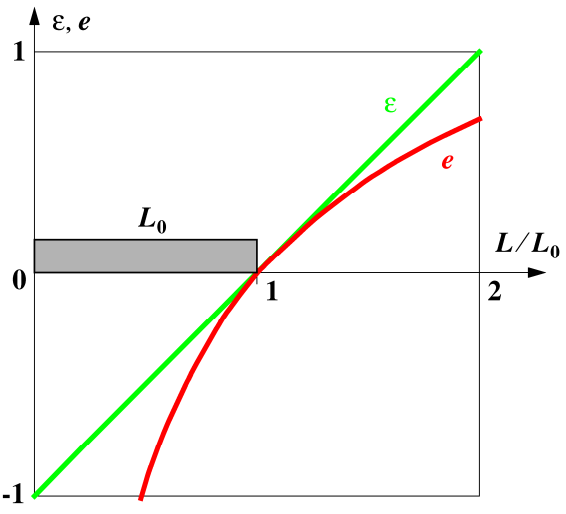
$$e \doteq \int_{L_0}^{L} \frac{1}{L} dl = \ln \frac{L}{L_0}$$

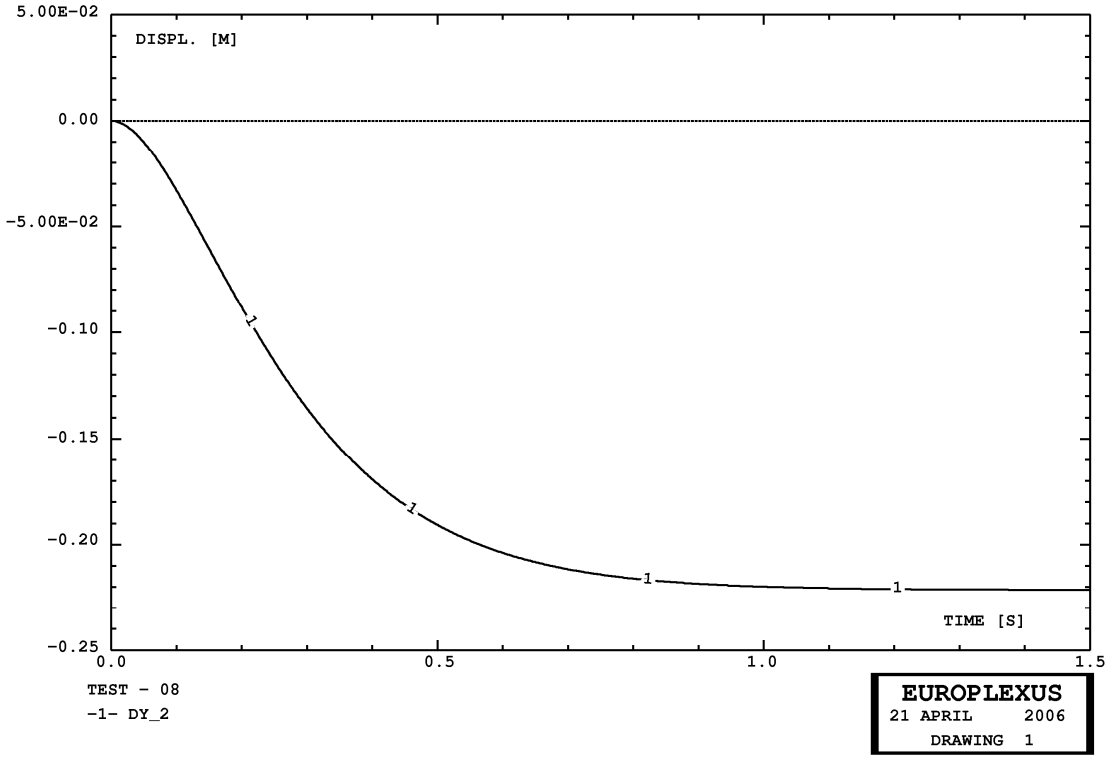
3) We have thus the relationships:

$$e = \ln \frac{L_0 + \Delta L}{L_0} = \ln (1 + \varepsilon) \qquad \text{and} \qquad \varepsilon = \exp (e) - 1$$

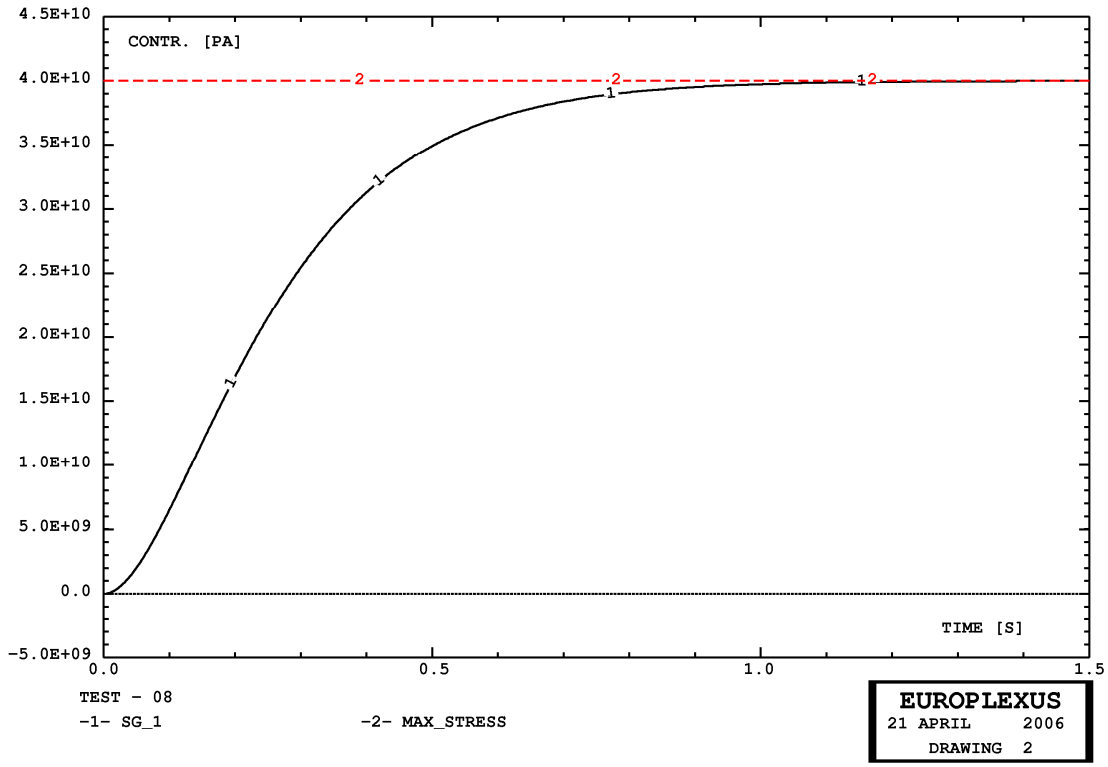
These functions have the following shape:

L / L_0	$\Delta L / L_0$	ε	e	Graph
0.0	-1.0	-1.0	$-\infty$	
0.5	-0.5	-0.5	-0.693	
1.0	0.0	0.0	0.000	
1.5	0.5	0.5	0.405	
2.0	1.0	1.0	0.693	

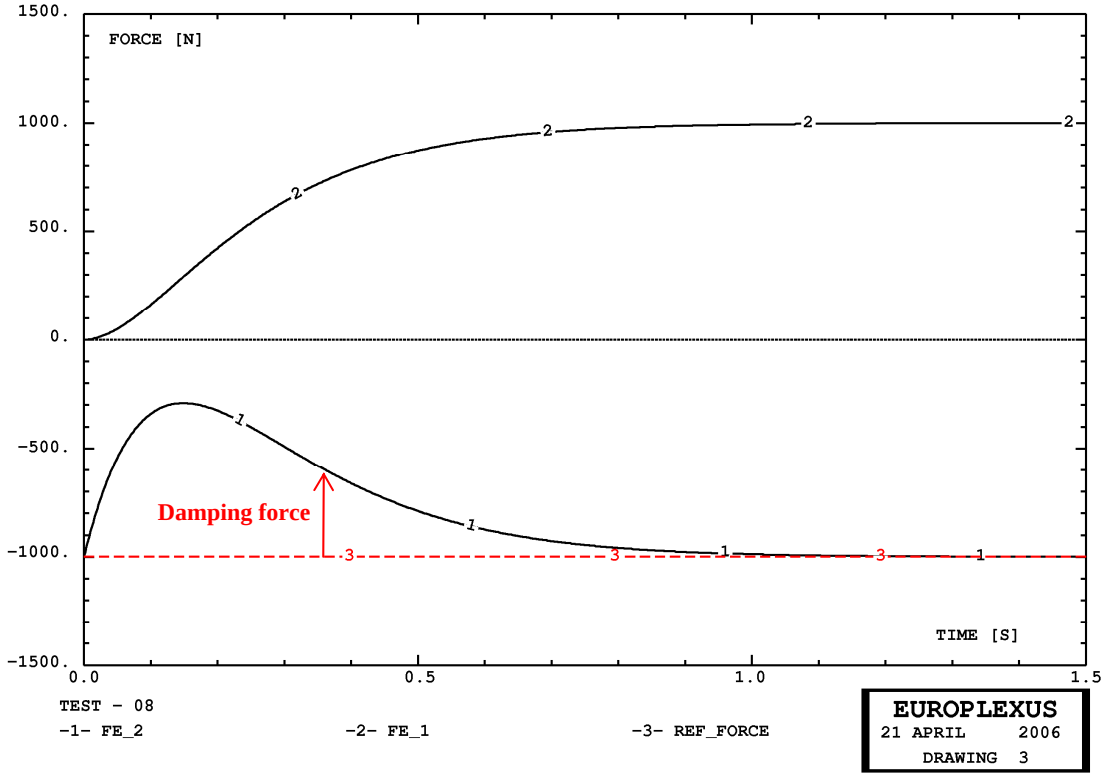




The resulting stress is 4×10^{10} as foreseen by the linear static analysis:

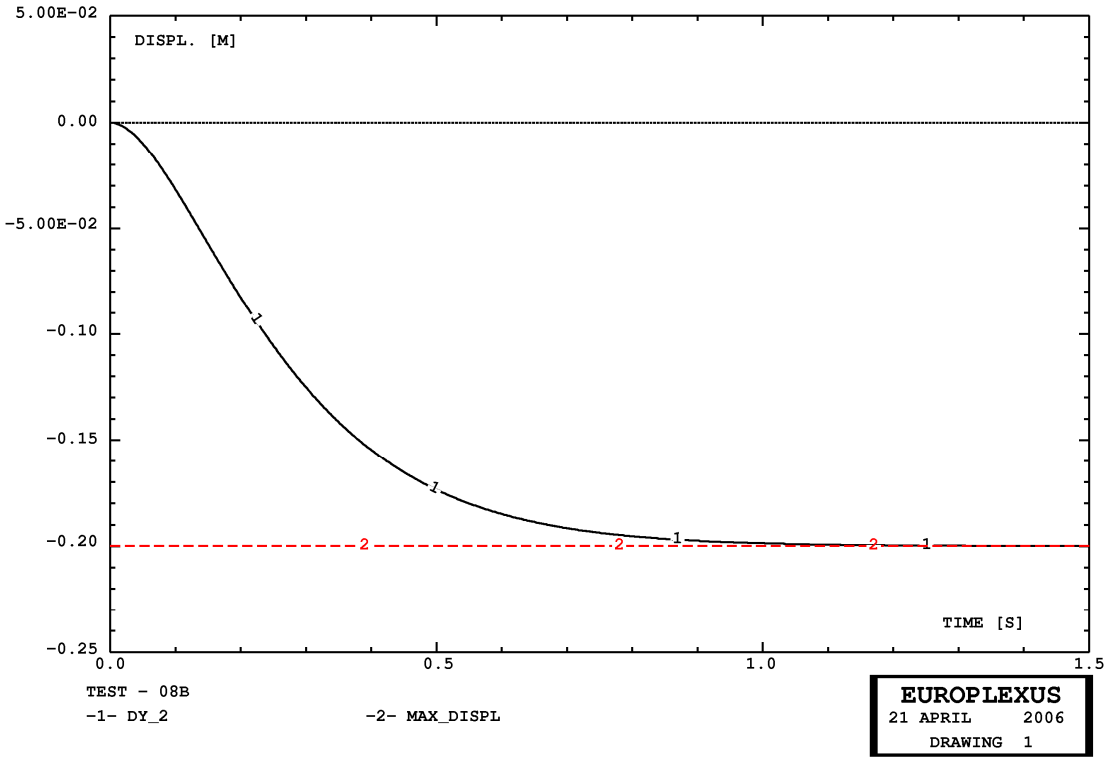


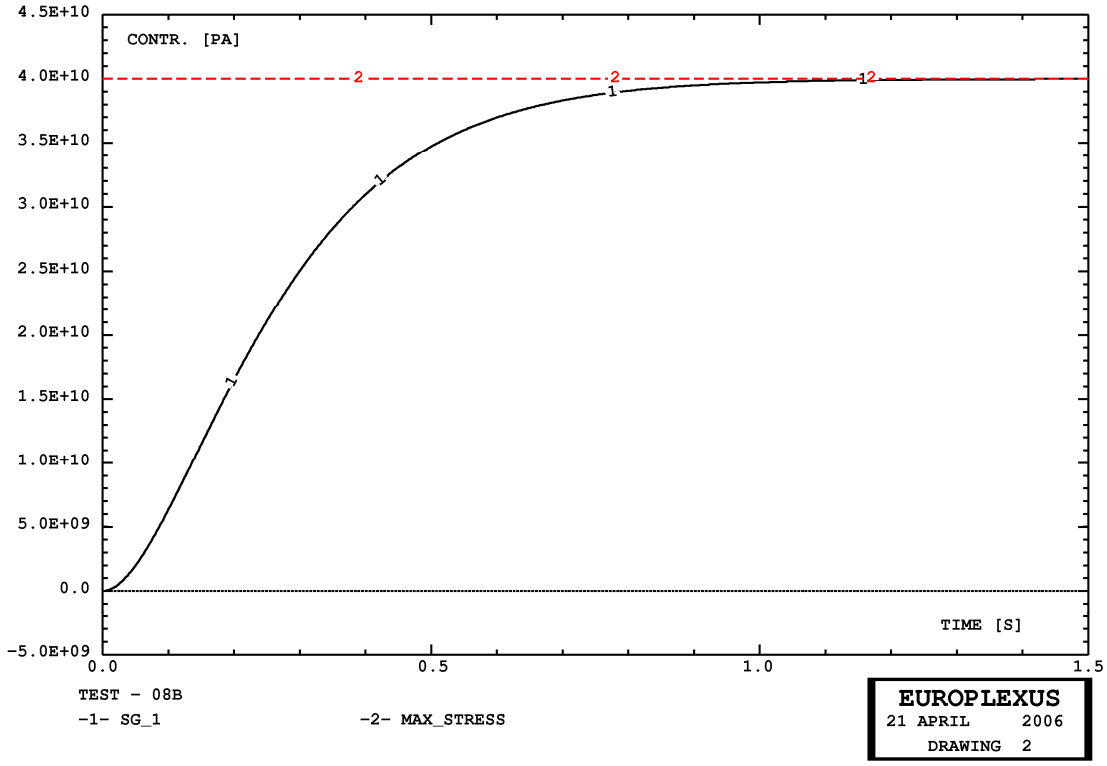
The total external forces at the two extremities have the form shown below. Note that the force applied to the moving end is the sum of the applied force (constant) and of the damping force caused by the quasi-static option, which is proportional to the velocity



TEST08B

Same as TEST08 but uses small-strain option OPTI EDSS. In that case the expected displacement is –0.2 and the expected stress is 4.E10. In this calculation we use the expected damping frequency for the linear case: $f_{sys} = 1.125$ Hz.





TEST12

Same as TEST01 but uses a time increment 100 times larger, i.e. 10 ms instead of 0.1 ms. This value violates the Courant condition, as it is readily verified. In fact in this case the element length is $L = 1$ m while the sound speed in the cable material is:

$$c = \sqrt{E/\rho} = \sqrt{2\times10^{11}/8000} = 5000 \text{ m/s}$$

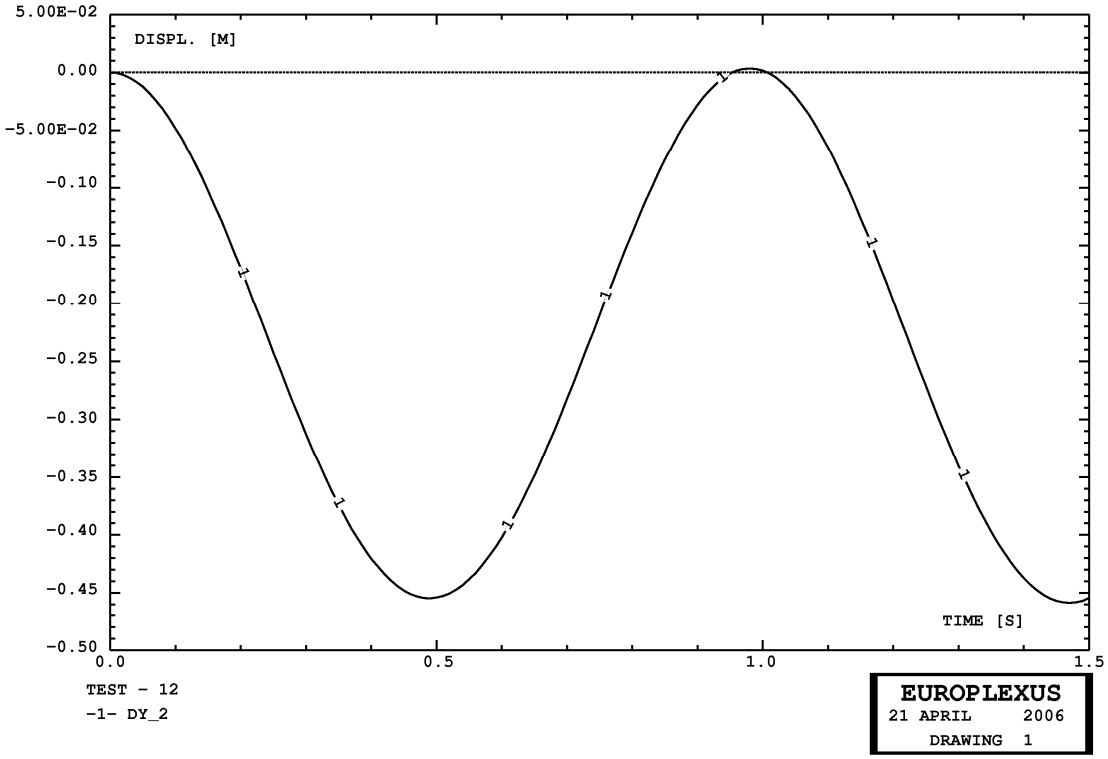
Therefore the estimated critical time increment would be:

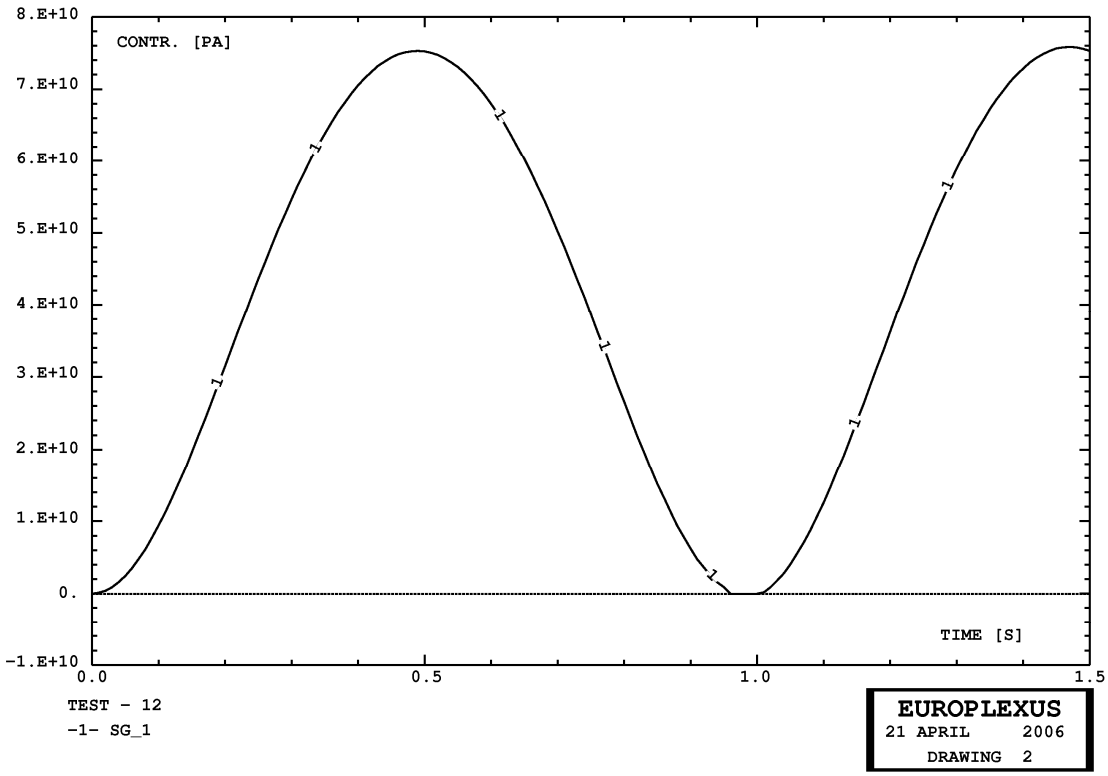
$$\Delta t^{\text{crit}} \simeq L/c = 1/5000 = 0.2 \text{ ms}$$

Nevertheless, if one runs the program with the excessive value of time increment, the obtained results are quite similar to those obtained with the stability-compliant value (see graphs below).

The reason is that this is a very special case. Having used just one element to "discretize" the problem geometry, there are no wave propagation phenomena in the numerical model: one node is fixed and the other one receives the applied load. Therefore, the stability condition does not apply in this case.

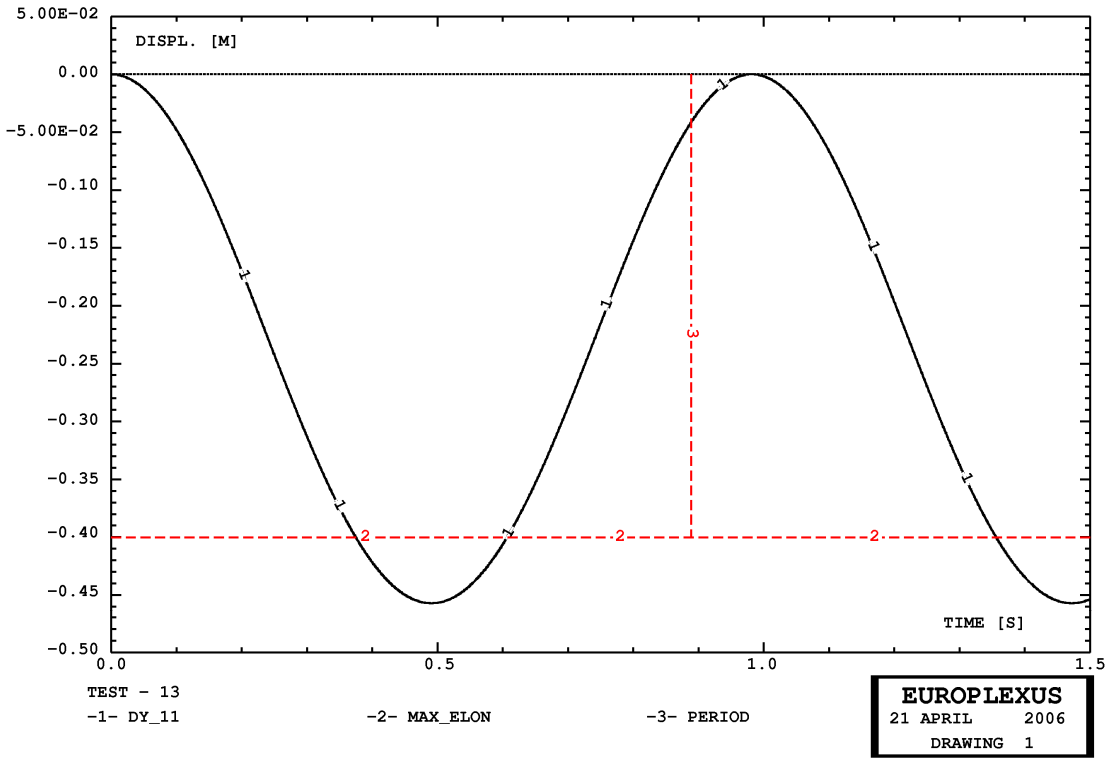
Try out a finer discretization, involving more than one element, to see the disastrous effect of using a time increment beyond the stability limit on the numerical solution.

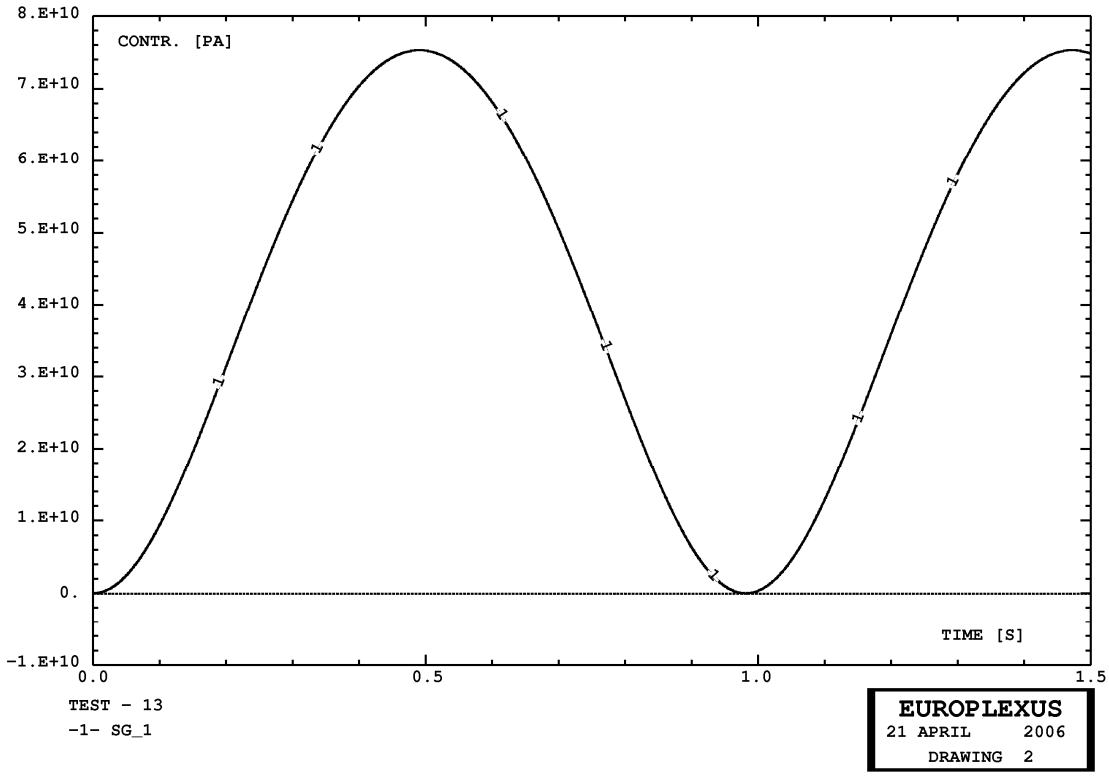

5.00E-02
0.00
-5.00E-02
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
-0.40
-0.45
-0.50
DISPL. [M]
0.0
0.5
1.0
1.5
TIME [S]
TEST - 12
-1- DY_2
EUROPLEXUS
21 APRIL 2006
DRAWING 1


8.E+10
7.E+10
6.E+10
5.E+10
4.E+10
3.E+10
2.E+10
1.E+10
0.
-1.E+10
CONTR. [PA]
0.0
0.5
1.0
1.5
TIME [S]
TEST - 12
-1- SG_1
EUROPLEXUS
21 APRIL 2006
DRAWING 2

TEST13

Same as TEST01 but uses a 10-element mesh (Δt 10 times smaller).





TEST14

Same as TEST13 but uses same Δt as TEST01. This calculation is unstable, as expected.

TEST21

To conclude this exercise, let us consider a similar problem whereby we replace the gravity $\underline{g}$ by an initial velocity $\underline{v}_0$ directed downwards.

The initial kinetic energy of the system is:

$$E_{K0} = \frac{1}{2} M v_0^2$$

The mass will stop when all this energy has been transformed into elastic energy in the cable or bar. Assuming linear elastic behaviour and Poisson's coefficient $\nu = 0$ the resistance force of the bar is:

$$R = \sigma S = E \varepsilon S = \frac{ES}{L_0} \lambda$$

where λ is the elongation:

$$\lambda \doteq L - L_0$$

The elastic energy is:

$$E_E = \int_0^{\Delta L} \frac{ES}{L_0} \lambda d\lambda = \frac{ES}{L_0} \frac{(\Delta L)^2}{2}$$

By posing $E_E = E_{K0}$ one obtains from the above expressions:

$$\Delta L = \sqrt{\frac{L_0 M}{ES}} v_0$$

In order to obtain an elongation of, say, 20 % of the initial length:

$$\Delta L = 0.2 L_0 = 0.2 \text{ m}$$

the initial velocity should be:

$$v_0 = \sqrt{\frac{ES}{L_0 M}} \Delta L = \sqrt{\frac{2.0 \times 10^{11} \cdot 2.5 \times 10^{-8}}{1 \cdot 100}} = 1.414 \text{ m/s}$$

Let us now compute the time τ to reach the maximum elongation. The equation of motion of the system may be written as:

$$M \ddot{\lambda} = -\frac{ES}{L_0} \lambda \quad \rightarrow \quad \ddot{\lambda} = -\frac{ES}{ML_0} \lambda$$

The solution of this equation, for the particular initial conditions considered in this problem, is the following harmonic motion:

$$\lambda(t) = \sin(\omega t)$$

with the pulsation given by:

$$\omega = \sqrt{\frac{ES}{ML_0}} = 7.071 \text{ s}^{-1}$$

i.e. the same value as in the case considered previously, with gravity and zero initial velocity. The desired time τ is clearly ¼ of an oscillation period T, and therefore is given by:

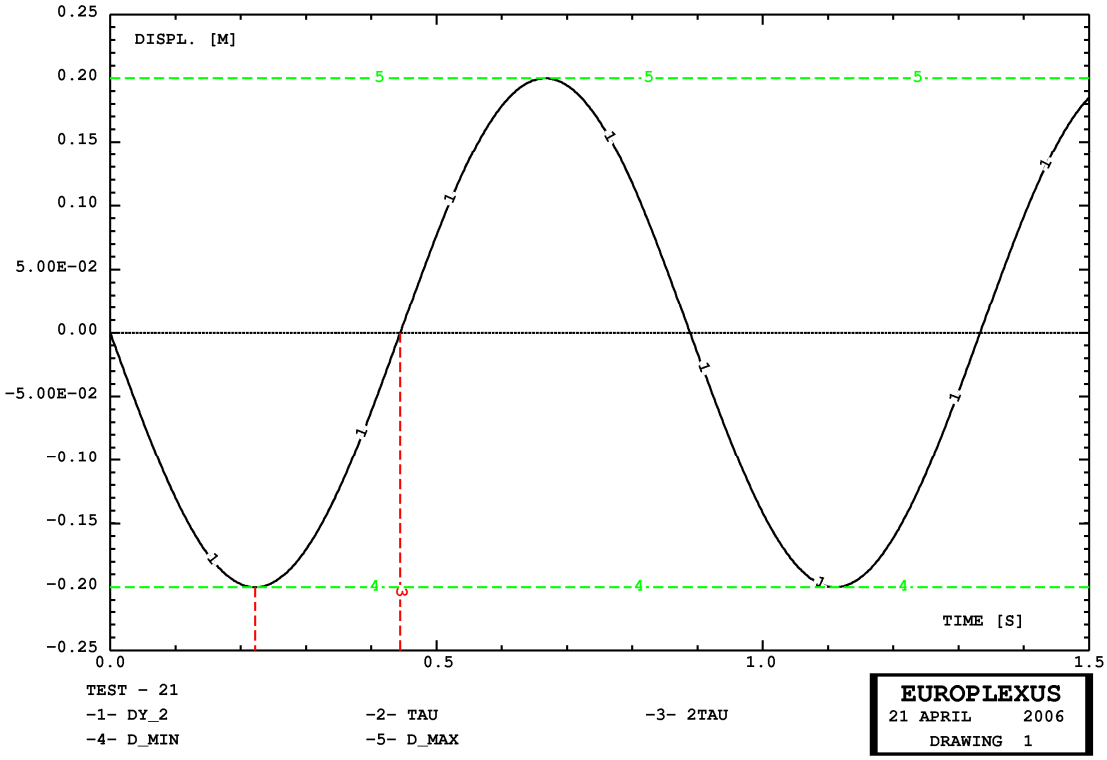
$$\tau = \frac{T}{4} = \frac{2\pi}{4\omega} = 0.222 \text{ s}$$

The mass returns at the initial position after a time $2\tau = 0.444$ s .
Note that these times do *not* depend upon the initial velocity of the mass.

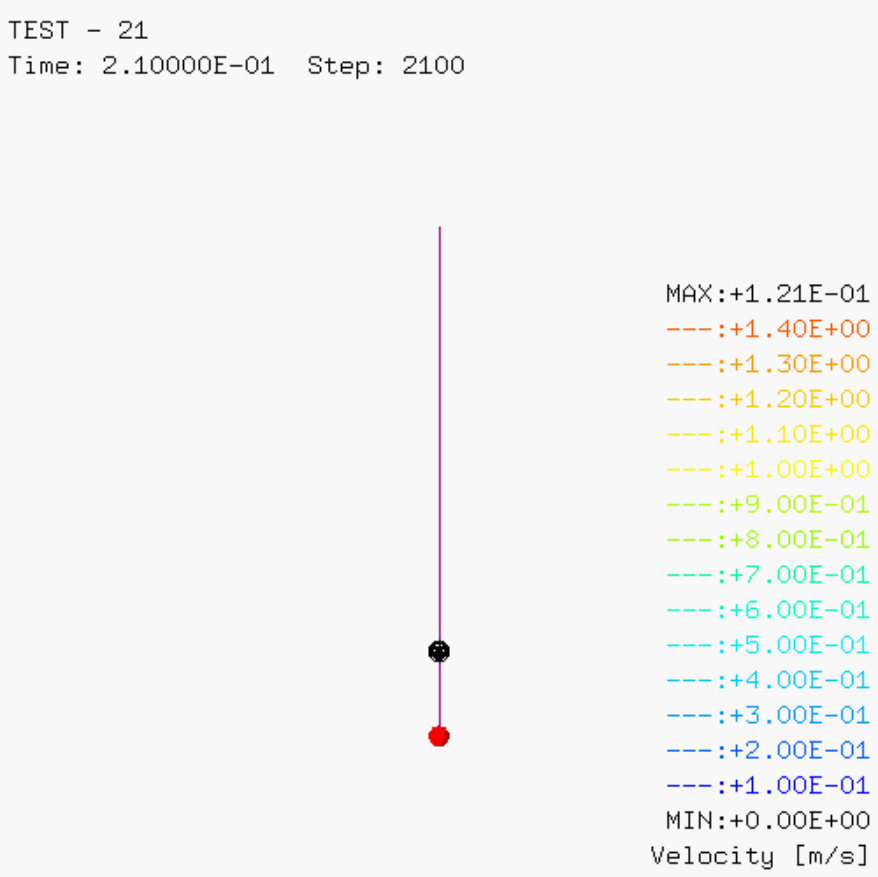
To check these analytical results, a calculation (TEST21) is performed, similar to case TEST11 i.e. by the small strain option EDSS, but without gravity and by an initial velocity of –1.414 m/s in the vertical direction. The input file is as follows:

```
TEST - 21
*------------------------------------------------------------------------
ECHO
*CONV win
*-------------------------------------------------------------Problem type
CPLA NONL LAGR
*-------------------------------------------------------------Dimensioning
DIME
  PT2L 2 FUN2 1 PMAT 1 ZONE 2
  TABL 1 2
  FORC 1
TERM
*--------------------------------------------------------------------Geometry
GEOM LIBR POIN 2 FUN2 1 PMAT 1 TERM
 0 0  0 -1
 1 2
 2
*-----------------------------------------------Geometrical complements
COMP EPAI 2.5E-8 LECT 1 TERM
*-----------------------------------------------------------Material data
MATE VM23 RO 8000. YOUN 2.0E11 NU 0.0 ELAS 2.0E11
          TRAC 1 2.0E11 1.E0
          LECT 1 TERM
     MASS 100.0 LECT 2 TERM
*-----------------------------------------------------Boundary conditions
LINK COUP
     BLOQ 2 LECT 1 TERM
*-----------------------------------------------------Initial conditions
INIT VITE 2 -1.4142 LECT 2 TERM
*------------------------------------------------------------------Outputs
ECRI DEPL VITE CONT ECRO TFREQ 0.5
     FICH ALIC TEMP FREQ 20
               POIN LECT 1 2 TERM
               ELEM LECT 1 TERM
*--------------------------------------------------------------------Options
OPTI PAS UTIL NOTEST
     EDSS
*-------------------------------------------------Transient calculation
CALCUL TINI 0. TEND 1.5 PASF 0.1E-3
*=============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
*-----------------------------------------------------Curve definitions
COUR 1 'dy_2'     DEPL COMP 2 NOEU LECT  2 TERM
COUR 2 'sg_1'     CONT COMP 1 ELEM LECT  1 TERM
COUR 3 'fe_2'     FORC COMP 2 NOEU LECT  2 TERM
COUR 4 'fe_1'     FORC COMP 2 NOEU LECT  1 TERM
DCOU 5 'tau' 2
       0.222 -0.20
       0.222 -0.25
DCOU 6 '2tau' 2
       0.444  0.00
       0.444 -0.25
DCOU 7 'd_min' 2
       0.  -0.20
       1.5 -0.20
DCOU 8 'd_max' 2
       0.   0.20
       1.5  0.20
*-------------------------------------------------------------------Plots
trac 1 5 6 7 8 axes 1.0 'DISPL. [M]' yzer
           colo noir roug roug vert vert
           dash 0    2    2    2    2
           noyl 0    1    1    1    1
trac 2 axes 1.0 'CONTR. [PA]' yzer
trac 3 4 axes 1.0 'FORCE [N]' yzer
*-----------------------------------------------Results qualification
QUAL DEPL COMP 2 LECT   2 TERM REFE  1.85058E-01 TOLE 1.E-2
     CONT COMP 1 LECT   1 TERM REFE -3.70116E+10 TOLE 1.E-2
*=========================================================================
FIN
```

The resulting displacement is shown next and is in excellent agreement with the expected value:

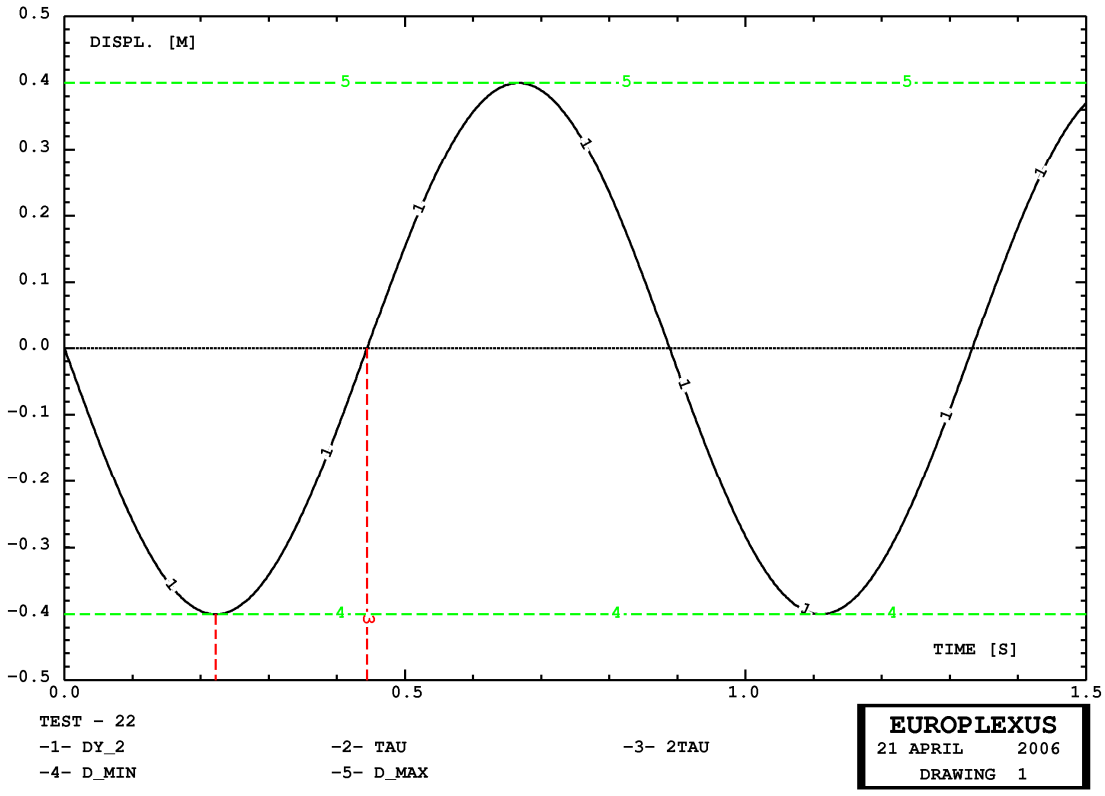


Here is an animation of results:



TEST22

To verify the independence of oscillation period from the initial velocity, we repeat the same calculation but with a twice larger initial velocity $v_0 = -2.828$ m/s . The result is shown next and has the expected shape (the elongation is twofold):

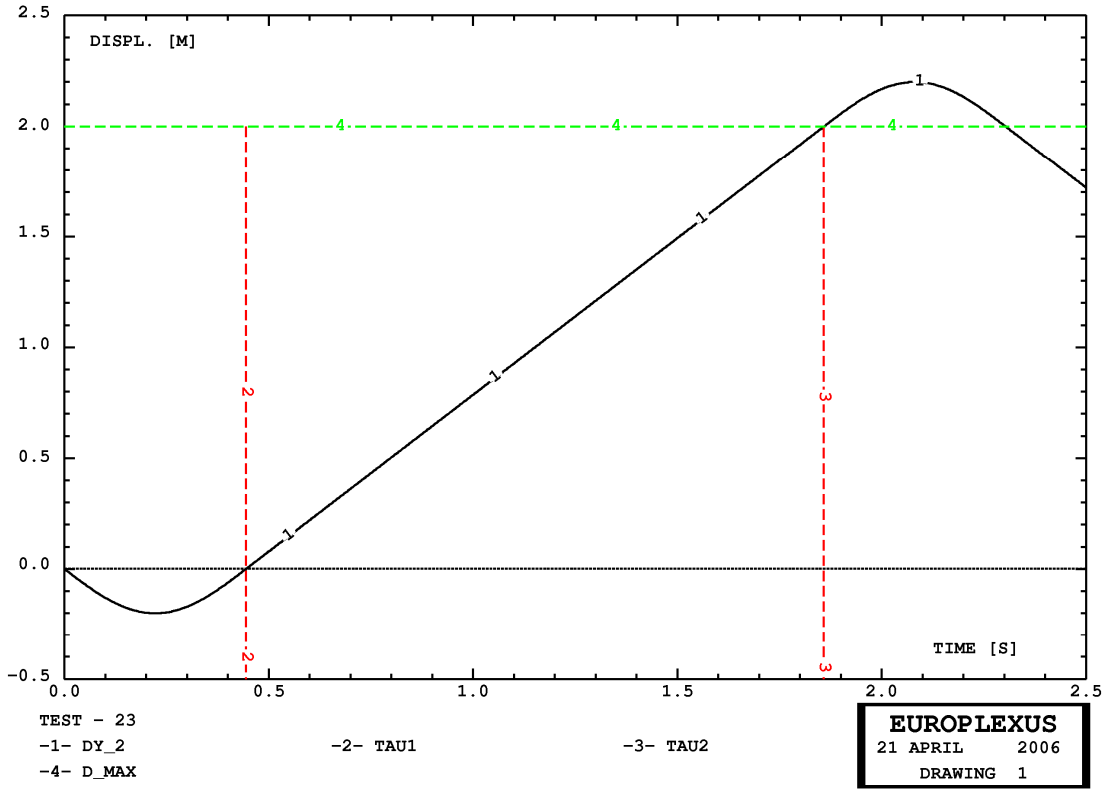


TEST23

In the previous two examples a material of type VM23 (Von Mises isotropic) was assigned to the cable, which therefore acted as a bar (same resistance in compression as in traction).

If one assumes a real cable (FUNE material), however, the behaviour will be different. Since there is no resistance to compression, the mass will have to bounce twice the initial cable length before exerting a traction (in the direction opposite to the initial one) on the cable.

This behaviour is simulated in the calculation TEST23. The picture below shows the displacement in this case:



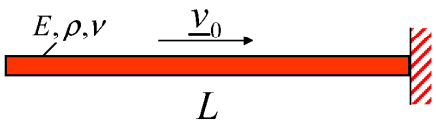
The load is reversed when the cable has reached the opposite orientation. The "load-free" period is:

$$2L/v_0 = (2\cdot 1)/1.4142 = 1.4142 \text{ s}$$

This result is fully confirmed by the numerical calculation, as may be verified graphically from the figure above.

Exercise 2 – Wave propagation

- Obtain 1D analytical solution
- Discuss numerical solution
- Why was cross-section not specified?
- Study effect of time increment
- Study effect of Poisson's ratio …



$L = 1$ m
$\underline{v}_0 = 100$ m/s
$E = 2 \times 10^{11}$ Pa
$\rho = 8000$ kg/m^3
$\nu = 0.3$

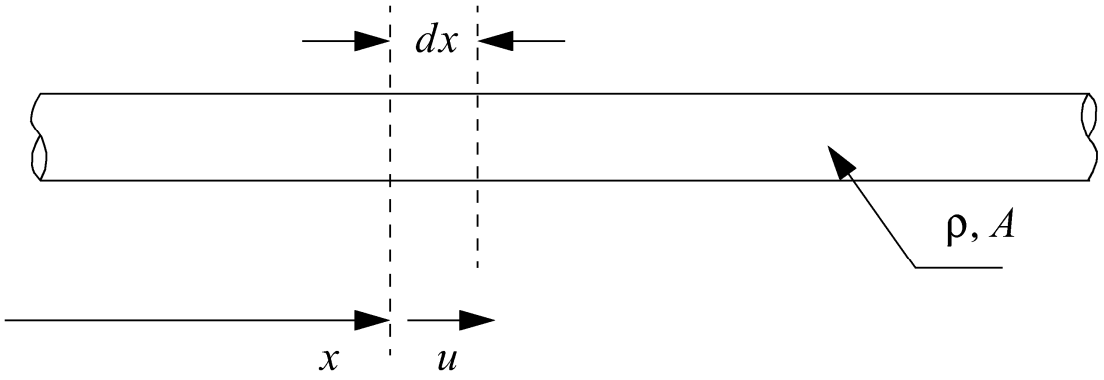
48

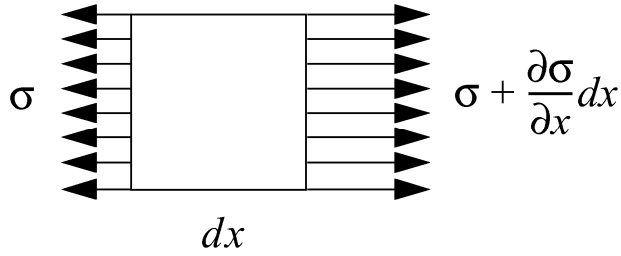
Linear dynamic analysis

Consider the longitudinal waves in a long bar subjected to axial loading.

Assume that:

- The cross section A is constant;
- The material, of density ρ, is homogeneous and isotropic;
- Plane, parallel cross sections remain plane and parallel;
- The stress σ is uniform in each cross section;
- We neglect the effect of lateral inertia.





The (dynamic) equilibrium is expressed by the following equation (equation of motion):

$$-\sigma A+\left(\sigma+\frac{\partial\sigma}{\partial x}dx\right)A=\rho A dx\frac{\partial^2 u}{\partial t^2}$$

from which we obtain:

$$\frac{\partial\sigma}{\partial x}=\rho\frac{\partial^2 u}{\partial t^2}$$

For an elastic material we have $\sigma = E\varepsilon$, and since the longitudinal deformation is $\varepsilon = \partial u/\partial x$, we may re-write the last equation as:

$$E\frac{\partial^2 u}{\partial x^2}=\rho\frac{\partial^2 u}{\partial t^2}$$

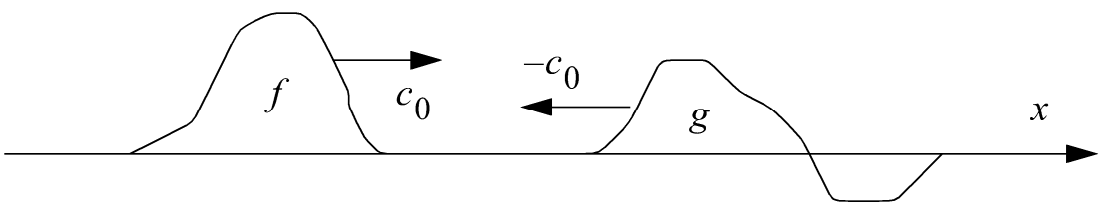
or, finally:

$$\frac{\partial^2 u}{\partial t^2}=c_0^2\frac{\partial^2 u}{\partial x^2}\qquad\text{with}\qquad c_0=\sqrt{E/\rho}$$

This is known as the (1-D) wave equation and the constant c_0 is the sound speed in the elastic material.

The general solution (D'Alembert's solution) to this equation reads:

$$u(x,t)=f(x-c_0t)+g(x+c_0t)$$



- The two waves f and g propagate without distortion
- The spatial form of f and g is determined by initial conditions and by boundary conditions

While the waves propagate at (constant) velocity c_0, the material particles move at velocity:

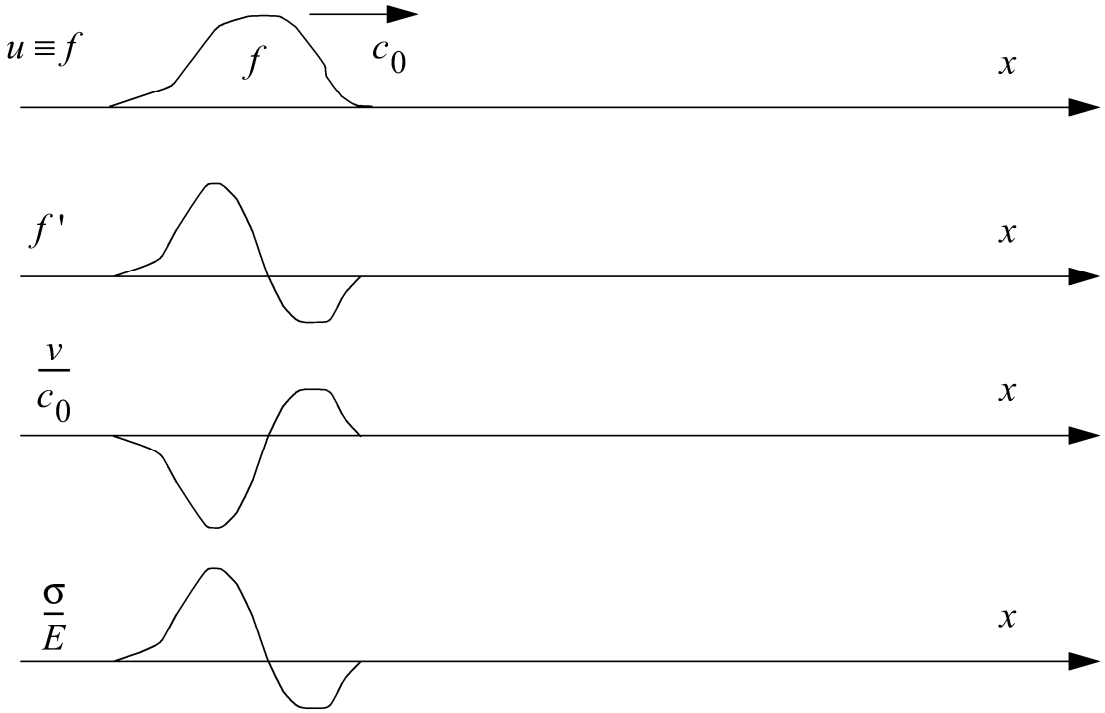
$$v(x,t) = \frac{\partial u}{\partial t} = -c_0 \frac{\partial f}{\partial t} = -c_0 f'(x - c_0 t) \qquad \text{with} \qquad f'(x - c_0 t) \doteq \frac{\partial f(x - c_0 t)}{\partial (x - c_0 t)}$$

But since:

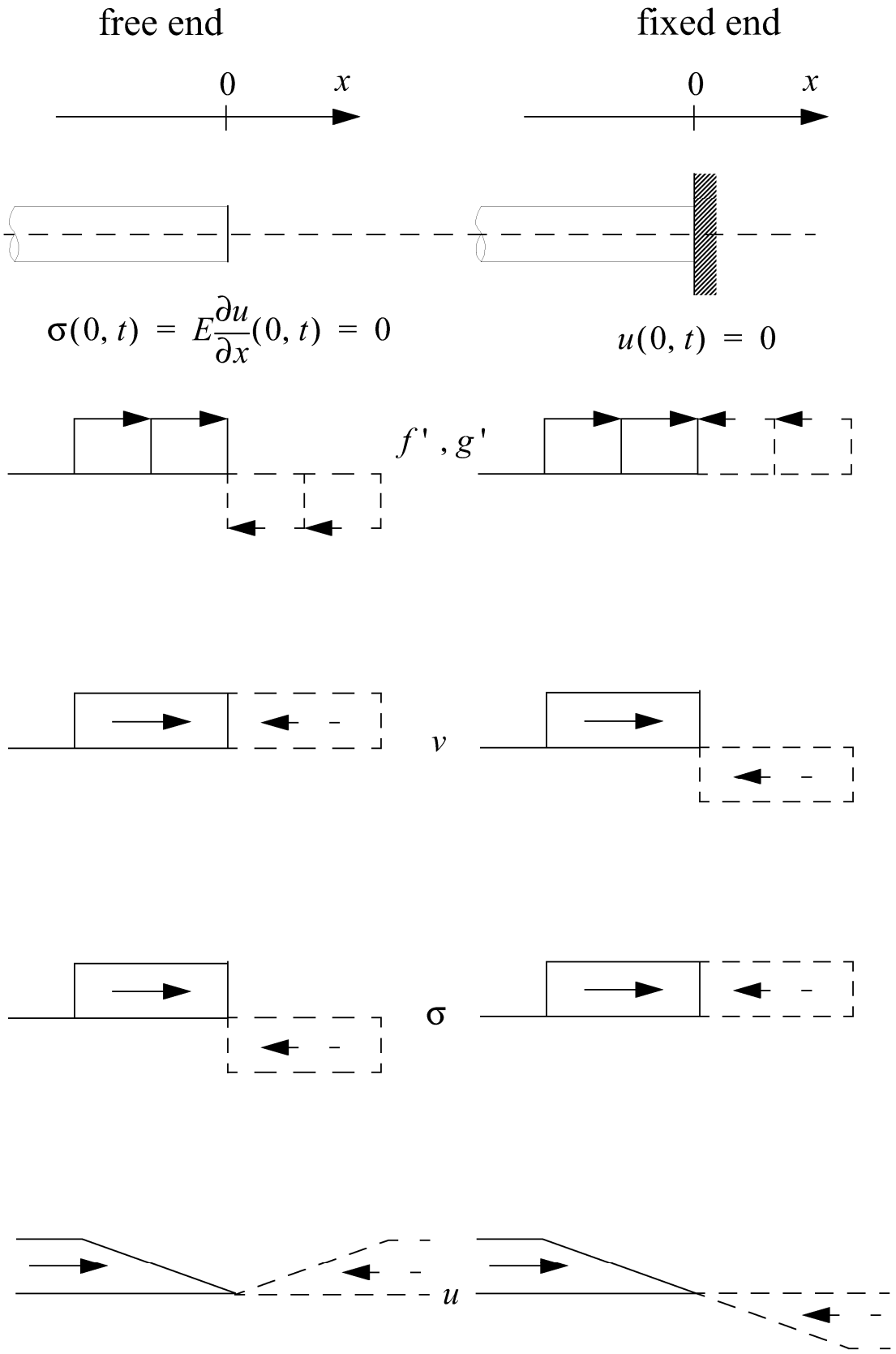
$$\sigma(x,t) = E\varepsilon = E\frac{\partial u}{\partial x} = Ef'(x - c_0 t)$$

we have:

$$v(x,t) = -\frac{c_0}{E}\sigma(x,t)$$



Simple 1-D wave propagation problems may be studied quite effectively by the method of images:



Analytical solution

For the bar impact problem proposed above, the analytical solution according to the linear 1-D wave propagation theory is as follows.

The sound speed in the material is:

$$c_0 = \sqrt{E/\rho} = \sqrt{2\times10^{11}/8000} = 5000 \text{ m/s}$$

From the relationship $v = -(c_0/E)\sigma$ we obtain for the stress:

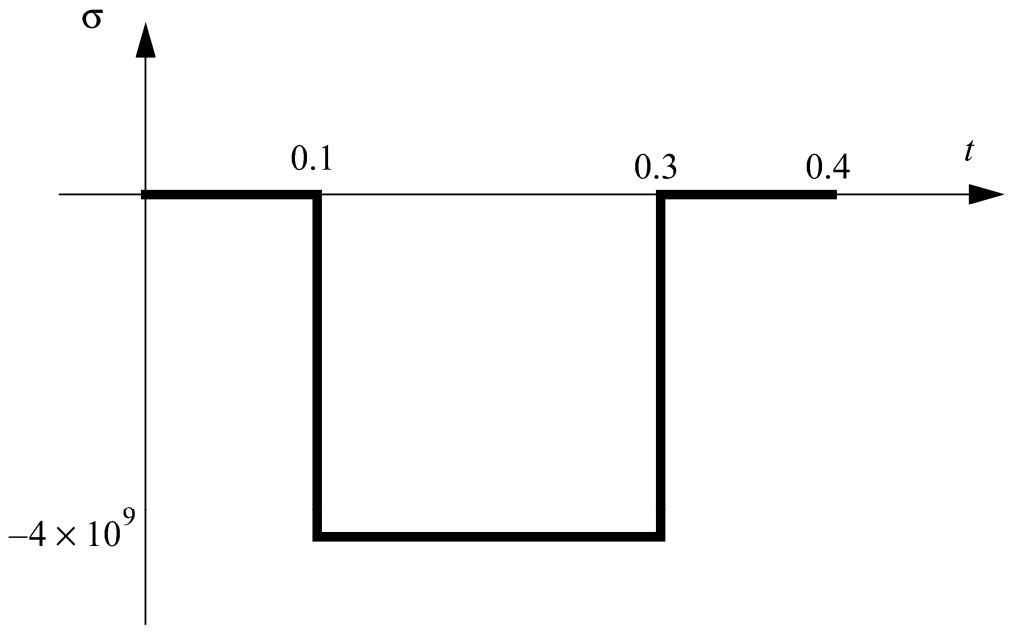
$$\sigma = -\frac{v}{c_0}E = -\frac{100}{5000}2\times10^{11} = -4\times10^{9}$$

and the longitudinal strain is:

$$\varepsilon = \sigma/E = 4\times10^{9}/2\times10^{11} = 0.02$$

- The impact against the rigid obstacle produces a step-like stress wave that enters the bar from the right end and travels towards the left at speed c_0.
- When the compression wave, at time $t_1 = L/c_0 = 1/5000 = 0.2$ ms, reaches the left end, which is free, it is reflected as a traction wave that moves to the right at the same speed and cancels out the compression.
- At time $t_2 = 2L/c_0 = 0.4$ ms the tension wave reaches the right end of the bar: the bar is stress-free and it starts rebounding towards the left with a velocity $-v$, i.e. opposite to the impact velocity.

The time history of longitudinal stress at the mid-point of the bar is therefore as follows:



Numerical Solutions

BARI01

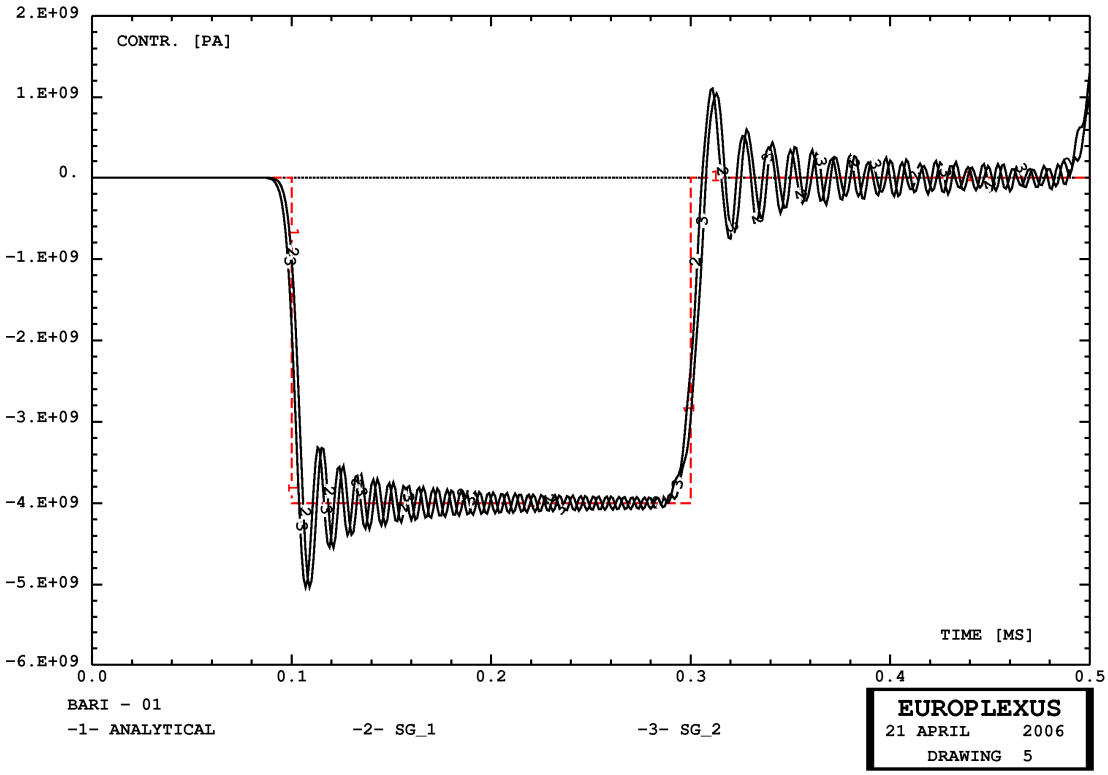
We discretize the bar with 100 elements of the FUN2 type, with an elastic material of type VM23 (resisting to both traction and compression) and use the `OPTI EDSS` option to impose small-strain formulation in the elements (see Exercise 1).

The EUROPLEXUS input file is:

```
BARI - 01
*-----------------------------------------------------------------------
ECHO
*CONV win
CAST mesh
*-------------------------------------------------------------Problem type
CPLA NONL LAGR LAGC
*-------------------------------------------------------------Dimensioning
DIME
  PT2L 102 FUN2 100 PMAT 1 ZONE 2
  BLOQ 2
  TABL 1 2
  FORC 1
  IMPA 1 PSIM 1
TERM
*-----------------------------------------------------------------Geometry
GEOM FUN2 bar PMAT obst TERM
*-----------------------------------------------Geometrical complements
COMP EPAI 2.5E-8 LECT bar TERM
*-------------------------------------------------------Material data
MATE VM23 RO 8000. YOUN 2.0E11 NU 0.0 ELAS 2.0E11
         TRAC 1 2.0E11 1.E0
         LECT bar TERM
     MASS 1.0 LECT obst TERM
*-----------------------------------------------Boundary conditions
LIAI freq 1
     BLOQ 12 LECT obst TERM
     IMPA DDL 1 COTE -1
         PROJ LECT obst TERM
         CIBL LECT p2   TERM
*-----------------------------------------------Initial conditions
INIT VITE 1 100.0 LECT bar TERM
*-----------------------------------------------------------------Outputs
ECRI DEPL VITE CONT ECRO TFREQ 0.1E-3
     FICH ALIC TEMP FREQ 1
              POIN LECT p3 p2 TERM
              ELEM LECT e1 e2 TERM
*-----------------------------------------------------------------Options
OPTI PAS UTIL NOTEST
     LOG 1
     EDSS
*-----------------------------------------------------Transient calculation
CALCUL TINI 0. TEND 0.5E-3 PASF 0.1E-5
*=============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------Curve definitions
COUR 1 'dx_2'     DEPL COMP 1 NOEU LECT p2 TERM
COUR 2 'dx_3'     DEPL COMP 1 NOEU LECT p3 TERM
COUR 3 'sg_1'     CONT COMP 1 ELEM LECT e1 TERM
COUR 4 'sg_2'     CONT COMP 1 ELEM LECT e2 TERM
DCOU 5 'Analytical' 6
       0.0     0.0
       0.1E-3  0.0
       0.1E-3 -4.E9
       0.3E-3 -4.E9
       0.3E-3  0.0
       0.5E-3  0.0
*-------------------------------------------------------------------------Plots
trac 1 axes 1.0 'DISPL. [M]'
trac 2 axes 1.0 'DISPL. [M]'
trac 3 axes 1.0 'CONTR. [PA]'
trac 4 axes 1.0 'CONTR. [PA]'
trac 5 3 4 axes 1.0 'CONTR. [PA]' yzer
           colo roug noir noir
           dash 2    0    0
*-----------------------------------------------Results qualification
QUAL DEPL COMP 1 LECT  p2 TERM REFE -9.76759E-3  TOLE 1.E-2
     DEPL COMP 1 LECT  p3 TERM REFE -9.86359E-3  TOLE 1.E-2
     CONT COMP 1 LECT  e1 TERM REFE  1.00128E+9  TOLE 1.E-2
     CONT COMP 1 LECT  e2 TERM REFE  1.31288E+9  TOLE 1.E-2
*=====================================================================
FIN
```

Note that we have also put the Poisson's coefficient ν to 0 in order to produce a numerical solution as close as possible to the linear 1-D wave theory (neglect the lateral inertia effect).

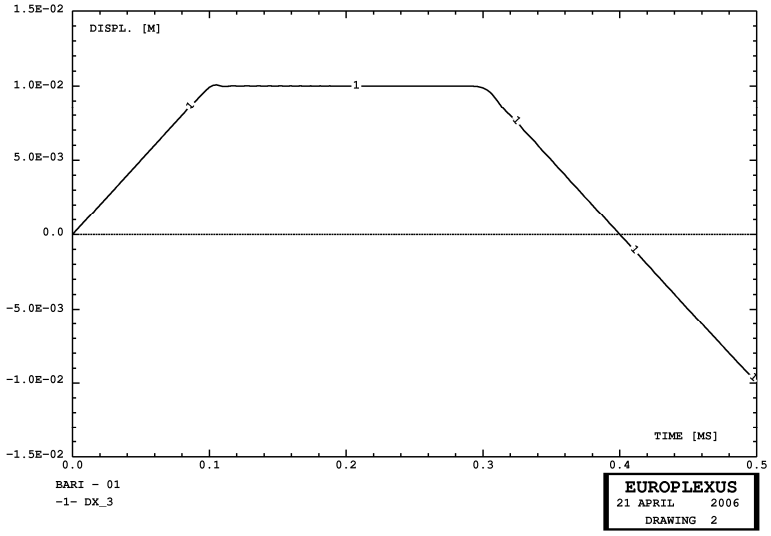
The resulting stress at the bar mid-point is:



The analytical solution is superposed (red line). Two lines are drawn for the numerical solution: they correspond to the elements immediately to the left and immediately to the right of the bar mid-point.
Note the relatively strong oscillations: recall that the central difference time integration scheme introduces no numerical damping.
The displacement of the bar central point is shown next. Note the rebound, with approximately the same velocity as the incident one.
As concerns the bar cross section, the 1-D response is independent from this parameter. We have assumed an arbitrary value here (2.5×10^{-8} , like in Example 1), because the numerical solution does not depend on this value (verify).

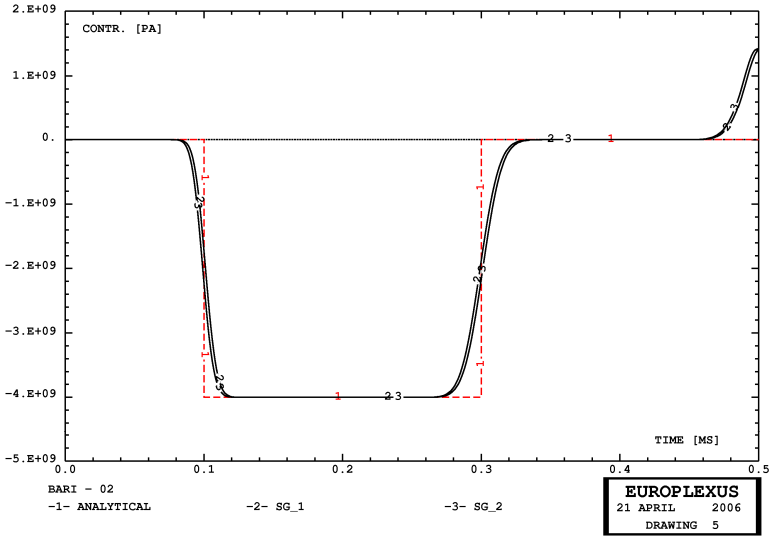
BARI01_B

Same as BARI01 but with a cross-section of 1.0: results in terms of stresses, displacements etc. are identical.



BARI02

We introduce some damping (10% of the critical value: `OPTI AMOR LINE 0.1`) to reduce the oscillations in the numerical solution. However, this has also an effect on wavefronts, which become less steep and thus deviate more from the analytical solution. The resulting stress at the bar mid-point is:

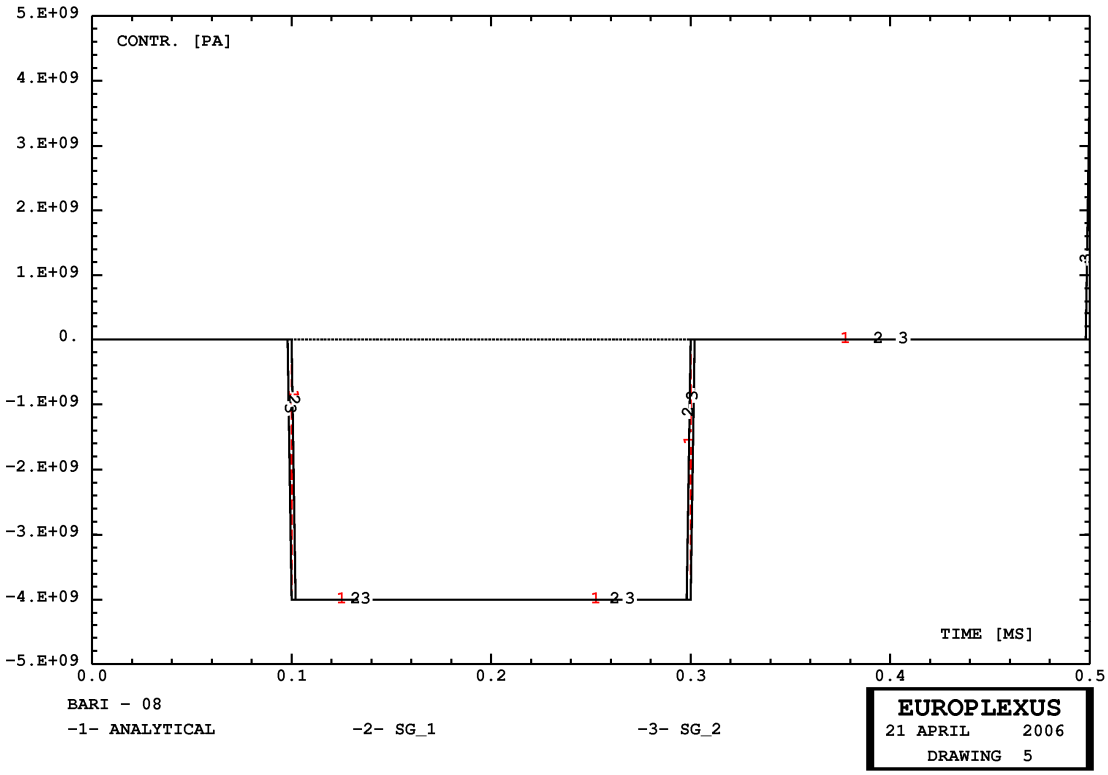


BARI08

We study the effect of the time increment. The critical time step for the chosen problem is:

$$\Delta t^{\text{crit}} \simeq \frac{L}{\sqrt{E/\rho}} = \frac{1/100}{5000} = 2\times 10^{-6} \text{ s}$$

In the previous runs we have assumed a fixed time increment $\Delta t = 1\times 10^{-6} = 0.5\cdot \Delta t^{\text{crit}}$. Let us see what happens by taking a time increment larger than the estimated stability limit. By assuming $\Delta t = 4\times 10^{-6} = 2.0\cdot \Delta t^{\text{crit}}$, the numerical solution "explodes" (∞ velocities) after just 10 time steps (try out to see).
By assuming $\Delta t = 2\times 10^{-6} = 1.0\cdot \Delta t^{\text{crit}}$, the numerical solution is carried out until the end and the results are very close to the analytical solution:



Note that this calculation is done <u>without</u> any added damping. The fact that an almost analytical result is obtained is remarkable, but it should be noted that in practice using a time step equal to the critical value is impossible for real calculations where the mesh size and/or the material properties change in space and in time.
It is always advisable to use a time increment as close as possible to the stability limit, but by bearing in mind that the latter is often just an estimation.

BARI08_B

Same as BARI08 but twice larger Δt: the calculation is unstable as expected.

BARI09

Use a 2-D geometry (elements of type Q42L). The solution is independent upon the extension along the y-direction.

Use the pinball model to describe the impact (see Part IV). The input file is:

```
BARI - 09
*-----------------------------------------------------------------------
ECHO
 CONV win
CAST mesh
*-------------------------------------------------------------Problem type
CPLA NONL LAGR
*-------------------------------------------------------------Dimensioning
DIME
  PT2L 26 Q42L 11
  TABL 1 2
  FORC 1
TERM
*-----------------------------------------------------------------Geometry
GEOM Q42L bar obst TERM
*-----------------------------------------------Geometrical complements
COMP EPAI 2.5E-8 LECT bar obst TERM
*-----------------------------------------------------------Material data
MATE VM23 RO 8000. YOUN 2.0E11 NU 0.0 ELAS 2.0E11
         TRAC 1 2.0E11 1.E0
         LECT bar obst TERM
*-------------------------------------------------------Boundary conditions
LINK COUP
     BLOQ 12 LECT obst TERM
     PINB BODY MLEV 3 LECT bartip TERM
          BODY MLEV 4 LECT obst   TERM
*-------------------------------------------------------Initial conditions
INIT VITE 1 100.0 LECT bar TERM
*-----------------------------------------------------------------Outputs
ECRI DEPL VITE CONT ECRO TFREQ 0.1E-3
     FICH ALIC TEMP FREQ 1
               POIN LECT p3 p2 TERM
               ELEM LECT e1 e2 TERM
     FICH ALIC FREQ 1
*-----------------------------------------------------------------Options
OPTI PAS UTIL NOTEST
     LOG 1
     PINS CNOR
*-----------------------------------------------------Transient calculation
CALCUL TINI 0. TEND 1.2E-3 PASF 0.1E-4
*=============================================================Direct Animation
PLAY

CAME   1 EYE   6.55000E-01  5.00000E-02  3.35978E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01

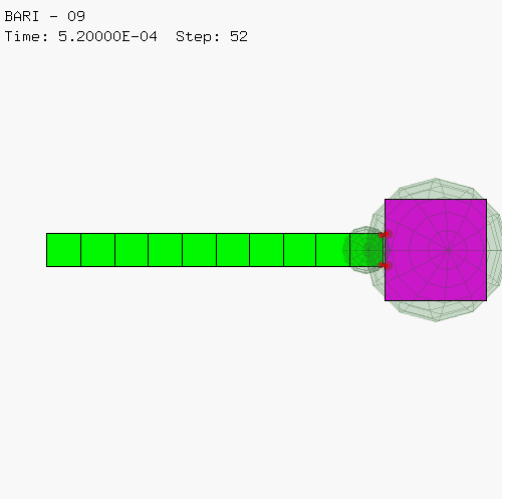
scen geom navi free
          pinb pare cdes
     !vect scco scal user prog 0.e0 pas 0.16e2 0.80e2 term
     !text vsca
     iso  fili fiel ecro 2 scal user prog 0.e0 pas 0.3e9 3.6e9 term
     text isca
     colo pape

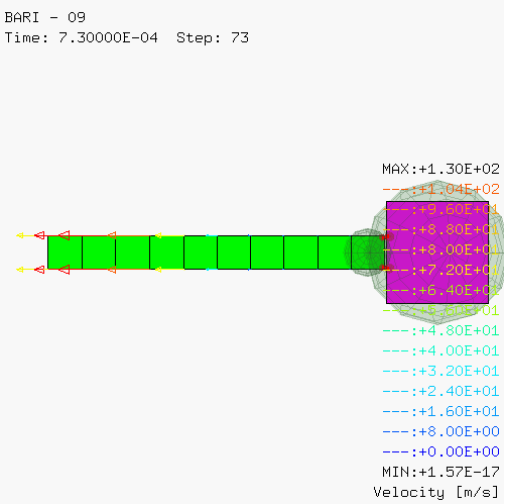
freq 1

sler cam1 1        nfra 1
trac offs fich avi       nocl nfto 121 fps 10 kfre 10 comp -1 rend
gotr loop 119 offs fich avi cont nocl                         rend
go
trac offs fich avi cont                                       rend

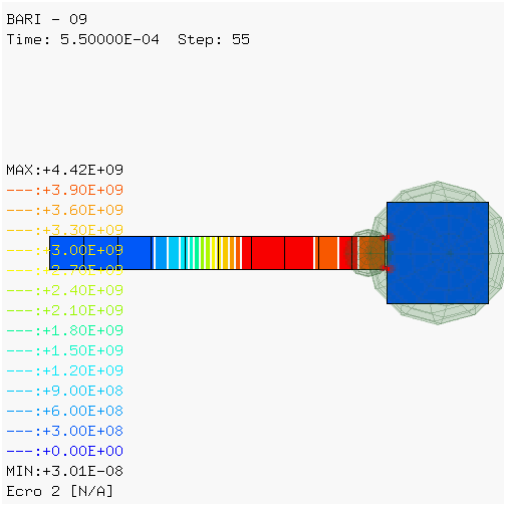
ENDPLAY
*=============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------------Curve definitions
COUR 1 'dx_2'     DEPL COMP 1 NOEU LECT p2 TERM
COUR 2 'dx_3'     DEPL COMP 1 NOEU LECT p3 TERM
COUR 3 'sg_1'     CONT COMP 1 ELEM LECT e1 TERM
COUR 4 'sg_2'     CONT COMP 1 ELEM LECT e2 TERM
*-------------------------------------------------------------------Plots
trac 1 axes 1.0 'DISPL. [M]'
trac 2 axes 1.0 'DISPL. [M]'
trac 3 axes 1.0 'CONTR. [PA]'
trac 4 axes 1.0 'CONTR. [PA]'
trac 3 4 axes 1.0 'CONTR. [PA]'
*-----------------------------------------------------Results qualification
QUAL DEPL COMP 1 LECT  p2 TERM REFE  9.28567E-3  TOLE 1.E-2
     DEPL COMP 1 LECT  p3 TERM REFE  1.08357E-2  TOLE 1.E-2
     CONT COMP 1 LECT  e1 TERM REFE  8.57355E+8  TOLE 2.E-2
     CONT COMP 1 LECT  e2 TERM REFE  6.61260E+7  TOLE 1.E-2
*=====================================================================
FIN
```

This produces an animation of the results. Either the geometry or the velocities:





or the Von Mises stress:

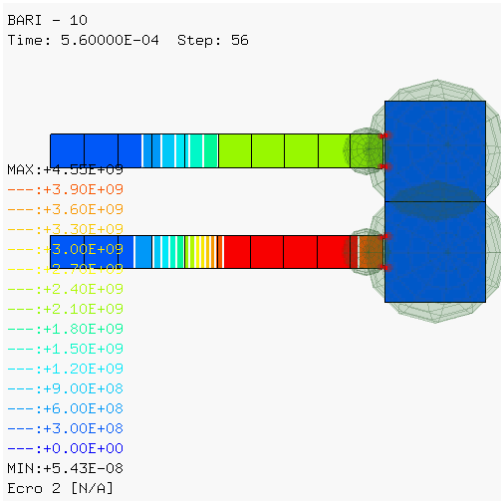


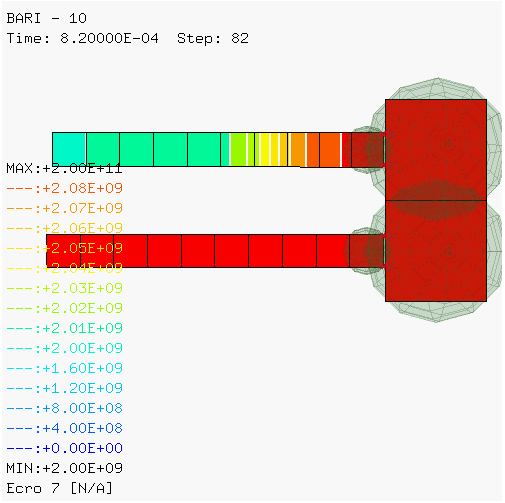
To change the type of animated results, comment/uncomment the appropriate lines in the "`scen`" directive, near the end of the input file.

BARI10

Same as BARI09 but compares two bars: the first one is elastic like in the previous example, but the second one is elasto-plastic with a yield stress of 2×10^9 Pa (corresponding to 1% axial strain) and a low plastic modulus.

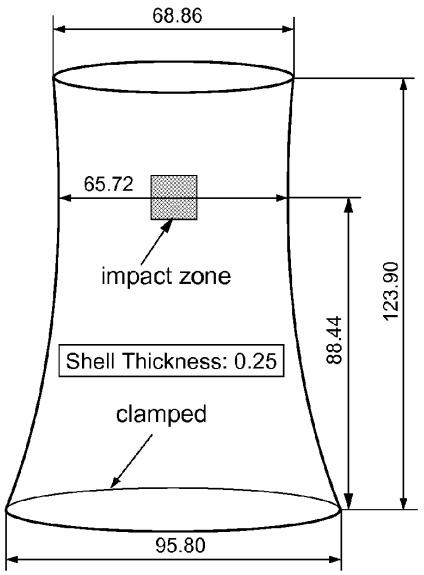
Compare the two solutions and discuss the results: the Von Mises stress and the current yield stress



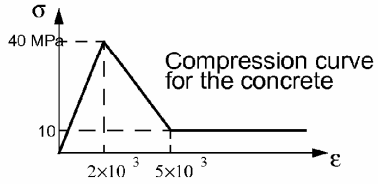


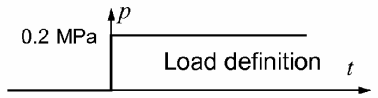
Exercise 3 – Impact on Cooling Tower

- Problem definition:



Layer N.	φ_L	Material
1	0.1	concrete
2	0.0025	steel
3	0.795	concrete
4	0.0025	steel
5	0.1	concrete





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TITLE:
Towe02: impact against a cooling tower.

PROBLEM:
This problem is a very schematic simulation of an impact against a cooling tower. The parabolic tower is 123.9 m high and has a ground diameter of 95.8 m, a minimum diameter of 65.72 m (at a height 0f 88.44 m) and a top diameter of 68.86 m. It is schematized (very roughly) by a shell of constant thickness, equal to 0.25 m, made of reinforced concrete. The geometry is axisymmetric, but the loading is not so the problem has to be treated in 3D. The applied load is a time-dependent pressure in a localised zone near the top, simulating an impact of a projectile or flying object. The base of the tower is assumed completely blocked and thanks to the presence of a vertical symmetry plane, only one half of the tower needs be modeled.

MESH:
The model is 3D and uses 800 triangular plate/shell elements COQI.

MATERIALS:
The tower is made of reinforced concrete, modelled by the DPSF material for the concrete and VMSF for the steel reinforcement. The structure is composed of 5 layers of which 3 are concrete and 2 reinforcement. The respective thickness fractions are 0.1, 0.0025, 0.795, 0.0025 and 0.1.

BOUNDARY CONDITIONS:
The tower is entirely blocked along the bottom basis. A symmetry plane is imposed.

LOADING:

The system is initially at rest, and starting at the initial time a step-wise external pressure is applied onto a square region near the top of the tower, simulating the impact zone. The pressure stays constant for a duration of 500 ms, then goes linearly to 0 in 100 ms.

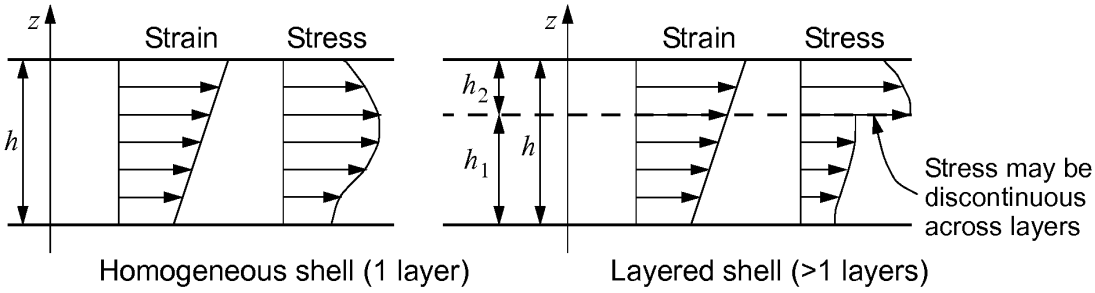
CALCULATION:
The calculation is performed up to 2000 ms. At the final time, the tower has undergone large plastifications in the impact zone and to some extent in the surrounding area.

RESULTS:
Although no comparison with experiments can be done on this problem, the results appear physically correct.

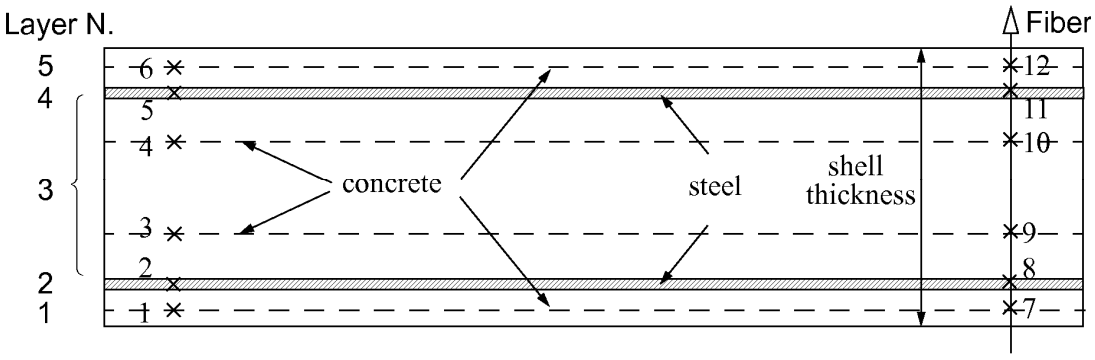
POST-TREATMENT
Several animations of the computed results from this calculation are available on the EUROPLEXUS Consortium Web site.

REFERENCES:
This calculation is detailed in:
1) J.J. Lopez Cela, F. Casadei and P. Pegon: "Fast Transient Analysis of Thin Shell Reinforced Concrete Structures with Drucker-Prager Model." SMiRT-14 Conference, Lyon (F), August 17-22, 1997.
For details on the reinforced concrete material model, see:
2) J.J. Lopez Cela, P. Pegon, F. Casadei: "Brittle Material Law with Drucker Prager Yield Surface and Softening Behaviour." Technical Note N. I.96.34, February 1996.
The layered shell model is described in:
3) F. Casadei, J.J. Lopez Cela: "A Multilayer Formulation for Shell Elements in PLEXIS-3C." Technical Note N. I.96.14, February 1996. (all these documents are available on the EUROPLEXUS Consortium Web site).

Shell model



Layers



Numerical Solutions

TOWE02

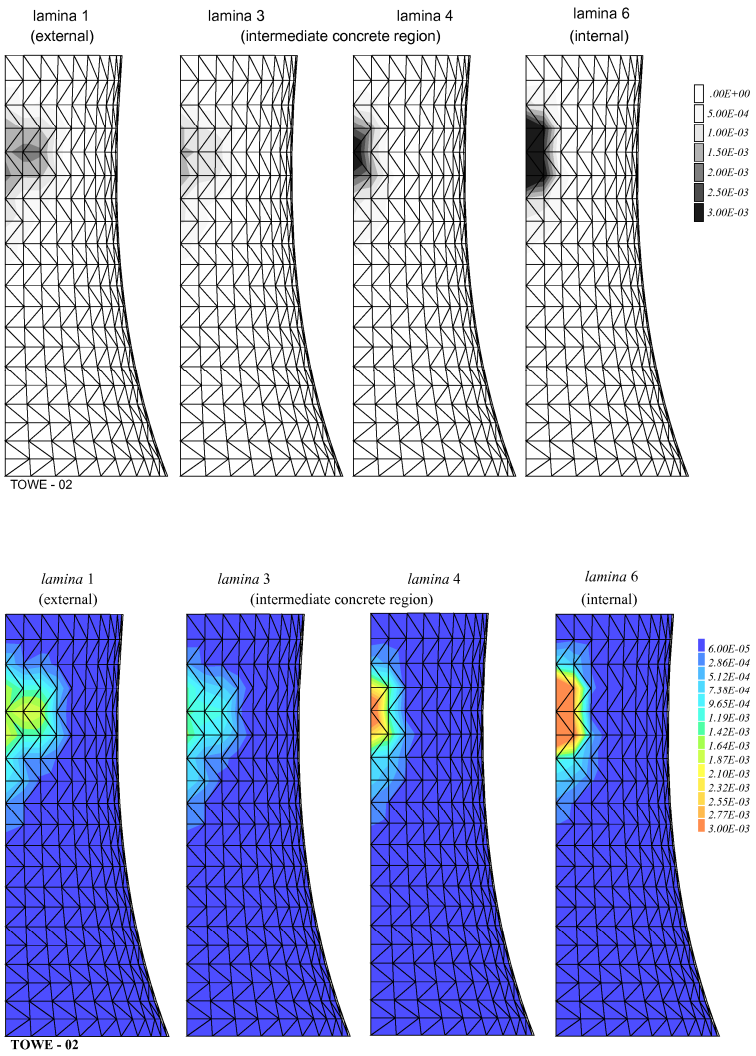
The mesh generation file (K2000):

```
*%siz 50
*
opti echo 1;
*
opti trac psc ftra 'towe02_mesh.ps';
*
opti titr 'TOWE - 02';
opti dime 3;
*
ncir=10;
nlon=20;
*
p11=47.90 0.0 0.0;
p12=34.43 0.0 123.90;
p13=28. 0.0 50.;
p21=0.0 47.90 0.0;
*
opti elem seg2;
line1 = para nlon p11 p13 p12;
opti donn 5;
*
p4=0.0 0.0 0.0;
p5=0.0 0.0 123.90;
*
opti elem tri3;
surf1= line1 ncir ROTA 90. p4 p5;
*
oeilz=0.0 0.0 1000.0;
oeilx=1000.0 0.0 0.0;
oeily=0.0 1000.0 0.0;
*
p21=0.0 47.90 0.0;
p22=0.0 34.43 123.90;
p23=0.0 28.0 50.0;
*
opti elem seg2;
line2 = para nlon p21 p23 p22;
*
opti elem tri3;
surf2= line2 ncir ROTA 90. p4 p5;
*
p31=-47.90 0.0 0.0;
p32=-34.43 0.0 123.90;
p33=-28. 0.0 50.;
opti elem seg2;
line3 = para nlon p31 p33 p32;
*
surf=surf1 et surf2;
tol = 0.0001;
elim tol surf;
*
*
opti elem seg2;
*
bloc1 = cerc ncir p11 p4 p21;
bloc2 =cerc ncir p21 p4 p31;
bloc = bloc1 et bloc2;
*
*
mesh=surf et bloc et line3;
elim tol mesh;
*
opti sauv form 'towe02.msh';
sauv form mesh;
*
opti trac psc;
trac cach mesh;
fin;
```

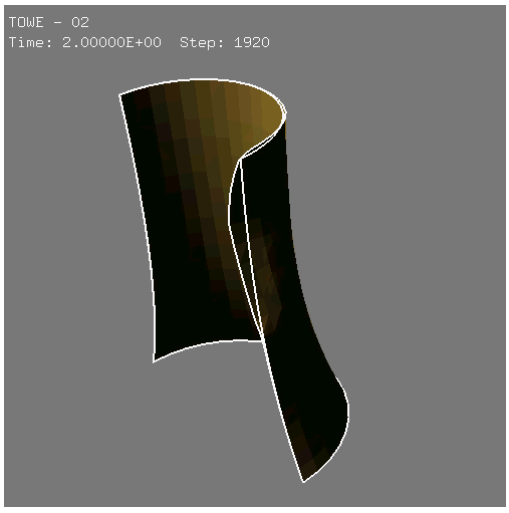
The EUROPLEXUS input file is:

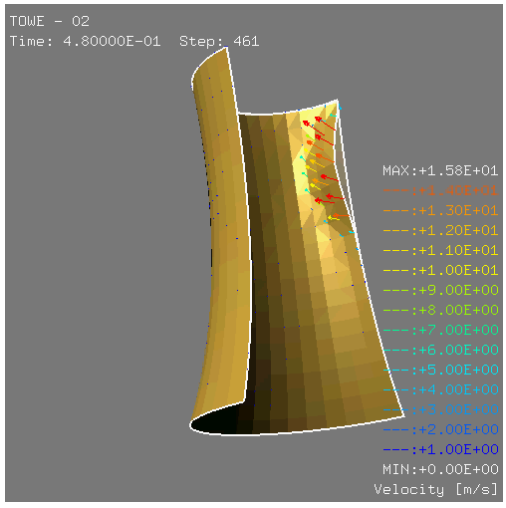
```
TOWE - 02
$
ECHO
!CONV win
CAST MESH
TRID NONL LAGR
$
$ Dimensioning
$
DIME
  PT6L 861 COQI 800
  FNOM 1 FTAB 2 FCOE 2
  PRES 4 3
  TABL 10 5
  ecrou 273600
  mtpo 21
TERM
$
$ Geometry
$
 GEOM COQI SURF TERM
$
COMP
  EPAI 0.25 LECT SURF TERM
  LAYE 5 FRAC 0.1 0.0025 0.795 0.0025 0.1
         NGPZ 1 1 2 1 1 LECT SURF TERM
$
$ Materials
$
$ concrete (softening)
MATE DPSF RO 2.4E3 YOUN 2.E10 NU 0.2 ALF1 1.299
     C1 5.7735E6 BETA 0.20 ETA 2.E-3
     TRAA 3 1.299 0.0 1.299 5.E-4 1.299 5.E+2
     TRAC 3 5.7735e6 0.0 1.44338E6 5.15E-3 1.44338E6 5.E+2
     LECT SURF TERM LAYE LECT 1 3 5 TERM
$
$ steel (elastoplastic)
     VMSF RO 7.8E3 YOUN 2.1E11 NU 0.3 ELAS 6.8E8
     ETA 0. TRAC 2 6.8E8 3.23810E-03 6.8E8 5.E+2
     LECT SURF TERM LAYE LECT 2 4 TERM
$
$ Boundary Conditions
$
LINK COUP
     BLOQ 123456 LECT BLOC TERM
     CONT SPLA NX 0 NY 1 NZ 0 LECT LINE1 LINE3 TERM
$
$ Loads
$
CHAR 1 FACT 2 PRES COQU 2.E5
              LECTURE 31 32 33 34 TERM
              TABL 4 0. 1. 0.5 1. 0.6 0. 10. 0.
$
ECRI DEPL TFRE 500.D-3
     FICH K200 TFRE 50.E-3
               POIN TOUS
               VARI DEPL ECRO ECRC LECT 1 2 3 TERM
     FICH ALIC TFRE 2.E-2
     FICH ALIC TEMP FREQ 1
          POIN LECT 33 41 TERM
          ELEM LECT 1 TERM
$
OPTI NOTE K2FB 1
         !K2FB 3
         !K2FB 4
         !K2FB 6
     log 1
CALC TINI 0.0 TEND 2000.D-3
*===================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR  1 'dx_n1' DEPL COMP 1 NOEU LECT 33 TERM
COUR  2 'dx_n2' DEPL COMP 1 NOEU LECT 41 TERM
*
trac 1 2 axes 1.0 'DISPL. [M]'
*
QUAL DEPL COMP 1 LECT 33 TERM REFE -9.79695E+0 TOLE 5.E-2
     DEPL COMP 1 LECT 41 TERM REFE -1.01268E+0 TOLE 5.E-2
*===================================================================
FIN
```

Some results: equivalent plastic strains in the 4 concrete laminae at 100 ms.



Final deformation (with superposed initial geometry) and Intermediate deformation with velocities:

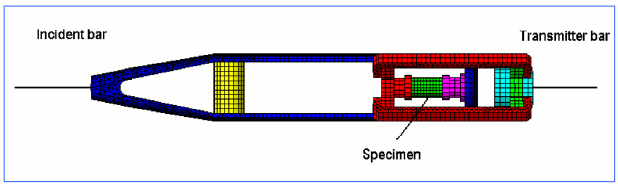




Exercise 4 – Hopkinson Bar



JRC Large Dynamic Test Facility (HopLab)



Fast Compression Test on Ductile Metallic Specimen

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TITLE:
Hopbar: simulation of an experiment on JRC's Hopkinson Bar.

PROBLEM:
At JRC a large Hopkinson bar is used to assess the dynamic behaviour of materials and small structural components at high rates of strain. The scope is to simulate an experiment of fast compressive loading of a ductile metallic specimen.

REFERENCES:
This calculation is detailed in:
1) C. Giry, G. Solomos, F. Casadei. "Numerical Analysis of the JRC Large Hopkinson Bar". Technical Note, PUBSY N. JRC46866, September 2008.
(all documents are available on the EUROPLEXUS Consortium Web site).

Numerical Solution

HOPKBARUR

The mesh generation file (K2000):

```
************************************************************************
*            Mesh Hopkinson test machine
*           ----------------------------
*
*                    (Units : m )
*
************************************************************************


*-----------------------------------------------------------------
* This file generates the mesh of the Large Hopkinson bar of the
* HopLab at the European Laboratory for Structural Assessement (ELSA)
* J.R.C. Ispra
*-----------------------------------------------------------------

*-----------------------------------------------------------------
* Choice of the type of test
*
* UNCONFME: Tests on unconfined metallic specimen. Two caps placed
* over the steel anvils in order to increase the surface of loading
* in contact with the specimen and to accomodate the lateral
* expansion of the specimen.
*     - Type of contact for Europlexus:
*           RIGI: Simple restrain on the displacement on x for
* the surfaces in contact (specimen - bars)  (CRIGI = VRAI)
*           GLIS: More complex condition using the Lagrange
* multiplier (nothing to write in this file)
*
* UNCONF: Tests on unconfined specimen made of other type of
* material (ex: concrete). The two caps are not used.
*     - Type of contact for Europlexus:
*           RIGI: Simple restrain on the displacement on x for
* the surfaces in contact (specimen - bars)  (CRIGI = VRAI)
*           GLIS: More complex condition using the Lagrange
* multiplier (nothing to write in this file)
*
*
* CONFIN: Tests on confined specimen (passive confinement with steel
* jacket).

UNCONFME= VRAI;
UNCONF= FAUX;
CONFIN= FAUX;

CRIGI= VRAI;


*-----------------------------------------------------------------

opti echo 1;
```

```
*---------------------------------------------------------------------
* Dimension, elements
* ...................
* The tetrahedrons are used for the operator VOLU. For the specimen,
* and the simple part of the inversion cages, cubes and prisms are
* used.
*---------------------------------------------------------------------

opti dime 3 elem TET4;


*---------------------------------------------------------------------
* Mesh size
* .........
* Inversion cages: 1.5 cm (dens1)
* Specimen: 0.5 cm (dens2)
* Bar elements far from the specimen: 20 cm (dens3)
* edens1 = dens1/100 (to erase double node)
*---------------------------------------------------------------------

dens1=0.015; edens1=dens1/100;
dens2=0.005; edens2=dens2/100;
dens3=0.2;


*---------------------------------------------------------------------
* Specimen size
* .............
* "widthsp" corresponds to the height of the specimen
* "diametsp": corresponds to the diameter of the specimen
* "widthja": corresponds to the width of the jacket (half the
* external diameter minus the internal diameter
*---------------------------------------------------------------------

widthsp = 0.1;

SI UNCONF;
diametsp = 0.06;
FINSI;
SI UNCONFME;
diametsp = 0.06;
FINSI;
SI CONFIN;
diametsp = 0.062;
FINSI;

widthja = 0.014;


**********************************************************************
*            Definition of the geometry of the machine
*           -------------------------------------------
**********************************************************************

* The mesh is composed of differents parts:
* -----------------------------------------
* --- The pulse generation device (bars) + the input bar (bars) + the
* inversion cages of the input bar (tetrahedrons, prisms and cubes) +
* the tube to avoid bending (prisms)
* --- The specimen (cubes and prisms)
* --- The output bar (bars) + the inversion cages of the output bar
*(tetrahedrons, prisms and cubes)
* --- The jacket for the confined tests (prisms and cubes)


dens dens1;

*---------------------------------------------------------------------
*  Pulse Generation device - Input bar - Inversion cage of the input
*  ................................................................
*---------------------------------------------------------------------

* Pulse generation system + Input bar
* ----------------------------------


len21 = -0.1429 ;
len20 = -1.42 + len21 ;
len19 = -8.48 + len20 ;
len18 = -0.75 + len19  ;
len17 = -0.6571 + len18 ;
len16 = -0.08 + len17 ;
len15 = -1.164 + len16 ;
len14 = -0.15 + len15 ;
len13 = -0.102 + len14 ;
len12 = -0.875 + len13 ;
len11 = -0.05 + len12 ;
len10 = -0.09 + len11 ;
len9 = -0.02 + len10 ;
len8 = -0.1 + len9 ;
len7 = -0.015 + len8 ;
len6 = -0.04 + len7 ;
len5 = -0.09 + len6 ;
len4 = -0.017 + len5 ;
len3 = -0.02 + len4 ;
len2 = -0.085 + len3 ;
len1 = -0.04 + len2 ;
lenca = -90. + len1;

*.....................................................................
* Evolutive size of the mesh in order to reduce the number of
* elements

dens dens3;
PLCA = (0.47442+lenca) 0. 0.;
* .....................................................................

dens dens1;
PL1 = (0.47442+len1) 0. 0.;
PL2 = (0.47442+len2) 0. 0.;
PL3 = (0.47442+len3) 0. 0.;
PL4 = (0.47442+len4) 0. 0.;
PL5 = (0.47442+len5) 0. 0.;
PL6 = (0.47442+len6) 0. 0.;
PL7 = (0.47442+len7) 0. 0.;
PL8 = (0.47442+len8) 0. 0.;
PL9 = (0.47442+len9) 0. 0.;
PL10 = (0.47442+len10) 0. 0.;
PL11 = (0.47442+len11) 0. 0.;
PL12 = (0.47442+len12) 0. 0.;
PL13 = (0.47442+len13) 0. 0.;
PL14 = (0.47442+len14) 0. 0.;
PL15 = (0.47442+len15) 0. 0.;
PL16 = (0.47442+len16) 0. 0.;
PL17 = (0.47442+len17) 0. 0.;
PL18 = (0.47442+len18) 0. 0.;
PL19 = (0.47442+len19) 0. 0.;
PL20 = (0.47442+len20) 0. 0.;
PL21 = (0.47442+len21) 0. 0.;
PL22 = (0.47442) 0. 0.;
PL23 = 0.53152 0. 0.;



LLOACA = PLCA D PL1 ;
LLOA1 = PL1 D PL2 ;
LLOA2 = PL2 D PL3 ;
LLOA3 = PL3 D PL4 ;
LLOA4 = PL4 D PL5 ;
LLOA5 = PL5 D PL6 ;
LLOA6 = PL6 D PL7 ;
LLOA7 = PL7 D PL8 ;
LLOA8 = PL8 D PL9 ;
LLOA9 = PL9 D PL10 ;
LLOA10 = PL10 D PL11 ;
LLOA11 = PL11 D PL12 ;
LLOA12 = PL12 D PL13 ;
LLOA13 = PL13 D PL14 ;
LLOA14 = PL14 D PL15 ;
LLOA15 = PL15 D PL16 ;
LLOA16 = PL16 D PL17 ;
LLOA17 = PL17 D PL18 ;
LLOA18 = PL18 D PL19 ;
LLOA19 = PL19 D PL20 ;
LLOA20 = PL20 D PL21 ;
LLOA21 = PL21 D PL22 ;
LLOA22 = PL22 D PL23 ;

linp = LLOACA et LLOA1 et LLOA2 et LLOA3 et LLOA4 et LLOA5 et LLOA6 et
LLOA7 et LLOA8 et LLOA9 et LLOA10 et LLOA11 et LLOA12 et LLOA13 et
LLOA14 et LLOA15 et LLOA16 et LLOA17 et LLOA18 et LLOA19 et LLOA20 et
 LLOA21 et LLOA22;


*.....................................................................
* SLOAD41 corresponds to the surface limit at right of the inversion cage
* of the input bar. This sruface will be linked to the input bar in
* Europlexus.

PLOA41 = 0.53152 0. -0.036;
PLOA42 = 0.53152 -0.036 0.;
PLOA43 = 0.53152 0. 0.036;
PLOA44 = 0.53152 0.036 0.;
l1LOA4 = PLOA41 CER3 PLOA42 PLOA43;
l2LOA4 = PLOA43 CER3 PLOA44 PLOA41;
ctloa4 = l1LOA4 et l2LOA4;
SLOAD41 = ctloa4 SURF 'PLAN';
elim SLOAD41 edens1;
*.....................................................................


* Inversion cage of the input bar
* -------------------------------


* ..............................Volume 2.....................................
*.....................................................................
width3 = 0.1 ;
nbd3 = nbel l1LOA4;

* For the operator DALL, we need to have the same number of elements for
* facing lines. The density nbd3 is taken from a line and apply to the
* the corresponding one in front.

P1S21 = 0.59152 (-0.015) -0.03816;
P2S21 = 0.59152 (0.015) -0.03816;
P3S21 = 0.59152 (-0.015) 0.03816;
P4S21 = 0.59152 (0.015) 0.03816;

P1S22 = 0.6472 (-0.03) -0.04017;
P2S22 = 0.6472 (-0.03) 0.04017;
P3S22 = 0.6472 0.03 -0.04017;
P4S22 = 0.6472 0.03 0.04017;
P5S22 = 0.6472 0.025 -0.04017;
P6S22 = 0.6472 0.025 0.04017;
P7S22 = 0.6472 (-0.025) -0.04017;
P8S22 = 0.6472 (-0.025) 0.04017;

P1S23 = 0.6222 0. -0.03927;
P2S23 = 0.6222 0. 0.03927;

P1S24 = 0.92 (-0.08) ((-1)*(width3/2));
P2S24 = 0.92 (-0.08) (width3/2);
P3S24 = 0.92 (-0.09176) ((-1)*(width3/2));
P4S24 = 0.92 (-0.09176) (width3/2);
P5S24 = 0.92 -0.1045 0.;

P1S31 = 0.92 0.08 ((-1)*(width3/2));
P2S31 = 0.92 0.08 (width3/2);
P3S31 = 0.92 0.09176 (width3/2);
P4S31 = 0.92 0.1045 0.;
P5S31 = 0.92 0.09176 ((-1)*(width3/2));

P1sym = 0. 0. 0. ;
P2sym = 0. 0. 1.;
P3sym = 1. 0. (-1.);
P4sym = 0. 1. 0.;
P5sym = 1. 0. 0.;

l1S21 = P1S22 CER3 P1S21 PLOA41;
l1S22 = PLOA41 CER3 P2S21 P3S22;
l1s2 = l1s21 et l1s22;
l2S2 = P3S22 d P5S31;
l4S2 = P1S31 d P5S22;
l5S2 = P5S22 CER3 P1S23 P7S22;
l51S2 = P8S22 CER3 P2S23 P6S22;
l6S2 = P7S22 d P1S24;
l7S2 = P1S24 d P3S24;
l8S2 = P3S24 d P1S22;
l9S2 = P8S22 d P7S22;
l10S2 = P5S22 d P6S22;
l11S2 = P1S24 d P2S24;
l13S2 = P2S24 d P8S22;
l14S2 = P6S22 d P2S31;
l16S2 = P2S22 d P4S24;
l17S2 = P4S24 CER3 nbd3 P5S24 P3S24;
l18S21 = P4S22 CER3 P4S21 PLOA43;
l18S22 = PLOA43 CER3 P3S21 P2S22;
l18S2 = l18S21 et l18S22;
L19S2 = l8s2 et l1s21;
L20S2 = l18s22 et l16s2;

l1S31 = P1S31 d P2S31;
l2S31 = P2S31 d P3S31;
l3S31 = P3S31 CER3 nbd3 P4S31 P5S31;
l4S31 = P5S31 d P1S31;


ct1S2 = l1S2 et l2S2 et l4S31 et l4S2 et l5S2 et l6S2 et l7S2 et l8S2;

S31 = (l1S31 et l2S31 et l3S31 et l4S31) surf PLAN;
S21 = ct1S2 SURF PLAN;
S22 = S21 syme 'PLAN' P1sym P5sym P4sym ;
S24 = S31 syme 'PLAN' P1sym P2sym P3sym ;
S25 = (l6S2 et l11S2 et l13S2 et l9S2) surf PLAN;
S26 = S25 syme 'PLAN' P1sym P2sym P3sym;
S27 = L19S2 l17s2 L20S2 (l1LOA4) dall 'QUELCONQUE';
S28 = S27 syme 'PLAN' P1sym P2sym P3sym;
S29 = L5S2 (INVE L9S2) L51S2 (INVE L10S2) dall 'QUELCONQUE';


S2 = S21 ET S22 ET SLOAD41 ET S24 ET S25 ET S26
ET S27 ET S28 ET S29 ET S31;
elim (S2) edens1;


vol2 = S2 VOLU;
elim vol2 edens1;
vol2 = (vol2 rege) couleur bleu;


* ..............................Volume 3.....................................
*.....................................................................

diamet3 = 0.209 ;
length3 = 0.8 ;
vl3 = length3 0. 0. ;
vecc3 = -0.34 0. 0.;


P1S32 = 1.05 0.08 ((-1)*(width3/2));
P2S32 = 1.05 0.08 (width3/2);
P3S32 = 1.05 0.09176 (width3/2);
P4S32 = 1.05 0.1045 0.;
P5S32 = 1.05 0.09176 ((-1)*(width3/2));

P1S34 = 1.72 0.08 ((-1)*(width3/2));
P2S34 = 1.72 0.08 (width3/2);
P3S34 = 1.72 0.09176 (width3/2);
P4S34 = 1.72 0.1045 0.;
P5S34 = 1.72 0.09176 ((-1)*(width3/2));


l1S32 = P1S32 d P2S32;
l2S32 = P2S32 d P3S32;
l3S32 = P3S32 CER3 nbd3 P4S32 P5S32;
l4S32 = P5S32 d P1S32;
```

```
l1S34 = P1S34 d P2S34;
l2S34 = P2S34 d P3S34;
l3S34 = P3S34 CER3 nbd3 P4S34 P5S34;
l4S34 = P5S34 d P1S34;


l1s3l = P2S31 d P2S32;
l2s3l = P1S32 d P1S31;
l3s3l = P5S31 d P5S32;
l4s3l = P3S32 d P3S31;

*.....................................................................
* Definition of the surface of the tube to obtain the  continuity
* with the volume 3
*
vecrig = 0. -0.16 0.;
diamrig1 = 0.095 ;
diamrig2 = 0.0865 ;
thickrig = ((diamrig1 - diamrig2)/2);

Prig11 = (0.9225 + (diamrig1/2)) 0.08 ((-1)*(diamrig1/2));
Prig12 = 0.9225 0.08 0.;
Prig13 = (0.9225 + (diamrig1/2)) 0.08 (diamrig1/2);
Prig14 = (0.9225 + diamrig1) 0.08 0.;

Prig21 = (0.9225 + (diamrig1/2)) 0.08 (((-1)*(diamrig1/2)+thickrig));
Prig22 = (0.9225+thickrig) 0.08 0.;
Prig23 = (0.9225 + (diamrig1/2)) 0.08 ((diamrig1/2)-thickrig);
Prig24 = (0.9225+thickrig+diamrig2) 0.08 0.;

lrig11 = Prig11 CER3 Prig12 Prig13;
lrig12 = Prig13 CER3 Prig14 Prig11;
lrig21 = Prig21 CER3 Prig22 Prig23;
lrig22 = Prig23 CER3 Prig24 Prig21;
*.....................................................................



S32 = (l1S32 et l2S32 et l3S32 et l4S32) surf PLAN;
S33 = S32 MOIN vecc3;
S34 = (l1S34 et l2S34 et l3S34 et l4S34) surf PLAN;

S311 = (l2S3l et (INVE l4S31) et l3S3l et l4S32) SURF 'PLAN';
S312 = (l1S3l et  l2S32 et l4S3l et (INVE l2S31)) SURF 'PLAN';
S313 = ((l1S32 et (INVE l1S31) et (INVE l1S31) et (INVE l2S3l)) et
(lrig11 et lrig12)) SURF 'PLAN';
S314 =  (((INVE lrig21) et (INVE lrig22)) et (lrig11 et lrig12))
SURF 'PLAN';
S315 = ((INVE lrig21) et (INVE lrig22)) SURF 'PLAN';
S316 = (INVE L3S32) L4S3l L3S31 L3S3l DALL 'QUELCONQUE';
S3 = S311 ET S312 ET S313 ET S314 ET S315 ET S316 ET S31 ET S32;
elim S3 edens1;


vol311 = S3 volu ;
vol312 = S32 volu S33;
vol313 = S33 volu S34;
vol31 = vol311 et vol312 et vol313;
vol32 = (vol31) syme 'PLAN' P1sym P2sym P3sym ;
elim vol31 edens1;
elim vol32 edens1;
vol3 = (vol31 et vol32) couleur bleu;
elim vol3 edens1;
elim (vol2 et vol3) edens1;

* .............................Aluminium tube.............................
*.....................................................................

Volrig = (S314 VOLU TRAN vecrig) couleur jaune ;
ELIM (volrig et vol32) edens1;



* .............................Volume 4...................................
*.....................................................................

length4 = 0.04;
diamet4 = 0.045;
width4 = 0.06172;
diamet41 = 0.09;
diamet42 = 0.062;
diamet43 = 0.078;
vecc4 = 0.01 0. 0.;

P1S41 = 1.72 0. -0.1045;
P2S41 = 1.72 0. ((-1)*(diamet4/2));
P3S41 = 1.72 (diamet4/2) 0. ;
P4S41 = 1.72 0. (diamet4/2);
P5S41 = 1.72 0. 0.1045;
P6S41 = 1.72 0. ((-1)*(diamet41/2));
P7S41 = 1.72 (diamet41/2) 0.;
P8S41 = 1.72 0. (diamet41/2);
P9S41 = 1.72 0. ((-1)*(diamet42/2));
P10S41 = 1.72 (diamet42/2) 0.;
P11S41 = 1.72 0. (diamet42/2);
PCE1S41 = 1.72 0. 0.;
PCE2S41 = 1.72 0.05664 0.03086;
PCE3S41 = 1.72 0.05664 -0.03086;
PCE4S41 = 1.72 0. -0.0645;
PCE5S41 = 1.72 0. 0.0645;

P1S42 = 1.76 0. (diamet4/2);
P2S42 = 1.76 0. 0.0645;
P3S42 = 1.76 0.0567 (width4/2);
P31S42 = 1.76 0.0645 0.;
P4S42 = 1.76 0.0567 ((-1)*(width4/2));
P5S42 = 1.76 0. -0.0645;
P6S42 = 1.76 0. ((-1)*(diamet4/2));
P7S42 = 1.76 (diamet4/2) 0. ;
PCES42 = 1.76 0. 0.;


PI1S412 = 1.73 0. ((-1)*(diamet4/2));
PI2S412 = 1.73 0. (diamet4/2);
PI3S412 = 1.73 (diamet4/2) 0.;

L1S41 = P3S34 CERC PCE1S41 P5S41;
l2S41 = P5S41 d P8S41;
l3S41 = P2S41 CER3 P3S41 P4S41;
l4S41 = P6S41 d P1S41;
L5S41 = P1S41 CERC PCE1S41 P5S34;
l6S41 = P8S41 CER3 P7S41 P6S41;
l7S41 = P4S41 d P2S41;
l8S41 = P6S41 d P9S41;
l9S41 = P11S41 d P8S41;
l10S41 = P9S41 CER3 P10S41 P11S41;
l11S41 = P11S41 d P4S41;
l12S41 = P2S41 d P9S41;

ds4n1= nbel l2S41;
ds4n2= nbel l1S41;
ds4n3= nbel l3S34;
ds4n4= nbel l5S41;
ds4n5= nbel l4S41;
* For the operator DALL, we need to have the same number of elements for
* facing lines. The density ds4ni is taken from a line and is applied to
* the corresponding one in front.

l1S42 = P1S42 d ds4n1 P2S42;
l2S42 = P2S42 CERC ds4n2 PCES42 P3S42;
l3S42 = P3S42 CER3 ds4n3 P31S42 P4S42;
l4S42 = P4S42 CERC ds4n4 PCES42 P5S42;
L5S42 = P5S42 d ds4n5 P6S42;
l6S42 = P6S42 CER3 P7S42 P1S42;

l1S43 = P3S34 CERC PCE2S41 P3S42;
l2S43 = P4S42 CERC PCE3S41 P5S34;
l3S43 = P1S41 CERC PCE4S41 P5S42;
l4S43 = P6S42 d PI1S412;
l5S43 = P2S42 CERC PCE5S41 P5S41;
l6S43 = PI2S412 d P1S42;
l7S43 = PI1S412 d PI2S412;
l8S43 = PI2S412 CER3 PI3S412 PI1S412;

S4121 = (l1S34 et l2S34 et l1S41 et l2S41 et l6S41 et l4S41 et l5S41 et
l4S34) surf PLAN;
S4122 = S4121 syme 'PLAN' P1sym P2sym P3sym;
S412 = S4121 et S4122;

S41311 = (l8S41 et l10S41 et l9S41 et l6S41) surf PLAN;
S41312 = S41311 syme 'PLAN' P1sym P2sym P3sym;
S4131 = S41311 et S41312;

S41321 = (l10S41 et l11S41 et (INVE l3S41) et l12S41) surf PLAN;
S41322 = S41321 syme 'PLAN' P1sym P2sym P3sym;
S4132 = S41321 et S41322;

S413 = S4131 et S4132;

S4141 = (l3S41 et l7S41) surf PLAN;
S4142 = S4141 syme 'PLAN' P1sym P2sym P3sym;
S414 = S4141 et S4142;

S341 = S34 syme 'PLAN' P1sym P2sym P3sym;
S41 = S34 ET S341 ET S412 ET S413 ET S414;
elim (S41 et S414) edens1;


S421 = (l1S42 et l2S42 et l3S42 et l4S42 et l5S42 et l6S42) surf PLAN;
S422 = S421 syme 'PLAN' P1sym P2sym P3sym;
S42 = S421 et S422;


S431 = l1S43 l3s42 l2s43 (INVE l3S34) dall 'QUELCONQUE';
S432 = S431 syme 'PLAN' P1sym P2sym P3sym;
S43 = S431 et S432;


S441 = l2S43 (INVE L5S41) l3S43 (INVE l4S42) dall 'QUELCONQUE';
S442 = l5S43 l1s41 l1s43 l2S42 dall 'QUELCONQUE';
S443 = S441 ET S442;
S444 = S443 syme 'PLAN' P1sym P2sym P3sym;
S44 = S444 et S443;
elim S44 edens1;

S451 = l8S43 l6S43 l6S42 l4S43 dall 'QUELCONQUE';
S452 = S451 syme 'PLAN' P1sym P2sym P3sym;
S45 = S451 et S452;


S461 = (l8S43 et l7S43) surf PLAN;
S462 = S461 syme 'PLAN' P1sym P2sym P3sym;
S46 = S461 et S462;

S4 = S41 ET S42 ET S43 ET S44 ET S45 ET S46;
elim S4 edens1;

vol41 = S4 volu ;
elim vol41 edens1;
vol41 = vol41 rege;



* ..............................Right punch................................
*.....................................................................

veccrp1 = 0.016 0. 0.;
veccrp2 = 0.026 0. 0.;
veccrp3 = 0.061 0. 0.;

SRP4111 = S4131 MOIN veccrp1;
SRP4112 = S4132 MOIN veccrp1;
SRP4113 = S414  MOIN veccrp1;

SRP4211 = S4131 MOIN veccrp2;
SRP4212 = S4132 MOIN veccrp2;
SRP4213 = S414  MOIN veccrp2;

SRP4311 = S4131 MOIN veccrp3;
SRP4312 = S4132 MOIN veccrp3;
SRP4313 = S414  MOIN veccrp3;

elim (SRP4111 et SRP4112 et SRP4113) edens1;
elim (SRP4211 et SRP4212 et SRP4213) edens1;
elim (SRP4311 et SRP4312 et SRP4313) edens1;


vol4311 = (S4131 VOLU SRP4111) couleur bleu;
vol4312 = (S4132 VOLU SRP4112) couleur bleu;
vol4313 = (S414 VOLU SRP4113) couleur bleu;
vol431 = vol4311 et vol4312 et vol4313;
vol4321 = (SRP4112 VOLU SRP4212) couleur bleu;
vol4322 = (SRP4113 VOLU SRP4213) couleur bleu;
vol432 = vol4321 et vol4322;
vol433 = vol431 et vol432;

vol4341 = (SRP4212 VOLU SRP4312) couleur bleu;
vol4342 = (SRP4213 VOLU SRP4313) couleur bleu;


SI CONFIN;
VGLIMR = (vol4341 et vol4342) couleur rose;
elim VGLIMR edens1;
Volrp = (VOL433 ET VGLIMR) couleur rose;
elim volrp edens1;
volrp = volrp rege;
elim (volrp et vol41) edens1;
SI CRIGI;
elim (volrp et vol41) edens1;
NSRP = CHAN 'POI1' (SRP4312 et SRP4313);
FINSI;
FINSI;


SI UNCONF;
VGLIMR = (vol4341 et vol4342) couleur rose;
elim VGLIMR edens1;
Volrp = (VOL433 ET VGLIMR) couleur rose;
elim volrp edens1;
volrp = volrp rege;
SI CRIGI;
elim (volrp et vol41) edens1;
NSRP = CHAN 'POI1' (SRP4312 et SRP4313);
FINSI;
FINSI;


SI UNCONFME;
vmeccrp2 = 0.051 0. 0.;
vmeccrp3 = 0.02 0. 0.;

Pm6S41 = 1.669 0. ((-1)*(diamet43/2));
Pm7S41 = 1.669 (diamet43/2) 0.;
Pm8S41 = 1.669 0. (diamet43/2);
Pm9S41 = 1.669 0. ((-1)*(diamet42/2));
Pm10S41 = 1.669 (diamet42/2) 0.;
Pm11S41 = 1.669 0. (diamet42/2);

lm6S41 = Pm8S41 CER3 Pm7S41 Pm6S41;
lm8S41 = Pm6S41 d Pm9S41;
lm9S41 = Pm11S41 d Pm8S41;
lm10S41 = Pm9S41 CER3 Pm10S41 Pm11S41;

Sm41311 = (lm8S41 et lm10S41 et lm9S41 et lm6S41) surf PLAN;
Sm41312 = Sm41311 syme 'PLAN' P1sym P2sym P3sym;
SmRP4211 = Sm41311 et Sm41312;

SmRP4212 = S4132 MOIN vmeccrp2;
SmRP4213 = S414  MOIN vmeccrp2;

SmRP4311 = SmRP4211 MOIN vmeccrp3;
SmRP4312 = SmRP4212 MOIN vmeccrp3;
SmRP4313 = SmRP4213 MOIN vmeccrp3;

elim (SmRP4211 et SmRP4212 et SmRP4213) edens1;
elim (SmRP4311 et SmRP4312 et SmRP4313) edens1;
```

```
vmol4321 = (SRP4112 VOLU SmRP4212) couleur bleu;
vmol4322 = (SRP4113 VOLU SmRP4213) couleur bleu;
vmol432 = vmol4321 et vmol4322;
vmol433 = vol431 et vmol432;

vmol4341 = (SmRP4212 VOLU SmRP4312) couleur bleu;
vmol4342 = (SmRP4213 VOLU SmRP4313) couleur bleu;
vmol4345 = (SmRP4211 VOLU SmRP4311) couleur bleu;

VGLIMR = (vmol4341 et vmol4342 et vmol4345)
couleur rose;
elim VGLIMR edens1;
Volrp = (VmOL433 ET VGLIMR) couleur rose;
elim volrp edens1;
volrp = volrp rege;
elim (volrp et vol41) edens1;

SI CRIGI;
NSRP = CHAN 'POI1' (SmRP4312 et SmRP4313 et SmRP4311);
FINSI;

FINSI;

* .............Volume of the inversion cage of the input bar.............
*.....................................................................

volinp =vol2 et vol41 et vol3;


elim volinp edens1;
volinp = (volinp rege) couleur bleu;

*---------------------------------------------------------------------
*               Output bar - Inversion cage of the output
*  ...................................................................
*---------------------------------------------------------------------


* ..............................Left cross.................................
*.....................................................................

posrp = 1.659;

SI UNCONF;
posrp = 1.659;
FINSI;
SI CONFIN;
posrp = 1.659;
FINSI;
SI UNCONFME;
posrp = 1.649;
FINSI;

diametcl = 0.062;
diametc2 = 0.078;
widthcl = 0.04;
gdiamecl = 0.12;

SI UNCONF;
posxcl = posrp - widthsp - widthcl - 0.045;
FINSI;
SI CONFIN;
posxcl = posrp - widthsp - widthcl - 0.045;
FINSI;
SI UNCONFME;
posxcl = posrp - widthsp - widthcl - 0.055;
FINSI;

veccl = widthcl 0. 0.;
veccl1 = ((-1)*widthcl) 0. 0.;
veccl2 = -0.01 0. 0.;
veccl3 = -0.035 0. 0.;
veccl4 = -0.02 0. 0.;

P1cl = posxcl (diametcl/2) 0.;
P11cl = posxcl 0.065 0.;
P2cl = posxcl 0.105 0.;
P3cl = posxcl 0.065 0.02;
P4cl = posxcl 0.0566 0.02;
P5cl = posxcl 0.0424 0.0424;
P6cl = posxcl 0.02 0.0566;
P61cl = posxcl 0.02 0.065;
P7cl = posxcl 0. 0.065;
P8cl = posxcl 0. 0.105;
P9cl = posxcl 0. (diametcl/2);
Pce1cl = posxcl 0. 0.;
Psymcl = posxcl 1. 0.;

l1cl = P1cl d P11cl;
l2cl = P3cl d P4cl;
l4cl = P4cl CER3 P5cl P6cl;
l5cl = P6cl d P61cl;
l6cl = P7cl d P61cl;
l7cl = P7cl d P9cl;
l8cl = P9cl CERC Pce1cl P1cl;
l9cl = P1cl d Pce1cl;
l10cl = Pce1cl d P9cl;
l11cl = P3cl d P11cl;


ctcl1 = l1cl et (INVE l11cl) ET l2cl ET L4CL ET L5CL ET (INVE l6cl)
ET l7cl ET L8CL;
ctclc = l8cl et l9cl et l10cl;

scl1 = ctcl1 SURF 'PLAN';
elim scl1 edens1;
scl2 = scl1 SYME DROIT P1cl P2cl;
scl3 = scl1 SYME DROIT P8cl P9cl;
scl4 = scl3 SYME DROIT Pce1cl Psymcl ;
SCL = SCL1 ET SCL2 ET SCL3 ET SCL4;

scllc11 = ctclc SURF 'PLAN';
scllc12 = scllc11 SYME PLAN P1sym P2SYM P3SYM;
scllc13 = (scllc11 et scllc12) SYME PLAN P1sym P4SYM P5SYM;
SCL1C1 = SCL1C11 ET SCL1C12 ET SCL1C13 ;
SCL1C2 = SCL1C1 MOINS veccl1;
SCL1C3 = SCL1C2 MOINS veccl2;
SCL1C4 = SCL1C3 MOINS veccl3;

elim scl edens1;

vcl1 = (scl VOLU TRAN veccl) couleur bleu;
vclc = (SCL1C1 VOLU SCL1C2) couleur bleu;

SI UNCONF;
vclc1 = (SCL1C2 VOLU SCL1C3) couleur bleu;
vclc2 = (SCL1C3 VOLU SCL1C4) couleur bleu;
vclc11 = vclc et vclc1;
elim vclc11 edens1;

VGLIML = vclc2 couleur rouge;
ELIM VGLIML edens1;
vollc = (vcl1 et vclc11 et VGLIML) couleur rouge;
ELIM vollc edens1;
SI CRIGI;
NSLC = CHAN 'POI1' SCL1C4;
FINSI;
FINSI;

SI CONFIN;
vclc1 = (SCL1C2 VOLU SCL1C3) couleur bleu;
vclc2 = (SCL1C3 VOLU SCL1C4) couleur bleu;
vclc11 = vclc et vclc1;
elim vclc11 edens1;

VGLIML = vclc2 couleur rouge;
ELIM VGLIML edens1;
vollc = (vcl1 et vclc11 et VGLIML) couleur rouge;
ELIM vollc edens1;
SI CRIGI;
NSLC = CHAN 'POI1' SCL1C4;
FINSI;
FINSI;

SI UNCONFME;
Pm1cl11 = (posxcl+widthcl+0.035) 0. (diametcl/2.);
Pm2cl11 = (posxcl+widthcl+0.035) (diametcl/2.) 0.;
Pm3cl11 = (posxcl+widthcl+0.035) 0. (diametc2/2.);
Pm4cl11 = (posxcl+widthcl+0.035) (diametc2/2.) 0.;
Pmce2cl1 = (posxcl+widthcl+0.035) 0. 0.;

Pm1cl12 = (posxcl + widthcl + 0.055) 0. (diametcl/2);
Pm2cl12 = (posxcl + widthcl + 0.055) (diametcl/2) 0.;
Pm3cl12 = (posxcl + widthcl + 0.055) 0. (diametc2/2);
Pm4cl12 = (posxcl + widthcl + 0.055) (diametc2/2) 0.;
Pmce2cl2 = (posxcl + widthcl + 0.055) 0. 0.;

lm1cl11 = CERC Pm1cl11 Pmce2cl1 Pm2cl11;
lm2cl11 = Pm2cl11 d Pmce2cl1;
lm3cl11 = Pmce2cl1 d Pm1cl11;
lm4cl11 = Pm2cl11 d Pm4cl11;
lm5cl11 = CERC Pm4cl11 Pmce2cl1 Pm3cl11;
lm6cl11 = Pm3cl11 d Pm1cl11;

lm1cl12 = Pm1cl12 CERC Pmce2cl2 Pm2cl12;
lm2cl12 = Pm2cl12 d Pmce2cl2;
lm3cl12 = Pmce2cl2 d Pm1cl12;
lm4cl12 = Pm2cl12 d Pm4cl12;
lm5cl12 = Pm4cl12 CERC Pmce2cl2 Pm3cl12;
lm6cl12 = Pm3cl12 d Pm1cl12;

cmtclc11 = lm1cl11 et lm2cl11 et lm3cl11 ;
cmtclc12 = lm1cl11 et lm4cl11 et lm5cl11 et lm6cl11;
cmtclc21 = lm1cl12 et lm2cl12 et lm3cl12 ;
cmtclc22 = lm1cl12 et lm4cl12 et lm5cl12 et lm6cl12;


smcllc11 = cmtclc11 SURF 'PLAN';
smcllc12 = smcllc11 SYME PLAN P1sym P2SYM P3SYM;
smcllc13 = (smcllc11 et smcllc12) SYME PLAN P1sym P4SYM P5SYM;
smcllc1 = smcllc11 et smcllc12 et smcllc13;

smcllc21 = cmtclc12 SURF 'PLAN';
smcllc22 = smcllc21 SYME PLAN P1sym P2SYM P3SYM;
smcllc23 = (smcllc21 et smcllc22) SYME PLAN P1sym P4SYM P5SYM;
smcllc2 = smcllc21 et smcllc22 et smcllc23;

smcllc31 = smcllc1 MOIN veccl4;
smcllc32 = smcllc2 MOIN veccl4;

vmclc1 = (SCL1C2 VOLU SmCL1C1) couleur bleu;
vmclc2 = (SmCL1C1 VOLU SmCL1C31) couleur bleu;
vmclc3 = (SmCL1C2 VOLU SmCL1C32) couleur bleu;
vmclc11 = vclc et vmclc1;
elim vmclc11 edens1;


VGLIML = (vmclc2 et vmclc3) couleur rouge;
ELIM VGLIML edens1;
vollc = (vcl1 et vmclc11 et VGLIML)
couleur rouge;
ELIM vollc edens1;
SI CRIGI;
NSLC = CHAN 'POI1' (SmCL1C32 et SmCL1C31);
FINSI;

FINSI;


* ............Right cross + Left nut + Right nut.........................
*.....................................................................


diametcr = 0.072;
diamecy1 = 0.055;
diamecy2 = 0.03;
diametcy = 0.0425;
widthcr = 0.04;
widthln = -0.05;
widthba = 0.025;
widthrn = 0.03;
gdiamecr = 0.129;
posxcr = (posxcl+0.41);
lengcr1 = 0.025+widthcr;
lengcr2 = 0.38+lengcr1;
lengcr3 = 0.5+lengcr2;
lengcr4 = 0.1+lengcr3;
lengcr51 = 0.001 + lengcr4;
lengcr5 = 1.+lengcr4;
lengcr6 = 100.+lengcr5;
veccr1 = -0.05 0. 0.;
veccr2 = 0.025 0. 0.;
veccr3 = ((-1)*widthba) 0. 0.;


P1cri = posxcr (diametcr/2) 0.;
P1crii = (posxcr+widthcr) (diametcr/2) 0.;
P1cyi = posxcr (diametcy/2) 0.;
P1cyii = (posxcr+widthcr) (diametcy/2) 0.;
P2cr = posxcr 0.105 0.;
P2bcr = (posxcr+widthcr) 0.105 0.;
P3cr = posxcr 0.0608 0.02;
P3bcr = (posxcr+widthcr) 0.0608 0.02;
P4cr = posxcr 0.02 0.0608;
P4bcr = (posxcr+widthcr) 0.02 0.0608;
P5cr = posxcr 0. 0.105;
P5bcr = (posxcr+widthcr) 0. 0.105;
P6cr = posxcr 0.02 0.065;
P6bcr = (posxcr+widthcr) 0.02 0.065;
P7cr = posxcr 0.065 0.02 ;
P7bcr = (posxcr+widthcr) 0.065 0.02 ;
P8cr = posxcr 0. 0.065;
P8bcr = (posxcr+widthcr) 0. 0.065;
P9cri = posxcr 0. (diametcr/2);
P9crii = (posxcr+widthcr) 0. (diametcr/2);
P9cyi = posxcr 0. (diametcy/2);
P9cyii = (posxcr+widthcr) 0. (diametcy/2);
P10cr = posxcr 0.065 0. ;
P10bcr = (posxcr+widthcr) 0.065 0. ;
Pccr = (posxcr+widthln) 0. 0.;
Pccri = posxcr 0. 0.;
Pccrii = (posxcr+widthcr) 0. 0.;

Psymcr = posxcr 1. 0.;
Psymbcr = (posxcr+widthcr) 1. 0.;


l1cr = P1CRi D P10cr;
l1bcr = P1CRii D P10bcr;
l2cr = P3CR CERC PCCRi P4cr;
l2bcr = P3bCR CERC PCCRii P4bcr;
l3cr = P8cr D P9CRi;
l3bcr = P8bcr D P9CRii;
l4cr = P3CR D P7cr;
l4bcr = P3bCR D P7bcr;
l5cr = P6cr D P4cr;
l5bcr = P6bcr D P4bcr;
l6cr = P7cr D P10cr;
l6bcr = P7bcr D P10bcr;
l7cr = P8cr D P6cr;
l7bcr = P8bcr D P6bcr;
L1CRi = P1CYi D P1CRi;
L2CRi = P1CRi CERC PCCRi P9CRi;
L3CRi = P9CRi D P9CYi;
L1CYi = P9CYi CERC PCCRi P1CYi;
L1CRii = P1CYii D P1CRii;
L2CRii = P1CRii CERC PCCRii P9CRii;
L3CRii = P9CRii D P9CYii;
L1CYii = P9CYii CERC PCCRii P1CYii;
L2CYii = P1CYii D PCCRii;
L3CYii = PCCRii D P9CYii;


ctcli = L1CRi et L2CRi et L3CRi et L1CYi;
ctcliii = L1CRii et L2CRii et L3CRii et L1CYii;
ctc2ii = L1CYii et L2CYii et L3CYii;
ctcr1 = l1cr ET (INVE l6cr) ET (INVE l4cr) ET l2cr ET (INVE l5cr) ET
(INVE l7cr) ET l3cr ET (INVE L2CRi);
```

```
ctcr2 = l1bcr ET (INVE l6bcr) ET (INVE l4bcr) ET l2bcr ET
(INVE l5bcr) ET (INVE l7bcr) ET l3bcr ET (INVE L2CRii);


s1oi = ctc1i SURF 'PLAN';
s2oi = s1oi SYME PLAN P1sym P2SYM P3SYM;
s3oi = (s1oi et s2oi) SYME PLAN P1sym P4SYM P5SYM;
s1oui = s1oi et s2oi et s3oi;
elim s1oui edens1;

s1oii = ctc1ii SURF 'PLAN';
s2oii = s1oii SYME PLAN P1sym P2SYM P3SYM;
s3oii = (s1oii et s2oii) SYME PLAN P1sym P4SYM P5SYM;
s4oii = ctc2ii SURF 'PLAN';
s5oii = s4oii SYME PLAN P1sym P2SYM P3SYM;
s6oii = (s4oii et s5oii) SYME PLAN P1sym P4SYM P5SYM;
s2ouii = s1oii et s2oii et s3oii;
s3ouii = s4oii et s5oii et s6oii;
s1ouii = s2ouii et s3ouii;
elim s1ouii edens1;

s1ouiii = s1ouii MOIN veccr3;
elim s1ouiii edens1;

scr11 = ctcr1 SURF 'PLAN';
scr12 = scr11 SYME DROIT P1cri P2cr;
scr13 = scr11 SYME DROIT P5cr P9cri;
scr14 = scr13 SYME DROIT Pccri Psymcr ;
scr21 = ctcr2 SURF 'PLAN';
scr22 = scr21 SYME DROIT P1crii P2bcr;
scr23 = scr21 SYME DROIT P5bcr P9crii;
scr24 = scr23 SYME DROIT Pccrii Psymbcr ;
scr1 = scr11 ET scr12 ET scr13 ET scr14;
scr2 = scr21 ET scr22 ET scr23 ET scr24;
elim scr2 edens1;


v1out = (s1oui volu s2ouii) couleur rouge;
v2out = (s1ouii volu s1ouiii) couleur rouge;
volout = v1out et v2out;
elim volout edens1;
volln = ((scr1 et s1oui) VOLU TRAN veccR1) couleur turquoise ;
elim volln edens1;
volln = volln rege;
Volrn = (scr2 VOLU TRAN veccr2) couleur turquoise ;
elim volrn edens1;
volrn = volrn rege;
volrc = (scr1 VOLU scr2) couleur verte;
elim volrc edens1;
elim (volrc et volrn et volln et volout) edens1;


* ............Bars of the inversion cage of the output bar..............
*.....................................................................................

dis1b = 0.025;
posxb = posxcl-dis1b;
dis2b = 0.45;

VECB1 = 0. 0.02 0.;

P1bar = posxb 0. 0.065;
P3bar = (posxb + dis1b + widthcr) 0. 0.065;
P31bar = (posxb + dis1b + widthcr) 0. 0.105;
P4bar = (posxb + dis1b + dis2b) 0. 0.105;
P5bar = (posxb + dis1b + dis2b) 0. 0.065;
P6bar = (posxb + dis1b + dis2b + dis1b) 0. 0.065;
P7bar = (posxb + dis1b + dis2b + dis1b) 0. 0.115;
P8bar = (posxb + dis1b + dis2b + dis1b - 0.015) 0. 0.13;
P9bar = (posxb + 0.015) 0. 0.13;
P10bar = (posxb ) 0. 0.115;

PSYB1 = 1. 0. 0.;
PSYB2 = 0. 1. 1.;
PSYB3 = 1. 0. 0.;
L1B = P1BAR D P7cl;
L2B = P7cl D P3BAR;
L3B = P3BAR D P31BAR;
L31B = P31BAR D P5cr;
L32B = P5cr D P8cr;
L4B = P8cr D P8bcr;
L5B = P8bcr D P6BAR;
L6B = P6BAR D P7BAR;
L7B = P7BAR D P8BAR;
L8B = P8BAR D P9BAR;
L9B = P9BAR D P10BAR;
L10B = P10BAR D P1BAR;
CT1 = L1B ET L2B ET L3B ET L31B ET L32B ET L4B ET L5B ET L6B ET L7B ET
L8B ET L9B ET L10B;

SB1 = CT1 SURF PLAN;
VB11 = SB1 VOLU TRAN VECB1;
VB12 = VB11 SYME PLAN P1sym P2sym P3sym;
VB1 = VB11 et VB12;
elim VB1 edens1;
VB2 = VB1 SYME PLAN P1sym P5sym P4sym;
VBB1 = VB1 ET VB2;
VBB2 = VBB1 SYME PLAN P1sym PSYB1 PSYB2;
Volba = (VBB1 ET VBB2) COULEUR ROUGE;
elim Volba edens1;
Volba = volba rege;
elim (Volba et volrc) edens1;
elim (Volba et vollc) edens1;
elim (volrc et volrn et volout et volln) edens1;


* .............................Output bar ..................................
*.....................................................................................


opti dime 3 elem SEG2;

Pout10 = (posxcr+lengcr1) 0. 0.;
Pout11 = (posxcr+lengcr2) 0. 0.;
Pout12 = (posxcr+lengcr3) 0. 0.;
Pout1 = (posxcr+lengcr4) 0. 0.;
Pout2 = (posxcr+lengcr5) 0. 0.;

lout10 = Pout10 d Pout11;
lout11 = Pout11 d Pout12;
lout12 = Pout12 d Pout1;
lout1 = Pout1 d Pout2;

dens dens3;
Pout3 = (posxcr+lengcr6) 0. 0.;
lout2 = Pout2 d Pout3;
lout = lout10 et lout11 et lout12 et lout1 et lout2;

DEPL (Volout et volba et vollc et VGLIML et volrc et volln et
volrn et lout)
TOUR 45 p1sym PSYB3;




opti dime 3 elem CUB8;
dens dens2;
*----------------------------------------------------------------------
*                              Specimen
*  ..................................................................
*----------------------------------------------------------------------

veccsp1 = ((-1)*(widthsp/2)) 0. 0.;
veccsp2 = ((-1)*widthsp) 0. 0.;

P1sp = (posrp + ((-1)*widthsp)) (diametsp/2) 0.;
P2sp = (posrp + ((-1)*widthsp)) 0. (diametsp/2);
Pcesp = (posrp + ((-1)*widthsp)) 0. 0.;

l1sp = P1sp CERC Pcesp P2sp;
l2sp = P2sp D Pcesp;
l3sp = Pcesp D P1sp;

ctsp1 = l1sp et l2sp et l3sp;


ssp1 = ctsp1 surf 'PLAN';
ssp2 =  ssp1 SYME PLAN P1sym P2SYM P3SYM ;
ssp3 = (ssp1 et ssp2) SYME PLAN P1sym P4SYM P5SYM;
ssp = ssp1 et ssp2 et ssp3;
ELIM ssp edens2;
ssp21 = ssp MOIN veccsp1;
ELIM ssp21 edens2;
ssp2 = ssp MOIN veccsp2;
ELIM ssp2 edens2;

volsp1 = (ssp VOLU ssp21) couleur verte;
ELIM volsp1 edens2;
volsp2 = (ssp21 VOLU ssp2) couleur verte;
ELIM volsp2 edens2;
volsp = volsp1 et volsp2;
ELIM volsp edens2;
volsp = (volsp rege) couleur verte;

VGLIL = VOLSP ELEM APPU LARG SSP;
VGLIR = VOLSP ELEM APPU LARG SSP2;
NSLSP = CHAN 'POI1' SSP;
NLOADSL = BARY SSP;
PSL = MANU POI1 NLOADSL;
NSRSP = CHAN 'POI1' SSP2;
NLOADSR = BARY SSP2;
PSR = MANU POI1 NLOADSR;

*----------------------------------------------------------------------
*                              Jacket
*  ..................................................................
*----------------------------------------------------------------------
diamjai = diametsp;
diamjae = diamjai + ((2)*(widthja));

P1ja = (posrp + 0.025) (diamjai/2) 0.;
P2ja = (posrp + 0.025) 0. (diamjai/2);
P3ja = (posrp + 0.025) ((diamjae/2)) 0.;
P4ja = (posrp + 0.025) 0. ((diamjae/2));
P5ja = (posrp + 0.025) ((-1)*(diamjai/2)) 0.;
P6ja = (posrp + 0.025) 0. ((-1)*(diamjai/2));
P7ja = (posrp + 0.025) ((-1)*(diamjae/2)) 0.;
P8ja = (posrp + 0.025) 0. ((-1)*(diamjae/2));
Pceja = (posrp + 0.025) 0. 0.;


P1ja1 = (posrp + 0.0075 + ((-1)*(0.5*widthsp))) (diamjai/2) 0.;
P2ja1 = (posrp + 0.0075 + ((-1)*(0.5*widthsp))) 0. (diamjai/2);
P3ja1 = (posrp + 0.0075 + ((-1)*(0.5*widthsp))) (diamjae/2) 0.;
P4ja1 = (posrp + 0.0075 + ((-1)*(0.5*widthsp))) 0. (diamjae/2);
P5ja1 = (posrp + 0.0075 + ((-1)*(0.5*widthsp))) ((-1)*(diamjai/2)) 0.;
P6ja1 = (posrp + 0.0075 + ((-1)*(0.5*widthsp))) 0. ((-1)*(diamjai/2));
P7ja1 = (posrp + 0.0075 + ((-1)*(0.5*widthsp))) ((-1)*(diamjae/2)) 0.;
P8ja1 = (posrp + 0.0075 + ((-1)*(0.5*widthsp))) 0. ((-1)*(diamjae/2));
Pceja1 = (posrp + 0.0075 + ((-1)*(0.5*widthsp))) 0. 0.;

P1ja2 = (posrp + 0.0025 + ((-1)*(0.5*widthsp))) (diamjai/2) 0.;
P2ja2 = (posrp + 0.0025 + ((-1)*(0.5*widthsp))) 0. (diamjai/2);
P3ja2 = (posrp + 0.0025 + ((-1)*(0.5*widthsp))) (diamjae/2) 0.;
P4ja2 = (posrp + 0.0025 + ((-1)*(0.5*widthsp))) 0. (diamjae/2);
P5ja2 = (posrp + 0.0025 + ((-1)*(0.5*widthsp))) ((-1)*(diamjai/2)) 0.;
P6ja2 = (posrp + 0.0025 + ((-1)*(0.5*widthsp))) 0. ((-1)*(diamjai/2));
P7ja2 = (posrp + 0.0025 + ((-1)*(0.5*widthsp))) ((-1)*(diamjae/2)) 0.;
P8ja2 = (posrp + 0.0025 + ((-1)*(0.5*widthsp))) 0. ((-1)*(diamjae/2));
Pceja2 = (posrp + 0.0025 + ((-1)*(0.5*widthsp))) 0. 0.;

P1ja3 = (posrp + ((-1)*(0.0025 + (0.5*widthsp)))) (diamjai/2) 0.;
P2ja3 = (posrp + ((-1)*(0.0025 + (0.5*widthsp)))) 0. (diamjai/2);
P3ja3 = (posrp + ((-1)*(0.0025 + (0.5*widthsp)))) (diamjae/2) 0.;
P4ja3 = (posrp + ((-1)*(0.0025 + (0.5*widthsp)))) 0. (diamjae/2);
P5ja3 = (posrp + ((-1)*(0.0025 + (0.5*widthsp)))) ((-1)*(diamjai/2)) 0.;
P6ja3 = (posrp + ((-1)*(0.0025 + (0.5*widthsp)))) 0. ((-1)*(diamjai/2));
P7ja3 = (posrp + ((-1)*(0.0025 + (0.5*widthsp)))) ((-1)*(diamjae/2)) 0.;
P8ja3 = (posrp + ((-1)*(0.0025 + (0.5*widthsp)))) 0. ((-1)*(diamjae/2));
Pceja3 = (posrp + ((-1)*(0.0025 + (0.5*widthsp)))) 0. 0.;

P1ja4 = (posrp + ((-1)*(0.0075 + (0.5*widthsp)))) (diamjai/2) 0.;
P2ja4 = (posrp + ((-1)*(0.0075 + (0.5*widthsp)))) 0. (diamjai/2);
P3ja4 = (posrp + ((-1)*(0.0075 + (0.5*widthsp)))) (diamjae/2) 0.;
P4ja4 = (posrp + ((-1)*(0.0075 + (0.5*widthsp)))) 0. (diamjae/2);
P5ja4 = (posrp + ((-1)*(0.0075 + (0.5*widthsp)))) ((-1)*(diamjai/2)) 0.;
P6ja4 = (posrp + ((-1)*(0.0075 + (0.5*widthsp)))) 0. ((-1)*(diamjai/2));
P7ja4 = (posrp + ((-1)*(0.0075 + (0.5*widthsp)))) ((-1)*(diamjae/2)) 0.;
P8ja4 = (posrp + ((-1)*(0.0075 + (0.5*widthsp)))) 0. ((-1)*(diamjae/2));
Pceja4 = (posrp + ((-1)*(0.0075 + (0.5*widthsp)))) 0. 0.;

P1ja5 = (posrp + ((-1)*(0.025 + widthsp))) (diamjai/2) 0.;
P2ja5 = (posrp + ((-1)*(0.025 + widthsp))) 0. (diamjai/2);
P3ja5 = (posrp + ((-1)*(0.025 + widthsp))) (diamjae/2) 0.;
P4ja5 = (posrp + ((-1)*(0.025 + widthsp))) 0. (diamjae/2);
P5ja5 = (posrp + ((-1)*(0.025 + widthsp))) ((-1)*(diamjai/2)) 0.;
P6ja5 = (posrp + ((-1)*(0.025 + widthsp))) 0. ((-1)*(diamjai/2));
P7ja5 = (posrp + ((-1)*(0.025 + widthsp))) ((-1)*(diamjae/2)) 0.;
P8ja5 = (posrp + ((-1)*(0.025 + widthsp))) 0. ((-1)*(diamjae/2));
Pceja5 = (posrp + ((-1)*(0.025 + widthsp))) 0. 0.;

l1ja = P1ja CERC Pceja P2ja;
nmja = nbel l1ja;
l2ja = P2ja CERC Pceja P5ja;
l3ja = P5ja CERC Pceja P6ja;
l4ja = P6ja CERC Pceja P1ja;
l5ja = P8ja CERC nmja Pceja P7ja;
l6ja = P7ja CERC nmja Pceja P4ja;
l7ja = P4ja CERC nmja Pceja P3ja;
l8ja = P3ja CERC nmja Pceja P8ja;


l1ja1 = P1ja1 CERC Pceja1 P2ja1;
l2ja1 = P2ja1 CERC Pceja1 P5ja1;
l3ja1 = P5ja1 CERC Pceja1 P6ja1;
l4ja1 = P6ja1 CERC Pceja1 P1ja1;
l5ja1 = P8ja1 CERC nmja Pceja1 P7ja1;
l6ja1 = P7ja1 CERC nmja Pceja1 P4ja1;
l7ja1 = P4ja1 CERC nmja Pceja1 P3ja1;
l8ja1 = P3ja1 CERC nmja Pceja1 P8ja1;



l1ja2 = P1ja2 CERC Pceja2 P2ja2;
l2ja2 = P2ja2 CERC Pceja2 P5ja2;
l3ja2 = P5ja2 CERC Pceja2 P6ja2;
l4ja2 = P6ja2 CERC Pceja2 P1ja2;
l5ja2 = P8ja2 CERC nmja Pceja2 P7ja2;
l6ja2 = P7ja2 CERC nmja Pceja2 P4ja2;
l7ja2 = P4ja2 CERC nmja Pceja2 P3ja2;
l8ja2 = P3ja2 CERC nmja Pceja2 P8ja2;

l1ja3 = P1ja3 CERC Pceja3 P2ja3;
l2ja3 = P2ja3 CERC Pceja3 P5ja3;
l3ja3 = P5ja3 CERC Pceja3 P6ja3;
l4ja3 = P6ja3 CERC Pceja3 P1ja3;
l5ja3 = P8ja3 CERC nmja Pceja3 P7ja3;
l6ja3 = P7ja3 CERC nmja Pceja3 P4ja3;
l7ja3 = P4ja3 CERC nmja Pceja3 P3ja3;
l8ja3 = P3ja3 CERC nmja Pceja3 P8ja3;

l1ja4 = P1ja4 CERC Pceja4 P2ja4;
l2ja4 = P2ja4 CERC Pceja4 P5ja4;
l3ja4 = P5ja4 CERC Pceja4 P6ja4;
l4ja4 = P6ja4 CERC Pceja4 P1ja4;
l5ja4 = P8ja4 CERC nmja Pceja4 P7ja4;
l6ja4 = P7ja4 CERC nmja Pceja4 P4ja4;
l7ja4 = P4ja4 CERC nmja Pceja4 P3ja4;
l8ja4 = P3ja4 CERC nmja Pceja4 P8ja4;

l1ja5 = P1ja5 CERC Pceja5 P2ja5;
l2ja5 = P2ja5 CERC Pceja5 P5ja5;
l3ja5 = P5ja5 CERC Pceja5 P6ja5;
l4ja5 = P6ja5 CERC Pceja5 P1ja5;
l5ja5 = P8ja5 CERC nmja Pceja5 P7ja5;
l6ja5 = P7ja5 CERC nmja Pceja5 P4ja5;
l7ja5 = P4ja5 CERC nmja Pceja5 P3ja5;
l8ja5 = P3ja5 CERC nmja Pceja5 P8ja5;
```

```
sja = ((l1ja et l2ja et l3ja et l4ja) et
(l5ja et l6ja et l7ja et l8ja)) surf 'PLAN';
sja1 = ((l1ja1 et l2ja1 et l3ja1 et l4ja1) et
(l5ja1 et l6ja1 et l7ja1 et l8ja1)) surf 'PLAN';
sja2 = ((l1ja2 et l2ja2 et l3ja2 et l4ja2) et
(l5ja2 et l6ja2 et l7ja2 et l8ja2)) surf 'PLAN';
sja3 = ((l1ja3 et l2ja3 et l3ja3 et l4ja3) et
(l5ja3 et l6ja3 et l7ja3 et l8ja3)) surf 'PLAN';
sja4 = ((l1ja4 et l2ja4 et l3ja4 et l4ja4) et
(l5ja4 et l6ja4 et l7ja4 et l8ja4)) surf 'PLAN';
sja5 = ((l1ja5 et l2ja5 et l3ja5 et l4ja5) et
(l5ja5 et l6ja5 et l7ja5 et l8ja5)) surf 'PLAN';

volja1 = sja volu sja1;
volja2 = sja1 volu sja2;
volja3 = sja2 volu sja3;
volja4 = sja3 volu sja4;
volja5 = sja4 volu sja5;
volja = (volja1 et volja2 et volja3 et volja4 et volja5)
couleur jaune;
elim volja edens1;

*------------------------------------------------------------------
*              Elements for the post-treatment in Europlexus
*  ................................................................
*------------------------------------------------------------------

Gauge1 = (linp ELEM APPU LARG PL18) ELEM 1;
Gauge3 = (linp ELEM APPU LARG PL19) ELEM 1;
Gauge4 = (linp ELEM APPU LARG PL20) ELEM 1;
Gauge5 = (linp ELEM APPU LARG PL21) ELEM 1;
Gauge6 = (lout ELEM APPU LARG Pout11) ELEM 1;
Gauge7 = (lout ELEM APPU LARG Pout12) ELEM 1;
VGSP = VOLSP ELEM APPU LARG ssp21;

*.....................................................................
* For the gauge 10, we take the average value of all the elements
* over the section in order to reproduce the experimental measure
* Warning! the number of elements will depend on the density
* chosen, the number should be adjuste when the value of dens1 is
* changed (the europlexus file also for the posttreatment.
*

VOL3PRI = vol3 elem pri6;
VG10 = (VOL3PRI) ELEM APPU LARG S33;
VG101 = VG10 ELEM 1 ;
VG102 = VG10 ELEM 2 ;
VG103 = VG10 ELEM 3 ;
VG104 = VG10 ELEM 4 ;
VG105 = VG10 ELEM 5 ;
VG106 = VG10 ELEM 6 ;
VG107 = VG10 ELEM 7 ;
VG108 = VG10 ELEM 8 ;
VG109 = VG10 ELEM 9 ;
VG110 = VG10 ELEM 10 ;
VG111 = VG10 ELEM 11 ;
VG112 = VG10 ELEM 12 ;
VG113 = VG10 ELEM 13 ;
VG114 = VG10 ELEM 14 ;
VG115 = VG10 ELEM 15 ;
VG116 = VG10 ELEM 16 ;
VG117 = VG10 ELEM 17 ;
VG118 = VG10 ELEM 18 ;
VG119 = VG10 ELEM 19 ;
VG120 = VG10 ELEM 20 ;
VG121 = VG10 ELEM 21 ;
VG122 = VG10 ELEM 22 ;
VG123 = VG10 ELEM 23 ;
VG124 = VG10 ELEM 24 ;
VG125 = VG10 ELEM 25 ;
VG126 = VG10 ELEM 26 ;
VG127 = VG10 ELEM 27 ;
VG128 = VG10 ELEM 28 ;
VG129 = VG10 ELEM 29 ;
VG130 = VG10 ELEM 30 ;
VG131 = VG10 ELEM 31 ;
VG132 = VG10 ELEM 32 ;
VG133 = VG10 ELEM 33 ;
VG134 = VG10 ELEM 34 ;
VG135 = VG10 ELEM 35 ;
VG136 = VG10 ELEM 36 ;
VG137 = VG10 ELEM 37 ;
VG138 = VG10 ELEM 38 ;
VG139 = VG10 ELEM 39 ;
VG140 = VG10 ELEM 40 ;
VG141 = VG10 ELEM 41 ;
VG142 = VG10 ELEM 42 ;
VG143 = VG10 ELEM 43 ;
VG144 = VG10 ELEM 44 ;
VG145 = VG10 ELEM 45 ;
VG146 = VG10 ELEM 46 ;
VG147 = VG10 ELEM 47 ;
VG148 = VG10 ELEM 48 ;
VG149 = VG10 ELEM 49 ;
VG150 = VG10 ELEM 50 ;
*.....................................................................

*------------------------------------------------------------------
*                          The whole mesh
*  ................................................................
*------------------------------------------------------------------

vinput = volinp et volrp ;
ELIM vinput edens1;
voutput = volout et vollc et volrc et volln et volrn et volba ;
ELIM voutput edens1;

SI UNCONFME;
mesh = vinput et voutput et volsp et volrig et lout et linp;
SI CRIGI;
mesh = vinput et voutput et volsp et volrig et lout et linp et PSR
et PSL;
FINSI;
FINSI;

SI UNCONF;
mesh = vinput et voutput et volsp et volrig et lout et linp;
SI CRIGI;
mesh = vinput et voutput et volsp et volrig et lout et linp et PSR
et PSL;
FINSI;
FINSI;

SI CONFIN;
mesh = vinput et voutput et volsp et volrig et lout et linp et volja;
SI CRIGI;
mesh = vinput et voutput et volsp et volrig et lout et linp et PSR
et PSL et VOLJA;
FINSI;
FINSI;

*.....................................................................
* Mesh by type of elements (used for the input file of Europlexus)
*
mesh2 = mesh elem seg2;
mesh4 = mesh elem tet4;
mesh6 = mesh elem pri6;
mesh8 = mesh elem cub8;

mess1 = 'Total number of element:';
mess2 = 'Total number of nodes:';
mess3 = 'Number of 3DOF nodes (PT3L):';
mess4 = 'Number of 6DOF nodes (PT6L):';
mess5 = 'Number of bar element (BR3D):';
mess6 = 'Number of tretraedric element (TETR):';
mess7 = 'Number of prismatic element (PRIS):';
mess8 = 'Number of cubic element (CUBE):';

nomb1 = (nbel mesh);
nomb2 = (nbno mesh);
nomb3 = ((nbno mesh) - (nbel mesh2 + 2));
nomb4 = (nbel mesh2 + 2);
nomb5 = (nbel mesh2);
nomb6 = (nbel mesh4);
nomb7 = (nbel mesh6);
nomb8 = (nbel mesh8);

*.....................................................................

*trak (vinput et voutput et volsp et volrig) 'NOSM';

tass mesh;

SI CONFIN;
  SI CRIGI;
    opti sauv form 'vl_jrc_hopbarcr.msh';
  SINON;
    opti sauv form 'vl_jrc_hopbarc.msh';
  FINSI;
FINSI;

SI UNCONF;
  SI CRIGI;
    opti sauv form 'vl_jrc_hopbarur.msh';
  SINON;
    opti sauv form 'vl_jrc_hopbaru.msh';
  FINSI;
FINSI;

SI UNCONFME;
  SI CRIGI;
    opti sauv form 'vl_jrc_hopbarur.msh';
  SINON;
    opti sauv form 'vl_jrc_hopbaru.msh';
  FINSI;
FINSI;

sauv form mesh;

SAUTER LIGNE;
mess mess1 nomb1;
mess mess2 nomb2;
mess mess3 nomb3;
mess mess4 nomb4;
mess mess5 nomb5;
mess mess6 nomb6;
mess mess7 nomb7;
mess mess8 nomb8;
SAUTER LIGNE;
```

The EUROPLEXUS input file is:

```
HOPBARUR

*-------------------------------------------------------------------------
$ The mesh generated by Cast3m is loaded in Europlexus (Hopbar.msh)
$
ECHO
!CONV win
CAST mesh
*-------------------------------------------------------------------------


*-------------------------------------------------------------Problem type
$ The problem is tridimensionnal. We use the Lagrangian coordinates.
$ The option LAGC (Lagrangian multiplier) allows us to deal with contact
$ problem (operator GLIS).
$
TRID LAGR LAGC
*-------------------------------------------------------------------------



*-----------------------------------------------------------Dimensioning
$ The characteristics of the mesh are given here (type of elements,
$ number). The corresponding values are given by Cast3m when running
$ the file Hopbar.dgibi.
$
DIME
  PT3L 10960 PT6L 3758 BR3D 3756 TETR 8319 PRIS 6914 CUBE 2240
  PMAT 2 ZONE 5
  BLOQ 1
 TERM
*-------------------------------------------------------------------------



*-------------------------------------------------------------Geometry
$ The types of element are assigned to the different parts of the mesh
$
GEOM TETR mesh4 PRIS mesh6 CUBE mesh8 BR3D mesh2 PMAT psr psl TERM
*-------------------------------------------------------------------------



*-----------------------------------------------Geometrical complements
$ For the bars, the area of the corresponding section has to be given.
$ LLOAC and the elements from LLOA1 to LLOA16 corresponds to the pulse
$ generation device of the Large Hopkinson bar. The other ones
$ corresponds to the input and output bars.

$

COMP
 SECT 3.20000E-03 LECT LLOACA TERM
 SECT 4.37435E-02 LECT LLOA1  TERM
 SECT 1.76715E-02 LECT LLOA2  TERM
 SECT 2.54469E-02 LECT LLOA3  TERM
 SECT 1.98557E-02 LECT LLOA4  TERM
 SECT 8.49487E-03 LECT LLOA5  TERM
 SECT 6.221E-03   LECT LLOA6  TERM
 SECT 6.221E-03   LECT LLOA7  TERM
 SECT 5.67450E-03 LECT LLOA8  TERM
 SECT 4.77836E-03 LECT LLOA9 LLOA10 TERM
 SECT 4.59635E-03 LECT LLOA11 TERM
 SECT 1.83854E-02 LECT LLOA13 TERM
 SECT 2.54469E-02 LECT LLOA14 TERM
 SECT 4.78708E-03 LECT LLOA15 TERM
 SECT 2.01062E-02 LECT LLOA16 TERM
 SECT 4.07150E-03 LECT LLOA12 LLOA17 LLOA18 LLOA19 LLOA20 LLOA21 LLOA22
                      LOUT   TERM
*-------------------------------------------------------------------------



*-----------------------------------------------------------Material data
$ The materials are assigned here. For the pulse generation device, the
$ input bar, the output bar and the inversion cages, the material is
$ a steel MSK. The jacket is also made of a steel MSK. The tube to avoid
$ bending is made of aluminium.
$ The material for the specimen depends on the tests modelled.
$ With the exception of the specimen, the materials behaves linearly.
$ This assumption has to be verified whan applying a high loading.
$


MATE

$ Inversion cages and input bar and output bar
$ ..............................................

LINE RO 7850. YOUN 2.E11 NU 0.3
     LECT vinput voutput lout linp TERM


$ Tube to avoid bending
$ ......................

LINE RO 2800. YOUN 7.0E10 NU 0.33
```

```
     LECT volrig TERM


$ Specimen
$ ........

VMIS DYNA RO 2704. YOUN 1.2E10 NU 0.33
     TRAC 4 6.E7 5.E-3 7.5E7 1.2E-2 1.04E8 7.E-2 1.2E8 1.5E-1
     SYMO D 6500. P 4.
     LECT volsp TERM

MASS 0.001 LECT psr psl TERM

*-------------------------------------------------------------------------


*-----------------------------------------------------Boundary conditions
$ The operator "GLIS" is used to deal with the contacts between the
$ specimen, the bars and the jacket.
$ The operator "RIGI" allows us to join the bars with the 3D mesh.
$ The condition "BLOQ" blocked the translation along x-direction of
$ the first point at left of the machine.
$


LINK COUP
      RIGI   CENT LECT psl TERM
             LIST LECT NSLSP NSLC TERM
             VECT VX 1.0
      RIGI   CENT LECT psr TERM
             LIST LECT NSRSP NSRP TERM
             VECT VX 1.0
      RIGI   CENT LECT Pout10 TERM
             LIST LECT slouiii TERM
             VECT VX 1.0
      RIGI   CENT LECT PL23 TERM
             LIST LECT SLOAD41 TERM
             VECT VX 1.0
      BLOQ 1 LECT PLCA TERM
*-------------------------------------------------------------------------


*-----------------------------------------------------Initial conditions
$ The initial conditions of the system are reproduced by applying a
$ state of stress to the pulse genration device. The stress is obtained
$ by dividing the prestressing force of the hydraulic actuator by the
$ area of the corresponding section of each elements.
$ The excel file can be used to calculate the initial condition for
$ the wanted force.
$

INIT CONT 1 2.63644E+08 LECT LLOACA TERM
 CONT 1 1.92865E+07 LECT LLOA1 TERM
 CONT 1 4.77414E+07 LECT LLOA2 TERM
 CONT 1 3.31537E+07 LECT LLOA3 LLOA14 TERM
 CONT 1 4.24897E+07 LECT LLOA4 TERM
 CONT 1 9.93141E+07 LECT LLOA5 TERM
 CONT 1 1.35612E+08 LECT LLOA6 TERM
 CONT 1 1.35612E+08 LECT LLOA7 TERM
 CONT 1 1.48676E+08 LECT LLOA8 TERM
 CONT 1 1.76558E+08 LECT LLOA9 TERM
 CONT 1 1.76558E+08 LECT LLOA10 TERM
 CONT 1 1.83550E+08 LECT LLOA11 TERM
 CONT 1 2.07211E+08 LECT LLOA12 TERM
 CONT 1 4.58875E+07 LECT LLOA13 TERM
*-------------------------------------------------------------------------


*-----------------------------------------------------------------Outputs
$ The location and the frequency of the outputs are chosen here.

ECRI DEPL VITE CONT ECRO TFRE 1.0E-2
     FICH SPLI ALIC     TFRE 1.0E-5
     FICH ALIC TEMP FREQ 50
                ELEM LECT Gauge1 Gauge3 Gauge4 Gauge5 Gauge6 Gauge7
                          VG101 VG102 VG103 VG104 VG105 VG106 VG107 VG108
                          VG109 VG110 VG111 VG112 VG113 VG114 VG115 VG116
                          VG117 VG118 VG119 VG120 VG121 VG122 VG123 VG124
                          VG125 VG126 VG127 VG128 VG129 VG130 VG131 VG132
                          VG133 VG134 VG135 VG136 VG137 VG138 VG139 VG140
                          VG141 VG142 VG143 VG144 VG145 VG146 VG147 VG148
                          VG149 VG150
                  TERM
*-------------------------------------------------------------------------

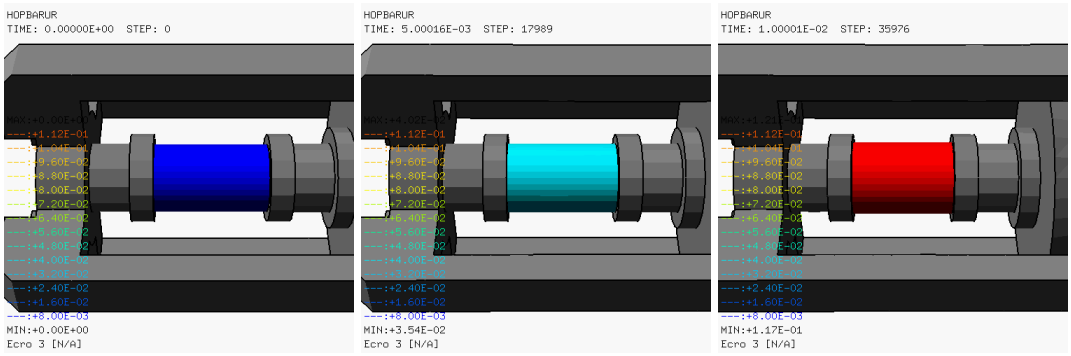

*-----------------------------------------------------------------Options
OPTI NOTE
     LOG 1

*-----------------------------------------------Transient calculation
$ The analysis is performed on 10 ms. It can be changed depending on
$ the wish of the user.
$

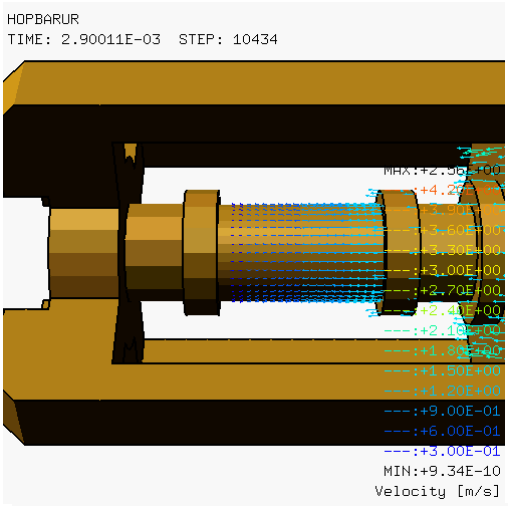
CALCUL TINI 0. TEND 10.E-3
*-------------------------------------------------------------------------

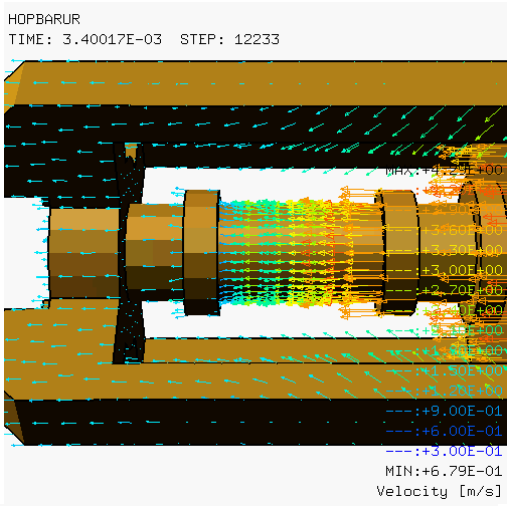
FIN
```

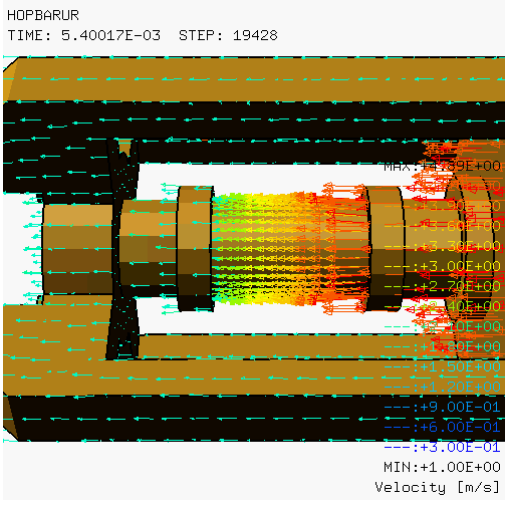
Some results: specimen progressive plastification.

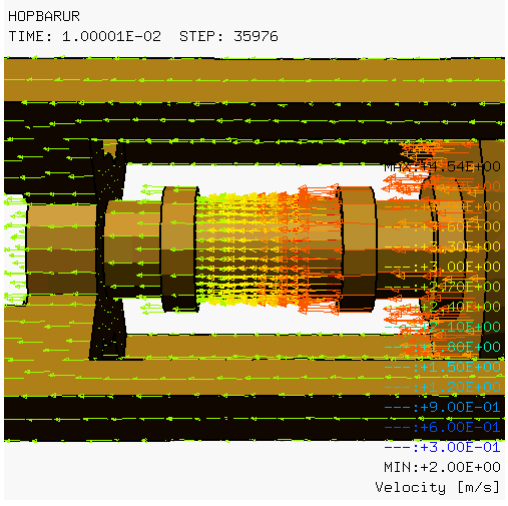


Computed velocities:

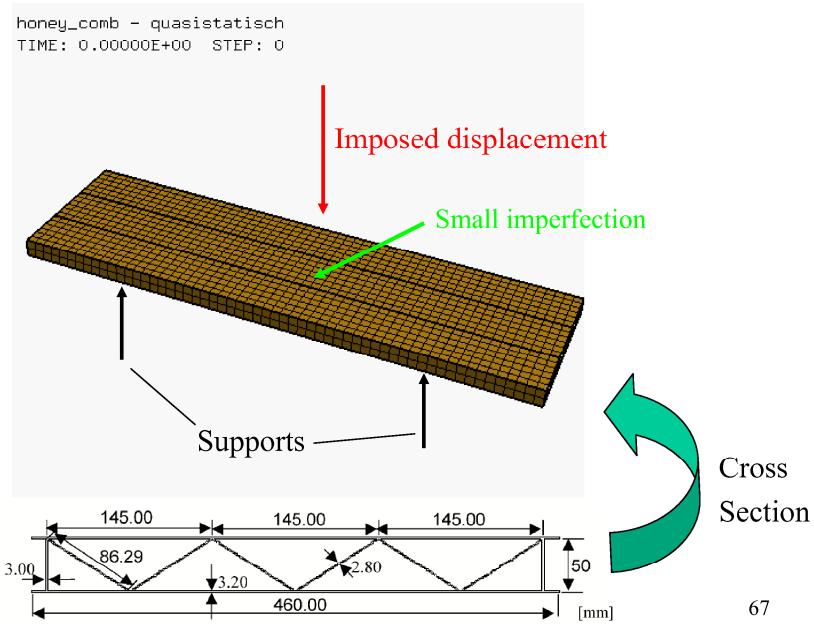








Exercise 5 – Honeycomb buckling



TITLE:
Honeycomb: 4-point bending of honeycomb structure for train carriages.

PROBLEM:
This problem has been taken from the paper listed below in the references and reproduces an experiment of 4-point bending of an extruded aluminum panel used in railway carriages. Loading is very slow (nominally static) in the experiment. In the numerical simulation, we use a somewhat faster imposed displacement for efficiency of the explicit calculation, but still in relatively slow regime.

MESH:
The model is 3D and uses 3712 elements Q4GS for the structure. A localized "defect" is introduced near the centre of the panel (see mesh generation file) to induce the right startup of the dynamic buckling mode.

MATERIALS:
An elasto-plastic VM23 material is used to simulate the aluminum. A failure criterion is introduced.

BOUNDARY CONDITIONS:
The panel is held fixed along two lines, and an imposed displacement is applied along other two lines (4-point bending). This induces some localized buckling of the panel.

LOADING:
The applied "load" is rather an applied displacement. The resulting reaction force (as computed by the code) is monitored and compared with the experimentally measured value.

CALCULATION:

The calculation is performed up to 100 ms. At the final time, the panel has undergone large motions and some localized buckling in its central part.

RESULTS:
Despite the use of a rather coarse mesh (much coarser than the meshes used in the calculations contained in the cited paper), results compare well with the experiment (see cited paper) both as concerns the buckling mode and the measured force. The experimental load curves are given in Figure 10 of the mentioned paper, while the obtained final shape of the panel is shown in Figure 25 of the paper.

POST-TREATMENT
An animation of the computed results from this calculation is available on the EUROPLEXUS Consortium Web site.

REFERENCES:
This problem is detailed in:

1) L. Zheng, D. Petry, T. Wierzbicki, H. Rapp: "Fracture prediction in 4-point bending of an extruded aluminium panel". Thin-Walled Structures 43 (2005), 565-590.

2) M. Larcher: “Simulations of a Metro Carriage Exposed to an Internal Detonation, PUBSY N. JRC50327, 2009.

Numerical Solution

HONEYCOMB

The mesh generation file (K2000):

```
OPTI echo 1;
OPTI dime 3 elem qua4;
den=0.025;
DENS den;
t1 = 0.05;
t2 = 0.145;

p1 = 0 0 0;
p2 = (t2/2.0) 0 0;
p3 = t2 0 0;
p4 = 0 t1 0;
p5 = t2 t1 0;
p6 = (t2*2.0) 0 0;
p7 = (t2*3.0) 0 0;

l1 = p1 p2 d p3 d;
l2 = p4 p5 d;
l3 = p4 p2 d p5 d;
l4 = p1 p4 d;
l5 = l4 plus p7;

l1 = l1 et (l1 plus p3) et (l1 plus p6);
l2 = l2 et (l2 plus p3) et (l2 plus p6);
l3 = l3 et (l3 plus p3) et (l3 plus p6);

pro = l1 et l2 et l3 et l4 et l5;

p9 = 0 0 1.45;

vol = pro tran 58 p9;

lb1 = l1 plus (0 0 0.125);
lb2 = l1 plus (0 0 1.325);
lb3 = 0 0 0.125;
lb4 = (t2*3.0) 0 0.125;
lll = l1 plus (0 0 0.525);
ll2 = l1 plus (0 0 0.925);

kod1 = faux;
REPE I0 (NBEL (vol ELEM QUA4));
  xx yy zz = coor (bary (vol ELEM QUA4 &I0));
  SI ( yy ega 0.000 0.0001);
     si (kod1);airb=airb et (vol ELEM QUA4 &I0);
     sinon; airb = vol ELEM QUA4 &I0;kod1 = vrai;
     fins;
  FINS;
FIN I0;

mesh = lb1 et lb2 et lb3 et lll et ll2 et vol et airb et lb4;
elim mesh 0.00001;

pcent = bary airb;

pdis1 = airb poin 'PROC' pcent;
edis1 = vol ELEM CONTENANT pdis1;
pdis2 = pdis1 plus p4;
edis2 = vol ELEM CONTENANT pdis2;

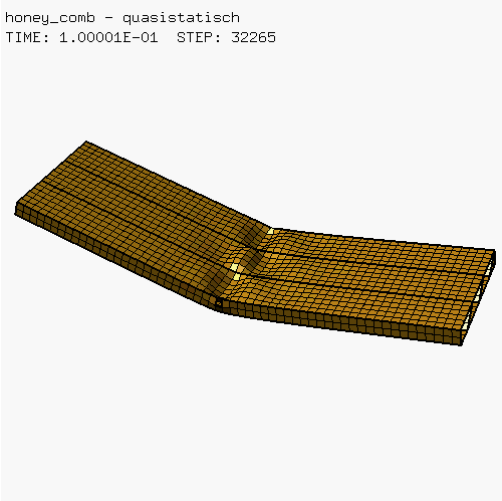
depl edis2 plus (0 0.0001 0);

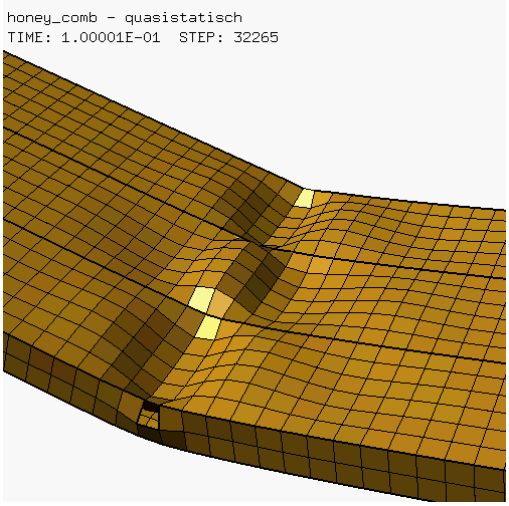
TASS mesh;
OPTI sauv form 'vl_jrc_honeycomb.msh';
sauv form mesh;
*
opti trac psc ftra 'vl_jrc_honeycomb_mesh.ps';
trac cach mesh;
fin;
```

The EUROPLEXUS input file is:

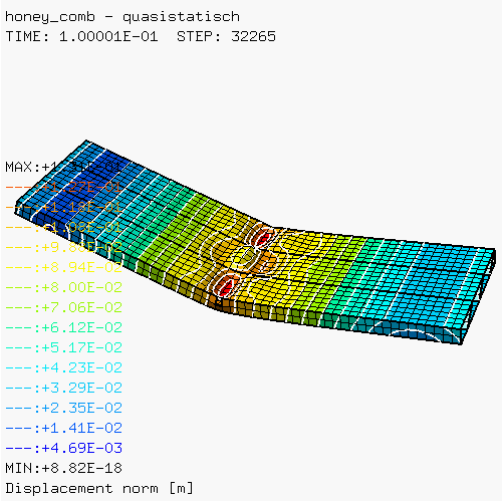
```
honey_comb - quasistatisch
ECHO
!VERI
!CONV WIN
CAST modell
TRID LAGR FAIL 1.0
OPTI TOLC 1e-1
$
DIME
  PT6L        3422     ZONE  2
  Q4GS        3712
  ECRO      892040
  TABL 1 2
  DEPL 38
TERM
$
GEOM
  Q4GS vol
TERM
$
COMP EPAI 0.003 LECT vol TERM
     COUL vert  LECT vol TERM
MATE VM23 RO 2700 YOUN 7E10 NU 0.3
          ELAS 200E6
          FAIL VMIS LIMI 245e6
          TRAC 2 200e6    2.85e-3
                 250e6    0.23
          LECT vol TERM
LINK COUP BLOQ 123 LECT lb3 TERM
          BLOQ  23 LECT lb4 TERM
          BLOQ   2 LECT lb1 lb2 TERM
CHAR 1 FACT 2 DEPL 2 0.08 LECT lll ll2 TERM
       TABL 2 0 0 1.1e-1 -1.1
REGI 'lb1' TOUT POIN LECT lb1 TERM
     'lb2' TOUT POIN LECT lb2 TERM
     'lll' TOUT POIN LECT lll TERM
     'll2' TOUT POIN LECT ll2 TERM
ECRI FICH ALIC tfreq 4e-3
     FICH ALIC TEMP tfreq 1e-4
               POIN LECT pdis1 TERM
               ELEM LECT edis1 lll ll2 lb1 lb2 TERM
     FICH FORM PVTK tFREQ 4e-3 VARI ECRO DEPL FAIL CONT
               GROU 1 OBJE LECT vol TERM
$
OPTI NOTE LOG 1
$
CALC TINI 0 TEND 1e-1
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
COUR 1 'resu1' RESU COMP 2 REGI 1
COUR 2 'resu2' RESU COMP 2 REGI 2
COUR 3 'resu3' RESU COMP 2 REGI 3
COUR 4 'resu4' RESU COMP 2 REGI 4
trac 1 2 3 4 axes 1.0 'FORCE [N]'
COUR 10 'dz_pdis' DEPL COMP 2 NOEU LECT pdis1 TERM
trac 10 axes 1.0 'DISPL. [M]'
COUR 5 ADD 1 2
COUR 11 MULC 10 -1.0
TRAC 5 text axes 1.0 'FORCE [N]' XAXE 11 1.0 'DISPL. [M]'
*
QUAL DEPL COMP 2 LECT pdis1 TERM REFE  -1.09634E-01 TOLE 2.E-2
*=================================================================
FIN
```

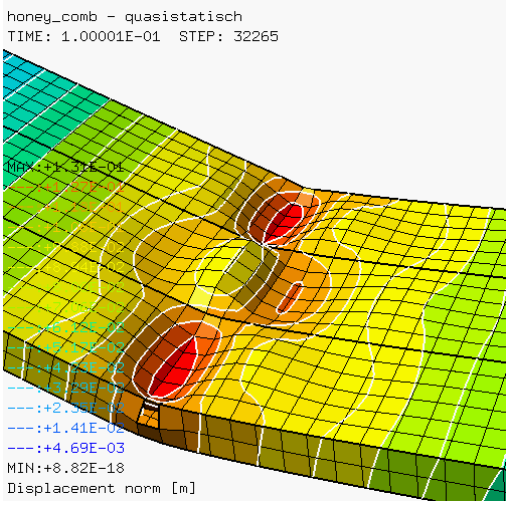
Some results: specimen final shape.



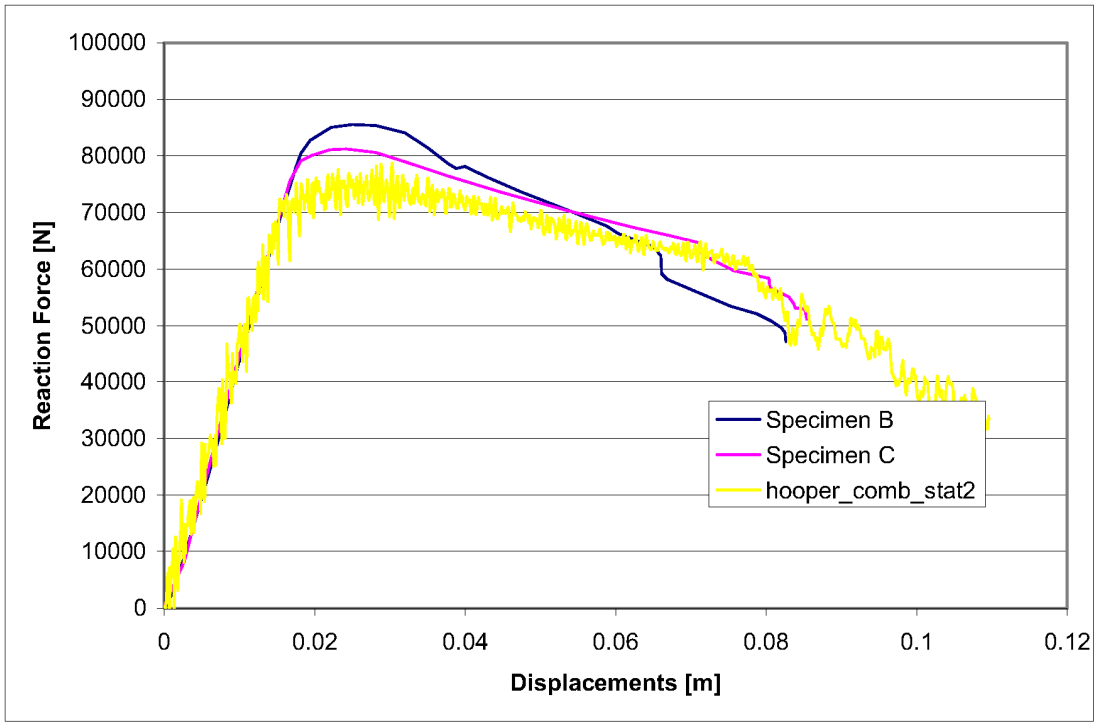


Buckling mode:

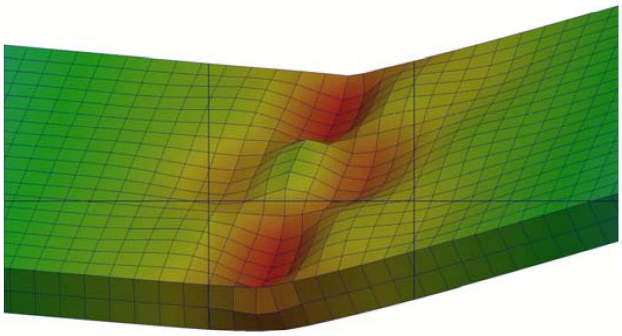




Comparison experiment/calculation: reaction forces



Final shape:





Universitat Politècnica de Catalunya, Barcelona, 15 – 19 April 2013

Numerical Simulation of Fast Transient Phenomena in Fluid-Structure Systems

A Short Course by F. Casadei
Retired from European Commission, Joint Research Centre
Institute for the Protection and Security of the Citizen
T.P. 480, I-21027 Ispra (VA), Italy.
E-mail: casadeifolco@gmail.com

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Contents

- I – Introduction (Structures)
- II – ALE formulation (Fluids)
- III – Classical Fluid-Structure Interaction
- IV – Advanced FSI (Failure/Fragmentation)
- V – Further topics and applications

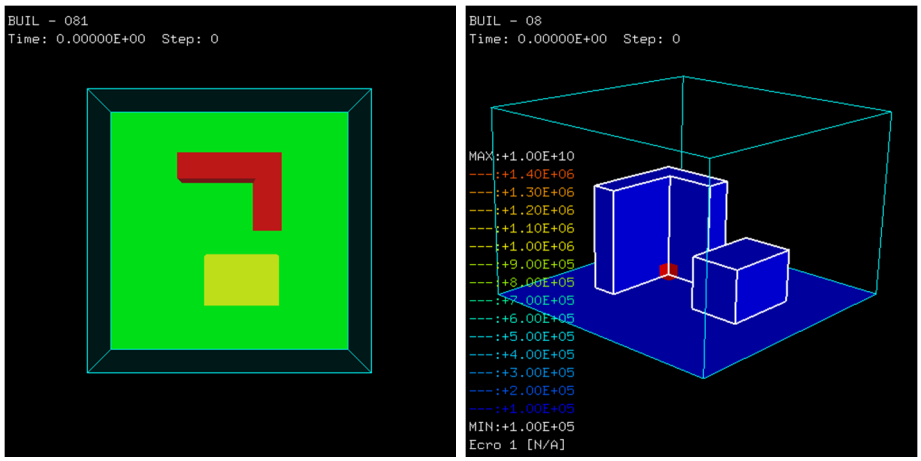
2

Detailed Contents of Part II

- Modeling the fluid domain
  - Euler equations
  - Finite Element discretization
  - Finite Volume discretization (N-C, C-C)
- Mesh rezoning algorithms
  - Motivation
  - Mean-based algorithms
  - Giuliani's algorithm
- Free surface modeling

3

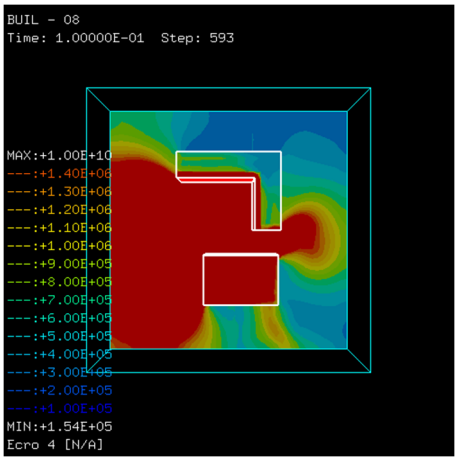
Purely Fluid Example: Building Vulnerability (Preliminary)



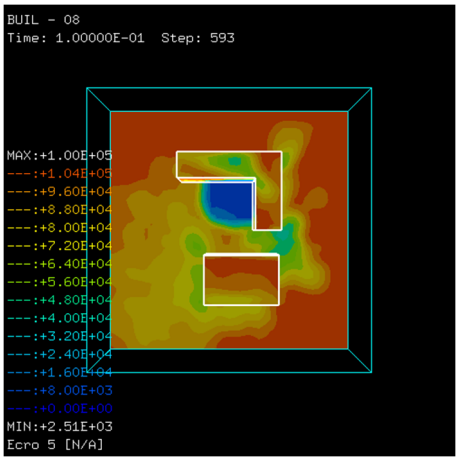
Model *Simulation*

4

Building Vulnerability (2)



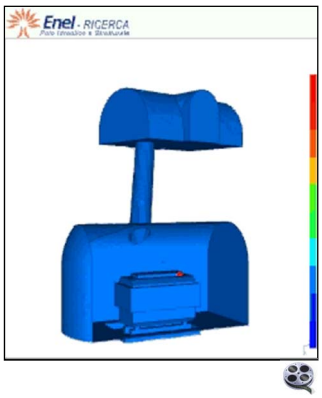
P_{max} contours

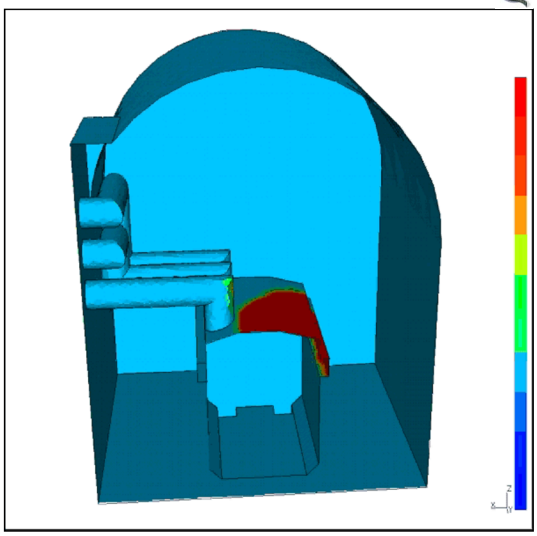


P_{min} contours

5

Some Further FSI Examples (Courtesy of ENEL-Hydro)

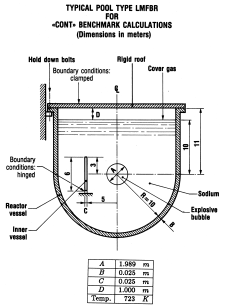




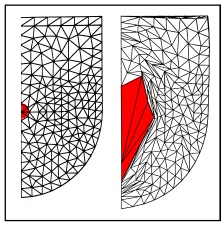
6

Modeling the fluid domain

- The fluid is assumed to be compressible and inviscid (high pressures and high pressure gradients)
- Viscous forces are negligible compared with pressure and inertia forces
- Governing equations are Euler equations, which express the conservation of mass, momentum and energy
- Plus suitable equation of state for the fluid material



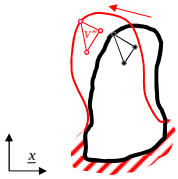
Lagrangian Calculation



7

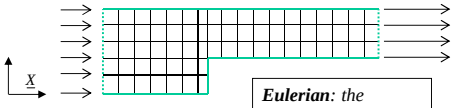
Modeling the fluid domain (2)

- The most "natural" description for the structural domain is the Lagrangian description



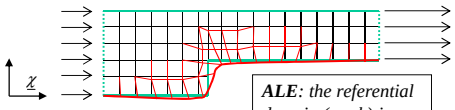
***Lagrangian**: the referential domain (mesh) is attached to material particles*

- In purely fluid problems, an Eulerian description is often more intuitive



***Eulerian**: the referential domain (mesh) is fixed*

- In problems involving both structures and fluids, a mixed description (ALE) can bring substantial benefits



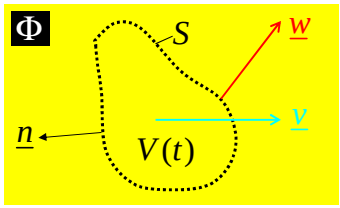
***ALE**: the referential domain (mesh) is arbitrarily moving*

8

Euler equations

- These equations are conveniently expressed in integral form:

Φ = fluid domain
$V(t)$ = control volume
$S(t)$ = control surface
$\underline{n}$ = unit normal
$\underline{v}(\underline{x},t)$ = fluid velocity (particles)
$\underline{w}(\underline{x},t)$ = arbitrary velocity (mesh)



Euler equations (2)

$$\frac{dM}{dt} \equiv \frac{d}{dt}\int_{V(t)} \rho \, dV = \underbrace{\oint_{S(t)} \rho(\underline{w}-\underline{v})\cdot\underline{n} \, dS}_{\text{transport}} \qquad \text{(Mass)}$$

$$\frac{d\underline{Q}}{dt} \equiv \frac{d}{dt}\int_{V(t)} \rho\underline{v} \, dV = \underbrace{\oint_{S(t)} \rho\underline{v}(\underline{w}-\underline{v})\cdot\underline{n} \, dS}_{\text{transport}} - \underbrace{\int_{V(t)} \nabla p \, dV}_{\text{pressure}} + \underbrace{\int_{V(t)} \rho\underline{g} \, dV}_{\text{body force}} \qquad \text{(Momentum)}$$

$$\frac{dE}{dt} \equiv \frac{d}{dt}\int_{V(t)} \rho e \, dV = \underbrace{\oint_{S(t)} \rho e(\underline{w}-\underline{v})\cdot\underline{n} \, dS}_{\text{transport}} - \underbrace{\oint_{S(t)} p\underline{v}\cdot\underline{n} \, dS}_{\text{pressure}} + \underbrace{\int_{V(t)} \rho\underline{g}\cdot\underline{v} \, dV}_{\text{body force}} \qquad \text{(Energy)}$$

M = mass of control volume
$\underline{Q}$ = momentum of control vol.
E = energy of control vol.
ρ = fluid density
p = pressure
$\underline{g}$ = gravity
e = total specific energy
∇ = gradient operator
$\cdot$ = scalar product

Plus suitable equation of state: $p = p(\rho, i)$

Euler equations (3)

- For a compressible fluid, the total specific energy is:

$$e = i + \frac{1}{2}v^2 \qquad (i = \text{ internal specific energy})$$

- Instead of the total energy equation, one can use the internal energy form:

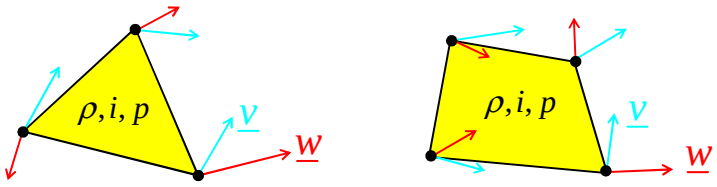
$$\frac{dI}{dt} \equiv \frac{d}{dt}\int_{V(t)} \rho i \, dV = \underbrace{\oint_{S(t)} \rho i(\underline{w} - \underline{v}) \bullet \underline{n} \, dS}_{\text{transport}} - \underbrace{\int_{V(t)} p\underline{\nabla} \bullet \underline{v} \, dV}_{\text{pressure}} \quad \text{(Internal energy)}$$

I = internal energy of control vol.

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Finite Element formulation

- Discretize via <u>linear</u> elements with velocities at nodes
- ρ and i (hence p) are <u>uniform</u> over each element



- Integral forms of mass and energy conservation can be used directly, provided $V(t)$ represents the current element volume
- Conservation of momentum is more complex

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Treatment of momentum equation

- Previous integral statement is unable to furnish enough equations, since the velocity field in each element depends upon Nd parameters (N being the number of nodes and d the space dimension).
- One formulates a variational statement associated with the differential form of the momentum equation expressed in mixed coordinates.
- Final result is principle of virtual power (corresponding to principle of virtual displacements in solid mechanics).

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Treatment of momentum equation (2)

- The principle of virtual power reads:

$$\int_{V(t)} \delta v_i \rho \frac{\partial v_i}{\partial t} dV = \int_{V(t)} \delta v_i \rho (\underline{w} - \underline{v}) \cdot \underline{\nabla} v_i dV + \int_{V(t)} \delta v_i \rho g_i dV + \int_{V(t)} p \frac{\partial (\delta v_i)}{\partial x_i} dV + \oint_{S(t)} \delta v_i T_i dS$$

v_i are the components of fluid velocity $\underline{v}$

δv_i are arbitrary admissible variations of the fluid velocity

g_i are the components of the acceleration of gravity

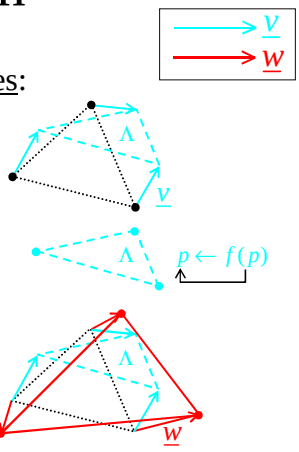
T_i are the component of prescribed boundary loads per unit area

x_i are spatial coordinates (current position of particles in fixed frame)

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Time integration

Each time increment is split into three phases:



1. Explicit Lagrangian phase: by posing $\underline{w} = \underline{v}$ all transport terms vanish
2. Implicit Lagrangian phase (see details below) whereby the pressure is iteratively refined (this stabilizes the solution)
3. Convective flux phase whereby the transport term contributions are added

- This scheme is not as limpid as the purely Lagrangian one. Second-order accuracy guaranteed only for phase 1.

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Time integration (2)

0. First compute $\underline{v}^{n+1/2} = \underline{v}^{n-1/2} + \Delta t \underline{a}_n$, where: $\underline{a}_n = \dfrac{\underline{F}_t^{\text{old}} + \underline{F}_p^n + \underline{F}_b^n + \underline{F}_s^n}{M}$

   $\underline{F}_t^{\text{old}}$ momentum transport forces at the end of previous step

   $\underline{F}_p^n$ pressure forces $\underline{F}_b^n$ body forces $\underline{F}_s^n$ surface forces

1. Obtain new "Lagrangian" configuration: $\boxed{\underline{x}^L = \underline{x}^n + \Delta t \cdot \underline{v}^{n+1/2}}$

2. Evaluate *L*-volume and *L*-density (mass *M* is constant!):

   $V^L = V^L(\underline{x}^L) \qquad \rho^L = M^n / V^L$

3. From the internal energy eqn. without the transport term, using the divergence theorem:

   $$\frac{d}{dt}(\rho i V) = -(p+q)\oint_S \underline{v} \bullet \underline{n}\, dS$$

   pseudo-viscous pressure

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Time integration (3)

Some pseudo-viscosity is needed to stabilize solution at shock fronts:

$$q' = \begin{cases} \rho[C_Q l^2 (\underline{\nabla} \cdot \underline{v})^2 - C_L l a (\underline{\nabla} \cdot \underline{v})] & \text{for } (\underline{\nabla} \cdot \underline{v}) < 0 \\ 0 & \text{for } (\underline{\nabla} \cdot \underline{v}) \geq 0 \end{cases} \qquad q = \min\left(q', \frac{|p|}{2}\right)$$

C_Q, C_L quadratic and linear coefficient a dilatational wave speed

l characteristic length of the element

4. Former expression can be approximated to the first order by:

$$\frac{(\rho i V)^L - (\rho i V)^n}{\Delta t} = -(p+q)^n \frac{V^L - V^n}{\Delta t}$$

5. By noting that $(\rho V)^L = (\rho V)^n = M^n$ we obtain for the internal energy:

$$\boxed{i^L = i^n - (p+q)^n \frac{V^L - V^n}{M^n}}$$

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Time integration (4)

6. The obtained i^L is just a first guess since the pressure changes over the step and must satisfy the state equation!

7. Obtain *L*-value implicitly by iterating the following expressions (just one or two iterations are usually sufficient):

$$\begin{cases} p^L = f(\rho^L, i^L) & f \text{ suitable state equation} \\ i^L = i^n - \left(\frac{p^n + p^L}{2} + q^n\right) \frac{V^L - V^n}{M^n} \end{cases}$$

8. Compute true end-of-step configuration: $\boxed{\underline{x}^{n+1} = \underline{x}^n + \Delta t \cdot \underline{w}^{n+1/2}}$

9. New volume: V^{n+1}

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Time integration (5)

10. Account for mass transport across element boundaries (face by face!) to compute new element mass:

$$M^{n+1} = M^n + \Delta t \cdot \oint_{S^n} \rho^L (\underline{w} - \underline{v})^{n+1/2} \bullet \underline{n}\, dS$$

11. For stabilization reasons, the density ρ_J (depending on face *J*) is computed as a weighted average of the neighbor elements' densities:

$$\boxed{\rho_J = \frac{1}{2}[(1-\alpha_J)\rho^e + (1+\alpha_J)\rho^{e'}]}$$

$$\alpha_J = \alpha_0 \cdot \text{ sign } (F) \qquad F = \Delta t \cdot \int_{S_J} (\underline{w} - \underline{v}) \bullet \underline{n}\, dS$$

$$0 < \alpha_0 < 1$$

$\alpha_0 = 0$: centered approximation (oscillations!)

$\alpha_0 = 1$: full donor (too diffusive!)

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Time integration (6)

12. The new element density is obtained as: $\rho_e^{n+1} = \dfrac{M_e^{n+1}}{V_e^{n+1}}$

13. Similar treatment then applied also to energy transport:

$$\frac{(Mi)^{n+1} - (Mi)^n}{\Delta t} = [\sum_J (\rho^L i^L)_J \int_{S_J} (\underline{w} - \underline{v})^{n+1/2} \cdot \underline{n}\, dS] + \frac{(Mi)^L - (Mi)^n}{\Delta t}$$

$$i^{n+1} = \frac{M^n}{M^{n+1}} i^L + \frac{\Delta t}{M^{n+1}} [\sum_J (\rho^L i^L)_J \int_{S_J} (\underline{w} - \underline{v})^{n+1/2} \cdot \underline{n}\, dS]$$

14. The final pressure is: $p^{n+1} = f(\rho^{n+1}, i^{n+1})$

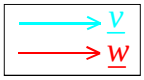
15. The nodal forces due to momentum transport (for the next step) are:

$$F_{tiI}^e = \int_{V^e} N_I \rho^L (\underline{w} - \underline{v})^{n+1/2} \cdot \underline{\nabla} v_i^{n+1/2}\, dV$$

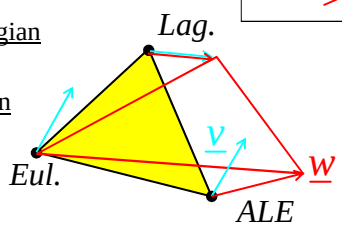
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ALE description

The ALE description is a generalization of the Lagrangian and Eulerian descriptions. On a node-by-node basis:



- When $\underline{w} \equiv \underline{v}$ the description is Lagrangian
- When $\underline{w} \equiv \underline{0}$ the description is Eulerian
- Else, the description is ALE

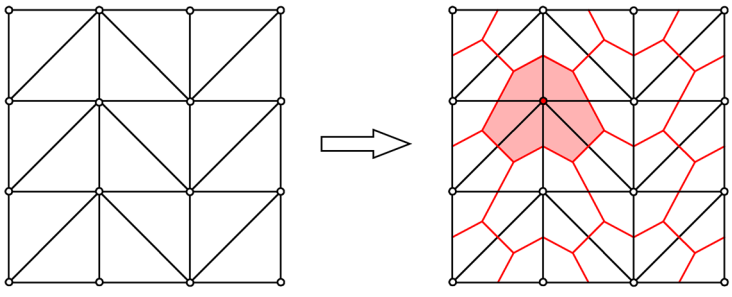


- Since $\underline{w}$ is arbitrary, it must be provided either by the user or via suitable automatic rezoning algorithms.

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N-C Finite Volume Formulation

- Node-centered FV fluid model:



FE FV

- Fully unstructured FV grid is automatically built up by the code from a FE grid of the fluid domain

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Euler Equations (NCFV)

- They are written in conservative form : $\frac{\partial \underline{U}}{\partial t} + \underline{\nabla} \cdot \underline{F} = \underline{0}$

  $\underline{U} \doteq \{\rho, \rho \underline{u}, \rho E\}$ (conserved variables)

  $\underline{F}(\underline{U}) \doteq \{\rho \underline{u}, \rho \underline{u}\underline{u} + p\underline{I}, (\rho E + p)\underline{u}\}$ (flux matrix)

- Here $\underline{u}$ is the fluid (particles) velocity
- A suitable equation of state relates the pressure p to the conserved variables
- The weak form of the conservation equations is obtained by integrating them over a generic control volume V (fixed in space) and by applying Green's (divergence) theorem $\frac{d}{dt}\int_V \underline{U}\, dV = -\oint_S \underline{F} \cdot \underline{n}\, dS$
- If the control volume moves in time with an arbitrary velocity $\underline{w}$, then by Reynold's transport theorem $\frac{d}{dt}\int_{V(t)} \underline{U}\, dV = \int_{V(t)} \left[\frac{\partial \underline{U}}{\partial t} + \underline{\nabla} \cdot (\underline{U}\underline{w}) \right] dV$

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Euler Equations (NCFV) - 2

- By Green's theorem in the RHS of the previous equation $\frac{d}{dt}\int_{V(t)} \underline{U}\, dV = \int_{V(t)} \frac{\partial \underline{U}}{\partial t} dV + \oint_{S(t)} \underline{U}(\underline{w} \cdot \underline{n}) dS$
- The discrete conserved variables are integral means over the generic control volume V_I $\underline{U}_I^n \doteq \frac{1}{V_I^n}\int_{V_I^n} \underline{U}^n(\underline{x}, t^n)\, dV$
- The above equations are integrated in time over an interval $\Delta t^n \doteq t^{n+1} - t^n$ and, after some further manipulations (omitted here for brevity), one obtains the following scheme
- The solution is advanced in time by the first-order explicit scheme (formally: forward Euler) $V_I^{n+1}\underline{U}_I^{n+1} = V_I^n \underline{U}_I^n + \Delta t^n \underline{\Phi}_I^*$

  where : $\underline{\Phi}_I^* \doteq \sum_{J \in \Psi(I)} N_{IJ}(\underline{U}_{IJ}^* w_{IJn} - \underline{\varphi}_{IJ}^*)$ (assembled numerical fluxes)

  $(\varphi_k^*)_{IJ} \doteq (\underline{F}_k^*)_{IJ} \cdot \underline{n}_{IJ}^*$ (flux matrix projection)

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$V_I^{n+1}\underline{U}_I^{n+1} = V_I^n\underline{U}_I^n + \Delta t^n \underline{\Phi}_I^*$

Euler Equations (NCFV) - 3

- The calculation of numerical fluxes is done (e.g.) by using Roe's approximate Riemann solver for the Riemann problem defined by each couple of neighboring volumes' physical states.
- The solution is advanced in time by the explicit "first-order" scheme presented above, irrespective of the desired accuracy.
- The obtained accuracy in space and time of the update depends only on the procedure used to compute the numerical fluxes $\underline{\Phi}_I^*$:
  - Choosing $t^* = t^n$ and node-centred values in space gives first-order accuracy in time and in space
  - Choosing $t^* = t^{n+1/2}$ and spatially extrapolated intra-cell boundary values gives second-order accuracy in time and in space

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Euler Equations (NCFV) - 4

- To obtain second-order accuracy in time and in space, the following predictor-corrector scheme in time is adopted, combined with spatial extrapolation of the conserved variables to intra-cell boundaries (van Leer's MUSCL-like technique)
  1. Compute spatial gradients of conserved variables at intra-cell boundaries, then at cell centres (by "min mod" limitation)
  2. Perform predictor step in time : advance provisionally the conserved variables by half a step by using the nodal gradients
  3. Use again the nodal gradients to extrapolate the variables in space onto the intra-cell boundaries (MUSCL)
  4. Corrector step in time : compute the assembled numerical fluxes according to Roe's scheme, then update the conserved variables

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NCFV / FE Synchronization

- To make the FE and NCFV formulations compatible, in view of performing FSI simulations by Lagrange multipliers, the two schemes must be properly synchronized:
  1. Shift the FV scheme forward in time by half step, so that conserved variables (and fluid velocity $\underline{u}$) are discretized at the same time instants as the structure velocity $\underline{v}$ (i.e. at half steps)

$$V_I^{n+3/2}\underline{U}_I^{n+3/2} = V_I^{n+1/2}\underline{U}_I^{n+1/2} + \frac{\Delta t^n + \Delta t^{n+1}}{2}\underline{\Phi}_I^*$$

  2. Use formally the same (CD) time integration scheme for both sub-domains, by identifying a suitable additional force term in the fluid sub-domain ("synchronizing" force term due to mass changes)

$$F_{\text{mass}}^{n+1} \doteq \frac{2}{\Delta t^n + \Delta t^{n+1}}(M^{n+3/2} - M^{n+1/2})u^{n+1/2}$$

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NCFV / FE Synchronization (2)

- The same (CD) time integration scheme can be used in both sub-domains :

$$\text{Equilibrium :} \quad a^{n+1} = \frac{(F_{\text{ext}} - F_{\text{int}} - F_{\text{mass}})^{n+1}}{M}$$

$$\text{Velocity update :} \quad s^{n+3/2} = s^{n+1/2} + \frac{\Delta t^n + \Delta t^{n+1}}{2}a^{n+1}$$

  provided one poses :

$$\text{For structure dofs :} \quad M = M_S^{n+1} \qquad s = v \qquad F_{\text{mass}} = 0$$

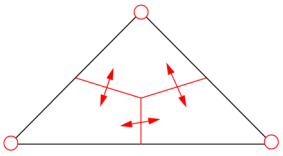
$$\text{For fluid dofs :} \quad M = M_F^{n+3/2} \qquad s = u \qquad F_{\text{mass}} = \frac{2}{\Delta t^n + \Delta t^{n+1}}\left(M^{n+3/2} - M^{n+1/2}\right)u^{n+1/2}$$

- Then, the same Lagrange multipliers method can be used to impose essential boundary conditions (constraints on velocities) in both sub-domains (and in particular for FSI)

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N-C Finite Volume Peculiarities

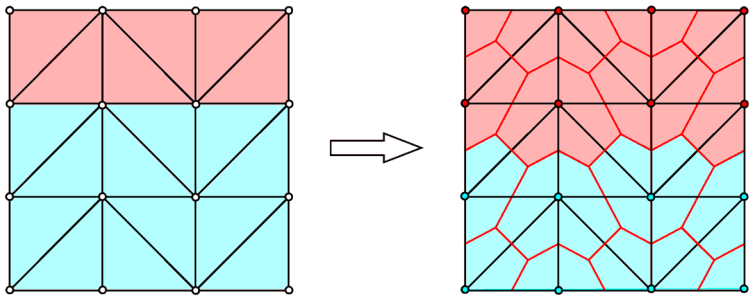
- All quantities (velocities and pressures) are discretized at nodes
- Physical status of FV depends only upon its volume, not on its shape (OK for fluid)
- However, geometry is still used to compute volume and fluxes
- Transport (among FVs, i.e. nodes) is computed internally to each FE : no need to know neighbor FEs



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Initial Conditions FE / NCFV

- Equivalence between FE and N-C FV initial conditions is not straightforward:

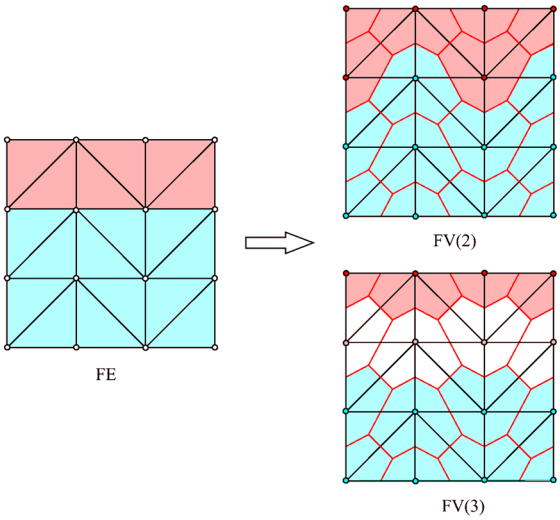


FE FV(1)

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Initial Conditions FE / NCFV (2)

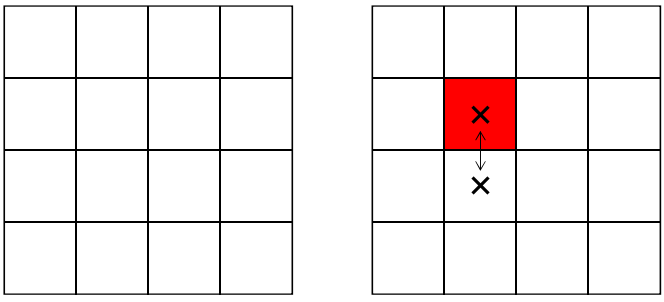
- Some possible remedies:



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C-C Finite Volume Formulation

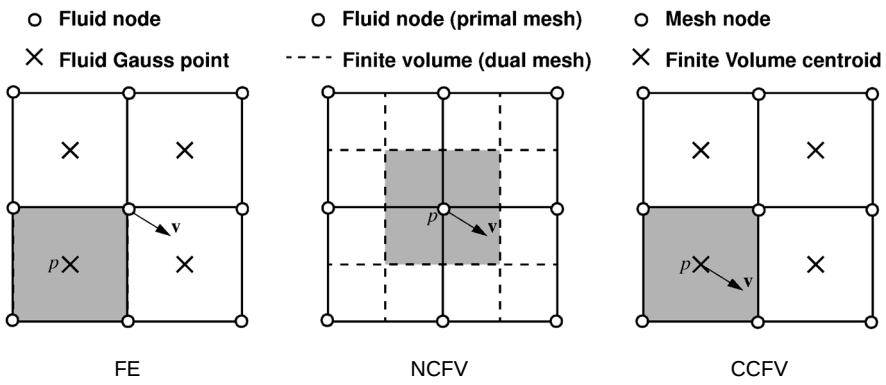
- Cell-centered FV fluid model (CEA : Galon, Beccantini):



- FV mesh coincides with classical FE mesh
- All quantities are discretized at "cell" (FV) centres
- Initial conditions are set like in FE

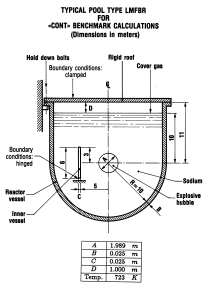
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Comparing FE, NCFV and CCFV meshes

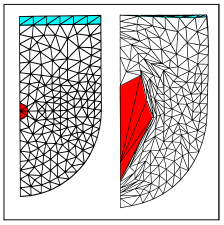


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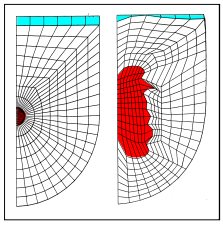
Mesh rezoning - motivations



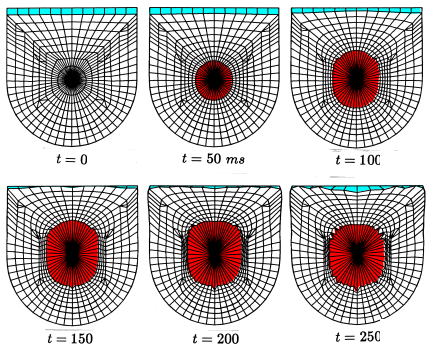
- Rezoning (ALE) is necessary because Lagrangian solutions suffer from excessive distortions and entanglement:



Lagrangian, triangles



ALE, manual rezoning, quadrangles

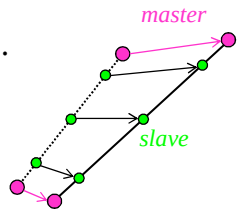


ALE, automatic rezoning (Giuliani's)

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Mesh rezoning - types

- Rezoning (in this context): motion of nodes belonging to an ALE mesh, at constant mesh topology.
- Do not confuse with remeshing, adaptivity etc.
- Kinematic:
  - Slave node follows master node
  - Nodes along a line are piloted by master end-points
  - Nodes inside a triangle, quadrangle, etc. move homeomorphically



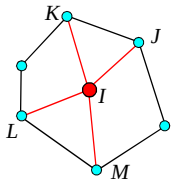
- Geometric:
  - Mean value algorithms
  - Giuliani's method: minimize triangles/tetrahedra distortion
- Mechanic:
  - Solve elasticity eqs. for dual mesh (ALE grid) considered as a solid (**continuum**, bar assembly, etc.). **Explicit** formulation to save CPU!

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Mean-based rezoning

- Simple: optimal position of a node is the mean of its neighbors:

$$\underline{x}_I^r = \frac{1}{n}\sum_{P=1}^{n} \underline{x}_P$$



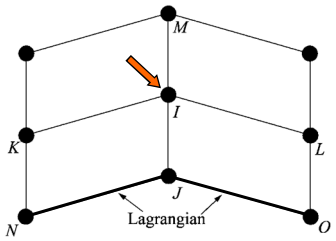
- Alternative: use displacement instead of position
- Drawbacks:
  - Rapidly tends to produce uniform mesh (which can be unwanted in some cases)
  - Fails in some special configurations (local mesh "curvature")

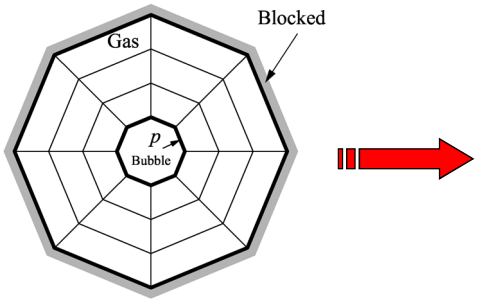
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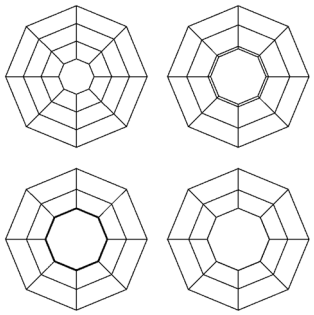
Mean-based rezoning (2)

- Pathological example:

$$\underline{x}_I^r = \frac{1}{4}(\underline{x}_J + \underline{x}_K + \underline{x}_L + \underline{x}_M)$$



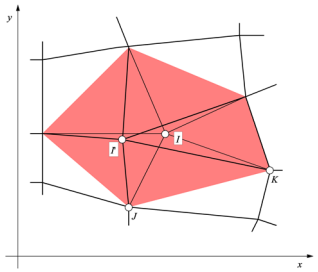




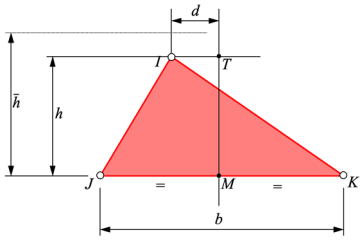
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Giuliani's automatic rezoning

- For each ALE node, identify an influence domain made of neighbor triangles (or tetrahedra in 3D)



- Measure "shear" and "stretch" of each triangle in the domain



shear = $f(d)$

stretch = $g(h)$

$\bar{h}$ is the mean height of triangles in the influence domain

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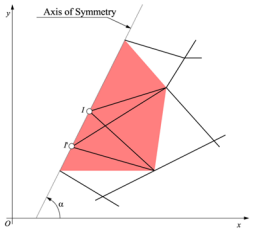
Giuliani's automatic rezoning (2)

- Minimize a function of total shear and stretch over the node's influence domain:

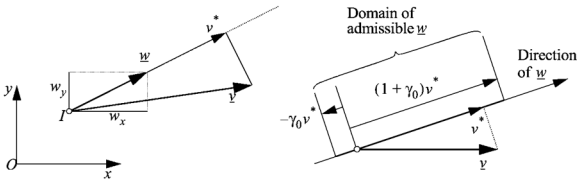
$$E = \sum_{i=1}^{N} \left(\frac{h_i - \bar{h}}{\bar{h}}\right)^2 + \sum_{i=1}^{N} \left(\frac{2d_i}{\bar{b}}\right)^2 = \text{minimum}$$

$\bar{h}$ *mean height,* $\bar{b}$ *mean base*

- Special care for nodes subjected to b.c.s:



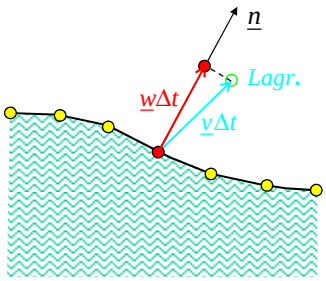
- It is essential to constrain the resulting grid velocity:



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Free surface modeling

- Lagrangian modeling is accurate but can lead to excessive mesh distortions
- Alternative: use Lagrangian description in the normal direction, ALE tangentially (slip)
  - Project along the normal:



  - Alternative: add correction to keep nodes almost equidistant

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Numerical representation of interfaces between (unmiscible) fluid components

Two alternative approaches:

1. **Component mixing not allowed**
   - ALE simulation and Lagrangian interface between the components
     - ☑ Exact interface location
     - ☒ Dramatic lack of robustness for complex interface motion
   - Interface reconstruction and cell division (*Volume-Of-Fluid*, *Level-Sets*…)
     - ☑ Accurate interface location
     - ☑ Handling of complex interface motion
     - ☒ Need for specific algorithms and operators to describe the interface
     - ☒ Difficult and time consuming geometric operations within a cell (especially in 3D)

2. **Artificial component mixing allowed**
   - With interface reconstruction (*Front Tracking*)
     - ☑ Accurate interface location
     - ☒ Need for a component mixing model
     - ☒ Need for specific algorithms and operators to describe the interface
   - Without interface reconstruction
     - ☑ No additional component to classical software
     - ☑ Very robust
     - ☒ Need for a **component mixing model**
     - ☒ Risk for **numerical diffusion of concentrations** and lack of accuracy for interface location and motion

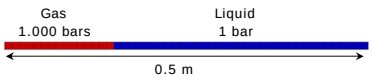
Chosen for **simplicity** and **robustness**
Component mixing model => **isobaric closure**
Numerical diffusion => **VOFIRE scheme**

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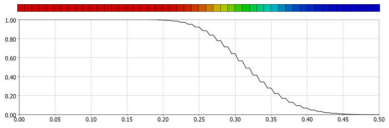
VOFIRE anti-diffusive scheme

[Despres, Lagoutière, Kokh, …]: "***Downwind*** *Scheme with Constraints*"

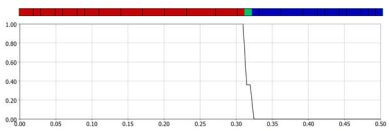
1D Liquid-Gas shock tube



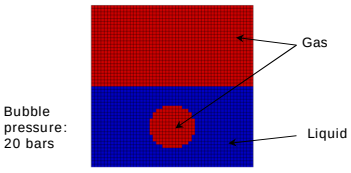
Gas fraction after 1 ms with classical Euler scheme

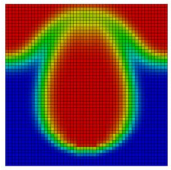


Gas fraction after 1 ms with anti-diffusion

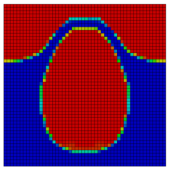


2D Gas bubble expansion





Gas fraction after 10 ms with classical Euler scheme



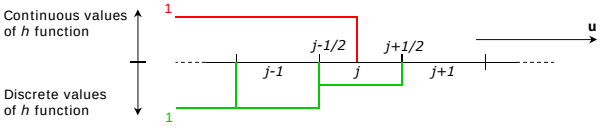
Gas fraction after 10 ms with anti-diffusion

- Introduced in EUROPLEXUS by V. Faucher (CEA)

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Anti-dissipation – Scheme for structured meshes (1/2)

Model problem: 1D-advection of Heavyside function *h* in constant velocity field **u**

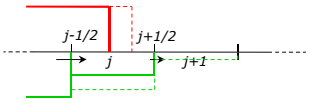


Question: which value $h_{j+1/2}$ to choose for *h* on cell boundary *j+1/2* to build function flux ?

Limit cases:

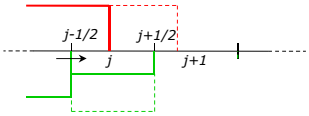
1. **Upwind**: $h_{j+1/2} = h_j$

   Flux is non-zero before the step propagates to cell boundary *j+1/2*
   ⇒ **Diffusion**



2. **Downwind**: $h_{j+1/2} = h_{j+1}$

   Flux is always zero ⇒ **No diffusion**
   Unstable increase of the discrete value in cell *j* when the step propagates beyond cell boundary *j+1/2*



Anti-dissipation – Scheme for structured meshes (2/2)

Key Concept [Despres, Lagoutière, Kokh, Dellacherie…]: *Downwind Scheme with Constraints*

Constraints:

- **Consistency** for the flux: $\min(h_j, h_{j+1}) \le h_{j+1/2} \le \max(h_j, h_{j+1})$ [C1]
- **Stability** for the advection scheme: $\min(h_{j-1}, h_j) \le h_j^* \le \max(h_{j-1}, h_j)$ [C2]

[C1] $\Leftrightarrow$ $m_{j+1/2} \le h_{j+1/2} \le M_{j+1/2}$

[C2] $\Leftrightarrow$ $m_{j-1/2} \le h_j + \mathbf{u}\frac{\Delta t}{\Delta x}(h_{j-1/2} - h_{j+1/2}) \le M_{j-1/2}$ $\Leftarrow$ $\begin{cases} m_{j-1/2} \le h_j + \mathbf{u}\frac{\Delta t}{\Delta x}(m_{j-1/2} - h_{j+1/2}) \\ h_j + \mathbf{u}\frac{\Delta t}{\Delta x}(M_{j-1/2} - h_{j+1/2}) \le M_{j-1/2} \end{cases}$

↓

Trust intervals for flux $h_{j+1/2}$

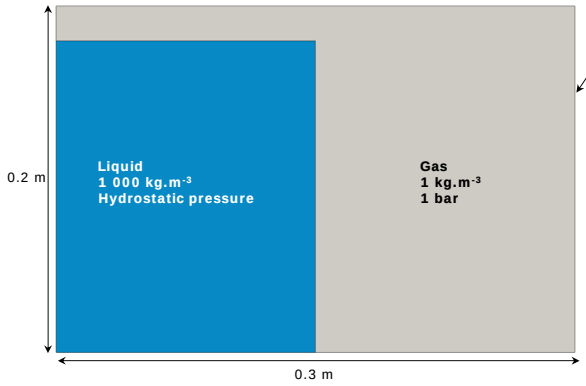
↓

Choice of the **value closest to downwind** within **intersection of trust intervals**

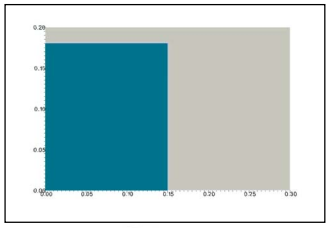
Extension to 2D / 3D structured meshes: straightforward using **Direction Splitting**

Sloshing under gravity loading

(Courtesy of CEA)



Structured mesh
Cell size: 1 mm

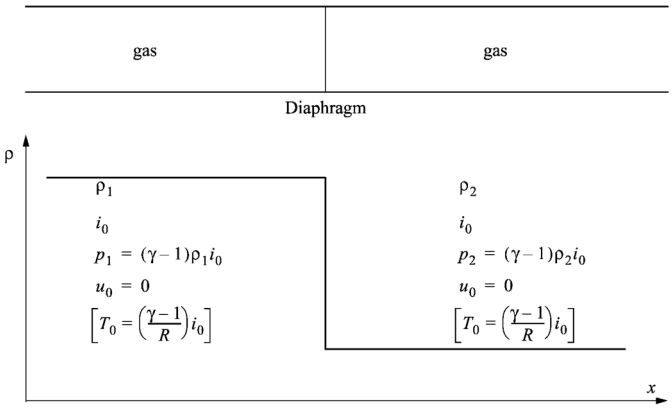




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Exercise 1 – Shock tube

- Initial conditions:



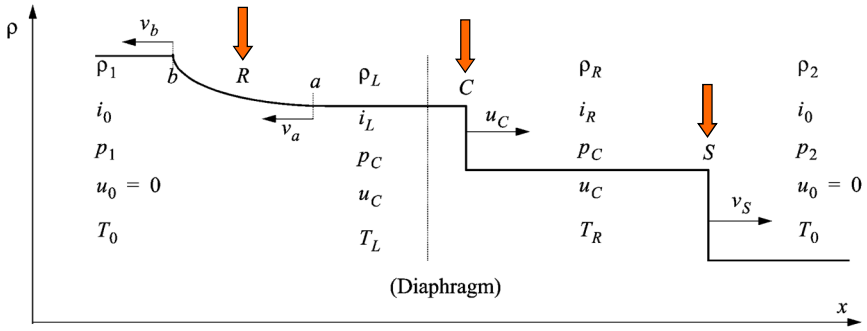
- Equation of state (polytropic gas): $p = (\gamma - 1)\rho i$

$\gamma \doteq c_P / c_V$ $\quad c_P \doteq$ specific heat at constant pressure
$c_V \doteq$ specific heat at constant volume

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Shock tube (2)

- Analytical solution (self-similar):



- Shock S moves to the right at speed v_S
- Contact discontinuity C (particle initially at diaphragm) moves to the right at speed u_C
- Rarefaction wave $R(a,b)$ moves to the left at speeds v_a, v_b

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Shock tube (3)

Suggested variations:

- Study influence of pseudo-viscosity and upwinding on Eulerian solution
- Obtain and discuss Lagrangian solution(s). Hint: try different amounts of pseudo-viscosity
- Obtain and discuss ALE solution(s). Compare automatic rezoning and mean-based rezoning
- Solve shock tube problem with Finite Volumes

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Shock tube (4)

- Assumed parameter values:

ρ_1	1.22
ρ_2	0.1237
γ	1.269
p_1	1.0×10^6
p_2	1.013×10^5
$i_1 = i_2$	3.046×10^6 $= i_0$

- Analytical solution:

λ	9.863	u_C	925.4
P	2.888	v_S	1672.
p_C	2.927×10^5	v_a	30.12
ρ_R	0.2771	v_b	−1020.
ρ_L	0.4635	c_0	1020.
i_R	3.928×10^6	c_a	895.2
i_L	2.348×10^6	c_b	1020.

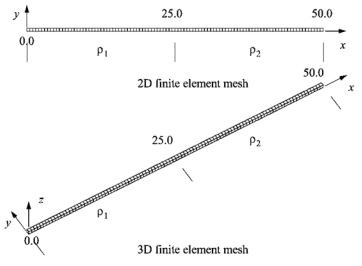
$\lambda \doteq \rho_1 / \rho_2 = p_1 / p_2$

$P \doteq p_C / p_2$

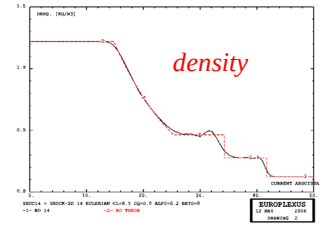
49

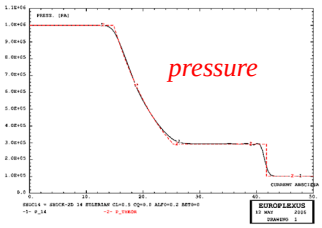
Shock tube (5)

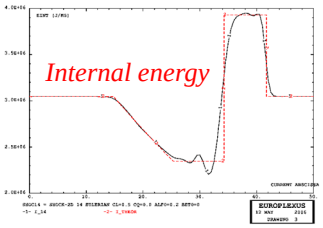
- Discretization:



- "Optimal" numerical solution (Eulerian):
  - $C_L = 0.5$, $C_Q = 0$
  - $\alpha_0 = 0.2$, $\beta_0 = 0$







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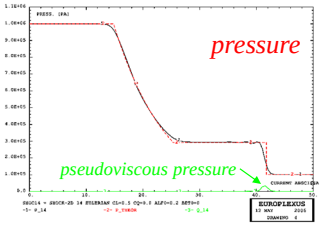
Shock tube (6)

- Influence of pseudoviscosity q' and upwinding:

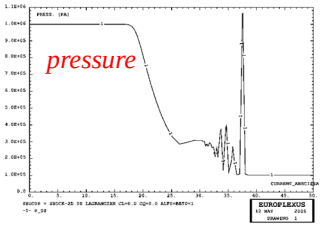
$$q' = \begin{cases} \rho[C_Q l^2 (\nabla \cdot \underset{\sim}{v})^2 - C_L l a (\nabla \cdot \underset{\sim}{v})] & \text{for } \nabla \cdot \underset{\sim}{v} < 0 \\ 0 & \text{for } \nabla \cdot \underset{\sim}{v} \geq 0 \end{cases}$$

l: characteristic length, a: wave speed

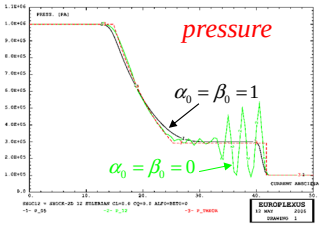
p.v. pressure in optimal Eulerian sol.



Lagrangian solution needs some p.v. to be stable



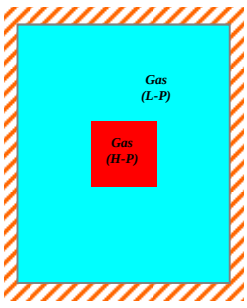
Eulerian solution needs some upwinding to be stable



Exercise 2 – Explosion in air-filled rigid tank

This is a purely fluid problem because the tank is rigid and therefore does not need to be modeled. There is only one type of fluid (single-phase, single-component). This considerably simplifies the modeling, since the bubble surface can be treated as ALE.

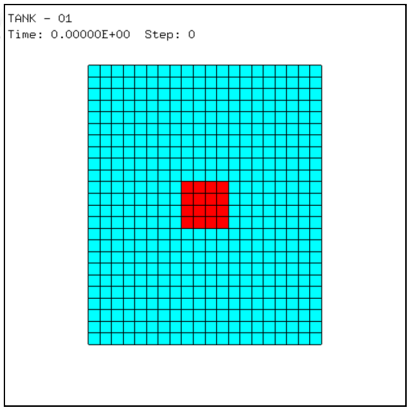
- Try out Lagrangian solution
- Try out Eulerian solution
- Try out ALE solution
- …

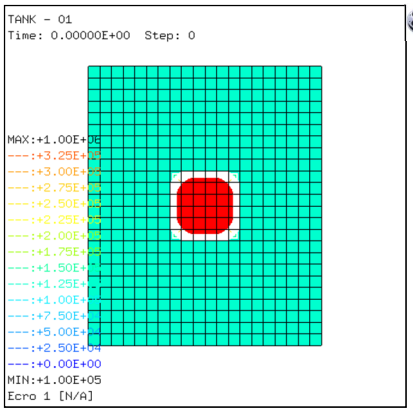


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Exercise 2 – Explosion in air-filled rigid tank (2)

- Lagrangian solution (TANK01):



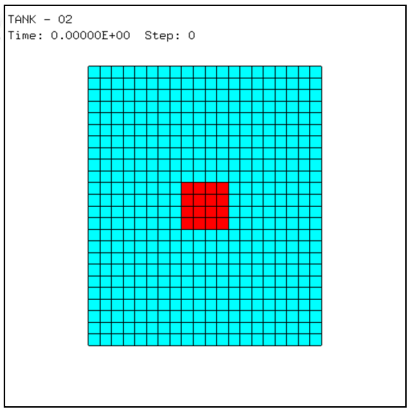


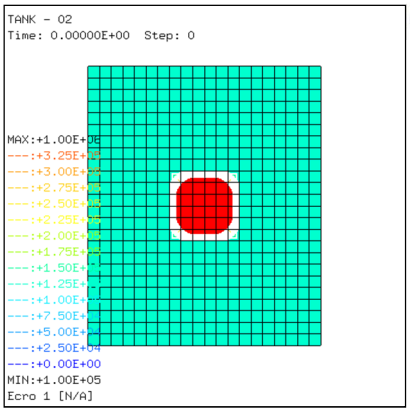
Mesh evolution *Fluid pressures*

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Exercise 2 – Explosion in air-filled rigid tank (3)

- Eulerian solution (TANK02):



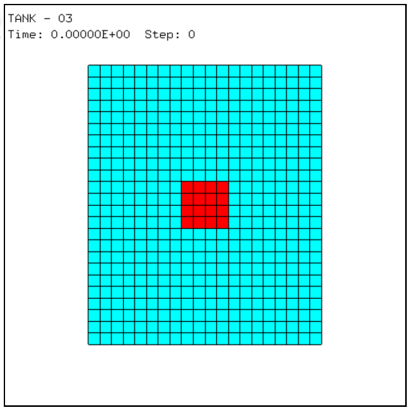


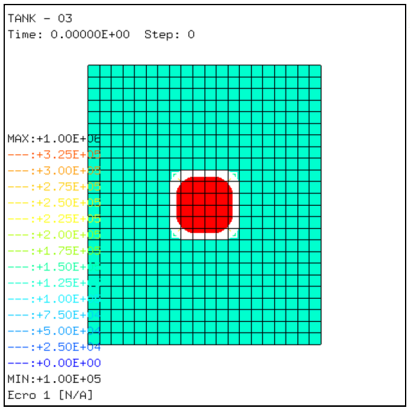
Mesh evolution *Fluid pressures*

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Exercise 2 – Explosion in air-filled rigid tank (4)

- ALE solution (with Lagrangian bubble interface) (TANK03):



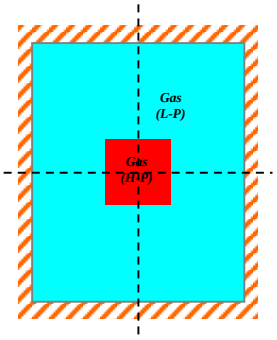


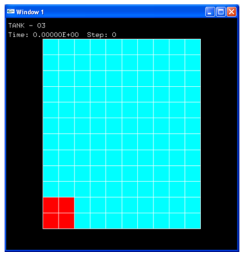
Mesh evolution *Fluid pressures*

55

Exercise 2 – Explosion in air-filled rigid tank (5)

Input file for ALE Solution (TANK03):





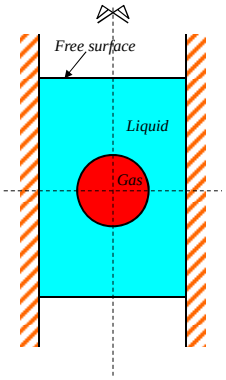

```
TANK - 03
*-----------------------------------------------------------------------
 ECHO
!CONV win
CAST mesh
*-------------------------------------------------------------Problem type
DPLA ALE
*-------------------------------------------------------------Dimensioning
DIME
 PT2L 143 FL24 145
 NALE 150 NBLE 150
TERM
*-----------------------------------------------------------------Geometry
GEOM FL24 flui TERM
*-----------------------------------------------------------Grid motion
GRIL LAGR LECT lag  TERM
     AUTO AUTR
*-------------------------------------------------------Material data
MATE FLUT RO 10  EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1 BET0 1 KINT 1
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1 LECT bull TERM
     FLUT RO 1   EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1 BET0 1 KINT 1
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1 LECT gaz  TERM
*-----------------------------------------------Boundary conditions
LINK COUP
     BLOQ 1 LECT blox TERM
     BLOQ 2 LECT bloy TERM
     CONT SPLA NX 1 NY 0 LECT symx TERM
     CONT SPLA NX 0 NY 1 LECT symy TERM
*-----------------------------------------------------------------Outputs
ECRI COOR DEPL VITE CONT ECRO TFRE 1.E-3
     FICH ALIC TEMP FREQ 1
               POIN LECT p4 p6 TERM
               ELEM LECT e1 e2 TERM
*-------------------------------------------------------------Options
OPTI NOTE
     CSTA 0.8
     LOG 1
     REZO GAM0 0.5
*-------------------------------------------------Transient calculation
CALCUL TINI 0 TEND 10.E-3
 . . .
```

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Exercise 3 – Bubble expansion in a Tube

This is a also a purely fluid problem because the tank is rigid and therefore does not need to be modeled. However, unlike the previous example, there are two different fluids interacting with each other. The tube wall is vertical so the BC can be trivially imposed as a blockage in the horizontal direction.

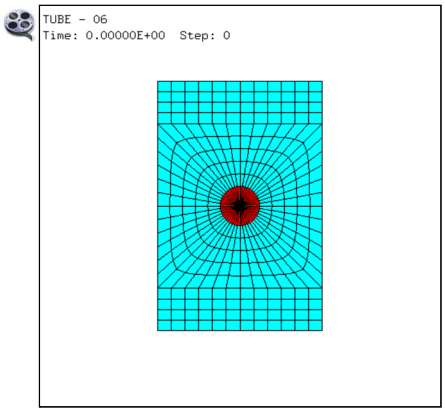
- Try out fully Lagrangian solution
- Try out ALE solution with Lagrangian bubble surface (single-component fluid material)
- Try out fully ALE solution with ALE bubble surface (multi-phase multi-component fluid material)



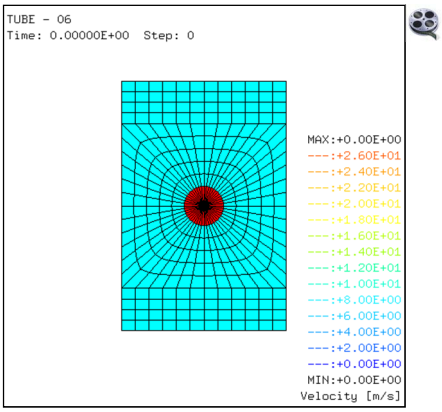
57

Exercise 3 – Bubble expansion in a Tube (2)

- Lagrangian solution (TUBE06):



Mesh

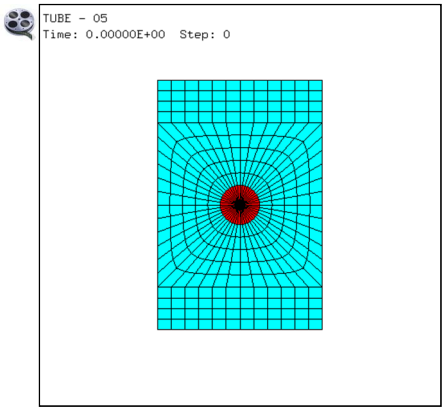


Fluid Velocities

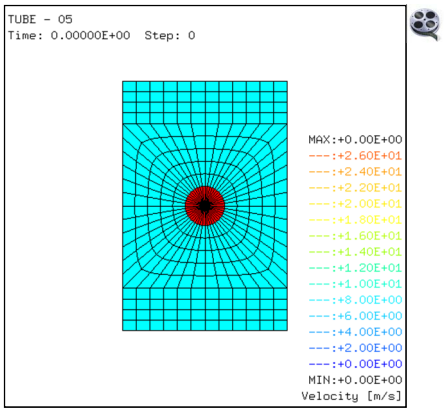
58

Exercise 3 – Bubble expansion in a Tube (3)

- ALE solution with Lagrangian bubble surface (single-component fluid material) (TUBE05):



Mesh

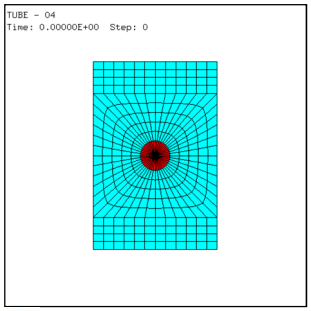


Fluid Velocities

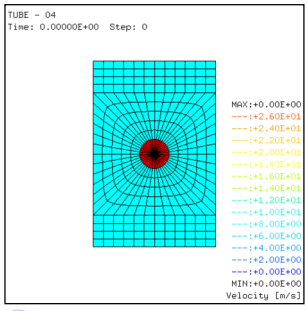
59

Exercise 3 – Bubble expansion in a Tube (4)

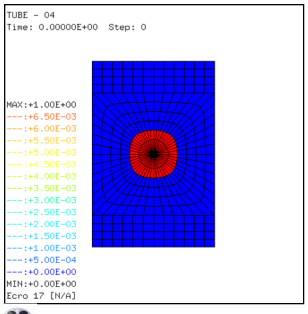
- ALE solution with ALE bubble surface (multi-phase multi-component fluid material) (TUBE04):



Mesh



Fluid Velocities

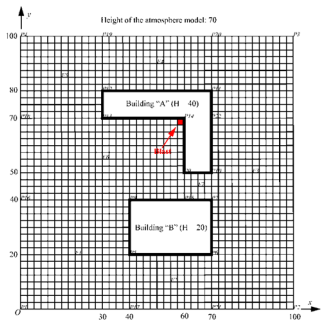


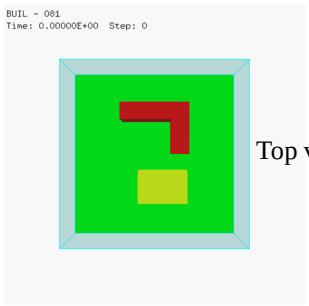
Bubble Mass Fraction

60

Exercise 4 – External blast on two buildings

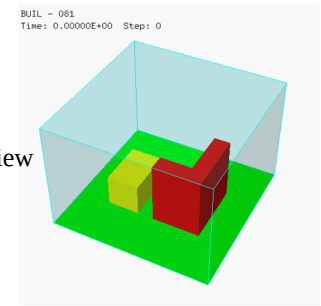
Geometry

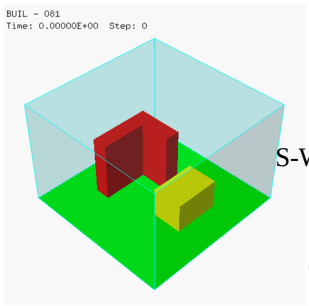




Top view

N-E view





S-W view

61

Exercise 4 – External blast on two buildings (2)

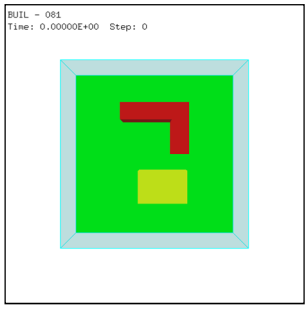
Input file for EULE Solution (BUIL08):

```
BUIL - 08
$
 ECHO
$VERI
!CONV win
CAST MESH
TRID EULE
$
DIME
 PTSL 47029
 CUBE 42496 CL3D 6080 ZONE 2
 BLOQ 10000
TERM
$
GEOM
  CUBE fluid
  CL3D absor
TERM
*
COMP COUL roug LECT explo TERM
          turq LECT air   TERM
          rose LECT absor TERM
*
MATE
$ high-pressure perfect gas (explosive bubble)
     GAZP RO 1000 GAMM 1.4 PINI 100000.E5
          PREF 1.E5 LECT explo TERM
$ air
     GAZP RO 1 GAMM 1.4 PINI 1.E5
          PREF 1.E5 LECT air TERM
$ absorbing
     IMPE ABSO RO 0 C 0
          LECT absor TERM
$
LIAI FREQ 1
     BLOQ 3 LECT bloc TERM
     FSR LECT fsrn TERM
$
ECRI VITE ECRO TFRE 100.E-3
     FICH ALIC TFRE 1.E-3
$
OPTI NOTEST
 csta 0.5e0
 log 1
CALCUL TINI 0 TEND 0.1E0
*-------------------------------------------------------------------
FIN
```

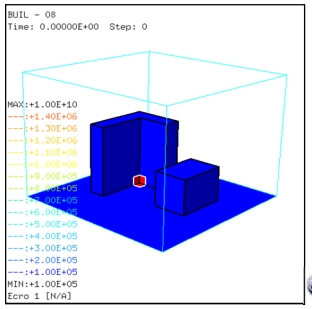
62

Exercise 4 – External blast on two buildings (3)

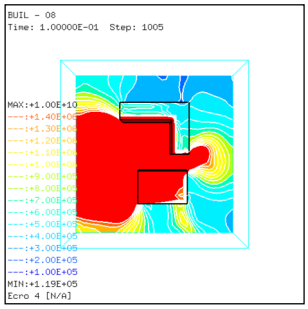
Geometry



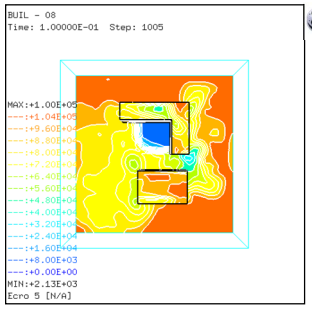
Pressure



Max pressure



Min pressure



63

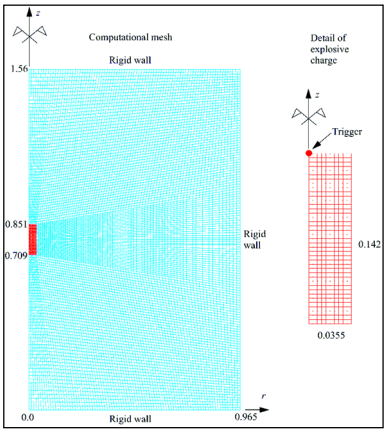
Exercise 5 – Confined detonation of solid TNT charge

Jones-Wilkins-Lee

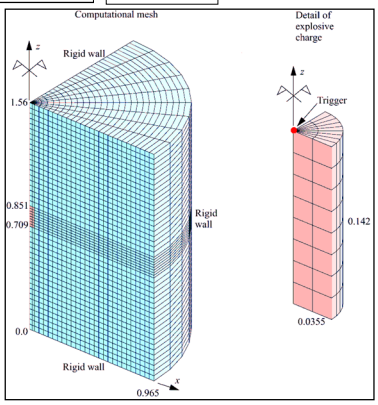
$$p(\rho,i) = A(1-\frac{\omega}{R_1 V})e^{-R_1 V} + B(1-\frac{\omega}{R_2 V})e^{-R_2 V} + \omega\rho i$$

$$V = \rho_0 / \rho \qquad \omega = \gamma - 1$$

Geometry:



2D axisymmetric model

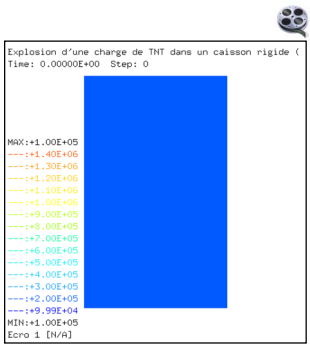


3D axisymmetric model

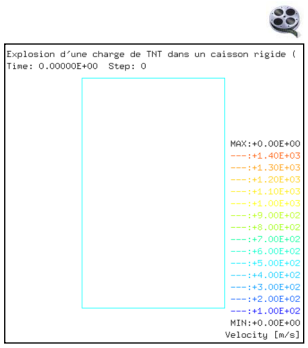
64

Exercise 5 – Confined detonation of solid TNT charge (2)

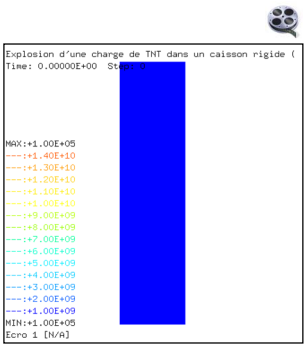
2D axisymmetric solution:



Pressure



Velocity

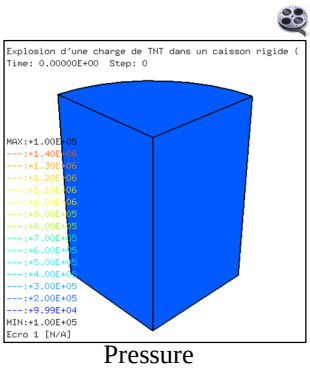


Charge pressure

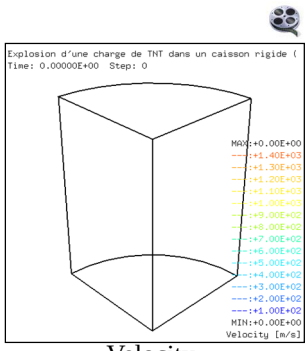
65

Exercise 5 – Confined detonation of solid TNT charge (3)

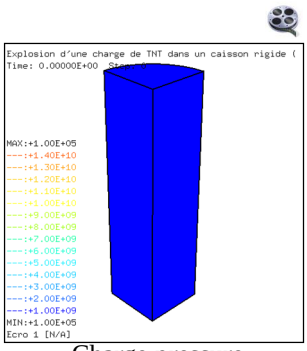
3D axisymmetric solution:



Pressure



Velocity

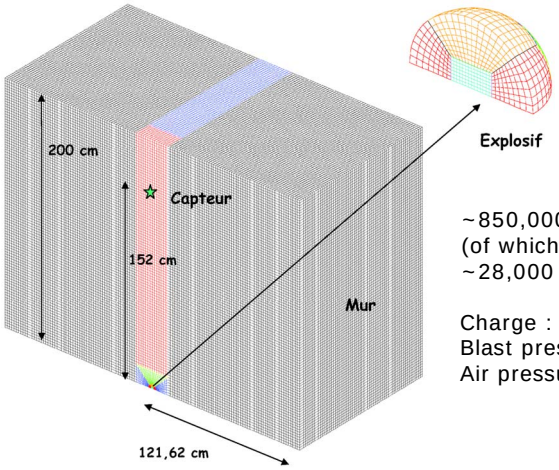


Charge pressure

66

CCFV modeling of spherical wave reflection

(Courtesy of CEA : P. Galon, A. Beccantini)



~850,000 CCFV cubes
(of which 3,000 in the explosive charge)
~28,000 absorbing elements (boundary)

Charge : solid C4
Blast pressure ~104,000 bar
Air pressure 1 bar

- Strong shock : high-explosive blast wave

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CCFV results

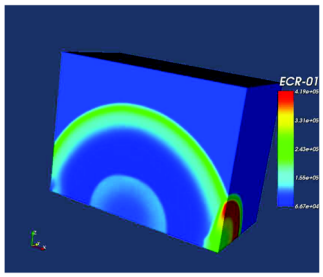


Figure 21 : Champ de pression à T = 1,5 (gaz JWL)

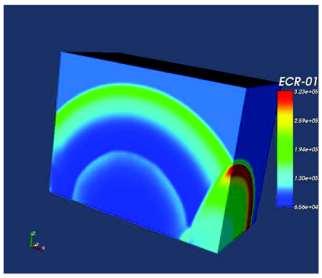


Figure 22 : Champ de pression T = 2 ms (gaz JWL)

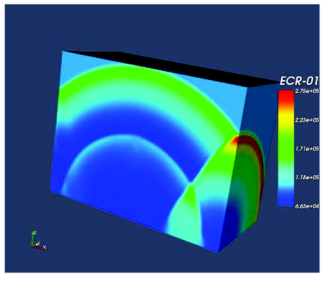


Figure 23 : Champ de pression à T = 3 ms (gaz JWL)

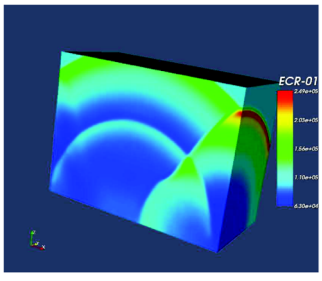
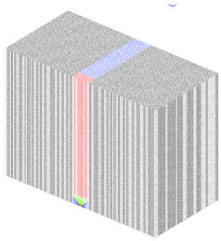
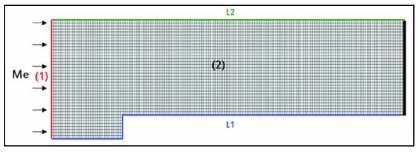


Figure 24 : Champ de Pression T = 3.5 ms (gaz JWL)

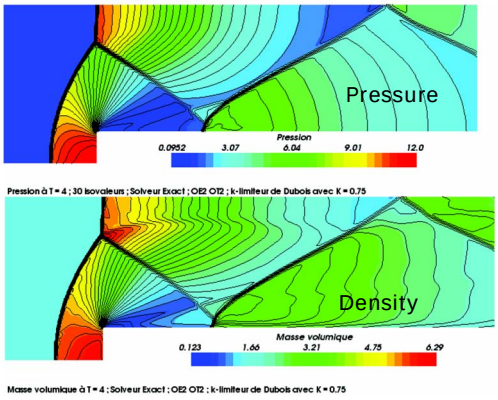


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CCFV modeling of Mach 3 Flow over Step (Woodward-Colella test) Courtesy of CEA



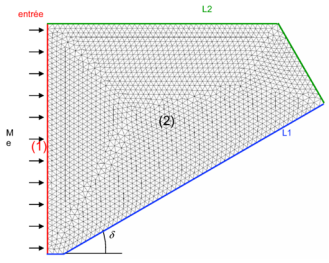
~27,000 CCFV quadrangles



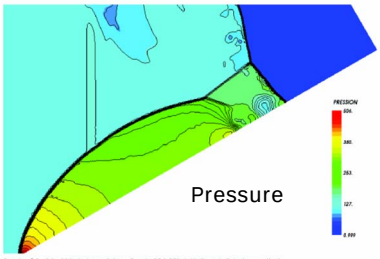
69

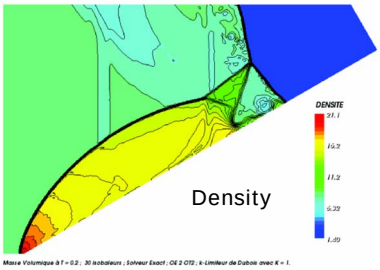
CCFV modeling of Shock Wave Reflection

(Courtesy of CEA)



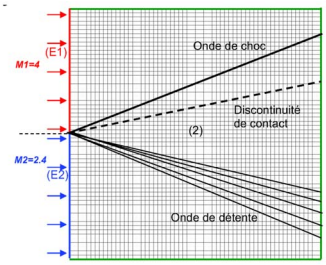
~100,000 CCFV triangles (irregular) for the solutions presented next



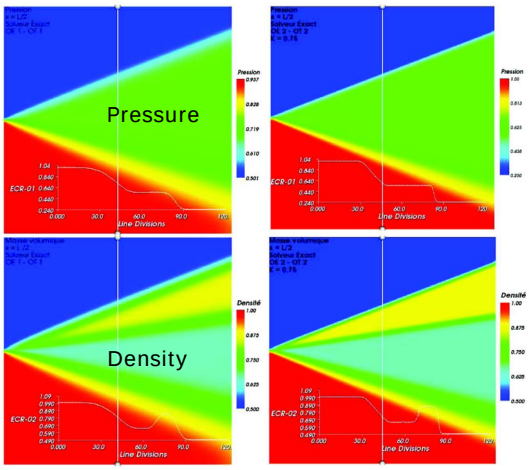


70

CCFV modeling of Interaction between Supersonic Jets (Courtesy of CEA)



~15,000 CCFV quadrangles

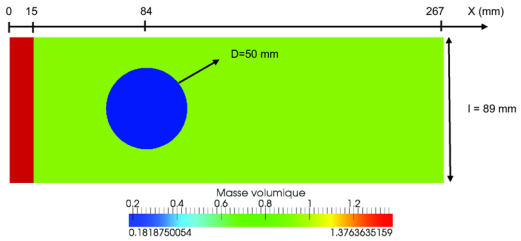


1st order in space and time

2nd order in space and time

71

CCFV modeling of Shock-Bubble Interaction (Richtmyer-Meshkov Instability)

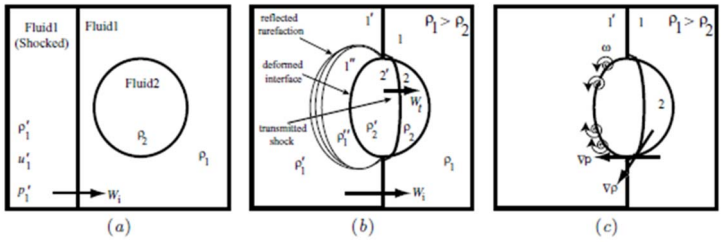


Shock wave interacting with a light gas bubble

72

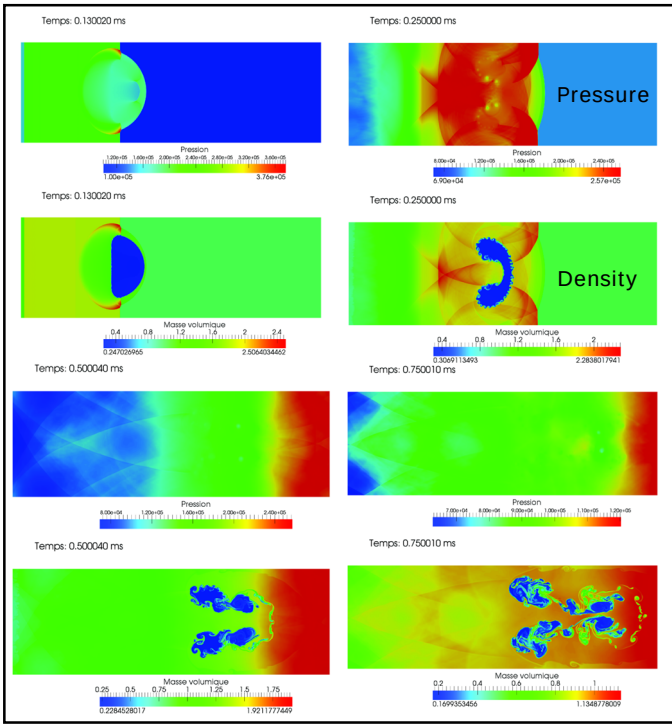
Example of Richtmyer-Meshkov Instability

When the shock wave impacts the bubble interface, some **vorticity** is generated near the interface with a production rate proportional to the vector product between the pressure gradient of the shock wave and the density gradient at the interface: $\sim \nabla p \wedge \nabla \rho / \rho^2$



Courtesy P. Galon, A. Beccantini (CEA)

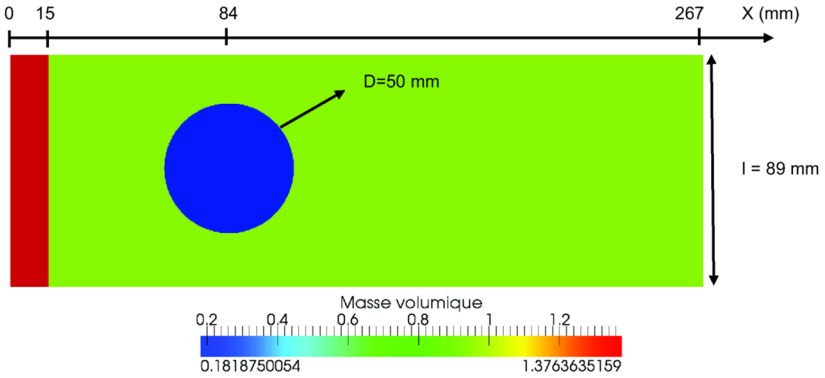
73



CCFV modeling of RMI (1.3 M elements)

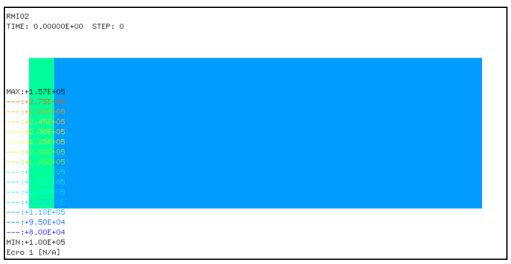
74

Exercise 6 – Richtmyer-Meshkov instability

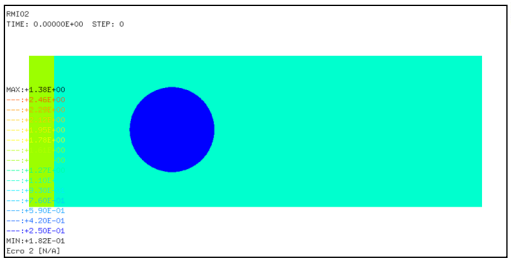


Solution with CCFV (1.3 Million elements)

Exercise 6 – Richtmyer-Meshkov instability (2)



Pressure



Density

Shock / bubble (He) interaction in air – M = 1.22

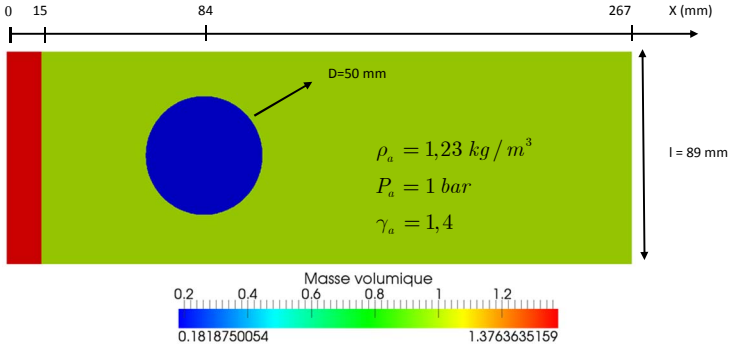
Courtesy P. Galon, A. Beccantini (CEA)

$\rho_a = 1{,}686\ kg/m^3$ $\rho_b = 0{,}2546\ kg/m^3$

$P_a = 1{,}59\ bar$ $P_b = 1\ bar$

$\gamma_a = 1{,}4$ $\gamma_a = 1{,}648$

$u_x = 114{,}5\ m/s$



- J.F Haas and B. Sturtevant. Interaction of weak shock waves with cylindrical and spherical gas inhomogeneities. J. Flui Mech. (1987), vol 181, pp 41-76.
- J.F Haas. Interaction of weak shock waves and discrete gas inhomogeneities, PHD Thesis, California Institute of Technology, 1984.

77

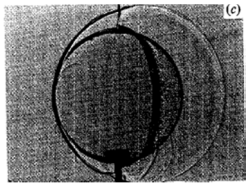


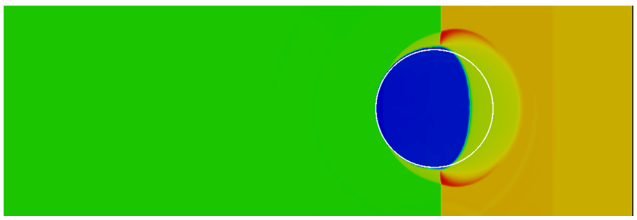
Experiment at t=0.032 ms
Calculation (density) at t=0.030 ms



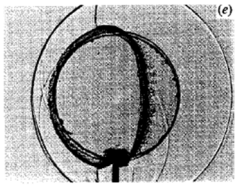
Expriment at t=0.052 ms
Calculation (density) at t=0.050 ms

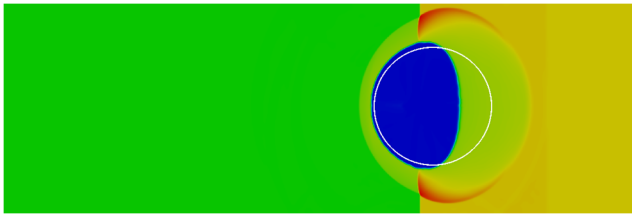
78





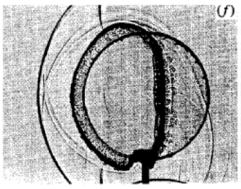
Experiment at t=0.062 ms
Calculation (density) at t=0.060 ms

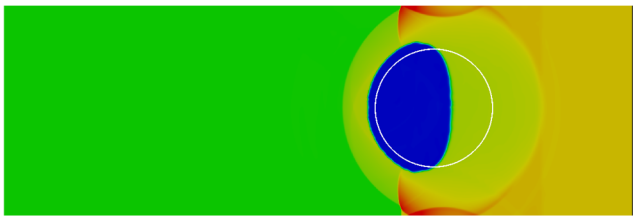




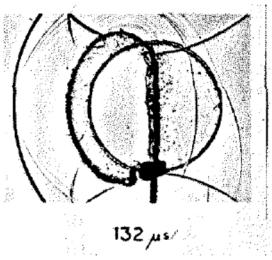
Experiment at t=0.082 ms
Calculation (density) at t=0.080 ms

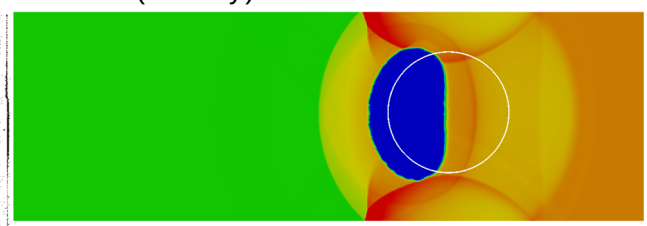
79





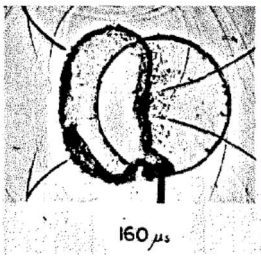
Experiment at t=0.102 ms
Calculation (density) at t=0.100 ms

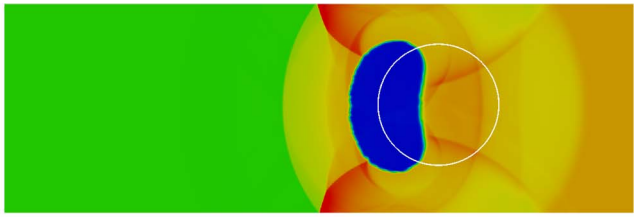




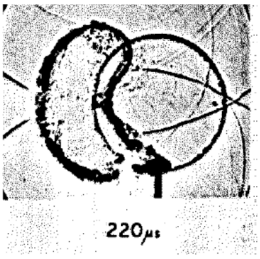
Experiment at t=0.132 ms
Calculation (density) at t=0.140 ms

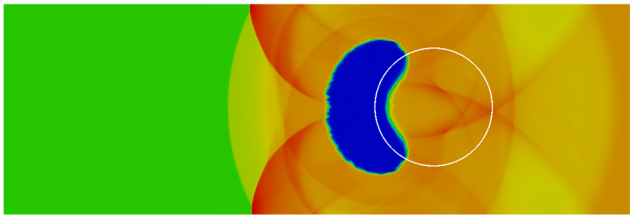
80





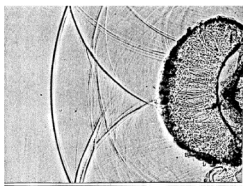
Experiment at t=0.160 ms
Calculation (density) at t=0.170 ms

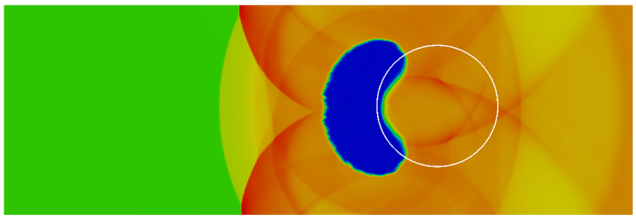




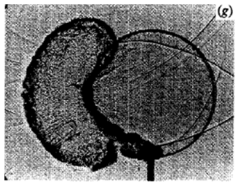
Experiment at t=0.220 ms
Calculation (density) at t=0.230 ms

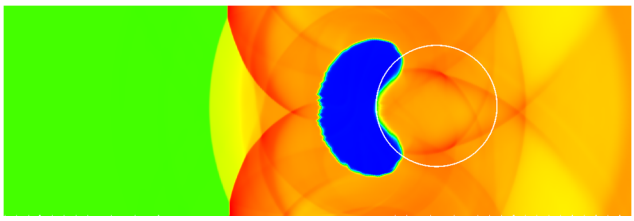
81





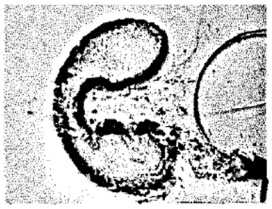
Experiment at t=0.225 ms
Calculation (density) at t=0.240 ms

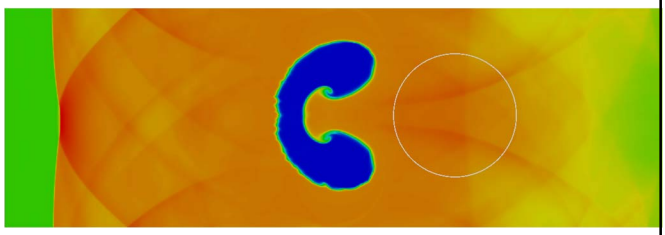




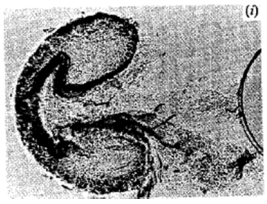
Experiment at t=0.245 ms
Calculation (density) at t=0.250 ms

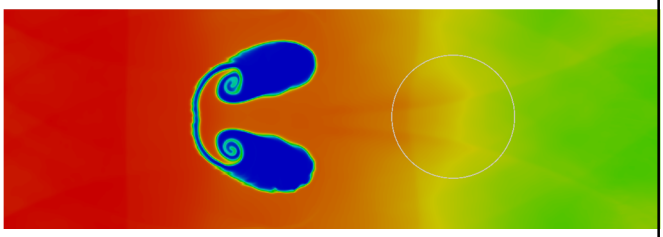
82





Experiment at t=0.427 ms
Calculation (density) at t=0.430 ms

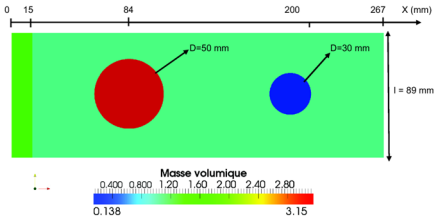




Experiment at t=0.674 ms
Calculation (density) at t=0.680 ms

83

CCFV modeling of RMI (2 bubbles)



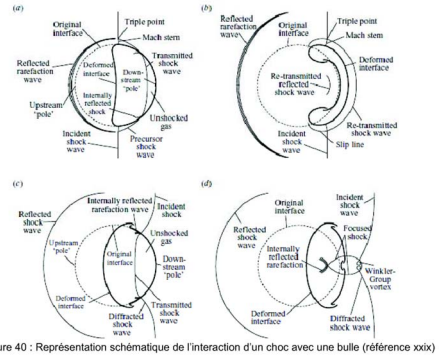
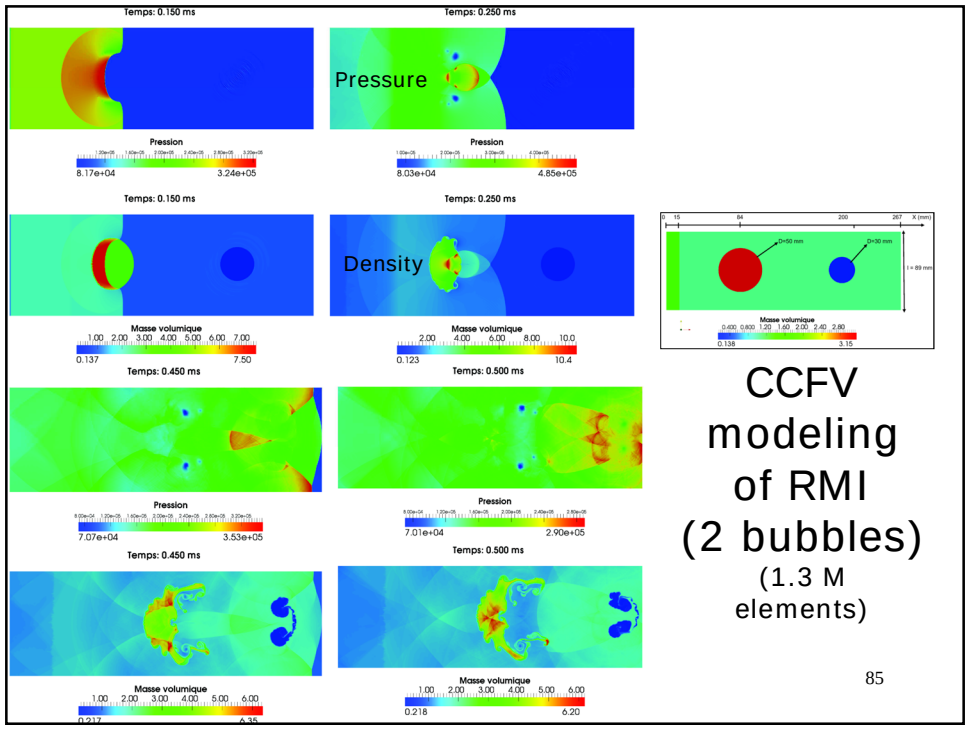


Figure 40 : Représentation schématique de l'interaction d'un choc avec une bulle (référence xxix)

Qualitative physical behavior

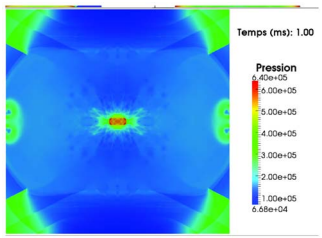
84



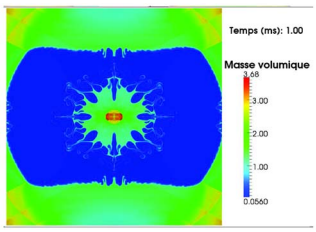
CCFV modeling of RMI (2 bubbles)

(1.3 M elements)

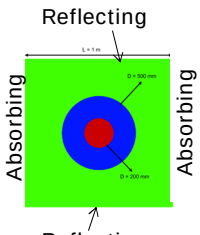
85

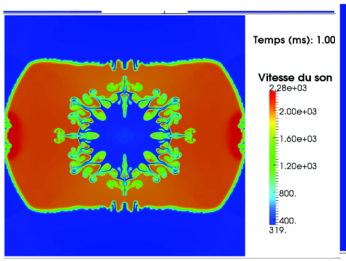


Pressure

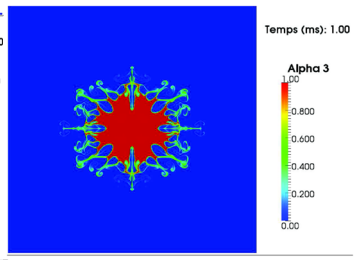


Density





Sound speed



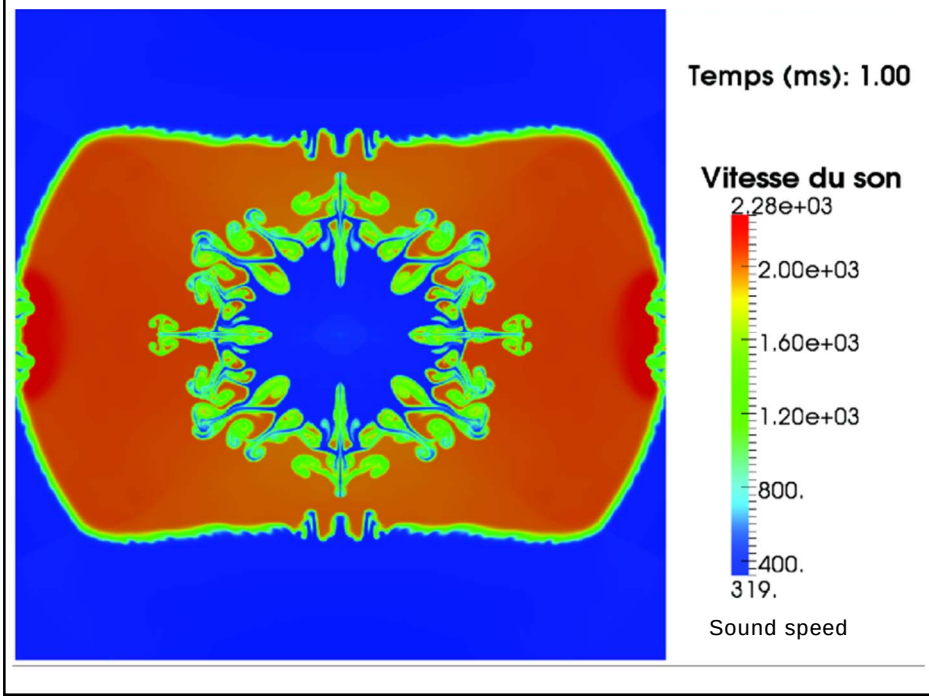
Mass fraction

Solution at 1 ms

CCFV modeling of RMI (2 concentric bubbles)

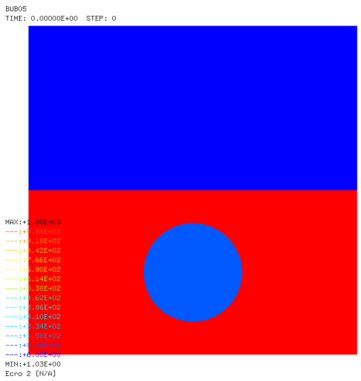
(1.8 M elements)

86



Sound speed

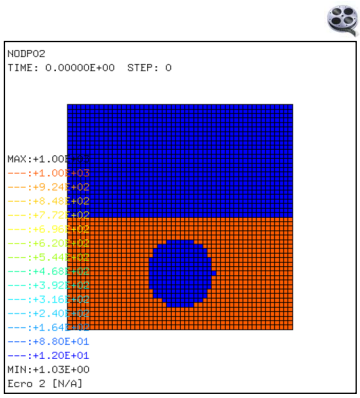
Exercise 7 – Gas bubble expansion in liquid



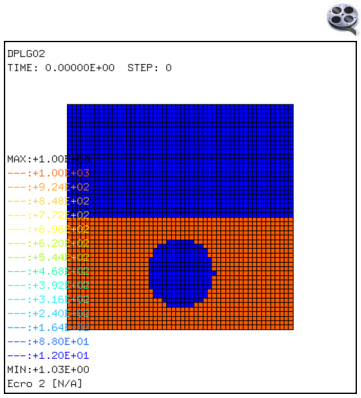
Solution with structured mesh (method of Despres, Lagoutière et al.)

88

Exercise 7 – Gas bubble expansion in liquid (2)



Without anti-diffusion

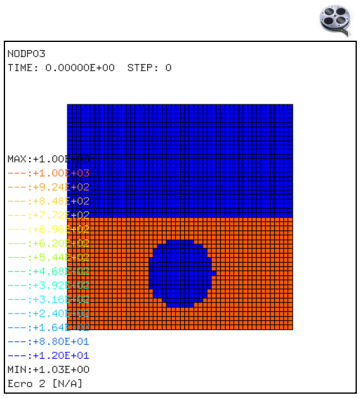


With anti-diffusion (DPLG)

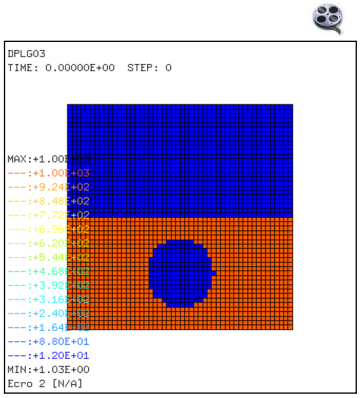
Mesh : 50 x 50 = 2,500 **CAR1** elements

89

Exercise 7 – Gas bubble expansion in liquid (3)



Without anti-diffusion

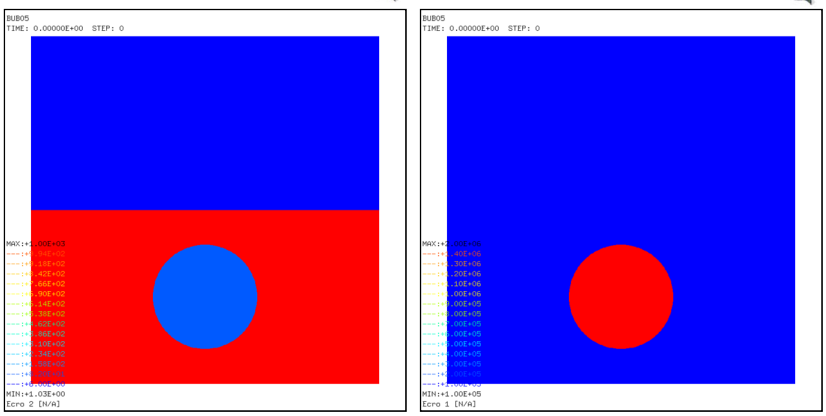


With anti-diffusion (DPLG)

Mesh : 50 x 50 = 2,500 **Q4VF** elements

90

Exercise 7 – Gas bubble expansion in liquid (4)

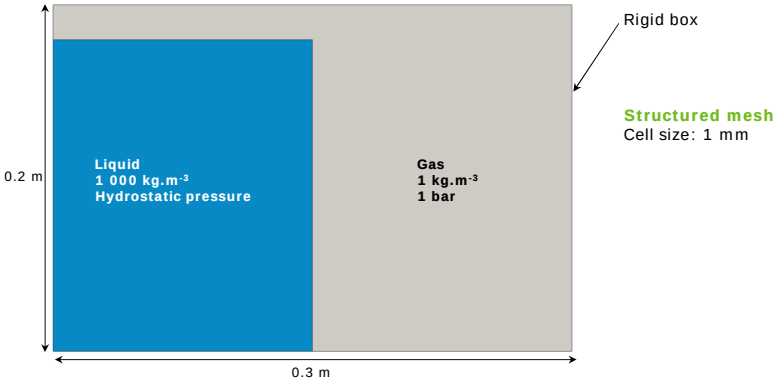


Density Pressure

Fine mesh : 800 x 800 = 640,000 CAR1 elements, **DPLG**

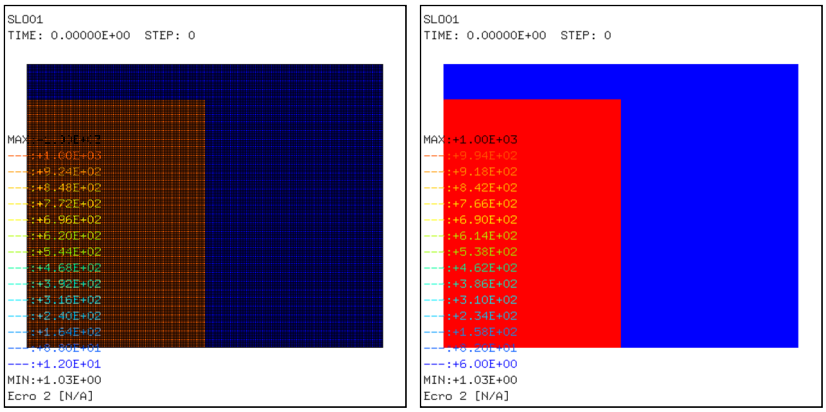
91

Exercise 8 – Sloshing under gravity loading



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Exercise 8 – Sloshing under gravity loading (2)

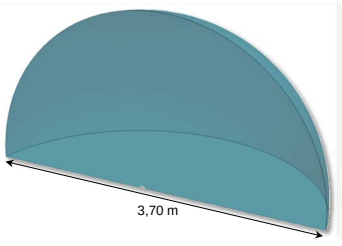


Solution with CAR1 (200 x 160 = 32,000 elements)

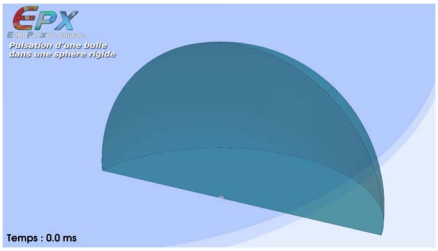
93

Pulsation of Bubble in Rigid Sphere

(Courtesy of CEA)



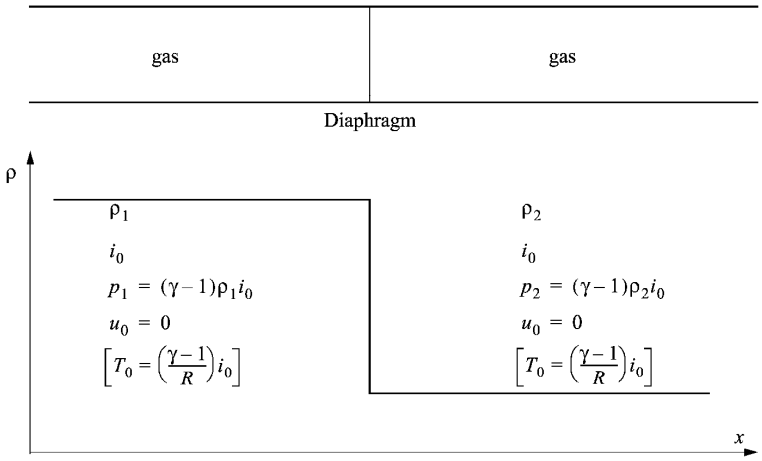
- Demonstration of capacity of following the life of a non-condensable bubble (cf. BORAX accident)
- *Initial conditions*: bubble of ~ **5 cl** at a pressure of **40 000 bar**
- Simulation of 3 periods
- Instability on the bubble surface at each collapse



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Exercise 1 – Shock tube

- Initial conditions:



- Equation of state (polytropic gas): $p = (\gamma - 1)\rho i$

$\gamma \doteq c_P / c_V$ $c_P \doteq$ specific heat at constant pressure
$c_V \doteq$ specific heat at constant volume

30

Geometric data:

The calculation is 2-D plane strain. The tube is 50 units long and 0.5 units wide (this dimension is irrelevant).

Materials

The fluids are perfect gases. The assumed initial conditions are:

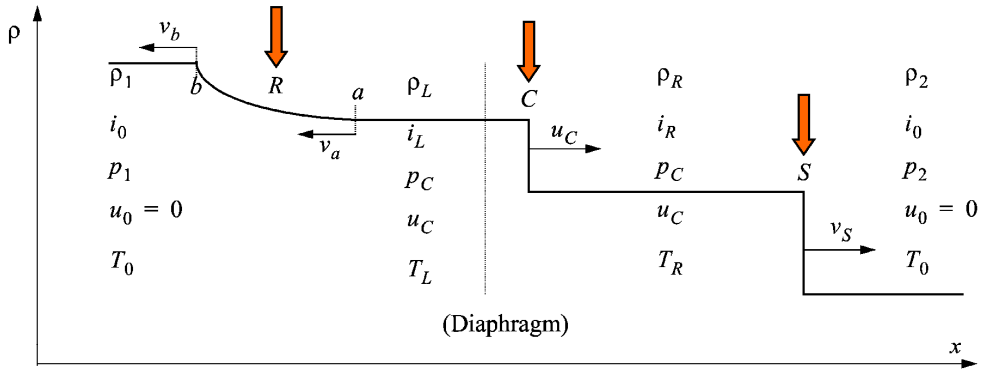
ρ_1	1.22
ρ_2	0.1237
γ	1.269
p_1	1.0×10^6
p_2	1.013×10^5
$i_1 = i_2$	3.046×10^6

The tube is rigid and does not need to be modelled.

Analytical solution (see e.g. Harlow & Amsden)

Shock tube (2)

- Analytical solution (self-similar):



- Shock S moves to the right at speed v_S
- Contact discontinuity C (particle initially at diaphragm) moves to the right at speed u_C
- Rarefaction wave $R(a,b)$ moves to the left at speeds v_a, v_b

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For the assumed initial values the solution is:

λ	9.863	u_C	925.4
P	2.888	v_S	1672.
p_C	2.927×10^5	v_a	30.12
ρ_R	0.2771	v_b	–1020.
ρ_L	0.4635	c_0	1020.
i_R	3.928×10^6	c_a	895.2
i_L	2.348×10^6	c_b	1020.

(with: $\lambda \doteq \rho_1 / \rho_2 = p_1 / p_2$ and $P \doteq p_C / p_2$).

Numerical solutions

First, we study the influence of pseudo-viscosity on Eulerian solutions:

$$q' = \begin{cases} \rho[C_Q l^2 (\nabla \cdot \underset{\sim}{v})^2 - C_L l a (\nabla \cdot \underset{\sim}{v})] & \text{for } \nabla \cdot \underset{\sim}{v} < 0 \\ 0 & \text{for } \nabla \cdot \underset{\sim}{v} \geq 0 \end{cases}$$

SHOC01

Eulerian, “average” pseudo-viscosity ($C_L = 0.5$, $C_Q = 2.56$), $\alpha_0 = \beta_0 = 1$ (full donor)
The input file is:

```
SHOC01 = SHOCK-2D 03 EULERIAN CL=0.5 CQ=2.56 ALF0=BET0=1
*--------------------------------------------------------------------------
ECHO
*CONV win
*-------------------------------------------------------------Problem type
DPLA NONL EULE
*-------------------------------------------------------------Dimensioning
DIME
  PT2L 202 FL24 100
  NALE 1 ELVC 201
  MTPO 101
TERM
*--------------------------------------------------------------------Geometry
GEOM LIBR POIN 202 FL24 100 TERM
 0.00000E+00 0.00000E+00 5.00000E-01 0.00000E+00 1.00000E+00 0.00000E+00
 1.50000E+00 0.00000E+00 2.00000E+00 0.00000E+00 2.50000E+00 0.00000E+00
 3.00000E+00 0.00000E+00 3.50000E+00 0.00000E+00 4.00000E+00 0.00000E+00
 4.50000E+00 0.00000E+00 5.00000E+00 0.00000E+00 5.50000E+00 0.00000E+00
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 7.50000E+00 0.00000E+00 8.00000E+00 0.00000E+00 8.50000E+00 0.00000E+00
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 1.05000E+01 0.00000E+00 1.10000E+01 0.00000E+00 1.15000E+01 0.00000E+00
 1.20000E+01 0.00000E+00 1.25000E+01 0.00000E+00 1.30000E+01 0.00000E+00
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 2.10000E+01 0.00000E+00 2.15000E+01 0.00000E+00 2.20000E+01 0.00000E+00
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 2.40000E+01 0.00000E+00 2.45000E+01 0.00000E+00 2.50000E+01 0.00000E+00
 2.55000E+01 0.00000E+00 2.60000E+01 0.00000E+00 2.65000E+01 0.00000E+00
 2.70000E+01 0.00000E+00 2.75000E+01 0.00000E+00 2.80000E+01 0.00000E+00
 2.85000E+01 0.00000E+00 2.90000E+01 0.00000E+00 2.95000E+01 0.00000E+00
 3.00000E+01 0.00000E+00 3.05000E+01 0.00000E+00 3.10000E+01 0.00000E+00
 3.15000E+01 0.00000E+00 3.20000E+01 0.00000E+00 3.25000E+01 0.00000E+00
 3.30000E+01 0.00000E+00 3.35000E+01 0.00000E+00 3.40000E+01 0.00000E+00
 3.45000E+01 0.00000E+00 3.50000E+01 0.00000E+00 3.55000E+01 0.00000E+00
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 3.90000E+01 0.00000E+00 3.95000E+01 0.00000E+00 4.00000E+01 0.00000E+00
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 1.25000E+01 5.00000E-01 1.30000E+01 5.00000E-01 1.35000E+01 5.00000E-01
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 1.55000E+01 5.00000E-01 1.60000E+01 5.00000E-01 1.65000E+01 5.00000E-01
 1.70000E+01 5.00000E-01 1.75000E+01 5.00000E-01 1.80000E+01 5.00000E-01
 1.85000E+01 5.00000E-01 1.90000E+01 5.00000E-01 1.95000E+01 5.00000E-01
 2.00000E+01 5.00000E-01 2.05000E+01 5.00000E-01 2.10000E+01 5.00000E-01
 2.15000E+01 5.00000E-01 2.20000E+01 5.00000E-01 2.25000E+01 5.00000E-01
 2.30000E+01 5.00000E-01 2.35000E+01 5.00000E-01 2.40000E+01 5.00000E-01
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 4.85000E+01 5.00000E-01 4.90000E+01 5.00000E-01 4.95000E+01 5.00000E-01
 5.00000E+01 5.00000E-01
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   5   6 107 106   6   7 108 107   7   8 109 108   8   9 110 109
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  89  90 191 190  90  91 192 191  91  92 193 192  92  93 194 193
  93  94 195 194  94  95 196 195  95  96 197 196  96  97 198 197
  97  98 199 198  98  99 200 199  99 100 201 200 100 101 202 201
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          BET0 1 KINT 0 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          LECT 1 PAS 1 50 TERM
     FLUT RO 0.1237 EINT 3.046E6 GAMM 1.269 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 0 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          LECT 51 PAS 1 100 TERM
*-----------------------------------------------------Boundary conditions
LINK COUP
     BLOQ 2 TOUS
     BLOQ 1 LECT 1 101 102 202 TERM
*-------------------------------------------------------------------Outputs
ECRI VITE ECRO TFRE 10.E-3
     FICH ALIC TFRE 10.E-3
     FICH ALIC TEMP FREQ 1
               POIN LECT 25 50 75 TERM
               ELEM LECT 25 50 75 TERM
     FICH XPLO DESC 'SHOC01' TFRE 10.E-3
               POIN LECT 1 PAS 1 101 TERM
*-----------------------------------------------------------------Options
OPTI NOTE
     CSTA 0.5
*-------------------------------------------------Transient calculation
CALCUL TINI 0. TEND 20.E-3
*=========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
*-----------------------------------------------------Curve definitions
COUR 1 'vx_a'     VITE COMP 1 NOEU LECT 25 TERM
COUR 2 'vx_b'     VITE COMP 1 NOEU LECT 50 TERM
COUR 3 'vx_c'     VITE COMP 1 NOEU LECT 75 TERM
COUR 4 'pr_a'     ECRO COMP 1 ELEM LECT 25 TERM
COUR 5 'pr_b'     ECRO COMP 1 ELEM LECT 50 TERM
COUR 6 'pr_c'     ECRO COMP 1 ELEM LECT 75 TERM
```

```
COUR 7 'ro_a'     ECRO COMP 2 ELEM LECT 25  TERM
COUR 8 'ro_b'     ECRO COMP 2 ELEM LECT 50  TERM
COUR 9 'ro_c'     ECRO COMP 2 ELEM LECT 75  TERM
*-----------------------------------------------------------------Plots
trac 1 2 3 axes 1.0 'VELOC. [M/S]'
trac 4 5 6 axes 1.0 'PRESS. [PA]'
trac 7 8 9 axes 1.0 'DENS. [KG/M3]'
*-------------------------------------------------Results qualification
QUAL ECRO COMP 2 LECT 25 TERM REFE 8.59884E-01  TOLE 1.E-2
     ECRO COMP 2 LECT 50 TERM REFE 5.23010E-01  TOLE 1.E-2
     ECRO COMP 2 LECT 75 TERM REFE 4.61656E-01  TOLE 1.E-2
*=========================================================POST-TREATMENT 2
SUIT
Post-treatment
ECHO
RESU ALIC GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
*-----------------------------------------------------Curve definitions
SCOU 1 'ro_01' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                      ECRO COMP 2
*-----------------------------------------------------------------Plots
trac 1 axes 1.0 'DENS. [KG/M3]'
list 1 axes 1.0 'DENS. [KG/M3]'
*-------------------------------------------------Results qualification
QUAL ECRO COMP 2 LECT 25 TERM REFE 8.59884E-01  TOLE 1.E-2
     ECRO COMP 2 LECT 50 TERM REFE 5.23010E-01  TOLE 1.E-2
     ECRO COMP 2 LECT 75 TERM REFE 4.61656E-01  TOLE 1.E-2
*=======================================================================
FIN
```

SHOC03

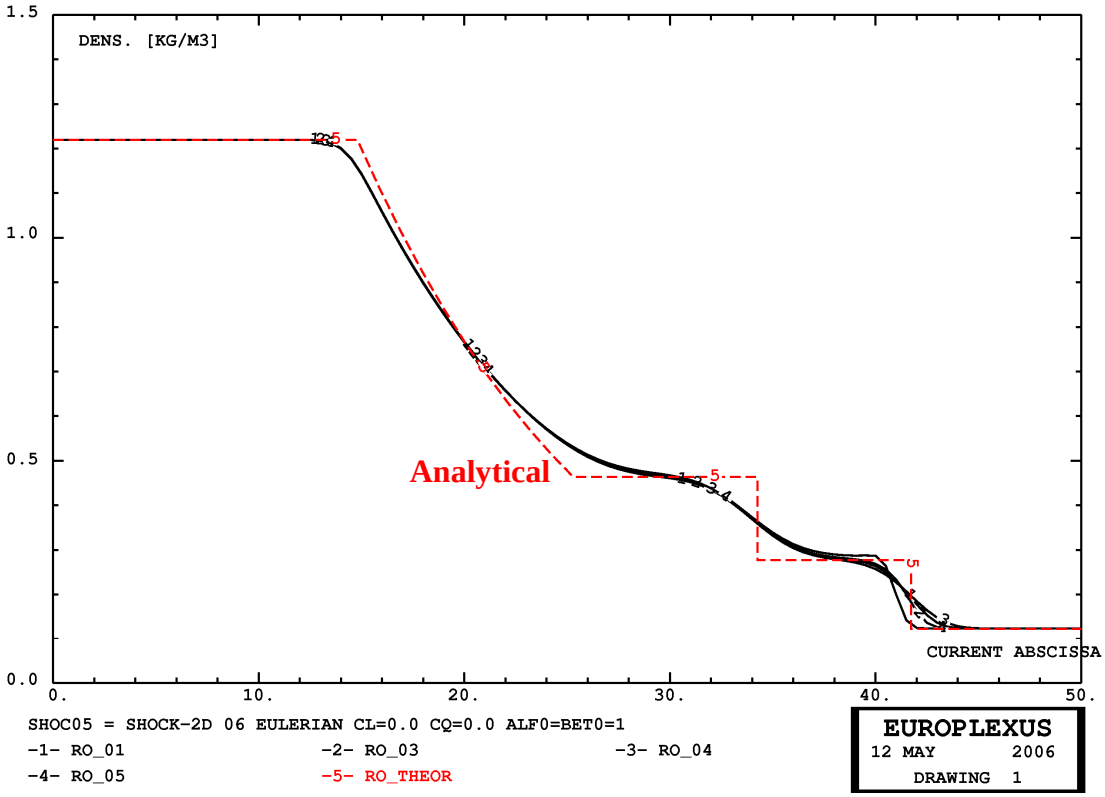
Same as SHOC01 but lower pseudo-viscosity ($C_L = 0.5$, $C_Q = 0$).

SHOC04

Same as SHOC01 but higher pseudo-viscosity ($C_L = 0.8$, $C_Q = 4.0$).

SHOC05

Same as SHOC01 but no pseudo-viscosity ($C_L = C_Q = 0$).



Conclusion: the pseudo-viscous pressure has a limited effect on results in Eulerian simulations. Solutions may be obtained even without any pseudo-viscosity.

Next, we investigate the effect of pseudo-viscosity on Lagrangian solutions:

SHOC08

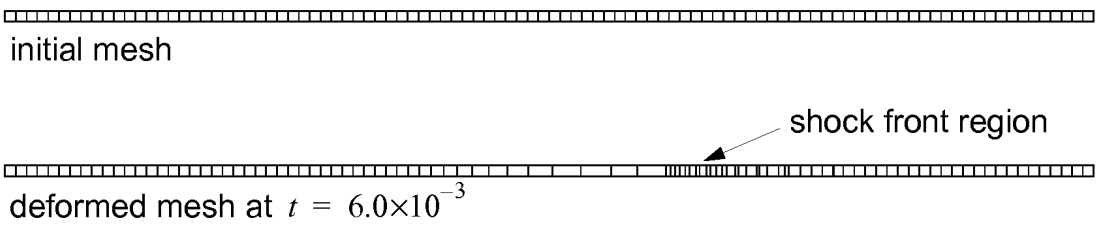
Lagrangian, no pseudo-viscosity ($C_L = C_Q = 0$). The solution is unstable.

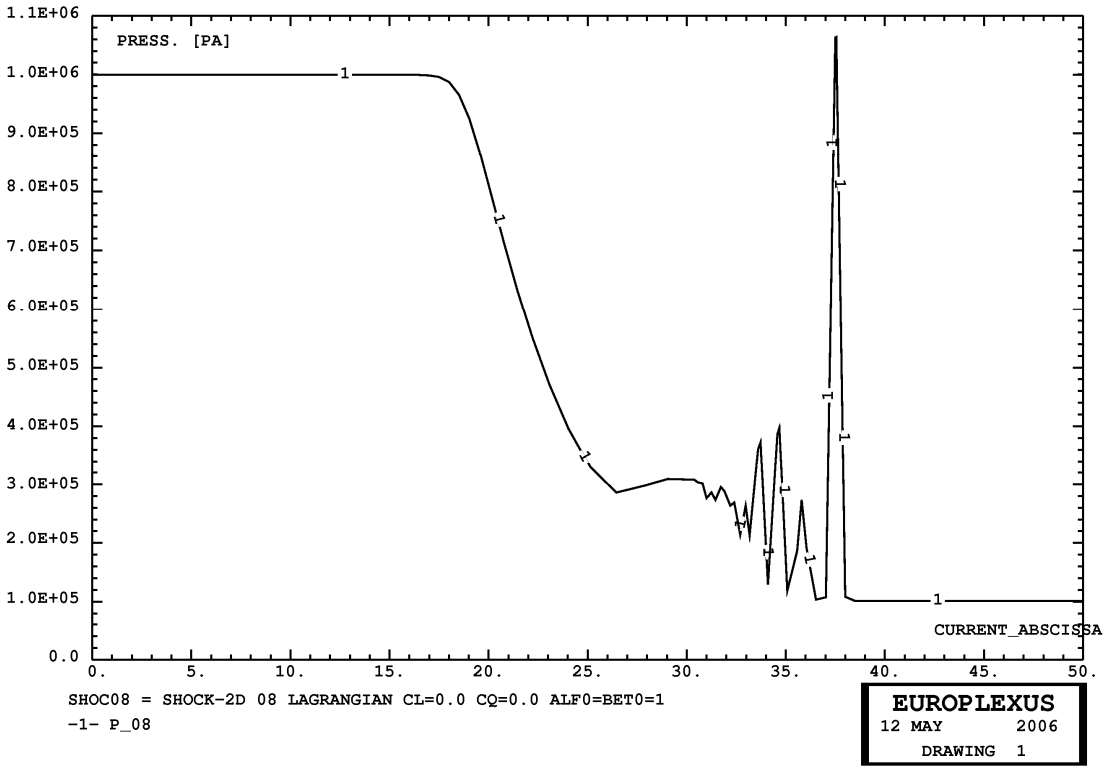
SHOC09

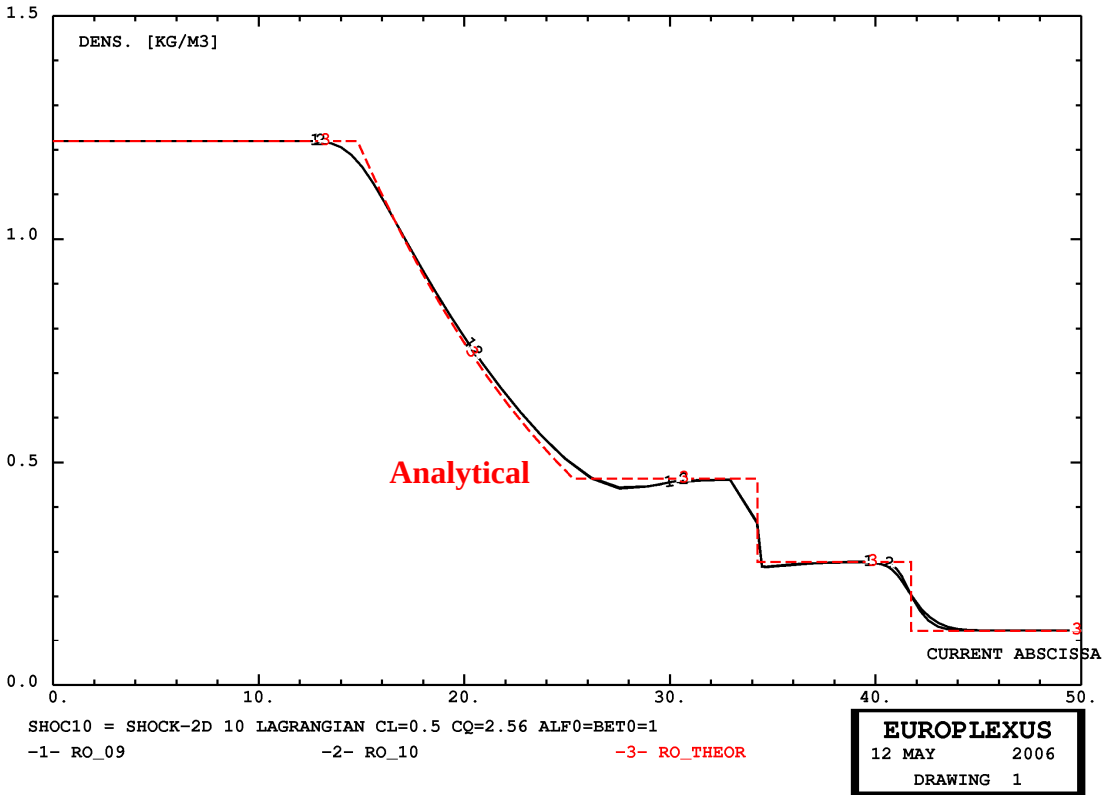
Same as SHOC08 but high pseudo-viscosity ($C_L = 0.8$, $C_Q = 4.0$).

SHOC10

Same as SHOC08 but "average" pseudo-viscosity ($C_L = 0.5$, $C_Q = 2.56$).





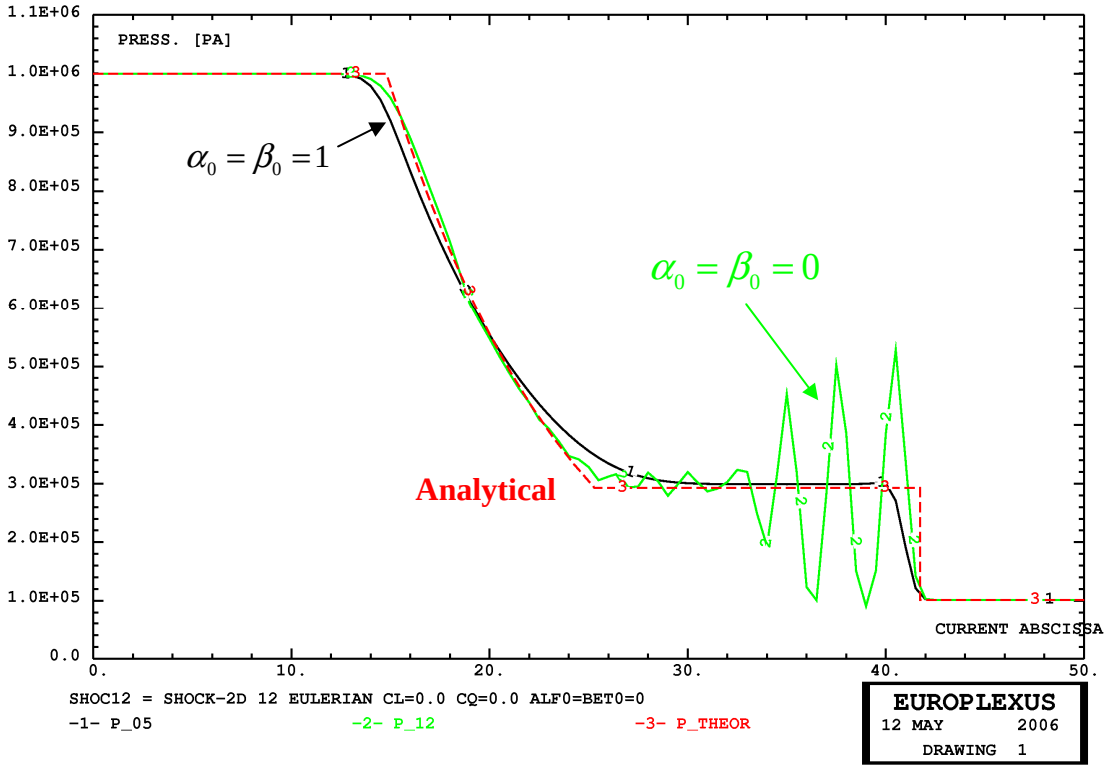


Conclusion: the pseudo-viscous pressure has a limited effect on results in Lagrangian simulations. Hovever, a small amout of pseudo-viscosity is needed otherwise the solution becomes unstable.

Finally, we investigate the effect of upwinding on Eulerian solutions:

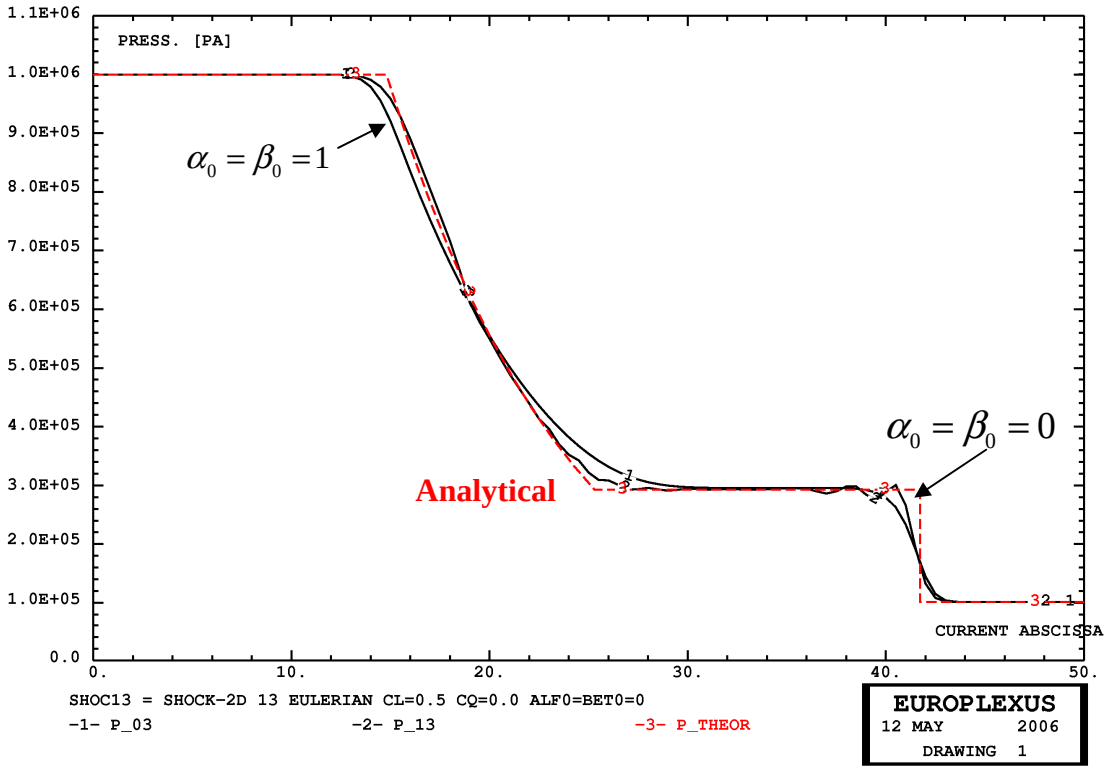
SHOC12

Eulerian, no pseudo-viscosity ($C_L = 0.0$, $C_Q = 0$), centred scheme ($\alpha_0 = \beta_0 = 0$). The solution presents strong oscillations but arrives to the final time.



SHOC13

Eulerian, very low pseudo-viscosity ($C_L = 0.5$, $C_Q = 0$), centred scheme ($\alpha_0 = \beta_0 = 0$). The solution presents some oscillations but is stable. Fronts are steeper than with the full-donor upwinding scheme.

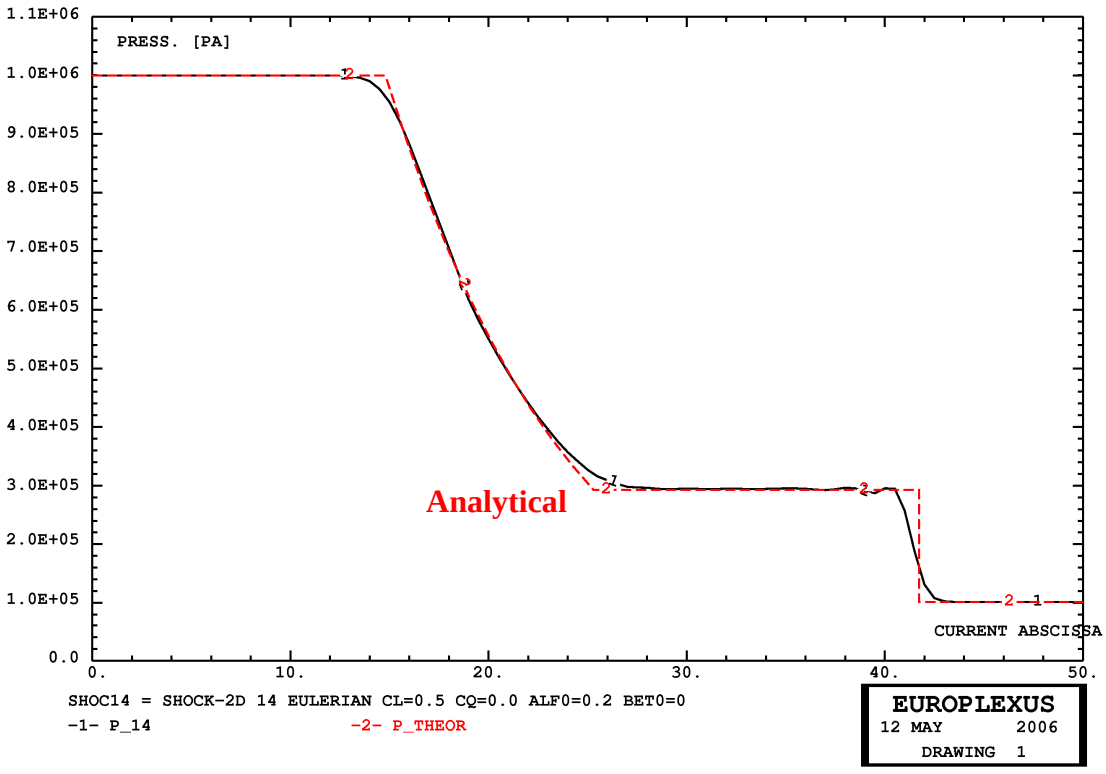


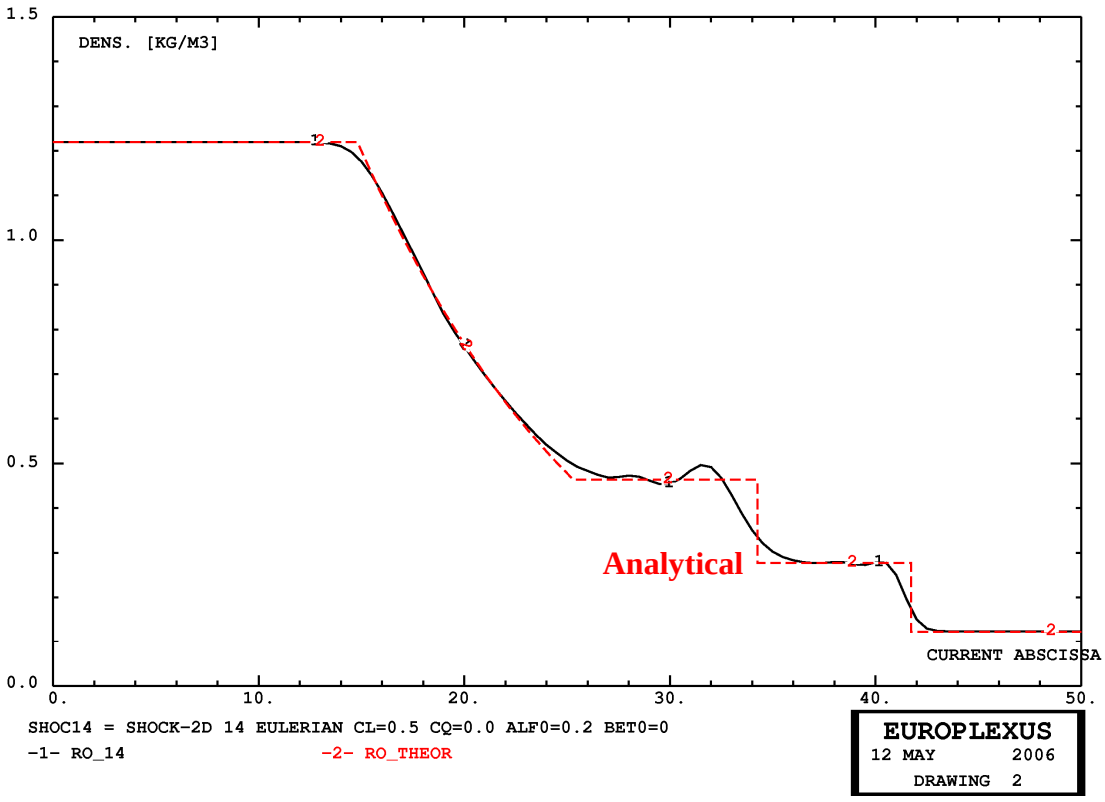
Conclusion: centred upwinding scheme produces steeper fronts than full-donor scheme. However, solutions present oscillations. A small amount of pseudo-viscosity is needed otherwise the solution becomes unstable.

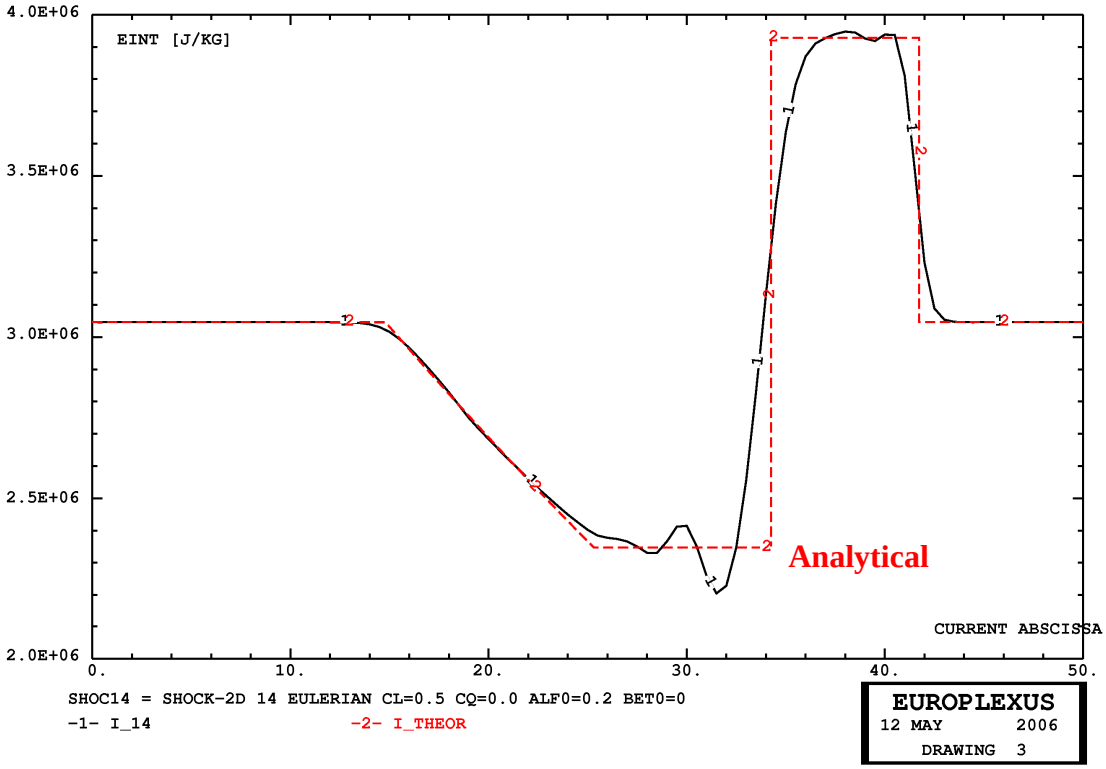
"Optimal" solution (for the present problem)

SHOC14

Eulerian, very low pseudo-viscosity ($C_L = 0.5$, $C_Q = 0$), intermediate upwinding for the mass equation ($\alpha_0 = 0.2$), centred scheme for the momentum equation ($\beta_0 = 0$).







General conclusions:

- Some pseudoviscosity is needed in Lagrangian solutions else they are unstable.
- Use as low pseudoviscosity as possible to obtain steep fronts.
- The full-donor scheme is somewhat over-diffusive, while the centred scheme yields sharper results.
- Use a slightly larger upwinding coefficient for the mass equation than for the momentum equation.

Shock tube problem solved with Finite Volumes

The same shock tube problems considered above with the FE technique may be solved by the alternative Finite Volume formulation available in the code.

To this end, besides the considerations on initial conditions, which in FE are associated with elements while in FV are associated with nodes, one has also to consider the fact that the two models assume quite different physical parameters for the input specification.

Hereafter, some guidelines are given on how to specify approximately equivalent initial material conditions with these two alternative models.

Initial conditions: FE vs. FV

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 (see Tab. 1).

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/m3), 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 /kmole K) and c_V (J /kmole K).

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 /kmole K), T is the absolute temperature (K) and w is the molar weight (kg/kmole). 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.

Finite Volumes	**Finite Elements**
Input parameters: p , T , R , c_V , w	Input parameters: ρ , i , γ
State equation: $p = RT\frac{\rho}{w}$	State equation: $p = (\gamma - 1)\rho i$
p = pressure (Pa)	
ρ = density (kg/m3),	
R = universal constant of gases (J /kmole K)	i = internal energy per unit mass i (J/kg)
w = molar weight (kg/kmole).	γ = ratio between c_P and c_V (-)
c_V = Specific heat at constant volume (J /kmole K)	N/a
T = temperature (K)	N/a

Tab. 1 – FE and FV models equations and parameters

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. They are summarised in the following tables 2 and 3:

FE	ρ (kg/m3)	i (J/kg)	γ (-)
LP zone	2.0	1.E+05	1.5
HP zone	2.0	5.E+05	1.5

Tab. 2 - FE model initial conditions

FV	p (Pa)	T (K)	c_V (J /kmole K)	R (J /kmole K)	w (kg/kmole)
LP zone	1.E+05	100.0	2.E+04	1.E+04	20.0
HP zone	5.E+05	500.0	2.E+04	1.E+04	20.0

Tab. 3 - FV model initial conditions

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/m3 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/kmole K, and we must choose a molar weight, say $w = 20$ kg/kmole for both gases. Then we obtain the specific heat at constant volume (same for both gases) from the relation $c_V = R/(\gamma - 1) = 2.E4$

Assuming for both gases the same initial density $\rho = 2$ kg/m3 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.

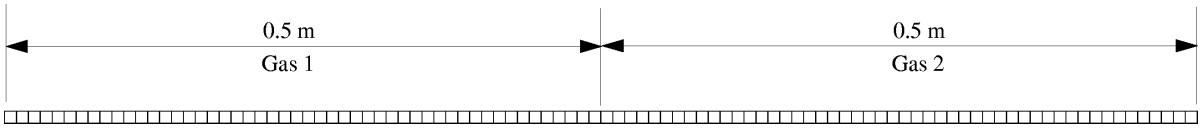
Example of shock tube problem solved by FV

The problem is similar but not identical to the ones considered previously.

LARR01

This numerical example concerns a shock tube with two components. The problem data have been taken from Larrouturou: a 1 m long, 1 cm wide shock tube is divided into two 0.5 m long zones, see Fig. 5, separated by a membrane that breaks at $t = 0$, thus initiating the transient. The left zone contains a pure perfect gas (A) with $\gamma_A = 1.4$, at a state defined by $p_A = 1$, $\rho_A = 1$, whereas the right zone contains another pure, perfect gas (B) with $\gamma_B = 1.2$ at a state defined by $p_B = 0.1$, $\rho_B = 0.125$. The test is a two-component version of the classical Sod problem.

A solution of this problem is obtained in two space dimensions using quadrilateral 'elements'. The 2D mesh consists of 100 quadrilateral elements, see sketch below.



Mesh for the Larrouturou test (2D quadrilaterals)

The general solution pattern is very similar to the one corresponding to the classical single-component Sod problem, although the three intermediate states separated by the characteristic waves are different, due to the different values for the two gases. The mass of gas A advances with the contact discontinuity and compresses gas B, where the typical shock wave develops.

The Figure below summarizes the results obtained at $t = 0.16$. As pointed out by Larrouturou, the modification in the Roe solver to perform the upwinding of the partial density fluxes is mandatory to preserve the positivity of the scheme.

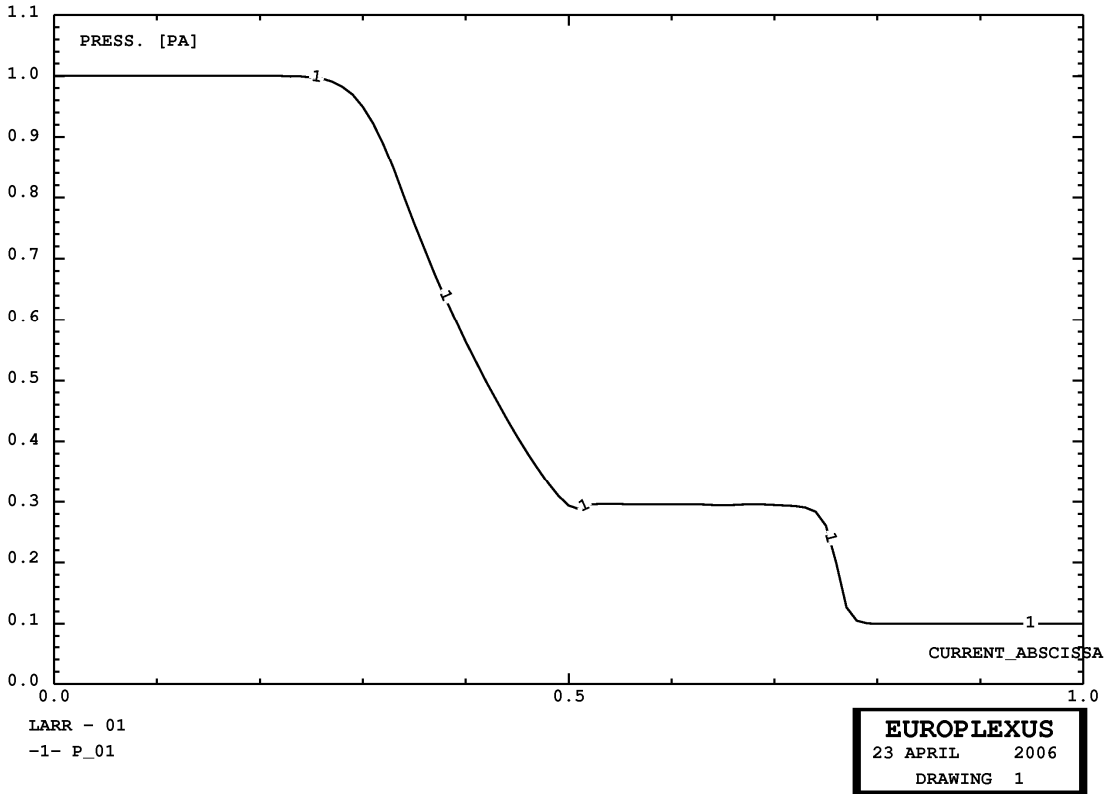
Altogether, pressure results exhibit a smaller dispersion than density and especially temperature results. Another expected result is that second-order solutions exhibit a substantially better spatial precision (steeper fronts) than first-order solutions.

The input files (mesh generation by K2000 plus input for EUROPLEXUS) read:

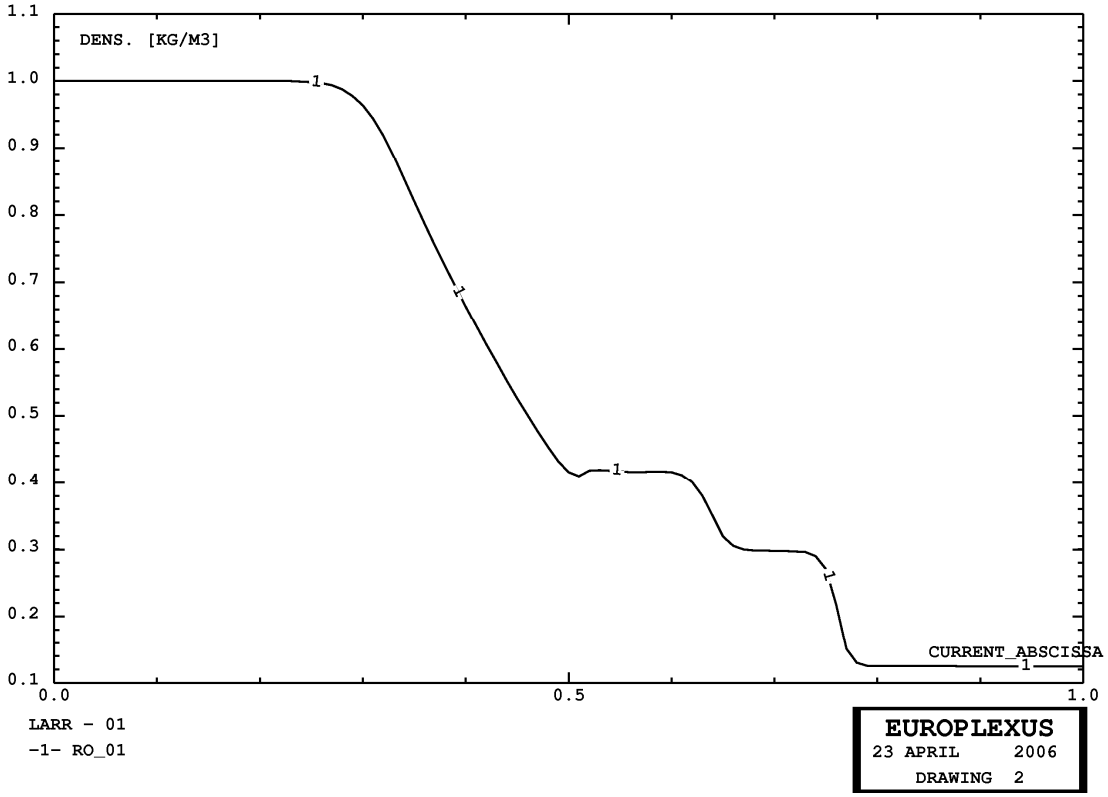
```
opti dime 2 echo 1 elem qua4;
opti titr 'LARR - 01';
*
p1=0 0;
p2=1 0;
 p3=0 0.01;
* p3=0 2.;
p4=0.5 0;
tol=0.001;
*
c1=p1 d 1 p3;
s1=c1 tran 50 p4;
p5=p4 'PLUS' p3;
c2=p4 d 1 p5;
s2=c2 tran 50 p4;
l1 = p1 d 100 p2;
flui=s1 et s2;
mesh=flui et l1;
elim mesh tol;
*
tass mesh;
*
opti sauv form 'larr01.msh';
sauv form mesh;
opti trac psc ftra 'larr01_mesh.ps';
trac qual mesh;
fin;
```

```
LARR - 01
$
 ECHO
$CONV WIN
CAST MESH
DPLA NONL EULE
$
DIME
 PT2L 202
 MC24 100 ZONE 1
 NDVC 804
 NALE 1
$ elvc only needed for xplot ...
 ELVC 500
 MTPO 101
TERM
$
GEOM
  MC24 FLUI
TERM
$
$ multicomponent material
$
MATE MCGP NCOM 2 R 1.00
          COMP 'A14' PM 2.5 CV1 2.5 CV2 0 CV3 0
          COMP 'B12' PM 2.5 CV1 5.0 CV2 0 CV3 0
          TOUS
$
INIT MCOM COMP 'A14'   MFRA 1.0 LECT S1 TERM
          COMP 'A14'   MFRA 0.0 LECT S2 TERM
          COMP 'B12'   MFRA 0.0 LECT S1 TERM
          COMP 'B12'   MFRA 1.0 LECT S2 TERM
          PRES 1.  LECT S1 TERM
          PRES 0.1 LECT S2 TERM
          TEMP 2.5 LECT S1 TERM
          TEMP 2.  LECT S2 TERM
          VEL1 0.0    TOUS
          VEL2 0.0    TOUS
          VEL3 0.0    TOUS
$
LINK COUP BLOQ 2 TOUS
          1 LECT 1 2 201 202 TERM
$
ECRI VITE ACCE FINT FEXT TFRE 0.08
     FICH K200 TFRE 0.01 POIN TOUS
     FICH ALIC TFRE 0.16
     FICH FORM XPLO TFRE 0.16 DESC 'LARR01'
               POIN LECT L1 TERM
     FICH FORM TPLO TFRE 0.0002 DESC 'LARR01'
               POIN LECT 17 15 13 11 9 7 5 3 1
TERM
$
OPTI NOTE CSTA 0.25
OPTI MC ORDR 2 NUFL ROE
 log 1
CALCUL TINI 0 TEND 0.16
SUIT
Post-treatment
ECHO
RESU ALIC GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
SCOU 1 'p_01'  NSTO 2 SAXE 1.0
       'current_abscissa' LECT L1 TERM MCPR
SCOU 2 'ro_01' NSTO 2 SAXE 1.0
       'current_abscissa' LECT L1 TERM MCRO
trac 1 axes 1.0 'PRESS. [PA]'
trac 2 axes 1.0 'DENS. [KG/M3]'
FIN
```

The pressure distribution at $t = 0.16$ is:



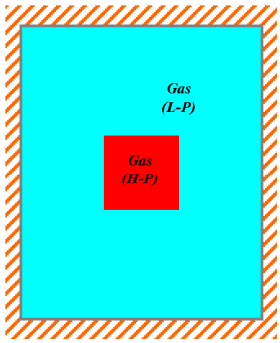
and the density:



Exercise 2 – Explosion in air-filled rigid tank

This is a purely fluid problem because the tank is rigid and therefore does not need to be modeled. There is only one type of fluid (single-phase, single-component). This considerably simplifies the modeling, since the bubble surface may be treated as ALE.

- Try out Lagrangian solution
- Try out Eulerian solution
- Try out ALE solution
- …



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Geometric data:

The calculation is 2-D plane strain. The tank is 10 units wide and 12 units high. The explosive bubble is 2 units wide and 2 units high.

Materials

The explosive bubble is a perfect gas with $\gamma = 1.4$, initial density 10 and initial specific energy 2.5×10^5, thus resulting in an initial pressure of:

$$p_0^{\text{bubble}} = (1.4-1)\cdot 10\cdot 2.5\times10^5 = 1.0\times10^6$$

The low-pressure surrounding gas has the same nature but an initial density of 1, thus resulting in an initial pressure of:

$$p_0^{\text{gas}} = (1.4-1)\cdot 1\cdot 2.5\times10^5 = 1.0\times10^5$$

The tank is rigid and does not need to be modelled.

Thanks to symmetries with respect to the x- and y-axes, only ¼ of the geometry needs to be modelled.

We want to study the effects of the explosion up to 10 ms of physical time.

Because the two fluids have the same nature (but different initial conditions), they may be freely intermixed with each other during the simulation. Therefore the bubble surface does not need to be modelled as Lagrangian, even by using a single-component model for the fluid.

TANK01

Lagrangian solution: the whole mesh is Lagrangian. The mesh generation file is:

```
*%siz 100
opti echo 1;
opti dime 2 elem qua4;
p0 = 0 0;
p1 = 5 0;
p2 = 5 6;
p3 = 0 6;
p4 = 1 0;
p5 = 1 1;
p6 = 0 1;
p7 = 5 1;
p8 = 1 6;
tol = 0.01;
n1 = 2;
n2 = 8;
n3 = 10;
c1 = p0 d n1 p4;
c2 = p4 d n1 p5;
c3 = p5 d n1 p6;
c4 = p6 d n1 p0;
bull = (dall c1 c2 c3 c4 plan) coul roug;
c1 = p4 d n2 p1;
c2 = p1 d n1 p7;
c3 = p7 d n2 p5;
c4 = p5 d n1 p4;
gaz1 = (dall c1 c2 c3 c4 plan) coul turq;
c1 = p5 d n2 p7;
c2 = p7 d n3 p2;
c3 = p2 d n2 p8;
c4 = p8 d n3 p5;
gaz2 = (dall c1 c2 c3 c4 plan) coul turq;
c1 = p6 d n1 p5;
c2 = p5 d n3 p8;
c3 = p8 d n1 p3;
c4 = p3 d n3 p6;
gaz3 = (dall c1 c2 c3 c4 plan) coul turq;
gaz = (gaz1 et gaz2 et gaz3) coul turq;
flui = bull et gaz;
elim tol flui;
symx = flui poin droi p0 p3 tol;
blox = flui poin droi p1 p2 tol;
symy = flui poin droi p0 p1 tol;
bloy = flui poin droi p3 p2 tol;
e1 = bull elem cont p0;
e2 = gaz  elem cont p2;
mesh = flui et symx et blox et symy et bloy et e1 et e2;
tass mesh;
opti sauv form 'tank01.msh';
sauv form mesh;
opti trac psc;
trac qual mesh;
list (nbel flui);
list (nbno flui);
fin;
```

The input file is:

```
TANK - 01
*------------------------------------------------------------------------
 ECHO
*CONV win
CAST mesh
*-------------------------------------------------------------Problem type
DPLA NONL LAGR
*-------------------------------------------------------------Dimensioning
DIME
 PT2L 143 FL24 145
TERM
*-----------------------------------------------------------------Geometry
GEOM FL24 flui TERM
*-----------------------------------------------------------Material data
MATE FLUT RO 10  EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1 BET0 1 KINT 1
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1 LECT bull TERM
     FLUT RO 1   EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1 BET0 1 KINT 1
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1 LECT gaz  TERM
*-------------------------------------------------------Boundary conditions
LINK COUP
     BLOQ 1 LECT blox TERM
     BLOQ 2 LECT bloy TERM
     CONT SPLA NX 1 NY 0 LECT symx TERM
     CONT SPLA NX 0 NY 1 LECT symy TERM
*-----------------------------------------------------------------Outputs
ECRI COOR DEPL VITE CONT ECRO TFRE 1.E-3
     FICH ALIC TEMP FREQ 1
               POIN LECT p4 p6 TERM
               ELEM LECT e1 e2 TERM
*-------------------------------------------------------------Options
OPTI NOTE
     CSTA 0.8
     LOG 1
*-----------------------------------------------Transient calculation
CALCUL TINI 0 TEND 10.E-3
*=========================================================Direct Animation
PLAY

CAME   1 EYE   0.00000E+00  0.00000E+00  3.90512E+01
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01

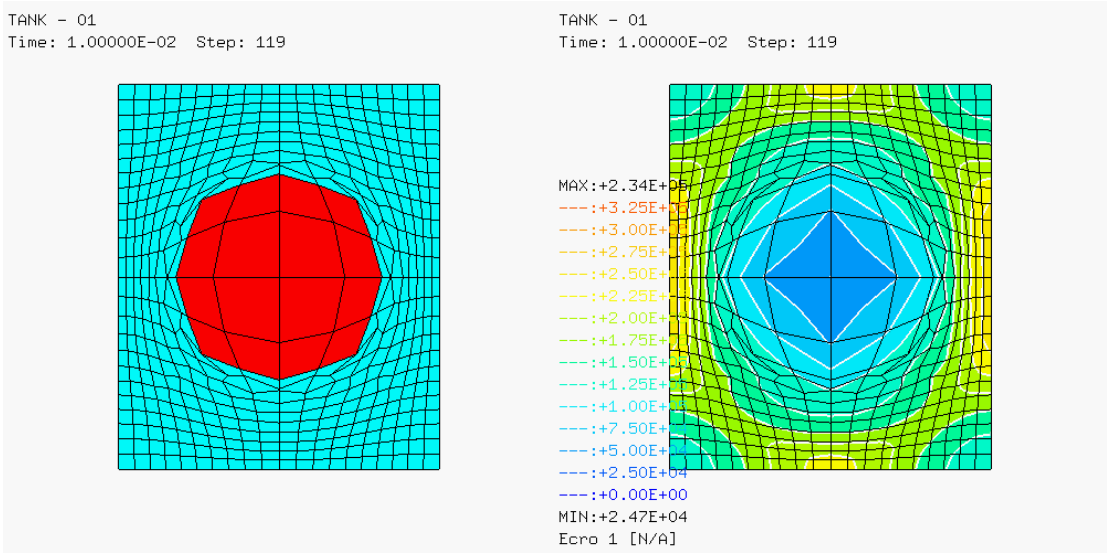
scen geom navi free
      iso  fili fiel ecro 1 scal user prog 0.e0 pas 0.25e5 3.25e5 term
      text isca
      colo pape

freq 1

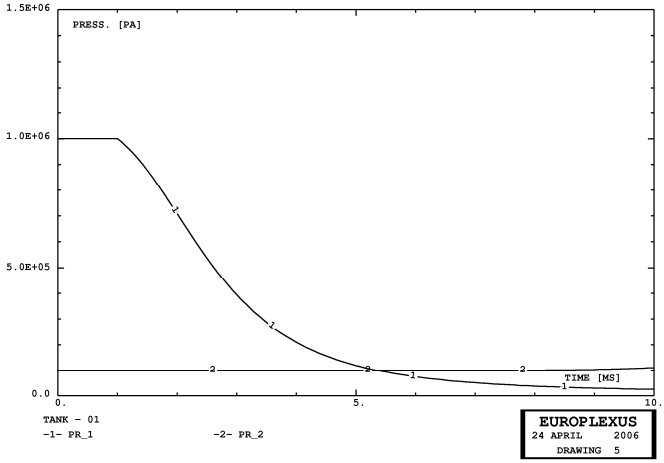
sler cam1 1        nfra 1
trac offs fich avi      nocl nfto 120 fps 10 kfre 10 comp -1
                                                    symx symy rend
gotr loop 118 offs fich avi cont nocl
                                                    symx symy rend
go
trac offs fich avi cont
                                                    symx symy rend

ENDPLAY
*=========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------Curve definitions
COUR 1 'dx_4'     DEPL COMP 1 NOEU LECT p4 TERM
COUR 2 'dy_6'     DEPL COMP 2 NOEU LECT p6 TERM
COUR 3 'pr_1'     ECRO COMP 1 ELEM LECT e1 TERM
COUR 4 'pr_2'     ECRO COMP 1 ELEM LECT e2 TERM
*-------------------------------------------------------------------Plots
trac 1 axes 1.0 'DISPL. [M]'
trac 2 axes 1.0 'DISPL. [M]'
trac 3 axes 1.0 'PRESS. [PA]'
trac 4 axes 1.0 'PRESS. [PA]'
trac 3 4 axes 1.0 'PRESS. [PA]'
*-----------------------------------------------Results qualification
QUAL DEPL COMP 1 LECT  p4 TERM REFE 2.21466E+00  TOLE 1.E-2
     DEPL COMP 2 LECT  p6 TERM REFE 2.21638E+00  TOLE 1.E-2
     CONT COMP 1 LECT  e1 TERM REFE 2.47193E+04  TOLE 1.E-2
     CONT COMP 1 LECT  e2 TERM REFE 1.10457E+05  TOLE 1.E-2
*=========================================================================
FIN
```

The numerical solution is able to proceed up to 10 ms. However, large distortions in the fluid mesh occur due to the large growth of the bubble. The final mesh and pressure distributions are:

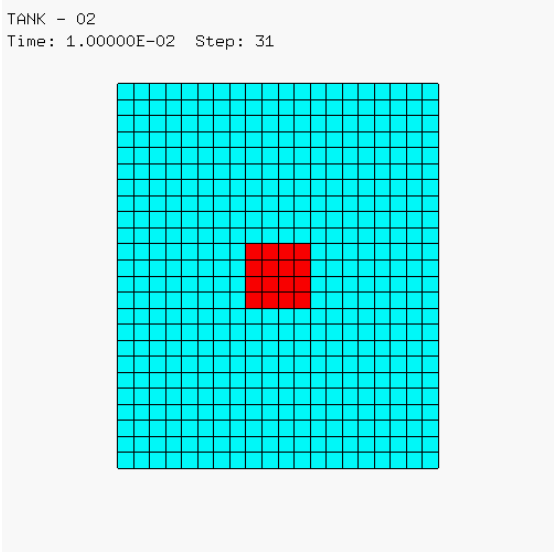


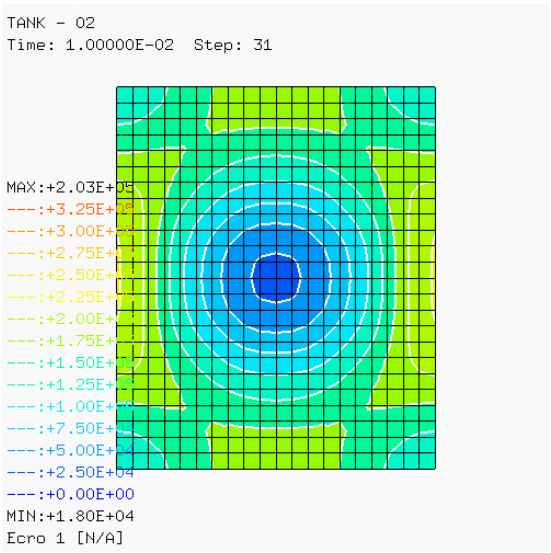
The computed fluid pressures at the bubble center and at the corners are shown hereafter:



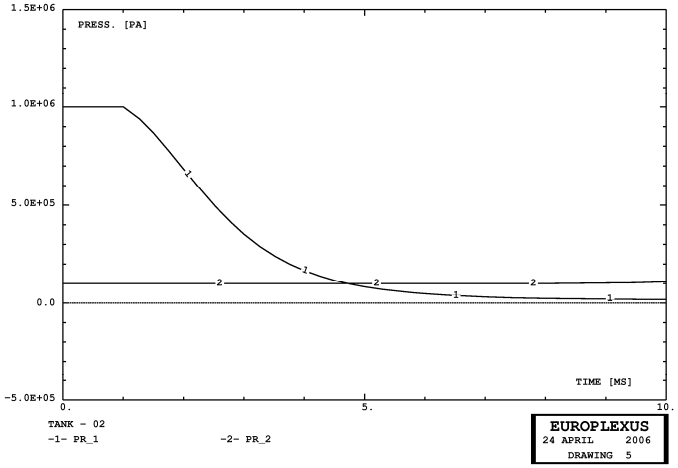
TANK02

Eulerian solution: the whole mesh is Eulerian. This solution is possible in the present example because there are no structures nor any Lagrangian fluid-sfluid interfaces. The mesh stays constant, of course, and the final pressure distribution is



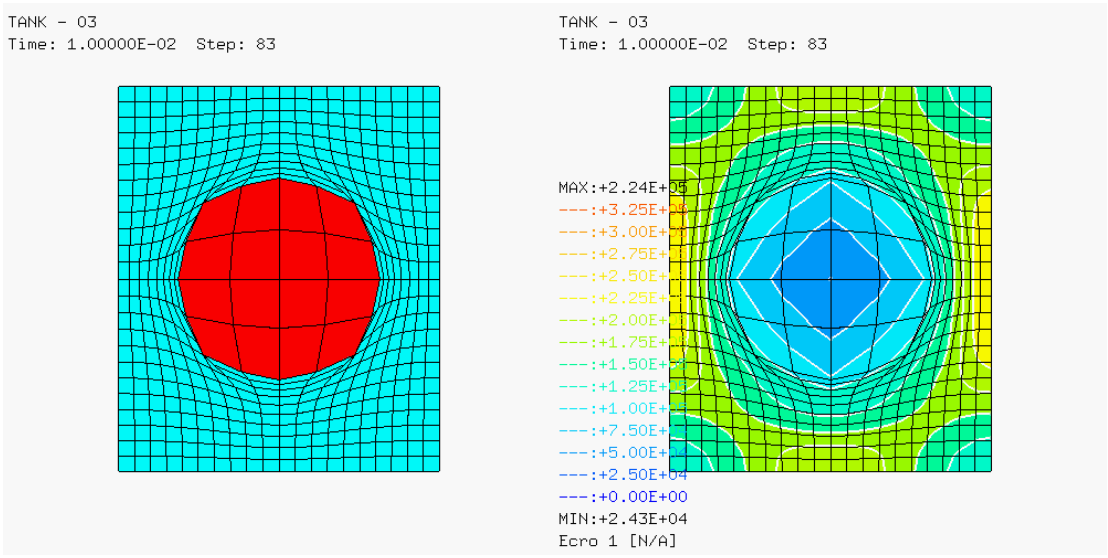


The computed pressure histories are:

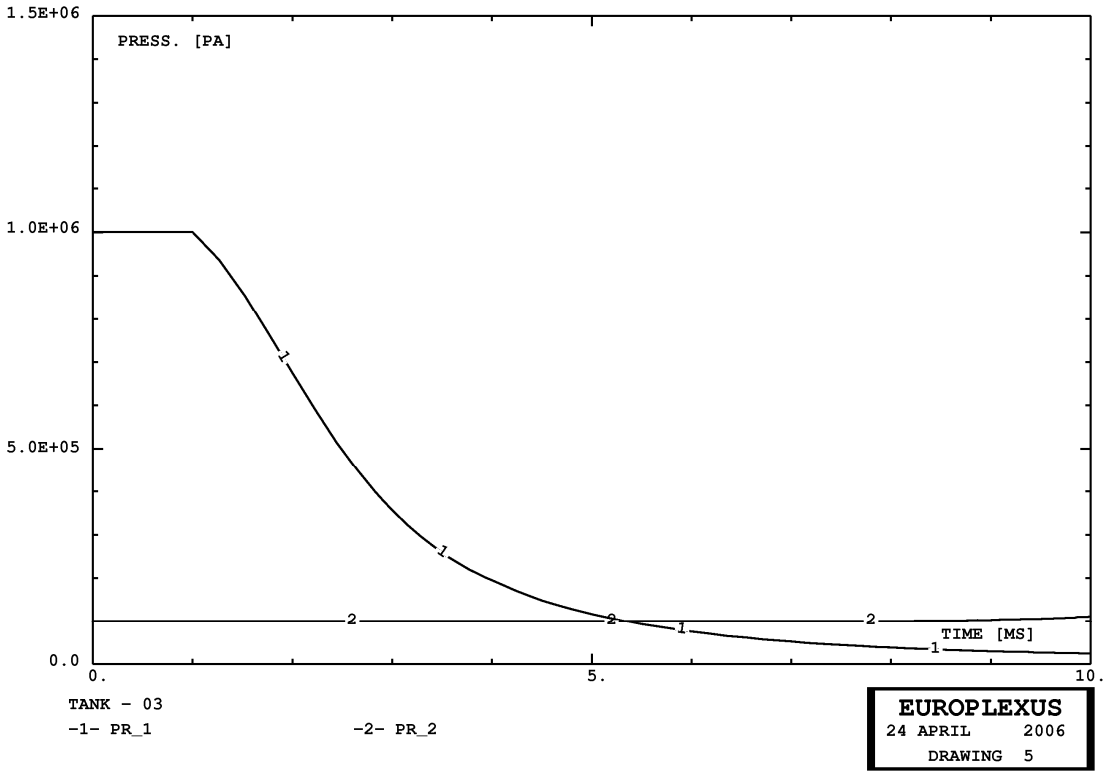


TANK03

ALE solution: the whole mesh is ALE, except the bubble surface, that is treated as Lagrangian (note that this is not strictly necessary in the present example, see the previous Eulerian solution). The final mesh is (compare with Lagrangian case) and the final pressure distribution:



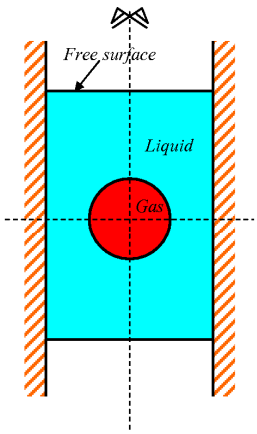
The computed pressure histories are:



Exercise 3 – Bubble expansion in a Tube

This is a also a purely fluid problem because the tank is rigid and therefore does not need to be modeled. However, unlike the previous example, there are two different fluids interacting with each other. The tube wall is vertical so the BC may be trivially imposed as a blockage in the horizontal direction.

- Try out fully Lagrangian solution
- Try out ALE solution with Lagrangian bubble surface (single-component fluid material)
- Try out fully ALE solution with ALE bubble surface (multi-phase multi-component fluid material)



41

Geometric data:

The calculation is 2-D axisymmetric. The tube is 26.4 units in diameter and the fluid zone is 40 units high. The explosive bubble is 6.29 units in diameter.

Materials

The explosive bubble is a perfect gas with $\gamma = 1.4$, initial density 100 and initial specific energy 2.5×10^5, thus resulting in an initial pressure of:

$$p_0^{\text{bubble}} = (1.4-1)\cdot 100 \cdot 2.5\times10^5 = 1.0\times10^7$$

The surrounding liquid has a density of 1000 and a bulk modulus of 2.0×10^9.

The tube is rigid and does not need to be modelled.

Thanks to symmetries with respect to the x- and y-axes, only ¼ of the geometry needs to be modelled.

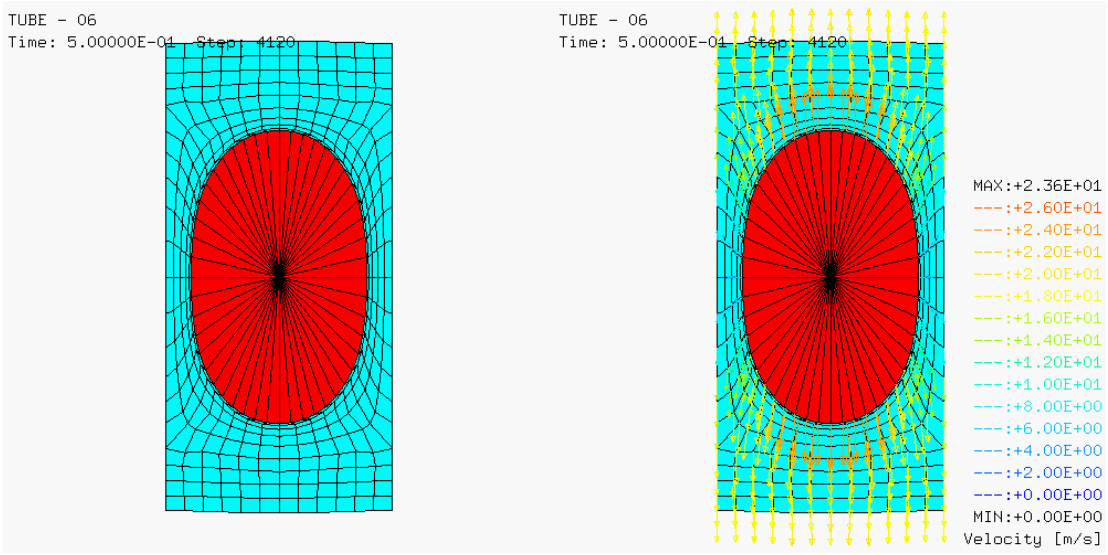
We want to study the effects of the explosion up to 500 ms of physical time.

Because the two fluids have different nature, they may be not be freely intermixed with each other during the simulation, unlike in the previous example. Therefore, if one takses a single-component model for the fluid materials, the bubble surface needs to be modelled as Lagrangian.

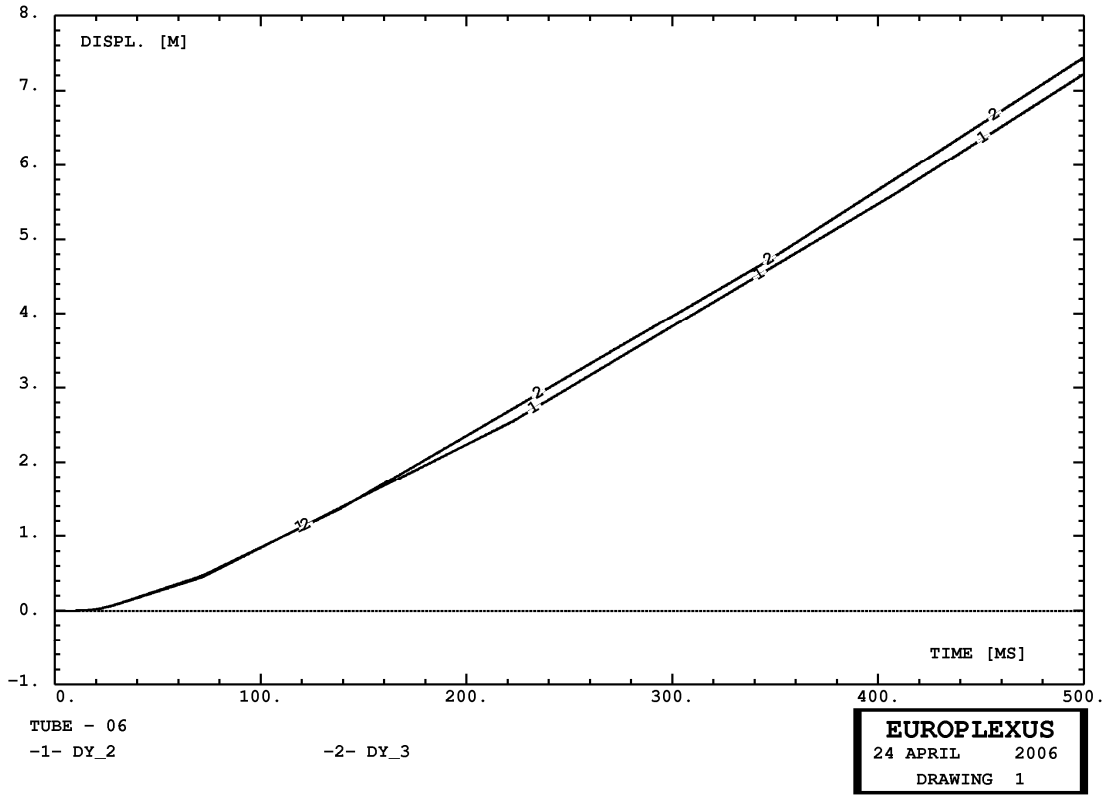
TUBE06

Lagrangian solution: the whole mesh is Lagrangian.

The numerical solution is able to proceed up to 500 ms. However, some large distortions in the fluid mesh occur due to the large growth of the bubble. The final mesh and the final velocity distribution is:

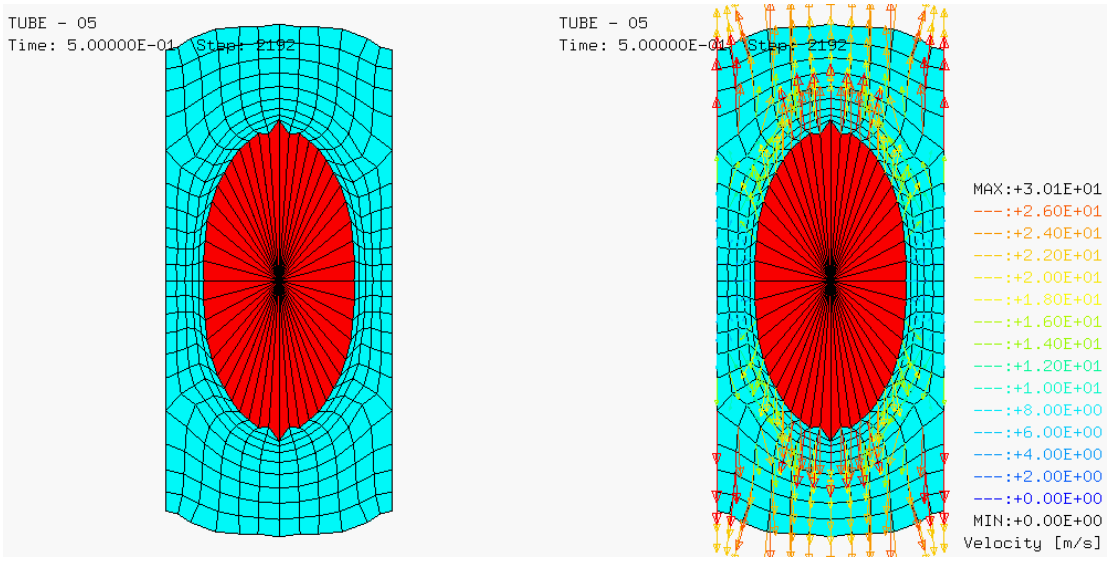


The computed vertical displacements of the upper right corner and of the upper centerpoint are shown hereafter:

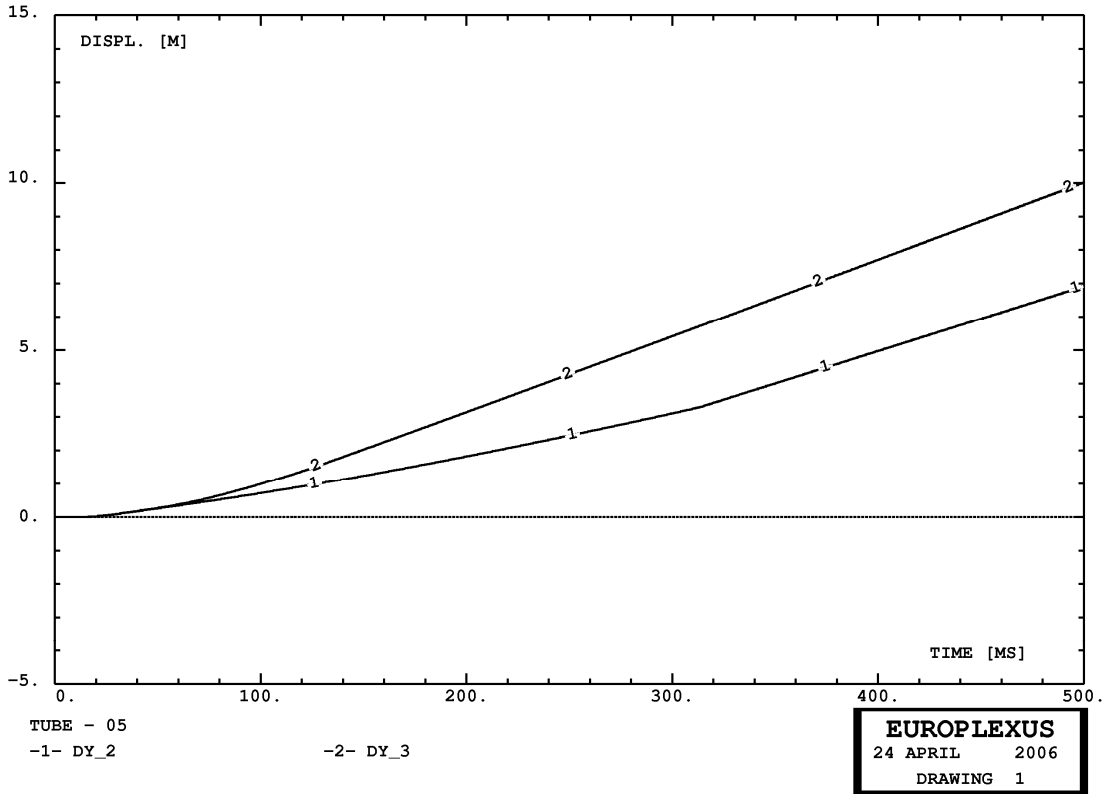


TUBE05

ALE solution with a single-component fluid material model: the whole mesh is ALE except the bubble interface that is Lagrangian. The final mesh and velocity is:

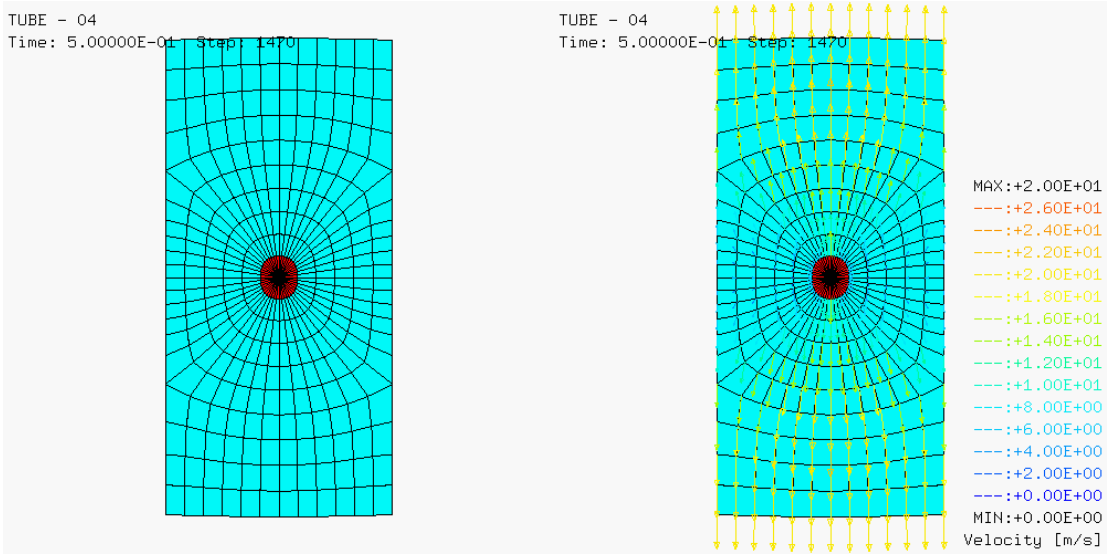


The computed displacements are:

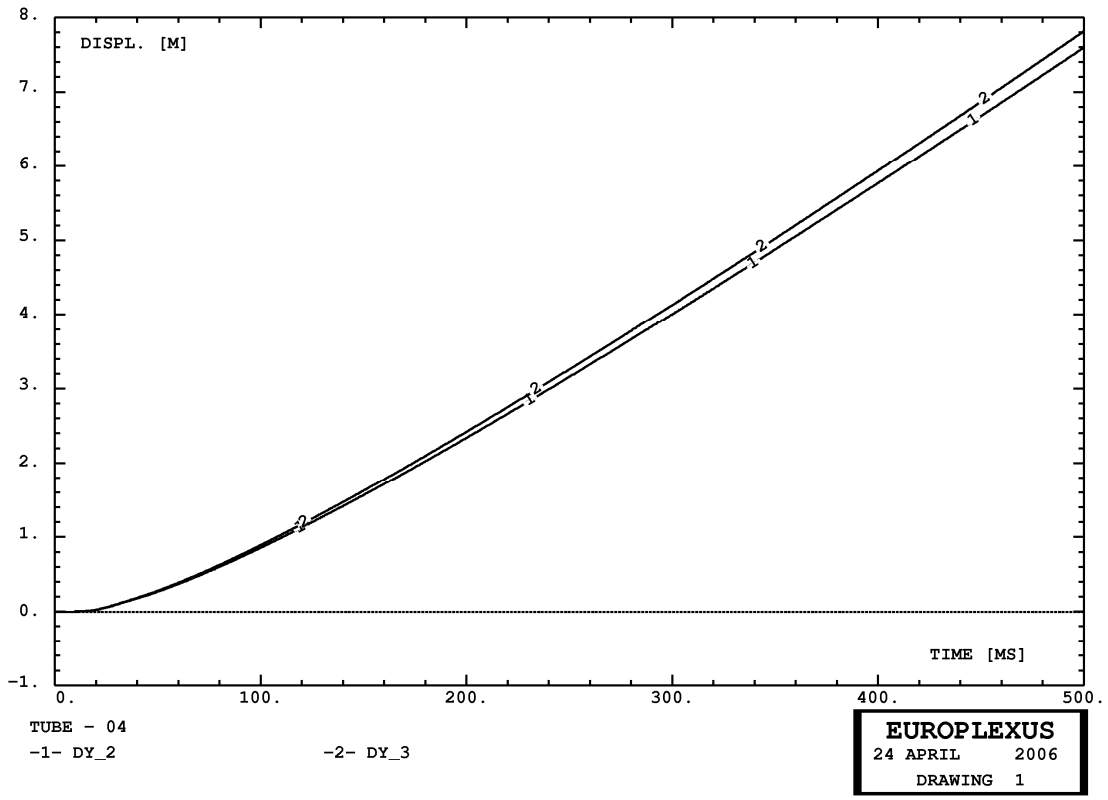


TUBE04

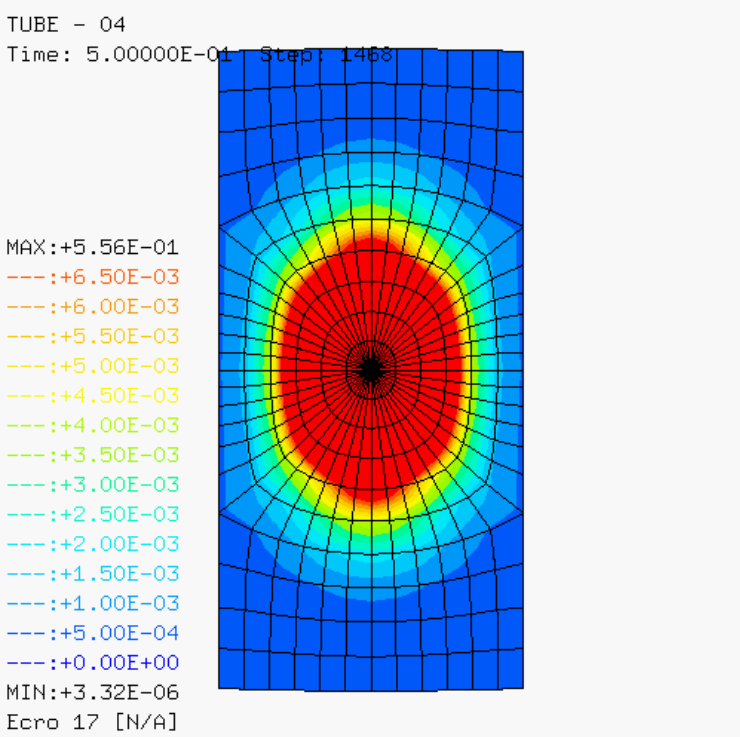
ALE solution with a multi-phase, multi-component fluid material model: the whole mesh is ALE including the bubble interface. The final mesh is (note that here colors do not represent materials!) and velocity is:



The computed displacements are:



To see the approximate position of the bubble interface, one may plot the mass fraction distribution of the bubble material component:



The input file for the test TUBE04 is:

```
TUBE - 04
*-------------------------------------------------------------------------
 ECHO
*CONV win
*-----------------------------------------------------------------Problem type
AXIS NONL ALE
*-----------------------------------------------------------------Dimensioning
DIME
 PT2L 107 FL23 12 FL24 84 ZONE 2
 NALE 1 NBLE 98
 NEPE 1020
 ECRO 3264
TERM
*-----------------------------------------------------------------------Geometry
GEOM LIBR POIN 107 FL23 12 FL24 84 TERM
 0.00000E+00 0.00000E+00 3.14500E+00 0.00000E+00 3.11810E+00
 4.10500E-01 3.03780E+00 8.13990E-01 2.90560E+00 1.20350E+00
 2.72360E+00 1.57250E+00 2.49510E+00 1.91460E+00 2.22390E+00
 2.22390E+00 1.91460E+00 2.49510E+00 1.57250E+00 2.72360E+00
 1.20350E+00 2.90560E+00 8.13990E-01 3.03780E+00 4.10500E-01
 3.11810E+00 0.00000E+00 3.14500E+00 5.15600E+00 0.00000E+00
 5.09970E+00 7.30510E-01 5.00880E+00 1.45180E+00 4.86420E+00
 2.15130E+00 4.64850E+00 2.81320E+00 4.34360E+00 3.41610E+00
 3.93350E+00 3.93350E+00 3.41610E+00 4.34360E+00 2.81320E+00
 4.64850E+00 2.15130E+00 4.86420E+00 1.45180E+00 5.00880E+00
 7.30510E-01 5.09970E+00 0.00000E+00 5.15600E+00 7.16700E+00
 0.00000E+00 7.11050E+00 1.06860E+00 7.02640E+00 2.12620E+00
 6.88680E+00 3.15600E+00 6.65900E+00 4.13330E+00 6.30030E+00
 5.02060E+00 5.76190E+00 5.76190E+00 5.02060E+00 6.30030E+00
 4.13330E+00 6.65900E+00 3.15600E+00 6.88680E+00 2.12620E+00
 7.02640E+00 1.06860E+00 7.11050E+00 0.00000E+00 7.16700E+00
 9.17800E+00 0.00000E+00 9.13620E+00 1.42630E+00 9.07480E+00
 2.84270E+00 8.96560E+00 4.23180E+00 8.76610E+00 5.56250E+00
 8.40820E+00 6.78060E+00 7.78260E+00 7.78260E+00 6.78060E+00
 8.40820E+00 5.56250E+00 8.76610E+00 4.23180E+00 8.96560E+00
 2.84270E+00 9.07480E+00 1.42630E+00 9.13620E+00 0.00000E+00
 9.17800E+00 1.11890E+01 0.00000E+00 1.11680E+01 1.80470E+00
 1.11370E+01 3.60290E+00 1.10790E+01 5.38310E+00 1.09600E+01
 7.11960E+00 1.07060E+01 8.75410E+00 1.01290E+01 1.01290E+01
 8.75410E+00 1.07060E+01 7.11960E+00 1.09600E+01 5.38310E+00
 1.10790E+01 3.60290E+00 1.11370E+01 1.80470E+00 1.11680E+01
 0.00000E+00 1.11890E+01 1.32000E+01 0.00000E+00 1.32000E+01
 2.20000E+00 1.32000E+01 4.40000E+00 1.32000E+01 6.60000E+00
 1.32000E+01 8.80000E+00 1.32000E+01 1.10000E+01 1.32000E+01
 1.32000E+01 1.10000E+01 1.32000E+01 8.80000E+00 1.32000E+01
 6.60000E+00 1.32000E+01 4.40000E+00 1.32000E+01 2.20000E+00
 1.32000E+01 6.29420E-06 1.32000E+01 1.32000E+01 1.49000E+01
 1.10000E+01 1.49000E+01 8.80000E+00 1.49000E+01 6.60000E+00
 1.49000E+01 4.40000E+00 1.49000E+01 2.20000E+00 1.49000E+01
 6.29420E-06 1.49000E+01 1.32000E+01 1.66000E+01 1.10000E+01
 1.66000E+01 8.80000E+00 1.66000E+01 6.60000E+00 1.66000E+01
 4.40000E+00 1.66000E+01 2.20000E+00 1.66000E+01 6.29420E-06
 1.66000E+01 1.32000E+01 1.83000E+01 1.10000E+01 1.83000E+01
 8.80000E+00 1.83000E+01 6.60000E+00 1.83000E+01 4.40000E+00
 1.83000E+01 2.20000E+00 1.83000E+01 6.29420E-06 1.83000E+01
 1.32000E+01 2.00000E+01 1.10000E+01 2.00000E+01 8.80000E+00
 2.00000E+01 6.60000E+00 2.00000E+01 4.40000E+00 2.00000E+01
 2.20000E+00 2.00000E+01 6.29420E-06 2.00000E+01
    2     3     1     3     4     1     4     5
    1     5     6     1     6     7     1
    7     8     1     8     9     1     9    10
    1    10    11     1    11    12     1
   12    13     1    13    14     1     2    15
   16     3     3    16    17     4     4    17    18     5
    5    18    19     6     6    19    20     7     7    20
   21     8     8    21    22     9     9    22    23    10
   10    23    24    11    11    24    25    12    12    25
   26    13    13    26    27    14    15    28    29    16
   16    29    30    17    17    30    31    18    18    31
   32    19    19    32    33    20    20    33    34    21
   21    34    35    22    22    35    36    23    23    36
   37    24    24    37    38    25    25    38    39    26
   26    39    40    27    28    41    42    29    29    42
   43    30    30    43    44    31    31    44    45    32
   32    45    46    33    33    46    47    34    34    47
   48    35    35    48    49    36    36    49    50    37
   37    50    51    38    38    51    52    39    39    52
   53    40    41    54    55    42    42    55    56    43
   43    56    57    44    44    57    58    45    45    58
   59    46    46    59    60    47    47    60    61    48
   48    61    62    49    49    62    63    50    50    63
   64    51    51    64    65    52    52    65    66    53
   54    67    68    55    55    68    69    56    56    69
   70    57    57    70    71    58    58    71    72    59
   59    72    73    60    60    73    74    61    61    74
   75    62    62    75    76    63    63    76    77    64
   64    77    78    65    65    78    79    66    73    80
   81    74    74    81    82    75    75    82    83    76
   76    83    84    77    77    84    85    78    78    85
   86    79    80    87    88    81    81    88    89    82
   82    89    90    83    83    90    91    84    84    91
   92    85    85    92    93    86    87    94    95    88
   88    95    96    89    89    96    97    90    90    97
   98    91    91    98    99    92    92    99   100    93
   94   101   102    95    95   102   103    96    96   103
  104    97    97   104   105    98    98   105   106    99
   99   106   107   100
*-----------------------------------------------------Geometric Complements
COMP GROU 2 'expl' LECT 1 PAS 1 12 TERM
           'liq'  LECT 13 PAS 1 96 TERM
     COUL roug LECT expl TERM
          turq LECT liq  TERM
*-------------------------------------------------------------Grid Motion
GRIL LAGR LECT 1          67 101 PAS 1 107 TERM
     ALE TOUS
     AUTO AUTR
*-------------------------------------------------------------Material data
MATE FLMP NLIQ 1 NGAS 1
     FLUT RO 1.E3 EINT 0 GAMM 2.E9 PB 0 ITER 1 ALF0 1 BET0 1 KINT 0
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 9 LECT 13 PAS 1 96 TERM
     FLUT RO 1.E2 EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1 BET0 1 KINT 0
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1 LECT 1 PAS 1 12 TERM
*-----------------------------------------------------Boundary conditions
LINK COUP
     BLOQ 1 LECT 1 67 68 PAS 1 73 80 PAS 7 101 14 PAS 13
                 79 PAS 7 107 TERM
     BLOQ 2 LECT 1 67 2 15 28 41 54 TERM
*-----------------------------------------------------------------Outputs
ECRI COOR DEPL VITE CONT ECRO TFRE 100.E-3
     FICH ALIC TEMP FREQ 1
          POIN LECT 101 107 TERM
          ELEM LECT 1 91 TERM
*-------------------------------------------------------------Options
OPTI NOTE
 csta 0.5
 log 1
 rezo gam0 0.5
*-----------------------------------------------Transient calculation
CALCUL TINI 0 TEND 500.E-3
*=============================================================ANIMATION
PLAY

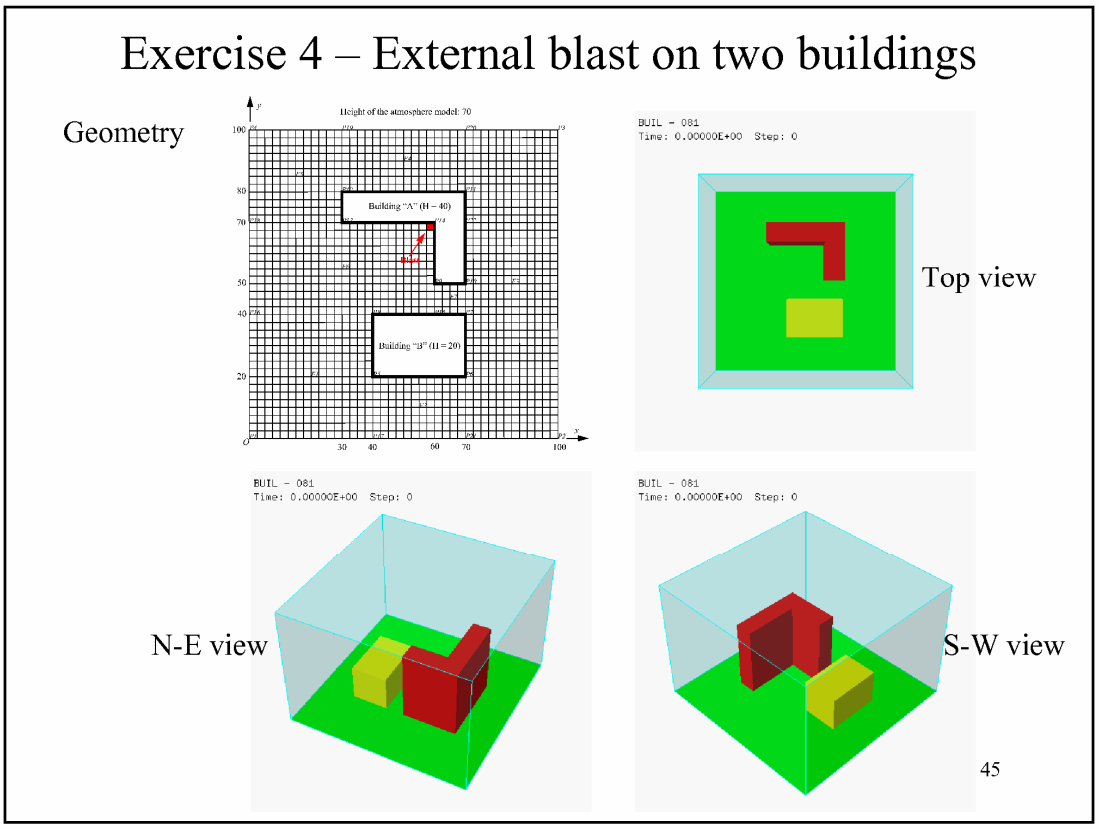
CAME   1 EYE   0.00000E+00  0.00000E+00  1.19817E+02
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   3.00000E+01

scen geom navi free
     !vect scco scal user prog 0.e0 pas 2.e0 2.6e1 term
     !text vsca
     iso  fill fiel ecro 17 scal user prog 0.e0 pas 0.0005e0 0.0065 term
     text isca
     colo pape

freq 0 tfre 2.e-3

sler cam1 1        nfra 1
trac offs fich avi      nocl nfto 251 fps 10 kfre 10 comp -1
                                                  symx symy rend
gotr loop 249  offs fich avi cont nocl
                                                  symx symy rend
go
trac offs fich avi cont
                                                  symx symy rend


ENDPLAY
*=========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------Curve definitions
COUR 1 'dy_2'     DEPL COMP 2 NOEU LECT 101 TERM
COUR 2 'dy_3'     DEPL COMP 2 NOEU LECT 107 TERM
COUR 3 'pr_1'     ECRO COMP 1 ELEM LECT 1    TERM
COUR 4 'pr_2'     ECRO COMP 1 ELEM LECT 91  TERM
*-------------------------------------------------------------------Plots
trac 1 2 axes 1.0 'DISPL. [M]' yzer
trac 3 4 axes 1.0 'PRESS. [PA]'
*-----------------------------------------------Results qualification
QUAL DEPL COMP 2 LECT 101 TERM REFE 7.59570E+00  TOLE 1.E-2
     DEPL COMP 2 LECT 107 TERM REFE 7.81536E+00  TOLE 1.E-2
     ECRO COMP 1 LECT   1 TERM REFE 1.81508E+04  TOLE 1.E-2
     ECRO COMP 1 LECT  91 TERM REFE 8.03899E+03  TOLE 1.E-2
*=====================================================================
FIN
```



Geometric data:
External blast in an urban area with two buildings. The model size is 100 x 100 m and the atmosphere is modelled up to a height of 70 m. The two buildings are 40 and 20 m high, respectively. A regular mesh of 40 x 40 x 28 elements is used.

Boundary conditions:
Buildings are treated as rigid in this analysis. Non-reflecting conditions (absorbing boundaries) are prescribed on the external surface of the atmosphere model to prevent non-realistic pressure wave reflections. FSR (fluid-structure rigid) conditions (see Part 3) are adopted at the interface between the atmosphere and the buildings or the ground.

Materials
The explosive bubble is a perfect gas with $\gamma = 1.4$, initial density 1000 and initial pressure 100000 bar. The surrounding atmosphere is also a perfect gas, with a density of 1 and a pressure of 1 bar.
We want to study the effects of the explosion up to 100 ms of physical time.

BUIL08

Eulerian solution: the whole mesh is Eulerian. The mesh generation file is:

```
opti echo 1;
opti trac psc;
opti dime 3 elem cub8;
p1 = 0 0 0;
p2 = 100 0 0;
p3 = 100 100 0;
p4 = 0 100 0;
p5 = 40 20 0;
```

```
p6 = 70 20 0;
p7 = 70 40 0;
p8 = 40 40 0;
p9 = 60 50 0;
p10 = 70 50 0;
p11 = 70 80 0;
p12 = 30 80 0;
p13 = 30 70 0;
p14 = 60 70 0;
p15 = 60 40 0;
p16 = 0 40 0;
p17 = 40 0 0;
p18 = 0 70 0;
p19 = 30 100 0;
p20 = 70 100 0;
p21 = 70 0 0;
p22 = 70 70 0;
tol = 0.01;
f1 = dall (p1 d 16 p17) (p17 d 8 p5 d 8 p8) (p8 d 16 p16)
          (p16 d 16 p1) plan;
f2 = dall (p17 d 12 p21) (p21 d 8 p6) (p6 d 12 p5)
          (p5 d 8 p17) plan;
f3 = dall (p21 d 12 p2) (p2 d 40 p3) (p3 d 12 p20)
          (p20 d 8 p11 d 4 p22 d 8 p10 d 4 p7 d 8 p6 d 8 p21) plan;
f4 = dall (p12 d 16 p11) (p11 d 8 p20) (p20 d 16 p19)
          (p19 d 8 p12) plan;
f5 = dall (p18 d 12 p13) (p13 d 4 p12 d 8 p19) (p19 d 12 p4)
          (p4 d 12 p18) plan;
f6 = dall (p16 d 16 p8 d 8 p15) (p15 d 4 p9 d 8 p14)
          (p14 d 12 p13 d 12 p18) (p18 d 12 p16) plan;
f7 = dall (p15 d 4 p7) (p7 d 4 p10) (p10 d 4 p9) (p9 d 4 p15) plan;
trac qual (f1 et f2 et f3 et f4 et f5 et f6 et f7);
z1 = 0 0 70;
v1 = f1 volu tran 28 z1;
v2 = f2 volu tran 28 z1;
v3 = f3 volu tran 28 z1;
v4 = f4 volu tran 28 z1;
v5 = f5 volu tran 28 z1;
v6 = f6 volu tran 28 z1;
v7 = f7 volu tran 28 z1;
z8 = 0 0 20;
p5u = p5 plus z8;
p6u = p6 plus z8;
p7u = p7 plus z8;
p8u = p8 plus z8;
f8 = dall (p5u d 12 p6u) (p6u d 8 p7u) (p7u d 12 p8u)
          (p8u d 8 p5u) plan;
v8 = f8 volu tran 20 (0 0 50);
z910 = 0 0 40;
p9u = p9 plus z910;
p10u = p10 plus z910;
p11u = p11 plus z910;
p12u = p12 plus z910;
p13u = p13 plus z910;
p14u = p14 plus z910;
p22u = p22 plus z910;
f9 = dall (p9u d 4 p10u) (p10u d 8 p22u) (p22u d 4 p14u)
          (p14u d 8 p9u) plan;
f10= dall (p13u d 16 p22u) (p22u d 4 p11u) (p11u d 16 p12u)
          (p12u d 4 p13u) plan;
trac qual (f1 et f2 et f3 et f4 et f5 et f6 et f7 et f8 et
           f9 et f10);
v9 = f9 volu tran 12 (0 0 30);
v10 = f10 volu tran 12 (0 0 30);
fluid = v1 et v2 et v3 et v4 et v5 et v6 et v7 et v8 et v9 et v10;
elim tol (fluid et p5u et p6u et p7u et p8u et p9u et p10u
          et p11u et p12u et p13u et p14u et p22u);
p1u = p1 plus z1;
p2u = p2 plus z1;
p3u = p3 plus z1;
p4u = p4 plus z1;
abs1 = dall (p1 d 28 p1u) (p1u d 40 p4u) (p4u d 28 p4)
            (p4 d 40 p1) plan;
abs2 = dall (p2 d 28 p2u) (p2u d 40 p1u) (p1u d 28 p1)
            (p1 d 40 p2) plan;
abs3 = dall (p3 d 28 p3u) (p3u d 40 p2u) (p2u d 28 p2)
            (p2 d 40 p3) plan;
```

```
abs4 = dall (p4 d 28 p4u) (p4u d 40 p3u) (p3u d 28 p3)
            (p3 d 40 p4) plan;
abs5 = dall (p1u d 40 p2u) (p2u d 40 p3u) (p3u d 40 p4u)
            (p4u d 40 p1u) plan;
absor = abs1 et abs2 et abs3 et abs4 et abs5;
elim tol (fluid et absor);

pexp = p14 plus (-2.5 -2.5 2.5);
*explo = fluid elem appu larg pexp;
explo = fluid elem appu larg p14;
list (nbel explo);
air = diff fluid explo;
list (nbel air);

fsrn = enve fluid;
list (nbno fsrn);
fsrn = diff fsrn absor;
list (nbno fsrn);
bloz = p1 d 40 p2 d 40 p3 d 40 p4 d 40 p1;
elim tol (bloz et fluid);
list (nbno bloz);
fsrn = chan poi1 fsrn;
bloz = chan poi1 bloz;
fsrn = diff fsrn bloz;
list (nbno fsrn);

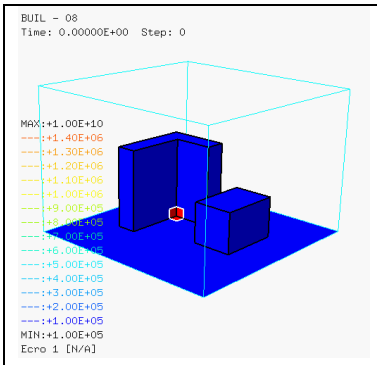
**explo = (fluid elem appu larg pexp) coul roug;
* explo = fluid elem appu larg pexp;
**air = (diff fluid explo) coul turq;
* air = diff fluid explo;
**fluid = (explo et air) coul jaun;
**fluid = explo et air;
mesh = fluid et absor et fsrn et bloz;
tass mesh;
opti sauv form 'buil08.msh';
sauv form mesh;
list (nbel fluid);
list (nbno fluid);
*list (nbel explo);
*list (nbel air);
list (nbel absor);
list (nbel mesh);
list (nbno mesh);
**trac cach face fluid;
**trac cach face (floor et explo);
**trac cach face absor;
 trac cach fluid;
* trac cach (floor et explo);
 trac cach absor;
```

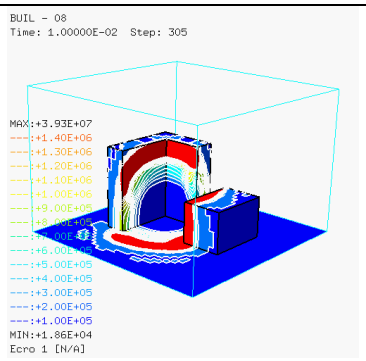
The input file is:

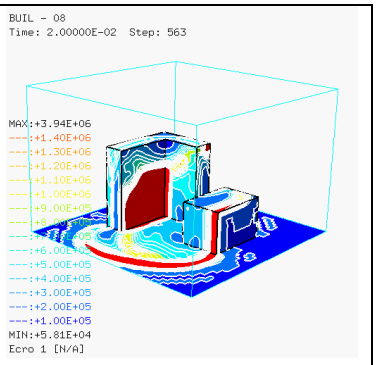
```
BUIL - 08
$
 ECHO
$VERI
!CONV win
CAST MESH
TRID NONL EULE
$
DIME
 PT3L 47029
 CUBE 42496 CL3D 6080 ZONE 2
 BLOQ 10000
TERM
$
GEOM
  CUBE fluid
  CL3D absor
TERM
*
COMP COUL roug LECT explo TERM
          turq LECT air   TERM
          rose LECT absor TERM
*
MATE
```

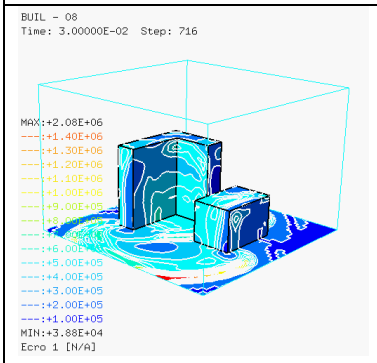
```
$ high-pressure perfect gas (explosive bubble)
     GAZP RO 1000 GAMM 1.4 PINI 100000.E5
          PREF 1.E5 LECT explo TERM
$ air
     GAZP RO 1 GAMM 1.4 PINI 1.E5
          PREF 1.E5 LECT air TERM
$ absorbing
     IMPE ABSO RO 0 C 0
          LECT absor TERM
$
LIAI FREQ 1
     BLOQ 3 LECT bloz TERM
     FSR LECT fsrn TERM
$
ECRI VITE ECRO TFRE 100.E-3
     FICH ALIC TFRE 1.E-3
$
OPTI NOTEST
 csta 0.5e0
 log 1
CALCUL TINI 0 TEND 0.1E0
*=================================================================
FIN
```

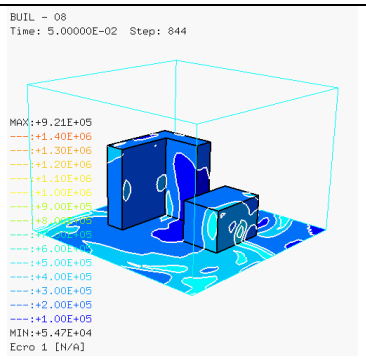
The fluid pressures on the building and on the ground at some selected instants are shown below:

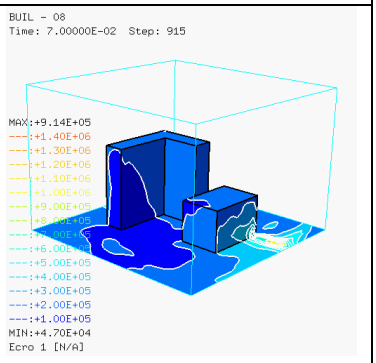
<table>
<tr><td> 

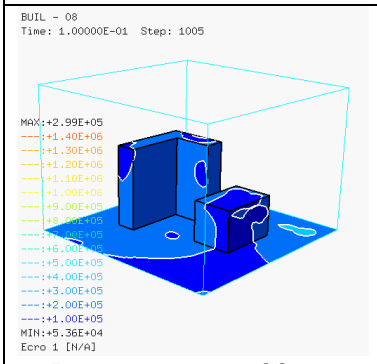
Pressure at t = 0</td><td> 

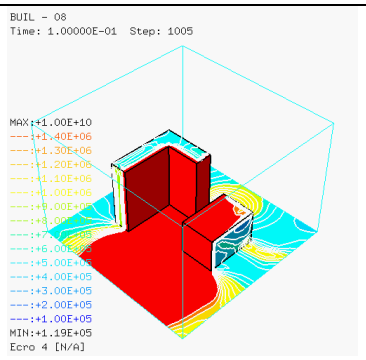
Pressure at t = 10 ms</td><td> 

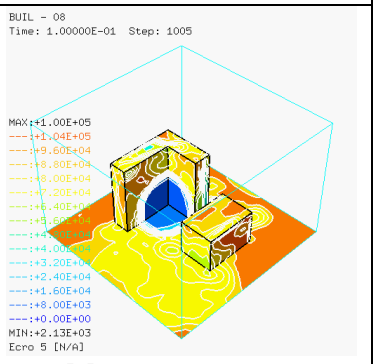
Pressure at t = 20 ms</td></tr>
<tr><td> 

Pressure at t = 30 ms</td><td> 

Pressure at t = 50 ms</td><td> 

Pressure at t = 70 ms</td></tr>
<tr><td> 

Pressure at t = 100 ms</td><td> 

Max pressure map</td><td> 

Min pressure map</td></tr>
</table>

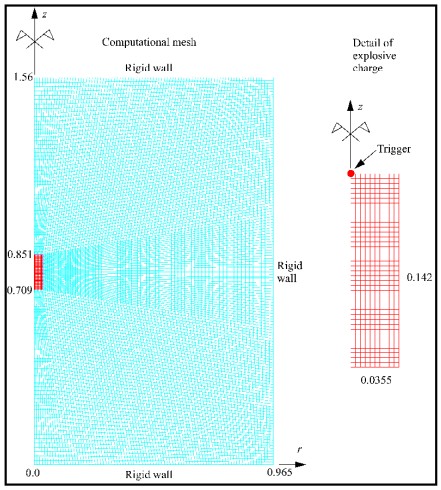
Exercise 5 – Confined detonation of solid TNT charge

Jones-Wilkins-Lee

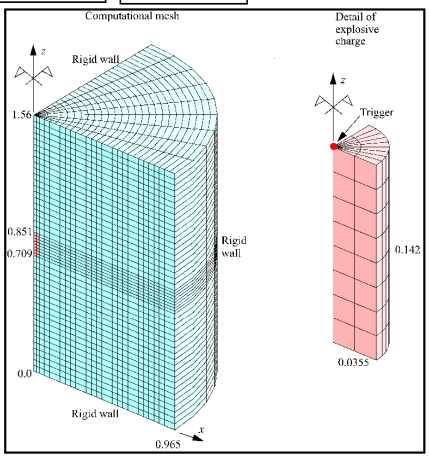
$$p(\rho,i) = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \omega\rho i$$

$$V = \rho_0 / \rho \qquad \omega = \gamma - 1$$

Geometry:



2D axisymmetric model



3D axisymmetric model

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Geometric data:

Internal blast in a rigid tank. The geometry is axisymmetric. The explosive charge is a cylinder of solid TNT.

Boundary conditions:

Tank walls are treated as rigid. FSR (fluid-structure rigid) conditions (see Part 3) are adopted along the outer surface of the fluid domain.

Materials

The explosive charge is modelled by the JWL (Jones-Wilkins-Lee) law. Detonation is initiated at the upper central point of the charge and is assumed to proceed at a speed of 6930 m/s. The rest of the tank is filled by air at atmospheric pressure.

We want to study the effects of the explosion up to 1.8 ms of physical time.

2D axisymmetric simulation:

JWLS2G

The mesh generation file is:

```
*$siz 50
*
TITRE 'Explosion de TNT dans un caisson' ;
*
option echo 0 ;
*
OPTION DIME 2 ELEM QUA4 ;
*
OPTION SORTIE 'jwls2g.msh';
option trac PSC FTRA 'jwls2g_mail.ps' ;
*
r_cais =  965.00e-3 ;
h_cais = 1560.00e-3 ;
r_tnt  =   35.50e-3 ;
h_tnt  =  142.00e-3 ;
*
nh1 = 10 ;
nv1 = 50 ;
nv3 = nv1 ;
*
* pour avoir des éléments carrés dans le tnt :
nv2 = ENTIER (nh1 * (h_tnt/r_tnt)) ;
nh = nv1+nv2+nv1 ;
* idem pour l'air (mailles carrées dans l'angle) :
nh2 = ENTIER (nh * r_cais / h_cais) ;
nh2 = nh2 - nh1 ;
*
h_bas = 0.5*(h_cais - h_tnt) ;
h_hau = h_bas + h_tnt ;
r_mil = r_cais * nh1 /(nh1+nh2) ;
h_mil = h_cais * nv1 / nh ;
*
OPTION DENS (r_tnt / nh1) ;
p4 =   0.  h_bas ;
p5 = r_tnt h_bas ;
p7 =   0.  h_hau ;
p8 = r_tnt h_hau ;
*
OPTION DENS (h_cais / nh) ;
p1 =   0.     0. ;
p2 = r_mil    0. ;
p3 = r_cais   0. ;
p6 = r_cais h_mil  ;
p9 = r_cais (h_cais - h_mil) ;
p10=   0.   h_cais ;
p11= r_mil  h_cais ;
p12= r_cais h_cais ;
*
l_45 = p4 DROIT nh1 p5 ;
l_58 = p5 DROIT nv2 p8 ;
l_87 = p8 DROIT nh1 p7 ;
l_74 = p7 DROIT nv2 p4 ;
*
l_12 = p1 DROIT nh1 p2 ;
l_23 = p2 DROIT nh2 p3 ;
l_36 = p3 DROIT nv1 p6 ;
l_69 = p6 DROIT nv2 p9 ;
l_912= p9 DROIT nv3 p12;
l_1211= p12 DROIT nh2 p11 ;
l_1110= p11 DROIT nh1 p10 ;
*
nv1 = 0 - nv1 ;
nh2 = 0 - nh2 ;
nv3 = 0 - nv3 ;
*
l_41 = p4 DROIT nv1 p1 ;
l_52 = p5 DROIT nv1 p2 ;
l_56 = p5 DROIT nh2 p6 ;
l_89 = p8 DROIT nh2 p9 ;
l_811= p8 DROIT nv3 p11;
```

```
l_710= p7 DROIT nv3 p10;
*
l_axe = l_41 ET L_74 ET L_710 ;
l_bas = l_12 ET l_23 ;
l_hau = l_1211 ET l_1110 ;
l_bor = l_36 ET l_69 ET l_912 ;
l_cont = l_axe ET l_bas ET l_bor ET l_hau ;
*
tnt = l_45 l_58 l_87 l_74 DALLER PLAN ;
tnt = tnt COUL ROUGE ;
*
air1 = l_12 l_52 l_45 l_41 DALLER PLAN ;
air2 = l_23 l_36 l_56 l_52 DALLER PLAN ;
air3 = l_56 l_69 l_89 l_58 DALLER PLAN ;
air4 = l_89 l_912 l_1211 l_811 DALLER PLAN ;
air5 = l_87 l_811 l_1110 l_710 DALLER PLAN ;
*
air = air1 ET air2 ET air3 ET air4 ET air5 ;
air = air COUL TURQUOISE ;
*
*-- capteurs :
e_p1  = air ELEM CONTENANT p1 ;
e_p3  = air ELEM CONTENANT p3 ;
e_p4  = air ELEM CONTENANT p4 ;
e_p7  = air ELEM CONTENANT p7 ;
e_p10 = air ELEM CONTENANT p10 ;
e_p12 = air ELEM CONTENANT p12 ;
e_bas  = air ELEM CONTENANT (BARY (p1 ET p3)) ;
e_face = air ELEM CONTENANT (BARY (p3 ET p12)) ;
e_haut = air ELEM CONTENANT (BARY (p10 ET p12)) ;
```

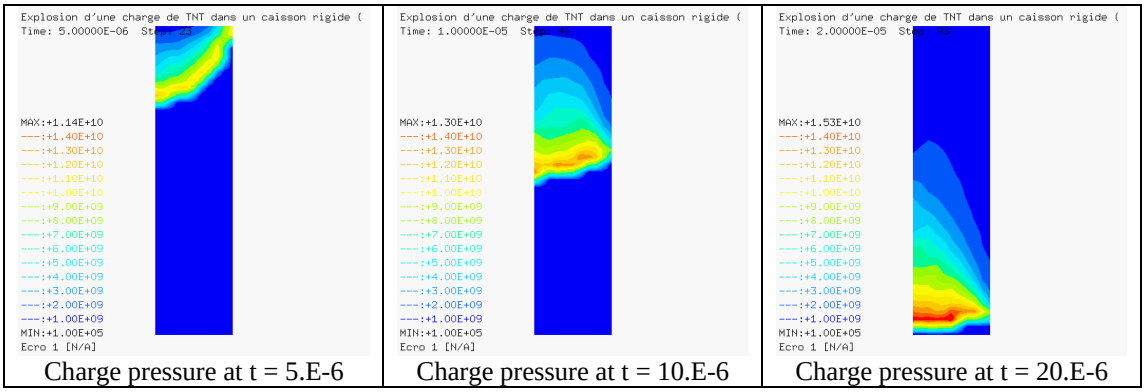
```
e_mil  = air ELEM CONTENANT (BARY (air ET tnt)) ;
e_sup  = air ELEM CONTENANT (BARY (p7 ET p10)) ;
e_inf  = air ELEM CONTENANT (BARY (p1 ET p4)) ;
e_capt = e_p1 ET e_p3 ET e_p4 ET e_p7 ET e_p10 ET e_p12 ET
         e_bas ET e_face ET e_haut ET e_mil ET e_sup ET e_inf ;
*
tout = air ET tnt ;
sort tout ;
*
trac tnt ;
trac tout ;
trac QUALIF tout ;
trac qualif e_capt ;
trac qualif l_cont ;
opti trac mif ftra 'jwls2g_mail.mif';
trac tnt ;
trac tout ;
trac QUALIF tout ;
trac qualif e_capt ;
trac qualif l_cont ;
*
mess 'NB_POIN        =' (NBNO tout) ;
mess 'NB_CAR1 (tnt)  =' (NBEL tnt) ;
mess 'NB_CAR1 (total)=' (NBEL tout) ;
*
**option donn 5 ;
*
option echo 1 ;
*
fin ;
```

The input file is:

```
Explosion d'une charge de TNT dans un caisson rigide ( JWLS )
*
ECHO
*
GIBI TOUT
*
AXIS NONL ALE
*
DIMENSION
    PTZL 12300  zone    2
    FL24 12100
    LIAIS 910  FSA   230
    NALE    1  NBLE 12300    ndvc 45620
    MTTI 30
TERM
*
GEOMETRIE
   FL24 tnt
   FL24 air
TERM
*
GRILLE
     EULER LECT tnt TERM
     ALE   TOUS
     MEAN  AUTRES
*
MATERIAU
**   l'air :  on calcule eint pour avoir P=1 bar (P=omeg*ro*eint)
*
    flut ro 1.3 eint 0.21978e6 gamm 1.35 PB 0
         ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
         CQ 2.56 PMIN 0 PREF 0 NUM 11
         a 3.738e11 b 3.747e9 r1 4.15 r2 0.90
         ros 1630
         LECT air  TERM
*
**  Le TNT :   on donne directement ro = ros
*              avec ignition au point P7
*              la vitesse de detonation est celle de Chapman-Jouguet
*
    flut ro 1630 eint 3.68e6 gamm 1.35 PB 0
         ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
         CQ 2.56 PMIN 0 PREF 0 NUM 11
         a 3.738e11 b 3.747e9 r1 4.15 r2 0.90
         d 6930 TDET 0.0 pini 1e5 xdet 0. ydet 851.0e-3
         LECT tnt TERM
*
LIAISON
   FSR      LECT  l_cont  TERM
*
ECRITURE
*--   listing :
      VITE ECROU           TFREQ 200e-6
           point lect e_capt p8 term
           elem  lect e_capt term
*
*--   dessins :
      FICHIER ALICE
        TIME PROG 5E-6 PAS   5E-6   25E-6
                       PAS  25E-6  200E-6
                       PAS 100E-6  1.2E-3
                       PAS 200E-6  2.0E-3   TERM
*
*--   courbes :
      FICHIER ALICE temps
              tfreq 2e-6
              point lect e_capt p8 term
              elem  lect e_capt term
*
OPTION NOTEST NOPRINT
       REZO  mvre   modu  GAM0 0.5
       DTDROP  0.002
       AMORT  QUAD 2.
       LOG 1
*
  CALCUL tini 0   pas1 1e-8  nmax 500000   tfin  1.80e-3
```

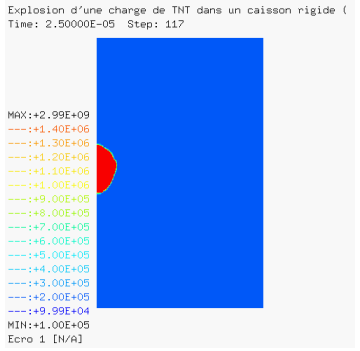
```
*
SUITE
Explosion d'une charge de TNT dans un caisson rigide ( JWLS )
*
ECHO
*
RESUL alic temp gardertitre
*
SORTIES GRAPHIQUES
*
AXTEMPS 1E6 'TEMPS (MicroS)'
*
*  Bilan :
courbe 10 'BILAN '      Bilan
   TRAC   10                axes 1 'Bilan'
*
*  Global :
courbe 41 'En. int. '   WINT
courbe 42 'En. cin. '   WCIN
courbe 43 'En. ext. '   WEXT
   TRAC   41 42 43          axes 1.e-3 'Global (KJ)'
*
*  Pressions (la mesure porte sur les courbes 4 et 5) :
COURBE  1 'P e_p7  '    ECROU COMP  1   lect e_p7    term
COURBE  2 'P e_p4  '    ECROU COMP  1   lect e_p4    term
COURBE  3 'P e_mil '    ECROU COMP  1   lect e_mil   term
COURBE  4 'P e_p1  '    ECROU COMP  1   lect e_p1    term
COURBE  5 'P e_p10 '    ECROU COMP  1   lect e_p10   term
COURBE  6 'P e_face'    ECROU COMP  1   lect e_face  term
COURBE  7 'P e_p3'      ECROU COMP  1   lect e_p3    term
COURBE  8 'P e_p12'     ECROU COMP  1   lect e_p12   term
 TRAC    1 2 3                  AXES 1E-5 'P (Bars)'   ! pres du tnt
 TRAC    4 5 6                  AXES 1E-5 'P (Bars)'   ! milieu caisson
 TRAC    7 8                    AXES 1E-5 'P (Bars)'   ! coins
*
*  Densite :
COURBE 21 'P e_p7  '    ECROU COMP  2   lect e_p7    term
COURBE 22 'P e_p4  '    ECROU COMP  2   lect e_p4    term
COURBE 23 'P e_mil '    ECROU COMP  2   lect e_mil   term
COURBE 24 'P e_p1  '    ECROU COMP  2   lect e_p1    term
COURBE 25 'P e_p10 '    ECROU COMP  2   lect e_p10   term
COURBE 26 'P e_face'    ECROU COMP  2   lect e_face  term
COURBE 27 'P e_p3'      ECROU COMP  2   lect e_p3    term
COURBE 28 'P e_p12'     ECROU COMP  2   lect e_p12   term
 TRAC   21 22 23                AXES 1.   'Rho (Kg/m3)'
 TRAC   24 25 26                AXES 1.   'Rho (Kg/m3)'
 TRAC   27 28                   AXES 1.   'Rho (Kg/m3)'
*
*  Vitesses ;
COURBE 31 'VY p7   '    VITES COMP  2   lect p7      term
COURBE 32 'VY p4   '    VITES COMP  2   lect p4      term
COURBE 33 'VX p8   '    VITES COMP  1   lect p8      term
COURBE 34 'VY p8   '    VITES COMP  2   lect p8      term
 TRAC   31 32           AXES 1.   'm/s'     ! faces du tnt
 TRAC   33 34           AXES 1.   'm/s'     ! coin haut tnt
*
*
VALIDATION
*
*  Avec le materiau JWL on ne connait pas de solution analytique
*  Dans l'experience on mesure les pressions en P1 et P10
*
* Pression :
    ECRO COMP 1  REFE 0.633e5  TOLE 0.20  LECT e_p1   term
    ECRO COMP 1  REFE 3.092e5  TOLE 0.05  LECT e_p3   term
    ECRO COMP 1  REFE 0.949e5  TOLE 0.05  LECT e_face term
    ECRO COMP 1  REFE 0.720e5  TOLE 0.20  LECT e_p10  term
    ECRO COMP 1  REFE 3.300e5  TOLE 0.05  LECT e_p12  term
* Masse volumique :
    ECRO COMP 2  REFE  0.628   TOLE 0.20  LECT e_p1   term
    ECRO COMP 2  REFE  2.135   TOLE 0.05  LECT e_p3   term
    ECRO COMP 2  REFE  0.788   TOLE 0.05  LECT e_face term
    ECRO COMP 2  REFE  0.732   TOLE 0.20  LECT e_p10  term
    ECRO COMP 2  REFE  2.158   TOLE 0.05  LECT e_p12  term
*
FIN
```

The charge pressures at some selected instants are shown below:

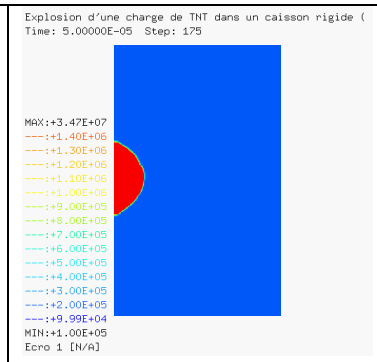


Charge pressure at t = 5.E-6	Charge pressure at t = 10.E-6	Charge pressure at t = 20.E-6

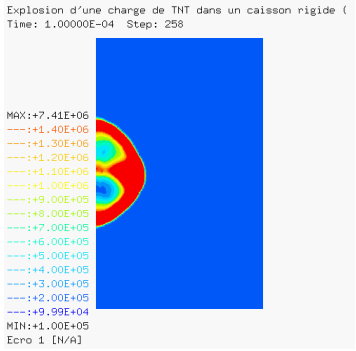
The fluid pressures and velocities at some selected instants are shown below:



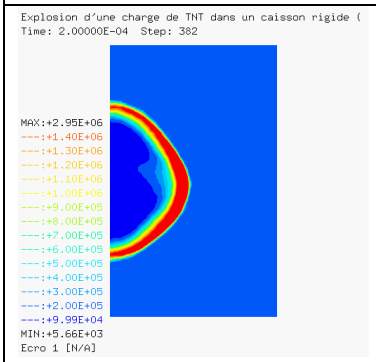
Pressure at t = 25.E-6



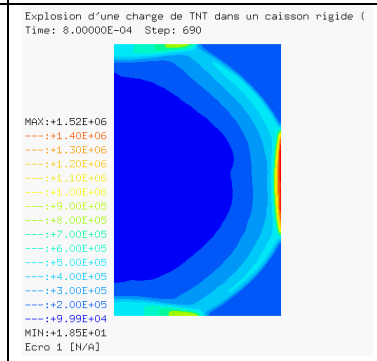
Pressure at t = 50.E-6



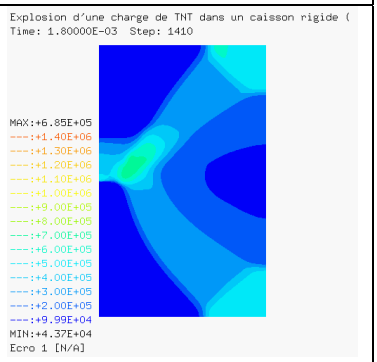
Pressure at t = 100.E-6



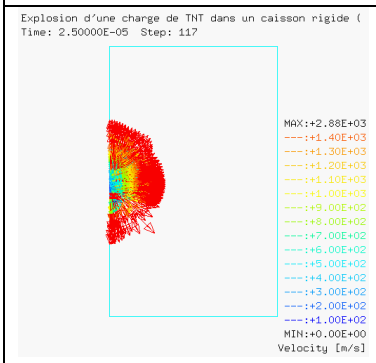
Pressure at t = 200.E-6



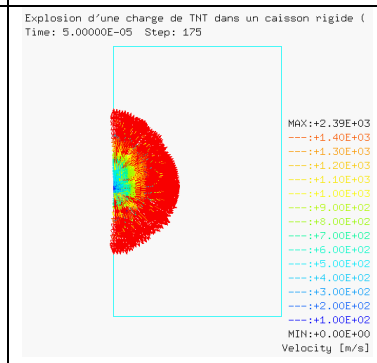
Pressure at t = 800.E-6



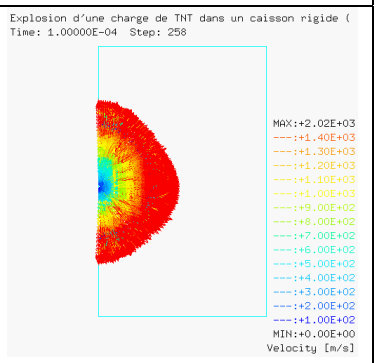
Pressure at t = 1800.E-6



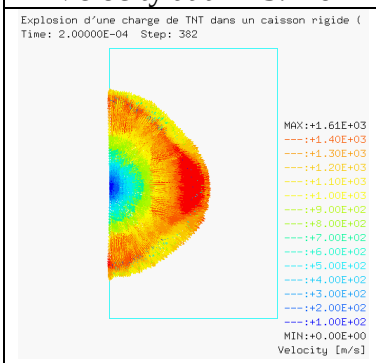
Velocity at t = 25.E-6



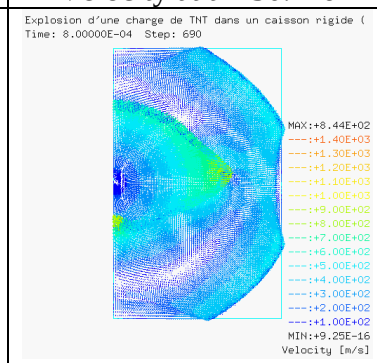
Velocity at t = 50.E-6



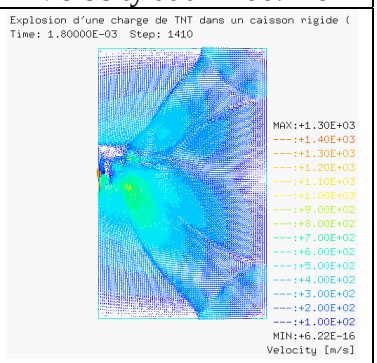
Velocity at t = 100.E-6



Velocity at t = 200.E-6



Velocity at t = 800.E-6



Velocity at t = 1800.E-6

3D axisymmetric simulation:

JWLS3G

The mesh generation file is:

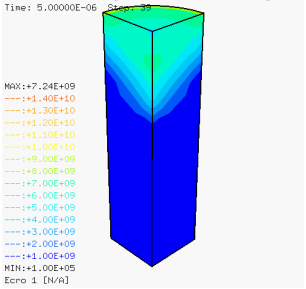
```
*%siz 100
*
TITRE 'Explosion de TNT dans un caisson' ;
*
option echo 0 ;
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxvolu3d.proc';
option echo 1 ;
*
OPTION DIME 3 ELEM CUB8 ;
*
OPTION SORTIE 'jwls3g.msh';
option trac PSC FTRA 'jwls3d_mail.ps' ;
*
p0 = 0 0 0;
p1 = 0.0355 0 0;
p2 = 0.965 0 0;
p3 = 0.965 0 0.709;
p4 = 0.965 0 0.851;
p5 = 0.965 0 1.56;
p6 = 0.0355 0 1.56;
p7 = 0 0 1.56;
p8 = 0 0 0.851;
p9 = 0 0 0.709;
p10 = 0.0355 0 0.709;
p11 = 0.0355 0 0.851;
tol = 1.e-5;
*
air1 = dall (p0 d 2 p1) (p1 d 20 p10) (p10 d 2 p9) (p9 d 20 p0) plan;
air2 = dall (p1 d 26 p2) (p2 d 20 p3) (p3 d 26 p10) (p10 d 20 p1) plan;
air3 = dall (p10 d 26 p3) (p3 d 8 p4) (p4 d 26 p11) (p11 d 8 p10) plan;
air4 = dall (p11 d 26 p4) (p4 d 20 p5) (p5 d 26 p6) (p6 d 20 p11) plan;
air5 = dall (p8 d 2 p11) (p11 d 20 p6) (p6 d 2 p7) (p7 d 20 p8) plan;
s_air = air1 et air2 et air3 et air4 et air5;
s_tnt = dall (p9 d 2 p10) (p10 d 8 p11) (p11 d 2 p8) (p8 d 8 p9) plan;
elim tol (s_air et s_tnt);
ax_tnt = p9 d 8 p8;
elim tol (s_tnt et ax_tnt);
tnt ier1 s1n = pxvolu3d s_tnt 9 90.0 ax_tnt tol;
tnt = tnt coul roug;

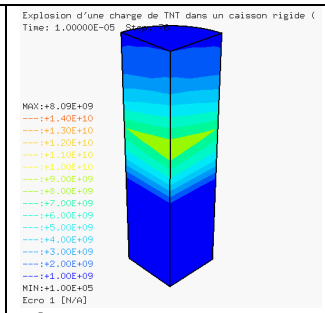
ax_air1 = p0 d 20 p9;
ax_air2 = p8 d 20 p7;
elim tol (s_air et ax_air1 et ax_air2);
air123 ier2 s2n = pxvolu3d (air1 et air2 et air3) 9 90.0 ax_air1 tol;
air45 ier3 s3n = pxvolu3d (air4 et air5) 9 90.0 ax_air2 tol;
air = air123 et air45;
air = air coul turq;
elim tol (air et tnt);
flui = air ET tnt;
flu8 = flui elem cub8;
flu6 = flui elem pri6;
fsrn = enve flui;
*
tout = flui ET fsrn ;
sort tout ;
*
trac tnt ;
trac face cach tnt ;
trac tout ;
trac face cach flui ;
trac QUALIF tout ;
opti trac mif ftra 'jwls3g_mail.mif';
trac tnt ;
trac face cach tnt ;
trac tout ;
trac face cach flui ;
trac QUALIF tout ;
*
mess 'NB_POIN        =' (NBNO tout) ;
mess 'NB_ELEM (tnt)  =' (NBEL tnt) ;
mess 'NB_ELEM (air)  =' (NBEL air) ;
mess 'NB_ELEM (flu8) =' (NBEL flu8) ;
mess 'NB_ELEM (flu6) =' (NBEL flu6) ;
*
**option donn 5 ;
*
option echo 1 ;
*
fin ;
```

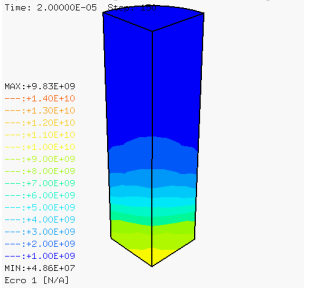
The input file is:

```
Explosion d'une charge de TNT dans un caisson rigide ( JWLS )
*
ECHO
!conv win
*
GIBI TOUT
*
TRID NONL EULE
*
DIMENSION
    PT3L 13769  zone    2
    FL38 11664 FL36 432
    NALE    1  NBLE 13769
    MTTI 30
TERM
*
GEOMETRIE
   FL38 flu8
   FL36 flu6
TERM
*
MATERIAU
**   l'air :  on calcule eint pour avoir P=1 bar (P=omeg*ro*eint)
*
    flut ro 1.3 eint 0.21978e6 gamm 1.35 PB 0
         ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
         CQ 2.56 PMIN 0 PREF 0 NUM 11
         a 3.738e11 b 3.747e9 r1 4.15 r2 0.90
         ros 1630
         LECT air TERM
*
**  Le TNT :   on donne directement ro = ros
*              avec ignition au point P7
*              la vitesse de detonation est celle de Chapman-Jouguet
*
    flut ro 1630 eint 3.68e6 gamm 1.35 PB 0
         ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
         CQ 2.56 PMIN 0 PREF 0 NUM 11
         a 3.738e11 b 3.747e9 r1 4.15 r2 0.90
         d 6930 TDET 0.0 pini 1e5 xdet 0. ydet 0. zdet 851.0e-3
         LECT tnt TERM
*
LINK COUP
   FSR      LECT  fsrn  TERM
*
ECRITURE
*--   listing :
       VITE ECROU            TFREQ 200e-6
            point lect 1 term
            elem  lect 1 TERM
*
*--   dessins :
       FICHIER ALICE
         TIME PROG 5E-6 PAS   5E-6   25E-6
                        PAS  25E-6  200E-6
                        PAS 100E-6  1.2E-3
                        PAS 200E-6  2.0E-3   TERM
*
*--   courbes :
      FICHIER ALICE temps
              tfreq 2e-6
              point lect 1 term
              elem  lect 1 term
*
OPTION NOTEST NOPRINT
       DTDROP  0.002
       AMORT  QUAD 2.
       LOG 1
       csta 0.4
*
  CALCUL tini 0   pas1 1e-8  nmax 500000   tfin  1.80e-3
*
FIN
```

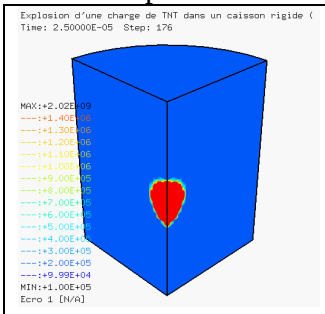
The charge pressures at some selected instants are shown below:

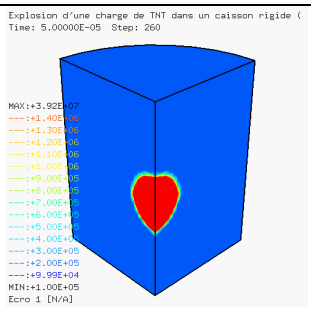

Charge pressure at t = 5.E-6

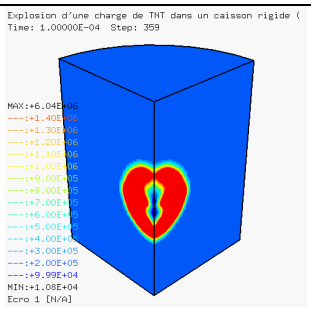

Charge pressure at t = 10.E-6

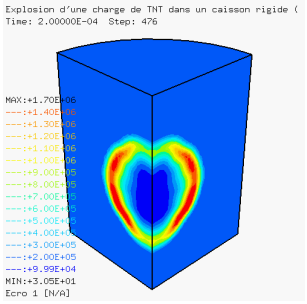

Charge pressure at t = 20.E-6

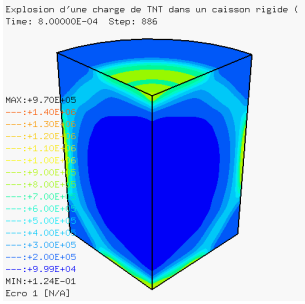
The fluid pressures and velocities at some selected instants are shown below:

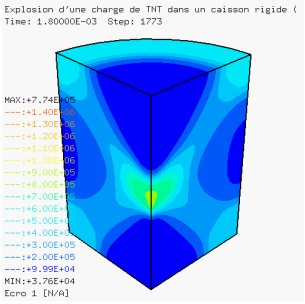

Pressure at t = 25.E-6

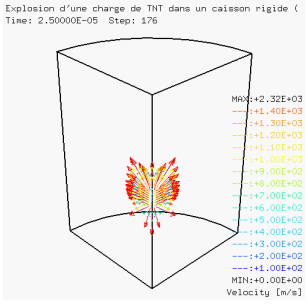

Pressure at t = 50.E-6

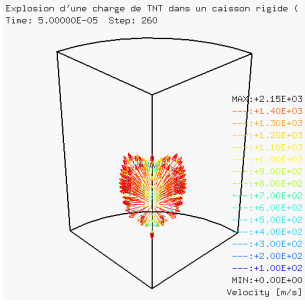

Pressure at t = 100.E-6

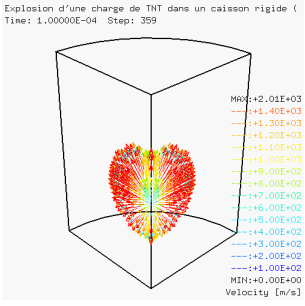

Pressure at t = 200.E-6

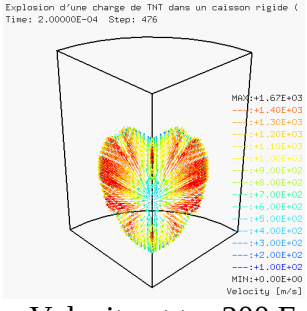

Pressure at t = 800.E-6

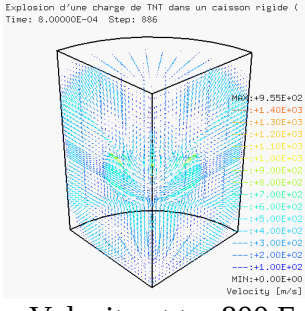

Pressure at t = 1800.E-6

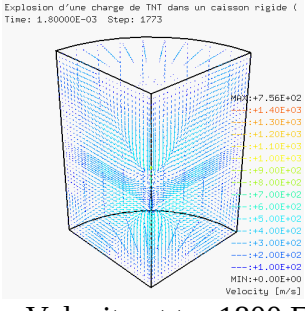

Velocity at t = 25.E-6


Velocity at t = 50.E-6

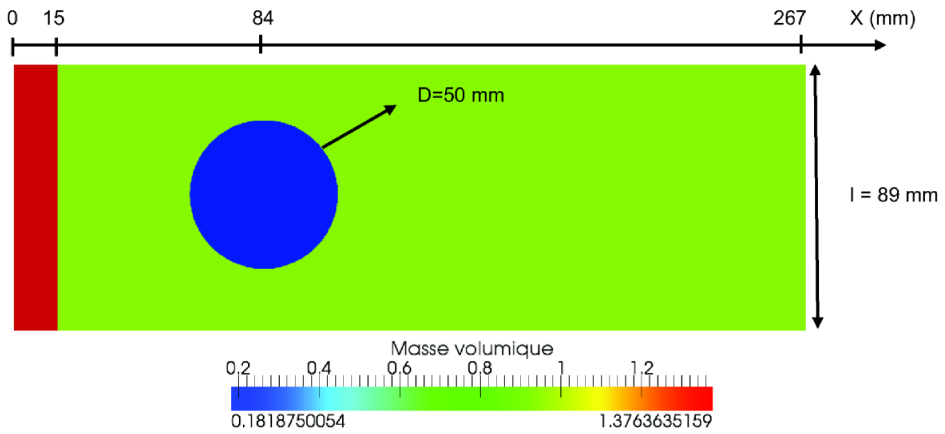

Velocity at t = 100.E-6


Velocity at t = 200.E-6


Velocity at t = 800.E-6


Velocity at t = 1800.E-6

Exercise 6 – Richtmyer-Meshkov instability



Solution with CCFV (1.3 Million elements)

70

Geometric data:

Shock wave in a gas, impinging on a gas bubble at a different density and giving rise to a Richtmyer-Meshkov instability. 2D plane simulation by 1.3 million CCFV, second order in time and in space.

Boundary conditions:

Absorbing boundary conditions along the left and right sides of the domain.

Initial conditions:

Initial velocity in the initial shock wave region.

Materials

The various gases are modelled by the SG2P material model: this material models a mixture of gases and liquids according to a so-called stiffened gas relationship.

RMI02

The mesh generation file is:

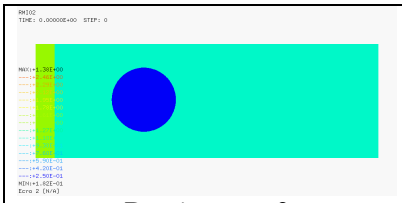
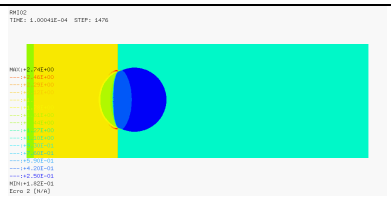
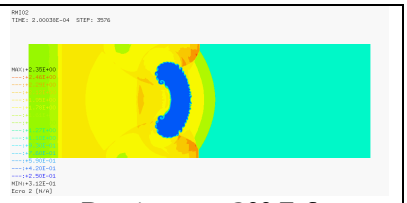
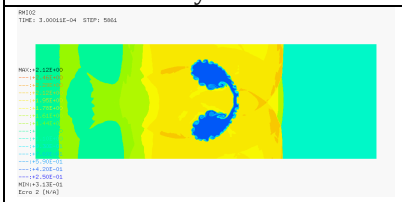
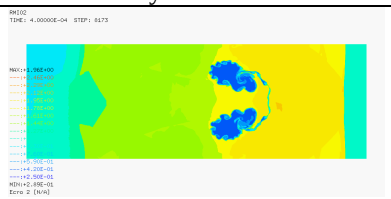
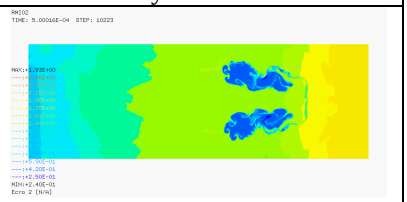
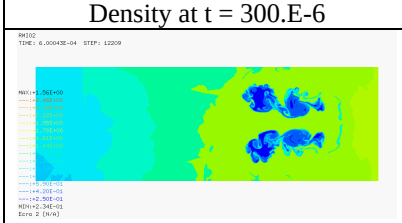
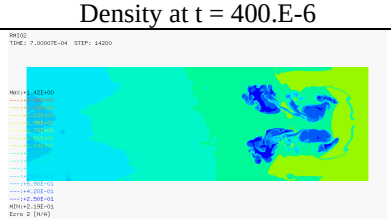
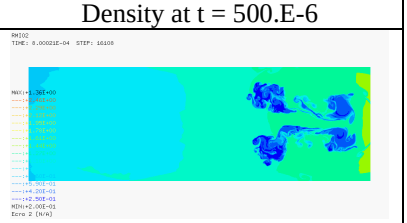
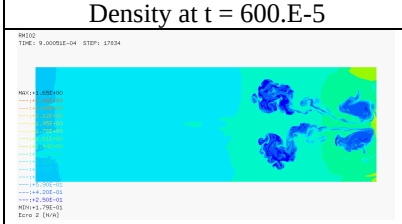
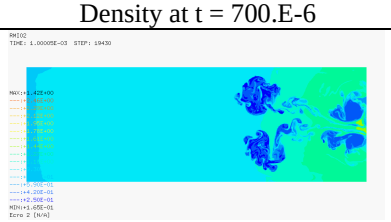
```
opti echo 1;
OPTI DIME 2 ELEM QUA4 ;
opti trac psc ftra 'rmi02_mesh.ps' ;
L1=267E-3 ;
L2=89E-3 ;
LS1=15E-3 ;
X1=84.33E-3 ;
X2=45.5E-3 ;
R1=25E-3 ;
*
* 1.3 Millions de Vf
*
RAf = 22;
*
* pas de swap avec raf = 32
* 2.8 Millions de Vf
*
*raf = 32 ;
NN1=90 * raf ;
NN2=30 * raf ;
DX1=L1 / NN1 ;
P1=0. 0. ;
P2=0. L2 ;
LG1=P1 D NN2 P2 ;
LG2=LG1 PLUS (LS1 0.) ;
NN3=ENTI (LS1 / DX1) ;
SS1=LG1 REGL NN3 LG2 ;
LG3=LG1 PLUS (L1 0.) ;
NN3=NN1 - NN3 ;
SS2=LG2 REGL NN3 LG3 ;
PC1=(X1 X2) ;
PC2=PC1 PLUS(1.E-10 1.E-10) ;
NUA1=SS2 POIN SPHE R1 PC1 PC2 ;
SPH1=SS2 ELEM APPUYE STRICTEMENT NUA1 ;
CT1=CONT (SS1 ET SS2) ;
SS2=DIFF SS2 SPH1 ;
CT2=CONT SPH1 ;
MUR1=DIFF CT1 (LG1 ET LG3) ;
TRAC (SS1 ET (SS2 COUL ROUGE) ET (SPH1 COUL VERT)) ;
TOUT=SS1 ET SS2 ET SPH1 ;
tass tout noop;
OPTI SAUV FORM 'rmi02.msh' ;
SAUV FORM TOUT ;
list (nbnoe tout) ;
list (nbel tout);
fin;
```

The input file is:

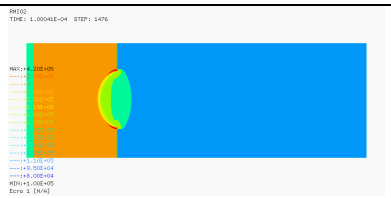
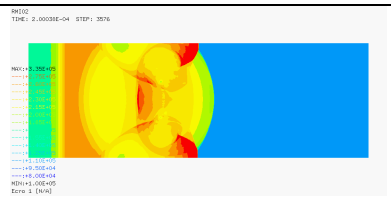
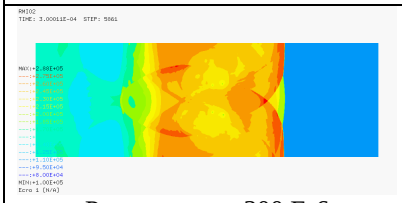
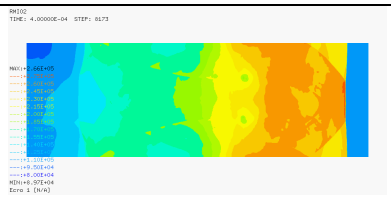
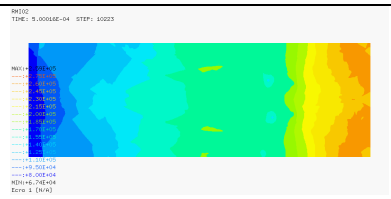
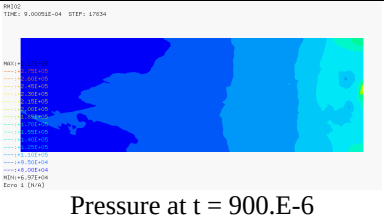
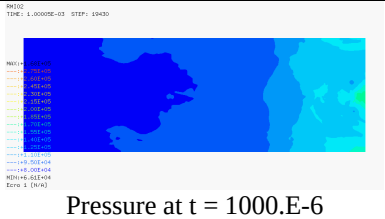
```
RMI02
ECHO
!CONV WIN
CAST tout
DPLA EULER
GEOM
  Q4VF TOUT
  CL2D LG1 LG3
TERM
MATE SG2P PINI 1.56980E5 PMIN 1e-3 PREF 1E5 NESP 2
       COMP1 ROI 1.376363 PI 0  GAMM 1.4 ALPH 1 Q 0 CP 0 CV 0 QPRI 0
       COMP2 ROI 0.192    PI 0. GAMM 1.4 ALPH 0 Q 0 CP 0 CV 0 QPRI 0
       LECT SS1 TERM
SG2P PINI 1E5 PMIN 1E-3 PREF 1E5 NESP 2
       COMP1 ROI 1 PI 0.  GAMM 1.4 ALPH 1 Q 0 CP 0 CV 0 Qpri 0
       COMP2 ROI 1 PI 0.  GAMM 1.4 ALPH 0 Q 0 CP 0 CV 0 Qpri 0
       LECT SS2 TERM
SG2P PINI 1E5 PMIN 1E-3 PREF 1E5 NESP 2
       COMP1 ROI 0.181875 PI 0.  GAMM 1.4 ALPH 0 Q 0 CP 0 CV 0 Qpri 0
       COMP2 ROI 0.181875 PI 0.  GAMM 1.4 ALPH 1 Q 0 CP 0 CV 0 Qpri 0
       LECT SPH1 TERM
CLVF ABSO RO 1.0
```

```
        LECT LG1 LG3 TERM
INITIAL
  VITC VITX 394.728 VITY 0. LECT SS1 TERM
ECRI FREQ 10 NOPO NOEL
  FICH PVTK TFREQ 1e-5
        VARI DEPL VITE ECRO VCVI
        GROUP 1 OBJET lect SS1 ss2 SPH1 TERM
  FICH SPLI ALIC TFRE 1.E-5
OPTION NOTEST log 1
  PASAUTO CSTA 0.5
  VFCC FCONV 6
        ORDRE 2
        OTPS 2
        RECONSTRUCTION 1
        LMAS 3
        LQDM 3
        LENE 3
        KMAS 0.75
        KQDM 0.75
        KENE 0.75
        CENER ! avec correction de l'énergie Interne
CALCUL TINI 0. TFIN 1.E-3
FIN
```

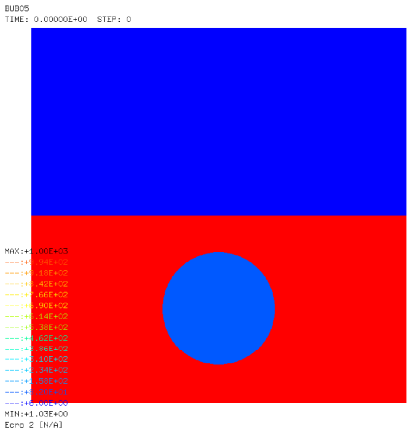
The computed densities at some selected instants are shown below:

 Density at t = 0	 Density at t = 100.E-6	 Density at t = 200.E-6
 Density at t = 300.E-6	 Density at t = 400.E-6	 Density at t = 500.E-6
 Density at t = 600.E-5	 Density at t = 700.E-6	 Density at t = 800.E-6
 Density at t = 900.E-6	 Density at t = 1000.E-6	

The computed pressures at some selected instants are shown below:

 Pressure at t = 0	 Pressure at t = 100.E-6	 Pressure at t = 200.E-6
 Pressure at t = 300.E-6	 Pressure at t = 400.E-6	 Pressure at t = 600.E-6
 Pressure at t = 600.E-6	 Pressure at t = 700.E-6	 Pressure at t = 800.E-6
 Pressure at t = 900.E-6	 Pressure at t = 1000.E-6	

Exercise 7 – Gas bubble expansion in liquid



Solution with structured mesh (method of Despres, Lagoutière et al.)

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Geometric data:
Compressed gas bubble expands in a liquid with free surface. A structured mesh is used.
Boundary conditions:
Rigid boundary.
Initial conditions:
High pressure in the bubble.
Materials
The various fluids are modelled by the ADCR material model: this material models a mixture of gases and liquids.
Solutions
Solutions are obtained with either FE or CCFV, without and with anti-diffusion according to the Despres-Lagoutière method.

NODP02

This solution uses a coarse mesh of Finite Elements without anti-diffusion. The mesh generation file is:

```
opti echo 1;
opti dime 2 elem qua4;
opti sauv form 'nodp02.msh';
opti trac psc ftra 'nodp02_mesh.ps';
*
p0 = 0 0;
p1 = 1 0;
p2 = 1 1;
p3 = 0 1;
*
n = 50;
*
c1 = p0 d n p1;
c2 = p1 d n p2;
c3 = p2 d n p3;
c4 = p3 d n p0;
*
flui = dall c1 c2 c3 c4 plan;
*
blox = c2 et c4;
bloy = c1 et c3;
*
mesh = flui et blox et bloy;
tass mesh noop;
sauv form mesh;
*
trac qual mesh;
*
fin;
```

The input file is:

```
NODP02
ECHO
!CONV win
CAST mesh
DPLA EULE
GEOM CAR1 flui TERM
COMP GROU 3 'gazz' LECT flui TERM COND YB GT 0.5
            'bull' LECT flui TERM COND SPHE XC 0.5 YC 0.25 R 0.15
            'liqu' LECT flui DIFF gazz bull TERM
     COUL roug LECT bull TERM
          bleu LECT liqu TERM
          turq LECT gazz TERM
MATE ADCR ! Bulle
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 2.E6
          CAR 0. CBU 1.
          LECT bull TERM
     ADCR ! Eau
```

```
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 0.
          LECT liqu TERM
     ADCR ! Couverture
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 1.
          LECT gazz TERM
LINK COUP BLOQ 1 LECT blox TERM
          BLOQ 2 LECT bloy TERM
ECRI VITE TFRE 1.2E-2 NOPO NOEL
     FICH ALIC TFRE 1.E-4
OPTI PAS AUTO CSTA 0.5 AMOR QUAD 4.
     LOG 1
CALC TINI 0. TFIN 1.2E-2
FIN
```

DPLG02

This solution uses a coarse mesh of Finite Elements with anti-diffusion according to the Despres-Lagoutière method. The input file is:

```
DPLG02
ECHO
!CONV win
CAST mesh
DPLA EULE
GEOM CAR1 flui TERM
COMP GROU 3 'gazz' LECT flui TERM COND YB GT 0.5
           'bull' LECT flui TERM COND SPHE XC 0.5 YC 0.25 R 0.15
           'liqu' LECT flui DIFF gazz bull TERM
     COUL roug LECT bull TERM
          bleu LECT liqu TERM
          turq LECT gazz TERM
MATE ADCR ! Bulle
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 2.E6
          CAR 0. CBU 1.
          LECT bull TERM
     ADCR ! Eau
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 0.
          LECT liqu TERM
     ADCR ! Couverture
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 1.
          LECT gazz TERM
LINK COUP BLOQ 1 LECT blox TERM
          BLOQ 2 LECT bloy TERM
ECRI VITE TFRE 1.2E-2 NOPO NOEL
     FICH ALIC TFRE 1.E-4
OPTI PAS AUTO CSTA 0.5 AMOR QUAD 4.
     DPLG
     LOG 1
CALC TINI 0. TFIN 1.2E-2
FIN
```

NODP03

This solution uses a coarse mesh of Cell-Centred Finite Volumes without anti-diffusion. The input file is:

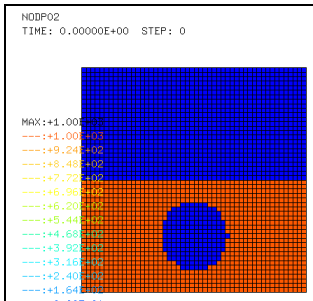
```
NODP02
ECHO
!CONV win
CAST mesh
DPLA EULE
GEOM CAR1 flui TERM
COMP GROU 3 'gazz' LECT flui TERM COND YB GT 0.5
           'bull' LECT flui TERM COND SPHE XC 0.5 YC 0.25 R 0.15
           'liqu' LECT flui DIFF gazz bull TERM
     COUL roug LECT bull TERM
          bleu LECT liqu TERM
          turq LECT gazz TERM
MATE ADCR ! Bulle
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 2.E6
          CAR 0. CBU 1.
          LECT bull TERM
     ADCR ! Eau
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 0.
          LECT liqu TERM
     ADCR ! Couverture
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 1.
          LECT gazz TERM
LINK COUP BLOQ 1 LECT blox TERM
          BLOQ 2 LECT bloy TERM
ECRI VITE TFRE 1.2E-2 NOPO NOEL
     FICH ALIC TFRE 1.E-4
OPTI PAS AUTO CSTA 0.5 AMOR QUAD 4.
     LOG 1
CALC TINI 0. TFIN 1.2E-2
FIN
```

DPLG03

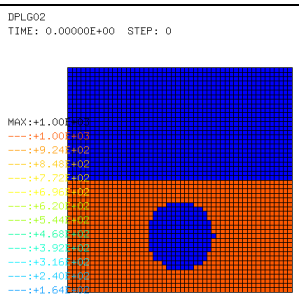
This solution uses a coarse mesh of Cell-Centred Finite Volumes with anti-diffusion according to the Despres-Lagoutière method. The input file is:

```
DPLG02
ECHO
!CONV win
CAST mesh
DPLA EULE
GEOM CAR1 flui TERM
COMP GROU 3 'gazz' LECT flui TERM COND YB GT 0.5
           'bull' LECT flui TERM COND SPHE XC 0.5 YC 0.25 R 0.15
           'liqu' LECT flui DIFF gazz bull TERM
     COUL roug LECT bull TERM
          bleu LECT liqu TERM
          turq LECT gazz TERM
MATE ADCR ! Bulle
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 2.E6
          CAR 0. CBU 1.
          LECT bull TERM
     ADCR ! Eau
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 0.
          LECT liqu TERM
     ADCR ! Couverture
          RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 1.
          LECT gazz TERM
LINK COUP BLOQ 1 LECT blox TERM
          BLOQ 2 LECT bloy TERM
ECRI VITE TFRE 1.2E-2 NOPO NOEL
     FICH ALIC TFRE 1.E-4
OPTI PAS AUTO CSTA 0.5 AMOR QUAD 4.
     DPLG
     LOG 1
CALC TINI 0. TFIN 1.2E-2
FIN
```

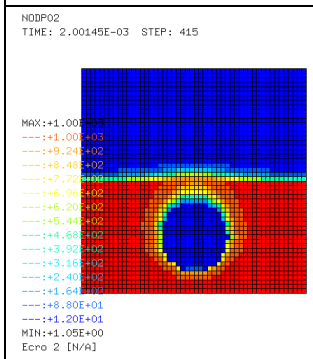
The computed densities at some selected instants for the Finite Element solutions are shown below:



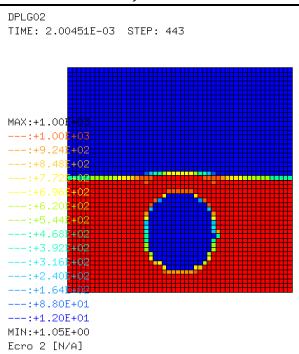
t = 0



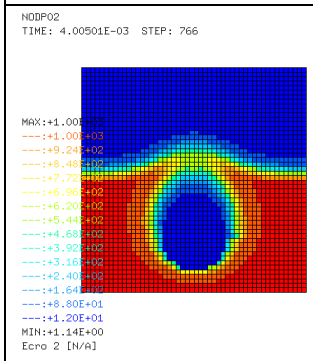
t = 0, anti-diffusion



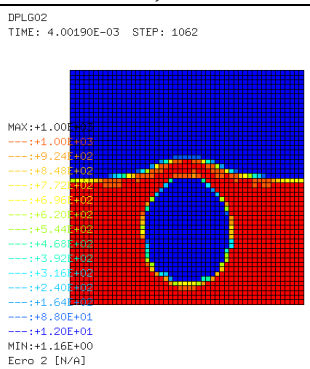
t = 2.E-3



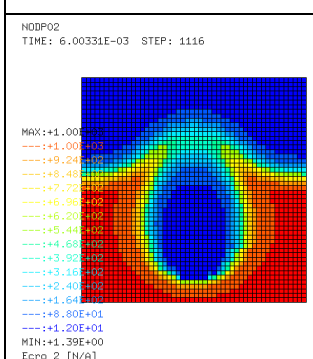
t = 2.E-3, anti-diffusion



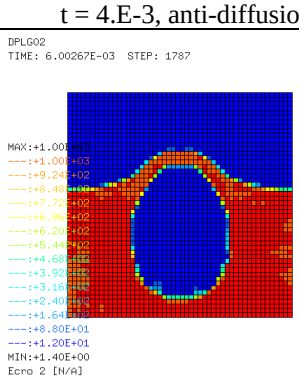
t = 4.E-3



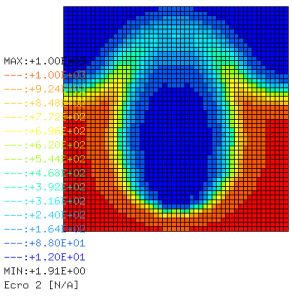
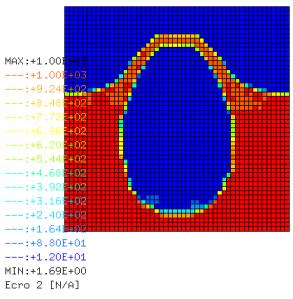
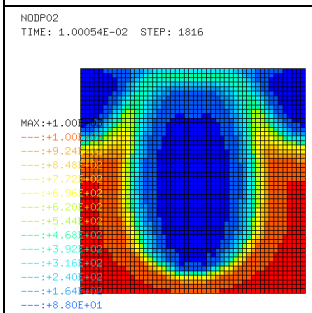
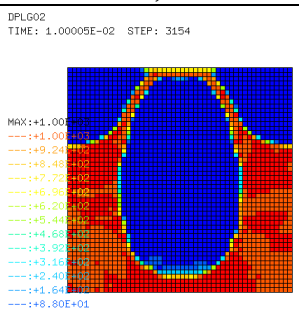
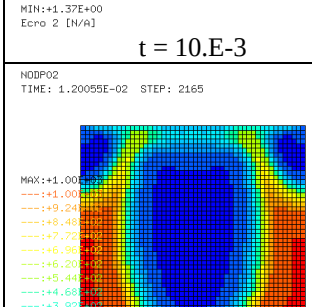
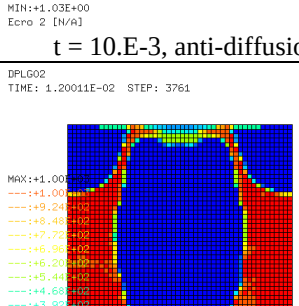
t = 4.E-3, anti-diffusion



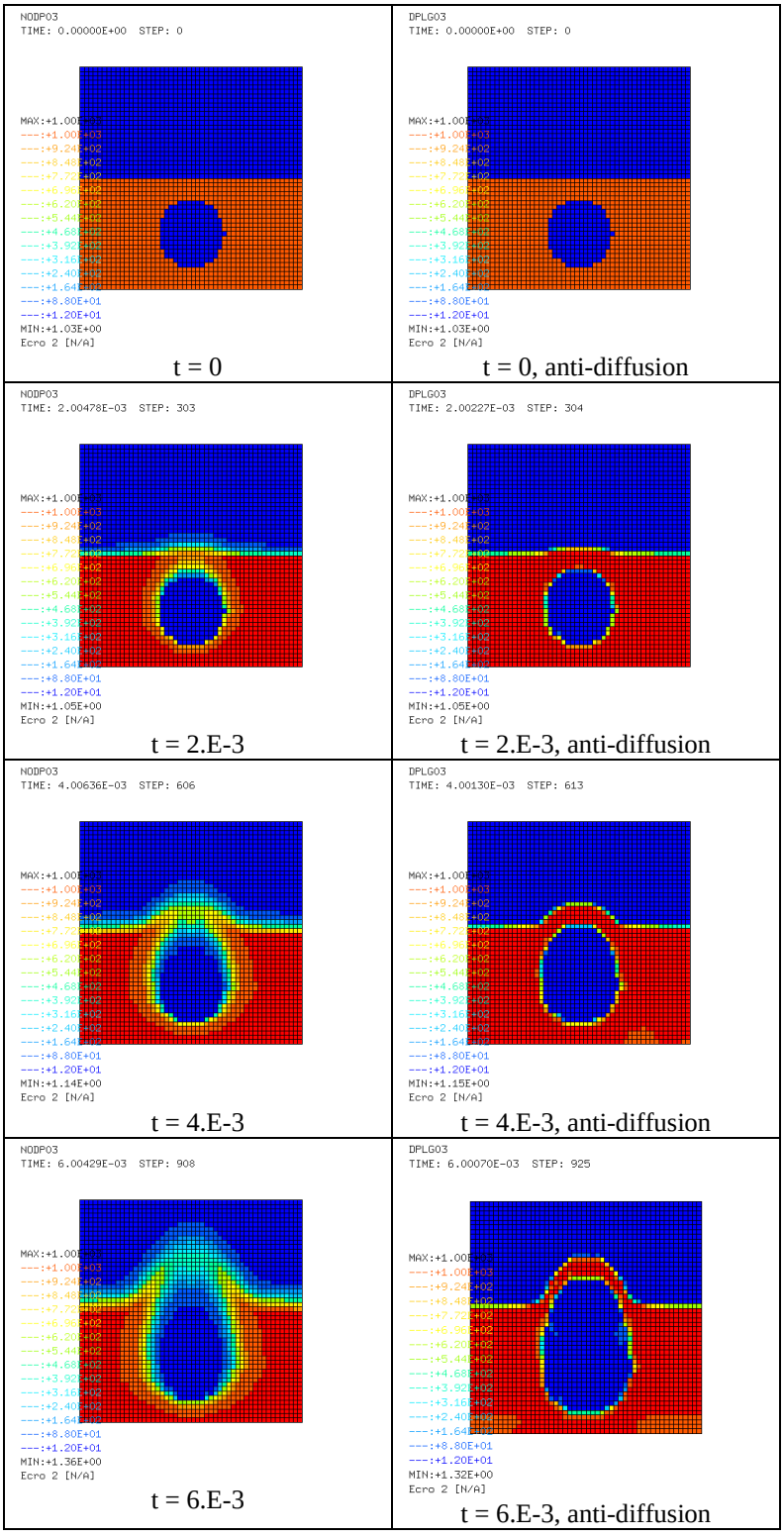
t = 6.E-3

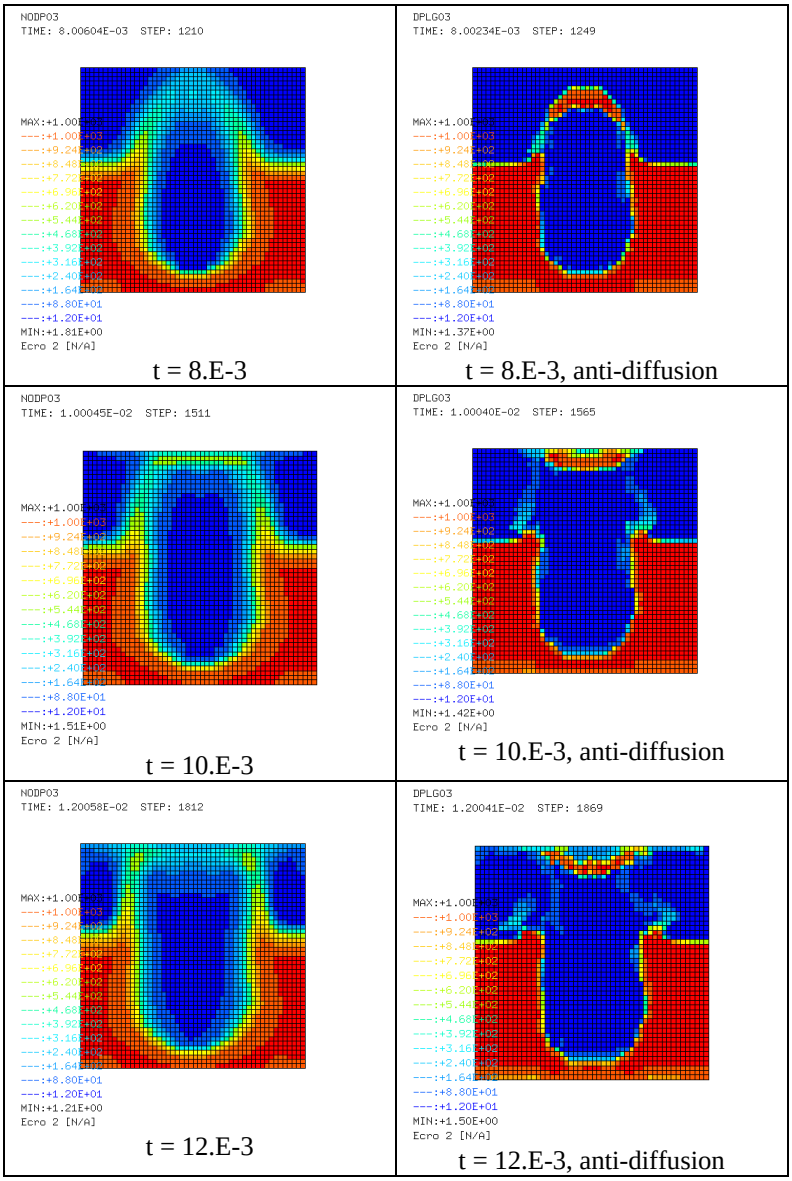


t = 6.E-3, anti-diffusion

 t = 8.E-3	 t = 8.E-3, anti-diffusion
 t = 10.E-3	 t = 10.E-3, anti-diffusion
 t = 12.E-3	 t = 12.E-3, anti-diffusion

The computed densities at some selected instants for the Cell-Centred Finite Volume solutions are shown below:





BUB05

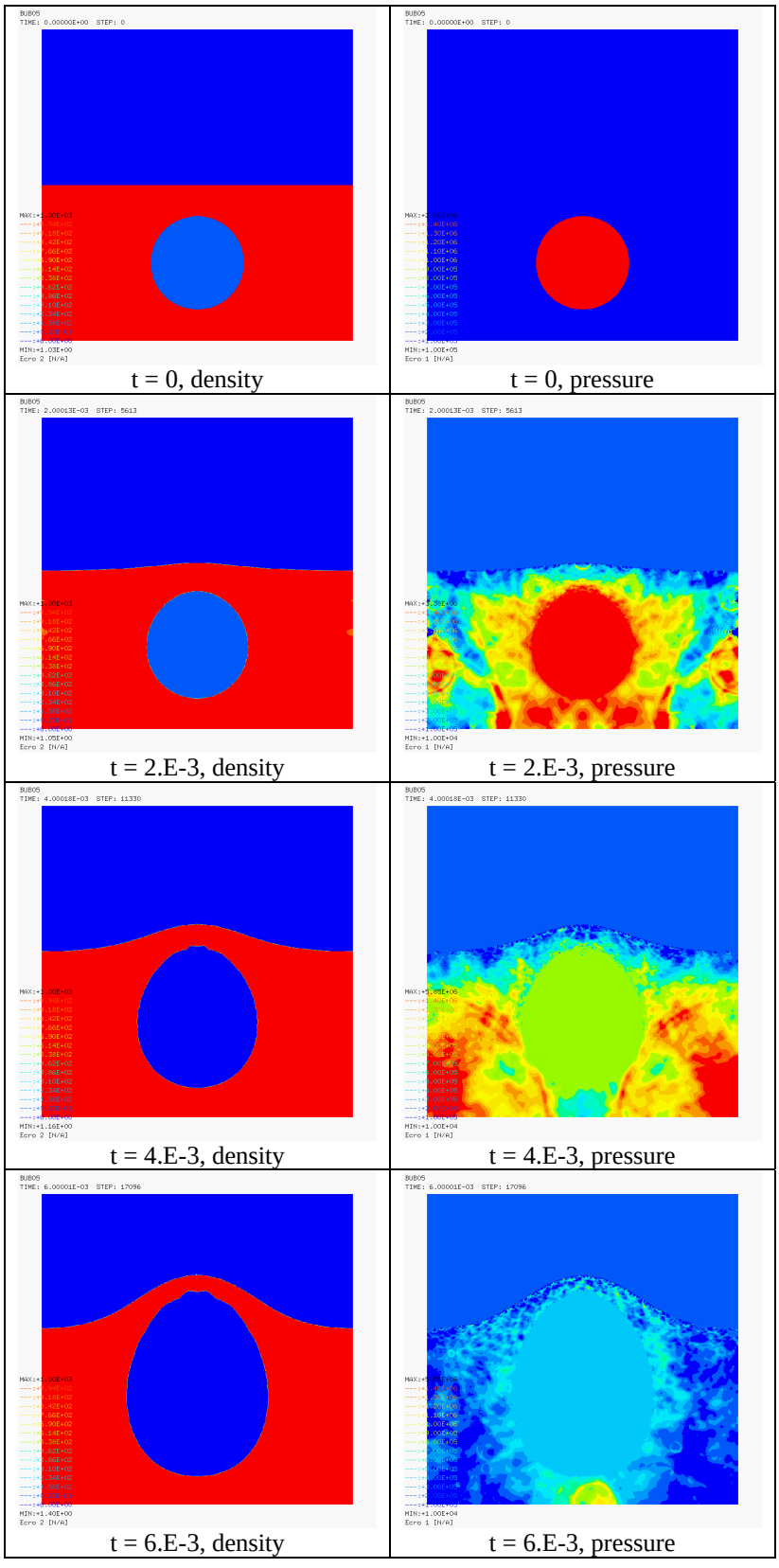
This solution uses a fine mesh with anti-diffusion.
The mesh generation file is:

```
opti echo 1;
opti dime 2 elem qua4;
opti sauv form 'bub05.msh';
opti trac psc ftra 'bub05_mesh.ps';
*
p0 = 0 0;
p1 = 1 0;
p2 = 1 1;
p3 = 0 1;
*
n = 800;
*
c1 = p0 d n p1;
c2 = p1 d n p2;
c3 = p2 d n p3;
c4 = p3 d n p0;
*
flui = dall c1 c2 c3 c4 plan;
*
blox = c2 et c4;
bloy = c1 et c3;
*
mesh = flui et blox et bloy;
tass mesh noop;
sauv form mesh;
*
trac qual mesh;
*
fin;
```

The input file is:

```
BUB05
ECHO
!CONV win
CAST mesh
DPLA EULE
GEOM CAR1 flui TERM
COMP GROU 3 'gazz' LECT flui TERM COND YB GT 0.5
           'bull' LECT flui TERM COND SPHE XC 0.5 YC 0.25 R 0.15
           'liqu' LECT flui DIFF gazz bull TERM
     COUL roug LECT bull TERM
          bleu LECT liqu TERM
          turq LECT gazz TERM
MATE ADCR RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 2.E6
          CAR 0. CBU 1.
          LECT bull TERM
     ADCR RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 0.
          LECT liqu TERM
     ADCR RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 1.
          LECT gazz TERM
LINK COUP BLOQ 1 LECT blox TERM
          BLOQ 2 LECT bloy TERM
ECRI VITE TFRE 1.2E-2 NOPO NOEL
     FICH ALIC TFRE 1.E-4
OPTI PAS AUTO CSTA 0.5 AMOR QUAD 4. DPLG
     LOG 1
CALC TINI 0. TFIN 1.2E-2
FIN
```

The computed densities at some selected instants are shown below:

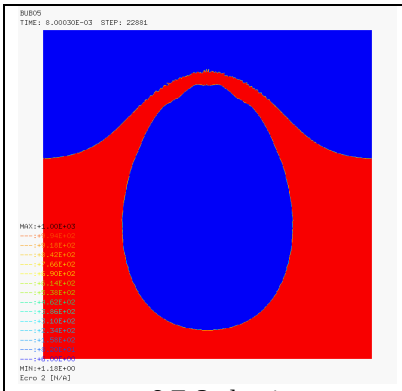


t = 0, density | t = 0, pressure

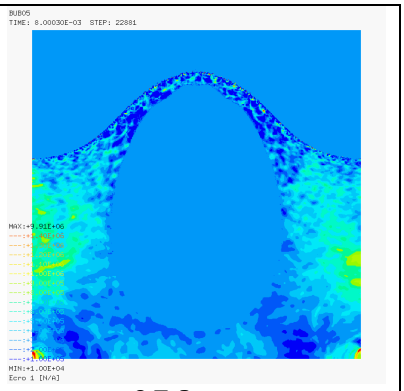
t = 2.E-3, density | t = 2.E-3, pressure

t = 4.E-3, density | t = 4.E-3, pressure

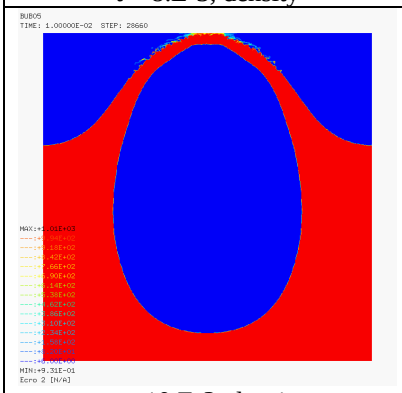
t = 6.E-3, density | t = 6.E-3, pressure



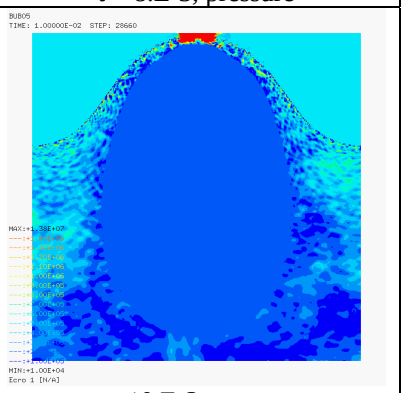
t = 8.E-3, density



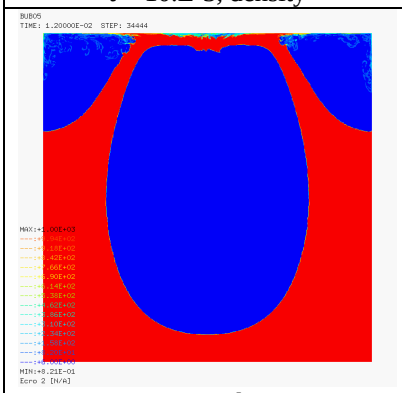
t = 8.E-3, pressure



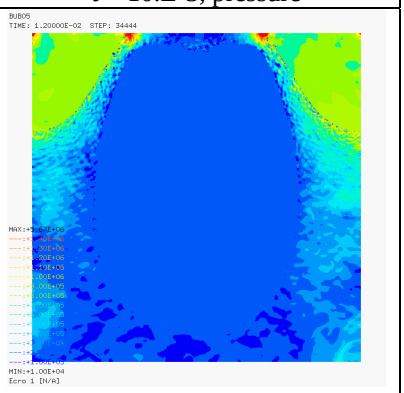
t = 10.E-3, density



t = 10.E-3, pressure

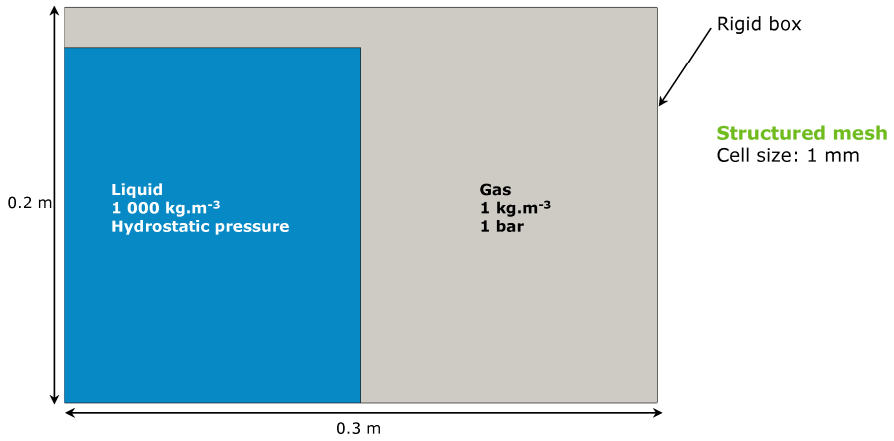


t = 12.E-3, density



t = 12.E-3, pressure

Exercise 8 – Sloshing under gravity loading



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Geometric data:
Square region occupied by liquid, falls down by gravity within a rigid container. The mesh is made of 160 x 200 elements.
Boundary conditions:
Rigid boundary.
Loading conditions:
Gravity.
Materials
The various fluids are modelled by the ADCR material model: this material models a mixture of gases and liquids.

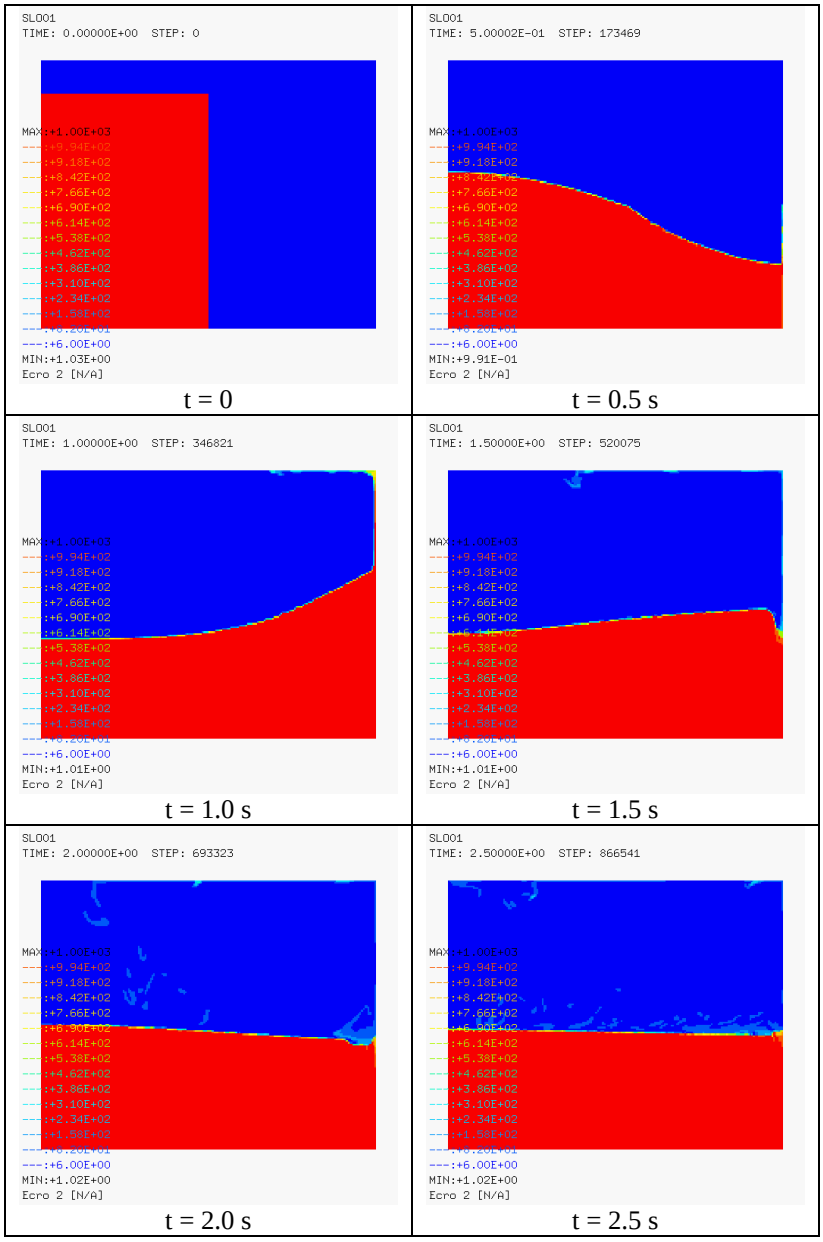
SLO01
This solution uses a coarse mesh without anti-diffusion.
The mesh generation file is:

```
opti echo 1;
opti dime 2 elem qua4;
opti sauv form 'slo01.msh';
opti trac psc ftra 'slo01_mesh.ps';
*
p0 = 0 0;
p1 = 2 0;
p2 = 2 1.6;
p3 = 0 1.6;
*
nx = 200;
ny = 160;
*
c1 = p0 d nx p1;
c2 = p1 d ny p2;
c3 = p2 d nx p3;
c4 = p3 d ny p0;
*
flui = dall c1 c2 c3 c4 plan;
*
blox = c2 et c4;
bloy = c1 et c3;
*
mesh = flui et blox et bloy;
tass mesh noop;
sauv form mesh;
*
trac qual mesh;
*
fin;
```

The input file is:

```
SLO01
ECHO
!CONV win
CAST mesh
DPLA EULE
GEOM CAR1 flui TERM
COMP GROU 2 'liqu' LECT flui TERM COND BOX X0 0 Y0 0 DX 1 DY 1.4
          'gazz' LECT flui DIFF liqu TERM
     COUL bleu LECT liqu TERM
          turq LECT gazz TERM
MATE ADCR RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 0.
          LECT liqu TERM
     ADCR RONA 1000. CNA 1500. PNA 1.E5 PSAT 1.E4 ROSAT 0.1
          ROBU 1. GBU 1.4 PBU 1.E5 NBU 1.4
          ROAR 1. GAR 1.4 PARG 1.E5 PREF 1.E5
          BETA 5E-3 PTOT 1.E5
          CAR 0. CBU 1.
          LECT gazz TERM
LINK COUP BLOQ 1 LECT blox TERM
          BLOQ 2 LECT bloy TERM
CHAR CONS GRAV 0 -9.81 LECT flui TERM
ECRI VITE TFRE 1.E-1 NOPO NOEL
          FICH ALIC TFRE 1.E-2
OPTI PAS AUTO CSTA 0.5 AMOR QUAD 4. DPLG
          LOG 1
CALC TINI 0. TFIN 5.0
FIN
```

The computed densities at some selected instants are shown below:



Universitat Politècnica de Catalunya, Barcelona, 15 – 19 April 2013

Numerical Simulation of Fast Transient Phenomena in Fluid-Structure Systems

A Short Course by F. Casadei
Retired from European Commission, Joint Research Centre
Institute for the Protection and Security of the Citizen
T.P. 480, I-21027 Ispra (VA), Italy.
E-mail: casadeifolco@gmail.com

1

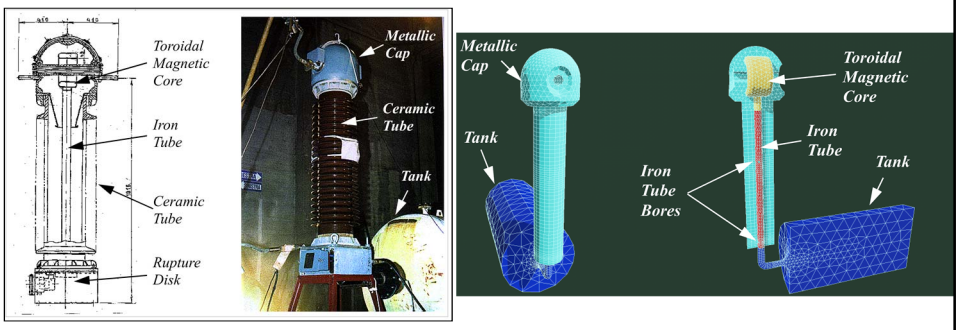
Contents

- I – Introduction (Structures)
- II – ALE formulation (Fluids)
- III – Classical Fluid-Structure Interaction
- IV – Advanced FSI (Failure/Fragmentation)
- V – Further topics and applications

2

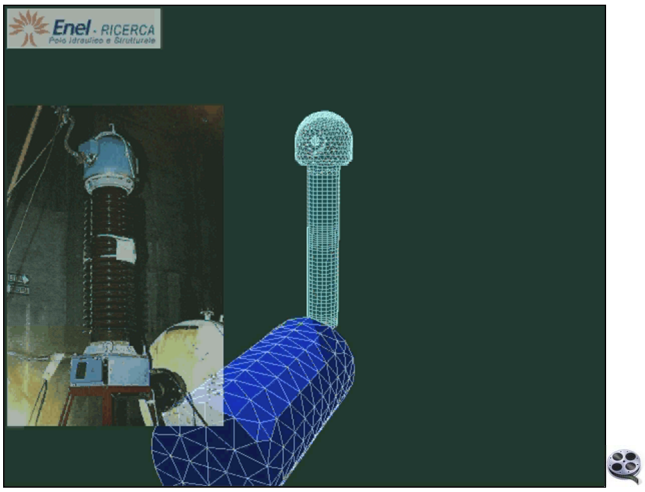
Further FSI Example

Electric arc in TA device *(Courtesy of ENEL-Hydro)*



3

Further FSI Example (2)



4

Detailed Contents (1/2)

- Motivation
- A classification of FSI algorithms
- Geometrical methods:
  - The FSA/FSR method
- Equilibrium-based methods:
  - The Uniform Pressure (UP) method
- A combined method:
  - The FSCR method

5

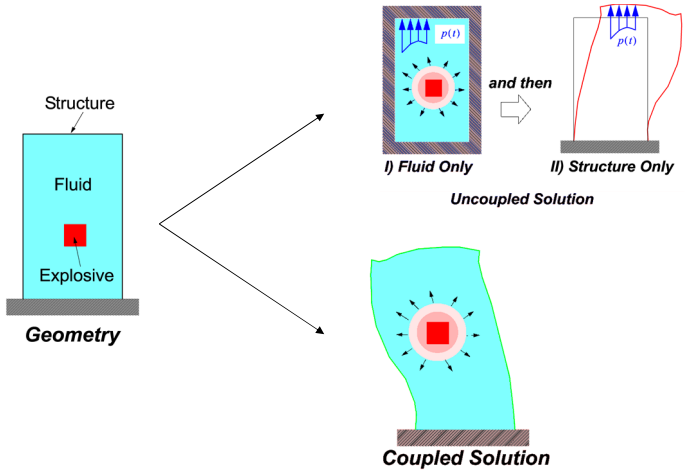
Detailed Contents (2/2)

- Application to Finite Volumes:
  - Weak FSI for NCFV
  - Weak FSI for CCFV (conforming)
- Non-conforming FSI:
  - For FE / NCFV (strong approach)
  - For CCFV (weak approach)
- Some special FSI techniques/applications:
  - Modeling of perforated structures
  - Sloshing problems

6

FSI Motivation

- Two possible approaches: uncoupled or fully coupled

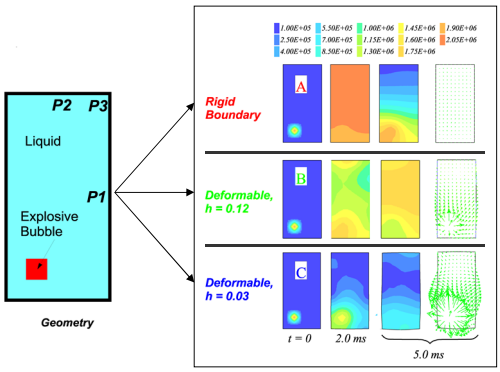


7

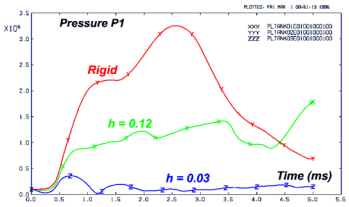
FSI Motivation (2)

Fully coupled analysis is mandatory in two classes of problems:

- With nearly incompressible fluids



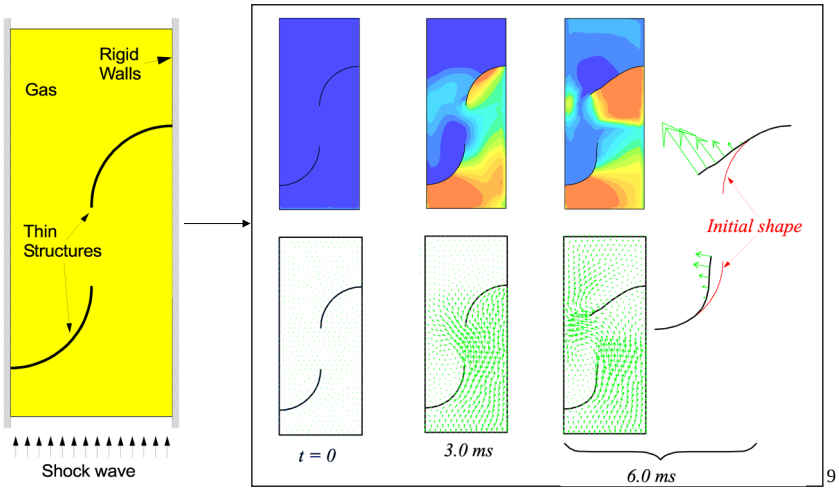
h=tank thickness



8

FSI Motivation (3)

- With very deformable structures



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A Classification of FSI Algorithms

- Each **FSI algorithm** consists of two parts:
  - A **detection** strategy
  - An **enforcement** strategy
- As concerns FSI detection, we distinguish:
  - **Basic** type (no structural failure, moderate rotations)
    - Conforming F-S meshes
    - Non-conforming F-S meshes
  - **Embedded** type (failure/fragmentation, large rotations)
- As concerns FSI enforcement, one can use:
  - **Strong** enforcement (via constraints on velocities)
  - **Weak** enforcement (via pressure forces / fluxes)

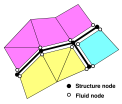
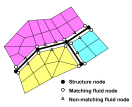
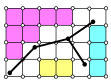
10

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 and **structure motion** provides weak feedback on fluid (S=master / F=slave)

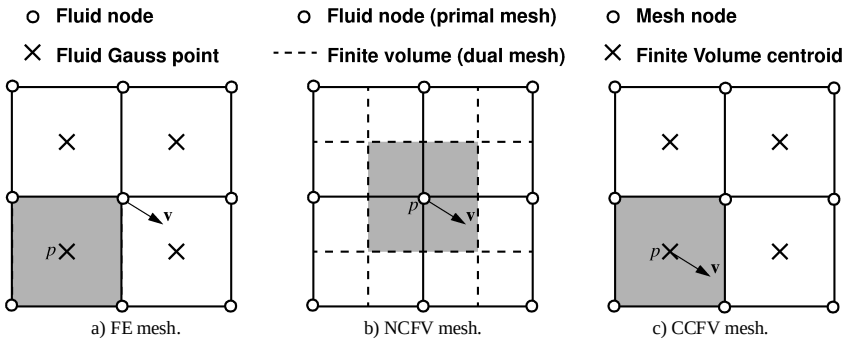
A Classification of FSI Algorithms

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

A Summary of FSI Algorithms

Spatial discretization for the fluid



a) FE mesh. b) NCFV mesh. c) CCFV mesh.

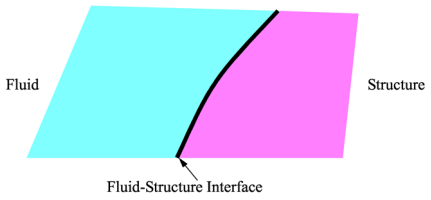
Both components of FSI algorithms must be adjusted to the chosen type of spatial discretization

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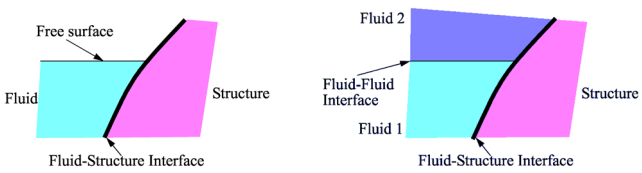
Basic FSI Algorithms

FSI for compressible, inviscid fluids can be:

- Permanent



- Non-permanent

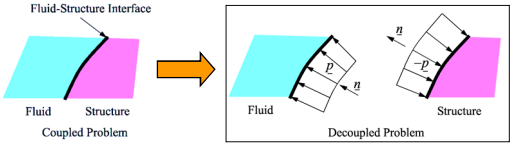


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Permanent FSI treatment

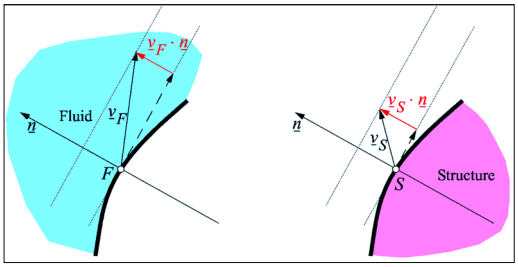
Fits naturally in ALE formulation:

- Ideally decouple problem by introducing contact pressure



  - Inviscid fluid: interaction pressure acts along the normal $\underline{n}$ to the interface

- Impose material velocity compatibility condition: $\underline{v}_F \bullet \underline{n} = \underline{v}_S \bullet \underline{n}$

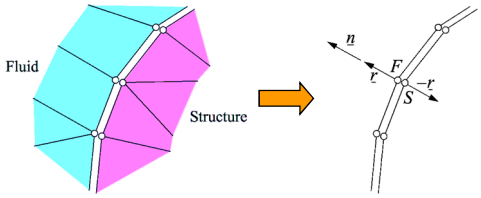


  - Tangential velocity components are unconstrained
  - Mesh velocities at interface obey: $\underline{w}_F = \underline{w}_S$

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Permanent FSI treatment (2)

- Upon discretization, contact pressure is replaced by interaction force $\underline{r}$



  - Interaction force $\underline{r}$ is the resultant of the contact pressure at each node of the interface

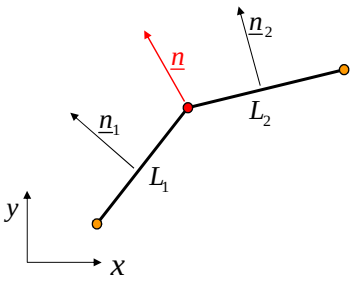
- For the moment, assume *nodal conformity* at the F-S interface
- Velocity compatibility condition $\underline{v}_F \bullet \underline{n} = \underline{v}_S \bullet \underline{n}$ is of the form $\underline{C}\underline{v} = \underline{b}$ therefore one can use Lagrange multipliers to find $\underline{r}$ (see Part 1)
- However, the following apparently simple question arises:

How does one define "the" normal to a discrete F-S interface?

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The 2-D plane case

Pioneering work (1980s) by Donea, Giuliani, Halleux:



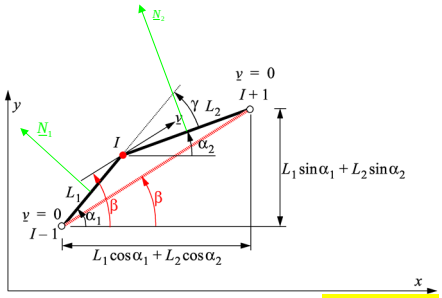
- Physical intuition: the discrete normal is some <u>average</u> of the adjacent sides normals: $\underline{n} = (\underline{n}_1 + \underline{n}_2) / \|\underline{n}_1 + \underline{n}_2\|$
- Works well only in 2D <u>plane</u> cases, and for <u>uniform</u> mesh: $L_1 = L_2$

- In more general cases, the <u>mass balance</u> is incorrect: some fluid is "gained" or "lost" at the interface corners

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The 2-D plane case (2)

Use geometric flux of <u>relative</u> velocity:



- Fluid <u>mass is conserved</u> when: $\Phi_1 + \Phi_2 = 0$

  $\Rightarrow \boxed{\tan\beta = \dfrac{L_1 \sin\alpha_1 + L_2 \sin\alpha_2}{L_1 \cos\alpha_1 + L_2 \cos\alpha_2}}$

- Assume structure is fixed and fluid is at rest at nodes *I-1* and *I+1*, while it has velocity $\underline{v}$ of slope β at node *I*.
- The fluid flux "entering" side L_1 is proportional to:

$$\Phi_1 = \|\underline{v} \bullet \underline{N}_1\| = vL_1 \cos(\frac{\pi}{2} + \alpha_1 - \beta) = vL_1 \sin(\alpha_1 - \beta)$$

- The fluid flux "entering" side L_2 is proportional to:

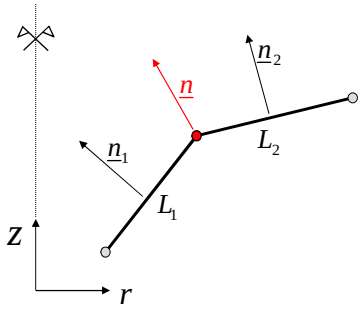
$$\Phi_2 = \|\underline{v} \bullet \underline{N}_2\| = vL_2 \cos(\frac{\pi}{2} + \alpha_2 - \beta) = vL_2 \sin(\alpha_2 - \beta)$$

- The angle β is the slope of the line connecting nodes *I-1* and *I+1*
- When $L_1 = L_2 = L$ this reduces to: $\tan\beta = \dfrac{\sin\alpha_1 + \sin\alpha_2}{\cos\alpha_1 + \cos\alpha_2}$, i.e.: $\boxed{\beta = \dfrac{\alpha_1 + \alpha_2}{2}}$

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Exercise 1 – the 2-D axisymmetric case

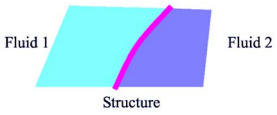
- Find analytical expression of the normal direction in 2-D axisymmetric geometry.
- Does the geometrical property (connecting line) hold also in this case?
- Show that the obtained expression tends to the one for plane geometry as the radius tends to infinity.



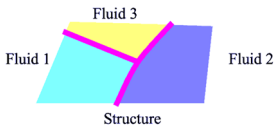
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Geometrically complex cases

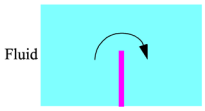
- Bilateral fluid contact:



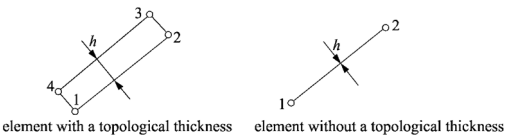
- Structural joints (bifurcations):



- Submerged structural edges:



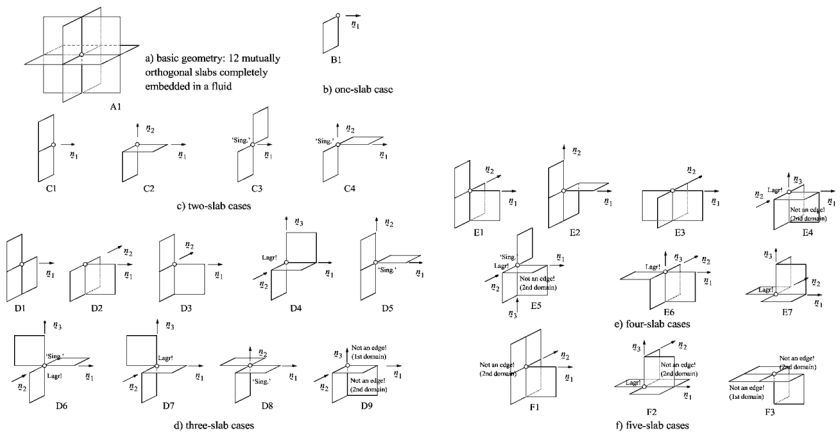
- Structural elements without topological thickness:



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Geometrically complex cases (2)

- 3-D box-like structures:



Types of classical FSI algorithms

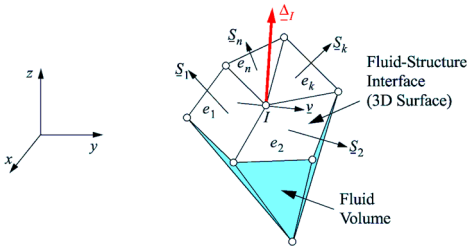
- Purely geometrical methods, based only upon topology of the F-S interface in the vicinity of node under consideration:
  - FSA algorithm (Fluid-Structure ALE)
- Non-geometrical methods, based upon equilibrium considerations:
  - UP algorithm (Uniform Pressure)
- Hybrid methods:
  - FSCR algorithm

The FSA algorithm

- Purely geometrical method, based upon local shape of fluid domain only (avoids ambiguities due to no-thickness structural elements).
- Normal direction obtained from zero net velocity flux condition across discrete interface (no fluid gains or losses):

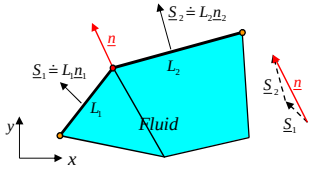
  $\underline{\Delta} \doteq$ influence domain of node

  $\underline{n} = \underline{\Delta} / \|\underline{\Delta}\|$ with $\underline{\Delta} = \sum_{k=1}^{n} \underline{S}_k$



- The 2-D plane case:

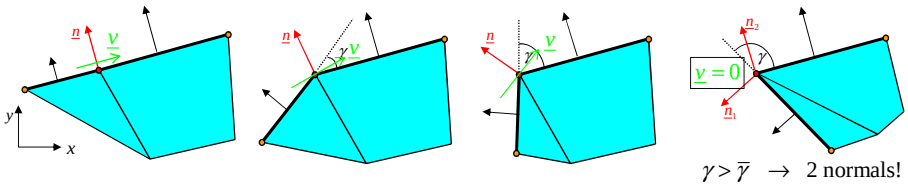
  $\underline{n} = (\underline{S}_1 + \underline{S}_2) / \|\underline{S}_1 + \underline{S}_2\|$



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The FSA algorithm (2)

- Effect of progressive "sharpening" of interface corner:



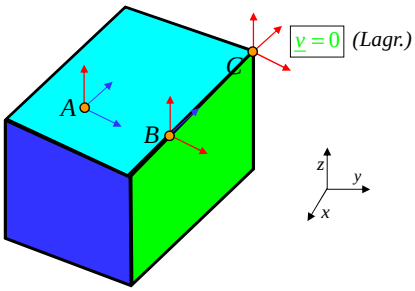
$\gamma > \bar{\gamma}$ → 2 normals!

- Face vectors $\underline{S}_k$ are subdivided into one or more groups. Vectors in same group form angle < than given value $\bar{\gamma}$.
- Each group is used to generate one normal.
- If the number of independent normals equals the space dimension, the node is set Lagrangian and "tied" to the structural node: $\underline{v}_F = \underline{v}_S$

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The FSA algorithm (3)

- Thus, in 3D cases one can have 1 or 2 normals in an ALE node:



A: 1 normal (blocked), 2 free

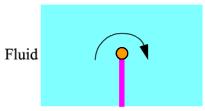
B: 2 normals (blocked), 1 free

C: 3 normals (blocked), node becomes Lagrangian, tied to structure

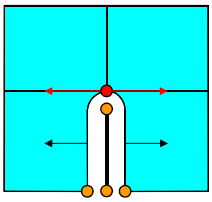
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The FSA algorithm (4)

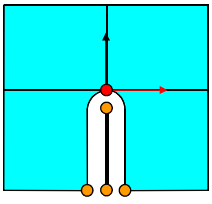
The case of submerged structural edges:



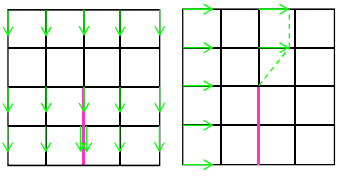
- If the structural element has no topological thickness, the node at the tip is a singular point as concerns the normal



- FSA strategy outlined so far would lead to two mutually opposite normals: one is redundant and should be rejected



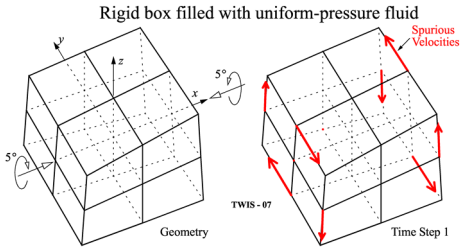
- Aligned flow is undisturbed, transversal flow "sticks" at tip



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Shortcomings of the FSA algorithm

- Onset of spurious velocities in 3-D models with warped element faces.
  Example: patch test



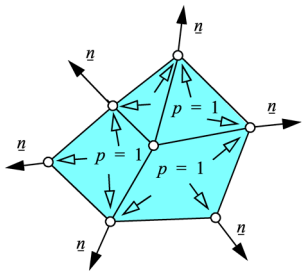
- Reason: slight but non-negligible accuracy mismatch in calculation of internal pressure forces and of reactions (direction of the normal)
- FSA method is purely geometrical and uses no information about internal fluid element formulation (e.g., spatial integration rules)

⇒ • Investigate alternative methods based on equilibrium

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The UP algorithm

The method simply relies upon the observation that:



→ Element's pressure forces $\underline{\varphi}_p^{\text{elem}}$

The direction of the discrete normal coincides with the resultant of internal forces due to an arbitrary but uniform pressure (say, p=1) in the whole fluid domain.

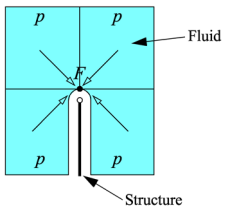
$$\underline{\varphi}_p^{\text{elem}} = \frac{1}{p}\,\underline{f}_p^{\text{elem}} \xrightarrow[\underline{\varphi}_p = \sum \underline{\varphi}_p^{\text{elem}}]{\text{Assembly}} \underline{n} = \underline{\varphi}_p \,/\, \left\| \underline{\varphi}_p \right\|$$

- Computationally inexpensive because $\underline{f}_p^{\text{elem}}$ are computed anyway.
- Ensures perfect equilibrium and therefore avoids shortcomings of purely geometrical methods e.g. with warped 3-D faces.

28

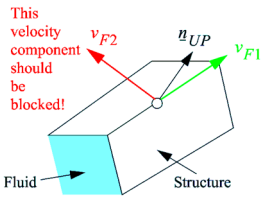
Shortcomings of the UP algorithm

- It fails at submerged structural edges with no topological thickness: the assembled force vanishes and thus the normal is undetermined.

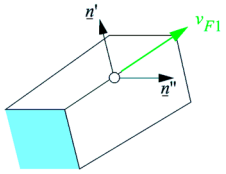


Element's pressure forces in node F

The assembled force for uniform pressure in node F is zero



UP Method: One Normal

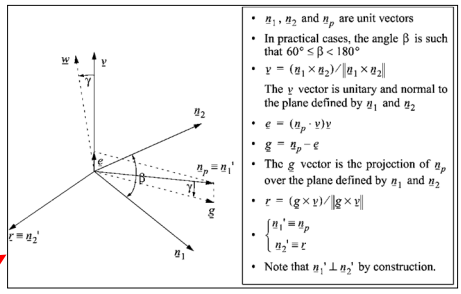


Geometric Method: Two Normals

- It can yield at most one normal per node.

The FSCR algorithm

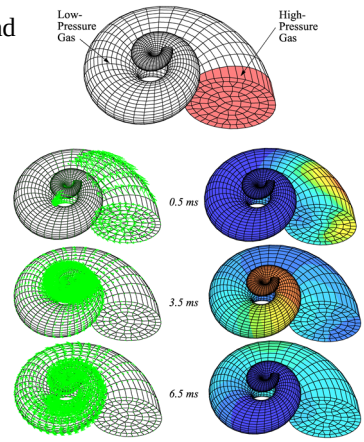
Combination of FSA and UP, exploiting respective strengths.



- Search normal(s) by FSA: $\underline{n}_1$ ($\underline{n}_2$).
- Search normal by UP: $\underline{n}_p$.
- If FSA yields influence domain composed only by mutually opposite faces, we know that $\underline{n}_p$ is undetermined: keep $\underline{n}_1$ ($\underline{n}_2$).
- In all other cases $\underline{n}_p$ is more accurate than $\underline{n}_1$ ($\underline{n}_2$). If there is only one FSA normal $\underline{n}_1$, we take $\underline{n}_p$ instead. Else there are two FSA normals $\underline{n}_1$, $\underline{n}_2$: we correct them so that $\underline{n}_p$ is contained in the plane defined by $\underline{n}'_1$, $\underline{n}'_2$.

The case of rigid structures (FSR)

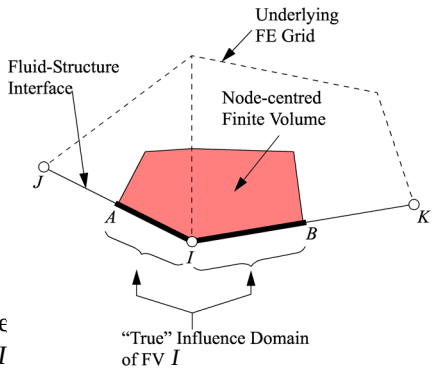
- When structural displacements are known to be negligible (rigid structures), only the fluid needs to be modeled
- The compatibility condition simplifies to: $\underline{v}_F \cdot \underline{n} = 0$
- The normal $\underline{n}$ is constant in time and needs to be computed only once
- The geometric and equilibrium-based methods can be used unchanged, apart from suitable simplifications
- Practical aspect: the automatic FS directives dramatically simplify the prescription of boundary conditions in geometrically complex cases



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Application to NC Finite Volumes

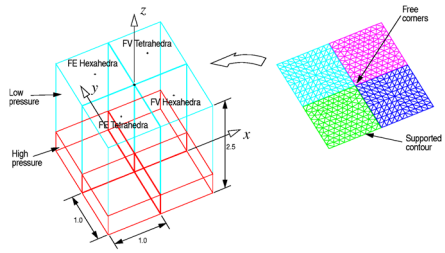
- The FS algorithms illustrated above in a FE context have been applied with success also to node-centered FV
- Some adjustments needed as shown above, since "native" FV time integration scheme is Forward Euler (not CD)
- The two schemes can be reconciled by adding a suitable force term to the equilibrium equation
- Velocity constraint on $\underline{v}_I$ can appear "too strong" since the boundary node (I) represents the (average of the) whole volume I

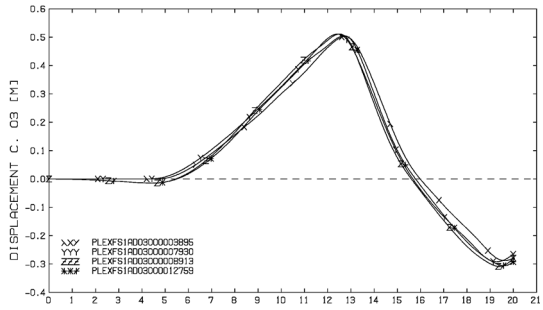


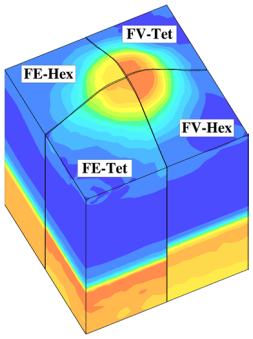
32

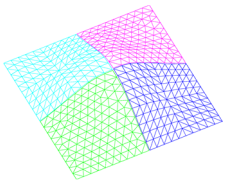
Application to NC Finite Volumes (2)

- Shock tube + FSI



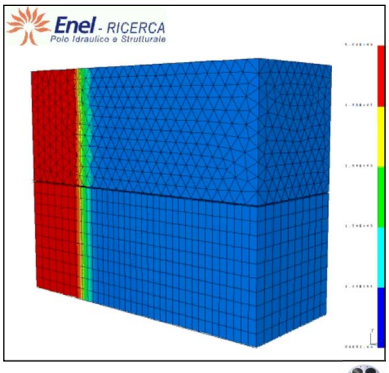


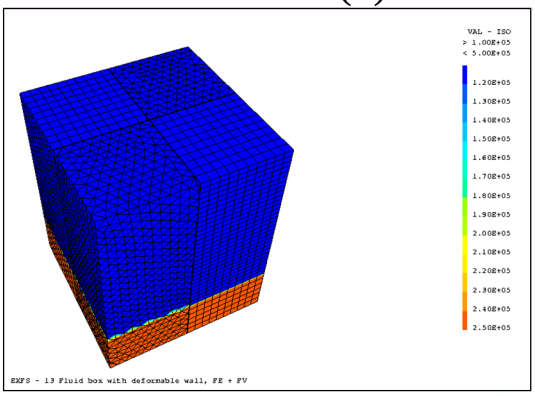


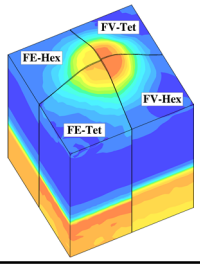


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Application to NC Finite Volumes (3)







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"Strong" *vs.* "Weak" Coupling

- The technique seen so far for the enforcement of boundary conditions, in particular of FSI, is sometimes denoted as **strong** coupling
- In fact, F and S are "strongly" linked together by the imposed constraints on velocities at F-S interface
- Especially in the CFD community, there exists another technique, sometimes called **weak** coupling
- In this technique, suitable fluid pressure forces are introduced and transmitted to the structure
- The structure (alone) then determines the motion of the F-S interface, and this provides a ("weak") feedback on the physical status of the fluid (via interface velocity)

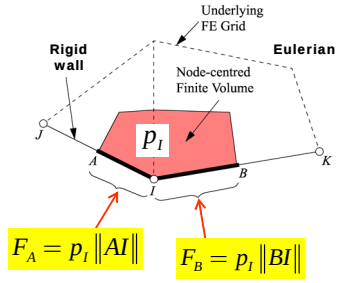
35

Weak BCs in NCFV

- "Weak" treatment of boundary conditions can be chosen in the NCFV model by adding the optional keyword **WBC**

OPTI MC … WBC

- In this case, the **LINK** directive should of course be omitted
- At the moment, this is limited to the representation of rigid walls in Eulerian calculations (no structure!)
- The code automatically recognizes the boundaries and applies suitable "external" pressure forces to the fluid

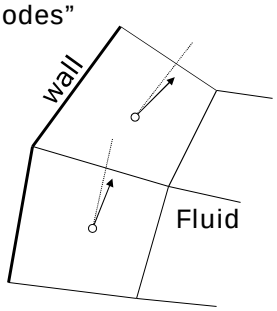


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Boundary Conditions in CC Finite Volumes

("Weak" formulation only, at the moment)

- Note : fluid velocities (like all other quantities) are defined at the volume centres, not at "nodes"
- At volume faces on the fluid boundary, fluxes are **not** computed (no neighbor)
- Therefore, zero normal velocity condition is "automatically" satisfied (in an approximate way) at a rigid wall (and, in a weak manner, also at cell centres)



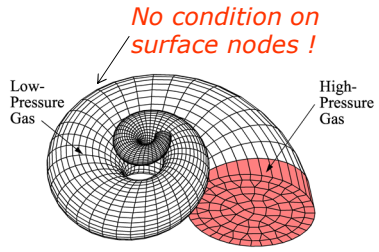
- If a structure is attached (merged nodes) to the fluid boundary, the code automatically computes pressure forces and applies them to the structure (weak FSI coupling) : no need to specify any link condition

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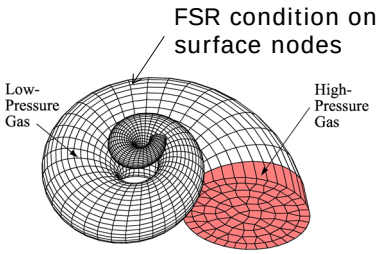
FSI with C-C Finite Volumes

(for a conforming FS mesh)

- To represent a rigid structural boundary, just leave the boundary "nodes" free (no need to use FSR condition)
- No flux calculation takes place at the boundary since volumes on the interface have no neighbors : a rigid-wall condition results automatically



C-C FV



FE or N-C FV

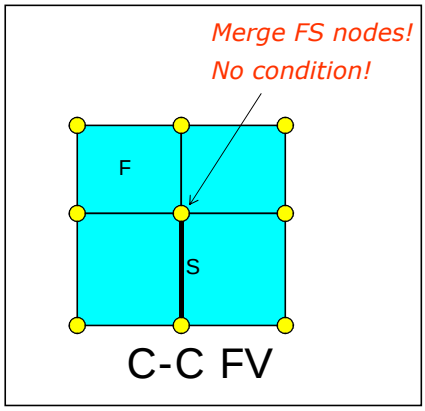
(Strong coupling)

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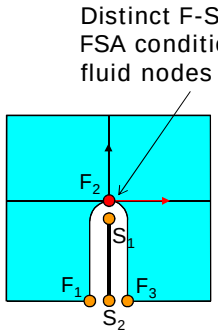
FSI with C-C Finite Volumes (2)

(for a conforming FS mesh)

- To represent a deformable structural boundary, just merge the structure and fluid nodes (no need to use FSA condition)



C-C FV



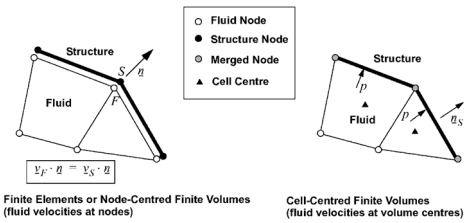
FE or N-C FV

FSI with C-C Finite Volumes (3)

(for a conforming FS mesh)

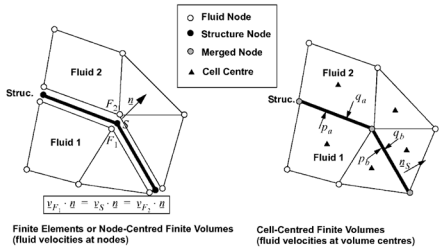
- The same technique works also in case of "double" (two-sided) FS Interface

Single FS Interface



FE or N-C FV C-C FV

Double FS Interface

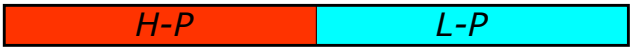


FE or N-C FV C-C FV

- The fact that velocities are discretized at cell centres facilitates the treatment of structure fragmentation (see Part IV)

Exercise 1a – Shock Tube

(FE / FV, Strong / Weak BCs)

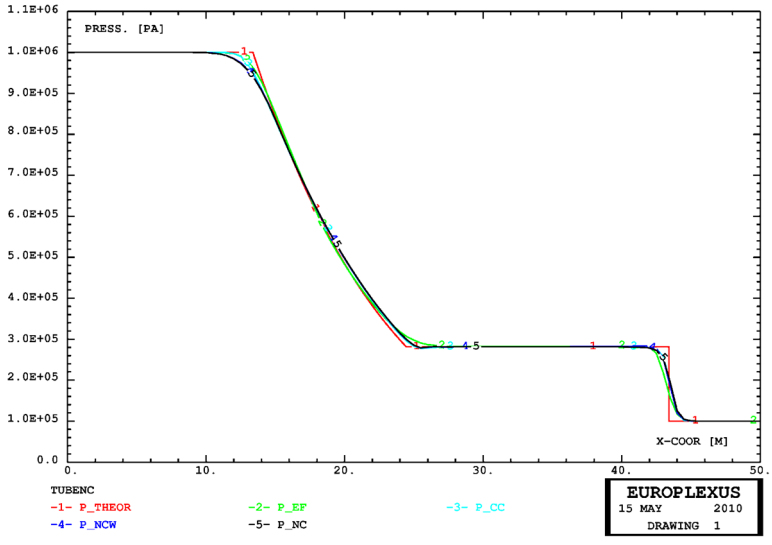


- Obtain various solutions and compare them with analytical solution (single-component perfect gas):
  - FE, strong BCs
  - NCFV, strong BCs
  - NCFV, weak BCs
  - CCFV, weak BCs

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Exercise 1a – Shock Tube

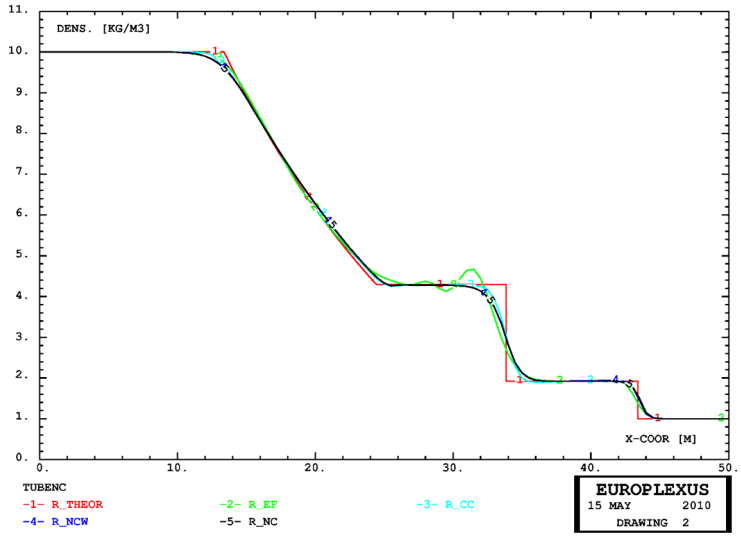
- Fluid pressures (red curve is the analytical solution)



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Exercise 1a – Shock Tube

- Fluid densities (red curve is the analytical solution)

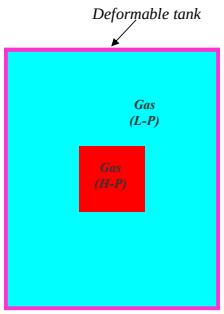


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Exercise 2 – Explosions in simple deformable containers

Add a deformable structure to the case studied in exercise 2 of Part II (air-filled tank).

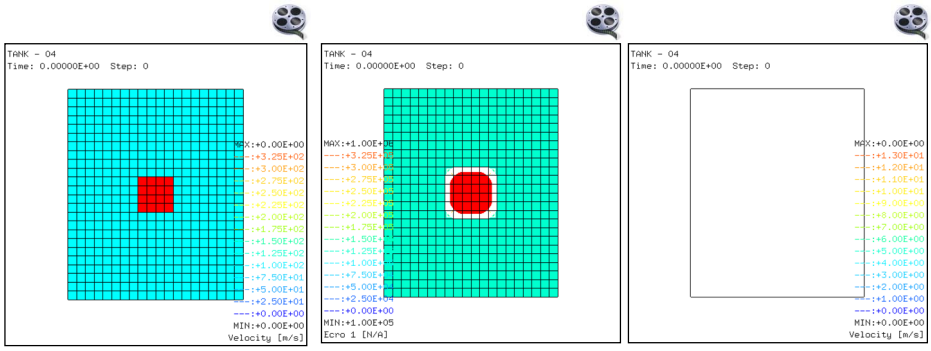
- Try out ALE solution with FSA



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Exercise 2 – Explosions in simple deformable containers (2)

- ALE solution with FSA (TANK04):



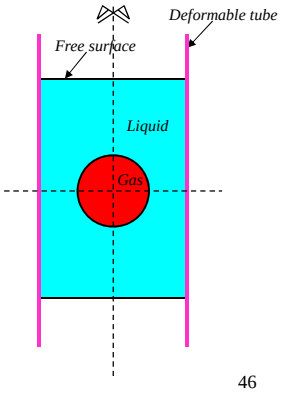
Velocities *Fluid Pressures* *Structure Velocities*

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Exercise 2 – Explosions in simple deformable containers (3)

Treat as deformable the tube of the case studied in exercise 3 of Part II.

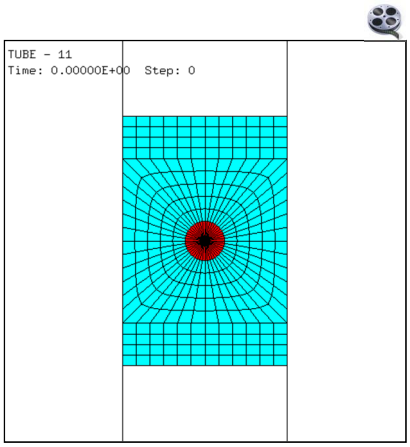
- Can one try out ALE solution with FSA?
- Alternative 1: use Lagrangian sliding
- Alternative 2: use FSA with multi-phase multi-component fluid model

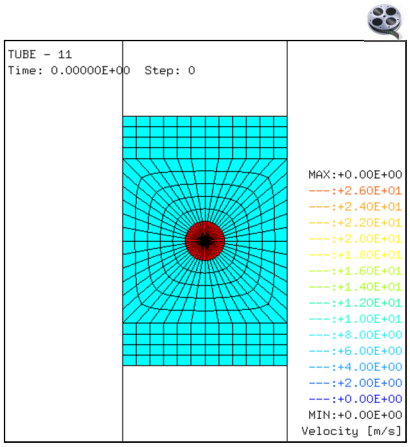


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Exercise 2 – Explosions in simple deformable containers (4)

- Alternative 1: use Lagrangian sliding (TUBE11):

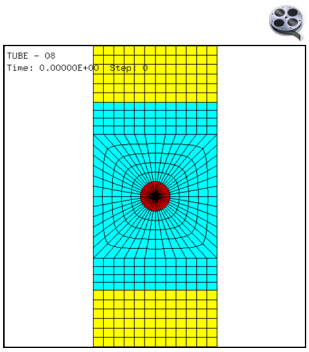


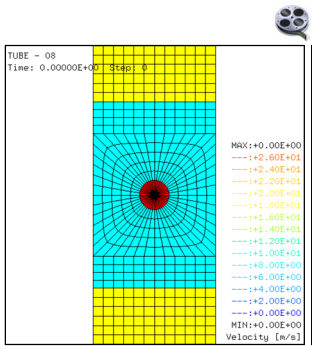


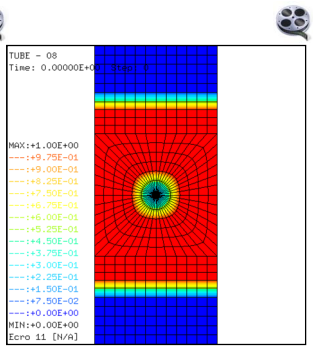
Mesh *Velocities*

Exercise 2 – Explosions in simple deformable containers (5)

- Alternative 2: use multi-phase multi-component fluid model (TUBE08):





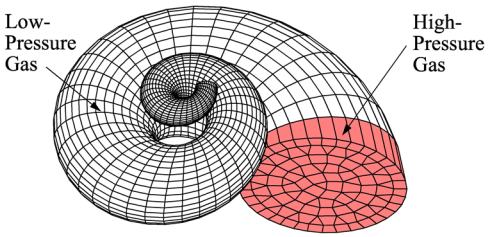


Mesh *Velocities* *Liquid fraction*

Exercise/Example 3 – Wave propagation in 3-D rigid tank

The rigid outer surface has a complex 3-D shape.

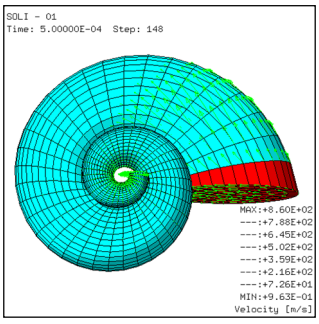
- Try out ALE solution with FSR



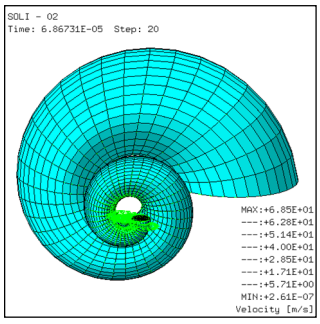
49

Exercise/Example 3 – Wave propagation in 3-D rigid tank (2)

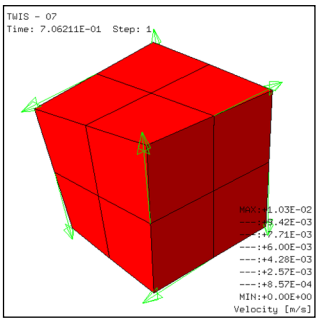
Spurious velocities:



FSR



FSR (Uniform pressure case)

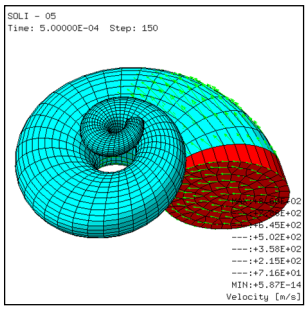


FSR (Patch test)

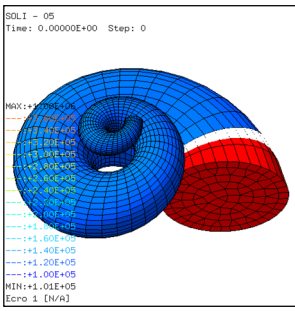
50

Exercise/Example 3 – Wave propagation in 3-D rigid tank (3)

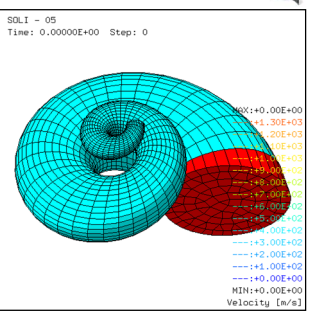
Solution with FSCR (SOLI05):



Velocities at 0.5 ms



Pressure



Velocity

Exercise/Example 3 – Wave propagation in 3-D rigid tank (4)

- *EUROPLEXUS input file (SOLI05):*

```
SOLI - 05
*-----------------------------------------------------------------------
 ECHO
 CONV win
CAST MESH
*-------------------------------------------------------------Problem type
TRID EULE
*-------------------------------------------------------------Dimensioning
DIME
 PT3L 8760 FL38 6264 FL36 2016 ZONE 2
 NALE 1 NBLE 1
TERM
*-----------------------------------------------------------------Geometry
GEOM FL38 SUR8 FL36 SUR6 TERM
*-----------------------------------------------------Geometric Complements
COMP COUL roug LECT sur1 TERM
          turq LECT sur2 TERM
*-------------------------------------------------------------Material data
MATE FLUT RO 1.22 EINT 3.046E6 GAMM 1.269 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT SUR1 TERM
     FLUT RO 0.1237 EINT 3.046E6 GAMM 1.269 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT SUR2 TERM
*-----------------------------------------------------------Boundary conditions
OPTI FSCR
LINK COUP FSR LECT FSRN TERM
*-------------------------------------------------------------------Outputs
ECRI VITE ECRO TFRE 7.0E-5
     ELEM LECT 1 TERM
     POIN LECT 1 TERM
     FICH K2000 TFRE 0.5E-3 POIN TOUS
               VARI DEPL VITE ECRO ECRC LECT 1 TERM
     FICH ALIC TFRE 7.0E-5
*-----------------------------------------------------------------Options
OPTI NOTE
     CSTA 0.5
     LOG 1
*-----------------------------------------------Transient calculation
CALCUL TINI 0 TEND 7.0E-3
```

```
*-------------------------------------------------------------ANIMATION
PLAY

CAME   1 EYE   2.95448E-01 -5.06866E+00  6.53167E+00
!        Q     9.56305E-01  2.92372E-01  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  5.59193E-01 -8.29038E-01
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  8.29038E-01  5.59193E-01
         FOV   1.68819E+01

scen
     vect scav
     text vsca
     lima on
     colo pape

sler caml 1 nfra 1

freq 0 tfre 0.5e-3

go
trac offs fich bmp rend

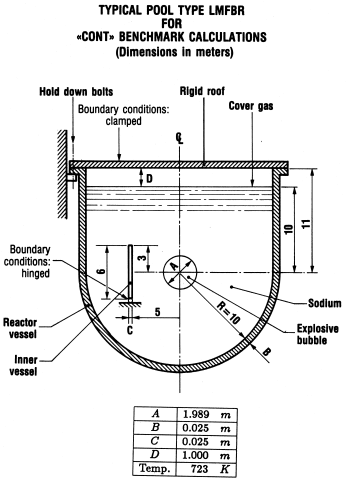
freq 0 tfre 7.0e-3
go

ENDPLAY
*-----------------------------------------------------------------------
FIN
```

Exercise/Example 4 – CONT problem

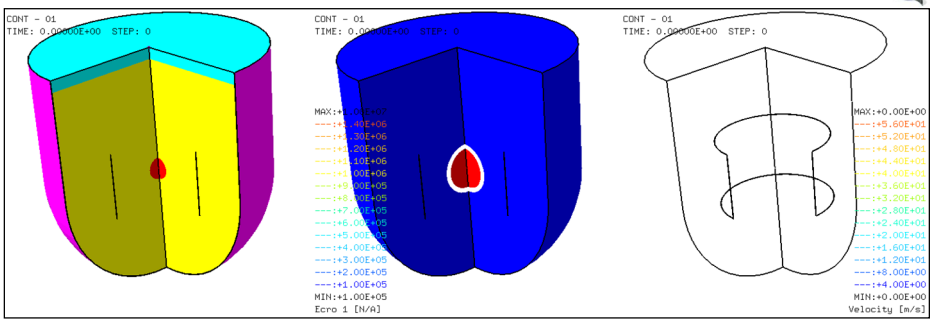
Three fluids plus deformable structures

- Try out ALE solution with Lagrangian fluid/fluid interfaces (single-component fluid model)
- Try out ALE solution with ALE fluid/fluid interfaces (multi-phase multi-component fluid model)



Exercise/Example 4 – CONT problem (2a)

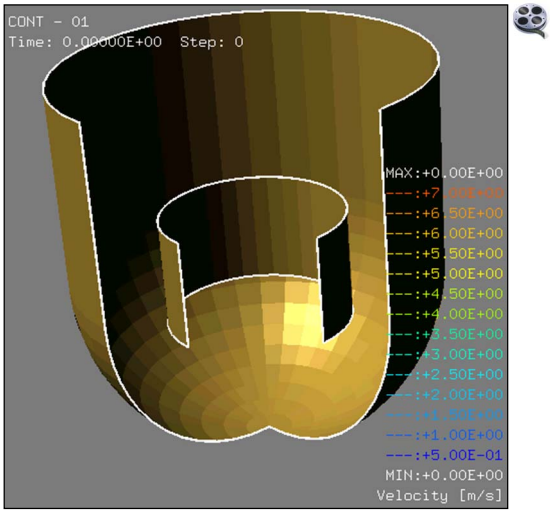
- ALE solution with Lagrangian fluid/fluid interfaces (single-component fluid model) (CONT01):



Materials *Pressures* *Velocities*

Exercise/Example 4 – CONT problem (2b)

- ALE solution with Lagrangian fluid/fluid interfaces (single-component fluid model) (CONT01):

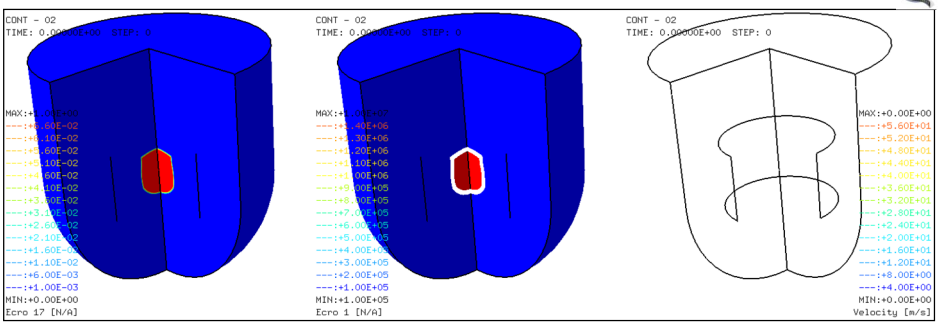


Structure Motion and Velocities

55

Exercise/Example 4 – CONT problem (3a)

- ALE solution with ALE fluid/fluid interfaces (multi-phase multi-component fluid model) (CONT02):

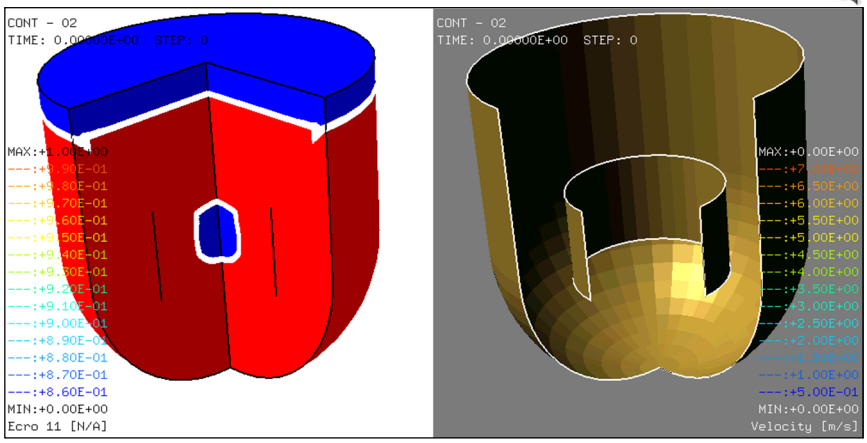


Bubble fraction *Pressure* *Velocity*

56

Exercise/Example 4 – CONT problem (3b)

- ALE solution with ALE fluid/fluid interfaces (multi-phase multi-component fluid model) (CONT02):



Sodium fraction

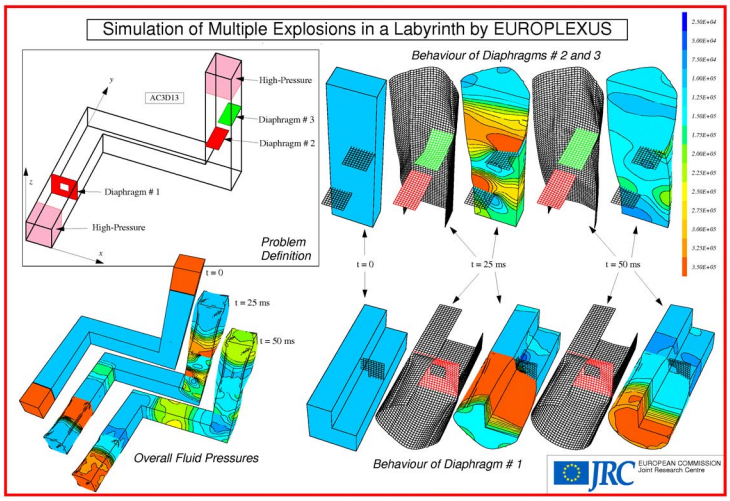
Structure Motion and Velocities

Exercise/Example 4 – CONT problem (4)

- *EUROPLEXUS input file (CONT02):*

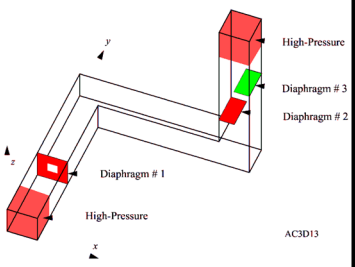
```
CONT - 02
*-----------------------------------------------------------------------
 ECHO
CAST mesh
!CONV win
*-------------------------------------------------------------Problem type
AXIS ALE
*-------------------------------------------------------------Dimensioning
DIME
   PT2L 278 PT3L 35 ZONE 3
   ED01 33 FL24 230 FL23 28
   NALE 18 NBLE 278
   ECRO 13128
TERM
*-----------------------------------------------------------------Geometry
GEOM ED01 stru FL23 flui3 FL24 flui4 TERM
*-----------------------------------------------Geometric Complements
COMP EPAI 2.5E-2 LECT stru TERM
*-------------------------------------------------------------Grid motion
GRIL LAGR LECT stru TERM
     AUTO AUTR
*-----------------------------------------------------------Material data
MATE VM23 RO 7800. YOUN 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT vessel TERM
     VM23 RO 7800. YOUN 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT shield TERM
     FLMP NLIQ 1 NGAS 2
     FLUT RO 832. EINT 98.68 GAMM 7.15D0 CL 0.5 CQ 2.56
          PB 2.71E5 PMIN 0. AHGF 0. ITER 2 ALF0 1.
          BET0 1. KINT 0 NUM 5
          LECT liqu TERM
     FLUT RO 2.4278E3 EINT 0. GAMM 0.75D0 CL 0.5 CQ 2.56
          PB 0. PMIN 0. AHGF 0. ITER 2 ALF0 1.
          BET0 1. KINT 0 NUM 4
          LECT bull TERM
     FLUT RO .242777373 EINT 6.865E5 GAMM 1.6 CL 0.5 CQ 2.56
          PB 0. PMIN 0. AHGF 0. ITER 2 ALF0 1.
          BET0 1. KINT 0 NUM 1
          LECT gas TERM
*-----------------------------------------------------Boundary conditions
LINK COUP
     BLOQ 1 LECT p2p TERM
     BLOQ 123 LECT p4p TERM
     CONT SPLA NX 1 NY 0 LECT symax TERM
     CONT SPLA NX 0 NY 1 LECT top   TERM
     FSA  LECT fsan TERM
*-----------------------------------------------------------------Outputs
ECRI COOR DEPL VITE ACCE CONT ECRO TFRE 250.E-3
     FICH ALIC TEMP FREQ 1
          POIN LECT p0 TERM
     FICH ALIC TFRE 2.5E-3
*-------------------------------------------------------------Options
OPTI NOTE
     log 1 csta 0.5
     REZO GAM0 0.8
     FLMP EPS1 1.E-5
*-----------------------------------------------Transient calculation
CALCUL TINI 0.0 TEND 250.E-3
*=============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------Curve definitions
COUR 1  'dy_1'    DEPL COMP 2 NOEU LECT p0  TERM
*-------------------------------------------------------------------Plots
trac 1 axes 1.0 'DISPL. [M]' yzer
*-----------------------------------------------------Results qualification
QUAL DEPL COMP 2 LECT  p0 TERM REFE -1.23718E-1 TOLE 1.E-2
*=======================================================================
FIN
```

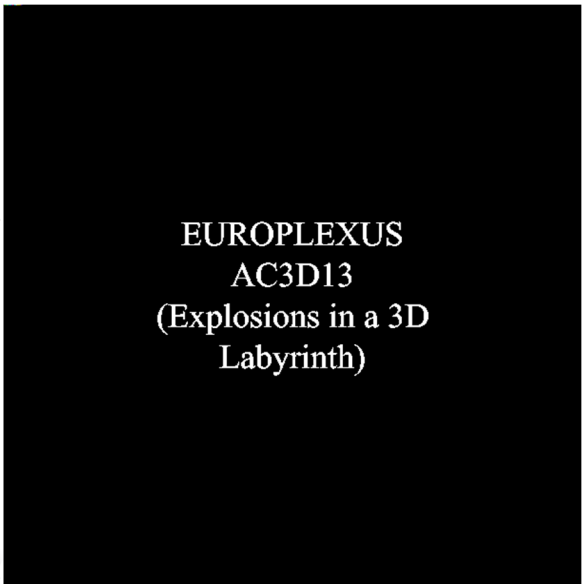
Exercise/Example 5 – Explosion in a 3-D Labyrinth



59

Exercise/Example 5 – Explosion in a 3-D Labyrinth

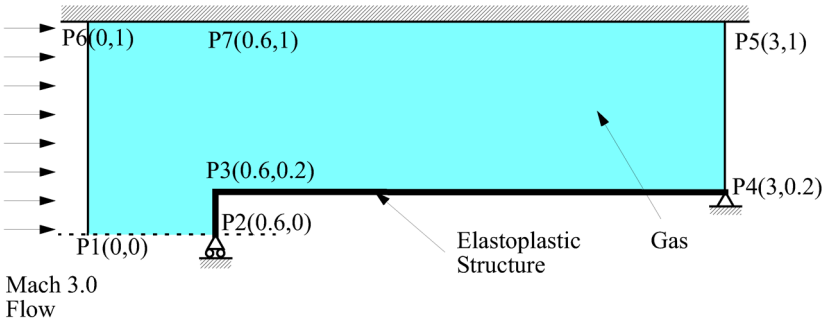




60

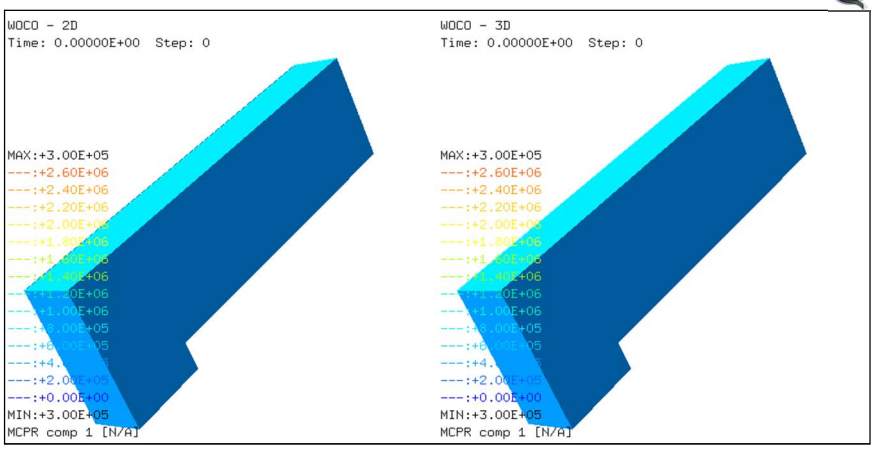
Exercise/Example 6 : Woodward-Colella Test (Node-Centered FV with deformable step)

Set up NC-FV model and treat the step as deformable:



61

Exercise/Example 6 : Woodward-Colella Test (2)



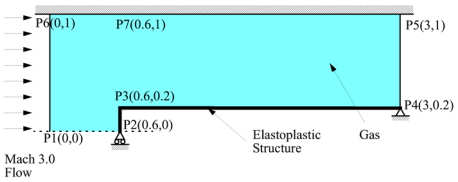
2D Solution (Pressure) *3D Solution (Pressure)*

62

Exercise/Example 6 : Woodward-Colella Test (3)

Mesh generation (2D):

```
*%siz 100
*
opti echo 1 dime 2 elem qua4;
opti titr 'WOCO - 2D';
*
p1 = 0 0;
p2 = 0.6 0;
p3 = 0.6 0.2;
p4 = 3 0.2;
p5 = 3 1;
p6 = 0 1;
p7 = 0.6 1;
tol = 0.001;
*
in = p1 d 40 p6;
s1 = in tran 24 (0.6 0);
s1 = chan s1 tri3;
*
la = p3 d 32 p7;
s2 = la tran 96 (2.4 0);
s2 = chan s2 tri3;
*
lh1 = p1 d 24 p2;
lh2 = p3 d 96 p4;
lh3 = p5 d 120 p6;
lv  = p2 d 8 p3;
out = p4 d 32 p5;
*
lfsa = lh2 et lv;
*
flui = s1 et s2;
mesh = flui et lfsa et in et out et lh1 et lh3;
```



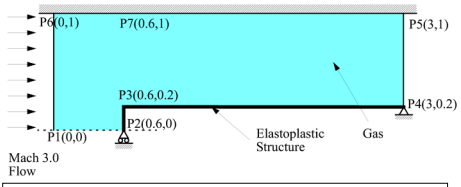

```
elim tol mesh;
*
p2s = p2 'PLUS' p1;
p3s = p3 'PLUS' p1;
p4s = p4 'PLUS' p1;
strt = p2s d 8 p3s d 96 p4s;
*
mesh = mesh et strt;
*
tass mesh;
*
opti sauv form 'woco2d.msh';
sauv form mesh;
opti trac psc ftra 'woco2d_mesh.ps';
trac mesh;
trac qual mesh;
```

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Exercise/Example 6 : Woodward-Colella Test (3)

Input (2D):

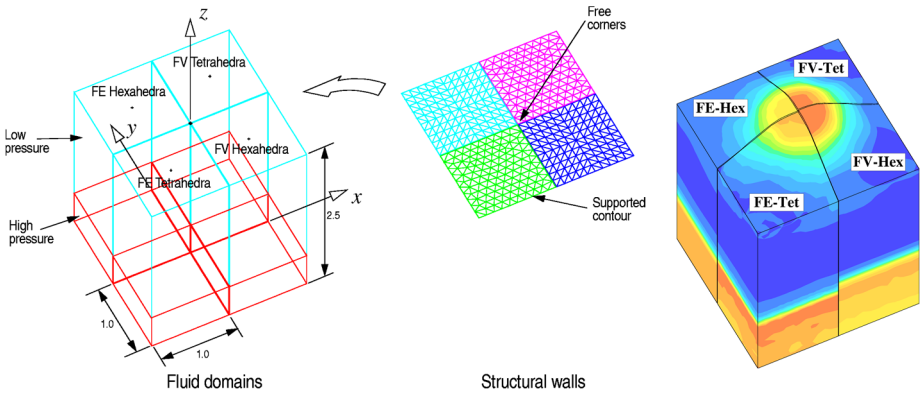
```
WOCO - 2D
ECHO
!CONV win
CAST MESH
DPLA ALE
DIME PT2L . . . TERM
GEOM
  MC23 flui
  ED01 strt
  CL22 in out
TERM
EPAI 0.020 LECT strt TERM
GRIL LAGR LECT strt   TERM
     EULE LECT in out TERM
     AUTO AUTR
$ multicomponent material
MATE MCGP NCOM 2 R 8312.
          COMP 'Air' PM 28.96 CV1 20780 CV2 0 CV3 0
          COMP 'Nitrogen' PM 28.96 CV1 20780 CV2 0 CV3 0
          LECT flui TERM
     MCFF BDFO 3 TEMP 400. PRES 300000.
          VEL1 1202.7 VEL2 0. VEL3 0.
          COMP 'Air'       MFRA 1.
          COMP 'Nitrogen'  MFRA 0.
          LECT in out TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT strt TERM
```




```
INIT MCOM COMP 'Air'      MFRA 1.0 LECT TOUS
          COMP 'Nitrogen' MFRA 0.0 LECT TOUS
          PRES 300000.     LECT TOUS
          TEMP 400.        LECT TOUS
          VEL1 1202.7      LECT TOUS
          VEL2 0.00        LECT TOUS
          VEL3 0.00        LECT TOUS
LINK COUP
     BLOQ 123 LECT p4s          TERM
     BLOQ 2   LECT p2s lh3 lh1 TERM
     FSA      LECT lfsa         TERM
$
ECRI . . .
$
OPTI NOTE CSTA 0.5
OPTI MC ORDR 2 NUFL ROE rezo gam0 0.5 log 1
CALCUL TINI 0 TEND 3.5E-3
```

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Exercise/Example 7 : Exfs Test (Comparison FE / NC-FV)

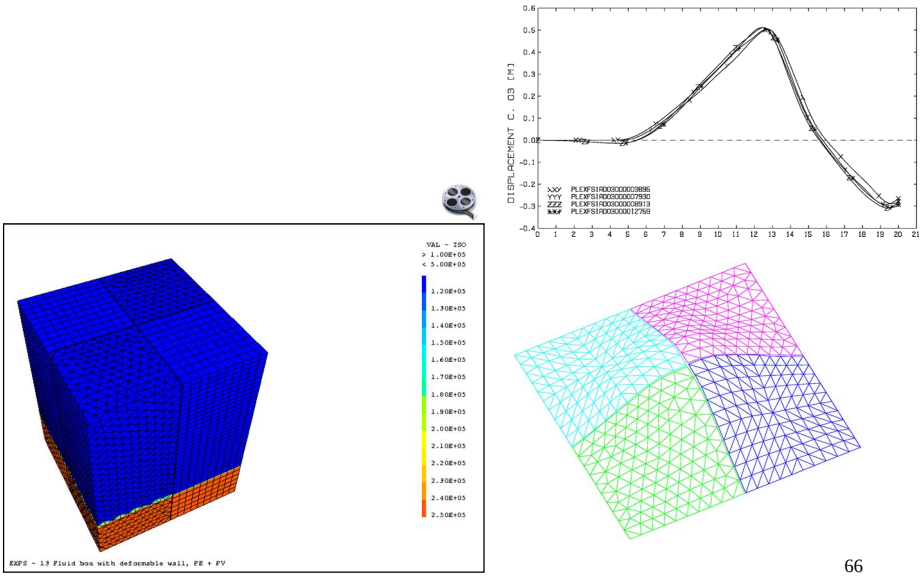


Fluid domains

Structural walls

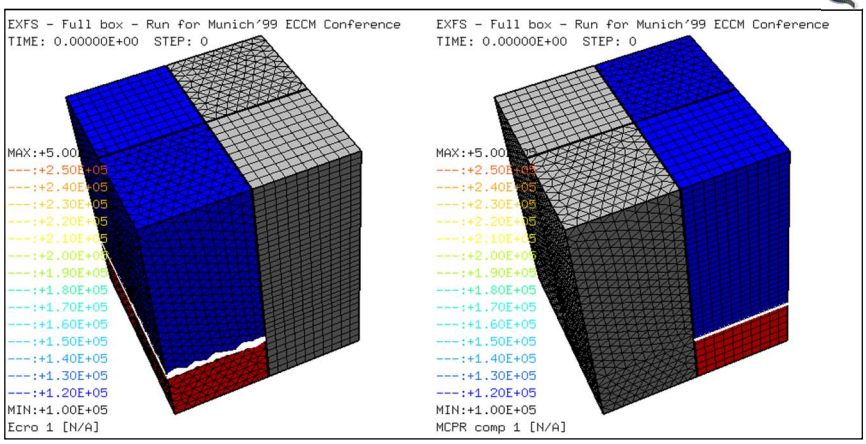
65

Exercise/Example 7 : Exfs Test (2)



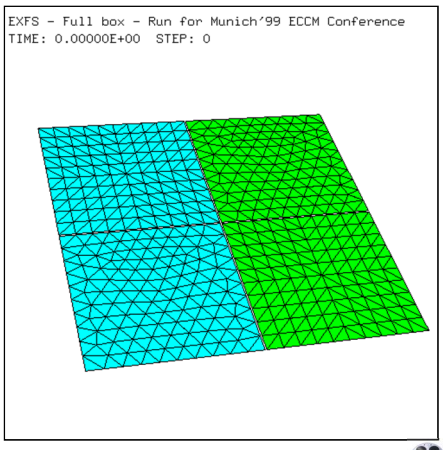
66

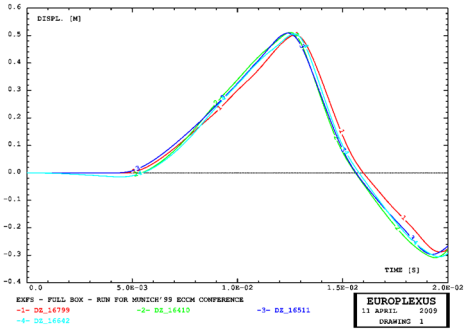
Exercise/Example 7 : Exfs Test (3)



FE *FV*

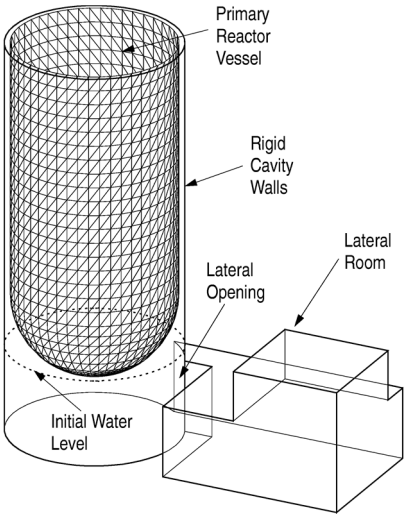
Exercise/Example 7 : Exfs Test (4)

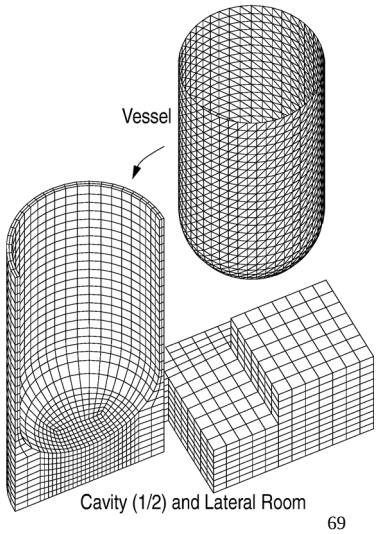




Exercise/Example 8
Steam Explosion in Reactor Cavity

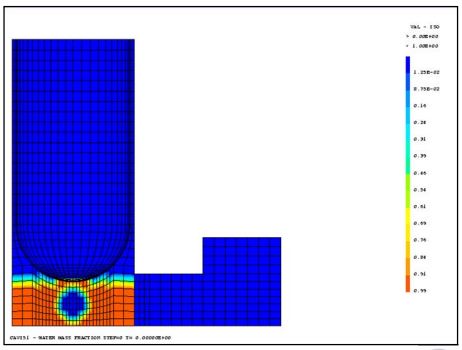
Geometry:



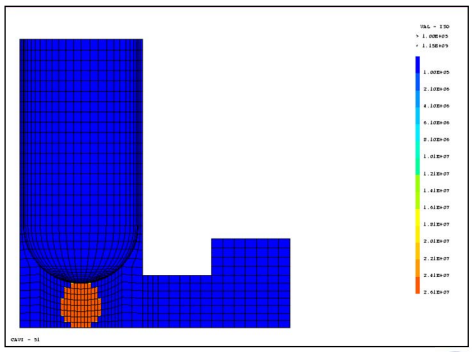


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Exercise/Example 8 : Steam Explosion in Reactor Cavity (2)



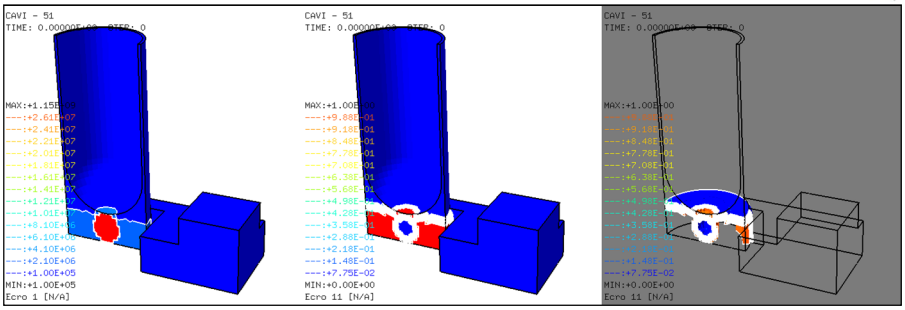
Water mass fraction



Pressure

70

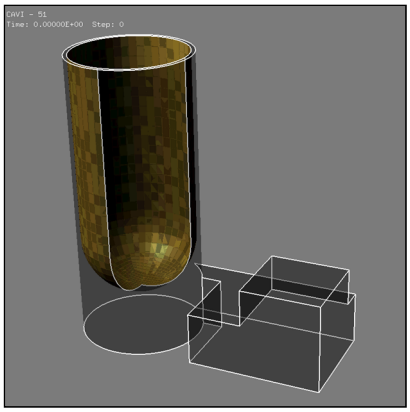
Exercise/Example 8 : Steam Explosion in Reactor Cavity (3)

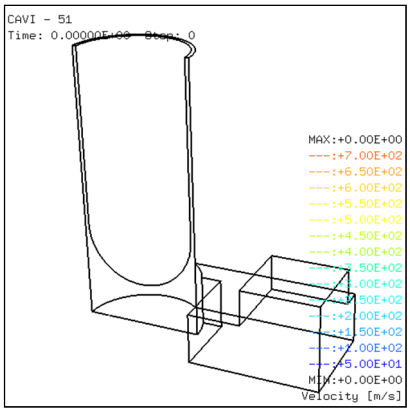


Pressure *Water* *Water (surfaces)*

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Exercise/Example 8 : Steam Explosion in Reactor Cavity (4)



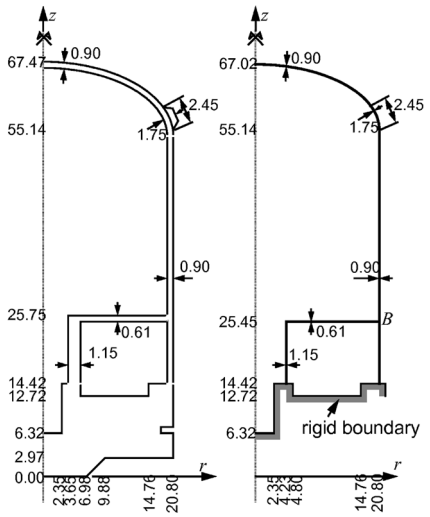


Structure *Velocities*

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Exercise/Example 9
Explosion in Secondary Containment

Geometry:

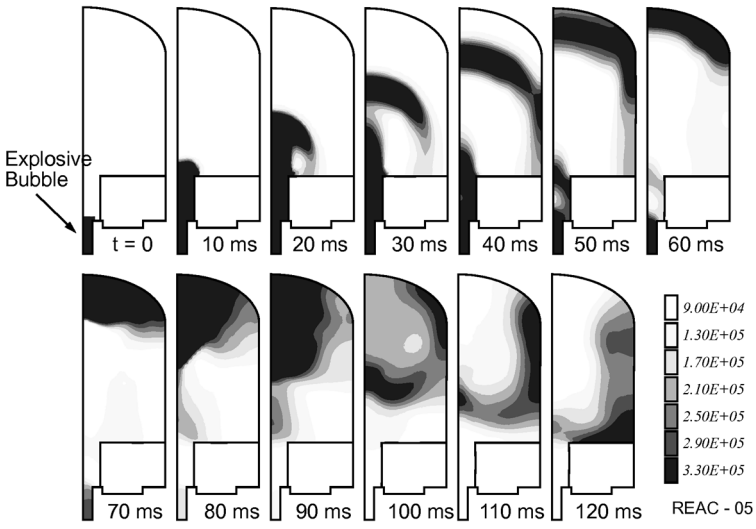


Layer N.	φ_L	Material
1	0.1	concrete
2	0.01	steel
3	0.78	concrete
4	0.01	steel
5	0.1	concrete

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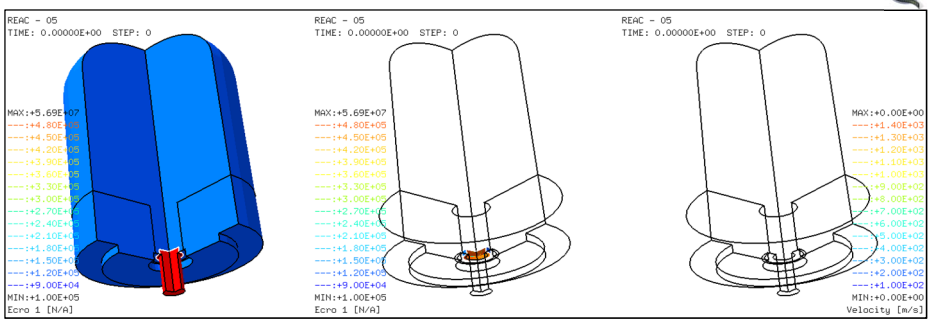
Exercise/Example 9
Explosion in Secondary Containment (2)

Geometry:



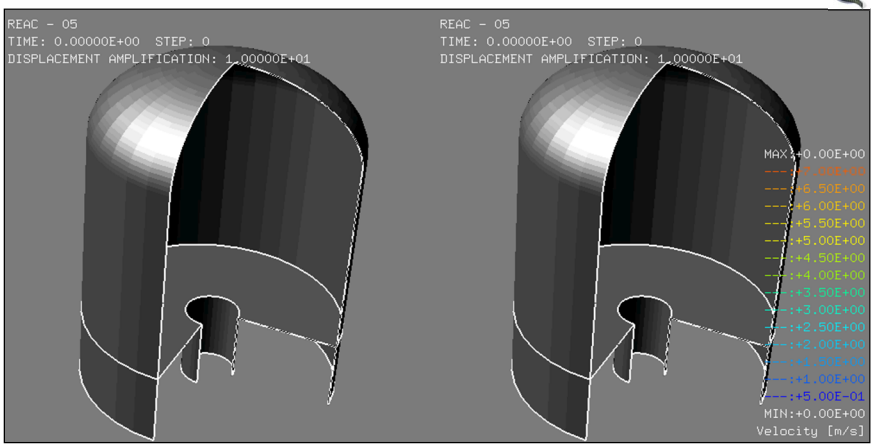
74

Exercise/Example 9
Explosion in Secondary Containment (3)



Pressure *Pressure (surfaces)* *Velocities*

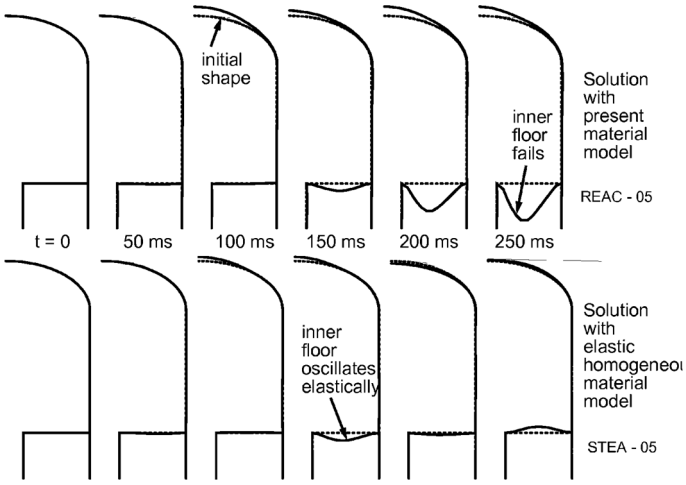
Exercise/Example 9
Explosion in Secondary Containment (4)



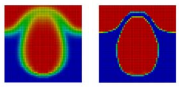
Structure *Structure velocities*

Exercise/Example 9
Explosion in Secondary Containment (5)

Comparison of elastic and reinforced concrete (elastoplastic) material solutions:



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Power excursion in a reactor with anti-diffusion (Courtesy of CEA)

Accident scenario: power excursion in a nuclear reactor core

↓

Generation of a high-pressure bubble (heat exchange fluid vapor and other components)

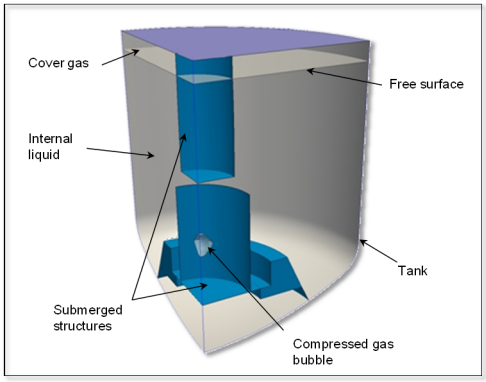
↓

Pressure waves on the tank: necessary to **dimension the confinement** to avoid leakage

Very complex physics in the core region (*FCI*)

Classically dimensioning realised by means of **simplified tests** with well-known components:

- **Explosive** instead of fuel / coolant interaction
- **Water** instead of the real coalant
- **No phase changes**

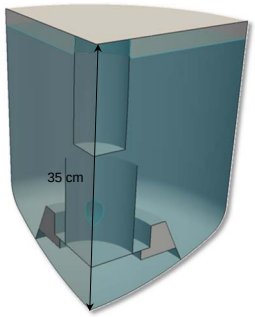


MARA10 test case for the dimensioning of a SFR tank

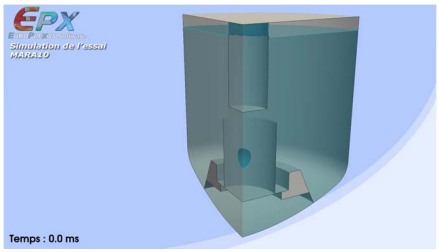
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The MARA10 Test

(Courtesy of CEA)



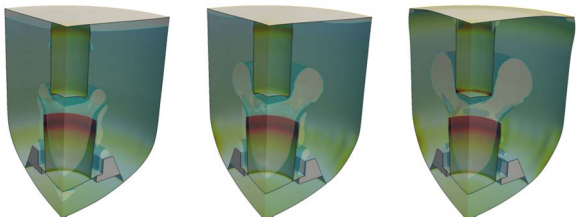
- *Initial conditions*: bubble of ~ **1 cl** at a pressure of **6 250 bar**
- Conforming FSI for the tank and non-conforming for the internal structures
- ALE description of internal fluid grid
- **Interaction between the explosive gas bubble and a cavitation bubble**
- **3D effects** due to the deformation of the tank



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Parallelization aspects

(Courtesy of CEA)



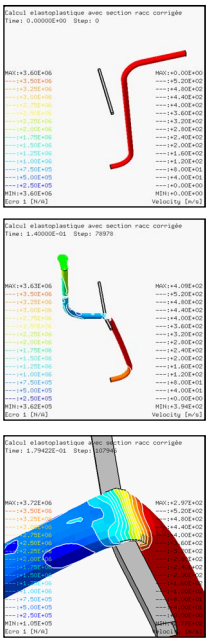
(a) t = 1.5 ms *(b) t = 2.5 ms* *(c) t = 3.5 ms*

	Temps écoulé pour 2500 cycles	*Speed-up* / 4 proc	Efficacité
4 processeurs	13939 s		
8 processeurs	5703 s	**2.44**	**1.22**
16 processeurs	4035 s	**3.45**	**0.86**
32 processeurs	2963 s	**4.70**	**0.59**

Interpretation

- Expensive tasks: **construction od FSI connections** and **construction of the global system**
- Data structure effects associated with linked lists
- Availability of **an alternative algorithm for FSI**

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Exercise/Example 10 - Pipe Whip

EUROPLEXUS (C) Animation

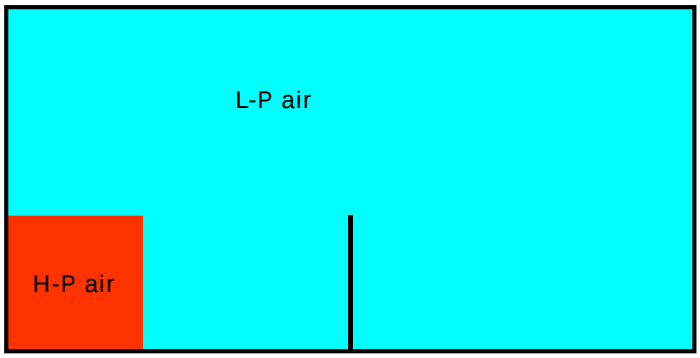
Pipe Whip Simulation

Author: F. Casadei

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Exercise/Example 10b – Comparison FE/FV

- Compare FE (strong), N-C FV (strong) and C-C FV (weak) in a simple 2D explosion test with conforming F-S mesh



Elasto-plastic structure

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Exercise/Example 10b – Comparison FE/FV (2)

FE

```
…
MATE FLUT RO 5.9485 EINT 4.20274E5 GAMM 1.4
          PB 0 PREF 1.E5 ITER 1 ALF0 1 BET0 1
          KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT expl TERM
     FLUT RO 1.1897 EINT 2.10137E5 GAMM 1.4
          PB 0 PREF 1.E5 ITER 1 ALF0 1 BET0 1
          KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT air TERM
…
```

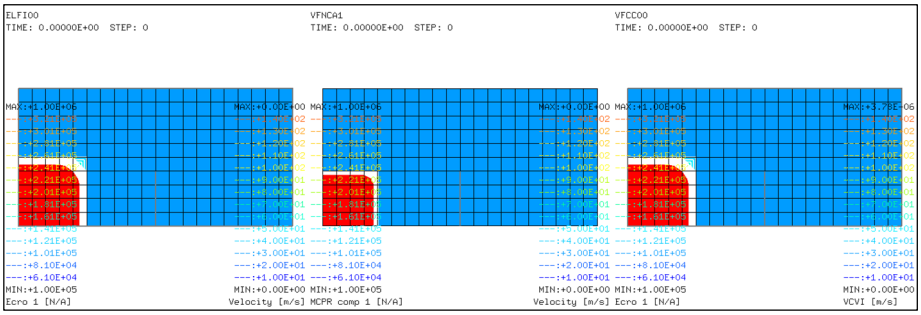
N-C FV

```
…
MATE MCGP NCOM 1 R 8.3143E3
          COMP 'Air' PM 29.0 CV1 2.07585E4
          CV2 0 CV3 0
          LECT flui TERM
     IMPE PIMP RO 1.1897 PRES 1.E5
          LECT pext TERM
…
INIT MCOM COMP 'Air' MFRA 1.0 LECT flui TERM
          PRES 1.E6 LECT expl TERM
          PRES 1.E5 LECT air  TERM
          TEMP 586.36 LECT expl TERM
          TEMP 293.16 LECT air  TERM
          VEL1 0.0 LECT flui TERM
          VEL2 0.0 LECT flui TERM
          VEL3 0.0 LECT flui TERM
…
OPTI MC ORDR 2 NUFL ROE
…
```

C-C FV

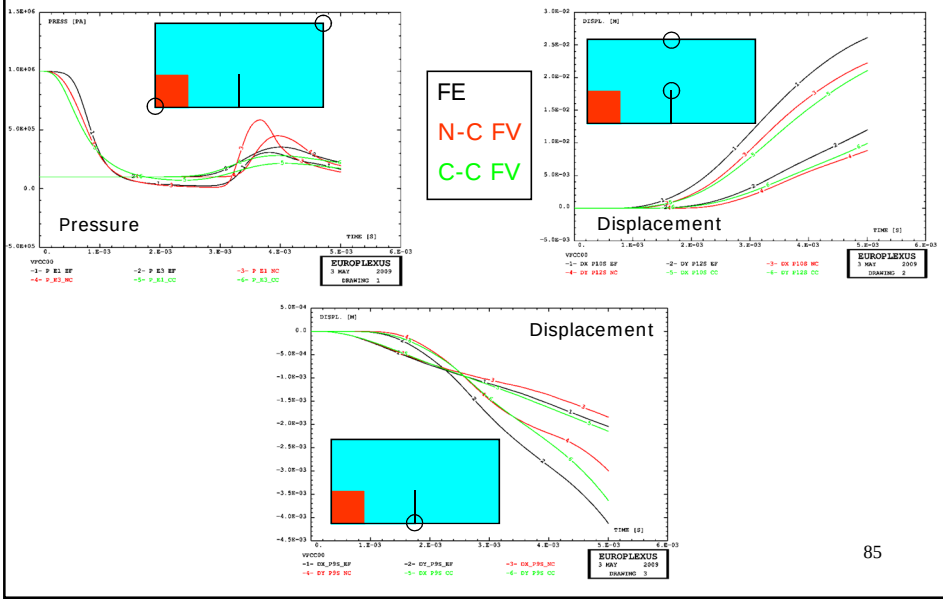
```
…
MATE GAZP RO 5.9485 GAMMA 1.4 CV 716.75
          PINI 1.E6 PREF 1.E5
          LECT expl TERM
     GAZP RO 1.1897 GAMMA 1.4 CV 716.75
          PINI 1.E5 PREF 1.E5
          LECT air TERM
…
OPTI VFCC FCON 1 ! Rusanov
…
```


Exercise/Example 10b – Comparison FE/FV (3)



FE N-C FV C-C FV

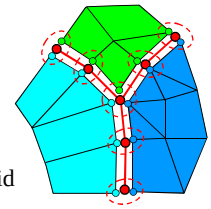
Exercise/Example 10b – Comparison FE/FV (4)



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Basic Non-conforming FSI Algorithms

- The FSI algorithms presented so far assumed nodal conformity of F-S interface

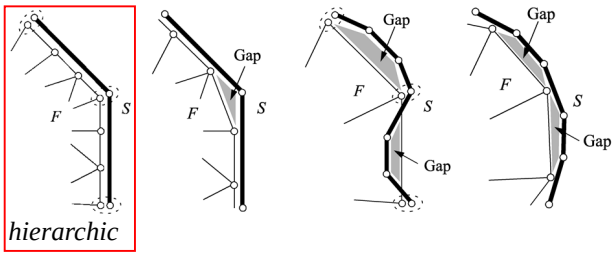


- This choice is justified (not too penalizing) in the majority of practical applications, because:
  - ➢ Linear-velocity, uniform-pressure elements used for the fluid
  - ➢ Zero-thickness shells linearly interpolated along membrane
  - ➢ External pressure on shells element-wise uniform
  - ➢ Conformity ensures maximum simplicity and optimal accuracy
- However, the conformity requirement can be removed to obtain an even more general treatment of permanent FSI, which can be very useful in specific advanced applications

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Non-conforming FSI (2)

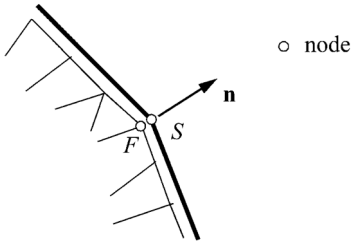
- Tentative classification:



- The hierarchic configuration is the most attractive in practical applications, since the stability step is usually larger in fluid elements than in structural ones (for a given mesh size), and it produces no gaps/overlaps

Non-conforming FSI (3)

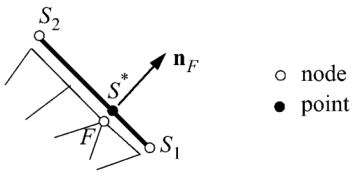
- Generalization of coupling (velocity compatibility) conditions:



Matching node F

$$\underline{v}_F \bullet \underline{n} = \underline{v}_S \bullet \underline{n}$$

$$\underline{w}_F = \underline{w}_S$$



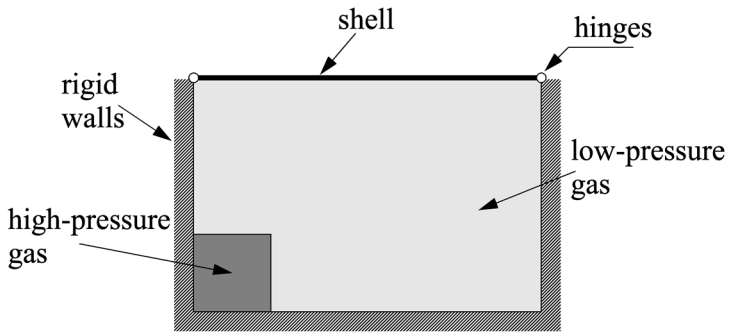
Non-matching node F

$$\underline{v}_F \bullet \underline{n}_F = \underline{v}_{S^*} \bullet \underline{n}_F = (c_1 \underline{v}_{S_1} + c_2 \underline{v}_{S_2}) \bullet \underline{n}_F$$

$$\underline{w}_F = \underline{w}_{S^*} = c_1 \underline{w}_{S_1} + c_2 \underline{w}_{S_2}$$

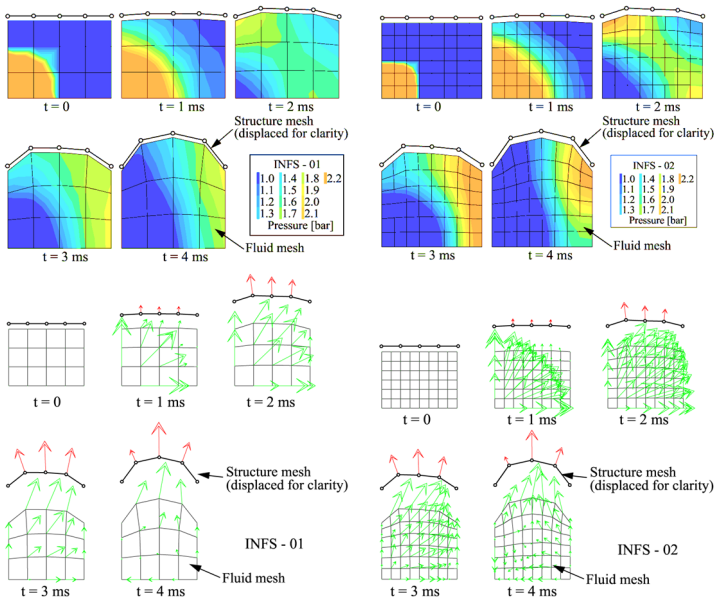
$\underline{n}_F$ is the normal to the fluid domain!

Example 4 – Explosion in a 2D box



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Example 4 – Explosion in a 2D box (2)



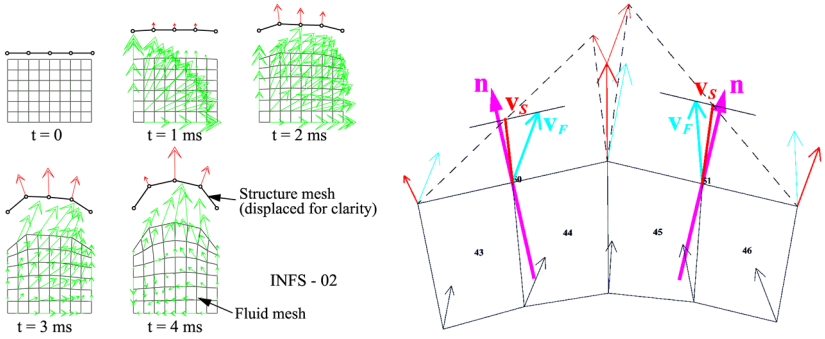
A – Conforming

B – Non-conforming

90

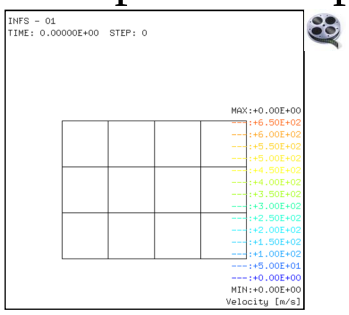
Example 4 – Explosion in a 2D box (3)

Graphical illustration of velocity compatibility condition in the non-conforming case

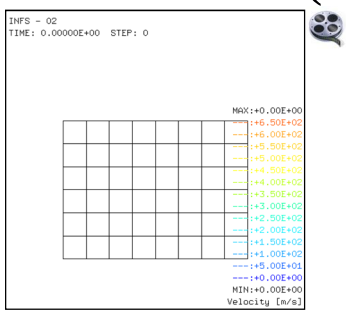


B – Non-conforming

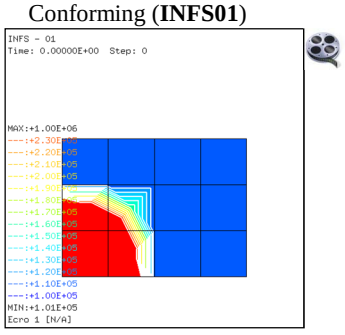
Example 4 – Explosion in a 2D box (4)

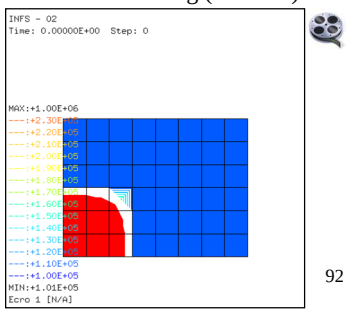


Conforming (**INFS01**)

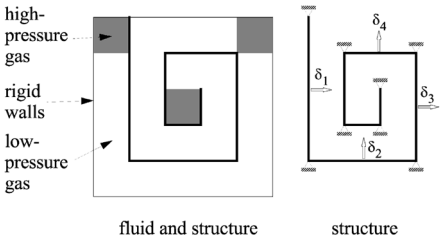


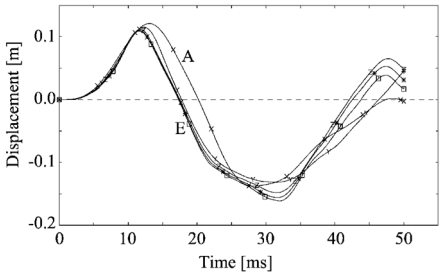
Non-conforming (**INFS02**)





Example 4b – Explosions in a labyrinth



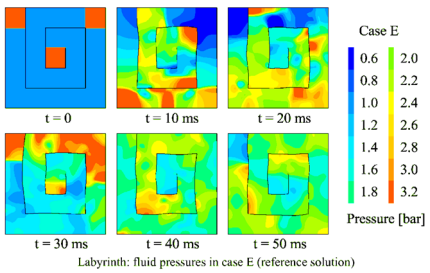


Labyrinth: displacement δ_1 in cases A to E (progressive mesh refinement)

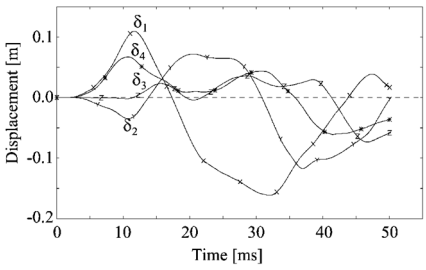
Case	Mesh refinement Φ (F/S)	Number of elements (F/S)	Time steps	CPU time [s]	CPU time ratio	Speed-up factor
A	1x/1x	100/32	1050	2.6	1.0	-
B	2x/2x	400/64	2100	11.7	4.5	-
C	4x/4x	1600/128	4200	77.5	29.8	-
D	8x/8x	6400/256	8400	587.3	225.9	-
E	16x/16x	25600/512	16789	4747.7	1826.0	-
F	8x/1x	6400/32	1416	110.1	42.3	5.3
G	16x/2x	25600/64	3063	933.7	359.1	5.1
H	16x/1x	25600/32	3087	960.2	369.3	4.9

93

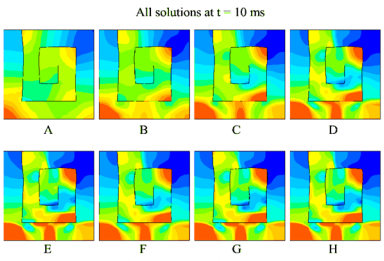
Example 4b – Explosions in a labyrinth (2)



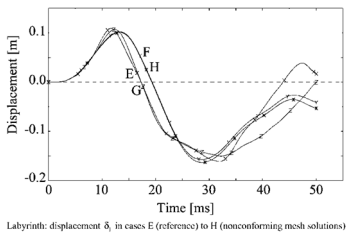
Labyrinth: fluid pressures in case E (reference solution)



Labyrinth: displacements δ_1 to δ_4 in case E (reference solution)



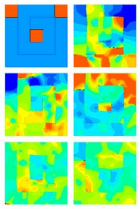
Labyrinth: fluid pressures at 10 ms in all test cases



Labyrinth: displacement δ_1 in cases E (reference) to H (nonconforming mesh solutions)

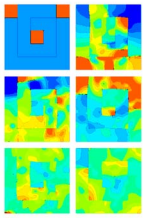
94

Example 4b – Explosions in a labyrinth (3)

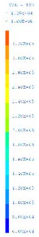


H

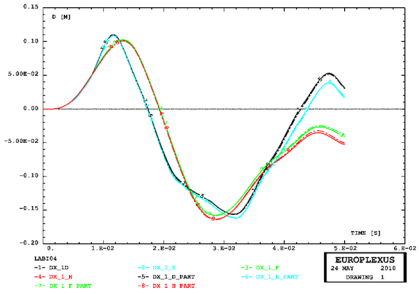




H + Partitioning



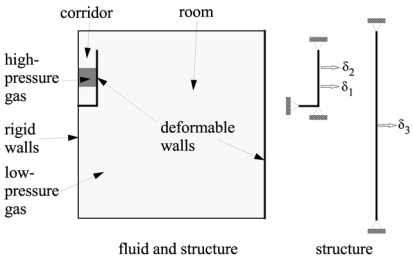
A speed-up of about 2 is achieved by partitioning in these calculations

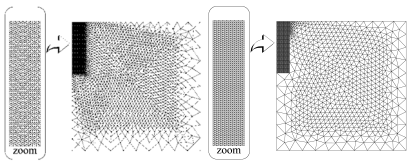


With or without Partitioning

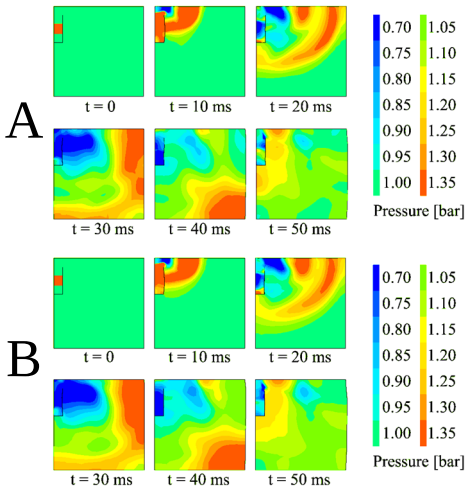
95

Example 5 – Explosion in a corridor





A – Conforming B – Non-conforming

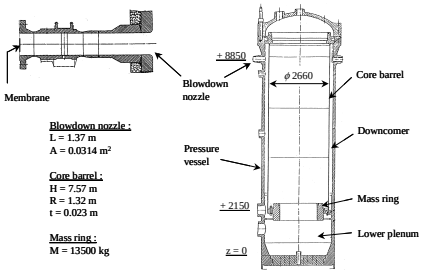


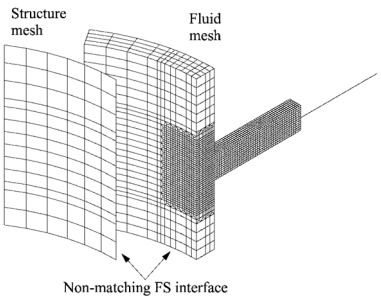
Case	Mesh refinement Φ (F/S)	Number of elements (F/S)	Time steps	CPU time [s]	CPU time ratio	Speed-up factor
A	16x/16x	5497/74	8400	334.7	1.00	-
B	16x/1x	3513/14	1437	39.1	0.12	8.6

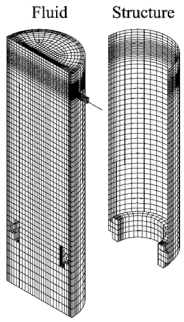
96

Example 6 – LOCA in the HDR

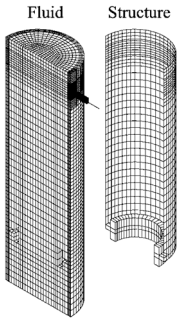
(Courtesy of EDF)







A - Conforming mesh

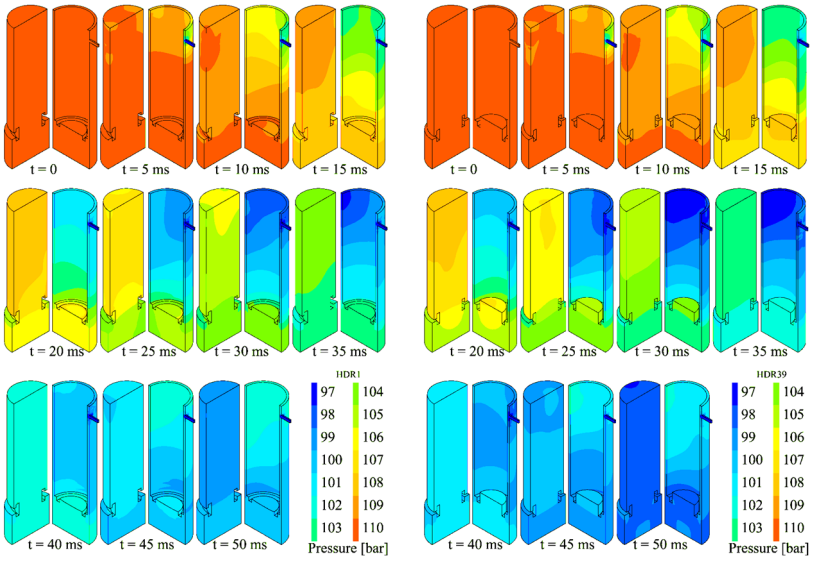


B - Nonconforming mesh

Case	Mesh type	Number of elements (F/S)	Time steps	CPU time [s]	CPU time ratio	Speed-up factor
A	Conforming	35854/2080	41981	83936	1.00	-
B	Nonconforming	34204/1148	15269	22131	0.26	3.8

97

Example 6 – LOCA in the HDR (2)

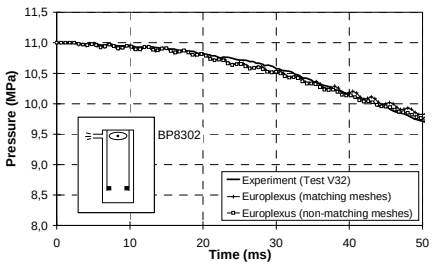


A – Conforming

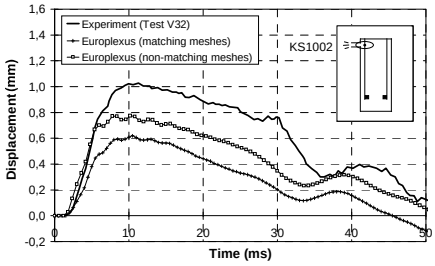
B – Non-conforming

98

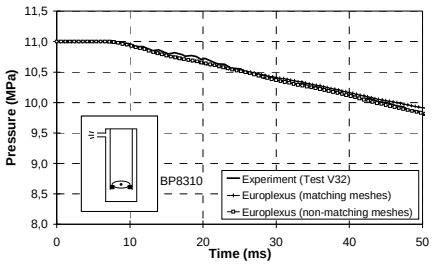
Example 6 – LOCA in the HDR (3)



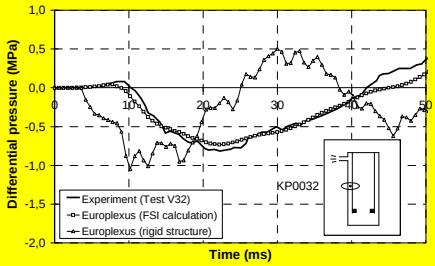
Upper core pressure



Core barrel radial displacement



Lower core pressure

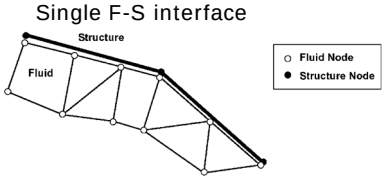


FSI effect on differential pressure

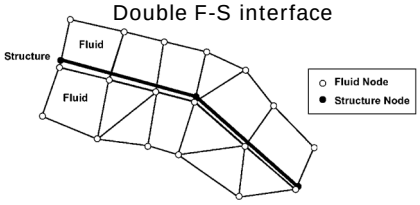
Non-conforming "weak" FSI with CCFV

- The non-conforming FSI algorithms presented above can be applied also to CCFV, but only via a "weak" treatment (pressure) for the moment

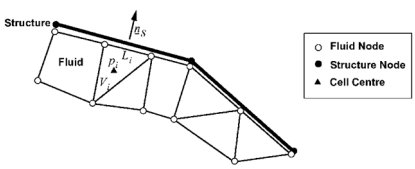
Single F-S interface

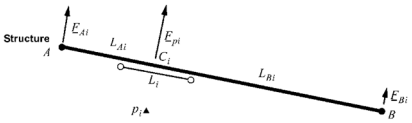


Double F-S interface



- Cell-centered fluid pressures are applied to the structure as shown below, as long as the structure is not failed. Fluxes are **not** computed across a neighboring (unfailed) structure. Matching nodes <u>can be merged or not</u>

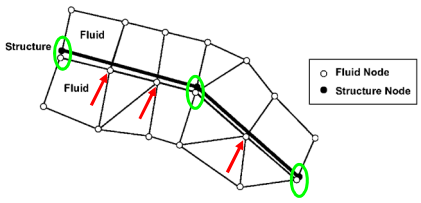




$$E_{Ai} = \frac{L_{Bi}}{L_{Ai}+L_{Bi}}E_{pi} = \frac{L_{Bi}}{L_S}E_{pi} \quad ; \quad E_{Bi} = \frac{L_{Ai}}{L_{Ai}+L_{Bi}}E_{pi} = \frac{L_{Ai}}{L_S}E_{pi}$$ .00

Non-conforming “weak” FSI with CCFV (2)

- The matching nodes **can** be merged **or not** (irrelevant)



Couple of matching nodes

Non-matching fluid node

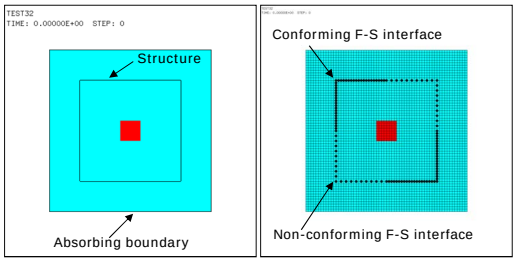
- The non-matching fluid nodes **must** be declared in a list:

OPTI VFCC ... NCFS /LECT/

101

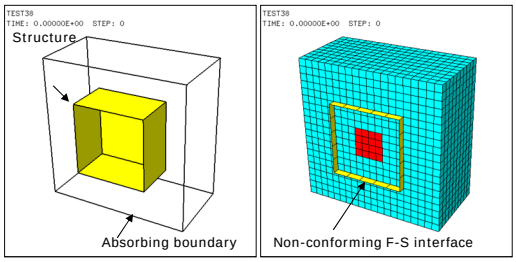
Example 6bis – Non-conforming FSI with CCVF

(Weak coupling, without or with structural failure)



2D case

(the dots indicate the structure nodes)



3D case

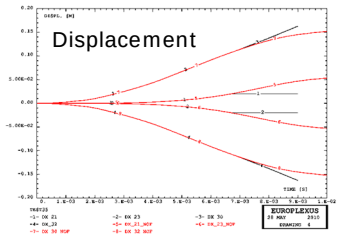
(half model shown for clarity)

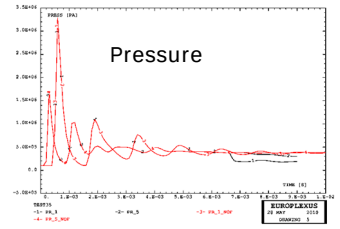
102

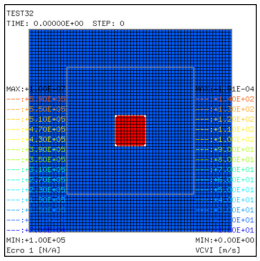
Example 6bis – Non-conforming FSI with CCVF (2)

(Weak coupling, without or with structural failure)

- 2D case :

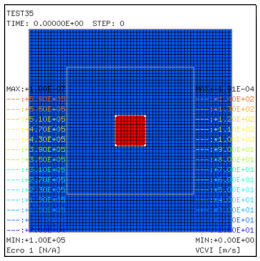






No failure

Comparison



Failure

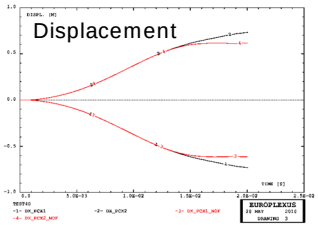
Example 6bis – Non-conforming FSI with CCVF (3)

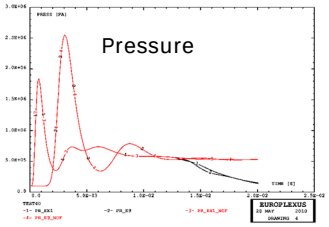
(Weak coupling, without or with structural failure)

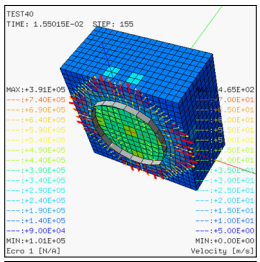
- 3D case :

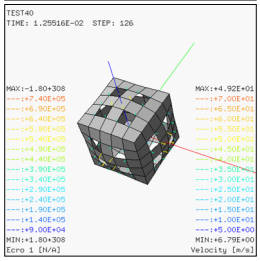
No failure

Failure



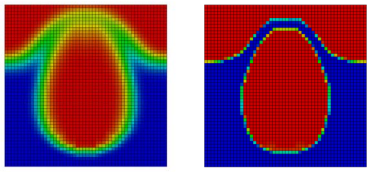






Case with failure

Anti-diffusion (VOFIRE) and FSI

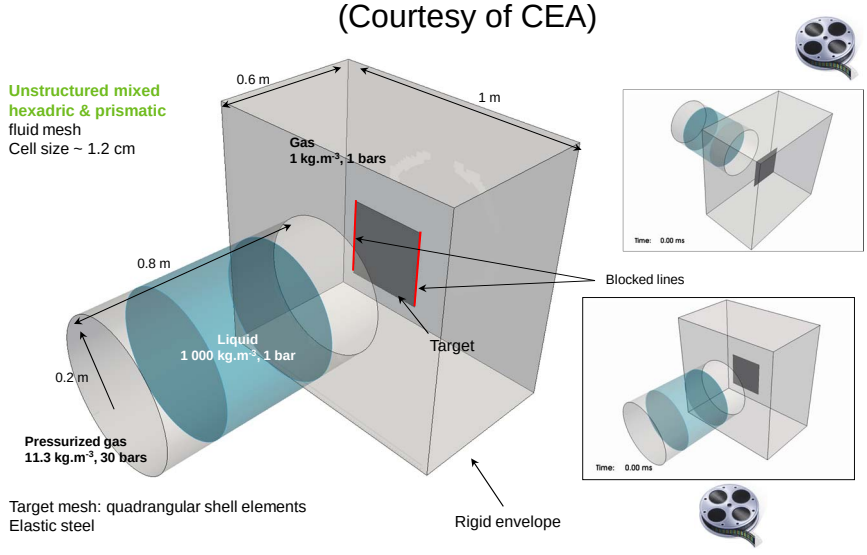


The anti-diffusion techniques presented in Part II (DPLG, VOFIRE) for purely fluid calculations can be very useful also in FSI problems. Some examples are given below.

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"Water cannon" on deformable plate

(Courtesy of CEA)



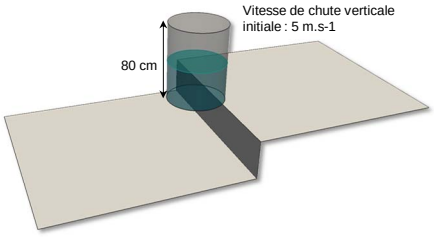
Target mesh: quadrangular shell elements
Elastic steel

Coupled Euler-Lagrange FSI

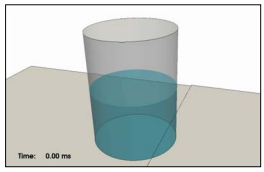
106

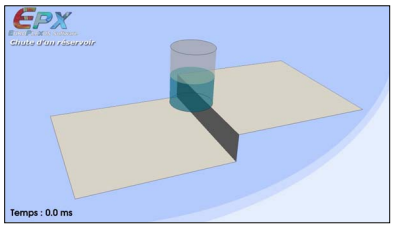
Internal sloshing in a falling tank

(Courtesy of CEA)



- Conforming FSI between the tank (elasto-plastic material) and the internal fluid
- Demonstration of **large rotations management in the automatic motion of the ALE fluid grid**
- **Dynamics of weak flow:**
  - Coarse fluid mesh in 3D (mesh size ~ 1 cm)
  - Gravity flow after rotation
- Expensive calculation (many time steps)





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Packaging dropped into a pool

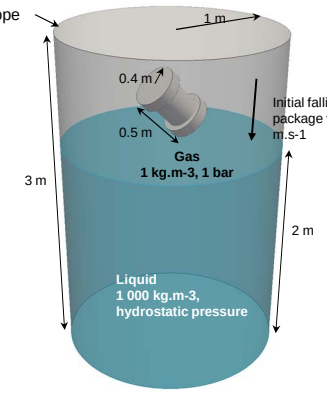
(Courtesy of CEA)

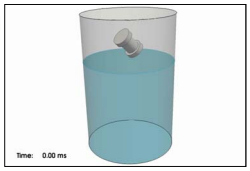
Rigid envelope

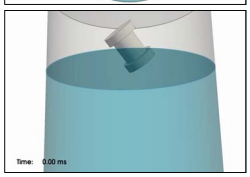
Unstructured hexaedric fluid mesh
Cell size ~ 2 cm

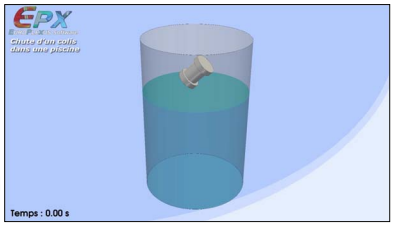
Package mesh:
hexaedric mesh
Elastic steel

Coupled Euler-Lagrange FSI



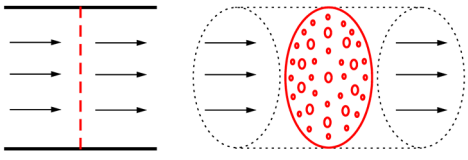






Special FSI Techniques/Applications (1)

- Modeling of perforated structures

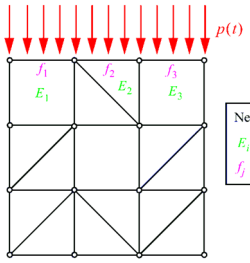


Examples of Perforated Plates

Boundary Condition Elements: CLxx

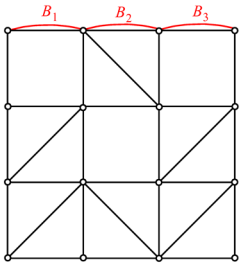
- Typical example: an externally applied pressure

❑ Use Loading directive (cumbersome!):
CHAR 1 FACT 2 PRES FACE ifac p0
/LECT/



Need to identify:
E_i : affected elements
f_j : affected faces

❑ Use special CLxx element with
IMPE PIMP material:

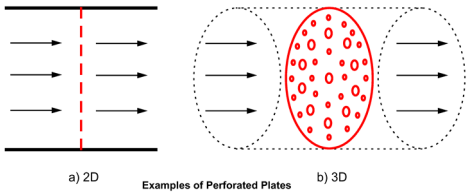


B_i : C.L. elements (mesh)

The type of boundary condition is specified by assigning to the C.L. element a special "impedance" material: pressure, absorbing, safety valve, grid, ...

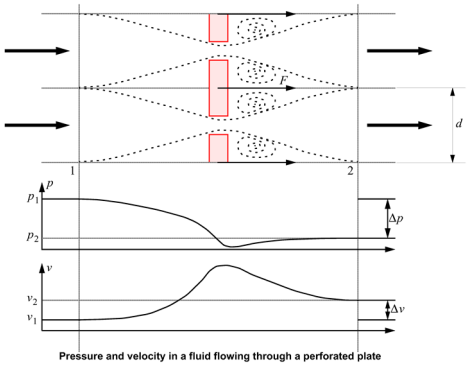
Boundary Condition Elements: CLxx (2)

- More complex example: perforated structures



Examples of Perforated Plates

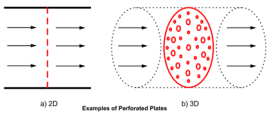
Geometry



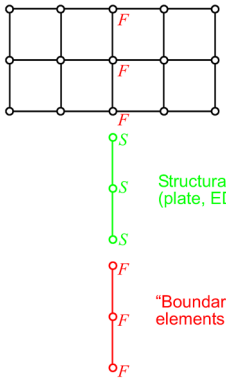
Pressure and velocity in a fluid flowing through a perforated plate

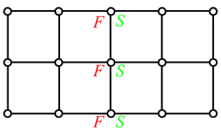
Complex physical behaviour

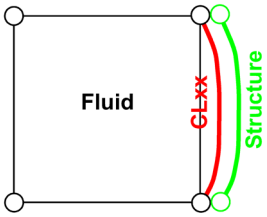
Boundary Condition Elements: CLxx (3)



Geometry







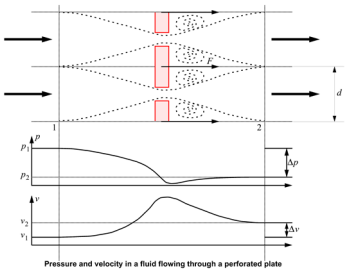
Model by means of CLxx

a) component meshes

b) assembled model

Modeling of a perforated plate

Boundary Condition Elements: CLxx (4)



Complex physical behaviour

Simplified model: `MATE IMPE PPLA ZETA zeta /LECT/`

$$\Delta p_{12} = \zeta \rho_1 \frac{v_1^2}{2}$$

ζ = resistance coefficient (constant)

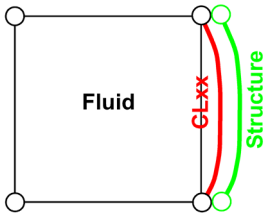
ρ_1 = density upstream (undisturbed region)

v_1 = relative velocity upstream (undisturbed)

$$\Delta p_{12} = \zeta \rho_1 \frac{|v_1| v_1}{2}$$

to account for sign effects

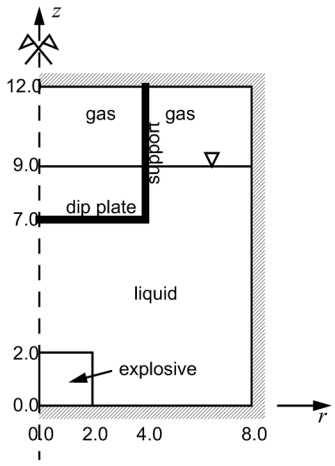
Boundary Condition Elements: CLxx (5)



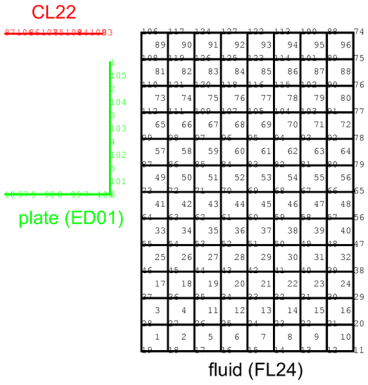
The model is <u>implemented</u> as follows:

1. *For each element CLxx representing a pressure drop across a perforated plate, search the structural node **S** corresponding to each node **F** of the element, and store this information in internal variables of the element;*
2. *When calculating 'internal' forces for such an element, evaluate first the pressure drop **Δp** across the element as a function of fluid and possibly plate velocity. Then, compute the nodal forces generated by this pressure drop: add these forces to the fluid nodes and subtract them from the structural nodes;*
3. *When calculating grid velocities for the ALE fluid nodes, assign to each fluid node **F** the same velocity as the corresponding structural node **S**.*

Exercise/Example 11 – Perforated Plate



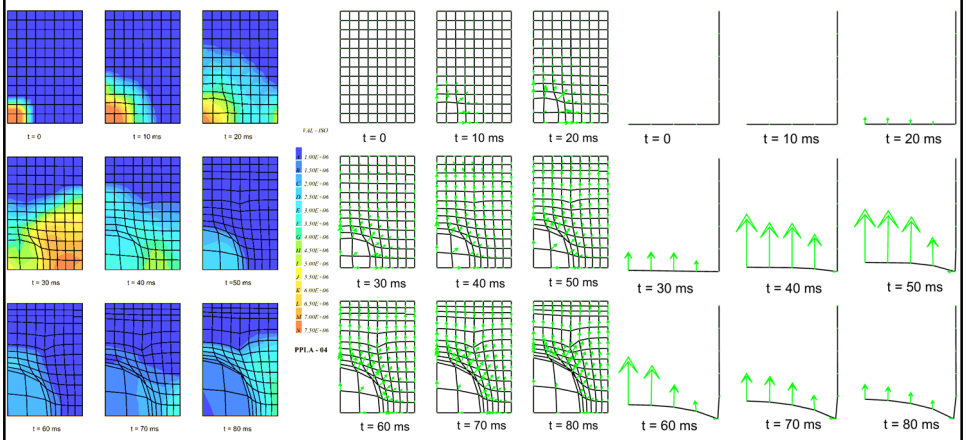
geometry



model

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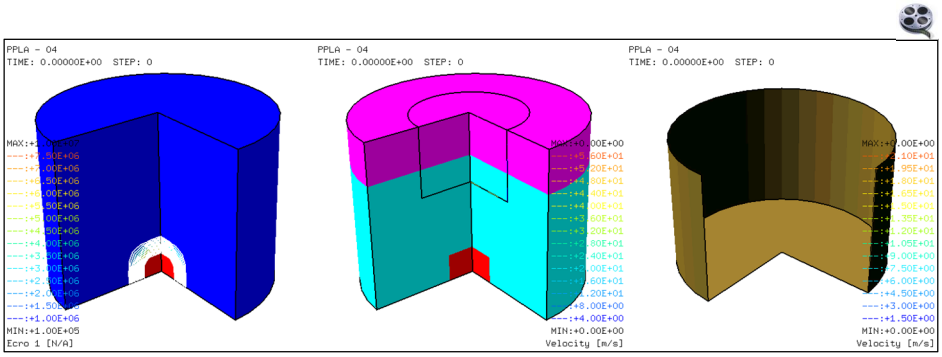
Exercise/Example 11 – Perforated Plate (2)



Pressures *Fluid velocities* *Structure velocities*

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Exercise/Example 11 – Perforated Plate (2)

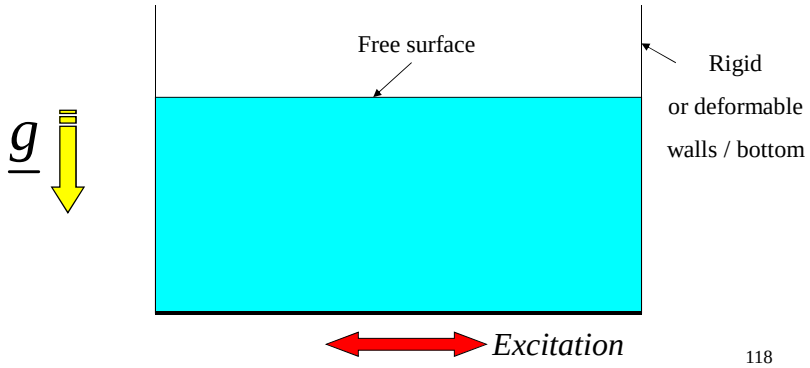


Pressures *Fluid velocities* *Structure velocities*

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Special FSI Techniques/Applications (2)

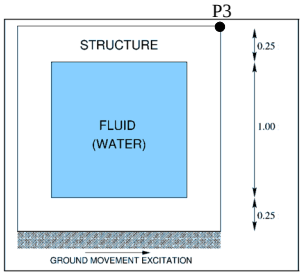
- Modeling of tank sloshing phenomena

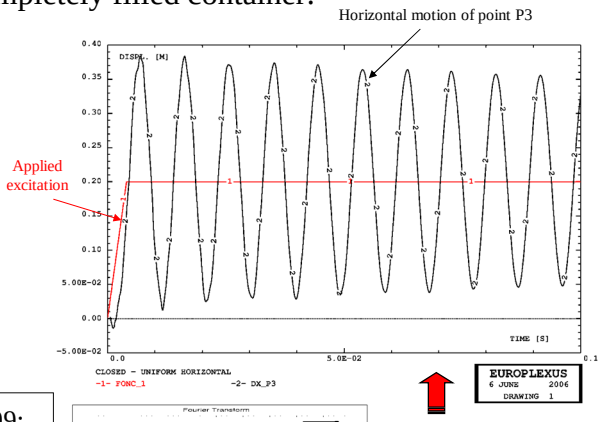


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Exercise/Example 12 – Sloshing (Courtesy of CRS4)

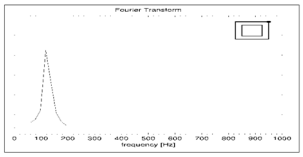
- A - Vibration of a completely filled container:





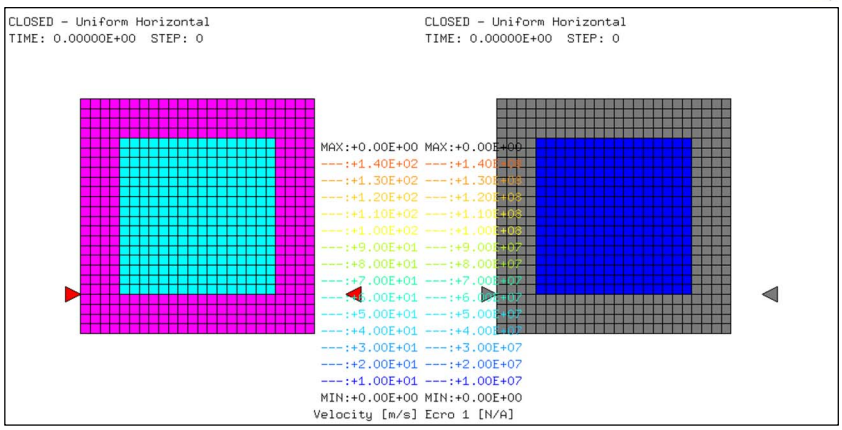
Bermudez & Rodriguez, 1999:

- 1st mode frequency : 117 Hz
- Estimated frequency : 102 Hz



Computed frequency: 106 Hz

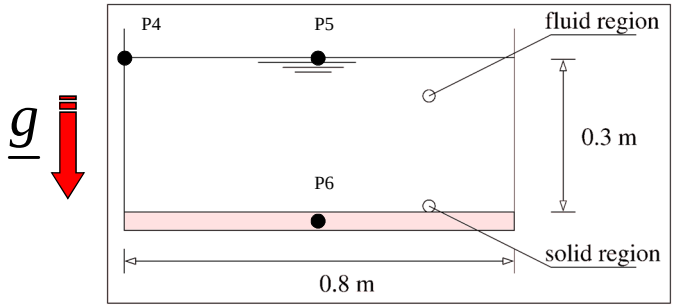
Exercise/Example 12 – Sloshing (2)



Velocity *Fluid pressure*

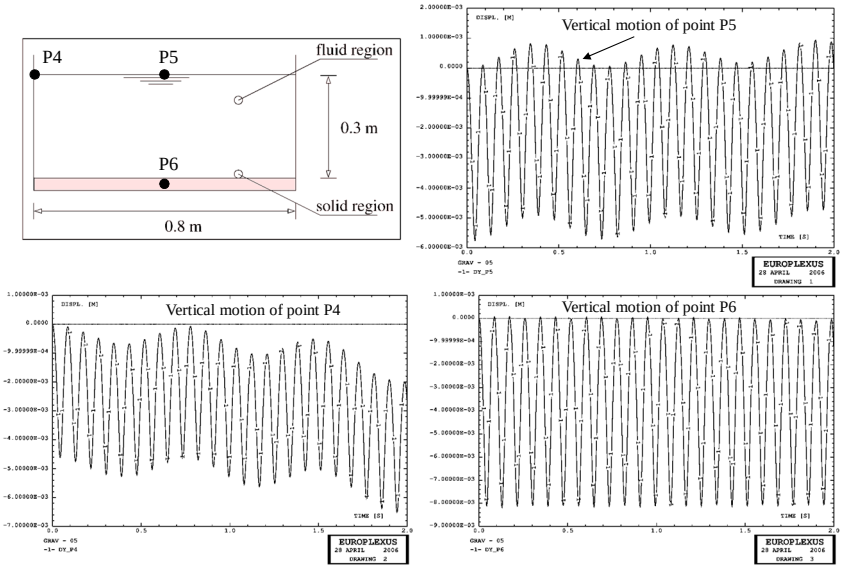
Exercise/Example 12 – Sloshing (3) (Courtesy of CRS4)

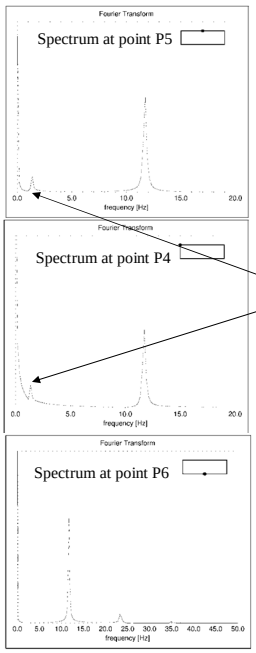
• B - Vibration of a partially filled container:



• Excitation : gravity starting at initial time

Exercise/Example 12 – Sloshing (4)



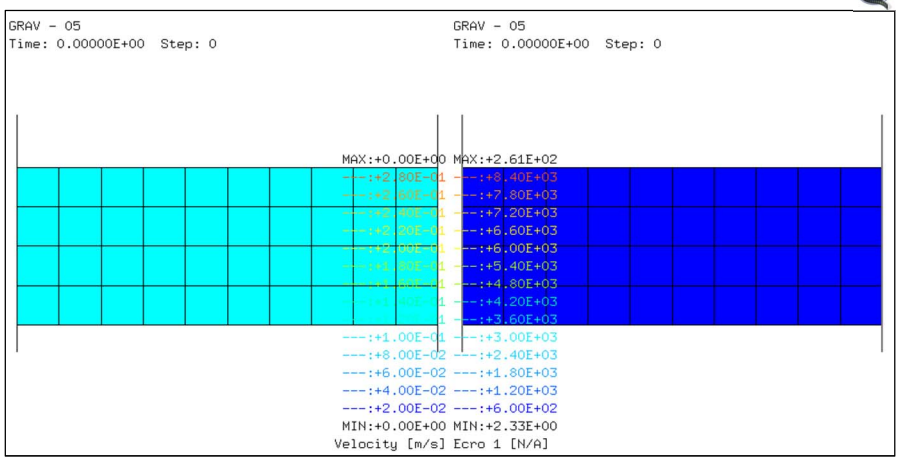


Exercise/Example 12 – Sloshing (5)

- All nodes have a harmonic component at 11.7 Hz
- Surface nodes have, in addition, a lower harmonic component at 1.3 Hz
- Linear theory predicts first symmetric sloshing mode at 1.41 Hz for a rigid tank
- As expected, flexible bottom somewhat reduces the value of the first sloshing frequency

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Exercise/Example 12 – Sloshing (6)

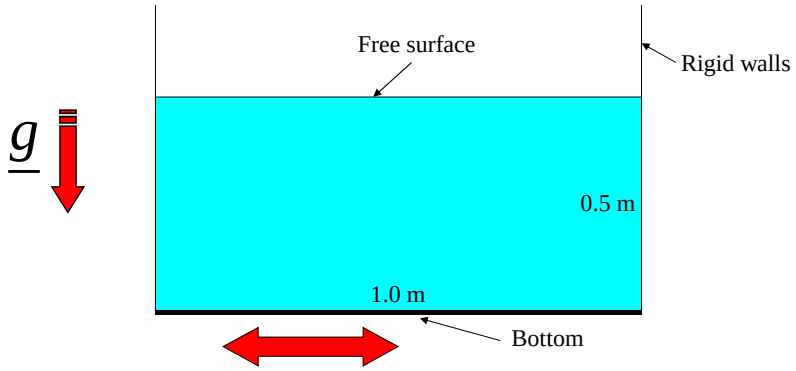


Velocity *Fluid pressure*

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Exercise/Example 12 – Sloshing (7) (Courtesy of CRS4)

• C - Vibration of a partially filled container:



• Excitation : imposed harmonic horizontal displacement

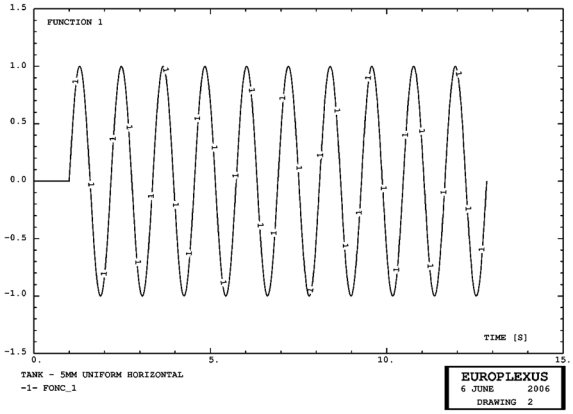
• Container bottom can be either rigid or flexible

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Exercise/Example 12 – Sloshing (8) (Courtesy of CRS4)

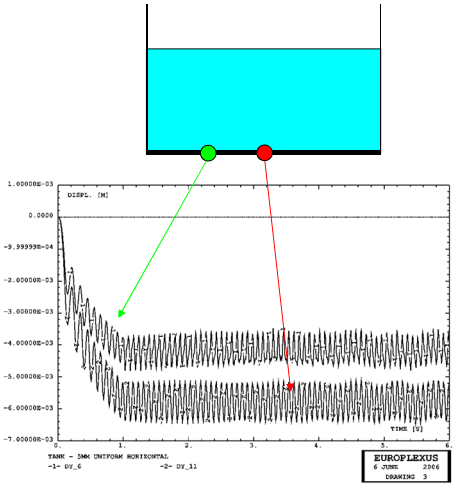
• First sloshing frequency (linear theory) is 5.316 Hz

• Excitation frequency is 5.311 Hz, amplitude 9.3 mm, starting at t = 1 s

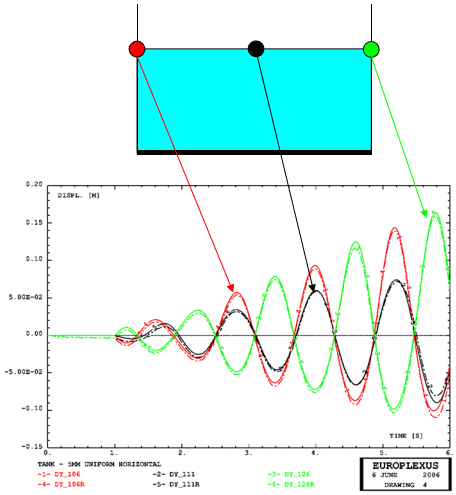


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Exercise/Example 12 – Sloshing (9) (Courtesy of CRS4)

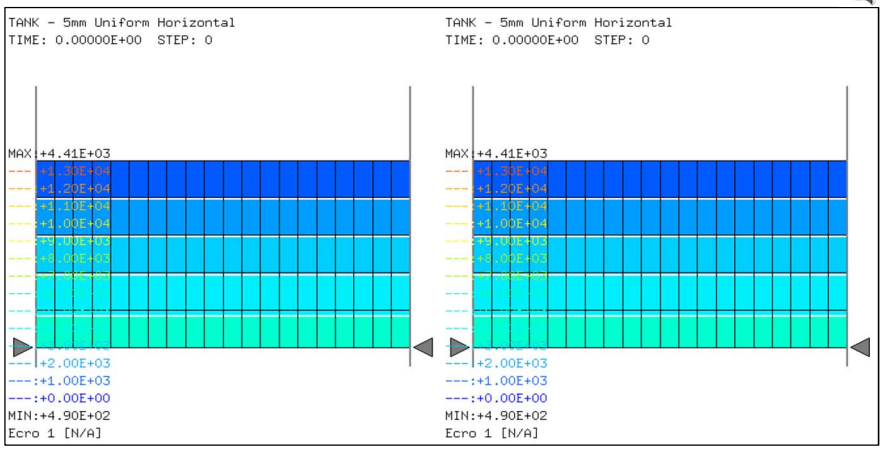


Displacement of bottom (flexible case)



Displacement of free surface (solid=rigid, dashed=flexible)

Exercise/Example 12 – Sloshing (10)



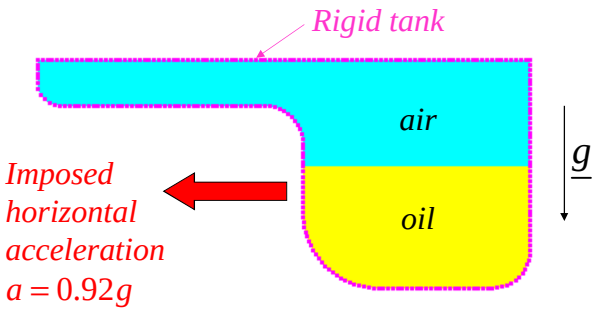
Pressure, rigid bottom

Pressure, flexible bottom

Exercise/Example 12 – Sloshing (11)

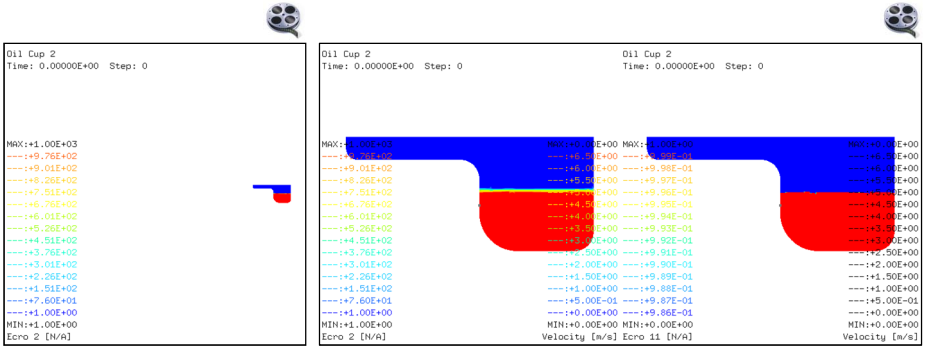
(Courtesy of Samtech)

• D – Accelerated oil cup:



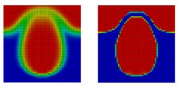
129

Exercise/Example 12 – Sloshing (12)

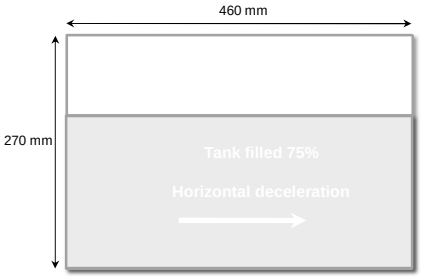


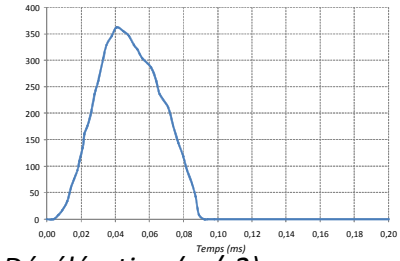
Density *Density* *Oil mass fraction*

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Sloshing in a decelerated tank with anti-diffusion (Courtesy of CEA)



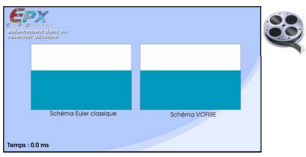


Décélération (m/s2)



Experimental results (Yamaha, 1988)

Form of the gas volume during the transient

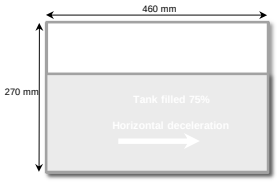


Numerical simulations

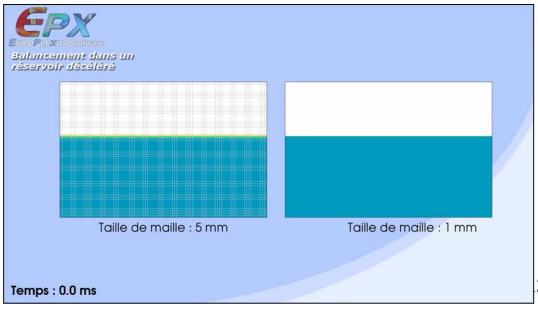
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Sloshing in a decelerated tank

(Courtesy of CEA)



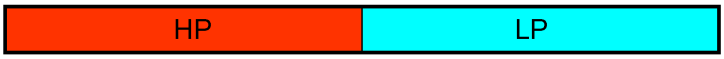
- Dynamic phenomenon driven by the **conversion of a slight overpressure, due to deceleration, in velocity along the walls**
- Need for precision and regularity of the pressure field
- **Strong pressure oscillations along the interface due to the mixing model**
- Large oscillations near the interface (checkerboarding effect)



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Exercise 1a – Shock Tube

(FE / FV, Strong / Weak BCs)



- Obtain various solutions and compare them with analytical solution (single-component perfect gas):
  - FE, strong BCs
  - NCFV, strong BCs
  - NCFV, weak BCs
  - CCFV, weak BCs

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Geometric data:

The shock tube is 50.0 units long and 0.5 units wide. It is divided in two equal zones.

Materials

The tube is filled by perfect gas. The left chamber has density 10, $\gamma = 1.5$, pressure 10 bar. The right part has density 1, $\gamma = 1.5$, pressure 1 bar.

Numerical Solutions

TUBEEF

This solution is obtained with Finite Elements (FL24). Boundary conditions are imposed in a strong manner (`LINK COUP BLOQ`). The input file is:

```
TUBEEF
ECHO
!CONV WIN
DPLA EULE
GEOM LIBR POIN 202 FL24 100 TERM
 0.00000E+00 0.00000E+00 5.00000E-01 0.00000E+00 1.00000E+00 0.00000E+00
 1.50000E+00 0.00000E+00 2.00000E+00 0.00000E+00 2.50000E+00 0.00000E+00
 3.00000E+00 0.00000E+00 3.50000E+00 0.00000E+00 4.00000E+00 0.00000E+00
 4.50000E+00 0.00000E+00 5.00000E+00 0.00000E+00 5.50000E+00 0.00000E+00
 6.00000E+00 0.00000E+00 6.50000E+00 0.00000E+00 7.00000E+00 0.00000E+00
 7.50000E+00 0.00000E+00 8.00000E+00 0.00000E+00 8.50000E+00 0.00000E+00
 9.00000E+00 0.00000E+00 9.50000E+00 0.00000E+00 1.00000E+01 0.00000E+00
 1.05000E+01 0.00000E+00 1.10000E+01 0.00000E+00 1.15000E+01 0.00000E+00
 1.20000E+01 0.00000E+00 1.25000E+01 0.00000E+00 1.30000E+01 0.00000E+00
 1.35000E+01 0.00000E+00 1.40000E+01 0.00000E+00 1.45000E+01 0.00000E+00
 1.50000E+01 0.00000E+00 1.55000E+01 0.00000E+00 1.60000E+01 0.00000E+00
 1.65000E+01 0.00000E+00 1.70000E+01 0.00000E+00 1.75000E+01 0.00000E+00
 1.80000E+01 0.00000E+00 1.85000E+01 0.00000E+00 1.90000E+01 0.00000E+00
 1.95000E+01 0.00000E+00 2.00000E+01 0.00000E+00 2.05000E+01 0.00000E+00
 2.10000E+01 0.00000E+00 2.15000E+01 0.00000E+00 2.20000E+01 0.00000E+00
 2.25000E+01 0.00000E+00 2.30000E+01 0.00000E+00 2.35000E+01 0.00000E+00
 2.40000E+01 0.00000E+00 2.45000E+01 0.00000E+00 2.50000E+01 0.00000E+00
 2.55000E+01 0.00000E+00 2.60000E+01 0.00000E+00 2.65000E+01 0.00000E+00
 2.70000E+01 0.00000E+00 2.75000E+01 0.00000E+00 2.80000E+01 0.00000E+00
 2.85000E+01 0.00000E+00 2.90000E+01 0.00000E+00 2.95000E+01 0.00000E+00
 3.00000E+01 0.00000E+00 3.05000E+01 0.00000E+00 3.10000E+01 0.00000E+00
 3.15000E+01 0.00000E+00 3.20000E+01 0.00000E+00 3.25000E+01 0.00000E+00
 3.30000E+01 0.00000E+00 3.35000E+01 0.00000E+00 3.40000E+01 0.00000E+00
 3.45000E+01 0.00000E+00 3.50000E+01 0.00000E+00 3.55000E+01 0.00000E+00
 3.60000E+01 0.00000E+00 3.65000E+01 0.00000E+00 3.70000E+01 0.00000E+00
 3.75000E+01 0.00000E+00 3.80000E+01 0.00000E+00 3.85000E+01 0.00000E+00
 3.90000E+01 0.00000E+00 3.95000E+01 0.00000E+00 4.00000E+01 0.00000E+00
 4.05000E+01 0.00000E+00 4.10000E+01 0.00000E+00 4.15000E+01 0.00000E+00
 4.20000E+01 0.00000E+00 4.25000E+01 0.00000E+00 4.30000E+01 0.00000E+00
 4.35000E+01 0.00000E+00 4.40000E+01 0.00000E+00 4.45000E+01 0.00000E+00
 4.50000E+01 0.00000E+00 4.55000E+01 0.00000E+00 4.60000E+01 0.00000E+00
 4.65000E+01 0.00000E+00 4.70000E+01 0.00000E+00 4.75000E+01 0.00000E+00
 4.80000E+01 0.00000E+00 4.85000E+01 0.00000E+00 4.90000E+01 0.00000E+00
 4.95000E+01 0.00000E+00 5.00000E+01 0.00000E+00 0.00000E+00 5.00000E-01
 5.00000E-01 5.00000E-01 1.00000E+00 5.00000E-01 1.50000E+00 5.00000E-01
 2.00000E+00 5.00000E-01 2.50000E+00 5.00000E-01 3.00000E+00 5.00000E-01
 3.50000E+00 5.00000E-01 4.00000E+00 5.00000E-01 4.50000E+00 5.00000E-01
 5.00000E+00 5.00000E-01 5.50000E+00 5.00000E-01 6.00000E+00 5.00000E-01
 6.50000E+00 5.00000E-01 7.00000E+00 5.00000E-01 7.50000E+00 5.00000E-01
 8.00000E+00 5.00000E-01 8.50000E+00 5.00000E-01 9.00000E+00 5.00000E-01
 9.50000E+00 5.00000E-01 1.00000E+01 5.00000E-01 1.05000E+01 5.00000E-01
 1.10000E+01 5.00000E-01 1.15000E+01 5.00000E-01 1.20000E+01 5.00000E-01
 1.25000E+01 5.00000E-01 1.30000E+01 5.00000E-01 1.35000E+01 5.00000E-01
 1.40000E+01 5.00000E-01 1.45000E+01 5.00000E-01 1.50000E+01 5.00000E-01
 1.55000E+01 5.00000E-01 1.60000E+01 5.00000E-01 1.65000E+01 5.00000E-01
 1.70000E+01 5.00000E-01 1.75000E+01 5.00000E-01 1.80000E+01 5.00000E-01
 1.85000E+01 5.00000E-01 1.90000E+01 5.00000E-01 1.95000E+01 5.00000E-01
 2.00000E+01 5.00000E-01 2.05000E+01 5.00000E-01 2.10000E+01 5.00000E-01
 2.15000E+01 5.00000E-01 2.20000E+01 5.00000E-01 2.25000E+01 5.00000E-01
 2.30000E+01 5.00000E-01 2.35000E+01 5.00000E-01 2.40000E+01 5.00000E-01
 2.45000E+01 5.00000E-01 2.50000E+01 5.00000E-01 2.55000E+01 5.00000E-01
 2.60000E+01 5.00000E-01 2.65000E+01 5.00000E-01 2.70000E+01 5.00000E-01
 2.75000E+01 5.00000E-01 2.80000E+01 5.00000E-01 2.85000E+01 5.00000E-01
 2.90000E+01 5.00000E-01 2.95000E+01 5.00000E-01 3.00000E+01 5.00000E-01
 3.05000E+01 5.00000E-01 3.10000E+01 5.00000E-01 3.15000E+01 5.00000E-01
 3.20000E+01 5.00000E-01 3.25000E+01 5.00000E-01 3.30000E+01 5.00000E-01
 3.35000E+01 5.00000E-01 3.40000E+01 5.00000E-01 3.45000E+01 5.00000E-01
 3.50000E+01 5.00000E-01 3.55000E+01 5.00000E-01 3.60000E+01 5.00000E-01
 3.65000E+01 5.00000E-01 3.70000E+01 5.00000E-01 3.75000E+01 5.00000E-01
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 3.80000E+01 5.00000E-01 3.85000E+01 5.00000E-01 3.90000E+01 5.00000E-01
 3.95000E+01 5.00000E-01 4.00000E+01 5.00000E-01 4.05000E+01 5.00000E-01
 4.10000E+01 5.00000E-01 4.15000E+01 5.00000E-01 4.20000E+01 5.00000E-01
 4.25000E+01 5.00000E-01 4.30000E+01 5.00000E-01 4.35000E+01 5.00000E-01
 4.40000E+01 5.00000E-01 4.45000E+01 5.00000E-01 4.50000E+01 5.00000E-01
 4.55000E+01 5.00000E-01 4.60000E+01 5.00000E-01 4.65000E+01 5.00000E-01
 4.70000E+01 5.00000E-01 4.75000E+01 5.00000E-01 4.80000E+01 5.00000E-01
 4.85000E+01 5.00000E-01 4.90000E+01 5.00000E-01 4.95000E+01 5.00000E-01
 5.00000E+01 5.00000E-01
   1   2 103 102   2   3 104 103   3   4 105 104   4   5 106 105
   5   6 107 106   6   7 108 107   7   8 109 108   8   9 110 109
   9  10 111 110  10  11 112 111  11  12 113 112  12  13 114 113
  13  14 115 114  14  15 116 115  15  16 117 116  16  17 118 117
  17  18 119 118  18  19 120 119  19  20 121 120  20  21 122 121
  21  22 123 122  22  23 124 123  23  24 125 124  24  25 126 125
  25  26 127 126  26  27 128 127  27  28 129 128  28  29 130 129
  29  30 131 130  30  31 132 131  31  32 133 132  32  33 134 133
  33  34 135 134  34  35 136 135  35  36 137 136  36  37 138 137
  37  38 139 138  38  39 140 139  39  40 141 140  40  41 142 141
  41  42 143 142  42  43 144 143  43  44 145 144  44  45 146 145
  45  46 147 146  46  47 148 147  47  48 149 148  48  49 150 149
  49  50 151 150  50  51 152 151  51  52 153 152  52  53 154 153
  53  54 155 154  54  55 156 155  55  56 157 156  56  57 158 157
  57  58 159 158  58  59 160 159  59  60 161 160  60  61 162 161
  61  62 163 162  62  63 164 163  63  64 165 164  64  65 166 165
  65  66 167 166  66  67 168 167  67  68 169 168  68  69 170 169
  69  70 171 170  70  71 172 171  71  72 173 172  72  73 174 173
  73  74 175 174  74  75 176 175  75  76 177 176  76  77 178 177
  77  78 179 178  78  79 180 179  79  80 181 180  80  81 182 181
  81  82 183 182  82  83 184 183  83  84 185 184  84  85 186 185
  85  86 187 186  86  87 188 187  87  88 189 188  88  89 190 189
  89  90 191 190  90  91 192 191  91  92 193 192  92  93 194 193
  93  94 195 194  94  95 196 195  95  96 197 196  96  97 198 197
  97  98 199 198  98  99 200 199  99 100 201 200 100 101 202 201
MATE FLUT RO 10.D0 EINT 2.D5 GAMM 1.5 PREF 0.D0 PB 0 ITER 1 ALF0 0.2
          BET0 0 KINT 0 AHGF 0 CL 0.5 CQ 0.0 PMIN 0 NUM 1
          LECT 1 PAS 1 50 TERM
     FLUT RO  1.D0 EINT 2.D5 GAMM 1.5 PREF 0.D0 PB 0 ITER 1 ALF0 0.2
          BET0 0 KINT 0 AHGF 0 CL 0.5 CQ 0.0 PMIN 0 NUM 1
          LECT 51 PAS 1 100 TERM
LINK COUP
     BLOQ 2 TOUS
     BLOQ 1 LECT 1 101 102 202 TERM
ECRI VITE ACCE FINT FEXT CONT ECRO TFRE 30.E-3
     FICH ALIC TFRE 30.E-3
OPTI PAS AUTO NOTE STEP IO CSTA 0.5
     LOG 1
CALC TINI 0 TEND 30.E-3
*===========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
*-----------------------------------------------------Curve definitions
SCOU 1 'p_ef' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                     ECRO COMP 1
SCOU 2 'r_ef' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                     ECRO COMP 2
SCOU 3 'i_ef' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                     ECRO COMP 4
*-----------------------------------------------Theoretical solutions
DCOU 51 'p_theor'  107
 0.00000E+00 1.00000E+06 1.33810E+01 1.00000E+06 1.34918E+01 9.88618E+05
 1.36025E+01 9.77345E+05 1.37132E+01 9.66178E+05 1.38240E+01 9.55119E+05
 1.39347E+01 9.44165E+05 1.40454E+01 9.33316E+05 1.41562E+01 9.22571E+05
 1.42669E+01 9.11929E+05 1.43776E+01 9.01390E+05 1.44883E+01 8.90952E+05
 1.45991E+01 8.80615E+05 1.47098E+01 8.70379E+05 1.48205E+01 8.60242E+05
 1.49313E+01 8.50203E+05 1.50420E+01 8.40262E+05 1.51527E+01 8.30419E+05
 1.52634E+01 8.20671E+05 1.53742E+01 8.11019E+05 1.54849E+01 8.01462E+05
 1.55956E+01 7.91999E+05 1.57064E+01 7.82629E+05 1.58171E+01 7.73352E+05
 1.59278E+01 7.64167E+05 1.60386E+01 7.55072E+05 1.61493E+01 7.46068E+05
 1.62600E+01 7.37154E+05 1.63707E+01 7.28329E+05 1.64815E+01 7.19592E+05
 1.65922E+01 7.10942E+05 1.67029E+01 7.02379E+05 1.68137E+01 6.93903E+05
 1.69244E+01 6.85511E+05 1.70351E+01 6.77205E+05 1.71458E+01 6.68982E+05
 1.72566E+01 6.60843E+05 1.73673E+01 6.52787E+05 1.74780E+01 6.44812E+05
 1.75888E+01 6.36919E+05 1.76995E+01 6.29107E+05 1.78102E+01 6.21375E+05
 1.79210E+01 6.13722E+05 1.80317E+01 6.06147E+05 1.81424E+01 5.98651E+05
 1.82531E+01 5.91232E+05 1.83639E+01 5.83890E+05 1.84746E+01 5.76624E+05
 1.85853E+01 5.69434E+05 1.86961E+01 5.62318E+05 1.88068E+01 5.55277E+05
 1.89175E+01 5.48309E+05 1.90282E+01 5.41415E+05 1.91390E+01 5.34592E+05
 1.92497E+01 5.27842E+05 1.93604E+01 5.21163E+05 1.94712E+01 5.14554E+05
 1.95819E+01 5.08015E+05 1.96926E+01 5.01546E+05 1.98034E+01 4.95146E+05
 1.99141E+01 4.88813E+05 2.00248E+01 4.82549E+05 2.01355E+01 4.76351E+05
 2.02463E+01 4.70220E+05 2.03570E+01 4.64155E+05 2.04677E+01 4.58155E+05
 2.05785E+01 4.52219E+05 2.06892E+01 4.46349E+05 2.07999E+01 4.40541E+05
 2.09106E+01 4.34797E+05 2.10214E+01 4.29116E+05 2.11321E+01 4.23496E+05
 2.12428E+01 4.17938E+05 2.13536E+01 4.12441E+05 2.14643E+01 4.07004E+05
 2.15750E+01 4.01627E+05 2.16858E+01 3.96309E+05 2.17965E+01 3.91050E+05
 2.19072E+01 3.85850E+05 2.20179E+01 3.80707E+05 2.21287E+01 3.75621E+05
 2.22394E+01 3.70592E+05 2.23501E+01 3.65620E+05 2.24609E+01 3.60703E+05
 2.25716E+01 3.55841E+05 2.26823E+01 3.51034E+05 2.27930E+01 3.46282E+05
 2.29038E+01 3.41583E+05 2.30145E+01 3.36937E+05 2.31252E+01 3.32344E+05
 2.32360E+01 3.27804E+05 2.33467E+01 3.23315E+05 2.34574E+01 3.18877E+05
 2.35682E+01 3.14491E+05 2.36789E+01 3.10155E+05 2.37896E+01 3.05868E+05
 2.39003E+01 3.01632E+05 2.40111E+01 2.97444E+05 2.41218E+01 2.93305E+05
 2.42325E+01 2.89213E+05 2.43433E+01 2.85170E+05 2.44540E+01 2.81174E+05
 3.38583E+01 2.81174E+05 3.38583E+01 2.81174E+05 4.34071E+01 2.81174E+05
 4.34071E+01 1.00000E+05 5.00000E+01 1.00000E+05
DCOU 52 'r_theor'  107
 0.00000E+00 1.00000E+01 1.33810E+01 1.00000E+01 1.34918E+01 9.92398E+00
 1.36025E+01 9.84839E+00 1.37132E+01 9.77323E+00 1.38240E+01 9.69851E+00
 1.39347E+01 9.62421E+00 1.40454E+01 9.55034E+00 1.41562E+01 9.47690E+00
 1.42669E+01 9.40388E+00 1.43776E+01 9.33129E+00 1.44883E+01 9.25912E+00
 1.45991E+01 9.18736E+00 1.47098E+01 9.11603E+00 1.48205E+01 9.04511E+00
 1.49313E+01 8.97460E+00 1.50420E+01 8.90451E+00 1.51527E+01 8.83483E+00
 1.52634E+01 8.76556E+00 1.53742E+01 8.69669E+00 1.54849E+01 8.62824E+00
 1.55956E+01 8.56018E+00 1.57064E+01 8.49254E+00 1.58171E+01 8.42529E+00
 1.59278E+01 8.35844E+00 1.60386E+01 8.29199E+00 1.61493E+01 8.22594E+00
 1.62600E+01 8.16029E+00 1.63707E+01 8.09503E+00 1.64815E+01 8.03016E+00
 1.65922E+01 7.96568E+00 1.67029E+01 7.90159E+00 1.68137E+01 7.83789E+00
 1.69244E+01 7.77457E+00 1.70351E+01 7.71164E+00 1.71458E+01 7.64909E+00
 1.72566E+01 7.58692E+00 1.73673E+01 7.52513E+00 1.74780E+01 7.46372E+00
 1.75888E+01 7.40269E+00 1.76995E+01 7.34203E+00 1.78102E+01 7.28175E+00
 1.79210E+01 7.22183E+00 1.80317E+01 7.16229E+00 1.81424E+01 7.10312E+00
 1.82531E+01 7.04431E+00 1.83639E+01 6.98587E+00 1.84746E+01 6.92780E+00
 1.85853E+01 6.87009E+00 1.86961E+01 6.81273E+00 1.88068E+01 6.75574E+00
 1.89175E+01 6.69911E+00 1.90282E+01 6.64283E+00 1.91390E+01 6.58691E+00
 1.92497E+01 6.53135E+00 1.93604E+01 6.47613E+00 1.94712E+01 6.42127E+00
 1.95819E+01 6.36675E+00 1.96926E+01 6.31258E+00 1.98034E+01 6.25876E+00
 1.99141E+01 6.20529E+00 2.00248E+01 6.15216E+00 2.01355E+01 6.09937E+00
 2.02463E+01 6.04693E+00 2.03570E+01 5.99481E+00 2.04677E+01 5.94303E+00
 2.05785E+01 5.89159E+00 2.06892E+01 5.84049E+00 2.07999E+01 5.78972E+00
 2.09106E+01 5.73928E+00 2.10214E+01 5.68918E+00 2.11321E+01 5.63940E+00
 2.12428E+01 5.58995E+00 2.13536E+01 5.54082E+00 2.14643E+01 5.49202E+00
 2.15750E+01 5.44354E+00 2.16858E+01 5.39539E+00 2.17965E+01 5.34755E+00
 2.19072E+01 5.30003E+00 2.20179E+01 5.25283E+00 2.21287E+01 5.20595E+00
 2.22394E+01 5.15938E+00 2.23501E+01 5.11313E+00 2.24609E+01 5.06718E+00
 2.25716E+01 5.02154E+00 2.26823E+01 4.97622E+00 2.27930E+01 4.93120E+00
 2.29038E+01 4.88649E+00 2.30145E+01 4.84209E+00 2.31252E+01 4.79798E+00
 2.32360E+01 4.75418E+00 2.33467E+01 4.71068E+00 2.34574E+01 4.66748E+00
 2.35682E+01 4.62458E+00 2.36789E+01 4.58197E+00 2.37896E+01 4.53966E+00
 2.39003E+01 4.49764E+00 2.40111E+01 4.45591E+00 2.41218E+01 4.41448E+00
 2.42325E+01 4.37333E+00 2.43433E+01 4.33247E+00 2.44540E+01 4.29190E+00
 3.38583E+01 4.29190E+00 3.38583E+01 1.92770E+00 4.34071E+01 1.92770E+00
 4.34071E+01 1.00000E+00 5.00000E+01 1.00000E+00
DCOU 53 'i_theor'  107
 0.00000E+00 2.00000E+05 1.33810E+01 2.00000E+05 1.34918E+01 1.99238E+05
 1.36025E+01 1.98478E+05 1.37132E+01 1.97719E+05 1.38240E+01 1.96962E+05
 1.39347E+01 1.96206E+05 1.40454E+01 1.95452E+05 1.41562E+01 1.94699E+05
 1.42669E+01 1.93947E+05 1.43776E+01 1.93197E+05 1.44883E+01 1.92449E+05
 1.45991E+01 1.91701E+05 1.47098E+01 1.90956E+05 1.48205E+01 1.90212E+05
 1.49313E+01 1.89469E+05 1.50420E+01 1.88727E+05 1.51527E+01 1.87988E+05
 1.52634E+01 1.87249E+05 1.53742E+01 1.86512E+05 1.54849E+01 1.85777E+05
 1.55956E+01 1.85043E+05 1.57064E+01 1.84310E+05 1.58171E+01 1.83579E+05
 1.59278E+01 1.82849E+05 1.60386E+01 1.82121E+05 1.61493E+01 1.81394E+05
 1.62600E+01 1.80669E+05 1.63707E+01 1.79945E+05 1.64815E+01 1.79222E+05
 1.65922E+01 1.78501E+05 1.67029E+01 1.77782E+05 1.68137E+01 1.77064E+05
 1.69244E+01 1.76347E+05 1.70351E+01 1.75632E+05 1.71458E+01 1.74918E+05
 1.72566E+01 1.74206E+05 1.73673E+01 1.73495E+05 1.74780E+01 1.72786E+05
 1.75888E+01 1.72079E+05 1.76995E+01 1.71371E+05 1.78102E+01 1.70666E+05
 1.79210E+01 1.69963E+05 1.80317E+01 1.69261E+05 1.81424E+01 1.68560E+05
 1.82531E+01 1.67861E+05 1.83639E+01 1.67163E+05 1.84746E+01 1.66467E+05
 1.85853E+01 1.65772E+05 1.86961E+01 1.65079E+05 1.88068E+01 1.64387E+05
 1.89175E+01 1.63696E+05 1.90282E+01 1.63007E+05 1.91390E+01 1.62320E+05
 1.92497E+01 1.61633E+05 1.93604E+01 1.60949E+05 1.94712E+01 1.60266E+05
 1.95819E+01 1.59584E+05 1.96926E+01 1.58904E+05 1.98034E+01 1.58225E+05
 1.99141E+01 1.57547E+05 2.00248E+01 1.56871E+05 2.01355E+01 1.56197E+05
 2.02463E+01 1.55524E+05 2.03570E+01 1.54852E+05 2.04677E+01 1.54182E+05
 2.05785E+01 1.53513E+05 2.06892E+01 1.52846E+05 2.07999E+01 1.52180E+05
 2.09106E+01 1.51516E+05 2.10214E+01 1.50853E+05 2.11321E+01 1.50192E+05
 2.12428E+01 1.49532E+05 2.13536E+01 1.48873E+05 2.14643E+01 1.48216E+05
 2.15750E+01 1.47561E+05 2.16858E+01 1.46907E+05 2.17965E+01 1.46254E+05
 2.19072E+01 1.45603E+05 2.20179E+01 1.44953E+05 2.21287E+01 1.44305E+05
 2.22394E+01 1.43658E+05 2.23501E+01 1.43012E+05 2.24609E+01 1.42368E+05
 2.25716E+01 1.41726E+05 2.26823E+01 1.41085E+05 2.27930E+01 1.40445E+05
 2.29038E+01 1.39807E+05 2.30145E+01 1.39170E+05 2.31252E+01 1.38535E+05
 2.32360E+01 1.37901E+05 2.33467E+01 1.37269E+05 2.34574E+01 1.36638E+05
 2.35682E+01 1.36008E+05 2.36789E+01 1.35380E+05 2.37896E+01 1.34754E+05
 2.39003E+01 1.34129E+05 2.40111E+01 1.33505E+05 2.41218E+01 1.32883E+05
 2.42325E+01 1.32262E+05 2.43433E+01 1.31643E+05 2.44540E+01 1.31025E+05
 3.38583E+01 1.31025E+05 3.38583E+01 2.91719E+05 4.34071E+01 2.91719E+05
 4.34071E+01 2.00000E+05 5.00000E+01 2.00000E+05
COUR 43 't_ef'    DIVC  3 666.667
COUR 63 't_theor' DIVC 53 666.667
*-------------------------------------------------------------------Plots
TRAC 1 51 AXES 1.0 'PRESS. [PA]'
       COLO noir roug
TRAC 2 52 AXES 1.0 'DENS. [KG/M3]'
       COLO noir roug
TRAC 43 63 AXES 1.0 'TEMP. [K]'
       COLO noir roug
TRAC 3 53 AXES 1.0 'EINT [J/KG]'
       COLO noir roug
LIST 1 AXES 1.0 'PRESS. [PA]'
LIST 2 AXES 1.0 'DENS. [KG/M3]'
LIST 3 AXES 1.0 'EINT [J/KG]'
LIST 43 AXES 1.0 'TEMP. [K]'
*-----------------------------------------------Results qualification
!QUAL ECRO COMP 2 LECT 25 TERM REFE 8.68046E-01  TOLE 1.E-2
!     ECRO COMP 2 LECT 50 TERM REFE 4.98674E-01  TOLE 1.E-2
!     ECRO COMP 2 LECT 75 TERM REFE 4.57575E-01  TOLE 1.E-2
*===================================================================
FIN
```

TUBECC

This solution is obtained with Cell-Centered Finite Volumes (Q4VF). Boundary conditions are imposed in a weak manner (no directive is needed). The input file is:

```
TUBECC
ECHO
!CONV WIN
DPLA EULE
GEOM LIBR POIN 202 Q4VF 100 TERM
...
,same mesh as before>
...
MATE GAZP RO 10.D0 GAMM 1.5 CV 666.667 PINI 1.E6 PREF 0.D0
          LECT 1 PAS 1 50 TERM
     GAZP RO  1.D0 GAMM 1.5 CV 666.667 PINI 1.E5 PREF 0.D0
          LECT 51 PAS 1 100 TERM
LINK COUP
     BLOQ 2 TOUS
     BLOQ 1 LECT 1 101 102 202 TERM
ECRI VITE ACCE FINT FEXT CONT ECRO TFRE 30.E-3
     FICH ALIC TFRE 30.E-3
OPTI PAS AUTO NOTE STEP IO CSTA 0.5
     LOG 1
          VFCC FCON 6    ! Solveur HLLC
               ORDR 2    ! Ordre 2 en espace
               OTPS 2    ! Ordre 2 en temps
               RECO 1    ! Reconstruction de type Green-Gauss
               LMAS 3    ! k-limiteur de Dubois (eq. masse)
               LQDM 3    ! k-limiteur de Dubois (eq. QDM)
               LENE 3    ! k-limiteur de Dubois (eq. energie)
               KMAS 0.75 ! Coefficient de limitation (eq. masse)
               KQDM 0.75 ! Coefficient de limitation (eq. QDM)
               KENE 0.75 ! Coefficient de limitation (eq. energie)
               CENE      ! Correction de l'energie interne
CALC TINI 0 TEND 30.E-3
*===========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
*-----------------------------------------------------Curve definitions
SCOU 1 'p_cc' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                     ECRO COMP 1
SCOU 2 'r_cc' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                     ECRO COMP 2
SCOU 3 't_ccc' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                     ECRO COMP 7
*-----------------------------------------------Theoretical solutions
DCOU 51 'p_theor'  107
<same as before>
DCOU 52 'r_theor'  107
<same as before>
DCOU 53 'i_theor'  107
<same as before>
COUR 43 't_cc'    ADDC 3 273.15
COUR 63 't_theor' DIVC 53 666.667
*-------------------------------------------------------------------Plots
TRAC 1 51 AXES 1.0 'PRESS. [PA]'
       COLO noir roug
TRAC 2 52 AXES 1.0 'DENS. [KG/M3]'
       COLO noir roug
TRAC 43 63 AXES 1.0 'TEMP. [K]'
       COLO noir roug
LIST 1 AXES 1.0 'PRESS. [PA]'
LIST 2 AXES 1.0 'DENS. [KG/M3]'
LIST 43 AXES 1.0 'TEMP. [K]'
*-----------------------------------------------Results qualification
!QUAL ECRO COMP 2 LECT 25 TERM REFE 8.68046E-01  TOLE 1.E-2
!     ECRO COMP 2 LECT 50 TERM REFE 4.98674E-01  TOLE 1.E-2
!     ECRO COMP 2 LECT 75 TERM REFE 4.57575E-01  TOLE 1.E-2
*===================================================================
FIN
```

TUBENC

This solution is obtained with Node-Centered Finite Volumes (MC24). Boundary conditions are imposed in a strong manner (`LINK COUP BLOQ`). The input file is:

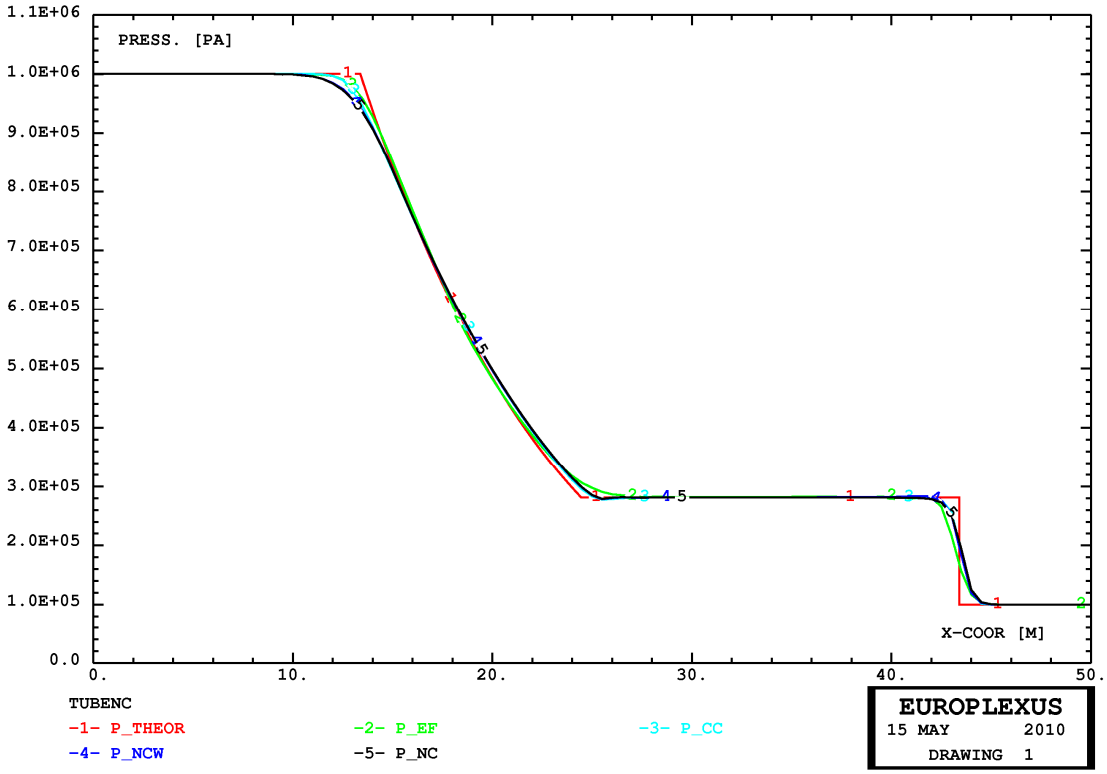
```
TUBENC
ECHO
!CONV WIN
DPLA EULE
DIME NDVC 804 TERM
GEOM LIBR POIN 202 MC24 100 TERM
...
<same mesh as before>
...
MATE MCGP NCOM 1 R 1.E4
          COMP 'aria' PM 30.E0 CV1 2.E4 CV2 0 CV3 0
          LECT tous TERM
INIT MCOM COMP 'aria' MFRA 1.0 LECT tous TERM
          PRES 1.D6 LECT  1 PAS 1  50 102 PAS 1 151 TERM
          PRES 5.D5 LECT 51          152          TERM
          PRES 1.D5 LECT 52 PAS 1 101 153 PAS 1 202 TERM
          TEMP 3.D2 LECT tous TERM
          VEL1 0.0  LECT tous TERM
          VEL2 0.0  LECT tous TERM
LINK COUP
     BLOQ 2 TOUS
     BLOQ 1 LECT 1 101 102 202 TERM
ECRI VITE ACCE FINT FEXT CONT ECRO MCVC MCVS TFRE 30.E-3
     FICH ALIC TFRE 30.E-3
OPTI PAS AUTO NOTE STEP IO CSTA 0.5
OPTI MC ORDR 2 NUFL ROE SYNC 1
 LOG 1
CALC TINI 0 TEND 30.E-3
*============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC GARD PSCR
SORT GRAP
AXTE 1.0 'X-Coor [m]'
*-----------------------------------------------------------Curve definitions
SCOU 1 'p_nc' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                     MCPR COMP 1
SCOU 2 'r_nc' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                     MCRO COMP 1
SCOU 3 't_nc' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                     MCTE COMP 4
*-----------------------------------------------------Theoretical solutions
DCOU 51 'p_theor'  107
<same as before>
DCOU 52 'r_theor'  107
<same as before>
DCOU 53 'i_theor'  107
<same as before>
COUR 63 't_theor' DIVC 53 666.667
RCOU 11 'p_ef' FICH 'tubeef.pun'
RCOU 12 'r_ef' FICH 'tubeef.pun'
RCOU 13 't_ef' FICH 'tubeef.pun'
RCOU 21 'p_cc' FICH 'tubecc.pun'
RCOU 22 'r_cc' FICH 'tubecc.pun'
RCOU 23 't_cc' FICH 'tubecc.pun'
RCOU 31 'p_ncw' FICH 'tubencw.pun'
RCOU 32 'r_ncw' FICH 'tubencw.pun'
RCOU 33 't_ncw' FICH 'tubencw.pun'
*-------------------------------------------------------------------Plots
TRAC 51 11 21 31 1 AXES 1.0 'PRESS. [PA]'
       COLO roug vert turq bleu noir
TRAC 52 12 22 32 2 AXES 1.0 'DENS. [KG/M3]'
       COLO roug vert turq bleu noir
TRAC 63 13 23 33 3 AXES 1.0 'TEMP. [K]'
       COLO roug vert turq bleu noir
TRAC 51 31 1 AXES 1.0 'PRESS. [PA]'
       COLO roug bleu noir
TRAC 52 32 2 AXES 1.0 'DENS. [KG/M3]'
       COLO roug bleu noir
TRAC 63 33 3 AXES 1.0 'TEMP. [K]'
       COLO roug bleu noir
LIST 1 AXES 1.0 'PRESS. [PA]'
LIST 2 AXES 1.0 'DENS. [KG/M3]'
LIST 3 AXES 1.0 'TEMP. [K]'
TRAC 51 11 21 31 1 AXES 1.0 'PRESS. [PA]'
       COLO noir noir noir noir noir
       DASH    4    3    5    2    0
TRAC 52 12 22 32 2 AXES 1.0 'DENS. [KG/M3]'
       COLO noir noir noir noir noir
       DASH    4    3    5    2    0
TRAC 63 13 23 33 3 AXES 1.0 'TEMP. [K]'
       COLO noir noir noir noir noir
       DASH    4    3    5    2    0
*-----------------------------------------------------Results qualification
!QUAL ECRO COMP 2 LECT 25 TERM REFE 8.68046E-01  TOLE 1.E-2
!     ECRO COMP 2 LECT 50 TERM REFE 4.98674E-01  TOLE 1.E-2
!     ECRO COMP 2 LECT 75 TERM REFE 4.57575E-01  TOLE 1.E-2
*====================================================================
FIN
```

TUBENCW

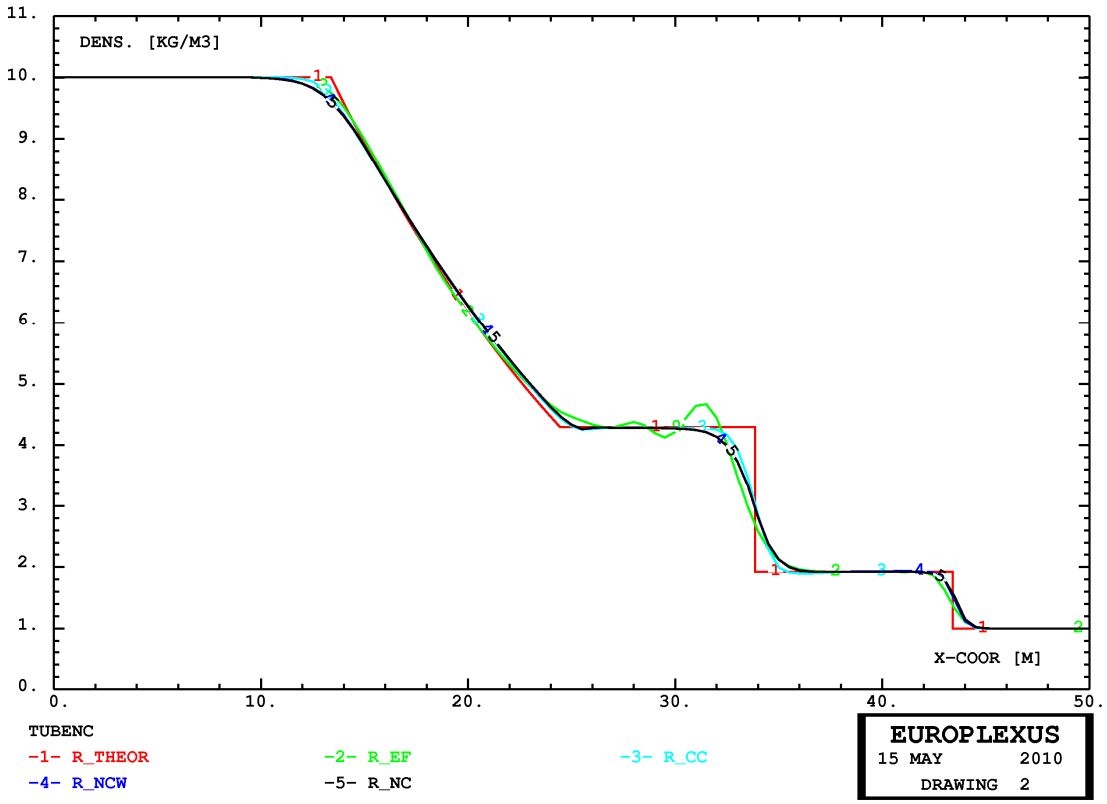
This solution is obtained with Node-Centered Finite Volumes (MC24). Boundary conditions are imposed in a weak manner (`OPTI MC WBC`). The input file is:

```
TUBENCW
ECHO
!CONV WIN
DPLA EULE
DIME NDVC 804 TERM
GEOM LIBR POIN 202 MC24 100 TERM
…
<same mesh as before>
…
MATE MCGP NCOM 1 R 1.E4
          COMP 'aria' PM 30.E0 CV1 2.E4 CV2 0 CV3 0
          LECT tous TERM
INIT MCOM COMP 'aria' MFRA 1.0 LECT tous TERM
          PRES 1.D6 LECT  1 PAS 1  50 102 PAS 1 151 TERM
          PRES 5.D5 LECT 51          152          TERM
          PRES 1.D5 LECT 52 PAS 1 101 153 PAS 1 202 TERM
          TEMP 3.D2 LECT tous TERM
          VEL1 0.0  LECT tous TERM
          VEL2 0.0  LECT tous TERM
ECRI VITE ACCE FINT FEXT CONT ECRO MCVC MCVS TFRE 30.E-3
     FICH ALIC TFRE 30.E-3
OPTI PAS AUTO NOTE STEP IO CSTA 0.5
OPTI MC ORDR 2 NUFL ROE SYNC 1 WBC
 LOG 1
CALC TINI 0 TEND 30.E-3
*============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC GARD PSCR
SORT GRAP
AXTE 1.0 'X-Coor [m]'
*-----------------------------------------------------------Curve definitions
SCOU 1 'p_ncw' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                      MCPR COMP 1
SCOU 2 'r_ncw' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                      MCRO COMP 1
SCOU 3 't_ncw' NSTO 2 SAXE 1.0 'current_abscissa' LECT 1 PAS 1 101 TERM
                      MCTE COMP 4
*-----------------------------------------------------Theoretical solutions
DCOU 51 'p_theor'  107
<same as before>
DCOU 52 'r_theor'  107
<same as before>
DCOU 53 'i_theor'  107
<same as before>
COUR 63 't_theor' DIVC 53 666.667
*-------------------------------------------------------------------Plots
TRAC 1 51 AXES 1.0 'PRESS. [PA]'
       COLO noir roug
TRAC 2 52  AXES 1.0 'DENS. [KG/M3]'
       COLO noir roug
TRAC 3 63 AXES 1.0 'TEMP. [K]'
       COLO noir roug
LIST 1 AXES 1.0 'PRESS. [PA]'
LIST 2 AXES 1.0 'DENS. [KG/M3]'
LIST 3 AXES 1.0 'TEMP. [K]'
*-----------------------------------------------------Results qualification
!QUAL ECRO COMP 2 LECT 25 TERM REFE 8.68046E-01  TOLE 1.E-2
!     ECRO COMP 2 LECT 50 TERM REFE 4.98674E-01  TOLE 1.E-2
!     ECRO COMP 2 LECT 75 TERM REFE 4.57575E-01  TOLE 1.E-2
*====================================================================
FIN
```

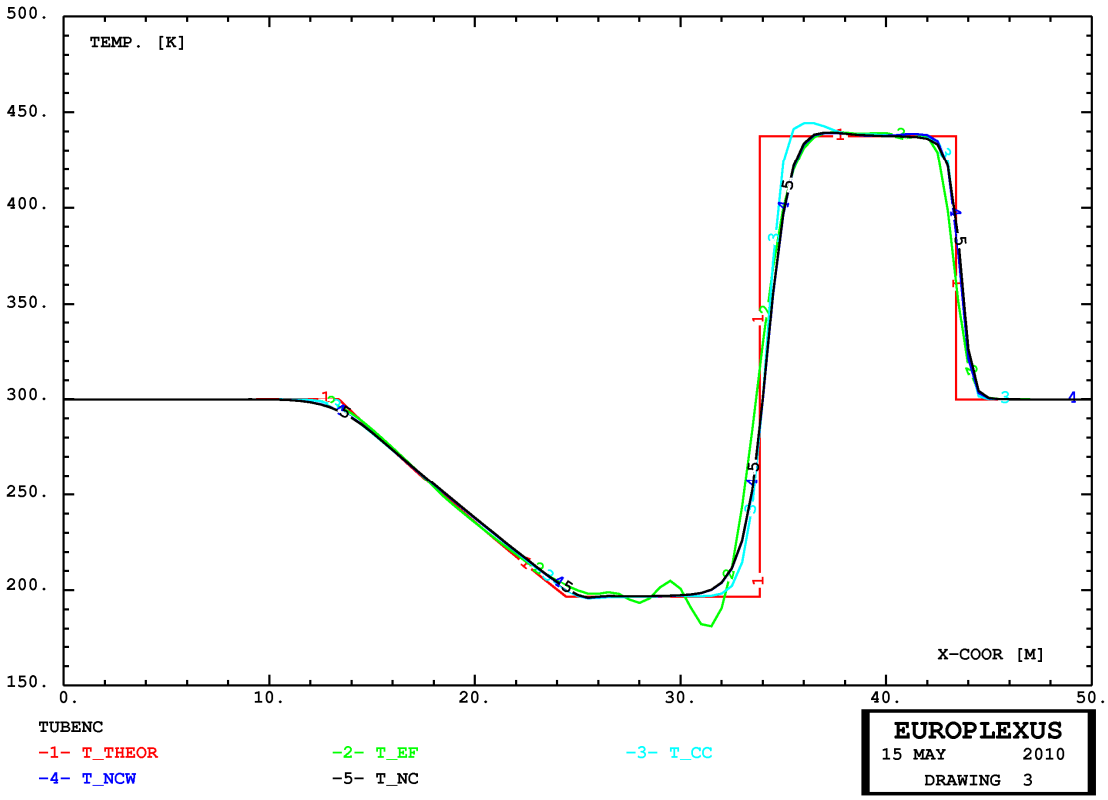
The final pressure along the tube is very similar in all solutions (in red the analytical solution)



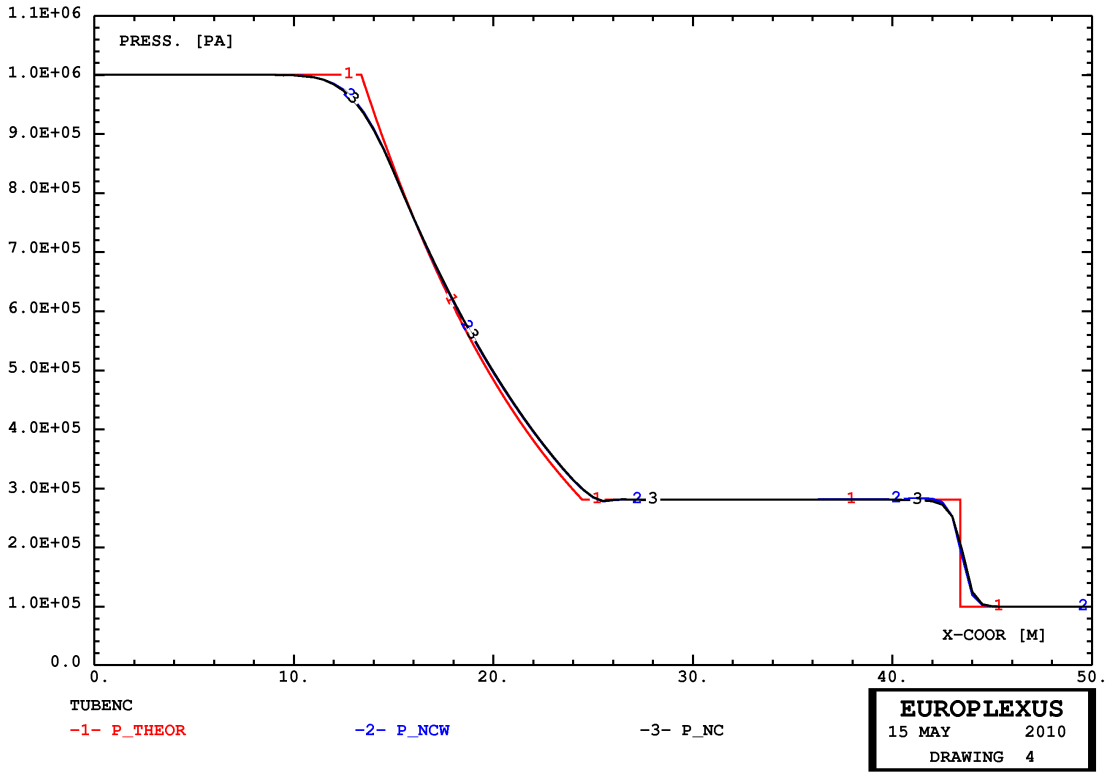
The final density along the tube is very similar in all solutions (in red the analytical solution)



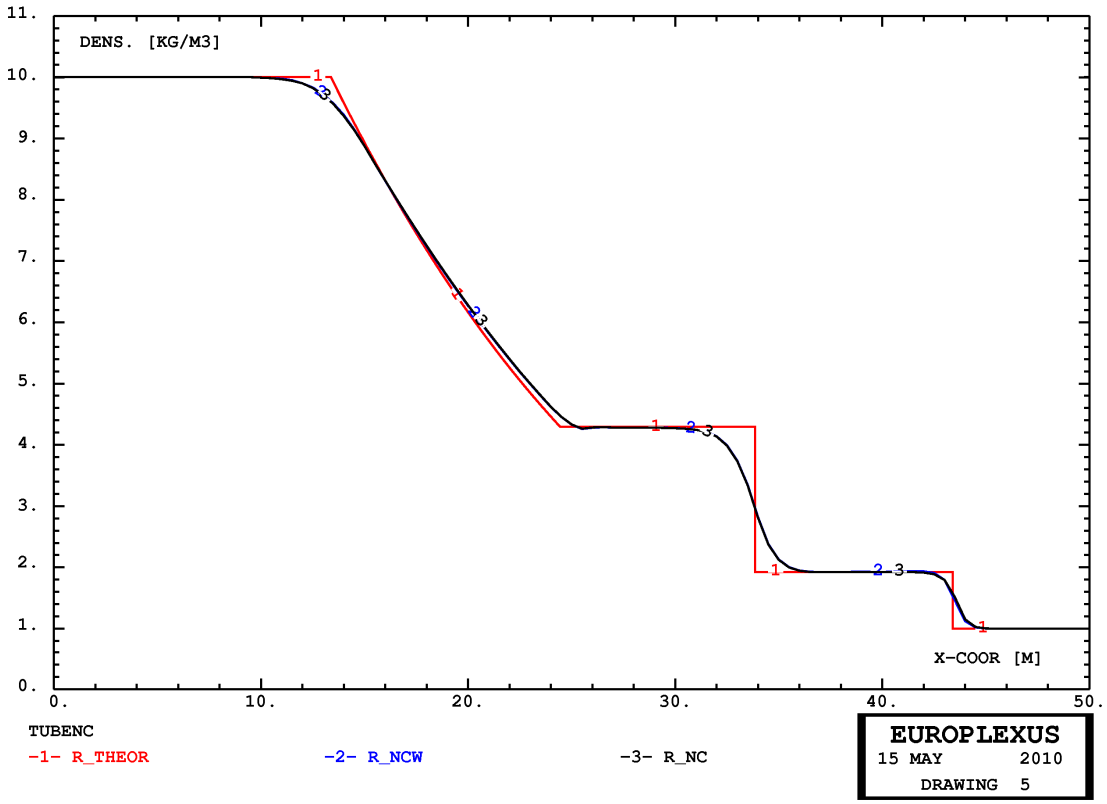
Here are the temperatures



The two NCFV solutions with strong or weak boundary conditions are almost identical. Here are the pressures:



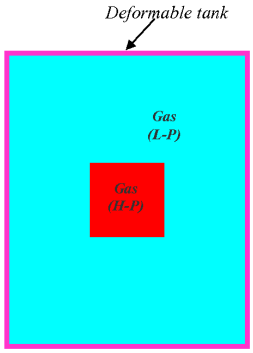
Here are the densities



Exercise 2 – Explosions in simple deformable containers

Add a deformable structure to the case studied in exercise 2 of Part II (air-filled tank).

- Try out ALE solution with FSA



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Geometric data:

For the fluid domain, same as exercise 2 of Part II. The structure is a thin shell of 0.01 units thickness

Materials

For the fluid domain, same as exercise 2 of Part II.

The structure material is a steel with the following characteristics: density 7800, Young's modulus 1.6×10^{11}, Poisson's coefficient 1/3, elastic limit 1.05×10^{8}, and a bilinear elasto-plastic traction curve characterized by the following points (σ,ε):1.05×10^{8}, 0.65626×10^{-3}, 1.6105×10^{10}, 1.00066.

Numerical Solution

TANK04

We use the FSA directive to prescribe the fluid-structure interaction along the external edge of the fluid domain. The mesh generation file is:

```
*%siz 100
opti echo 1;
opti dime 2 elem qua4;
p0 = 0 0;
p1 = 5 0;
p2 = 5 6;
p3 = 0 6;
p4 = 1 0;
p5 = 1 1;
p6 = 0 1;
p7 = 5 1;
p8 = 1 6;
tol = 0.01;
n1 = 2;
n2 = 8;
n3 = 10;
```

```
c1 = p0 d n1 p4;
c2 = p4 d n1 p5;
c3 = p5 d n1 p6;
c4 = p6 d n1 p0;
bull = (dall c1 c2 c3 c4 plan) coul roug;
lag = c2 et c3;
c1 = p4 d n2 p1;
c2 = p1 d n1 p7;
c3 = p7 d n2 p5;
c4 = p5 d n1 p4;
gaz1 = (dall c1 c2 c3 c4 plan) coul turq;
c1 = p5 d n2 p7;
c2 = p7 d n3 p2;
c3 = p2 d n2 p8;
c4 = p8 d n3 p5;
gaz2 = (dall c1 c2 c3 c4 plan) coul turq;
```

```
c1 = p6 d n1 p5;
c2 = p5 d n3 p8;
c3 = p8 d n1 p3;
c4 = p3 d n3 p6;
gaz3 = (dall c1 c2 c3 c4 plan) coul turq;
gaz = (gaz1 et gaz2 et gaz3) coul turq;
flui = bull et gaz;
elim tol flui;
p1p = p1 plus p0;
p2p = p2 plus p0;
p3p = p3 plus p0;
str1 = (p1p d (n1 + n3) p2p) coul rose;
str2 = (p2p d (n1 + n2) p3p) coul rose;
stru = (str1 et str2) coul rose;
lag = lag et stru;
```

```
symx = (flui poin droi p0 p3 tol) et p3p;
fsan = flui poin droi p1 p2 tol;
symy = (flui poin droi p0 p1 tol) et p1p;
fsan = fsan et (flui poin droi p3 p2 tol);
e1 = bull elem cont p0;
e2 = gaz  elem cont p2;
mesh = flui et stru et symx et symy et fsan et e1 et e2 et lag;
tass mesh;
opti sauv form 'tank04.msh';
sauv form mesh;
opti trac psc;
trac qual mesh;
list (nbel flui);
list (nbno flui);
fin;
```

The input file is:

```
TANK - 04
*------------------------------------------------------------------------
 ECHO
*CONV win
CAST mesh
*-------------------------------------------------------------Problem type
DPLA NONL ALE
*-----------------------------------------------------------Dimensioning
DIME
 PT3L 23 PT2L 143 FL24 145 ED01 22 ZONE 2
 NALE 150 NBLE 150
TERM
*----------------------------------------------------------------Geometry
GEOM FL24 flui ED01 stru TERM
*-------------------------------------------------------Geometric complements
COMP EPAI 0.01 LECT stru TERM
*-----------------------------------------------------------Grid motion
GRIL LAGR LECT lag  TERM
     ALE  LECT flui TERM
     AUTO AUTR
*---------------------------------------------------------Material data
MATE FLUT RO 10  EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1 BET0 1 KINT 1
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1 LECT bull TERM
     FLUT RO 1   EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1 BET0 1 KINT 1
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1 LECT gaz  TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
*-----------------------------------------------------Boundary conditions
LINK COUP
     CONT SPLA NX 1 NY 0 LECT symx TERM
     CONT SPLA NX 0 NY 1 LECT symy TERM
     FSA LECT fsan TERM
*------------------------------------------------------------------Outputs
ECRI COOR DEPL VITE CONT ECRO TFRE 1.E-3
     FICH ALIC TEMP FREQ 1
               POIN LECT p1 p3 TERM
               ELEM LECT e1 e2 TERM
*-------------------------------------------------------------------Options
OPTI NOTE
     CSTA 0.5
     LOG 1
     REZO GAM0 0.5
*-----------------------------------------------------Transient calculation
CALCUL TINI 0 TEND 10.E-3
*=====================================================================
PLAY

CAME   1 EYE   0.00000E+00  0.00000E+00  3.90512E+01
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
```

```
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01

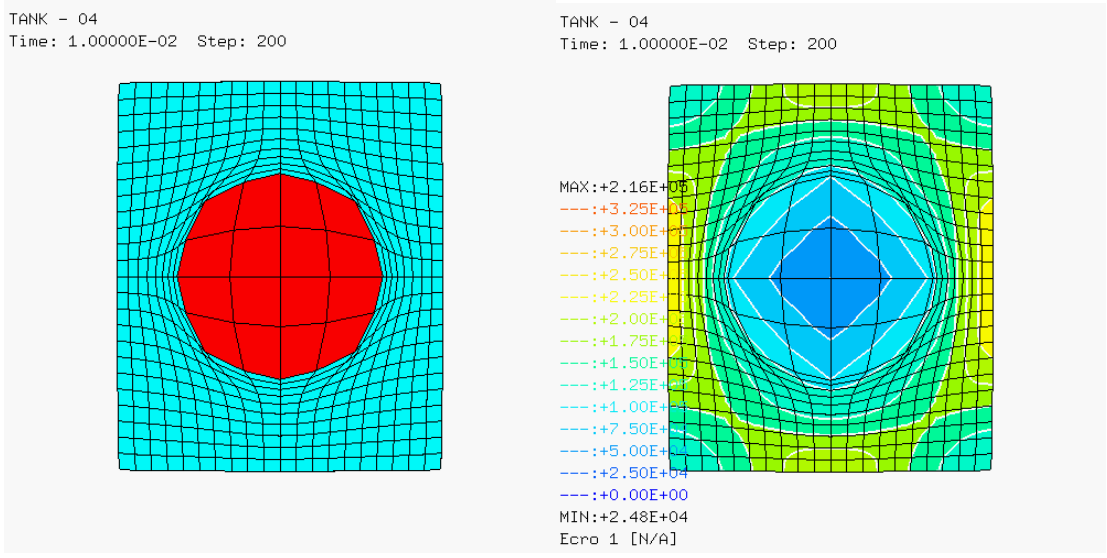
scen geom navi free
     !vect scco scal user prog 0 pas 25 325 term
     !text vsca
     !iso  fili fiel ecro 1 scal user prog 0.e0 pas 0.25e5 3.25e5 term
     !text isca
     !vect scco scal user prog 0.e0 pas 1.e0 1.3e1 term
     !text vsca
      colo pape

freq 1

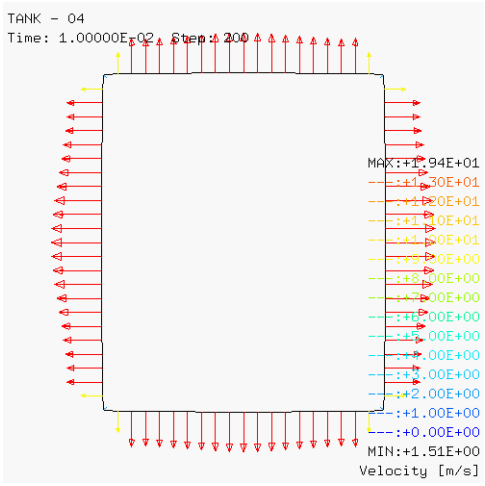
sler cam1 1        nfra 1
trac offs fich avi      nocl nfto 161 fps 10 kfre 10 comp -1
                                                !obje lect flui term
                                                !obje lect stru term
                                                     symx symy rend
gotr loop 159 offs fich avi cont nocl
                                                !obje lect flui term
                                                !obje lect stru term
                                                     symx symy rend
go
trac offs fich avi cont
                                                !obje lect flui term
                                                !obje lect stru term
                                                     symx symy rend

ENDPLAY
*=========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------------Curve definitions
COUR 1 'dx_1'     DEPL COMP 1 NOEU LECT p1 TERM
COUR 2 'dy_3'     DEPL COMP 2 NOEU LECT p3 TERM
COUR 3 'pr_1'     ECRO COMP 1 ELEM LECT e1 TERM
COUR 4 'pr_2'     ECRO COMP 1 ELEM LECT e2 TERM
*-------------------------------------------------------------------------Plots
trac 1 2 axes 1.0 'DISPL. [M]' yzer
trac 3 4 axes 1.0 'PRESS. [PA]'
*-----------------------------------------------------Results qualification
QUAL DEPL COMP 1 LECT  p1 TERM REFE 7.70209E-02  TOLE 1.E-2
     DEPL COMP 2 LECT  p3 TERM REFE 6.65486E-02  TOLE 1.E-2
     CONT COMP 1 LECT  e1 TERM REFE 2.47742E+04  TOLE 1.E-2
     CONT COMP 1 LECT  e2 TERM REFE 1.05241E+05  TOLE 1.E-2
*=====================================================================
FIN
```

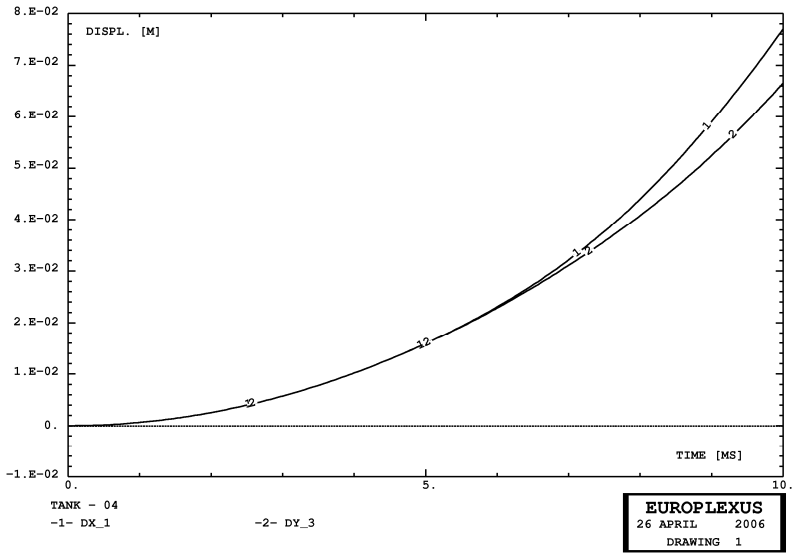
The resulting final deformed mesh with superposed velocity field and the final pressure field is:



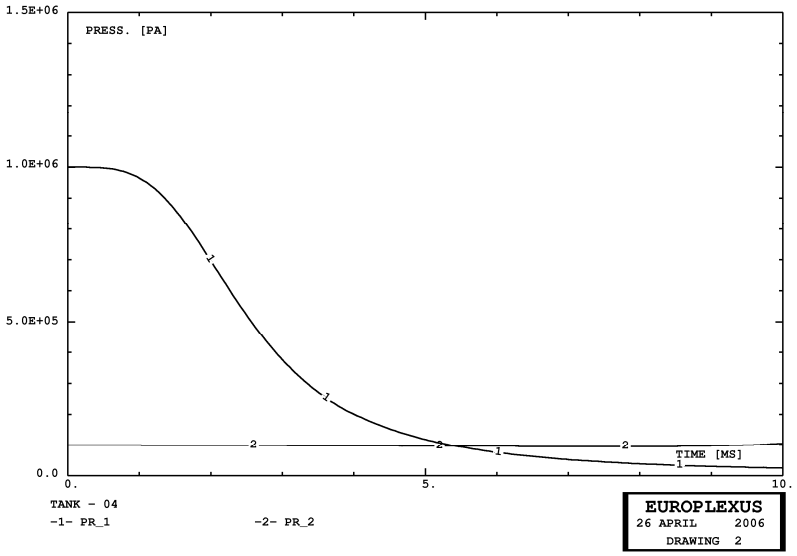
The final structure velocities:



The displacements of the horizontal and vertical mid-points are:



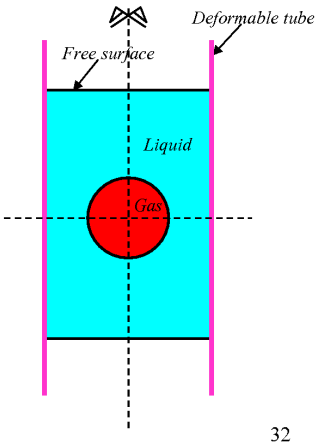
and the fluid pressure histories:



Exercise 2 – Explosions in simple deformable containers (3)

Treat as deformable the tube of the case studied in exercise 3 of Part II.

- Can one try out ALE solution with FSA?
- Alternative 1: use Lagrangian sliding
- Alternative 2: use FSA with multi-phase multi-component fluid model



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ALE solution with FSA: it is <u>not</u> possible (with a single-component fluid material model), because the F-S contact in this case is <u>non-permanent</u> due to the fact that the liquid free surface (Lagrangian) slides along the tube wall (Lagrangian).

<u>Alternative 1</u>
Use Lagrangian sliding between the liquid and the tube.

TUBE11

The input file is:

```
TUBE - 11
*-----------------------------------------------------------------------
 ECHO
 CONV win
*-------------------------------------------------------------Problem type
AXIS NONL ALE
*-------------------------------------------------------------Dimensioning
DIME
 PT3L 38 PT2L 107 FL23 12 FL24 84 ED41 18 ZONE 3
 NALE 1 NBLE 98
 FSSL 100
TERM
*-----------------------------------------------------------------Geometry
GEOM LIBR POIN 145 FL23 12 FL24 84 ED41 18 TERM
 0.00000E+00 0.00000E+00 3.14500E+00 0.00000E+00 3.11810E+00
 4.10500E-01 3.03780E+00 8.13990E-01 2.90560E+00 1.20350E+00
 2.72360E+00 1.57250E+00 2.49510E+00 1.91460E+00 2.22390E+00
 2.22390E+00 1.91460E+00 2.49510E+00 1.57250E+00 2.72360E+00
 1.20350E+00 2.90560E+00 8.13990E-01 3.03780E+00 4.10500E-01
 3.11810E+00 0.00000E+00 3.14500E+00 5.15600E+00 0.00000E+00
 5.09970E+00 7.30510E-01 5.00880E+00 1.45180E+00 4.86420E+00
 2.15130E+00 4.64850E+00 2.81320E+00 4.34360E+00 3.41610E+00
 3.93350E+00 3.93350E+00 3.41610E+00 4.34360E+00 2.81320E+00
 4.64850E+00 2.15130E+00 4.86420E+00 1.45180E+00 5.00880E+00
 7.30510E-01 5.09970E+00 0.00000E+00 5.15600E+00 7.16700E+00
 0.00000E+00 7.11050E+00 1.06860E+00 7.02640E+00 2.12620E+00
 6.88680E+00 3.15600E+00 6.65900E+00 4.13330E+00 6.30030E+00
 5.02060E+00 5.76190E+00 5.76190E+00 5.02060E+00 6.30030E+00
 4.13330E+00 6.65900E+00 3.15600E+00 6.88680E+00 2.12620E+00
 7.02640E+00 1.06860E+00 7.11050E+00 0.00000E+00 7.16700E+00
 9.17800E+00 0.00000E+00 9.13620E+00 1.42630E+00 9.07480E+00
 2.84270E+00 8.96560E+00 4.23180E+00 8.76610E+00 5.56250E+00
 8.40820E+00 6.78060E+00 7.78260E+00 7.78260E+00 6.78060E+00
 8.40820E+00 5.56250E+00 8.76610E+00 4.23180E+00 8.96560E+00
 2.84270E+00 9.07480E+00 1.42630E+00 9.13620E+00 0.00000E+00
 9.17800E+00 1.11890E+01 0.00000E+00 1.11680E+01 1.80470E+00
 1.11370E+01 3.60290E+00 1.10790E+01 5.38310E+00 1.09600E+01
 7.11960E+00 1.07060E+01 8.75410E+00 1.01290E+01 1.01290E+01
 8.75410E+00 1.07060E+01 7.11960E+00 1.09600E+01 5.38310E+00
 1.10790E+01 3.60290E+00 1.11370E+01 1.80470E+00 1.11680E+01
 0.00000E+00 1.11890E+01 1.32000E+01 0.00000E+00 1.32000E+01
 2.20000E+00 1.32000E+01 4.40000E+00 1.32000E+01 6.60000E+00
 1.32000E+01 8.80000E+00 1.32000E+01 1.10000E+01 1.32000E+01
 1.32000E+01 1.10000E+01 1.32000E+01 8.80000E+00 1.32000E+01
 6.60000E+00 1.32000E+01 4.40000E+00 1.32000E+01 2.20000E+00
 1.32000E+01 6.29420E-06 1.32000E+01 1.32000E+01 1.49000E+01
 1.10000E+01 1.49000E+01 8.80000E+00 1.49000E+01 6.60000E+00
 1.49000E+01 4.40000E+00 1.49000E+01 2.20000E+00 1.49000E+01
 6.29420E-06 1.49000E+01 1.32000E+01 1.66000E+01 1.10000E+01
 1.66000E+01 8.80000E+00 1.66000E+01 6.60000E+00 1.66000E+01
 4.40000E+00 1.66000E+01 2.20000E+00 1.66000E+01 6.29420E-06
 1.66000E+01 1.32000E+01 1.83000E+01 1.10000E+01 1.83000E+01
 8.80000E+00 1.83000E+01 6.60000E+00 1.83000E+01 4.40000E+00
 1.83000E+01 2.20000E+00 1.83000E+01 6.29420E-06 1.83000E+01
 1.32000E+01 2.00000E+01 1.10000E+01 2.00000E+01 8.80000E+00
 2.00000E+01 6.60000E+00 2.00000E+01 4.40000E+00 2.00000E+01
 2.20000E+00 2.00000E+01 6.29420E-06 2.00000E+01
 13.2 0 13.2 2.2 13.2 4.4 13.2 6.6 13.2 8.8 13.2 11
 13.2 13.2 13.2 14.9 13.2 16.6 13.2 18.3 13.2 20 13.2 22
 13.2 24 13.2 26 13.2 28 13.2 30 13.2 32 13.2 34 13.2 36
 13.22 0 13.22 2.2 13.22 4.4 13.22 6.6 13.22 8.8 13.22 11
 13.22 13.2 13.22 14.9 13.22 16.6 13.22 18.3 13.22 20 13.22 22
 13.22 24 13.22 26 13.22 28 13.22 30 13.22 32 13.22 34 13.22 36
     2     3     1           3     4     1           4     5
     1           5     6     1           6     7     1
     7     8     1           8     9     1           9    10
     1          10    11     1          11    12     1
    12    13     1          13    14     1           2    15
    16     3     3    16    17     4     4    17    18     5
     5    18    19     6     6    19    20     7     7    20
    21     8     8    21    22     9     9    22    23    10
    10    23    24    11    11    24    25    12    12    25
    26    13    13    26    27    14    15    28    29    16
    16    29    30    17    17    30    31    18    18    31
    32    19    19    32    33    20    20    33    34    21
    21    34    35    22    22    35    36    23    23    36
    37    24    24    37    38    25    25    38    39    26
    26    39    40    27    28    41    42    29    29    42
    43    30    30    43    44    31    31    44    45    32
    32    45    46    33    33    46    47    34    34    47
    48    35    35    48    49    36    36    49    50    37
    37    50    51    38    38    51    52    39    39    52
    53    40    41    54    55    42    42    55    56    43
    43    56    57    44    44    57    58    45    45    58
    59    46    46    59    60    47    47    60    61    48
    48    61    62    49    49    62    63    50    50    63
    64    51    51    64    65    52    52    65    66    53
    54    67    68    55    55    68    69    56    56    69
    70    57    57    70    71    58    58    71    72    59
    59    72    73    60    60    73    74    61    61    74
    75    62    62    75    76    63    63    76    77    64
    64    77    78    65    65    78    79    66    73    80
    81    74    74    81    82    75    75    82    83    76
    76    83    84    77    77    84    85    78    78    85
    86    79    80    87    88    81    81    88    89    82
    82    89    90    83    83    90    91    84    84    91
    92    85    85    92    93    86    87    94    95    88
    88    95    96    89    89    96    97    90    90    97
    98    91    91    98    99    92    92    99   100    93
    94   101   102    95    95   102   103    96    96   103
   104    97    97   104   105    98    98   105   106    99
    99   106   107   100
```

```
 109 108 127 128
 110 109 128 129
 111 110 129 130
 112 111 130 131
 113 112 131 132
 114 113 132 133
 115 114 133 134
 116 115 134 135
 117 116 135 136
 118 117 136 137
 119 118 137 138
 120 119 138 139
 121 120 139 140
 122 121 140 141
 123 122 141 142
 124 123 142 143
 125 124 143 144
 126 125 144 145
*-----------------------------------------------------Geometric Complements
COMP GROU 3 'expl' LECT 1 PAS 1 12 TERM
           'liq'  LECT 13 PAS 1 96 TERM
           'stru' LECT 97 PAS 1 114 TERM
     COUL roug LECT expl TERM
          turq LECT liq  TERM
          rose LECT stru TERM
     EPAIS 0.02 LECT stru TERM
*-------------------------------------------------------------Grid Motion
GRIL LAGR LECT 1 PAS 1 14 67 PAS 1 73 PAS 7 101 PAS 1 107 PAS 1 145 TERM
     ALE TOUS
     AUTO AUTR
*-----------------------------------------------------------Material data
MATE FLUT RO 1.E3 EINT 0 GAMM 2.E9 PB 0 ITER 1 ALF0 1 BET0 1 KINT 0
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 9 LECT 13 PAS 1 96 TERM
     FLUT RO 1.E2 EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1 BET0 1 KINT 0
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1 LECT 1 PAS 1 12 TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
*-----------------------------------------------------Boundary conditions
LINK COUP
     BLOQ 1 LECT 1 14 PAS 13
                 79 PAS 7 107 TERM
     BLOQ 2 LECT 1 67 2 15 28 41 54 108 127 TERM
     BLOQ 3 LECT 108 127 TERM
LINK DECO
     FSS LAGR NCT1 10
              LECT 61 67 68 TERM
              LECT 62 68 69 TERM
              LECT 63 69 70 TERM
              LECT 64 70 71 TERM
              LECT 65 71 72 TERM
              LECT 66 72 73 TERM
              LECT 73 73 80 TERM
              LECT 79 80 87 TERM
              LECT 85 87 94 TERM
              LECT 91 94 101 TERM
          NPOI 11
          NCT2 18
              LECT 97 108 109 TERM
              LECT 98 109 110 TERM
              LECT 99 110 111 TERM
              LECT 100 111 112 TERM
              LECT 101 112 113 TERM
              LECT 102 113 114 TERM
              LECT 103 114 115 TERM
              LECT 104 115 116 TERM
              LECT 105 116 117 TERM
              LECT 106 117 118 TERM
              LECT 107 118 119 TERM
              LECT 108 119 120 TERM
              LECT 109 120 121 TERM
              LECT 110 121 122 TERM
              LECT 111 122 123 TERM
              LECT 112 123 124 TERM
              LECT 113 124 125 TERM
              LECT 114 125 126 TERM
          NPOI 19
*-------------------------------------------------------------------Outputs
ECRI COOR DEPL VITE CONT ECRO TFRE 100.E-3
     FICH ALIC TEMP FREQ 1
              POIN LECT 101 107 TERM
              ELEM LECT 1 91 TERM
*-------------------------------------------------------------------Options
OPTI NOTE
 csta 0.5
 log 1
 rezo gam0 0.5
*-----------------------------------------------Transient calculation
CALCUL TINI 0 TEND 500.E-3
*=================================================================ANIMATION
PLAY

CAME   1 EYE   0.00000E+00  0.00000E+00  1.19817E+02
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   3.00000E+01

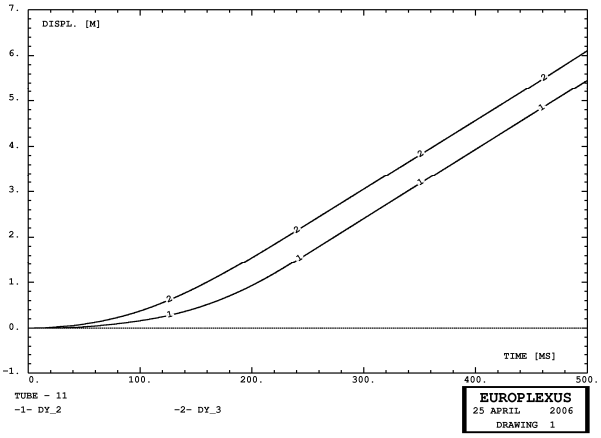
scen geom navi free
     !vect scco scal user prog 0.e0 pas 2.e0 2.6e1 term
     !text vsca
      colo pape

freq 0 tfre 2.e-3

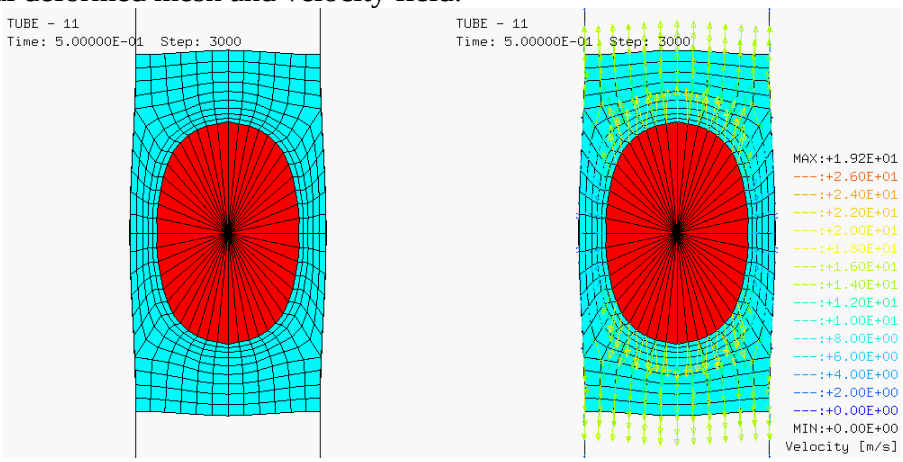
sler cam1 1        nfra 1
trac offs fich avi      nocl nfto 251 fps 10 kfre 10 comp -1
                                                    symx symy rend
gotr loop 249 offs fich avi cont nocl
                                                    symx symy rend
go
trac offs fich avi cont
                                                    symx symy rend

ENDPLAY
*=========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------Curve definitions
COUR 1 'dy_2'     DEPL COMP 2 NOEU LECT 101 TERM
COUR 2 'dy_3'     DEPL COMP 2 NOEU LECT 107 TERM
COUR 3 'pr_1'     ECRO COMP 1 ELEM LECT 1   TERM
COUR 4 'pr_2'     ECRO COMP 1 ELEM LECT 91  TERM
*-------------------------------------------------------------------Plots
trac 1 2 axes 1.0 'DISPL. [M]' yzer
trac 3 4 axes 1.0 'PRESS. [PA]'
*-----------------------------------------------Results qualification
QUAL DEPL COMP 2 LECT 101 TERM REFE 5.43306E+00  TOLE 1.E-2
     DEPL COMP 2 LECT 107 TERM REFE 6.07702E+00  TOLE 1.E-2
     ECRO COMP 1 LECT   1 TERM REFE 3.80273E+04  TOLE 1.E-2
     ECRO COMP 1 LECT  91 TERM REFE 0.00000E+00  TOLE 1.E-2
*=================================================================
FIN
```

The surface displacements are:



The final deformed mesh and velocity field:

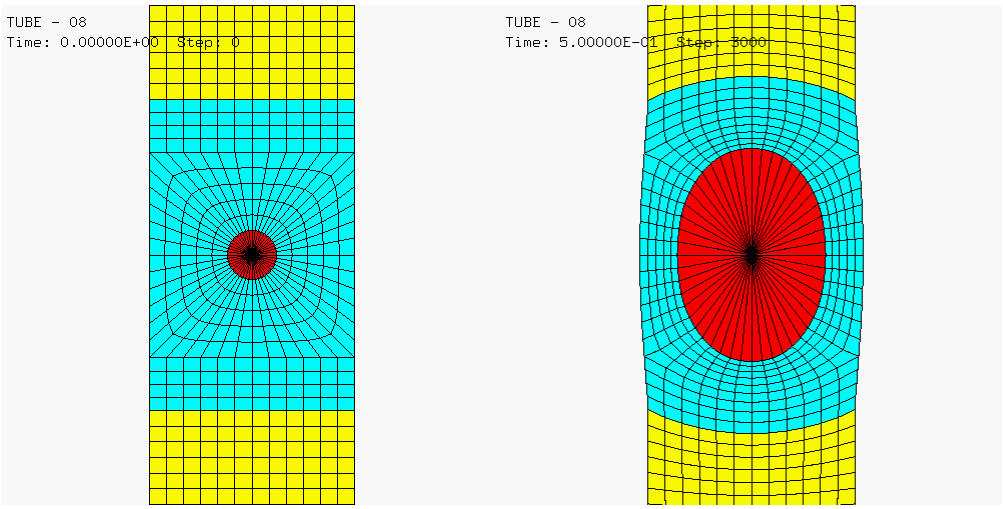


Alternative 2

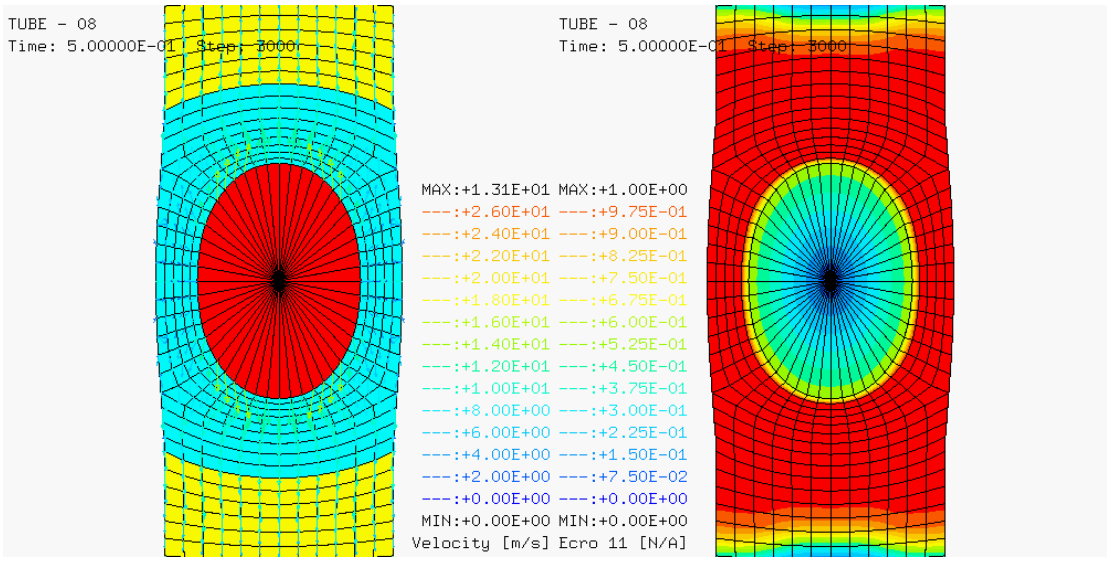
Use multi-phase multi-component fluid model to get rid of Lagrangian fluid/structure interfaces, and standard FSA model for fluid-structure interaction.

TUBE08

To make this type of simulation possible, we model an additional fluid region (in itially filled by air at atmospheric pressure) above the liquid free surface. This region (in yellow in the following drawings) will be filled by the rising liquid during the transient. The initial mesh and the final mesh are (note that the red zone indicates the bubble, whose surface is Lagrangian, but the other two zones are not representative of materials, since the liquid-air interface is ALE):



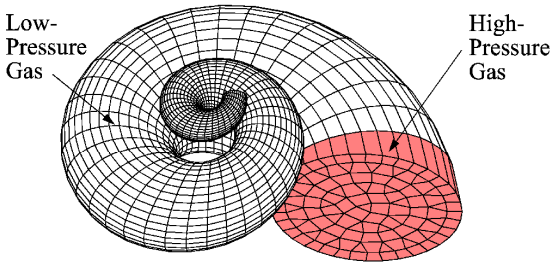
The final velocities and liquid mass fractions:



Exercise/Example 3 – Wave propagation in 3-D rigid tank

The rigid outer surface has a complex 3-D shape.

- Try out ALE solution with FSR



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Geometric data:

Complex shell-like 3D shape. The walls are assumed to be rigid, so this is a purely fluid problem.

Materials

The explosive bubble is made of a high-pressure perfect gas. The rest of the domain is filled by the same gas but at a lower pressure.

Numerical Solution

SOLI01

We use the FSR directive to prescribe the boundary conditions at the complex 3D surface of the domain. The input file is:

```
SOLI - 01
*------------------------------------------------------------------
 ECHO
 CONV win
CAST MESH
*-------------------------------------------------------------Problem type
TRID NONL EULE
*-------------------------------------------------------------Dimensioning
DIME
 PT3L 8760 FL38 6264 FL36 2016 ZONE 2
 NALE 1 NBLE 1
 MTEL 115
TERM
*------------------------------------------------------------------Geometry
GEOM FL38 SUR8 FL36 SUR6 TERM
*-----------------------------------------------Geometric Complements
COMP COUL roug LECT sur1 TERM
          turq LECT sur2 TERM
*-----------------------------------------------------Material data
MATE FLUT RO 1.22 EINT 3.046E6 GAMM 1.269 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT SUR1 TERM
     FLUT RO 0.1237 EINT 3.046E6 GAMM 1.269 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT SUR2 TERM
*-----------------------------------------------Boundary conditions
LINK COUP FSR LECT FSRN TERM
*-------------------------------------------------------------------Outputs
ECRI VITE ECRO TFRE 3.5E-3 ELEM LECT SUR1 TERM
     FICH K2000 TFRE 0.5E-3 POIN TOUS
                VARI DEPL VITE ECRO ECRC LECT 1 TERM
```

```
*-------------------------------------------------------------------Options
OPTI NOTE
     CSTA 0.5
     LOG 1
*-----------------------------------------------Transient calculation
CALCUL TINI 0 TEND 0.5E-3
*=================================================================ANIMATION
PLAY

CAME   1 EYE   2.95448E-01 -1.39852E+00  8.01450E+00
!        Q     9.96195E-01  8.71557E-02  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  1.73648E-01 -9.84808E-01
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  9.84808E-01  1.73648E-01
         FOV   1.68819E+01

scen
     vect scav
     text vsca
     lima on
     colo pape

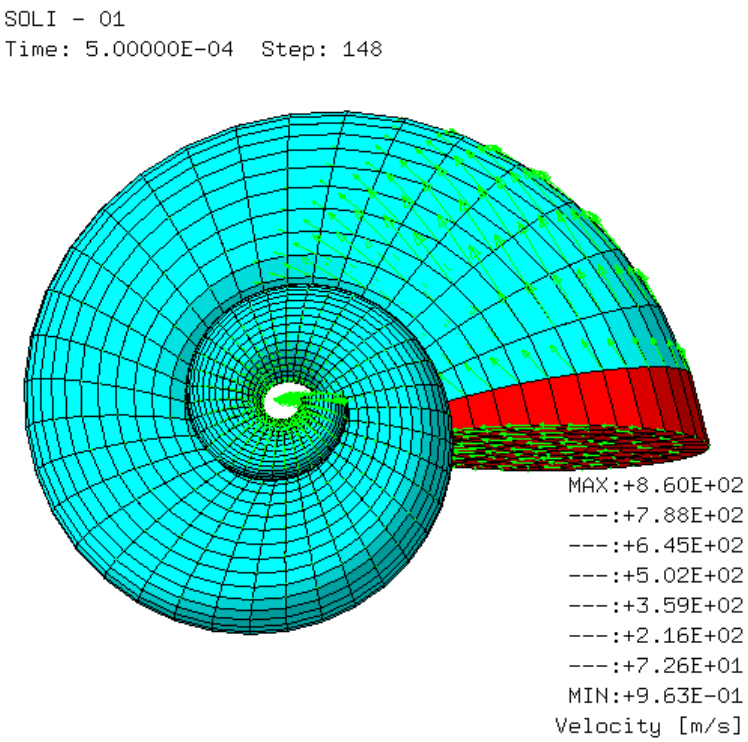
sler cam1 1 nfra 1

freq 0 tfre 0.5e-3

go
trac offs fich bmp rend

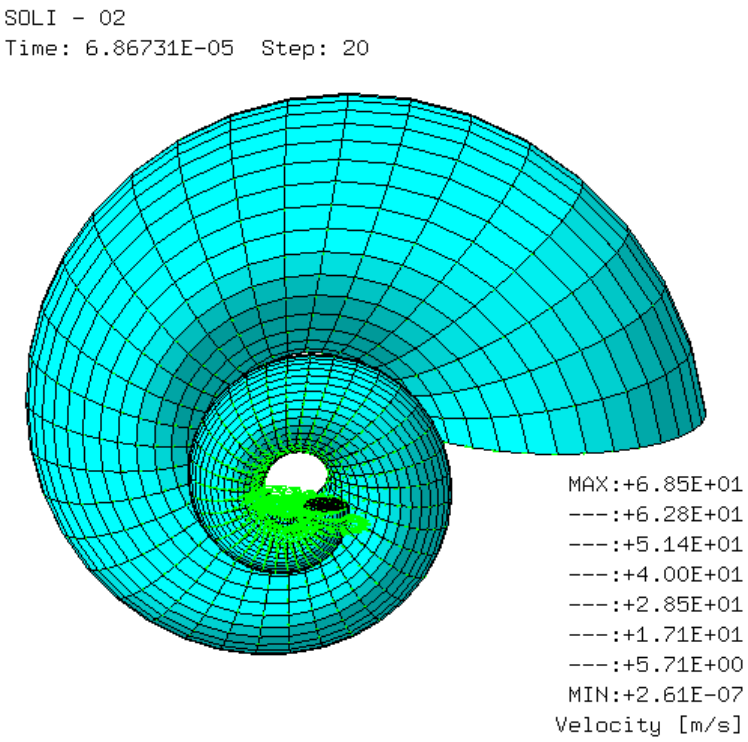
ENDPLAY
*=====================================================================
FIN
```

At 0.5 ms, spurious (non-physical) velocities appear at the thin end of the fluid domain:



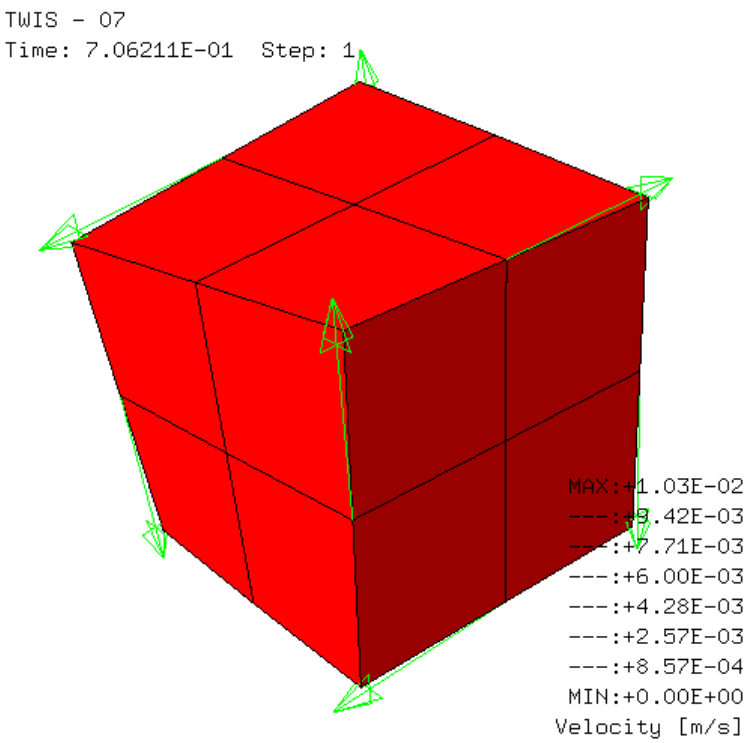
SOLI02

Same as SOLI01 but the entire domain is at the same (low) pressure and should therefore be in equilibrium. After only 20 steps, we see the development of non-negligible, spurious fluid velocities:



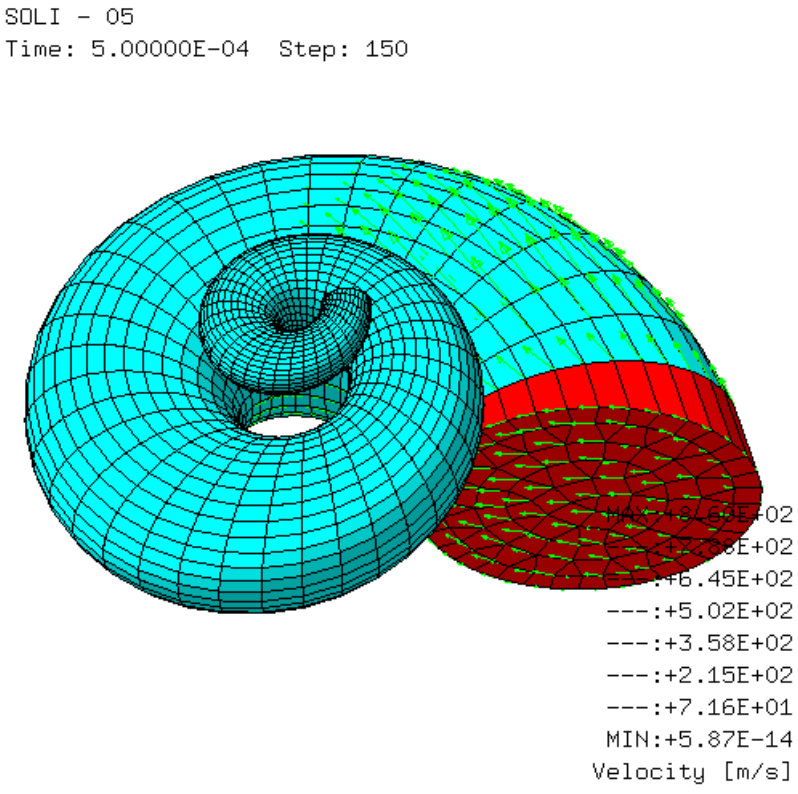
TWIS07

We study the phenomenon by a simple patch test of 8 fluid elements with uniform pressure and a warped geometry. Here is the result after just one time step:

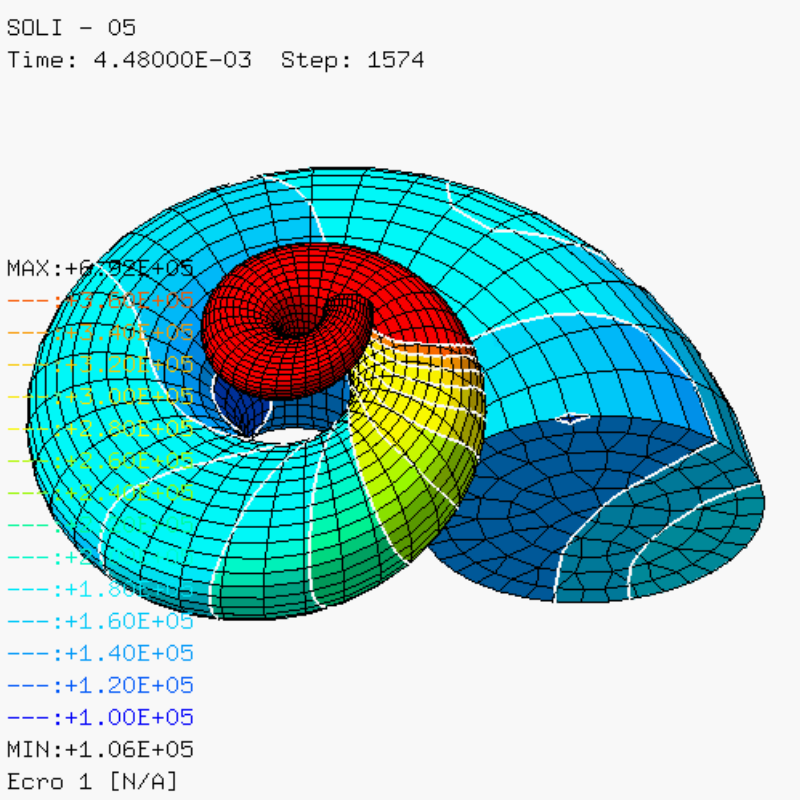


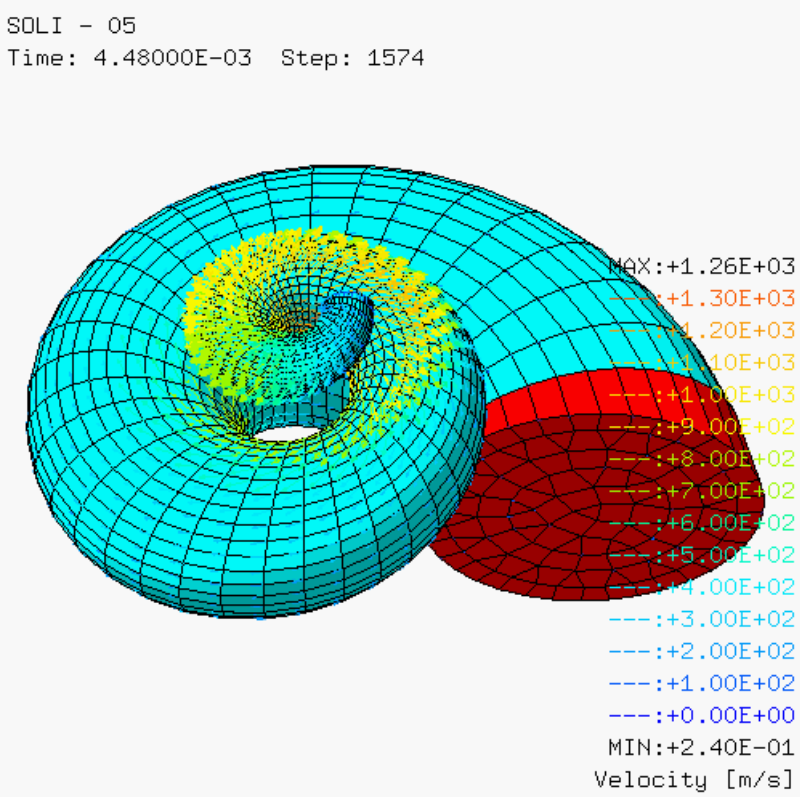
SOLI05

To avoid the spurious velocities, we use the FSCR method (FSCR input option)



Here is an example of the computed pressures and velocities:

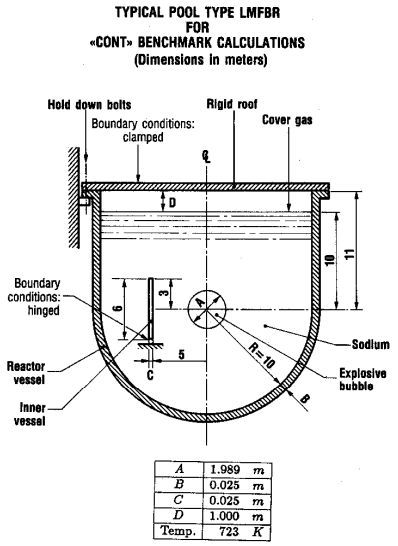




Exercise/Example 4 – CONT problem

Three fluids plus deformable structures

- Try out ALE solution with Lagrangian fluid/fluid interfaces (single-component fluid model)
- Try out ALE solution with ALE fluid/fluid interfaces (multi-phase multi-component fluid model)



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This is a well-known reactor safety benchmark problem from the 1970's/80s.

Geometric data:

Simplified sodium-cooled fast breeder reactor (axisymmetric) with internal shield. The roof is rigid.

Materials

The explosive bubble is made of a misture of molten fuel and fluid sodium (corium). The pool is filled by liquid sodium. An argon cover gas fills the region below the roof. The tank and inner shield are made of elasto-plastic steel.

Numerical Solution

CONT01

We use the standard single-component fluid material model. This means that the two fluid-fluid interfaces are treated as Lagrangian. Due to sliding of the sodium/argon interface along the tank, the FSA model may not be used alone to describe fluid-structure interactions (use is made of Lagrangian sliding locally). The input file is:

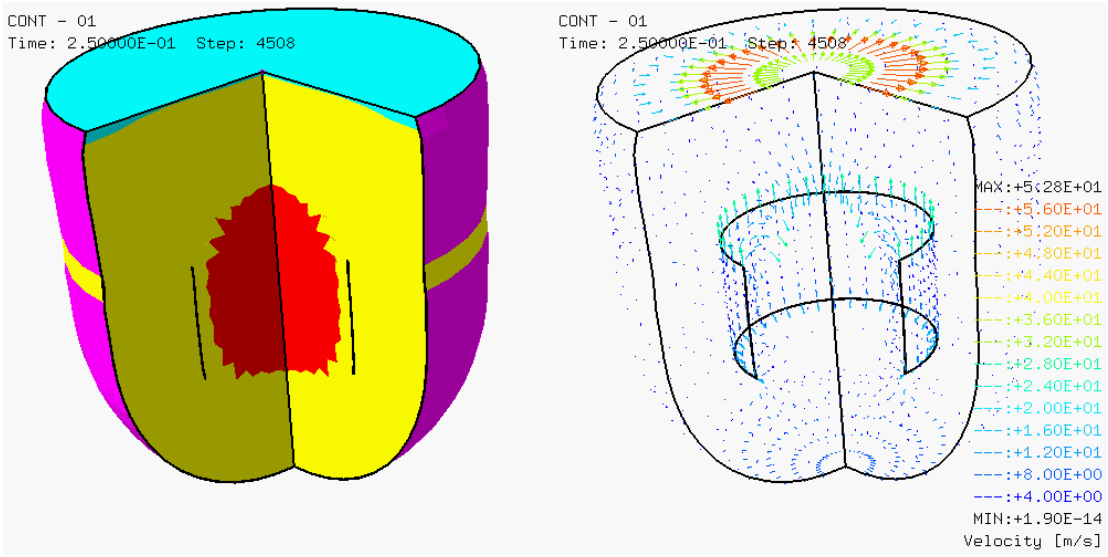
```
CONT - 01
*-------------------------------------------------------------------------
 ECHO
 !CONV win
*-----------------------------------------------------------Problem type
AXIS NONL ALE lagc
*-----------------------------------------------------------Dimensioning
DIME
   PT2L 293 PT3L 70 ZONE 3
   ED41 33 FLU1 267 pmat 1
   BLOQ 100
   FSSA 100
   FSSL 100
   UNIL 50
   LIAI 900
   NALE 1 NBLE 232
   MTPO 9 MTEL 8
   impa 1 psim 7
TERM
opti noecho
*-----------------------------------------------------------------Geometry
GEOM LIBR POIN 355 ED41 33 FLU1 266 pmat 1 TERM
 0.00000E+00 0.00000E+00 0.00000E+00-2.50000E-02 1.28440E+00
 8.28200E-02 1.28760E+00 5.80290E-02 2.54760E+00 3.29920E-01
 2.55400E+00 3.05750E-01 3.76850E+00 7.37220E-01 3.77790E+00
 7.14060E-01 4.92700E+00 1.29800E+00 4.93930E+00 1.27620E+00
 6.00390E+00 2.00290E+00 6.01890E+00 1.98290E+00 6.98130E+00
 2.84020E+00 6.99880E+00 2.82230E+00 7.84310E+00 3.79620E+00
```

```
7.86270E+00 3.78070E+00 8.57500E+00 4.85500E+00 8.59640E+00
4.84210E+00 9.07990E+00 5.81000E+00 9.10260E+00 5.79950E+00
9.47890E+00 6.81400E+00 9.50260E+00 6.80600E+00 9.76730E+00
7.85510E+00 9.79170E+00 7.84970E+00 9.94170E+00 8.92130E+00
9.96660E+00 8.91860E+00 1.00000E+01 1.00000E+01 1.00250E+01
1.00000E+01 1.00000E+01 1.12000E+01 1.00250E+01 1.12000E+01
1.00000E+01 1.24000E+01 1.00250E+01 1.24000E+01 1.00000E+01
1.36000E+01 1.00250E+01 1.36000E+01 1.00000E+01 1.48000E+01
1.00250E+01 1.48000E+01 1.00000E+01 1.60000E+01 1.00250E+01
1.60000E+01 1.00000E+01 1.70000E+01 1.00250E+01 1.70000E+01
1.00000E+01 1.80000E+01 1.00250E+01 1.80000E+01 1.00000E+01
1.90000E+01 1.00250E+01 1.90000E+01 1.00000E+01 2.00000E+01
1.00250E+01 2.00000E+01 1.00000E+01 2.10000E+01 1.00250E+01
2.10000E+01 5.00000E+00 7.00000E+00 5.02500E+00 7.00000E+00
5.00000E+00 7.60000E+00 5.02500E+00 7.60000E+00 5.00000E+00
8.20000E+00 5.02500E+00 8.20000E+00 5.00000E+00 8.80000E+00
5.02500E+00 8.80000E+00 5.00000E+00 9.40000E+00 5.02500E+00
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  283  283   72  312  283  283
  355
* added pmat: element 300, node 355
opti echo
*-----------------------------------------------Geometric Complements
COMP EPAI 2.5E-2 LECT 1 PAS 1 23 24 PAS 1 33 TERM
     GROU 5 'vessel'  LECT 1 PAS 1 23 TERM
            'shield'  LECT 24 PAS 1 33 TERM
            'liqu'    LECT 34 35 64 PAS 1 291 298 PAS 1 299 TERM
            'bull'    LECT 36 PAS 1 63 TERM
            'gaz'     LECT 292 PAS 1 297 TERM
     COUL jaun LECT liqu TERM
          roug LECT bull TERM
          turq LECT gas  TERM
          rose LECT vessel shield TERM
*-------------------------------------------------------------Grid motion
GRIL LAGR LECT 1 PAS 1 48 49 PAS 1 70 74 PAS 1 102 319
          335 PAS 1 340 341 PAS 1 347 198 221 355 TERM
     EULE LECT 348 PAS 1 354 TERM
     ALE  LECT 34 PAS 1 299 TERM
     AUTO AUTR
*-------------------------------------------------------Material data
MATE VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00666
          LECT vessel TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00666
          LECT shield TERM
     FLUT RO 832. EINT 98.68 GAMM 7.15D0 CL 0.5 CQ 2.56 PB 2.71E5
          PMIN 0. AHGF 0. ITER 2 ALF0 1. BET0 1. KINT 0 NUM 5
          LECT liqu TERM
     FLUT RO 2.4278E3 EINT 0. GAMM 0.75D0 CL 0.5 CQ 2.56 PB 0.
          PMIN 0. AHGF 0. ITER 2 ALF0 1. BET0 1. KINT 0 NUM 4
          LECT bull TERM
     FLUT RO .242777373 EINT 6.865E5 GAMM 1.6 CL 0.5 CQ 2.56 PB 0.
          PMIN 0. AHGF 0. ITER 2 ALF0 1. BET0 1. KINT 0 NUM 1
          LECT gas TERM
     mass 1.0 lect 300 term
*-----------------------------------------------------Boundary conditions
LIAIS freq 1 RENUM
 BLOQ 1 LECT 1 2 47 48 49 50 73 74 102 103 131 132 160 161 189 190
             231 232 260 261 289 290 318 319 347 348 354 TERM
      2 LECT 47 PAS 1 50 348 PAS 1 354 TERM
      3 LECT 1 2 47 48 TERM
*UNIL 2 -1 20.99 LECT 341 PAS 1 347 TERM
      12 lect 355 term
 impa ddl 2 cote -1
      proj lect 300 term
      cibl lect 341 pas 1 347 term
LINK DECO
  FSS ALE  NCOT 26
       LECT 1 3 1 320 319 0 0 0 0 1 0 TERM
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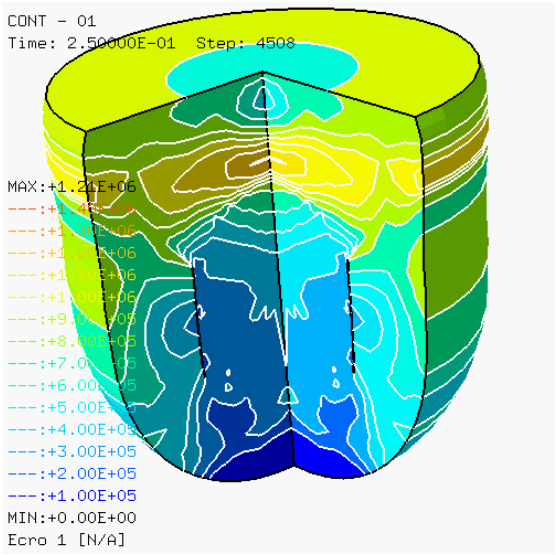
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LECT 3 7 5 322 321 0 0 0 0 1 1 TERM
LECT 4 9 7 323 322 0 0 0 0 1 1 TERM
LECT 5 11 9 324 323 0 0 0 0 1 1 TERM
LECT 6 13 11 325 324 0 0 0 0 1 1 TERM
LECT 7 15 13 326 325 0 0 0 0 1 1 TERM
LECT 8 17 15 327 326 0 0 0 0 1 1 TERM
LECT 9 19 17 328 327 0 0 0 0 1 1 TERM
LECT 10 21 19 329 328 0 0 0 0 1 1 TERM
LECT 11 23 21 330 329 0 0 0 0 1 1 TERM
LECT 12 25 23 331 330 0 0 0 0 1 1 TERM
LECT 13 27 25 332 331 0 0 0 0 1 1 TERM
LECT 14 29 27 333 332 0 0 0 0 1 1 TERM
LECT 15 31 29 334 333 0 0 0 0 1 1 TERM
LECT 16 -33 31 -335 334 0 0 0 0 1 1 TERM
LECT 24 51 49 201 199 52 50 202 200 1 -1 TERM
LECT 25 53 51 203 201 54 52 204 202 1 1 TERM
LECT 26 55 53 205 203 56 54 206 204 1 1 TERM
LECT 27 57 55 207 205 58 56 208 206 1 1 TERM
LECT 28 59 57 209 207 60 58 210 208 1 1 TERM
LECT 29 61 59 211 209 62 60 212 210 1 1 TERM
LECT 30 63 61 213 211 64 62 214 212 1 1 TERM
LECT 31 65 63 215 213 66 64 216 214 1 1 TERM
LECT 32 67 65 217 215 68 66 218 216 1 1 TERM
LECT 33 69 67 219 217 70 68 220 218 -1 1 TERM
NPOI 28
LAGR NCT1 10
        LECT 277 -334 335 TERM
        LECT 278 335 336 TERM
        LECT 279 336 337 TERM
        LECT 280 337 338 TERM
        LECT 281 338 339 TERM
        LECT 282 339 340 TERM
        LECT 283 340 198 TERM
        LECT 34 198 221 TERM
        LECT 35 221 341 TERM
        LECT 292 341 348 TERM
    NPOI 11
    NCT2 8
        LECT 16 -31 33 TERM
        LECT 17 33 35 TERM
```

```
        LECT 18 35 37 TERM
        LECT 19 37 39 TERM
        LECT 20 39 41 TERM
        LECT 21 41 43 TERM
        LECT 22 43 45 TERM
        LECT 23 45 47 TERM
      NPOI 9
*-------------------------------------------------------------------Outputs
ECRITURE COOR DEPL VITE CONT ECRO TFRE 250.E-3
          POIN LECT 1 74 102 59 69 341 347 43 332 TERM
          ELEM LECT 36 63 292 297 34 262 1 21 TERM
    fich alic temp FREQ 1
          POIN LECT 1 74 102 59 69 341 347 43 332 TERM
          ELEM LECT 36 63 292 297 34 262 1 21 TERM
    FICH ALIC TFRE 2.5E-3
*-------------------------------------------------------------------Options
OPTI AMORT QUAD 2.56 NOTEST
     NOCR LECT 292 PAS 1 297 183 196 TERM
     cstab 0.45
     REZO GAM0 0.8
     log 1
*-----------------------------------------------Transient calculation
CALC TINI 0.0 DTMI 1E-9 TEND 250.E-3
*=============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------Curve definitions
COUR 1  'dy_1'   DEPL COMP 2 NOEU LECT 1    TERM
COUR 2  'dy_341'  DEPL COMP 2 NOEU LECT 341 TERM
*-------------------------------------------------------------------Plots
trac 1 2 axes 1.0 'DISPL. [M]' yzer
*-----------------------------------------------Results qualification
QUAL DEPL COMP 2 LECT   1 TERM REFE -6.27942E-2 TOLE 1.E-2
     DEPL COMP 2 LECT 341 TERM REFE  4.39215E-1 TOLE 1.E-2
*===================================================================
FIN
```

The final mesh (colors indicate materials in this case) and fluid velocities are:



The final fluid pressures:

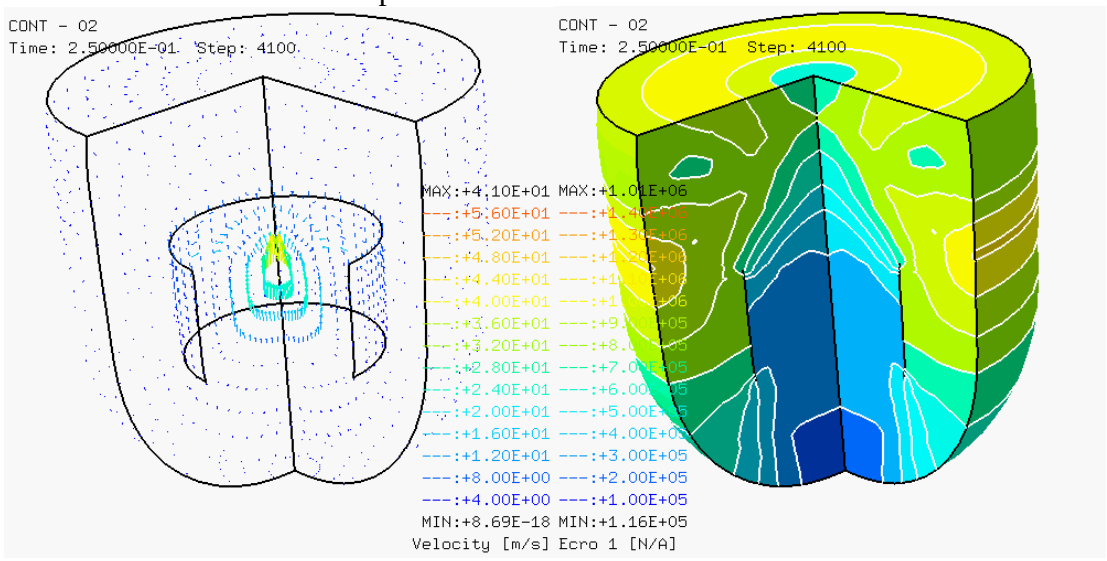


CONT02

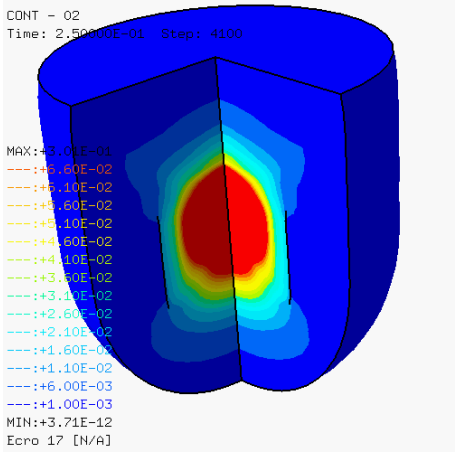
This example uses the multi-phase multi-component fluid material model. This means that the two fluid-fluid interfaces may be treated as ALE and the FSA model may be used to describe fluid-structure interactions. The input file is:

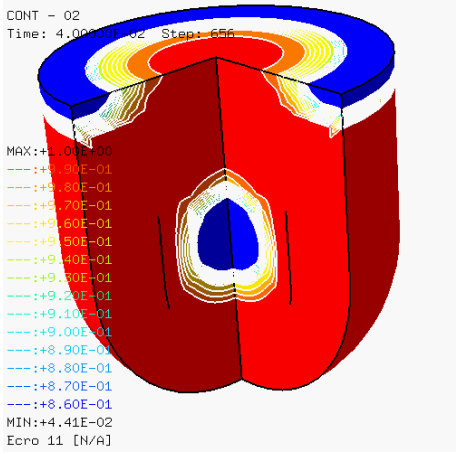
```
CONT - 02
*-----------------------------------------------------------------------
 ECHO
CAST mesh
!CONV win
*-----------------------------------------------------------Problem type
AXIS NONL ALE
*-----------------------------------------------------------Dimensioning
DIME
   PT2L 278 PT3L 35 ZONE 3
   ED01 33 FL24 230 FL23 28
   NALE 18 NBLE 278
   MTPO 29
   MTEL 24
   ECRO 13128
TERM
*-------------------------------------------------------------Geometry
GEOM ED01 stru FL23 flui3 FL24 flui4 TERM
*-----------------------------------------------Geometric Complements
COMP EPAI 2.5E-2 LECT stru TERM
*---------------------------------------------------------Grid motion
GRIL LAGR LECT stru TERM
     ALE LECT flui TERM
     AUTO AUTR
*-------------------------------------------------------Material data
MATE VM23 RO 7800. YOUN 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT vessel TERM
     VM23 RO 7800. YOUN 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT shield TERM
     FLMP NLIQ 1 NGAS 2
     FLUT RO 832. EINT 98.68 GAMM 7.15D0 CL 0.5 CQ 2.56
          PB 2.71E5 PMIN 0. AHGF 0. ITER 2 ALF0 1.
          BET0 1. KINT 0 NUM 5
          LECT liqu TERM
     FLUT RO 2.4278E3 EINT 0. GAMM 0.75D0 CL 0.5 CQ 2.56
          PB 0. PMIN 0. AHGF 0. ITER 2 ALF0 1.
          BET0 1. KINT 0 NUM 4
          LECT bull TERM
     FLUT RO .242777373 EINT 6.865E5 GAMM 1.6 CL 0.5 CQ 2.56
          PB 0. PMIN 0. AHGF 0. ITER 2 ALF0 1.
          BET0 1. KINT 0 NUM 1
          LECT gas TERM
*-----------------------------------------------Boundary conditions
LINK COUP
     BLOQ 1 LECT p2p TERM
     BLOQ 123 LECT p4p TERM
     CONT SPLA NX 1 NY 0 LECT symax TERM
     CONT SPLA NX 0 NY 1 LECT top   TERM
     FSA  LECT fsan TERM
*-------------------------------------------------------------------Outputs
ECRI COOR DEPL VITE ACCE CONT ECRO TFRE 250.E-3
     FICH ALIC TEMP FREQ 1
          POIN LECT p0 TERM
     FICH ALIC TFRE 2.5E-3
*-----------------------------------------------------------------Options
OPTI NOTE
     log 1 csta 0.5
     REZO GAM0 0.8
     FLMP EPS1 1.E-5
*-----------------------------------------------Transient calculation
CALCUL TINI 0.0 TEND 250.E-3
*=============================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------Curve definitions
COUR 1  'dy_1'    DEPL COMP 2 NOEU LECT p0  TERM
*-------------------------------------------------------------------Plots
trac 1 axes 1.0 'DISPL. [M]' yzer
*-----------------------------------------------Results qualification
QUAL DEPL COMP 2 LECT  p0 TERM REFE -1.23718E-1 TOLE 1.E-2
*=====================================================================
FIN
```

The final fluid velocities and pressures:

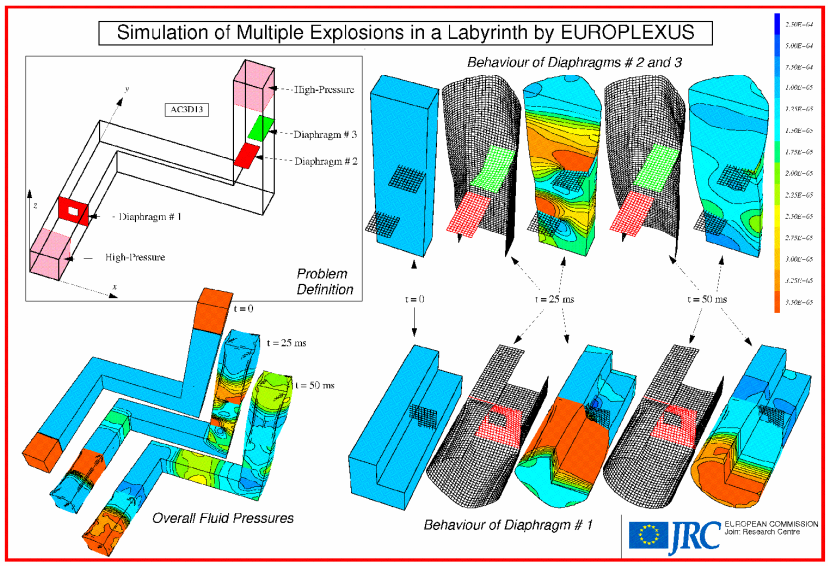


The final bubble material mass fraction (giving an idea of the size and form of the bubble) and an intermediate time view of the liquid sodium mass fraction:





Exercise/Example 5 – Explosion in a 3-D Labyrinth



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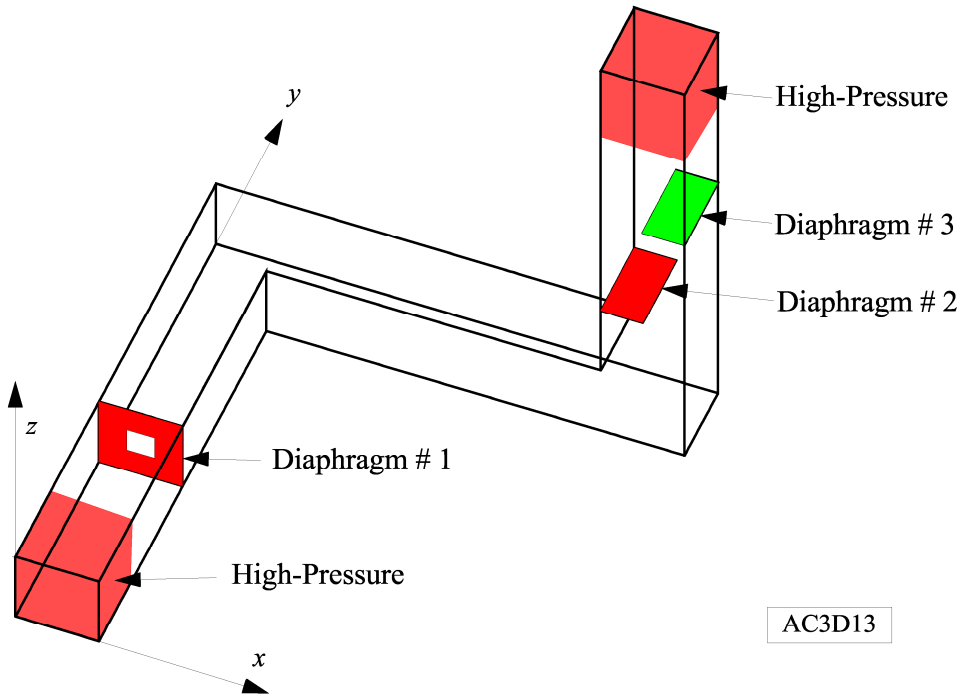
This example consists in a long 3D metallic pipe with a square cross section of 3×3 units, sealed at both ends, containing a gas at room pressure. At the initial time, two "explosions" take place at the ends of the pipe, simulated by the presence of the same gas, but at a much higher initial pressure.

The gas starts flowing through the pipe, but its motion is partly affected by the presence of internal structures within the pipe: a diaphragm (#1) with a square central hole near the first extremity, and two diaphragms (#2 and #3) that obstruct one half of the flow section, creating a sort of labyrinth, at the second extremity. All the pipe walls, and the internal structures, are deformable and characterized by an elasto-plastic behaviour. The pressures and structural material properties are so chosen that very large motions and relatively large deformations occur in the structure. The whole model measures $18\times18\times18$ units.

The above figure shows the deformed shapes of the pipe, with superposed fluid pressure maps. The displacements are the real ones (not scaled up). Note the strong wave propagation effects, the partial wave reflections at obstacles, and the "ballooning" effect of the thin pipe walls in regions at high pressure. This is a severe test, among other things, for the automatic rezoning algorithms, which must keep the fluid mesh reasonably uniform under large motions. Details of the pressure drop across the various obstacles and of the deformation of diaphragms and pipe walls are also illustrated.

It may be interesting for users to note that the EUROPLEXUS input file for this application consists of less than 60 lines of data. The mesh is prepared by a pre-processor and the two domains, structure and fluid, are meshed separately (but with matching nodes in this first example). Suitable FSI conditions are then computed by the code in a totally automatic way and without any user directive or intervention.

Geometric data:



Materials

The explosive bubbles are made of a high-pressure perfect gas (10 bar). The rest of the fluid domain is filled by the same gas but at a lower pressure (1 bar).

The structure is elasto-plastic steel material. The tube is 1.2 cm thick, the first diaphragm is 1.0 cm thick and the other two diaphragms are 1.5 cm thick.

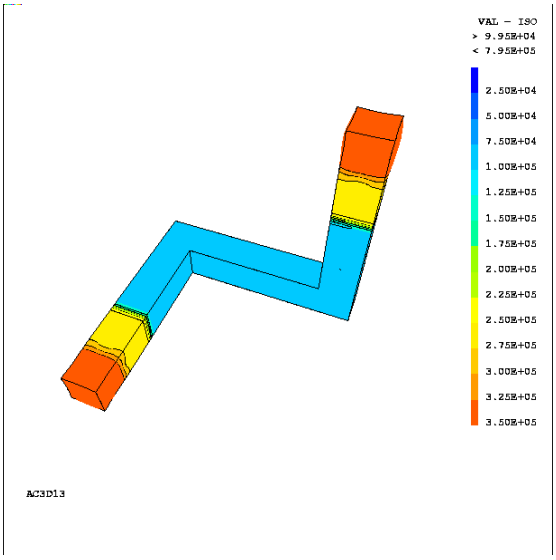
Numerical Solution

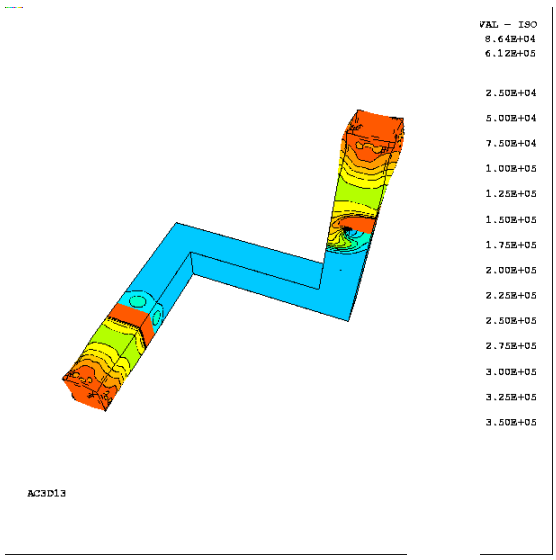
AC3D13

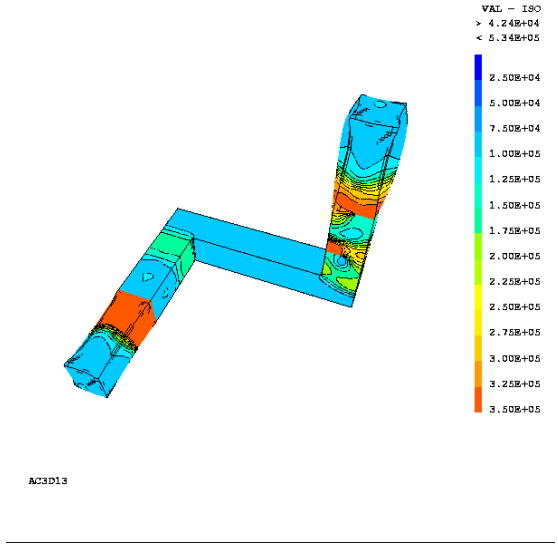
We use the FSA directive to prescribe the boundary conditions at the complex 3D surface of the fluid domain. The input file is:

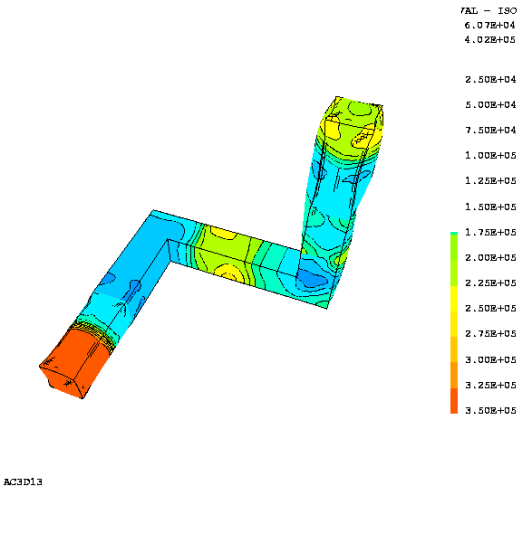
```
AC3D13
ECHO
 CONV win
CAST mesh
TRID NONL ALE
DIME
  PT6L 21956 PT3L 104983 FL38 93312 Q4GS 21996 ZONE 2
  NALE 7527 NBLE 1
  ECRO 5678928
  NEPE 232
  mtpo 3 mtel 4
  ndvc 494238
TERM
GEOM FL38 flui Q4GS stru TERM
COMP EPAI 0.010 LECT diap1 TERM
     EPAI 0.015 LECT diap2 TERM
     EPAI 0.015 LECT diap3 TERM
     EPAI 0.012 LECT tube  TERM
GRIL LAGR LECT stru TERM
     EULE LECT fsan TERM
     ALE  LECT flui TERM
     MEAN AUTR
OPTI REZO MVRE MODU LIAI
MATE VM23 RO 8000 YOUNG 2.E11 NU 0.3 ELAS 4.E8
          TRAC 3 4.E8 2.E-3 2.4E9 1.002E0 2.4E9 10.
          LECT stru TERM
     FLUT RO 10. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 0 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT expl TERM
     FLUT RO  1. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 0 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT gas TERM
OPTI FSCR
LINK COUP
     FSA LECT fsan TERM
ECRI DEPL VITE ECRO TFRE 10.E-3
     POIN LECT tpln TERM
     ELEM LECT tple TERM
     TRAC TPLO DESC 'AC3D13' TFRE 51.E-6
          POIN LECT tpln TERM
          ELEM LECT tple TERM
     fich alic temp TFRE 51.E-6
          POIN LECT tpln TERM
          ELEM LECT tple TERM
     FICH FORM spli K200 TFRE 0.5E-3
          POIN TOUS
          VARI DEPL VITE ECRO ECRC LECT 1 3 TERM
OPTI NOTE
  CSTA 0.5D0
  MOMT 2
  LOG 1
CALCUL TINI 0. TEND 50.E-3
*
SUIT
Post-treatment
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR 1 'dy_d1' DEPL COMP 2 NOEU LECT d1 TERM
COUR 2 'dz_d2' DEPL COMP 3 NOEU LECT d2 TERM
COUR 3 'dz_d3' DEPL COMP 3 NOEU LECT d3 TERM
COUR 4 'p_e1'  ECRO COMP 1 ELEM LECT e1 TERM
COUR 5 'p_e2'  ECRO COMP 1 ELEM LECT e2 TERM
COUR 6 'p_e3'  ECRO COMP 1 ELEM LECT e3 TERM
COUR 7 'p_e4'  ECRO COMP 1 ELEM LECT e4 TERM
*
trac 1 2 3 axes 1.0 'D [M]'
trac 4 5 6 7 axes 1.0 'P [PA]'
*
*QUAL VITE comp 1 lect 51 term REFE 8.25539E+2 TOLE 5.E-3
*     ECRO comp 1 lect 50 term REFE 3.41392E+5 TOLE 5.E-3
FIN
```

Some results: global deformed mesh views with fluid pressures:

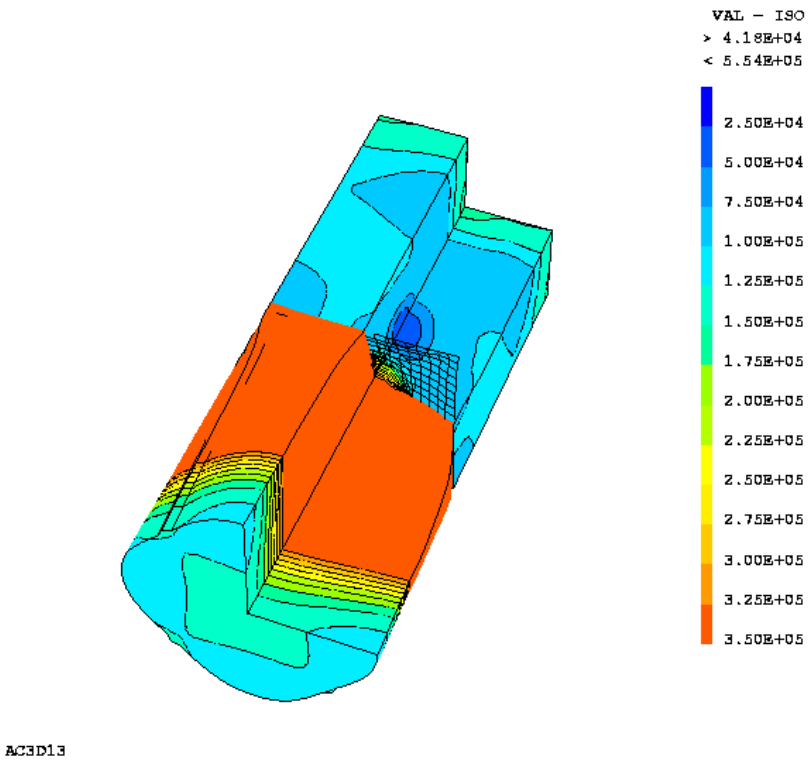




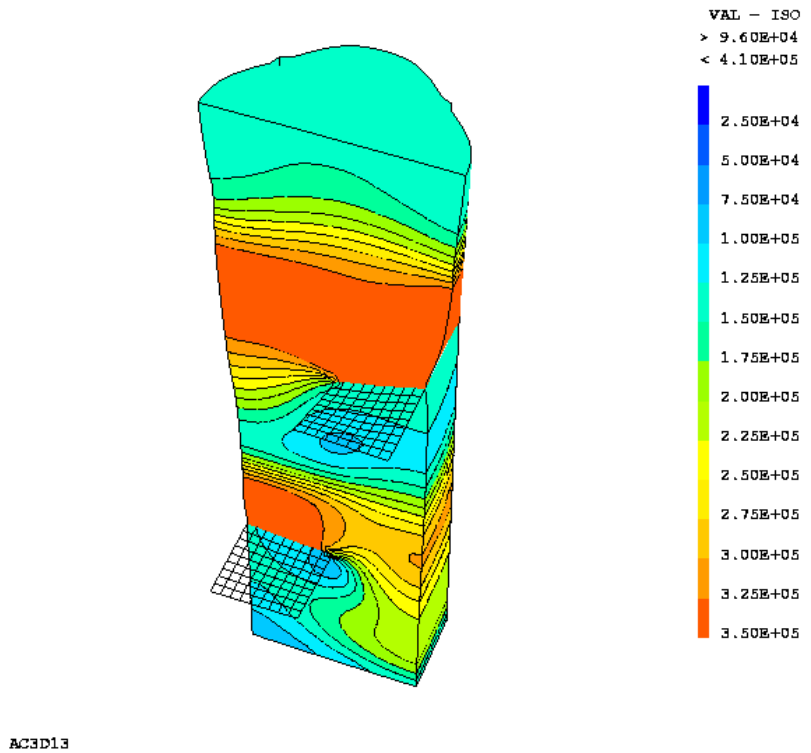




Detail of first diaphragm:

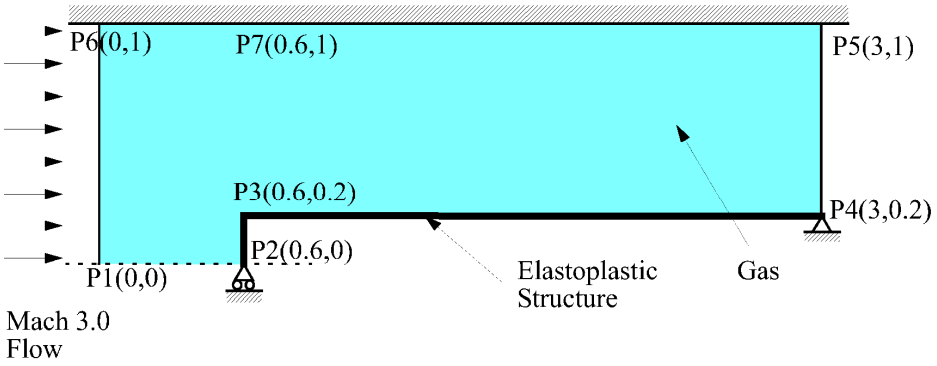


Detail of second and third diaphragms:



Exercise/Example 6 : Woodward-Colella Test (FV with deformable step)

Set up FV model and treat the step as deformable:



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The well-known Woodward-Colella test in 2D, revisited by using a deformable structure (FSI). Supersonic flow over a forward-facing deformable step.

PROBLEM:

This is the well-known Woodward-Colella problem, a benchmark used to validate CFD codes. A channel is filled by gas flowing at Mach 3, initially in uniform conditions. The channel is 3 m long, 1 m high and 0.4 m wide (but the problem may be considered as 2-D plane). A deformable step is introduced at time 0 at 0.6 m downstream from the channel inlet. The step is 0.2 m high and its thickness and material law are chosen so as to undergo relatively large deformations during the transient solution. An ALE calculation with fluid-structure interaction is performed. Mesh rezoning is done automatically by Giuliani's algorithm.

MESH:

The model is 2D plane deformation and uses 8064 MC34 triangular finite volumes (4193 nodes) for the fluid domain, and 104 beam/shell elements for the step.

MATERIALS:

The step is made of elasto-plastic metallic material (VM23), while the fluid is a mixture of perfect gases (MCGP). A special MCFF material is used to model the inlet and outlet conditions(far field).

BOUNDARY CONDITIONS:

The step is entirely blocked at the outlet, and blocked in thevertical direction only in the front tip. At the inlet and outlet suitable boundary conditions are prescribed in the fluid. The boundary conditions at the channel inlet also correspond to the initial conditions. The same boundary conditionsare assumed at the channel outlet, although they will not be taken into consideration by the numerical scheme, since they

correspond to a supersonic outlet where all the characteristic lines leave the computational domain.

LOADING:

The system is initially at rest, but not in equilibrium since the pressure in the fluid will tend to deform the step, which is disturbing the initially uniform flow field.

CALCULATION:

The calculation is performed up to 3.5 ms. At the final time, the shock detached from the step has hit the upper part of the channel being reflected again towards the downstream portion of the step.

RESULTS:

These results have been found in good agreement with those reported in the literature for the case with rigid step.

POST-TREATMENT

Several animations of the computed results from this calculation are available on the EUROPLEXUS Consortium Web site.

REFERENCES:

The original problem is described in:

1) P. Woodward and P. Colella: "The numerical simulation of Two-Dimensional Fluid Flow with Strong Shocks", J. Comp. Phys., 54, pp. 115-173 (1984).

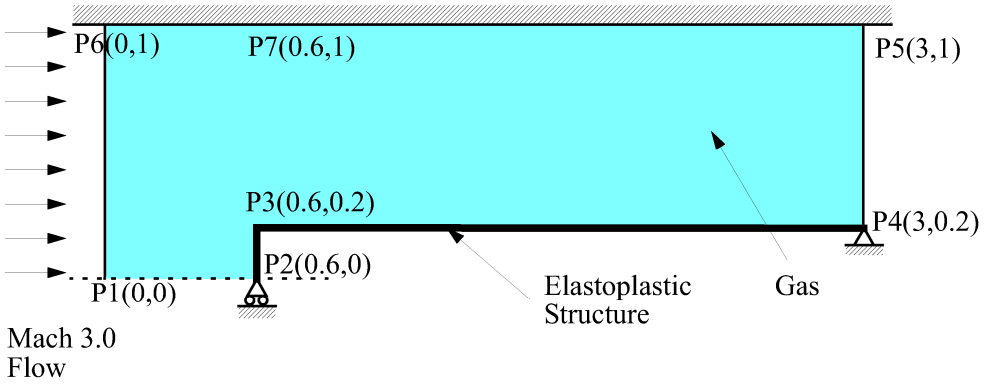
This calculation is detailed in the following two references, both available in the EUROPLEXUS Consortium Web site:

2) A. Soria, F. Casadei: "Modelling of Arbitrary Lagrangian-Eulerian Multicomponent Flow with Fluid-Structure Interaction in PLEXIS-3C." Special Publication N. I.95.01, Jan. 1995.

3) A. Soria, F. Casadei: "Arbitrary Lagrangian-Eulerian Multicomponent Compressible Flow with Fluid-Structure Interaction." International Journal for Numerical Methods in Fluids, Vol. 25, pp. 1263--1284, December 1997.

Numerical Solutions

WOCO2D



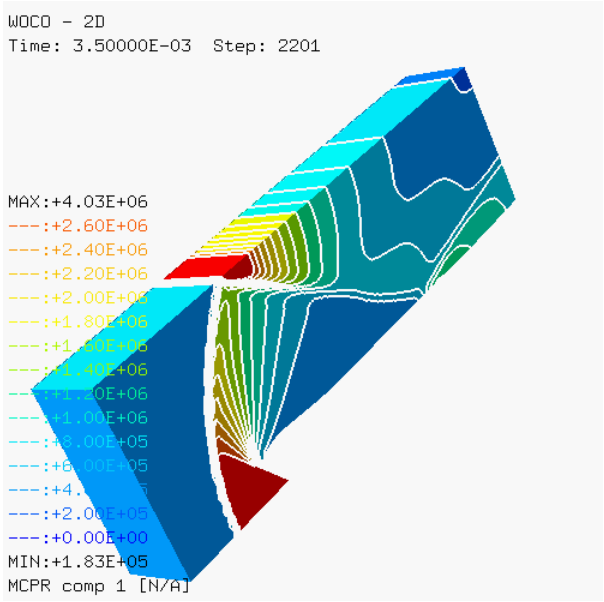
The mesh generation file (K2000) is:

```
*%siz 100
*
opti echo 1 dime 2 elem qua4;
opti titr 'WOCO - 2D';
*
p1 = 0 0;
p2 = 0.6 0;
p3 = 0.6 0.2;
p4 = 3 0.2;
p5 = 3 1;
p6 = 0 1;
p7 = 0.6 1;
tol = 0.001;
*
in = p1 d 40 p6;
s1 = in tran 24 (0.6 0);
s1 = chan s1 tri3;
*
la = p3 d 32 p7;
s2 = la tran 96 (2.4 0);
s2 = chan s2 tri3;
*
lh1 = p1 d 24 p2;
lh2 = p3 d 96 p4;
lh3 = p5 d 120 p6;
lv  = p2 d 8 p3;
out = p4 d 32 p5;
*
lfsa = lh2 et lv;
*
flui = s1 et s2;
mesh = flui et lfsa et in et out et lh1 et lh3;
*
elim tol mesh;
*
p2s = p2 'PLUS' p1;
p3s = p3 'PLUS' p1;
p4s = p4 'PLUS' p1;
strt = p2s d 8 p3s d 96 p4s;
*
mesh = mesh et strt;
*
tass mesh;
*
opti sauv form 'woco2d.msh';
sauv form mesh;
opti trac psc ftra 'woco2d_mesh.ps';
trac mesh;
trac qual mesh;
```

The EUROPLEXUS input file reads:

```
WOCO - 2D
$
 ECHO
!CONV win
CAST MESH
DPLA NONL ALE
$
DIME
 PT2L 4193 PT3l 105 ZONE 3
 ED01 104 CL22 72 MC23 8064
 NDVC 24513
 NALE 42 NBLE 4119
 TABL 1 10
 ELVC 500
 mtpo 10
TERM
$
GEOM
  MC23 flui
  ED01 strt
  CL22 in out
TERM
EPAI 0.020 LECT strt TERM
$
$OPTI DUMP
$
GRIL LAGR LECT strt   TERM
     EULE LECT in out TERM
     ALE  LECT flui   TERM
     AUTO AUTR
$
$ multicomponent material
MATE MCGP NCOM 2 R 8312.
          COMP 'Air' PM 28.96 CV1 20780 CV2 0 CV3 0
          COMP 'Nitrogen' PM 28.96 CV1 20780 CV2 0 CV3 0
          LECT flui TERM
     MCFF BDFO 3 TEMP 400. PRES 300000.
          VEL1 1202.7 VEL2 0. VEL3 0.
          COMP 'Air'      MFRA 1.
          COMP 'Nitrogen' MFRA 0.
          LECT in out TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT strt TERM
$
INIT MCOM COMP 'Air'      MFRA 1.0 LECT TOUS
          COMP 'Nitrogen' MFRA 0.0 LECT TOUS
          PRES 300000.    LECT TOUS
          TEMP 400.       LECT TOUS
          VEL1 1202.7     LECT TOUS
          VEL2 0.00       LECT TOUS
          VEL3 0.00       LECT TOUS
$
LINK COUP
     BLOQ 123 LECT p4s         TERM
     BLOQ 2   LECT p2s lh3 lh1 TERM
     FSA      LECT lfsa        TERM
$
ECRI DEPL VITE MCVA POIN LECT p1 p2 p2s p3 p3s p4 p4s p5 p6 p7 TERM
          TFREQ 0.5E-3
     FICH K200 TFREQ 0.5E-3 POIN TOUS
     FICH ALIC TFRE 1.0E-5
$
OPTI NOTE CSTA 0.5
OPTI MC ORDR 2 NUFL ROE
 rezo gam0 0.5
 log 1
CALCUL TINI 0 TEND 3.5E-3
*=================================================================
SUIT
Post-treatment (time curves from alice file)
ECHO
*
RESU ALIC GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR  1 'dx_p2'   DEPL COMP 1 NOEU LECT p2 TERM
COUR  2 'dx_p3'   DEPL COMP 1 NOEU LECT p3 TERM
COUR  3 'dy_p3'   DEPL COMP 2 NOEU LECT p3 TERM
COUR  4 'vx_p1'   VITE COMP 1 NOEU LECT p1 TERM
COUR  5 'vx_p4'   VITE COMP 1 NOEU LECT p4 TERM
COUR  6 'pr_p7'   MCPR COMP 1 NOEU LECT p7 TERM
COUR  7 'pr_p2'   MCPR COMP 1 NOEU LECT p2 TERM
COUR  8 'pr_p4'   MCPR COMP 1 NOEU LECT p4 TERM
*
trac 1 2 3  axes 1.0 'DISPL. [M]'
trac 4 5    axes 1.0 'VELOC. [M/S]'
trac 6 7 8  axes 1.0 'PRESS [PA]'
*
QUAL DEPL COMP 1 LECT p2   TERM REFE  1.30900E-1 TOLE 2.E-2
     DEPL COMP 1 LECT p3   TERM REFE  1.18235E-2 TOLE 2.E-2
     DEPL COMP 2 LECT p3   TERM REFE -3.93403E-2 TOLE 2.E-2
     VITE COMP 1 LECT p1   TERM REFE  1.20270E+3 TOLE 2.E-2
     VITE COMP 1 LECT p4   TERM REFE  1.09280E+3 TOLE 2.E-2
     MCPR COMP 1 LECT p7   TERM REFE  3.00000E+5 TOLE 2.E-2
     MCPR COMP 1 LECT p2   TERM REFE  3.23207E+6 TOLE 2.E-2
     MCPR COMP 1 LECT p4   TERM REFE  7.07217E+5 TOLE 2.E-2
*=================================================================
FIN
```

Some results: final pressure distribution:



WOCO3D

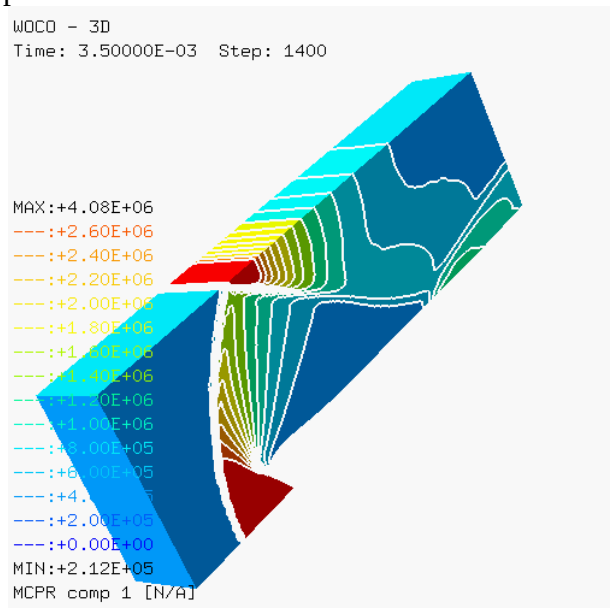
The mesh generation file (K2000) is:

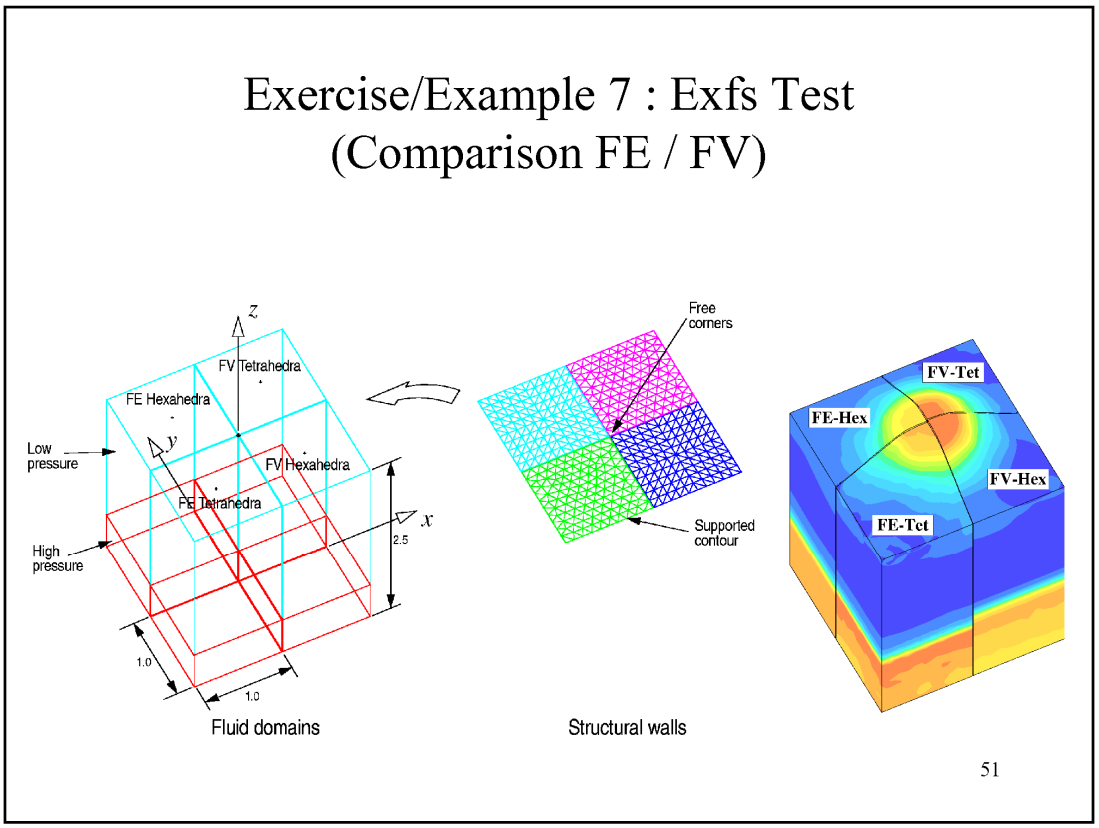
```
*%siz 100
*
opti echo 1 dime 3 elem cub8;
opti titr 'WOCO - 3D';
*
p1 = 0 0 0;
p2 = 0.6 0 0;
p3 = 0.6 0.2 0;
p4 = 3 0.2 0;
p5 = 3 1 0;
p6 = 0 1 0;
p7 = 0.6 1 0;
vz = 0 0 0.4;
tol = 0.001;
*
in = p1 d 40 p6;
s1 = in tran 24 (0.6 0 0);
s1 = chan s1 tri3;
*
la = p3 d 32 p7;
s2 = la tran 96 (2.4 0 0);
s2 = chan s2 tri3;
*
lh1 = p1 d 24 p2;
lh2 = p3 d 96 p4;
lh3 = p5 d 120 p6;
lv  = p2 d 8 p3;
out = p4 d 32 p5;
*
in  = in  tran 1 vz;
lh1 = lh1 tran 1 vz;
lh2 = lh2 tran 1 vz;
lh3 = lh3 tran 1 vz;
lv  = lv  tran 1 vz;
out = out tran 1 vz;
*
lfsa = lh2 et lv;
*
flui = (s1 et s2) volu tran 1 vz;
mesh = flui et lfsa et in et out et lh1 et lh3;
*
elim tol mesh;
*
p2s = p2 'PLUS' p1;
p3s = p3 'PLUS' p1;
p4s = p4 'PLUS' p1;
strt = p2s d 8 p3s d 96 p4s;
strt = strt tran 1 vz;
p2su = p2s 'PLUS' vz;
p4su = p4s 'PLUS' vz;
elim tol (strt et p2su et p4su);
*
mesh = mesh et strt;
*
tass mesh;
*
opti sauv form 'woco3d.msh';
sauv form mesh;
opti trac psc ftra 'woco3d_mesh.ps';
trac cach mesh;
trac cach qual mesh;
```

The EUROPLEXUS input file reads:

```
WOCO - 3D
$
 ECHO
!CONV win
CAST MESH
TRID NONL ALE
$
DIME
 PT3L 8386 PT6L 210 ZONE 3
 Q4GS 104 CL3Q 72 MC36 8064
 NDVC 57410
 NALE 84 NBLE 8238
 ELVC 500
 mtpo 10
TERM
$
GEOM
   MC36 flui
   Q4GS strt
   CL3Q in out
TERM
EPAI 0.020 LECT strt TERM
$
$OPTI DUMP
$
GRIL LAGR LECT strt   TERM
     EULE LECT in out TERM
     ALE  LECT flui   TERM
     AUTO AUTR
$
$ multicomponent material
MATE MCGP NCOM 2 R 8312.
          COMP 'Air' PM 28.96 CV1 20780 CV2 0 CV3 0
          COMP 'Nitrogen' PM 28.96 CV1 20780 CV2 0 CV3 0
          LECT flui TERM
     MCFF BDFO 3 TEMP 400. PRES 300000.
          VEL1 1202.7 VEL2 0. VEL3 0.
          COMP 'Air'       MFRA 1.
          COMP 'Nitrogen'  MFRA 0.
          LECT in out TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT strt TERM
$
INIT MCOM COMP 'Air'      MFRA 1.0 LECT TOUS
          COMP 'Nitrogen' MFRA 0.0 LECT TOUS
          PRES 300000.     LECT TOUS
          TEMP 400.        LECT TOUS
          VEL1 1202.7      LECT TOUS
          VEL2 0.00        LECT TOUS
          VEL3 0.00        LECT TOUS
$
LINK COUP
     BLOQ 123456 LECT p4s p4su          TERM
     BLOQ 2      LECT p2s p2su lh3 lh1 TERM
     BLOQ 3      LECT TOUS             TERM
     FSA         LECT lfsa             TERM
$
ECRI DEPL VITE MCVA POIN LECT p1 p2 p2s p3 p3s p4 p4s p5 p6 p7 TERM
          TFREQ 0.5E-3
     FICH K200 TFREQ 0.5E-3 POIN TOUS
     FICH ALIC TFRE 1.0E-5
$
OPTI NOTE CSTA 0.5
OPTI MC ORDR 2 NUPL ROE
 rezo gam0 0.5
 log 1
CALCUL TINI 0 TEND 3.5E-3
*===============================================================
SUIT
Post-treatment (time curves from alice file)
ECHO
*
RESU ALIC GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR  1 'dx_p2'   DEPL COMP 1 NOEU LECT p2 TERM
COUR  2 'dx_p3'   DEPL COMP 1 NOEU LECT p3 TERM
COUR  3 'dy_p3'   DEPL COMP 2 NOEU LECT p3 TERM
COUR  4 'vx_p1'   VITE COMP 1 NOEU LECT p1 TERM
COUR  5 'vx_p4'   VITE COMP 1 NOEU LECT p4 TERM
COUR  6 'pr_p7'   MCPR COMP 1 NOEU LECT p7 TERM
COUR  7 'pr_p2'   MCPR COMP 1 NOEU LECT p2 TERM
COUR  8 'pr_p4'   MCPR COMP 1 NOEU LECT p4 TERM
*
trac 1 2 3  axes 1.0 'DISPL. [M]'
trac 4 5    axes 1.0 'VELOC. [M/S]'
trac 6 7 8  axes 1.0 'PRESS [PA]'
*
QUAL DEPL COMP 1 LECT p2   TERM REFE  1.25965E-1 TOLE 2.E-2
     DEPL COMP 1 LECT p3   TERM REFE  1.00924E-2 TOLE 2.E-2
     DEPL COMP 2 LECT p3   TERM REFE -3.69872E-2 TOLE 2.E-2
     VITE COMP 1 LECT p1   TERM REFE  1.20270E+3 TOLE 2.E-2
     VITE COMP 1 LECT p4   TERM REFE  0.00000E+0 TOLE 2.E-2
     MCPR COMP 1 LECT p7   TERM REFE  3.00000E+5 TOLE 2.E-2
     MCPR COMP 1 LECT p2   TERM REFE  3.42310E+6 TOLE 2.E-2
     MCPR COMP 1 LECT p4   TERM REFE  4.53681E+5 TOLE 2.E-2
*===============================================================
FIN
```

Some results: final pressure distribution:





This example is a patch of four shock tubes, each one closed by a deformable plate at one extremity and blocked at the other extremity. The tubes are physically identical to each other but they are discretized in a different manner:

- FE hexahedra
- FE tetrahedra
- FV hexahedra
- FV tetrahedra

The scope of the test is first to show that FE and FV may be mixed up in a single EUROPLEXUS calculation (provided the two sub-domains do not communicate with each other), and second to compare the performance of the different fluid models. Since the tubes are placed side-by-side, visual comparison may be done very effectively.

Numerical Solutions

EXFS13

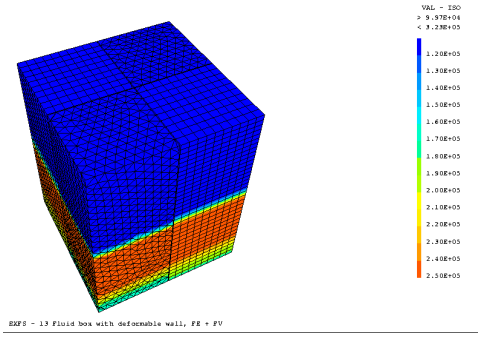
The EUROPLEXUS input file reads:

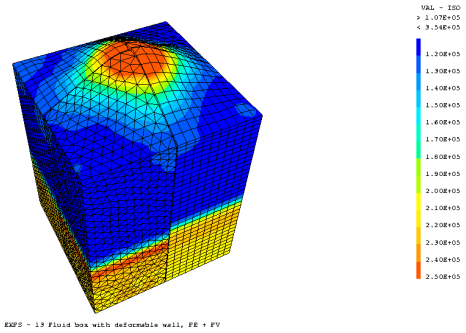
```
$-----------------------------------------------------------------$
EXFS - Full box - Run for Munich'99 ECCM Conference
$VERI
ECHO
 CONV win
CAST FORM MESH
TRID NONL ALE
$-----------------------------------------------------------------$
DIME
  ZONE      6
  PT3L  16389
  PT6L    504            NBLE  16389
  NALE    163
  MNTI     10            NDVC  72438
  NEPE 253328            ECRO 398076
  MC34  18796
  MC38   3500            FL34  18940
  FL38   3400            COQI    840
  MTPO    504
  MTEL    840
  CL3I    840
TERM
$-----------------------------------------------------------------$
GEOM
     FL34  EXFETFL AIFETFL
     MC34  EXFETMC AIFETMC
     FL38  EXFEHFL AIFEHFL
     MC38  EXFEHMC AIFEHMC
     COQI  WALTFL WALTMC WALHFL WALHMC
     CL3I  PIMP
TERM
$-----------------------------------------------------------------$
GRIL
LAGR LECT WALTFL WALTMC WALHFL WALHMC TERM
ALE  LECT EXFETFL AIFETFL EXFETMC AIFETMC EXFEHFL AIFEHFL EXFEHMC
     AIFEHMC TERM
AUTO AUTR
$-----------------------------------------------------------------$
EPAI 2.5e-3 LECT WALTFL WALTMC WALHFL WALHMC TERM
$-----------------------------------------------------------------$
MATE
$
$....( STRUCTURE ).....................................................$
VM23 RO  5000.  YOUN 1.0E09  NU 0.3 ELAS 1.0E09
     TRAC 1  1.0E+09  1.0E+00
     LECT WALTFL WALTMC WALHFL WALHMC TERM
$
$....( FLUID ).........................................................$
$ (Volume of the 4 high-energy zones:   Vol=.5448 m^3
$
$ ------ Flut material -------
$
$ High energy zone
FLUT RO 2. EINT 5.E5 GAMM 1.5 PB 0 ITER 1 ALF0 1 BET0 1
     KINT 0 AHGF 0 CL 0.0 CQ 2.00 PMIN 0  NUM 1
     LECT EXFETFL EXFEHFL TERM
$ Low energy zone
FLUT RO 2. EINT 1.E5 GAMM 1.5 PB 0 ITER 1 ALF0 1 BET0 1
```

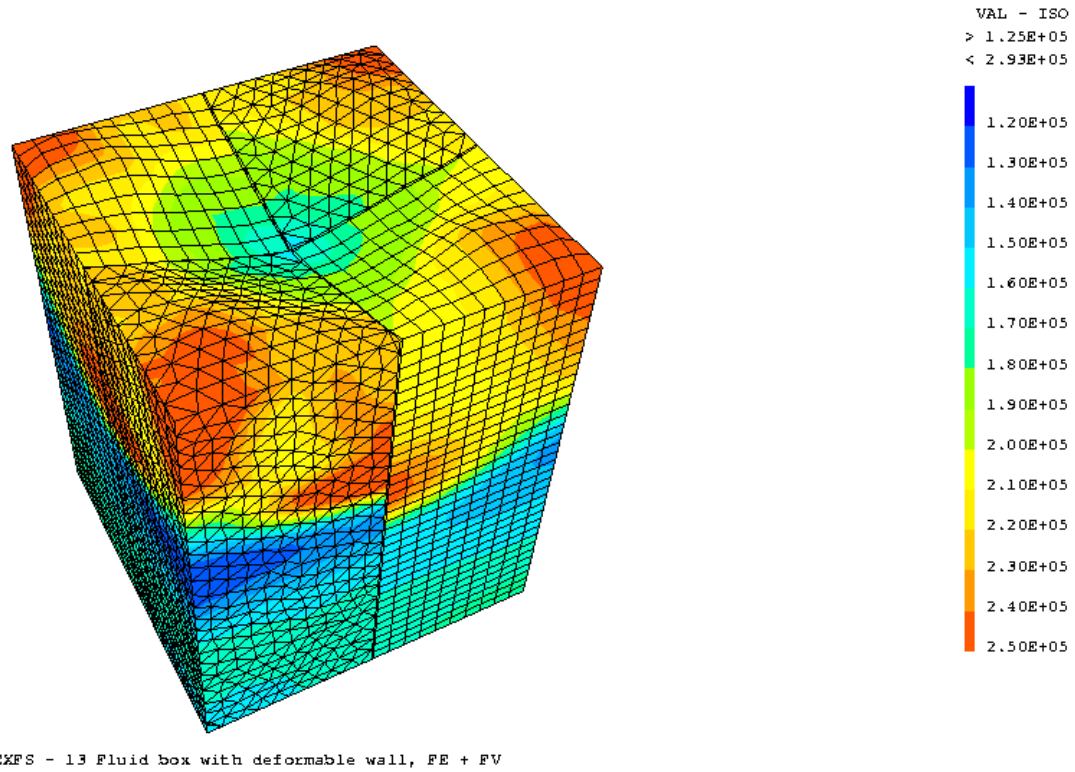
```
     KINT 0 AHGF 0 CL 0.0 CQ 2.00 PMIN 0  NUM 1
     LECT AIFETFL AIFEHFL TERM
$
$ ------ Mcgp material -------
$
MCGP NCOM 1 R 10000
     COMP 'Oxigen1' PM 20. CV1 20000 CV2 0 CV3 0
     LECT EXFETMC AIFETMC EXFEHMC AIFEHMC TERM
$
$ ------ Imposed Pressure -------
$
IMPE PIMP RO 1.0 PREF 0.0 PRES 1.0E5
          TABP 2    0.0 1.0    1.0 1.0
          LECT PIMP TERM
$
$-------------------------------------------------------------------$
INIT MCOM
     COMP 'Oxigen1' MPRA 1.0
     LECT EXFETMC AIFETMC EXFEHMC AIFEHMC TERM
    PRES 1.E5  LECT AIFVTMC AIFVHMC TERM
    PRES 5.E5  LECT EXFVTMC EXFVHMC TERM
    TEMP 100.  LECT AIFVTMC AIFVHMC TERM
    TEMP 500.  LECT EXFVTMC EXFVHMC TERM
$-------------------------------------------------------------------$
OPTI FSCR
LINK COUP BLOQ 1 LECT bloc1 TERM
          2 LECT bloc2 TERM
```

```
          3 LECT bloc3 TERM
        123 LECT blocall TERM
     CONT SPLA NX 1 NY 0 NZ 0 LECT symx TERM
     CONT SPLA NX 0 NY 1 NZ 0 LECT symy TERM
     FSA LECT fsan TERM
$-------------------------------------------------------------------$
ECRI
      fich form spli k200 TFRE 1.e-3
           poin tous
           vari depl vite mcxx ecro ecrc lect 1 2 4 term
$TRAC FORM IDEA TFRE 1.e-3
$VARI DEPL MCVA FLVA
$POIN LECT LAGR TERM
$ELEM LECT WALTFL WALTMC WALHFL WALHMC TERM
$
TRAC TPLO TFRE 25.E-6  DESC 'EXFS13'
          POIN LECT TPLNTFL TPLNTMC TPLNHFL TPLNHMC TERM
$-------------------------------------------------------------------$
OPTI NOTE
OPTI MC ORDR 2 LOG 1
REZO GAM0 0.5 LIAI MVRE MODU
 csta 0.5
$-------------------------------------------------------------------$
CALC TINI 0 TEND 20.E-3
$-------------------------------------------------------------------$
FIN
$-------------------------------------------------------------------$
```

Some results: pressure distributions:

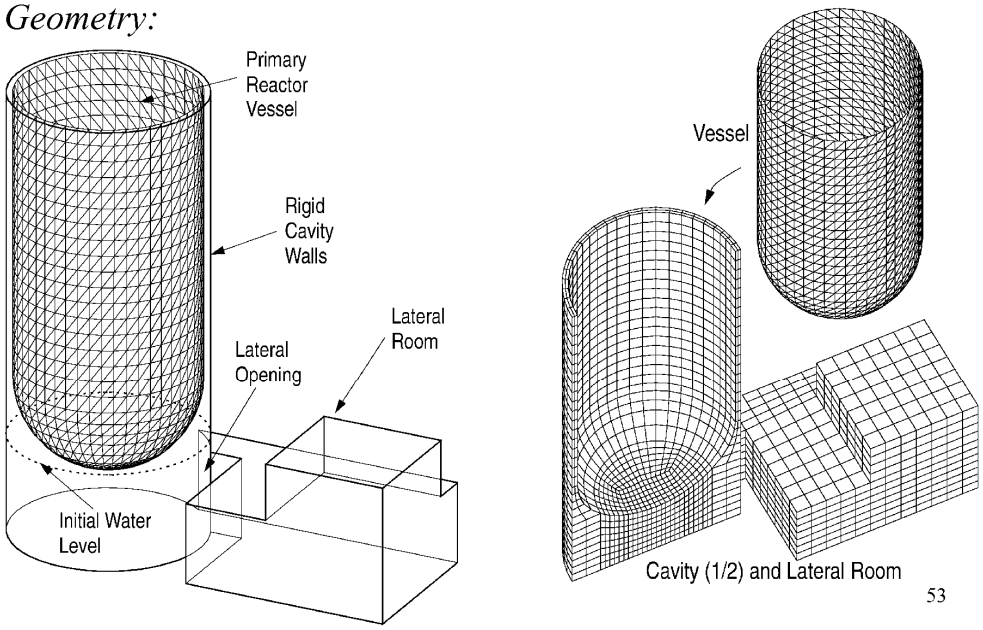






Exercise/Example 8
Steam Explosion in Reactor Cavity

Geometry:



TITLE:
Cavi51: steam explosion in a 3D cavity.
PROBLEM:
This problem was suggested by ISMES (I) in the mid-nineties as a check of the code capability to model an extremely violent phenomenon, the steam explosion caused by sudden drop of hot corium material (following an HCDA) into a pool of liquid water situated in a cavity between the primary reactor vessel (supposed to be unperforated!) and the rigid cylindrical walls. The problem is 3D because of a lateral corridor that opens in the cavity and puts it in communication with an external room. All walls are considered rigid, but the deformations (plasticity) of the primary vessel must be modeled.
MESH:
The model is 3D and uses 7664 elements FL38 for the fluid and 3072 shell elements COQI for the vessel. The calculation is ALE and starts with a hot and high-pressure steam bubble at the center of the liquid pool.
MATERIALS:
Because of the huge distortions and the thinness of the cavity the only way to simulate this test is by means of the multi-phase multi-component fluid material model (FLMP). This consists of three components: the liquid water (WT0 model) for the pool, a perfect gas for the air and another perfect gas, initially at high pressure and temperature, for the steam bubble. The structure uses the VM23 elasto-plastic material.
BOUNDARY CONDITIONS:
The vessel is entirely blocked along the top circle. The fluid-structure interaction is automaticcaly modelled by the FSA directive along the fluid-vessel interface, and by FSR along the external surface of the fluid (the cavity walls are supposed rigid).
LOADING:
The system is initially at rest, but not in equilibrium.
CALCULATION:
The calculation is performed up to 50 ms. At the final time, the vessel has undergone large plastifications at the bottom and also near the top (water-hammer effect), and the liquid water has invaded bothe the cavity and the external room.
RESULTS:
Although no comparison with experiments can be done on this problem, the results appear physically correct.

POST-TREATMENT
Several animations of the computed results from this calculation are available on the EUROPLEXUS Consortium Web site.

REFERENCES:
This calculation is detailed in:
F. Casadei: "Generalization of the Finite Element Model for Compressible Fluids in PLEXIS-3C to Multi-Phase Flows." Technical Note N. I.97.33, March 1997. (available on the EUROPLEXUS Consortium Web site).

Numerical Solution

CAVI51
The mesh generation file (K2000) is:

```
*%siz 300

opti echo 0;
opti donn 'D:\Users\Folco\plexis3c\proc\pxordpoi.proc';
opti donn 'D:\Users\Folco\plexis3c\proc\pxrota3d.proc';
opti donn 'D:\Users\Folco\plexis3c\proc\pxvolu3d.proc';
opti donn 'D:\Users\Folco\plexis3c\proc\px4to3.proc';
opti echo 1;
opti trac psc ftra 'vl_jrc_cavi51_mesh.ps';
*
opti titr 'CAVI - 51';
opti dime 3 elem cub8;
*
p0=0 0 0;
p1=2.35 0 0;
p2=2.35 0 11;
p3=2.20 0 11;p3p=p3 plus p0;
p4=2.35 0 3.9;
p5=2.20 0 3.9;p5p=p5 plus p0;
p6=0 0 1.7;p6p=p6 plus p0;
p7=0 0 1.45;
p8=0.6 0 0.85;
pcb=0 0 0.85;
pcv=0 0 3.9;
p9=0 0 0.25;
p10=0.709882641 0 1.817677586;
p10p=p10 plus p0;
p11=0.75 0 1.7;
p12=2.35 0 1.7;p12b=2.35 0 2.0;
p13p=p5p plus (0 0 0.39444);
p14=2.35 0 2.9571;
p15=2.0141 0 3.0148;
tol=0.001;
*
p101=1.55563 0 0;
p102=1.55563 0 2.34437;
p103=0 0 2.34437;
p104=2.35 0 2.3;
*
nr=12;
ang=90.0;
ang1=23.18;ang2=31.82;ang3=35.00;
nr1=4;nr2=4;nr3=4;
*
p105=p101 tour ang1 p0 p6;
p106=p105 tour (ang2 * 0.5) p0 p6;
p107=p105 tour ang2 p0 p6;
p108=p107 tour ang3 p0 p6;
p108b=p108 plus p0;
p109=0.7 0.7 0;
p110=p108 tour 45.0 p0 p6;
p111=p110 tour 45.0 p0 p6;
p112=-0.7 0.7 0;
p113=0 0.78 0;
p113b=p113 plus p0;
p114=-0.78 0 0;
p115=0.78 0 0;
p0b=p0 plus p0;
*
c1=p101 d 2 p1;
c2=p1 d 6 p12 d 1 p12b d 1 p104;
c3=p104 d 2 p102;
c4=p102 d 8 p101;
fluido1=daller c1 c2 c3 c4 plan;
*
c1=p102 d 2 p104;
c2=p104 d 2 p14 d 3 p4 d 18 p2;
c3=p2 d 2 p3;
c4=p3 d 18 p5 c 3 pcv p15 c 2 pcv p102;
fluido2=daller c1 c2 c3 c4 plan;
fluido12=fluido1 et fluido2;
elim tol fluido12;
*
oeil=0 -10000 0;
*trac oeil fluido12;
*opti donn 5;
*
fluv01=fluido12 volu nr1 rota ang1 p0 p6;
flus01=fluido12 tour ang1 p0 p6;
fluv02=flus01 volu nr2 rota ang2 p0 p6;
flus02=flus01 tour ang2 p0 p6;
fluv03=flus02 volu nr3 rota ang3 p0 p6;
flus03=flus02 tour ang3 p0 p6;
fluv1=fluv01 et fluv02 et fluv03;
elim tol fluv1;
*trac oeil cach fluv1;
*opti donn 5;
*
fluv2=flus03 volu nr rota ang p0 p6;
flus2=flus03 tour ang p0 p6;
fluv3=flus2 volu nr rota ang p0 p6;
flus3=flus2 tour ang p0 p6;
fluv4=flus3 volu nr rota ang p0 p6;
flus4=flus3 tour ang p0 p6;
fluv=fluv1 et fluv2 et fluv3 et fluv4;
elim tol fluv;
*trac oeil cach fluv;
*opti donn 5;
*
c1=p115 d 6 p101;
c2=p101 c 4 p0 p105 c 2 p0 p106;
c3=p106 d 6 p109;
c4=p109 d 6 p115;
bas01=daller c1 c2 c3 c4 plan;
*
c1=p109 d 6 p106;
c2=p106 c 2 p0 p107 c 4 p0 p108;
c3=p108 d 6 p113;
c4=p113 d 6 p109;
bas02=daller c1 c2 c3 c4 plan;
*
c1=p0 d 6 p115;
c2=p115 d 6 p109;
c3=p109 d 6 p113;
c4=p113 d 6 p0;
bas03=daller c1 c2 c3 c4 plan;
*
bas1=bas01 et bas02 et bas03;
elim tol bas1;
*
*trac (0 0 1000000) bas1;
*opti donn 5;
*
c1=p113b d 6 p108b;
c2=p108b c 6 p0 p110;
c3=p110 d 6 p112;
c4=p112 d 6 p113b;
bas11=daller c1 c2 c3 c4 plan;
*
c1=p112 d 6 p110;
c2=p110 c 6 p0 p111;
c3=p111 d 6 p114;
c4=p114 d 6 p112;
bas12=daller c1 c2 c3 c4 plan;
*
c1=p0b d 6 p113b;
c2=p113b d 6 p112;
c3=p112 d 6 p114;
c4=p114 d 6 p0b;
bas13=daller c1 c2 c3 c4 plan;
*
bas2=bas11 et bas12 et bas13;
elim tol bas2;
*
*trac (0 0 1000000) (bas1 et bas2);
*opti donn 5;
vol1=bas1 volu 8 tran p103;
elim tol (vol1 et fluv1);
*trac oeil cach (vol1 et fluv1);
*opti donn 5;
nn=nbno vol1;
vol1p=chan poi1 vol1;
i=0;repe lop1 nn;i=i+1;
  ni=vol1p poin i;
  xi yi zi=coor ni;
  zpstar=((2.2d0 * 2.2d0)-(xi*xi)-(yi*yi))**(0.5d0);
  facp=(3.9d0-zpstar)/2.34437;
  zinew=zi*facp;
  dzi=zinew-zi;
  depl ni plus (0 0 dzi);
fin lop1;
*trac oeil cach (vol1 et fluv1);
*opti donn 5;
vol2=bas2 volu 8 tran p103;
*elim tol (vol2 et fluv2);
*trac oeil cach vol2;
*opti donn 5;
nn=nbno vol2;
vol2p=chan poi1 vol2;
i=0;repe lop2 nn;i=i+1;
  ni=vol2p poin i;
  xi yi zi=coor ni;
  zpstar=((2.2d0 * 2.2d0)-(xi*xi)-(yi*yi))**(0.5d0);
  facp=(3.9d0-zpstar)/2.34437;
  zinew=zi*facp;
  dzi=zinew-zi;
  depl ni plus (0 0 dzi);
fin lop2;
*opti donn 5;
*trac oeil cach (vol2 et fluv2);
*opti donn 5;
*
vol3=vol2 syme plan p0 p6 p111;
vol4=vol3 syme plan p0 p6 p108;
fluidc=fluv et vol1 et vol2 et vol3 et vol4;
elim tol fluidc;
*trac oeil cach fluidc;
*opti donn 5;
*
nn=nbel fluidc;
ngas=0;
i=0;repe lop2a nn;i=i+1;
  ei=fluidc elem i;
  bi=bary ei;
  xb yb zb=coor bi;
  si (zb > 1.7);
    ngas=ngas+1;
    si (ngas ega 1);
      gas=ei;
    sinon;
      gas=gas et ei;
    finsi;
  finsi;
fin lop2a;
*
liqubull=diff fluidc gas;
*
nn=nbel liqubull;
nbul=0;
r2=0.6*0.6;
i=0;repe lop2b nn;i=i+1;
  ei=liqubull elem i;
  bi=bary ei;
  xb yb zb=coor bi;
  distpcb=(xb*xb)+(yb*yb)+((zb-0.85)*(zb-0.85));
  si (distpcb <eg r2);
    nbul=nbul+1;
    si (nbul ega 1);
      bull=ei;
    sinon;
      bull=bull et ei;
    finsi;
  finsi;
fin lop2b;
*
liqu=diff liqubull bull;
*
fluisur=enve fluidc;
nn=nbel fluisur;
nstr=0;
```

```
r2=2.2*2.2;
i=0;repe lop3 nn;i=i+1;
  ei=fluisur elem i;
  bi=bary ei;
  xb yb zb=coor bi;
  si (zb > 3.9);
    rb2=(xb*xb)+(yb*yb);
    si (rb2 <eg r2);
      nstr=nstr+1;
      si (nstr ega 1);
        fluidstr=ei;
      sinon;
        fluidstr=fluidstr et ei;
      finsi;
    finsi;
  sinon;
    distpcv=(xb*xb)+(yb*yb)+((zb-3.9)*(zb-3.9));
    si (distpcv <eg r2);
      nstr=nstr+1;
      si (nstr ega 1);
        fluidstr=ei;
      sinon;
        fluidstr=fluidstr et ei;
      finsi;
    finsi;
  finsi;
fin lop3;
*trac oeil cach fluidstr;
*opti donn 5;
*
fsan=chan poi1 fluidstr;
*
strucq=fluidstr plus p0;
*opti donn 5;
struc=px4to3 strucq;
struc=orie struc poin pcv;
*
*trac oeil cach fsan;
*trac oeil cach struc;
*opti donn 5;
*
nbs='NBEL' struc;
nna=0;nnb=0;nnc=0;
x y zp5p=coor p4;
x y zp13p=coor p13p;
kkk=0;repe labst nbs;kkk=kkk+1;
  elkkk=struc 'ELEM' kkk;
  x y z = coor ('BARY' elkkk);
  si (< z zp5p);
    si (ega nna 0);
      stra=elkkk;
      nna=nna+1;
    sinon;
      stra=stra et elkkk;
    finsi;
  sinon;
    si (> z zp13p);
      si (ega nnc 0);
        strc=elkkk;
        nnc=nnc+1;
      sinon;
        strc=strc et elkkk;
      finsi;
    sinon;
      si (ega nnb 0);
        strb=elkkk;
        nnb=nnb+1;
      sinon;
        strb=strb et elkkk;
      finsi;
    finsi;
  finsi;
fin labst;
*
*trac oeil cach stra;
*trac oeil cach strb;
*trac oeil cach strc;
*opti donn 5;
*
nbs='NBEL' struc;
nn1=0;nn2=0;nn3=0;nn4=0;
i=0;repe labs2 nbs;i=i+1;
  ei=struc elem i;
  bi=bary ei;
  xb yb zb=coor bi;
  si (xb > 0);
    si (yb > 0);
      nn1=nn1+1;
      si (nn1 ega 1);
        str1=ei;
      sinon;
        str1=str1 et ei;
      finsi;
    sinon;
      nn4=nn4+1;
      si (nn4 ega 1);
        str4=ei;
      sinon;
        str4=str4 et ei;
      finsi;
    finsi;
  sinon;
    si (yb > 0);
      nn2=nn2+1;
      si (nn2 ega 1);
        str2=ei;
      sinon;
        str2=str2 et ei;
      finsi;
    sinon;
      nn3=nn3+1;
      si (nn3 ega 1);
        str3=ei;
      sinon;
        str3=str3 et ei;
      finsi;
    finsi;
  finsi;
fin labs2;
list(nbel str1);
list(nbel str2);
list(nbel str3);
list(nbel str4);
```

```
*opti donn 5;
*
str1=orie str1 poin pcv;
str2=orie str2 poin pcv;
str3=orie str3 poin pcv;
str4=orie str4 poin pcv;
*vi=@visor str1 0.1 'VERT';
*trac (1000 -2000 3000) vi str1;
*vi=@visor str2 0.1 'VERT';
*trac (1000 -2000 3000) vi str2;
*vi=@visor str3 0.1 'VERT';
*trac (1000 -2000 3000) vi str3;
*vi=@visor str4 0.1 'VERT';
*trac (1000 -2000 3000) vi str4;
*opti donn 5;
list(nbel str3);
*
p16l=2.1603 0.925 0;p16m=2.1603 0.925 2;
p17l=1.3479 1.925 0;p17m=1.3479 1.925 2;
p18l=2.95 0.925 0;p18m=2.95 0.925 2;
p19l=2.95 1.925 0;p19m=2.95 1.925 2;
p20l=2.95 -1.925 0;p20m=2.95 -1.925 2;
p21l=8 -1.925 0;p21m=8 -1.925 2;p21u=8 -1.925 3.404;
p22l=8 1.925 0;p22m=8 1.925 2;
p23l=5 -1.925 0;p23m=5 -1.925 2;p23u=5 -1.925 3.404;
p24l=5 1.075 0;p24m=5 1.075 2;p24u=5 1.075 3.404;
p25l=8 1.075 0;p25m=8 1.075 2;p25u=8 1.075 3.404;
p26l=5 1.925 0;p26m=5 1.925 2;
c1=p16l d 4 p18l;
c2=p18l d 4 p19l;
c3=p19l d 4 p17l;
c4=c 4 p17l p0 p16l;
cam1b=daller c1 c2 c3 c4 plan;
c1=p18l d 5 p24l d 7 p25l;
c2=p25l d 4 p22l;
c3=p22l d 7 p26l d 5 p19l;
c4=p19l d 4 p18l;
cam2b=daller c1 c2 c3 c4 plan;
c1=p20l d 5 p23l;
c2=p23l d 7 p24l;
c3=p24l d 5 p18l;
c4=p18l d 7 p20l;
cam3b1=daller c1 c2 c3 c4 plan;
c1=p23l d 7 p21l;
c2=p21l d 7 p25l;
c3=p25l d 7 p24l;
c4=p24l d 7 p23l;
cam3b2=daller c1 c2 c3 c4 plan;
cam3b=cam3b1 et cam3b2;
elim tol cam3b;
cambb=cam1b et cam2b et cam3b;
elim tol cambb;
vz1=p12 'MOIN' p1;
vz2=p12b 'MOIN' p12;
cam1=cam1b 'VOLU' 6 'TRAN' vz1 'VOLU' 1 'TRAN' vz2;
cam2=cam2b 'VOLU' 6 'TRAN' vz1 'VOLU' 1 'TRAN' vz2;
cam31=cam3b1 'VOLU' 6 'TRAN' vz1 'VOLU' 1 'TRAN' vz2;
cam32=cam3b2 'VOLU' 6 'TRAN' vz1 'VOLU' 1 'TRAN' vz2;
cam3=cam31 et cam32;
camb=cam1 et cam2 et cam3;
elim tol camb;
c1=p23m d 7 p21m;
c2=p21m d 7 p25m;
c3=p25m d 7 p24m;
c4=p24m d 7 p23m;
cam4b=daller c1 c2 c3 c4 plan;
vz3=0 0 1.404;
cam4=cam4b 'VOLU' 4 'TRAN' vz3;
cam=camb et cam4;
elim tol cam;
*
fluid=fluidc et cam;
elim tol fluid;
*
gas=gas et cam;
*
surfc=enve fluid;
fsrn=chan poi1 surfc;
fsrn=fsrn diff fsan;
*trac oeil fsrn;
*
vert=p2 moin p1;
p0t=p0 plus vert;
p1t=p1 plus vert;
p17t=p17l plus vert;
blocall=struc poin plan p0t p1t p17t tol;
*
tpn1 = struc poin proc p6;
tpn2 = struc poin proc p5;
tpn3 = struc poin proc (2.2 0 10.211111);
tpn = tpn1 et tpn2 et tpn3;
*
mesh=fluid et struc et blocall et fsan et fsrn et tpn;
tass mesh;
*
nn='NBEL' struc;
coco='CHAI' 'Elements in struc =' nn;
mess coco;
nn='NBEL' fluid;
coco='CHAI' 'Elements in fluid =' nn;
mess coco;
nn='NBNO' struc;
coco='CHAI' 'Nodes in struc =' nn;
mess coco;
nn='NBNO' fluid;
coco='CHAI' 'Nodes in fluid =' nn;
mess coco;
nn='NBNO' blocall;
coco='CHAI' 'Nodes in blocall =' nn;
mess coco;
nn='NBNO' fsan;
coco='CHAI' 'Nodes in fsan =' nn;
mess coco;
nn='NBNO' fsrn;
coco='CHAI' 'Nodes in fsrn =' nn;
mess coco;
*
opti sauv form 'vl_jrc_cavi51.msh';
sauv form mesh;
opti trac psc;
trac cach mesh;
list(nbel str3);
fin;
```

The EUROPLEXUS input file reads:

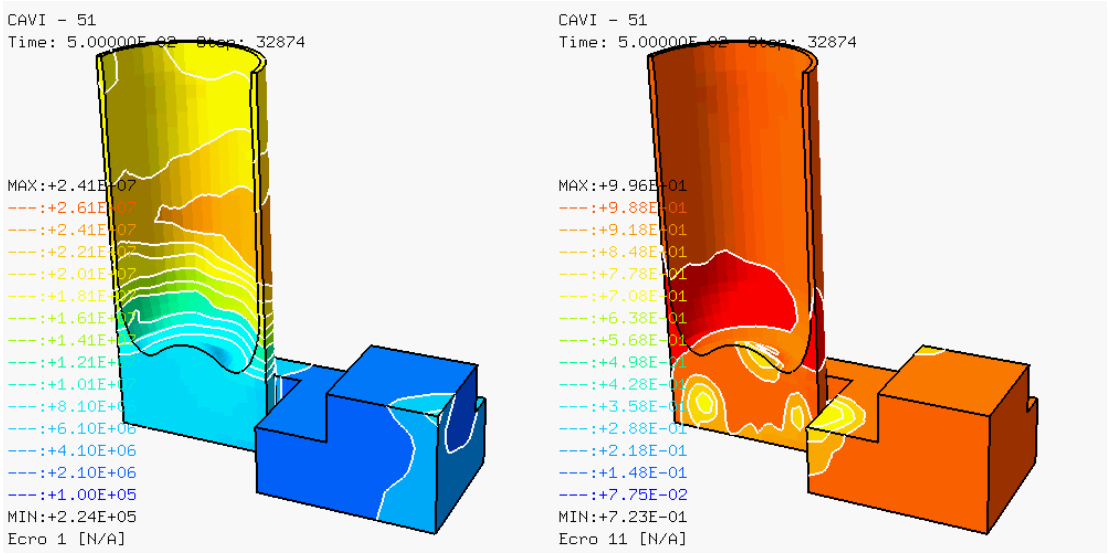
```
CAVI - 51
$
 ECHO
 !CONV win
CAST MESH
TRID NONL ALE
$
DIME
 PT6L 1561 PT3L 9913
 FL38 7664 COQI 3072 ZONE 2
 NALE 521 NBLE 4639
 nepe 160
 ECRO 868832
 mtti 10
TERM
$
GEOM
  FL38 fluid
  COQI struc
TERM
$
```

```
COMP
  EPAI 0.13   LECT stra TERM
       0.15   LECT strb TERM
       0.1968 LECT strc TERM
  COUL roug LECT bull TERM
       bleu LECT liqu TERM
       turq LECT gas CAM TERM
       jaun LECT struc TERM
$
GRIL LAGR LECT struc         TERM
     EULE LECT cam fsan fsrn TERM
     ALE  LECT fluid         TERM
     AUTO                    AUTR
$
MATE
$ steel
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT struc TERM
     FLMP NLIQ 1 NGAS 2
$ WT0 liquid water
```

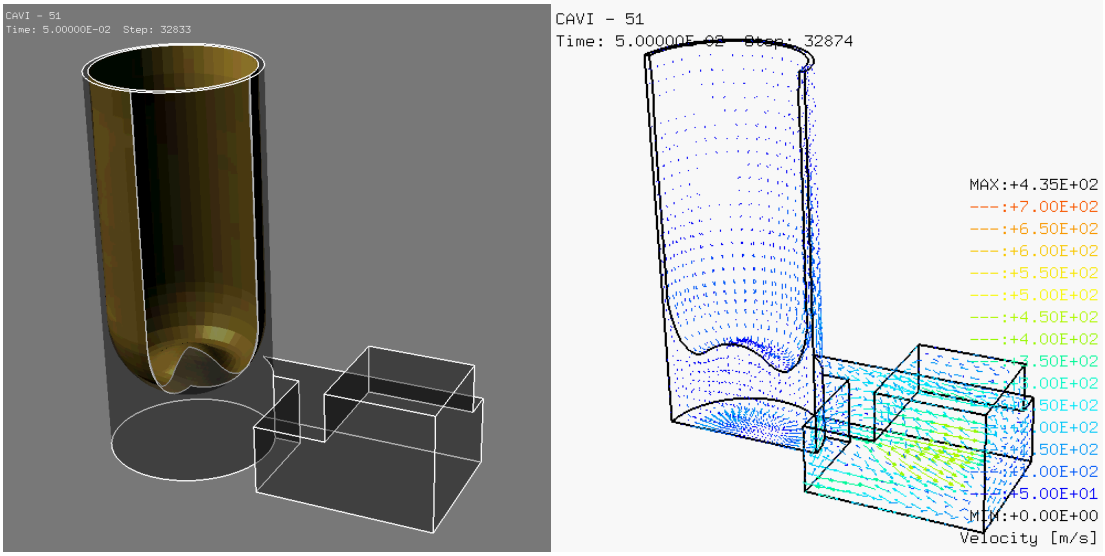
```
     FLUT RO 1000.0454482d0 EINT 0.0d0 GAMM 7.15d0
          PB 3.010d9 ITER 1 ALF0 1 RREF 1000.0d0
          CONV 0.1d0 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 8
          LECT liqu TERM
$ high-pressure perfect gas (explosive bubble)
     FLUT RO 954. EINT 3.010E6 GAMM 1.4 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT bull TERM
$ air
     FLUT RO 1.2 EINT 2.0833E5 GAMM 1.4 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT gas CAM TERM
$
LINK COUP
     BLOQ 123456 LECT blocall TERM
     FSA          LECT fsan    TERM
     FSR          LECT fsrn    TERM
$
ECRI DEPL VITE ECRO TFRE 1.E-3
          POIN LECT 1 TERM
          ELEM LECT 1 PAS 1 10 TERM
     FICH ALIC TFRE 5.E-4
     FICH ALIC TEMP TFRE 5.E-5
          POIN LECT tpn TERM
          ELEM LECT 1 TERM
$
OPTI NOTE
 momt 2
```

```
 log 1
 dtml
 REZO GAM0 0.5
 FLMP EPS1 5.0E-4 EPS2 1.0E-4
CALCUL TINI 0 TEND 50.E-3
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR  1 'dz_n1' DEPL COMP 3 NOEU LECT tpn1 TERM
COUR  2 'dx_n2' DEPL COMP 1 NOEU LECT tpn2 TERM
COUR  3 'dx_n3' DEPL COMP 1 NOEU LECT tpn3 TERM
*
trac 1 2 3 axes 1.0 'DISPL. [M]'
trac 2 3   axes 1.0 'DISPL. [M]'
*
QUAL DEPL COMP 3 LECT tpn1 TERM REFE  1.23254E+0 TOLE 5.E-2
     DEPL COMP 1 LECT tpn2 TERM REFE -1.24733E-2 TOLE 1.E-1
     DEPL COMP 1 LECT tpn3 TERM REFE -4.01831E-2 TOLE 5.E-2
*=================================================================
FIN
```

Some results: final pressure distribution and final water distribution:

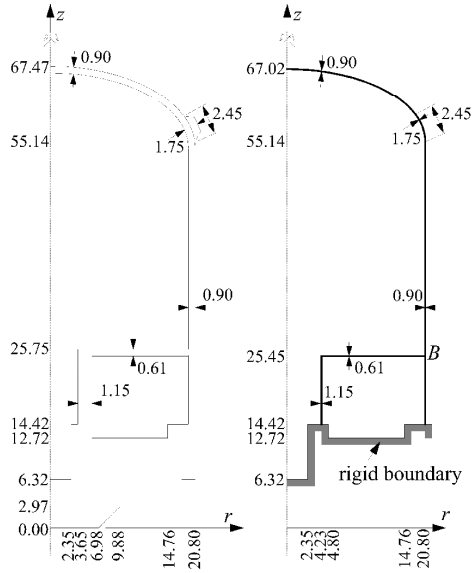


Final structure deformation and velocity distribution:



Exercise/Example 9
Explosion in Secondary Containment

Geometry:



Layer N.	φ_L	Material
1	0.1	concrete
2	0.01	steel
3	0.78	concrete
4	0.01	steel
5	0.1	concrete

57

TITLE:

Reac05: propagation of steam explosion pressure waves in the secondary containment of a nuclear reactor. Similar to Stea05 but with reinforced concrete material model for the building.

PROBLEM:

This problem was suggested by ISMES (I) in the early-nineties. It represents the effects of a steam or gas explosion on the secondary containment building of a nuclear reactor. The explosion takes place in a liquid water pool located immediately below the primary containment (reactor vessel) and produces strong pressure waves, which propagate across the atmosphere in the reactor building, interacting with its walls and with some schematized internal structures. The explosive products are schematized by a high-pressure gas.

MESH:

The model is 2D axisymmetric and uses 24 elements FL23 and 957 elements FL24 to represent the fluid, and 88 shell elements ED01 for the building walls and internals. Shell elements are made of 5 layers each, 3 of which representing the concrete and 2 for the steel reinforcements. The calculation is ALE and starts with a hot and high-pressure steam bubble in the lower part of the building.

MATERIALS:

The bottom of the building is assumed to be rigid, while the walls and internals, which are made of reinforced concrete material, are represented by the DPSF model, a Drucker-Prager constitutive law with softening and viscoplastic regularization, for the concrete, and by the VMSF (von Mises elasto-plastic material with softening) for the steel reinforcement.

BOUNDARY CONDITIONS:

The fluid-structure interaction along the deformable building walls is automaticcaly modelled by the FSA directive.

LOADING:
The system is initially at rest, but not in equilibrium.
CALCULATION:
The calculation is performed up to 250 ms. This time is sufficient to see propagation of the pressure waves to the top of the building and several reflections.
RESULTS:
Although no comparison with experiments can be done on this problem, the results appear physically correct.
POST-TREATMENT
Several animations of the computed results from this calculation are available on the EUROPLEXUS Consortium Web site.

REFERENCES:
This calculation is detailed in:
1) F. Casadei: "Simulation of a Gas Explosion in a Reactor Containment by PLEXIS-3C." Technical Note N. I.93.148, November 1993.
2) J.J. Lopez Cela, F. Casadei and P. Pegon: "Fast Transient Analysis of Thin Shell Reinforced Concrete Structures with Drucker-Prager Model." SMiRT-14 Conference, Lyon (F), August 17-22, 1997.
(both available on the EUROPLEXUS Consortium Web site).

Numerical Solution

REAC05

The mesh generation file (K2000) is:

```
*%siz 100
*
opti echo 1;
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxpdroit.proc';
*
opti titr 'REAC - 05';
opti dime 2 elem qua4;
*
p0=0 0;
p1=0.00 6.32;
p2=2.35 6.32;
p3=2.35 14.42;
p4=4.23 14.42;p4p=p4 plus p0;p4i=p4 plus p0;
p5=4.80 14.42;
p6=4.80 12.72;
p7=14.76 12.72;
p8=14.76 14.42;
p9=20.35 14.42;p9i=p9 plus p0;
p10=4.23 25.45;p10p=p10 plus p0;p10i=p10 plus p0;
p11=20.35 25.45;p11p=p11 plus p0;p11i=p11 plus p0;
p12=20.35 55.14;p12p=p12 plus p0;
p13=0.00 67.02;p13p=p13 plus p0;
p14=0.00 55.14;
p15=0.00 25.45;
p16=0.00 14.42;
*
tol=0.01;
*
c1=p1 d 4 p2;
c2=p2 d 8 p3;
c3=p3 d 4 p16;
c4=p16 d 8 p1;
boll=daller c1 c2 c3 c4 plan;
*
c1=p16 d 4 p3 d 3 p4;
c2=p4 d 10 p10;
c3=p10 d 7 p15;
c4=p15 d 10 p16;
flu1=daller c1 c2 c3 c4 plan;
*
c1=p15 d 7 p10 d 13 p11;
c2=p11 d 25 p12;
c3=p12 d 20 p14;
c4=p14 d 25 p15;
flu2=daller c1 c2 c3 c4 plan;
*
ella=20.35;
ellb=11.87;
rapp=ella / ellb;
cir=cerc 30 (p14 plus (ellb 0)) p14
            (p14 plus (0 ellb));
ell=cir affi rapp p14 p12;
*
p12d=ell poin proc p12;
conf p12d p12;
p13d=ell poin proc p13;
conf p13d p13;
*
co=(p14 d 20 p12) et ell et (p13 d 10 p14);
*
* it is necessary to eliminate double points
* in co so that it is seen as a closed contour
* by operator surf
*
elim tol co;
flu3=surf co plan;
*
str1=p4p d 10 p10p;
str2=p10p d 13 p11p;
str3=p9 d 10 p11p;
str4=p11p d 25 p12p;
str5=ell plus p0;
grosso=(str5 elem 1) et (str5 elem 2) et
       (str5 elem 3) et (str5 elem 4);
sottile=diff str5 grosso;
p12pd=str5 poin proc p12p;
conf p12pd p12p;
p13pd=str5 poin proc p13p;
conf p13pd p13p;
*
flui=flu1 et flu2 et flu3;
elim tol (boll et flui);
stru=str1 et str2 et str3 et str4 et str5;
elim tol stru;
*
c1=p4i d 1 p5 d 7 p8 d 5 p9i;
c2=p9i d 10 p11i;
c3=p11i d 13 p10i;
c4=p10i d 10 p4i;
flu4a=daller c1 c2 c3 c4 plan;
c1=p5 d 2 p6;
c2=p6 d 7 p7;
c3=p7 d 2 p8;
c4=p8 d 7 p5;
flu4b=daller c1 c2 c3 c4 plan;
flu4=flu4a et flu4b;
elim tol flu4;
*
flui=flui et flu4;
flut=flui elem 'TRI3';
fluq=flui elem 'QUA4';
mesh=boll et flut et fluq et stru;
*
simx=mesh poin droi p1 p13 tol;
blocy=boll poin droi p1 p2 tol;
blocy=blocy et (pxpdroit flu1 p3 p4 tol);
blocy=blocy et (pxpdroit flu4 p4i p5 tol);
blocy=blocy et (pxpdroit flu4 p6 p7 tol);
blocy=blocy et (pxpdroit flu4 p8 p9i tol);
blocy=blocy et p4p et p9;
blocx=boll poin droi p2 p3 tol;
blocx=blocx et (pxpdroit flu4 p5 p6 tol);
blocx=blocx et (pxpdroit flu4 p7 p8 tol);
blocx=blocx et p4p et p9;
blocr=p4p et p9;
*
fsa=flu1 poin droi p4 p10 tol;
fsa=fsa et (pxpdroit flu2 p10 p11 tol);
fsa=fsa et (flu2 poin droi p11 p12 tol);
fsa=fsa et (chan poi1 ell);
fsa=fsa et (flu4 poin droi p4i p10i tol);
fsa=fsa et (flu4 poin droi p10i p11i tol);
fsa=fsa et (flu4 poin droi p11i p9i tol);
*
tn1=str1 poin proc ((p4p plus p10p) / 2);
tn2=p10p;
tn3=str2 poin proc ((p10p plus p11p) / 2);
tn4=p11p;
tn5=str3 poin proc ((p9 plus p11p) / 2);
tn6=str4 poin proc ((p11p plus p12p) / 2);
tn7=p12p;
elmid=10.175 65.42;
tn8=str5 poin proc elmid;
tn9=p13p;
*
k=boll poin proc ((p1 plus p3) / 2);
te1=boll elem 'CONTENENT' k;
te1=te1 elem 1;
k=flu1 poin proc ((p16 plus p10) / 2);
te2=flu1 elem 'CONTENENT' k;
te2=te2 elem 1;
k=flu2 poin proc ((p15 plus p14) / 2);
```

```
te3=flu2 elem 'CONTENENT' k;
te3=te3 elem 1;
k=flu2 poin proc ((p15 plus p12) / 2);
te4=flu2 elem 'CONTENENT' k;
te4=te4 elem 1;
k=flu2 poin proc ((p11 plus p12) / 2);
te5=flu2 elem 'CONTENENT' k;
te5=te5 elem 1;
k=p14;
te6=flu2 elem 'CONTENENT' k;
te6=te6 elem 1;
k=flu2 poin proc ((p14 plus p12) / 2);
te7=flu2 elem 'CONTENENT' k;
te7=te7 elem 1;
k=p12;
te8=flu2 elem 'CONTENENT' k;
te8=te8 elem 1;
k=flu3 poin proc elmid;
te9=flu3 elem 'CONTENENT' k;
te9=te9 elem 1;
k=p13;
te10=flu3 elem 'CONTENENT' k;
te10=te10 elem 1;
k=str1 poin proc ((p4p plus p10p) / 2);
te11=str1 elem 'CONTENENT' k;
te11=te11 elem 1;
k=str2 poin proc ((p10p plus p11p) / 2);
te12=str2 elem 'CONTENENT' k;
te12=te12 elem 1;
k=str3 poin proc ((p9 plus p11p) / 2);
te13=str3 elem 'CONTENENT' k;
te13=te13 elem 1;
k=p11p;
te14=str3 elem 'CONTENENT' k;
te14=te14 elem 1;
te15=str2 elem 'CONTENENT' k;
te15=te15 elem 1;
te16=str4 elem 'CONTENENT' k;
te16=te16 elem 1;
k=str4 poin proc ((p11p plus p12p) / 2);
te17=str4 elem 'CONTENENT' k;
te17=te17 elem 1;
k=p12p;
```

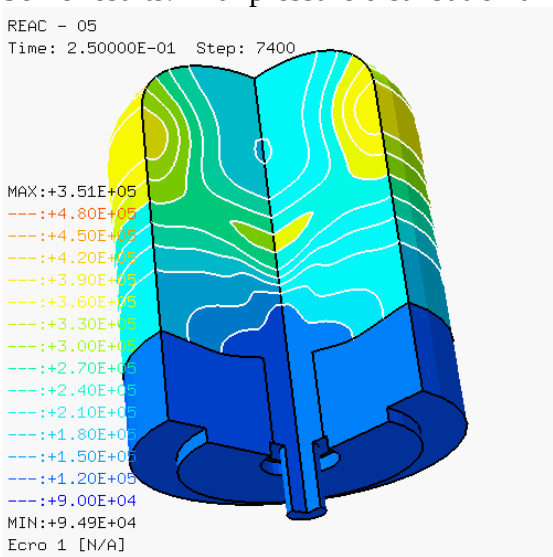
```
te18=str4 elem 'CONTENENT' k;
te18=te18 elem 1;
k=str5 poin proc elmid;
te19=str5 elem 'CONTENENT' k;
te19=te19 elem 1;
k=p13p;
te20=str5 elem 'CONTENENT' k;
te20=te20 elem 1;
tpln=tn1 et tn2 et tn3 et tn4 et tn5 et tn6
         et tn7 et tn8 et tn9;
tple=te1 et te2 et te3 et te4 et te5 et te6
         et te7 et te8 et te9 et te10 et te11
         et te12 et te13 et te14 et te15
         et te16 et te17 et te18 et te19
         et te20;
tpln1=tn3 et tn6;
tple1=te20 et te17 et te12;
xpln=boll poin droi p1 p2 tol;
xpln=xpln et (boll poin droi p2 p3 tol);
xpln=xpln et (pxpdroit flu1 p3 p4 tol);
xpln=xpln et (pxpdroit flu1 p4 p10 tol);
xpln=xpln et (pxpdroit flu2 p10 p11 tol);
xpln=xpln et (pxpdroit flu2 p11 p12 tol);
xpln=xpln et ell;
xpln=chan poi1 xpln;
*
ss=chan poi1 stru;
lag=ss et p1 et p2 et p3 et p5
       et p6 et p7 et p8;
*
mesh=boll et flut et fluq et stru
     et simx et blocx et blocy et blocr
     et lag et fsa et tpln et tple
     et xpln et tpln1 et tple1;
tass mesh;

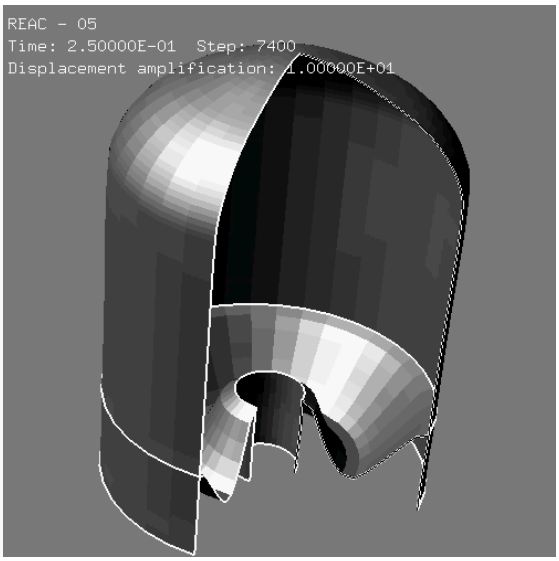
opti sauv form 'vl_jrc_reac05.msh';
sauv form mesh;
*
opti trac psc ftra 'vl_jrc_reac05_mesh.ps';
trac mesh;
fin;
```

The EUROPLEXUS input file reads:

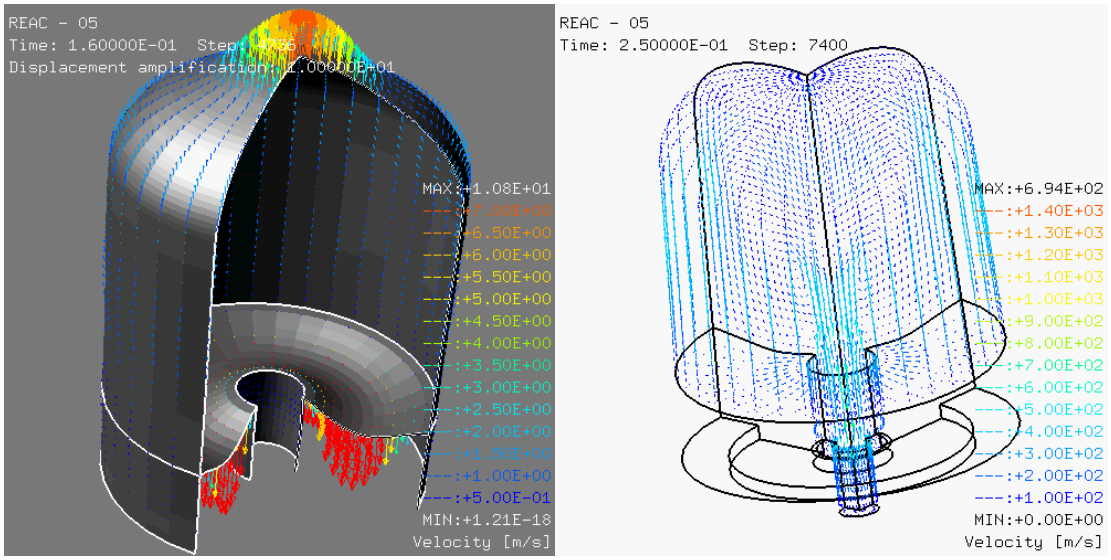
```
REAC - 05
$ dpsf material, ed01 with layers
 ECHO
*CONV win
CAST MESH
AXIS NONL ALE
$
DIME
 PT3L 89 PT2L 1088
 FL23 24 FL24 957 ED01 88 ZONE 3
 NALE 43 NBLE 1088
 PRES 65 MTEL 88
 ELVC 186 MTPO 94
 ECRO 28821
TERM
$
GEOM
  FL23 FLUT FL24 FLUQ BOLL
  ED01 STRU
TERM
$
COMP
  EPAI 1.15 LECT STR1 TERM
       0.61 LECT STR2 TERM
       0.90 LECT STR3 STR4 SOTTILE TERM
       1.75 LECT GROSSO TERM
  LAYE 5 FRAC 0.1 0.01 0.78 0.01 0.1
         NGPZ 1 1 2 1 1 LECT STRU TERM
$
GRIL LAGR LECT LAG TERM
     EULE LECT FSA TERM
     ALE  LECT FLUI TERM
     AUTO AUTR
$
$ concrete (softening)
MATE DPSF RO 2.4E3 YOUN 2.E10 NU 0.2 ALF1 1.299
     C1 5.7735E6 BETA 0.20 ETA 7.E-5
     TRAA 3 1.299 0.0 1.299 5.E-4 1.299 5.E+2
     TRAC 3 5.7735e6 0.0 1.44338E6 5.15E-3 1.44338E6 5.E+2
     LECT STRU TERM LAYE LECT 1 3 5 TERM
$
$ steel (elastoplastic)
     VMSF RO 7.8E3 YOUN 2.1E11 NU 0.3 ELAS 6.8E8
     ETA 0. TRAC 2 6.8E8 3.23810E-03 6.8E8 5.E+2
     LECT STRU TERM LAYE LECT 2 4 TERM
$ high-pressure perfect gas
     FLUT RO 111.50 EINT 12.764E5 GAMM 1.4 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1 LECT BOLL TERM
$ same gas at a lower pressure
     FLUT RO 1.2 EINT 2.0833E5 GAMM 1.4 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1 LECT FLUI TERM
$
CHAR 1 FACT 2 PRES COQU 1.E5
              LECT STR3 STR4 STR5 TERM
              TABL 2 0. 1. 100. 1.
$
link coup
     BLOQ 1 LECT BLOCX TERM
          2 LECT BLOCY TERM
          3 LECT BLOCR TERM
     CONT SPLA NX 1 NY 0 LECT SIMX TERM
     FSA  LECT FSA TERM
$
ECRI DEPL VITE ECRO TFRE 25.E-3
               POIN LECT TPLN TERM
               ELEM LECT TPLE TERM
     FICH ALIC TFRE 2.5E-3
     FICH ALIC TEMP TFRE 2.5E-4
                POIN LECT TPLN TERM
                ELEM LECT TPLE TERM
     FICH K200 TFRE 10.E-3 POIN TOUS
                VARI DEPL VITE ECRO ECRC LECT 1 2 4 8 TERM
$
OPTI NOTE
     log 1
     REZO GAM0 0.5
CALCUL TINI 0 TEND 250.E-3
*=========================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR  1 'dy_n3' DEPL COMP 2 NOEU LECT tn3 TERM
COUR  2 'dy_n9' DEPL COMP 2 NOEU LECT tn9 TERM
*
trac 1 2 axes 1.0 'DISPL. [M]'
*
QUAL DEPL COMP 2 LECT tn3 TERM REFE -9.17858E-1 TOLE 5.E-2
     DEPL COMP 2 LECT tn9 TERM REFE  2.25577E-1 TOLE 5.E-2
*=========================================================================
FIN
```

Some results: final pressure distribution and final structure deformation:

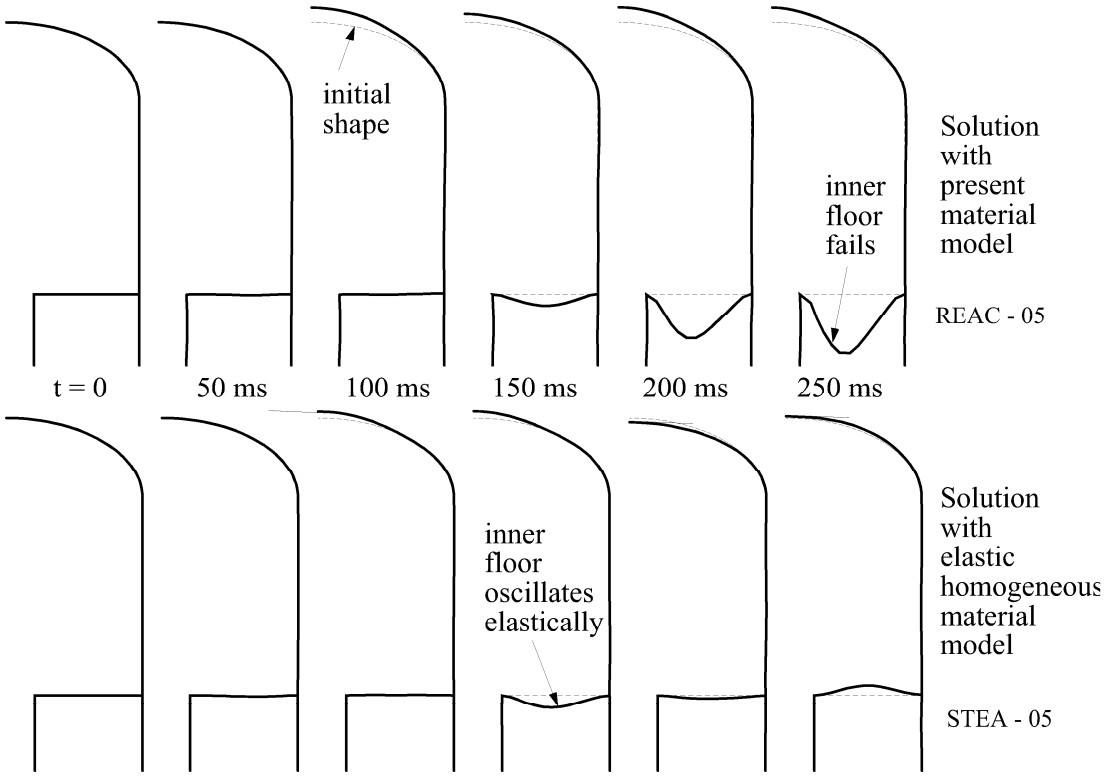




Intermediate structure velocities and final fluid velocities:

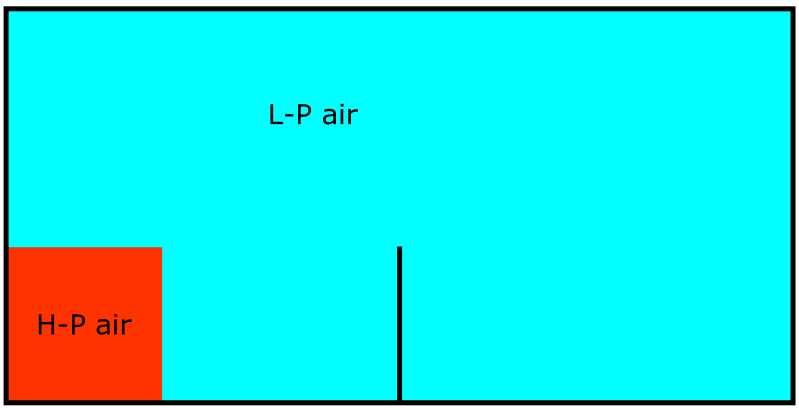


Comparison of elastic and concrete (elastoplastic) material solutions:



Exercise/Example 10b – Comparison FE/FV

- Compare FE (strong), N-C FV (strong) and C-C FV (weak) in a simple 2D explosion test with conforming F-S mesh



75

TITLE:
Elfi00/Vfnca1/Vfcc00: explosion in a 2D deformable container with an internal diaphragm.

PROBLEM:
The purpose is to compare Finite Element, Finite Volume (Node-Centred) and Finite Volume (Cell-Centred) solutions of this problem and to highlight the particularities of each model.

MESH:
The model is 2D plane strain and contains 20 x 10 finite elements (or finite volumes) in the fluid. The structural mesh is conforming to the fluid mesh.

MATERIALS:
The structure is an elasto-plastic VM23 material. The explosive and the gas (air) are rep;resented by perfect gases at high and low pressures, respectively. The two gases may mix up.

BOUNDARY CONDITIONS:
The fluid-structure interaction along the deformable container walls is automatically modelled by the FSA directive in the FE and N-C FV solutions. The C-C FV solution requires no specific directive and the fluid and structure nodes are merged together.

LOADING:
The system is initially at rest, but not in equilibrium.

CALCULATION:
The calculation is performed up to 5 ms. This time is sufficient to see propagation of the pressure waves to the top of the box and several reflections.

RESULTS:
Although no comparison with experiments can be done on this problem, the results appear physically correct.

POST-TREATMENT
Several animations of the computed results are presented. Time curves of the fluid pressures and structure displacements are compared.

Numerical Solutions (Finite Elements)

ELFI00

The mesh generation file (K2000) is:

```
opti echo 1;
opti titr 'ELFI00';
opti sauv form 'elfi00.msh';
opti trac psc ftra 'elfi00_mesh.ps';
*
opti dime 2 elem qua4;
*
p1 = 0 0;
p2 = 2 0;
p3 = 2 1;
p4 = 0 1;
p5 = 0.4 0;
p6 = 0.4 0.4;
p7 = 0 0.4;
p8 = 0.4 1;
*
tol = 0.001;
*
c1 = p1 d 4 p5;
c2 = p5 d 4 p6;
c3 = p6 d 4 p7;
c4 = p7 d 4 p1;
expl = dall c1 c2 c3 c4 plan;
*
p9l = 1 0;
p9r = 1 0;
p10 = 1 0.4;
p11 = 2 0.4;
*
c1 = p5 d 6 p9l;
c2 = p9l d 4 p10;
c3 = p10 d 6 p6;
c4 = p6 d 4 p5;
air1a = dall c1 c2 c3 c4 plan;
*
c1 = p9r d 10 p2;
c2 = p2 d 4 p11;
c3 = p11 d 10 p10;
c4 = p10 d 4 p9r;
air1b = dall c1 c2 c3 c4 plan;
*
c1 = p6 d 6 p10 d 10 p11;
c2 = p11 d 6 p3;
c3 = p3 d 16 p8;
c4 = p8 d 6 p6;
air1c = dall c1 c2 c3 c4 plan;
*
elim tol (air1a et air1c);
elim tol (air1b et air1c);
air1 = air1a et air1b et air1c;
*
c1 = p7 d 4 p6;
c2 = p6 d 6 p8;
c3 = p8 d 4 p4;
c4 = p4 d 6 p7;
air2 = dall c1 c2 c3 c4 plan;
elim tol (air1c et air2);
elim tol (expl et air2);
elim tol (expl et air1a);
*
air = air1 et air2;
flui = expl et air;
*
e1 = expl elem cont p1;
e3 = air1 elem cont p3;
*
p1s = p1 plus p1;
p2s = p2 plus p1;
p3s = p3 plus p1;
p4s = p4 plus p1;
p9s = p9l plus p1;
p10s = p10 plus p1;
p12s = 1 1;
c1s = p1s d 10 p9s d 10 p2s;
c2s = p2s d 10 p3s;
c3s = p3s d 10 p12s d 10 p4s;
c4s = p4s d 10 p1s;
c5s = p9s d 4 p10s;
stru = c1s et c2s et c3s et c4s et c5s;
*
nfsa = cont flui;
*
mesh = flui et stru et e1 et e3 et nfsa;
*
sauv form mesh;
trac qual mesh;
*
list (nbel mesh);
list (nbno mesh);
*
fin;
```

The EUROPLEXUS input file reads:

```
ELFI00
ECHO
!conv win
CAST mesh
DPLA ALE
DIME
 PT2L 235 PT3L 64 FL24 200 ED01 64 ZONE 2
 NALE 26 NBLE 167
TERM
GEOM FL24 flui ED01 stru TERM
COMP EPAI 0.01 LECT stru TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
GRIL LAGR LECT stru TERM
     EULE LECT nfsa TERM
     AUTO AUTR
MATE FLUT RO 5.9485 EINT 4.20274E5 GAMM 1.4 PB 0 PREF 1.E5
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT expl TERM
     FLUT RO 1.1897 EINT 2.10137E5 GAMM 1.4 PB 0 PREF 1.E5
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT air TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
LINK COUP FSA LECT nfsa TERM
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
CALC TINI 0.0 PAS1 1.E-5 TFIN 5.E-3
*=====================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=====================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=====================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
```

```
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  3 'p_e1'    ECRO COMP 1 ELEM LECT e1 TERM
COUR  4 'p_e3'    ECRO COMP 1 ELEM LECT e3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
*
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
QUAL ECRO COMP 1 LECT e1 TERM REFE  1.63342E+5 TOLE 5.E-3
     ECRO COMP 1 LECT e3 TERM REFE  2.22104E+5 TOLE 5.E-3
*=================================================================
FIN
```

Numerical Solutions (Node-Centred Finite Volumes)

VFNCA1

The mesh generation file (K2000) is:

```
opti echo 1;
opti titr 'VFNCA1';
opti sauv form 'vfnca1.msh';
opti trac psc ftra 'vfnca1_mesh.ps';
*
opti dime 2 elem qua4;
*
p1 = 0 0;
p2 = 2 0;
p3 = 2 1;
p4 = 0 1;
p5 = 0.4 0;
p6 = 0.4 0.4;
p7 = 0 0.4;
p8 = 0.4 1;
*
tol = 0.001;
*
c1 = p1 d 4 p5;
c2 = p5 d 4 p6;
c3 = p6 d 4 p7;
c4 = p7 d 4 p1;
expl = dall c1 c2 c3 c4 plan;
*
p9l = 1 0;
p9r = 1 0;
p10 = 1 0.4;
p11 = 2 0.4;
*
c1 = p5 d 6 p9l;
c2 = p9l d 4 p10;
c3 = p10 d 6 p6;
c4 = p6 d 4 p5;
air1a = dall c1 c2 c3 c4 plan;
*
c1 = p9r d 10 p2;
c2 = p2 d 4 p11;
c3 = p11 d 10 p10;
c4 = p10 d 4 p9r;
air1b = dall c1 c2 c3 c4 plan;
*
c1 = p6 d 6 p10 d 10 p11;
c2 = p11 d 6 p3;
c3 = p3 d 16 p8;
c4 = p8 d 6 p6;
air1c = dall c1 c2 c3 c4 plan;
*
elim tol (air1a et air1c);
elim tol (air1b et air1c);
air1 = air1a et air1b et air1c;
*
c1 = p7 d 4 p6;
c2 = p6 d 6 p8;
c3 = p8 d 4 p4;
c4 = p4 d 6 p7;
air2 = dall c1 c2 c3 c4 plan;
elim tol (air1c et air2);
elim tol (expl et air2);
elim tol (expl et air1a);
*
air = air1 et air2;
flui = expl et air;
*
e1 = expl elem cont p1;
e3 = air1 elem cont p3;
*
p1s = p1 plus p1;
p2s = p2 plus p1;
p3s = p3 plus p1;
p4s = p4 plus p1;
p9s = p9l plus p1;
p10s = p10 plus p1;
p12s = 1 1;
c1s = p1s d 10 p9s d 10 p2s;
c2s = p2s d 10 p3s;
c3s = p3s d 10 p12s d 10 p4s;
c4s = p4s d 10 p1s;
c5s = p9s d 4 p10s;
stru = c1s et c2s et c3s et c4s et c5s;
*
c1p = p2s d 10 p9s d 10 p1s;
c2p = p3s d 10 p2s;
c3p = p4s d 10 p12s d 10 p3s;
c4p = p1s d 10 p4s;
pext = c4p et c3p et c2p et c1p;
elim tol (stru et pext);
*
nfsa = cont flui;
*
mesh = flui et stru et pext et e1 et e3 et nfsa;
*
sauv form mesh;
trac qual mesh;
*
list (nbel mesh);
list (nbno mesh);
*
fin;
```

The EUROPLEXUS input file reads:

```
VFNCA1
ECHO
!conv win
CAST mesh
DPLA ALE
DIME
 PT2L 235 PT3L 64 MC24 200 ED01 64 CL22 60 ZONE 3
 NALE 26 NBLE 167 NDVC 868
TERM
GEOM MC24 flui ED01 stru CL22 pext TERM
COMP EPAI 0.01 LECT stru TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
          jaun LECT pext TERM
GRIL LAGR LECT stru TERM
     EULE LECT nfsa TERM
     AUTO AUTR
MATE MCGP NCOM 1 R 8.3143E3
          COMP 'Air' PM 29.0 CV1 2.07585E4 CV2 0 CV3 0
          LECT flui TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
     IMPE PIMP RO 1.1897 PRES 1.E5 PREF 0
          LECT pext TERM
INIT MCOM COMP 'Air' MFRA 1.0 LECT flui TERM
          PRES 1.E6 LECT expl TERM
          PRES 1.E5 LECT air  TERM
          TEMP 586.36 LECT expl TERM
          TEMP 293.16 LECT air  TERM
          VEL1 0.0 LECT flui TERM
          VEL2 0.0 LECT flui TERM
          VEL3 0.0 LECT flui TERM
LINK COUP FSA LECT nfsa TERM
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO MCVA TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p4 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
     MC ORDR 2 NUFL ROE
CALC TINI 0.0 PAS1 1.E-5
     TFIN 5.E-3
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  3 'p_e1'    MCPR COMP 1 NOEU LECT p1 TERM
COUR  4 'p_e3'    MCPR COMP 1 NOEU LECT p3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
```

```
COUR 101 'p_p4'    MCPR COMP 1 NOEU LECT p4 TERM
COUR 102 'r_p4'    MCRO COMP 1 NOEU LECT p4 TERM
COUR 103 't_p4'    MCTE COMP 1 NOEU LECT p4 TERM
COUR 104 'yl_p4'   MCMF COMP 1 NOEU LECT p4 TERM
*
RCOU 13 'p_e1' FICH 'vfncan.pun' RENA 'p_e1_an'
RCOU 14 'p_e3' FICH 'vfncan.pun' RENA 'p_e3_an'
RCOU 15 'dx_p10s' FICH 'vfncan.pun' RENA 'dx_p10s_an'
RCOU 16 'dy_p12s' FICH 'vfncan.pun' RENA 'dy_p12s_an'
RCOU 17 'dx_p9s' FICH 'vfncan.pun' RENA 'dx_p9s_an'
RCOU 18 'dy_p9s' FICH 'vfncan.pun' RENA 'dy_p9s_an'
*
TRAC 3 4 13 14 AXES 1.0 'PRESS [PA]'
     COLO noir noir roug roug
TRAC 5 6 15 16 AXES 1.0 'DISPL. [M]'
     COLO noir noir roug roug
TRAC 7 8 17 18 AXES 1.0 'DISPL. [M]'
     COLO noir noir roug roug
TRAC 101 AXES 1.0 'PRESS. [PA]'
TRAC 102 AXES 1.0 'DENS. [KG/M3]'
TRAC 103 AXES 1.0 'TEMP. [K]'
TRAC 104 AXES 1.0 'FRAC. [-]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
QUAL MCPR COMP 1 LECT p1 TERM REFE  1.56019E+5 TOLE 5.E-3
     MCPR COMP 1 LECT p3 TERM REFE  3.16715E+5 TOLE 5.E-3
*===============================================================
FIN
```

Numerical Solutions (Cell-Centred Finite Volumes)

VFCC00

The mesh generation file (K2000) is:

```
opti echo 1;
opti titr 'VFCC00';
opti sauv form 'vfcc00.msh';
opti trac psc ftra 'vfcc00_mesh.ps';
*
opti dime 2 elem qua4;
*
p1 = 0 0;
p2 = 2 0;
p3 = 2 1;
p4 = 0 1;
p5 = 0.4 0;
p6 = 0.4 0.4;
p7 = 0 0.4;
p8 = 0.4 1;
*
tol = 0.001;
*
c1 = p1 d 4 p5;
c2 = p5 d 4 p6;
c3 = p6 d 4 p7;
c4 = p7 d 4 p1;
expl = dall c1 c2 c3 c4 plan;
*
c1 = p5 d 16 p2;
c2 = p2 d 10 p3;
c3 = p3 d 16 p8;
c4 = p8 d 6 p6 d 4 p5;
air1 = dall c1 c2 c3 c4 plan;
*
c1 = p7 d 4 p6;
c2 = p6 d 6 p8;
c3 = p8 d 4 p4;
c4 = p4 d 6 p7;
air2 = dall c1 c2 c3 c4 plan;
*
air = air1 et air2;
flui = expl et air;
elim tol flui;
*
e1 = expl elem cont p1;
e3 = air1 elem cont p3;
*
p1s = p1 plus p1;
p2s = p2 plus p1;
p3s = p3 plus p1;
p4s = p4 plus p1;
p9s = 1 0;
p10s = 1 0.4;
p12s = 1 1;
c1s = p1s d 10 p9s d 10 p2s;
c2s = p2s d 10 p3s;
c3s = p3s d 10 p12s d 10 p4s;
c4s = p4s d 10 p1s;
c5s = p9s d 4 p10s;
stru = c1s et c2s et c3s et c4s et c5s;
*
elim tol (flui et stru);
*
mesh = flui et stru et e1 et e3;
*
sauv form mesh;
trac qual mesh;
*
list (nbel mesh);
list (nbno mesh);
*
fin;
```

The EUROPLEXUS input file reads:

```
VFCC00
ECHO
!conv win
CAST mesh
DPLA ALE
DIME
 PT2L 231 PT3L 64 Q4VF 200 ED01 64 ZONE 2
 NALE 26 NBLE 167
TERM
GEOM Q4VF flui ED01 stru TERM
COMP EPAI 0.01 LECT stru TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
GRIL LAGR LECT stru TERM
     AUTO AUTR
MATE GAZP RO 5.9485 GAMMA 1.4 CV 716.75 PINI 1.E6 PREF 1.E5
          LECT expl TERM
     GAZP RO 1.1897 GAMMA 1.4 CV 716.75 PINI 1.E5 PREF 1.E5
          LECT air TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
     VFCC FCON 1 ! rusanov
CALC TINI 0.0 PAS1 1.E-5 TFIN 5.E-3
*===============================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*===============================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*===============================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*===============================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'vcvi_e1' VCVI NORM ELEM LECT e1 TERM
COUR  2 'vcvi_e3' VCVI NORM ELEM LECT e3 TERM
COUR  3 'p_e1'    ECRO COMP 1 ELEM LECT e1 TERM
COUR  4 'p_e3'    ECRO COMP 1 ELEM LECT e3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
*
TRAC 1 2 AXES 1.0 'VELOC. [M/S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
LIST 1 2 AXES 1.0 'VELOC. [M/S]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
! J'ai l'impression che la qualification de VCVi ne marche pas ...
!QUAL VCVI COMP 1 LECT e1 TERM REFE  0.00000E+0 TOLE 5.E-3
!     VCVI COMP 2 LECT e3 TERM REFE  0.00000E+0 TOLE 5.E-3
QUAL ECRO COMP 1 LECT e1 TERM REFE  1.72471E+5 TOLE 5.E-3
     ECRO COMP 1 LECT e3 TERM REFE  2.18842E+5 TOLE 5.E-3
*===============================================================
FIN
```

Comparison of Numerical Solutions

EFVFA1

The EUROPLEXUS input file is:

```
EFVFA1
ECHO
*
RESU ALIC TEMP 'vfcc00.alt' GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 33 'p_e1_cc'    ECRO COMP 1 ELEM LECT e1 TERM
COUR 34 'p_e3_cc'    ECRO COMP 1 ELEM LECT e3 TERM
COUR 35 'dx_p10s_cc' DEPL COMP 1 POIN LECT p10s TERM
COUR 36 'dy_p12s_cc' DEPL COMP 2 POIN LECT p12s TERM
COUR 37 'dx_p9s_cc'  DEPL COMP 1 POIN LECT p9s TERM
COUR 38 'dy_p9s_cc'  DEPL COMP 2 POIN LECT p9s TERM
*
RCOU 13 'p_e1'    FICH 'elfi00.pun' RENA 'p_e1_ef'
RCOU 14 'p_e3'    FICH 'elfi00.pun' RENA 'p_e3_ef'
RCOU 15 'dx_p10s' FICH 'elfi00.pun' RENA 'dx_p10s_ef'
RCOU 16 'dy_p12s' FICH 'elfi00.pun' RENA 'dy_p12s_ef'
RCOU 17 'dx_p9s'  FICH 'elfi00.pun' RENA 'dx_p9s_ef'
RCOU 18 'dy_p9s'  FICH 'elfi00.pun' RENA 'dy_p9s_ef'
*
RCOU 23 'p_e1'    FICH 'vfnca1.pun' RENA 'p_e1_nc'
RCOU 24 'p_e3'    FICH 'vfnca1.pun' RENA 'p_e3_nc'
RCOU 25 'dx_p10s' FICH 'vfnca1.pun' RENA 'dx_p10s_nc'
RCOU 26 'dy_p12s' FICH 'vfnca1.pun' RENA 'dy_p12s_nc'
RCOU 27 'dx_p9s'  FICH 'vfnca1.pun' RENA 'dx_p9s_nc'
RCOU 28 'dy_p9s'  FICH 'vfnca1.pun' RENA 'dy_p9s_nc'
*
TRAC 13 14 23 24 33 34 AXES 1.0 'PRESS [PA]'
     COLO noir noir roug roug vert vert
TRAC 15 16 25 26 35 36 AXES 1.0 'DISPL. [M]'
     COLO noir noir roug roug vert vert
TRAC 17 18 27 28 37 38 AXES 1.0 'DISPL. [M]'
     COLO noir noir roug roug vert vert
*=================================================================
```

The initial conditions of the gases in the Finite Element model (`FLUT` material) are:

	$\gamma = c_P / c_V$	ρ	i	p
Low-pressure	1.4	1.1897 Kg/m^3	2.10137E5 J/Kg	1.0E5 Pa
High-pressure	1.4	5.9485 Kg/m^3	4.20274E5 J/Kg	1.0E6 Pa

The FE model is built, as usual, by keeping the fluid and structural nodes distinct (although superposed). All fluid nodes along the F-S interface are subjected to the `LINK FSA` condition.

The Node-Centered Finite Volume input mesh is basically the same as for the FE model, since the N-C volumes are built up automatically by the code. The only notable difference is the presence of an additional layer of CL22 boundary condition elements placed along the external envelope of the structure (merged nodes with the structure). These elements are used to simulate the presence of the external atmosphere to the structure, by means of a constant imposed pressure of 1.0E5 Pa (assigned via the `IMPE PIMP` material model). In the FE (and in the C-C FV) model this is not necessary because the fluid material (`FLUT` or `GAZP`, respectively) admits a PREF parameter (reference pressure) which can be set to 1.0E5 Pa. However, unfortunately this does not seem to be possible with the `MCGP` material used by N-C Finite Volumes.

The initial conditions of the gases in the Node-Centered Finite Volume model are:

w	R	c_V
29 Kg/Kmol	8314.3 J/Kmol·K	20785.75 J/ Kmol·K

and:

	T	p
Low-pressure	293.16 K	1.0E5 Pa
High-pressure	586.36 K	1.0E6 Pa

As concerns fluid-structure interaction, the same `LINK FSA` condition as used in the FE model is repeated here.

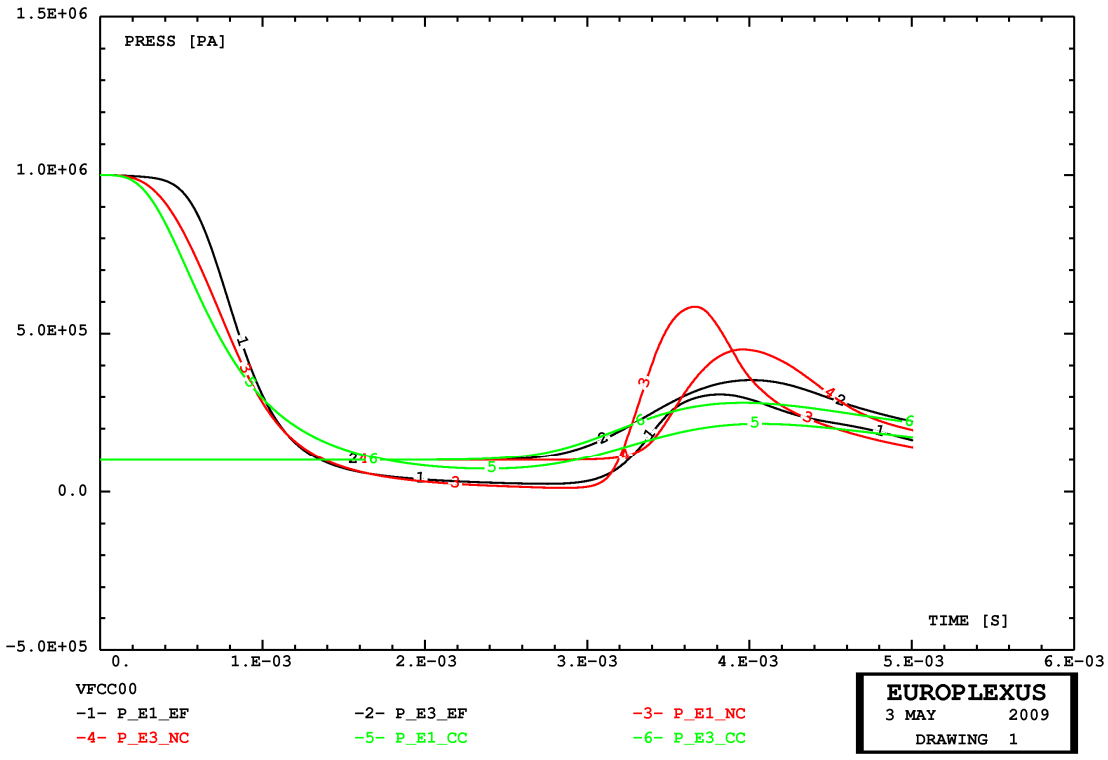
The Cell-Centered Finite Volume input mesh is similar to the FE model, but the structure and fluid nodes are merged together (`ELIM` command in Cast3m). No FSA condition is needed in this case.

The initial conditions of the gases in the Cell-Centered Finite Volume model (`GAZP` material) are similar to those for FE (`FLUT` material):

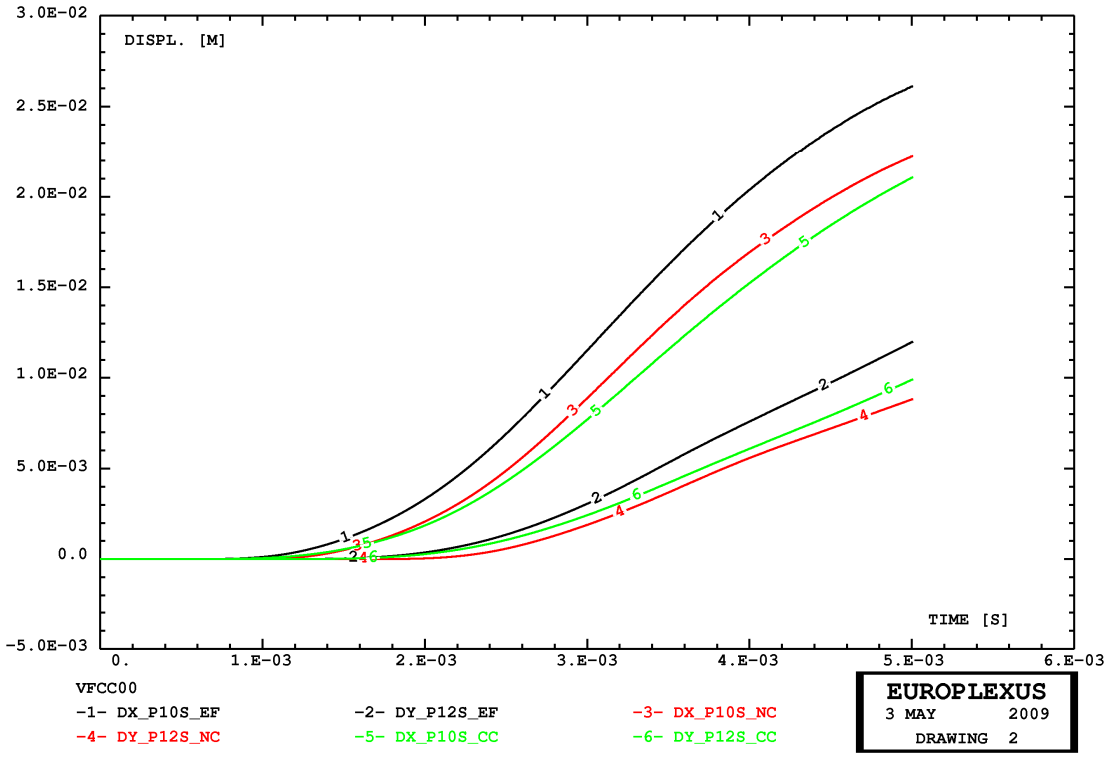
	$\gamma = c_P / c_V$	ρ	c_V	p
Low-pressure	1.4	1.1897 Kg/m^3	716.75 J/ Kg·K	1.0E5 Pa
High-pressure	1.4	5.9485 Kg/m^3	716.75 J/ Kg·K	1.0E6 Pa

Note that the initial pressure is given directly rather than specifying the specific internal energy. Furthermore, the (optional) specific heat at constant volume c_V is specified. This has no effect on the solution, but is used to compute and print the temperatures.

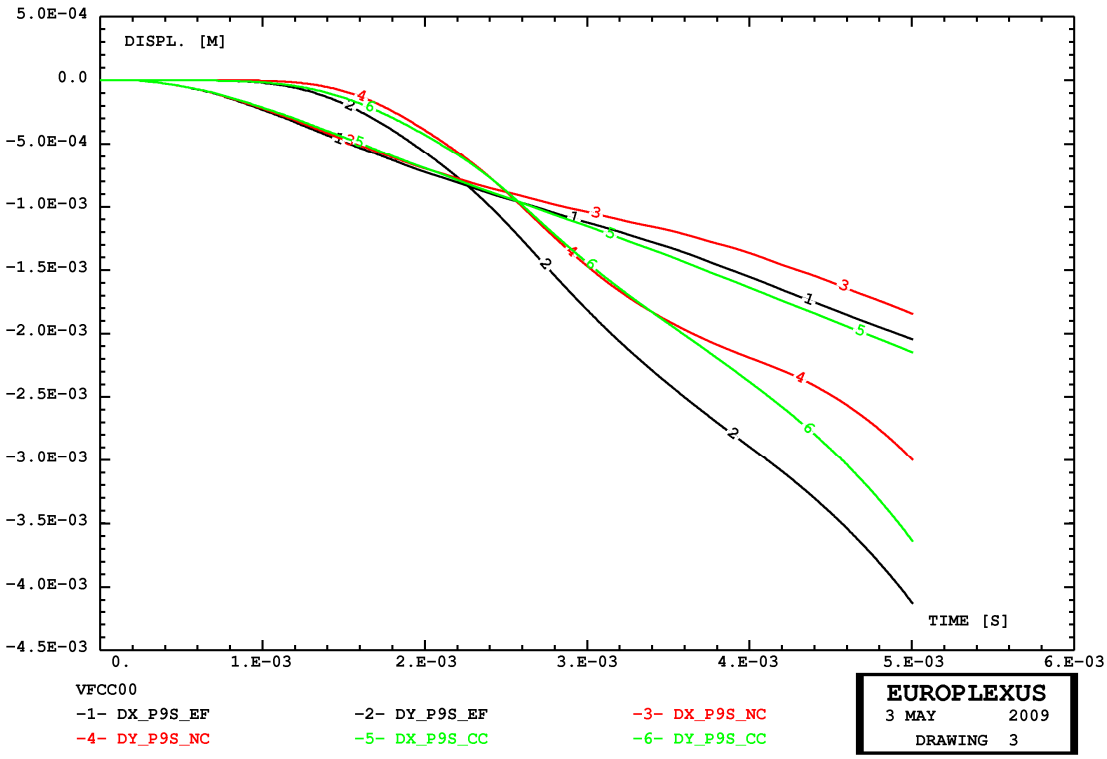
As already mentioned, both in the FE and in the C-C FV models a reference pressure value of `PREF 1.E5` is specified for both gases.
Some results: fluid pressures:



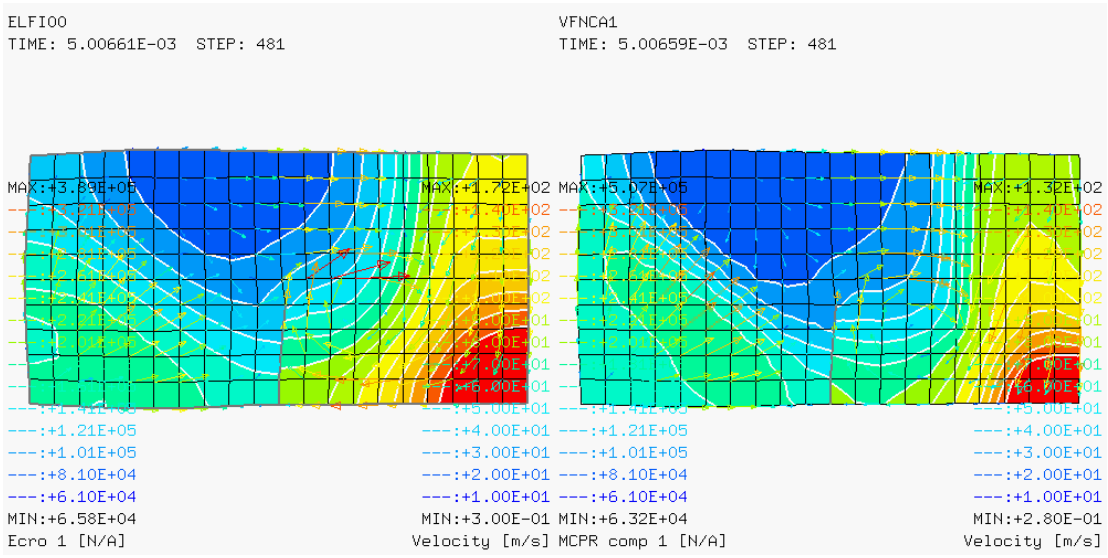
Structural displacements:



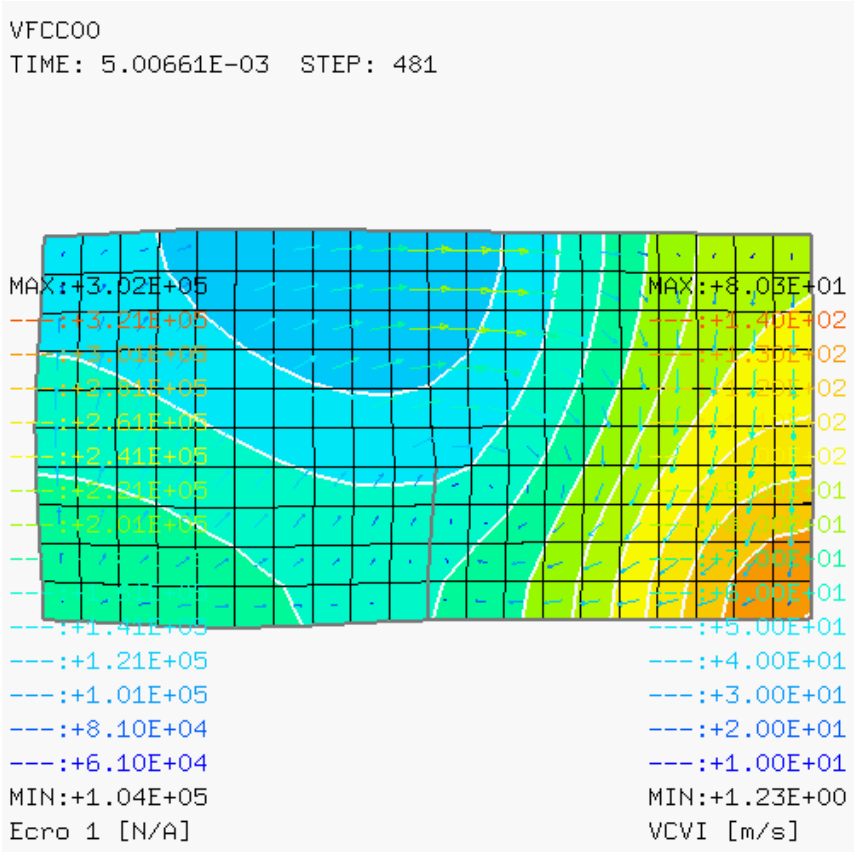
Structural displacements in another point:



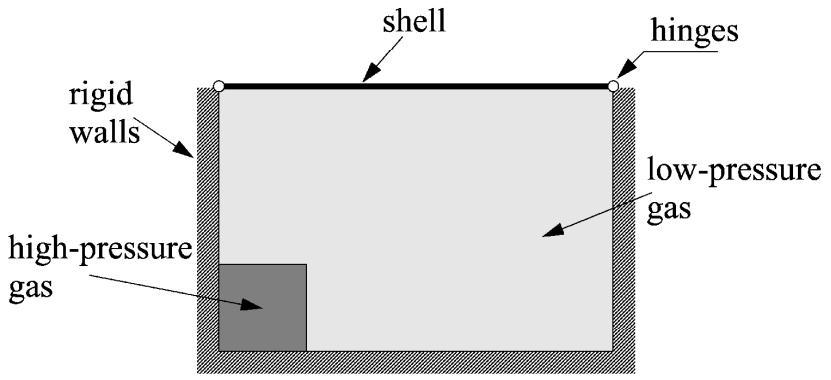
Final solution with Finite Elements and with Node-Centred Finite Volumes:



Final solution with Cell-Centred Finite Volumes:



Example 4 – Explosion in a 2D box



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Geometric data and materials:

The box is 4 units wide and 3 units high. The bubble is square in shape and has unit sides. The walls are rigid except the top, which is sealed by a metallic lamina.

The fluids are perfect gases. The structure is steel with an elasto-plastic law.

Numerical Solutions

INFS01

This model uses conforming FSI. The fluid mesh uses 4 by 3 elements only and the structure is discretized by 4 elements of the ED01 type.

The mesh generation file is:

```
*%siz 50
*
opti titr 'INFS - 01';
opti echo 1;
*
opti dime 2 elem qua4;
*
p1=0 0;
p2=4 0;
p3=0 3;
p4=4 3;
p5=1 0;
p6=0 1;
p7=1 1;
p8=4 1;
p3s=p3 plus (0 0);
p4s=p4 plus (0 0);
tol=0.001;

c1=p1 d 1 p5;
c2=p5 d 1 p7;
c3=p7 d 1 p6;
c4=p6 d 1 p1;
bull=daller c1 c2 c3 c4 plan;

c1=p5 d 3 p2;
c2=p2 d 1 p8;
c3=p8 d 3 p7;
c4=p7 d 1 p5;
gas1=daller c1 c2 c3 c4 plan;

c1=p6 d 1 p7 d 3 p8;
c2=p8 d 2 p4;
c3=p4 d 4 p3;
c4=p3 d 2 p6;
gas2=daller c1 c2 c3 c4 plan;

gas = gas1 et gas2;

stru=p3s d 4 p4s;

flui=bull et gas;
elim tol flui;

mesh = flui et stru;

bloqx=mesh poin droi p1 p3 tol;
bloqx=bloqx et (mesh poin droi p2 p4 tol);
bloqy=mesh poin droi p1 p2 tol;
bloqy=bloqy et p3 et p4  et p3s et p4s;

fsan=flui poin droi p3 p4 tol;

mesh=mesh et bloqx et bloqy et fsan;
tass mesh;

opti sauv form 'infs01.msh';
sauv form mesh;

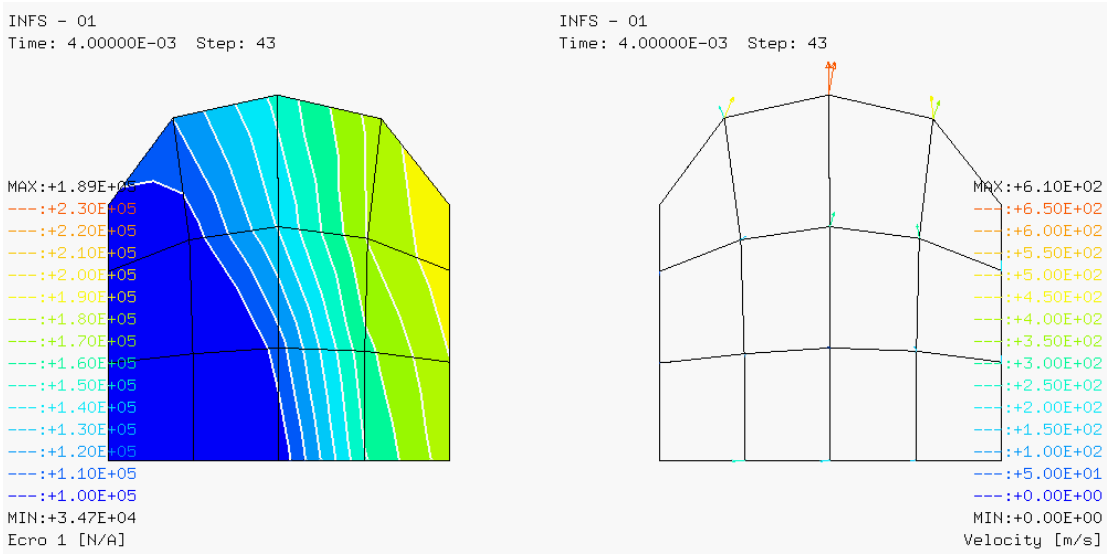
opti trac psc ftra 'infs01_mesh.ps';
trac mesh;
```

The input file is:

```
INFS - 01
*-----------------------------------------------------------------------
 ECHO
 CONV win
CAST MESH
*-----------------------------------------------------------Problem type
DPLA NONL ALE
*-----------------------------------------------------------Dimensioning
DIME
 PT3L 5 PT2L 20 FL24 12 ED01 4 ZONE 2
 NALE 5 NBLE 20
 MTPO 6 MTEL 1
TERM
*-------------------------------------------------------------Geometry
GEOM FL24 FLUI ED01 STRU TERM
*-----------------------------------------------Geometric Complements
COMP EPAI 0.0001 LECT STRU TERM
     coul blan lect flui term
*---------------------------------------------------------Grid motion
GRIL LAGR LECT stru TERM
     EULE LECT fsan TERM
     ALE  LECT FLUI TERM
     AUTO AUTR
*-------------------------------------------------------Material data
MATE VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT STRU TERM
     FLUT RO 1.22 EINT 3.046E6 GAMM 1.269 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 0 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          LECT BULL TERM
     FLUT RO 0.1237 EINT 3.046E6 GAMM 1.269 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 0 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          LECT GAS TERM
*-----------------------------------------------Boundary conditions
LINK COUP
     BLOQ 1 LECT BLOQX TERM
          2 LECT BLOQY TERM
     FSA  LECT fsan TERM
*-----------------------------------------------------------------Outputs
ECRI COOR DEPL VITE CONT ECRO FINT FEXT TFRE 1.0E-3
     FICH K200 TFRE 1.E-3
               POIN TOUS
               VARI DEPL VITE FEXT ECRO ECRC LECT 1 TERM
     FICH TPLO FREQ 1 DESC 'INFS01'
               POIN LECT 16 18 19 22 23 24 TERM
               ELEM LECT 1 TERM
     FICH ALIC TEMP FREQ 1
               POIN LECT 16 18 19 22 23 24 TERM
               ELEM LECT 1 TERM
*-------------------------------------------------------------Options
OPTI NOTE
 csta 0.5
 liaj
```

```
 log 1
 REZO GAM0 0.5
*-----------------------------------------------------Transient calculation
CALC TINI 0 TEND 4.E-3
*=================================================================ANIMATION
PLAY
CAME   1 EYE   2.00000E+00  2.14602E+00  1.46675E+01
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
SCEN GEOM NAVI FREE
     !ISO  FILI FIEL ECRO 1 SCAL USER PROG 1.0D5 PAS 1.0D4 2.3D5 TERM
     !TEXT ISCA
      VECT SCCO SCAL USER PROG 0 PAS 50 650 TERM
      TEXT VSCA
      colo pape
sler cam1 1       nfra 1
trac offs fich avi                nocl nfto 44  fps 5 kfre 10 comp -1
                                                !obje lect flui term
                                                                REND
FREQ 1
GOTR LOOP 42  OFFS FICH AVI CONT NOCL
                                                !obje lect flui term
                                                                REND
GOTR          OFFS FICH AVI CONT
                                                !obje lect flui term
                                                                REND
ENDPLAY
*=========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------Curve definitions
COUR 1 'dy_16'  DEPL COMP 2 NOEU LECT 16  TERM
COUR 2 'dy_18'  DEPL COMP 2 NOEU LECT 18  TERM
COUR 3 'dy_19'  DEPL COMP 2 NOEU LECT 19  TERM
COUR 4 'vx_18'  VITE COMP 1 NOEU LECT 18  TERM
COUR 5 'vy_18'  VITE COMP 2 NOEU LECT 18  TERM
*-------------------------------------------------------------------Plots
trac 1 2 3   axes 1.0 'DISPL. [M]'
trac 4 5     axes 1.0 'V [M/S]'
*-----------------------------------------------Results qualification
QUAL DEPL COMP 2 LECT  16 TERM REFE  1.02416E+0 TOLE 5.E-3
     DEPL COMP 2 LECT  18 TERM REFE  1.29205E+0 TOLE 5.E-3
     DEPL COMP 2 LECT  19 TERM REFE  1.01223E+0 TOLE 5.E-3
*=================================================================
FIN
```

The deformed final mesh at 4 ms with superposed fluid pressures and the velocities are:



INFS02

We use a twice finer fluid mesh but the same structural mesh. Therefore, the F-S interface is non-conforming.

The mesh generation file is:

```
*%siz 50
*
opti titr 'INFS - 02';
opti echo 1;
*
opti dime 2 elem qua4;
*
p1=0 0;
p2=4 0;
p3=0 3;
p4=4 3;
p5=1 0;
```

```
p6=0 1;
p7=1 1;
p8=4 1;
p3s=p3 plus (0 0);
p4s=p4 plus (0 0);
tol=0.001;

c1=p1 d 2 p5;
c2=p5 d 2 p7;
c3=p7 d 2 p6;
c4=p6 d 2 p1;
bull=daller c1 c2 c3 c4 plan;
```

```
c1=p5 d 6 p2;
c2=p2 d 2 p8;
c3=p8 d 6 p7;
c4=p7 d 2 p5;
gas1=daller c1 c2 c3 c4 plan;

c1=p6 d 2 p7 d 6 p8;
c2=p8 d 4 p4;
c3=p4 d 8 p3;
c4=p3 d 4 p6;
gas2=daller c1 c2 c3 c4 plan;

gas = gas1 et gas2;

stru=p3s d 4 p4s;

flui=bull et gas;
elim tol flui;
```

```
mesh = flui et stru;

bloqx=mesh poin droi p1 p3 tol;
bloqx=bloqx et (mesh poin droi p2 p4 tol);
bloqy=mesh poin droi p1 p2 tol;
bloqy=bloqy et p3 et p4  et p3s et p4s;

fsan=flui poin droi p3 p4 tol;

mesh=mesh et bloqx et bloqy et fsan;
tass mesh;

opti sauv form 'infs02.msh';
sauv form mesh;

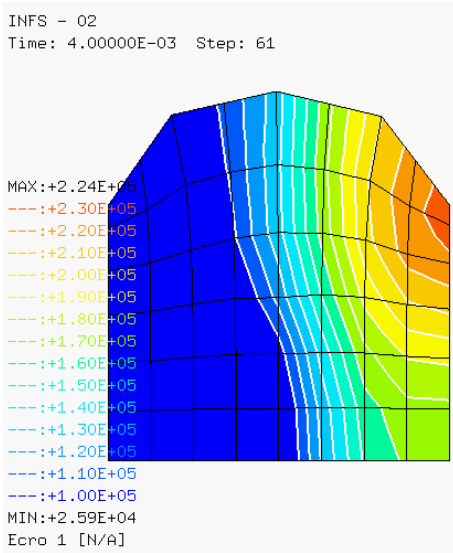
opti trac psc ftra 'infs02_mesh.ps';
trac mesh;
```

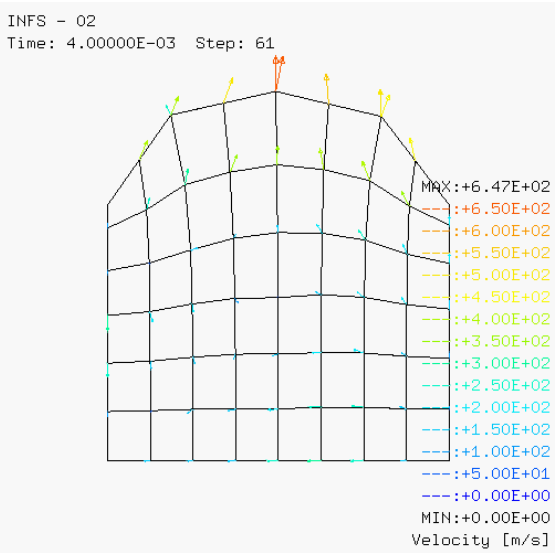
The input file:

```
INFS - 02
*------------------------------------------------------------------------
 ECHO
 CONV win
 CAST MESH
*-------------------------------------------------------------Problem type
DPLA NONL ALE
*---------------------------------------------------------Dimensioning
DIME
 PT3L 5 PT2L 63 FL24 48 ED01 4 ZONE 2
 NALE 9 NBLE 63
 MTPO 6 MTEL 1
TERM
*-----------------------------------------------------------Geometry
GEOM FL24 FLUI ED01 STRU TERM
*-----------------------------------------------Geometric Complements
EPAI 0.0001 LECT STRU TERM
     coul blan lect flui term
*-------------------------------------------------------Grid motion
GRIL LAGR LECT stru TERM
     EULE LECT fsan TERM
     ALE  LECT FLUI TERM
     AUTO AUTR
*-------------------------------------------------------Material data
MATE VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT STRU TERM
     FLUT RO 1.22 EINT 3.046E6 GAMM 1.269 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 0 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          LECT BULL TERM
     FLUT RO 0.1237 EINT 3.046E6 GAMM 1.269 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 0 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          LECT GAS TERM
*-----------------------------------------------------Boundary conditions
LINK COUP
     BLOQ 1 LECT BLOQX TERM
          2 LECT BLOQY TERM
     FSA  NCFS LECT fsan TERM
*------------------------------------------------------------------Outputs
ECRI COOR DEPL VITE CONT ECRO FINT FEXT TFRE 1.0E-3
     FICH K200 TFRE 1.E-3
               POIN TOUS
               VARI DEPL VITE FEXT ECRO ECRC LECT 1 TERM
     FICH TPLO FREQ 1 DESC 'INFS02'
               POIN LECT 57 59 61 65 66 67 TERM
               ELEM LECT 1 TERM
     FICH ALIC TEMP FREQ 1
               POIN LECT 57 59 61 65 66 67 TERM
               ELEM LECT 1 TERM
*-------------------------------------------------------------------Options
OPTI NOTE
 csta 0.5
 liaj
 log 1
```

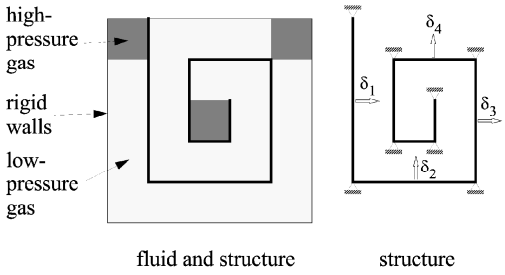
```
 REZO GAM0 0.5
*-----------------------------------------------------Transient calculation
CALCUL TINI 0 TEND 4.E-3
*=================================================================ANIMATION
PLAY
CAME   1 EYE   2.00000E+00  2.14602E+00  1.46675E+01
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
SCEN GEOM NAVI FREE
     !ISO  FILI FIEL ECRO 1 SCAL USER PROG 1.0D5 PAS 1.0D4 2.3D5 TERM
     !TEXT ISCA
     VECT SCCO SCAL USER PROG 0 PAS 50 650 TERM
     TEXT VSCA
     colo pape
sler cam1 1        nfra 1
trac offs fich avi               nocl nfto 62  fps 5 kfre 10 comp -1
                                               !obje lect flui term
                                                REND
FREQ 1
GOTR LOOP 60  OFFS FICH AVI CONT NOCL
                                               !obje lect flui term
                                                REND
GOTR          OFFS FICH AVI CONT
                                               !obje lect flui term
                                                REND
ENDPLAY
*=============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------Curve definitions
COUR 1 'dy_65'  DEPL COMP 2 NOEU LECT 65  TERM
COUR 2 'dy_66'  DEPL COMP 2 NOEU LECT 66  TERM
COUR 3 'dy_67'  DEPL COMP 2 NOEU LECT 67  TERM
COUR 4 'vx_59'  VITE COMP 1 NOEU LECT 59  TERM
COUR 5 'vy_59'  VITE COMP 2 NOEU LECT 59  TERM
*------------------------------------------------------------------Plots
trac 1 2 3   axes 1.0 'DISPL. [M]'
trac 4 5     axes 1.0 'V [M/S]'
*-----------------------------------------------Results qualification
QUAL DEPL COMP 2 LECT  65 TERM REFE  1.05700E+0 TOLE 5.E-3
     DEPL COMP 2 LECT  66 TERM REFE  1.33322E+0 TOLE 5.E-3
     DEPL COMP 2 LECT  67 TERM REFE  1.03977E+0 TOLE 5.E-3
*=================================================================
FIN
```

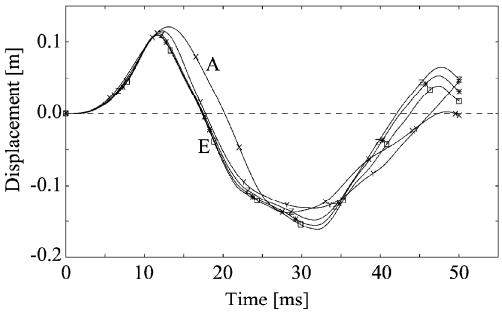
The final mesh and pressures and velocities are:





Example 4b – Explosions in a labyrinth





Labyrinth: displacement δ_i in cases A to E (progressive mesh refinement)

Case	Mesh refinement Φ (F/S)	Number of elements (F/S)	Time steps	CPU time [s]	CPU time ratio	Speed-up factor
A	1x/1x	100/32	1050	2.6	1.0	-
B	2x/2x	400/64	2100	11.7	4.5	-
C	4x/4x	1600/128	4200	77.5	29.8	-
D	8x/8x	6400/256	8400	587.3	225.9	-
E	16x/16x	25600/512	16789	4747.7	1826.0	-
F	8x/1x	6400/32	1416	110.1	42.3	5.3
G	16x/2x	25600/64	3063	933.7	359.1	5.1
H	16x/1x	25600/32	3087	960.2	369.3	4.9

23

Geometric data and materials:

The box is 5 units wide and 5 units high. The bubbles are square in shape and have unit sides. The external walls are rigid and the internal structure is deformable.

The fluids are perfect gases. The structure is steel with an elasto-plastic law.

Numerical Solutions

LABI01 (A)

This model uses conforming FSI. The fluid mesh 100 elements only and the structure is discretized by 32 elements of the ED01 type.

The mesh generation file is:

```
*%siz 4000
opti echo 1;
opti titr 'LABI - 01';
opti sauv form 'labi01.msh';
opti trac psc ftra 'labi01_mesh.ps';
opti dime 2 elem qua4;

tol = 0.01;
ns = 2;
nf = 2;

up    =  0  1;
down  =  0 -1;
right =  1  0;
left  = -1  0;

ps1 = 1 5;
ps2 = 1 1;
ps3 = 4 1;
ps4 = 4 4;
ps5 = 2 4;
ps6 = 2 2 ;
ps7 = 3 2;
ps8 = 3 3;
stru1 = ps1 d (ns * 4) ps2;
stru2 = ps2 d (ns * 3) ps3;
stru3 = ps3 d (ns * 3) ps4;
stru4 = ps4 d (ns * 2) ps5;
stru5 = ps5 d (ns * 2) ps6;
stru6 = ps6 d (ns * 1) ps7;
stru7 = ps7 d (ns * 1) ps8;
stru = stru1 et stru2 et stru3 et stru4 et stru5 et stru6 et stru7;
trac qual stru;

pf1 = 1 5;
pf2 = 0 5;
c1 = pf1 d nf pf2;
flu1 = c1 tran nf down;
flu2 = flu1 plus down;
elim tol (flu1 et flu2);
flu3 = flu2 plus down;
elim tol (flu2 et flu3);
flu4 = flu3 plus down;
elim tol (flu3 et flu4);
flu5 = flu4 plus down;
elim tol (flu4 et flu5);
flu6 = flu5 plus right;
elim tol (flu5 et flu6);
flu7 = flu6 plus right;
elim tol (flu6 et flu7);
flu8 = flu7 plus right;
elim tol (flu7 et flu8);
flu9 = flu8 plus right;
elim tol (flu8 et flu9);
flu10 = flu9 plus up;
elim tol (flu9 et flu10);
flu11 = flu10 plus up;
elim tol (flu10 et flu11);
flu12 = flu11 plus up;
elim tol (flu11 et flu12);
flu13 = flu12 plus up;
elim tol (flu12 et flu13);
flu14 = flu13 plus left;
elim tol (flu13 et flu14);
flu15 = flu14 plus left;
elim tol (flu14 et flu15);
```

```
flu16 = flu15 plus left;
elim tol (flu15 et flu16);
flu17 = flu16 plus down;
elim tol (flu16 et flu17);
flu18 = flu17 plus down;
elim tol (flu17 et flu18);
flu19 = flu18 plus down;
elim tol (flu18 et flu19);
flu20 = flu19 plus right;
elim tol (flu19 et flu20);
flu21 = flu20 plus right;
elim tol (flu20 et flu21);
flu22 = flu21 plus up;
elim tol (flu21 et flu22);
flu23 = flu22 plus up;
elim tol (flu22 et flu23);
flu24 = flu23 plus left;
elim tol (flu23 et flu24);
flu25 = flu24 plus down;
elim tol (flu24 et flu25);

expl = flu1 et flu13 et flu25;
gas = flu2 et flu3 et flu4 et flu5 et
      flu6 et flu7 et flu8 et flu9 et flu10 et
      flu11 et flu12 et flu14 et flu15 et
      flu16 et flu17 et flu18 et flu19 et flu20 et
      flu21 et flu22 et flu23 et flu24;
flui = expl et gas;
trac qual flui;

coco = cont flui;

d1 = stru poin proc (1 3);
d2 = stru poin proc (2.5 1);
d3 = stru poin proc (4 2.5);
d4 = stru poin proc (3 4);
tpln = d1 et d2 et d3 et d4;
pe1 = 0 5;
pe2 = 0 0;
pe3 = 5 0;
pe4 = 5 5;
pe5 = 1 5;
pe6 = 1 1;
pe7 = 2 2;
```

```
e1 = flu1 elem cont (flu1 poin proc pe1);
e2 = flu5 elem cont (flu5 poin proc pe2);
e3 = flu9 elem cont (flu9 poin proc pe3);
e4 = flu13 elem cont (flu13 poin proc pe4);
e5 = flu16 elem cont (flu16 poin proc pe5);
e6 = flu19 elem cont (flu19 poin proc pe6);
e7 = flu25 elem cont (flu25 poin proc pe7);
tple = e1 et e2 et e3 et e4 et e5 et e6 et e7;
trac qual (coco et tple et tpln);
*opti trac mif;
*trac qual (coco et tple et tpln);

*fsan = (flu1 et flu2 et flu3 et flu4) poin droi p1s p2s tol;
*fsan = fsan et
*       ((flu16 et flu17 et flu18 et flu19) poin droi p1s p2s tol);
*fsan = fsan et ((flu6 et flu7 et flu8) poin droi p2s p3s tol);
*fsan = fsan et ((flu19 et flu20 et flu21) poin droi p2s p3s tol);
*fsan = fsan et ((flu10 et flu11 et flu12) poin droi p3s p4s tol);
*fsan = fsan et ((flu21 et flu22 et flu23) poin droi p3s p4s tol);
fsan = cont flui;
fsan = chan poi1 fsan;
fsrn = flui poin droi pe1 pe2 tol;
fsrn = fsrn et (flui poin droi pe2 pe3 tol);
fsrn = fsrn et (flui poin droi pe3 pe4 tol);
fsrn = fsrn et (flui poin droi pe4 pe1 tol);
fsrn = chan poi1 fsrn;
fsan = fsan diff (fsan inte fsrn);
trac fsan;
trac fsrn;
bloc = ps1 et ps2 et ps3 et ps4 et ps5 et ps6 et ps7 et ps8;

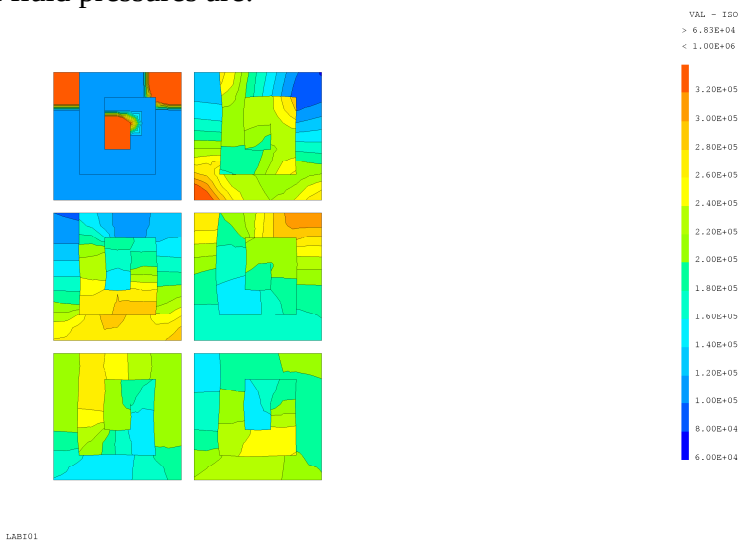
mesh = flui et stru et fsan et fsrn et tple et tpln et bloc;
tass mesh;
sauv form mesh;
list (nbno flui);
list (nbno stru);
list (nbno fsan);
list (nbno fsrn);
list (nbel flui);
list (nbel stru);
opti trac mif;
trac stru;
trac (cont flui);
fin;
```

The input file is:

```
LABI01
ECHO
*CONV win
CAST mesh
DPLA ALE
DIME
  NALE 21 NBLE 1
  BLOQ 1200
  FSA 75 IFSA 202
  LIAI 358
  ndvc 196
TERM
GEOM FL24 flui ED01 stru TERM
COMP EPAI 0.01 LECT stru TERM
GRIL LAGR LECT stru TERM
     EULE LECT fsrn fsan TERM
     MEAN AUTR
OPTI REZO MVRE MODU LIAI
MATE VM23 RO 8000 YOUNG 2.E11 NU 0.3 ELAS 4.E8
          TRAC 3 4.E8 2.E-3 2.4E9 1.002E0 2.4E9 10.
          LECT stru TERM
     FLUT RO 10. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT expl TERM
     FLUT RO  1. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT gas TERM
LIAI freq 1
     BLOQ 123 LECT bloc TERM
     FSR LECT fsrn TERM
     FSA LECT fsan TERM
ECRI DEPL VITE ECRO TFRE 10.E-3
     POIN LECT tpln TERM
     ELEM LECT tple TERM
     TRAC TPLO DESC 'LABI01' TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
     fich alic temp TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
```

```
     FICH FORM K200 TFRE 2.E-3
          POIN TOUS
          VARI DEPL VITE ECRO ECRC LECT 1 3 TERM
OPTI NOTE
  CSTA 0.5D0
* MOMT 2
  FSCR
  LOG 1
CALCUL TINI 0. TEND 50.E-3
*
SUIT
Post-treatment
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dx_1'  DEPL COMP 1 POIN LECT d1 TERM
COUR  2 'dy_2'  DEPL COMP 2 POIN LECT d2 TERM
COUR  3 'dx_3'  DEPL COMP 1 POIN LECT d3 TERM
COUR  4 'dy_4'  DEPL COMP 2 POIN LECT d4 TERM
COUR  5 'p_e1'  ECRO COMP 1 ELEM LECT e1 TERM
COUR  6 'p_e2'  ECRO COMP 1 ELEM LECT e2 TERM
COUR  7 'p_e3'  ECRO COMP 1 ELEM LECT e3 TERM
COUR  8 'p_e4'  ECRO COMP 1 ELEM LECT e4 TERM
COUR  9 'p_e5'  ECRO COMP 1 ELEM LECT e5 TERM
COUR 10 'p_e6'  ECRO COMP 1 ELEM LECT e6 TERM
COUR 11 'p_e7'  ECRO COMP 1 ELEM LECT e7 TERM
*
trac 1 2 3 4 axes 1.0 'D [M]'
trac 5 6 7 8 axes 1.0 'P [PA]'
trac 9 10 11 axes 1.0 'P [PA]'
LIST 1 2 3 4 axes 1.0 'D [M]'
LIST 5 6 7 8 axes 1.0 'P [PA]'
LIST 9 10 11 axes 1.0 'P [PA]'
*
*QUAL VITE comp 1 lect 51 term REFE 8.25539E+2 TOLE 5.E-3
*     ECRO comp 1 lect 50 term REFE 3.41392E+5 TOLE 5.E-3
FIN
```

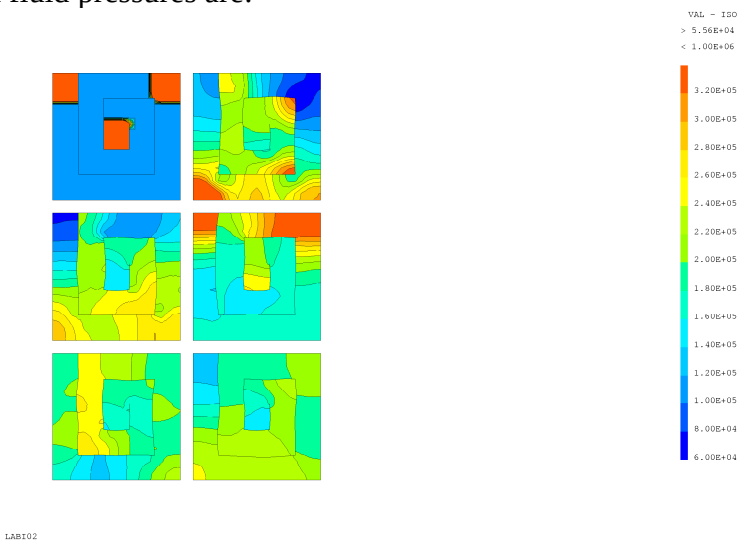
The computed fluid pressures are:



LABI02 (B)

Twice finer conforming FSI solution. The fluid mesh uses 400 elements and the structure is discretized by 64 elements of the ED01 type.

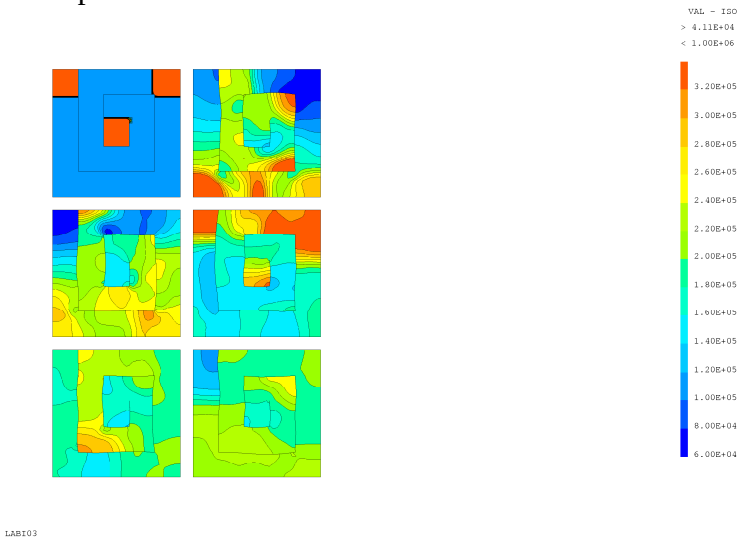
The computed fluid pressures are:



LABI03 (C)

Four-times finer conforming FSI solution. The fluid mesh uses 1600 elements and the structure is discretized by 128 elements of the ED01 type.

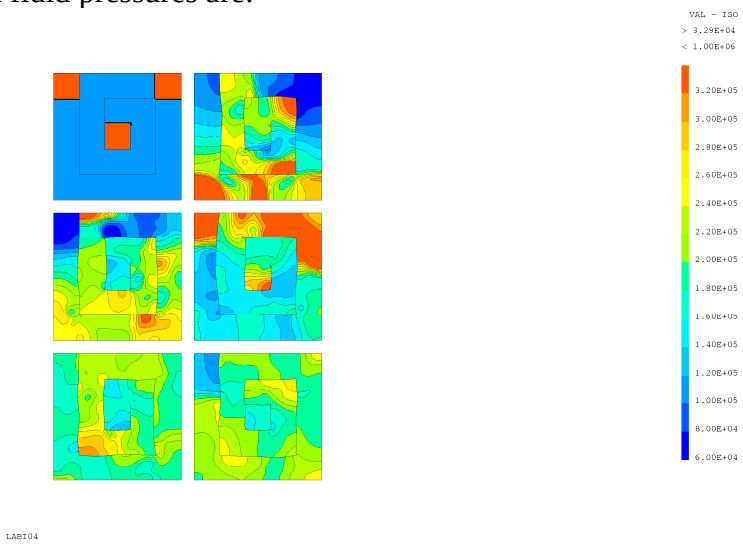
The computed fluid pressures are:



LABI04 (D)

Eight-times finer conforming FSI solution. The fluid mesh uses 6400 elements and the structure is discretized by 256 elements of the ED01 type.

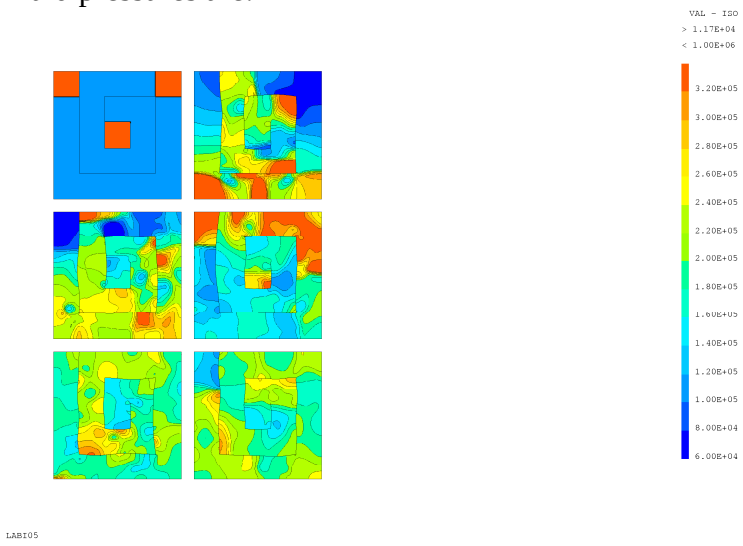
The computed fluid pressures are:



LABI05 (E)

Sixteen-times finer conforming FSI solution. The fluid mesh uses 25600 elements and the structure is discretized by 512 elements of the ED01 type.

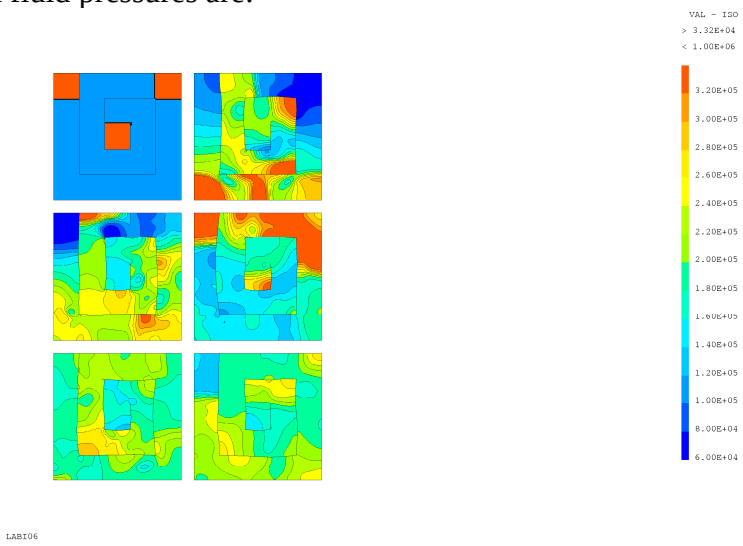
The computed fluid pressures are:



LABI06 (F)

Eight-times finer non-conforming FSI solution. The fluid mesh uses 6400 elements and the structure is discretized by 32 elements of the ED01 type.

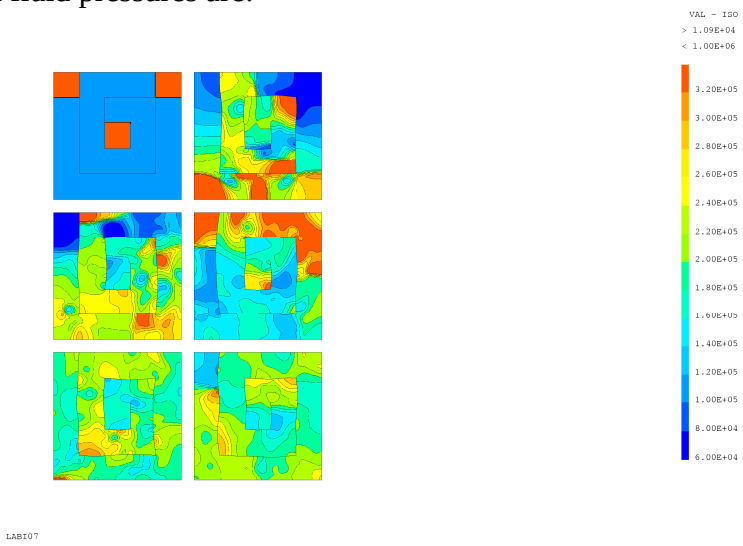
The computed fluid pressures are:



LABI07 (G)

Sixteen-times (two time in the structure) finer non-conforming FSI solution. The fluid mesh uses 25600 elements and the structure is discretized by 64 elements of the ED01 type.

The computed fluid pressures are:



LABI08 (H)

Sixteen-times finer non-conforming FSI solution. The fluid mesh uses 25600 elements and the structure is discretized by 32 elements of the ED01 type.

The mesh generation file is:

```
*%siz 4000
opti echo 1;
opti titr 'LABI - 08';
opti sauv form 'labi08.msh';
opti trac psc ftra 'labi08_mesh.ps';
opti dime 2 elem qua4;

tol = 0.01;
ns = 2;
nf = 32;

up    =  0  1;
down  =  0 -1;
right =  1  0;
left  = -1  0;

ps1 = 1 5;
ps2 = 1 1;
ps3 = 4 1;
ps4 = 4 4;
ps5 = 2 4;
ps6 = 2 2 ;
ps7 = 3 2;
ps8 = 3 3;
stru1 = ps1 d (ns * 4) ps2;
stru2 = ps2 d (ns * 3) ps3;
stru3 = ps3 d (ns * 3) ps4;
stru4 = ps4 d (ns * 2) ps5;
stru5 = ps5 d (ns * 2) ps6;
stru6 = ps6 d (ns * 1) ps7;
stru7 = ps7 d (ns * 1) ps8;
stru = stru1 et stru2 et stru3 et stru4 et stru5 et stru6 et stru7;
trac qual stru;

pf1 = 1 5;
pf2 = 0 5;
c1 = pf1 d nf pf2;
flu1 = c1 tran nf down;
flu2 = flu1 plus down;
elim tol (flu1 et flu2);
flu3 = flu2 plus down;
elim tol (flu2 et flu3);
flu4 = flu3 plus down;
elim tol (flu3 et flu4);
flu5 = flu4 plus down;
elim tol (flu4 et flu5);
flu6 = flu5 plus right;
elim tol (flu5 et flu6);
flu7 = flu6 plus right;
elim tol (flu6 et flu7);
flu8 = flu7 plus right;
elim tol (flu7 et flu8);
flu9 = flu8 plus right;
elim tol (flu8 et flu9);
flu10 = flu9 plus up;
elim tol (flu9 et flu10);
flu11 = flu10 plus up;
elim tol (flu10 et flu11);
flu12 = flu11 plus up;
elim tol (flu11 et flu12);
flu13 = flu12 plus up;
elim tol (flu12 et flu13);
flu14 = flu13 plus left;
elim tol (flu13 et flu14);
flu15 = flu14 plus left;
elim tol (flu14 et flu15);
flu16 = flu15 plus left;
elim tol (flu15 et flu16);
flu17 = flu16 plus down;
elim tol (flu16 et flu17);
flu18 = flu17 plus down;
elim tol (flu17 et flu18);
flu19 = flu18 plus down;
elim tol (flu18 et flu19);
flu20 = flu19 plus right;
elim tol (flu19 et flu20);
flu21 = flu20 plus right;
elim tol (flu20 et flu21);
flu22 = flu21 plus up;
elim tol (flu21 et flu22);
flu23 = flu22 plus up;
elim tol (flu22 et flu23);
flu24 = flu23 plus left;
elim tol (flu23 et flu24);
flu25 = flu24 plus down;
elim tol (flu24 et flu25);

expl = flu1 et flu13 et flu25;
gas = flu2 et flu3 et flu4 et flu5 et
      flu6 et flu7 et flu8 et flu9 et flu10 et
      flu11 et flu12 et flu14 et flu15 et
      flu16 et flu17 et flu18 et flu19 et flu20 et
      flu21 et flu22 et flu23 et flu24;
flui = expl et gas;
trac qual flui;

coco = cont flui;

d1 = stru poin proc (1 3);
d2 = stru poin proc (2.5 1);
d3 = stru poin proc (4 2.5);
d4 = stru poin proc (3 4);
tpln = d1 et d2 et d3 et d4;
pe1 = 0 5;
pe2 = 0 0;
pe3 = 5 0;
pe4 = 5 5;
pe5 = 1 5;
pe6 = 1 1;
pe7 = 2 2;
e1 = flu1 elem cont (flu1 poin proc pe1);
e2 = flu5 elem cont (flu5 poin proc pe2);
e3 = flu9 elem cont (flu9 poin proc pe3);
e4 = flu13 elem cont (flu13 poin proc pe4);
e5 = flu16 elem cont (flu16 poin proc pe5);
e6 = flu19 elem cont (flu19 poin proc pe6);
e7 = flu25 elem cont (flu25 poin proc pe7);
tple = e1 et e2 et e3 et e4 et e5 et e6 et e7;
trac qual (coco et tple et tpln);
*opti trac mif;
*trac qual (coco et tple et tpln);

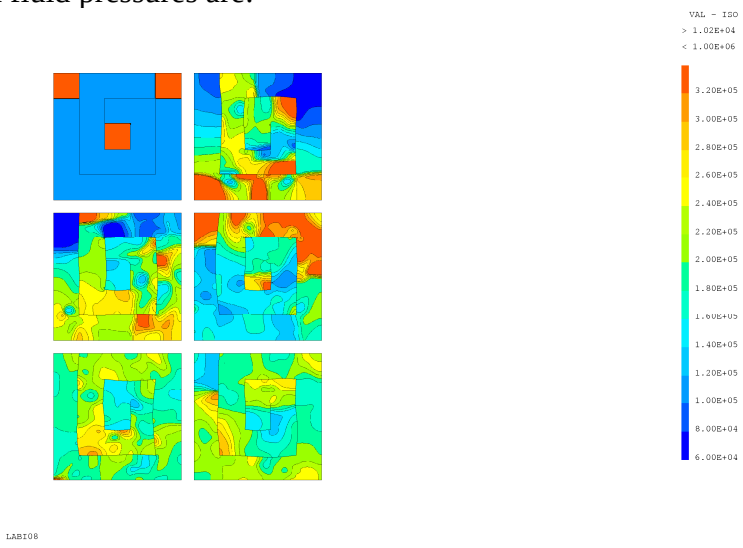
*fsan = (flu1 et flu2 et flu3 et flu4) poin droi p1s p2s tol;
*fsan = fsan et
*       ((flu16 et flu17 et flu18 et flu19) poin droi p1s p2s tol);
*fsan = fsan et ((flu6 et flu7 et flu8) poin droi p2s p3s tol);
*fsan = fsan et ((flu19 et flu20 et flu21) poin droi p2s p3s tol);
*fsan = fsan et ((flu10 et flu11 et flu12) poin droi p3s p4s tol);
*fsan = fsan et ((flu21 et flu22 et flu23) poin droi p3s p4s tol);
fsan = cont flui;
fsan = chan poi1 fsan;
fsrn = flui poin droi pe1 pe2 tol;
fsrn = fsrn et (flui poin droi pe2 pe3 tol);
fsrn = fsrn et (flui poin droi pe3 pe4 tol);
fsrn = fsrn et (flui poin droi pe4 pe1 tol);
fsrn = chan poi1 fsrn;
fsan = fsan diff (fsan inte fsrn);
trac fsan;
trac fsrn;
bloc = ps1 et ps2 et ps3 et ps4 et ps5 et ps6 et ps7 et ps8;

mesh = flui et stru et fsan et fsrn et tple et tpln et bloc;
tass mesh;
sauv form mesh;
list (nbno flui);
list (nbno stru);
list (nbno fsan);
list (nbno fsrn);
list (nbel flui);
list (nbel stru);
fin;
```

The input file is:

```
LABI08
ECHO
*CONV win
CAST mesh
DPLA ALE
DIME
  NALE 597 NBLE 1
  BLOQ 1200
  FSA 1035 IFSA 4042
  LIAI 7318
  ndvc 99076
TERM
GEOM FL24 flui ED01 stru TERM
COMP EPAI 0.01 LECT stru TERM
GRIL LAGR LECT stru TERM
     EULE LECT fsrn fsan TERM
     MEAN AUTR
OPTI REZO MVRE MODU LIAI
MATE VM23 RO 8000 YOUNG 2.E11 NU 0.3 ELAS 4.E8
          TRAC 3 4.E8 2.E-3 2.4E9 1.002E0 2.4E9 10.
          LECT stru TERM
     FLUT RO 10. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT expl TERM
     FLUT RO  1. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT gas TERM
LIAI freq 1
     BLOQ 123 LECT bloc TERM
     FSR LECT fsrn TERM
     FSA NCFS LECT fsan TERM
ECRI DEPL VITE ECRO TFRE 10.E-3
     POIN LECT tpln TERM
     ELEM LECT tple TERM
     TRAC TPLO DESC 'LABI08' TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
     fich alic temp TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
     FICH FORM K200 TFRE 2.E-3
          POIN TOUS
          VARI DEPL VITE ECRO ECRC LECT 1 3 TERM
OPTI NOTE
  CSTA 0.5D0
* MOMT 2
  FSCR
  LOG 1
CALCUL TINI 0. TEND 50.E-3
*
SUIT
Post-treatment
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dx_1'  DEPL COMP 1 POIN LECT d1 TERM
COUR  2 'dy_2'  DEPL COMP 2 POIN LECT d2 TERM
COUR  3 'dx_3'  DEPL COMP 1 POIN LECT d3 TERM
COUR  4 'dy_4'  DEPL COMP 2 POIN LECT d4 TERM
COUR  5 'p_e1'  ECRO COMP 1 ELEM LECT e1 TERM
COUR  6 'p_e2'  ECRO COMP 1 ELEM LECT e2 TERM
COUR  7 'p_e3'  ECRO COMP 1 ELEM LECT e3 TERM
COUR  8 'p_e4'  ECRO COMP 1 ELEM LECT e4 TERM
COUR  9 'p_e5'  ECRO COMP 1 ELEM LECT e5 TERM
COUR 10 'p_e6'  ECRO COMP 1 ELEM LECT e6 TERM
COUR 11 'p_e7'  ECRO COMP 1 ELEM LECT e7 TERM
*
trac 1 2 3 4 axes 1.0 'D [M]'
trac 5 6 7 8 axes 1.0 'P [PA]'
trac 9 10 11 axes 1.0 'P [PA]'
LIST 1 2 3 4 axes 1.0 'D [M]'
LIST 5 6 7 8 axes 1.0 'P [PA]'
LIST 9 10 11 axes 1.0 'P [PA]'
*
*QUAL VITE comp 1 lect 51 term REFE 8.25539E+2 TOLE 5.E-3
*     ECRO comp 1 lect 50 term REFE 3.41392E+5 TOLE 5.E-3
FIN
```

The computed fluid pressures are:

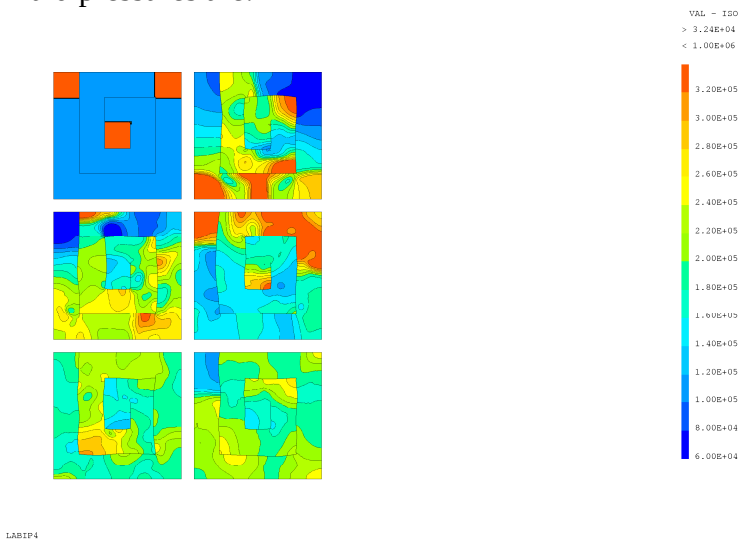


Solutions with space partitioning (OPTI PART)

LABIP4 (DP)

Eight-times finer conforming FSI solution. The fluid mesh uses 6400 elements and the structure is discretized by 256 elements of the ED01 type. Uses spatial partitioning.

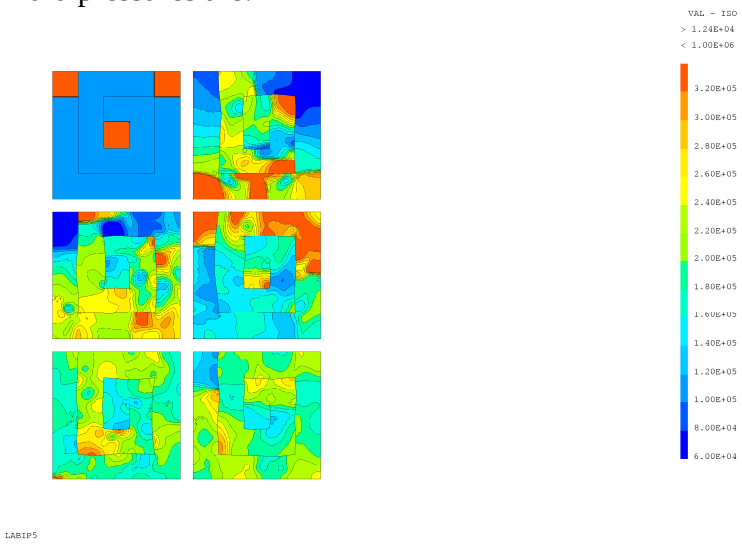
The computed fluid pressures are:



LABIP5 (EP)

Sixteen-times finer conforming FSI solution. The fluid mesh uses 25600 elements and the structure is discretized by 512 elements of the ED01 type. Uses spatial partitioning.

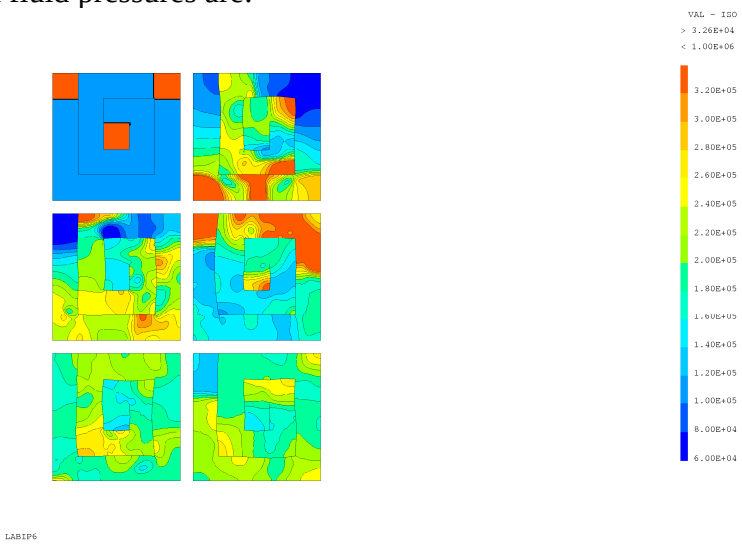
The computed fluid pressures are:



LABIP6 (FP)

Eight-times finer non-conforming FSI solution. The fluid mesh uses 6400 elements and the structure is discretized by 32 elements of the ED01 type. Uses spatial partitioning.

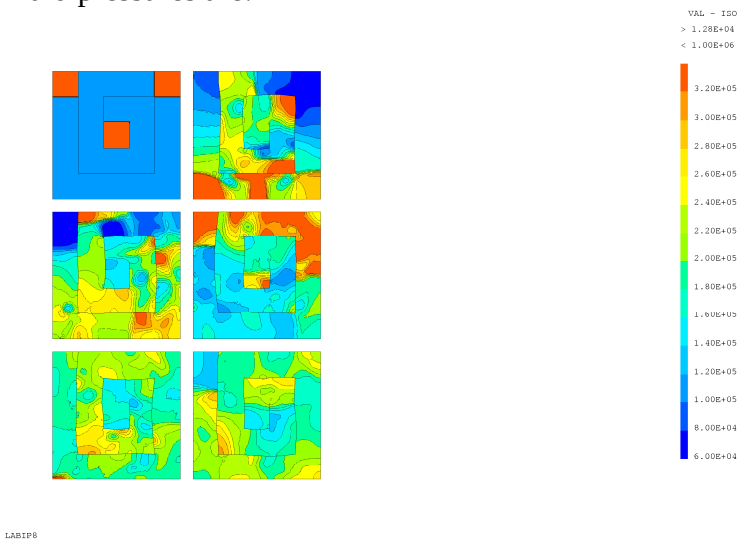
The computed fluid pressures are:



LABIP8 (HP)

Sixteen-times finer non-conforming FSI solution. The fluid mesh uses 25600 elements and the structure is discretized by 32 elements of the ED01 type. Uses spatial partitioning.

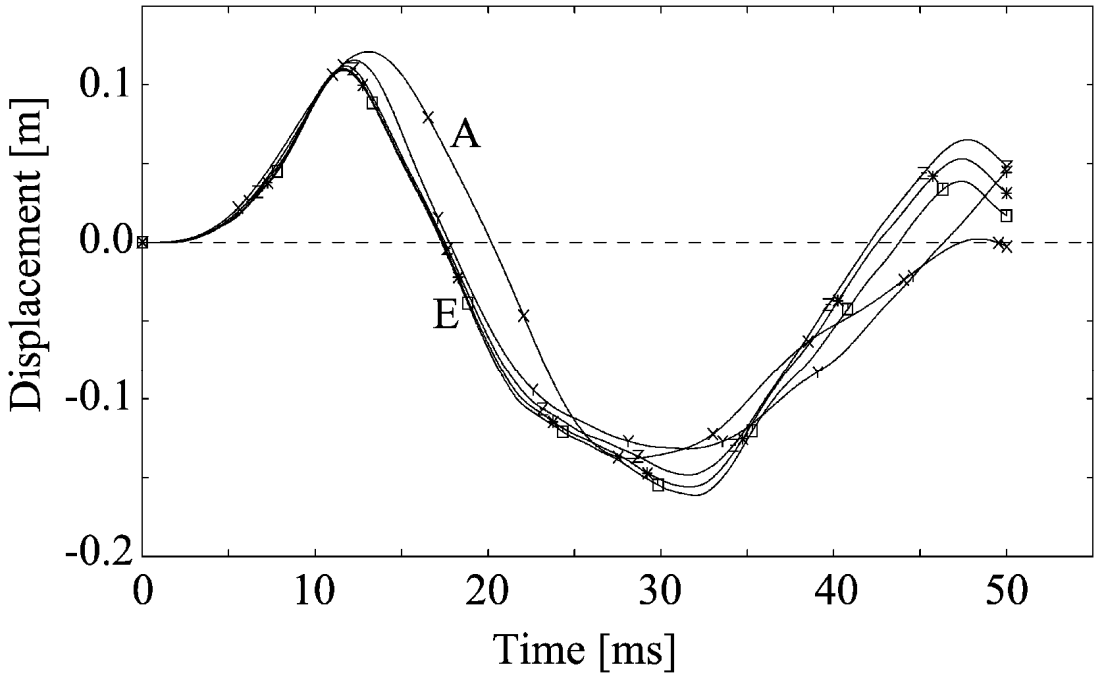
The computed fluid pressures are:



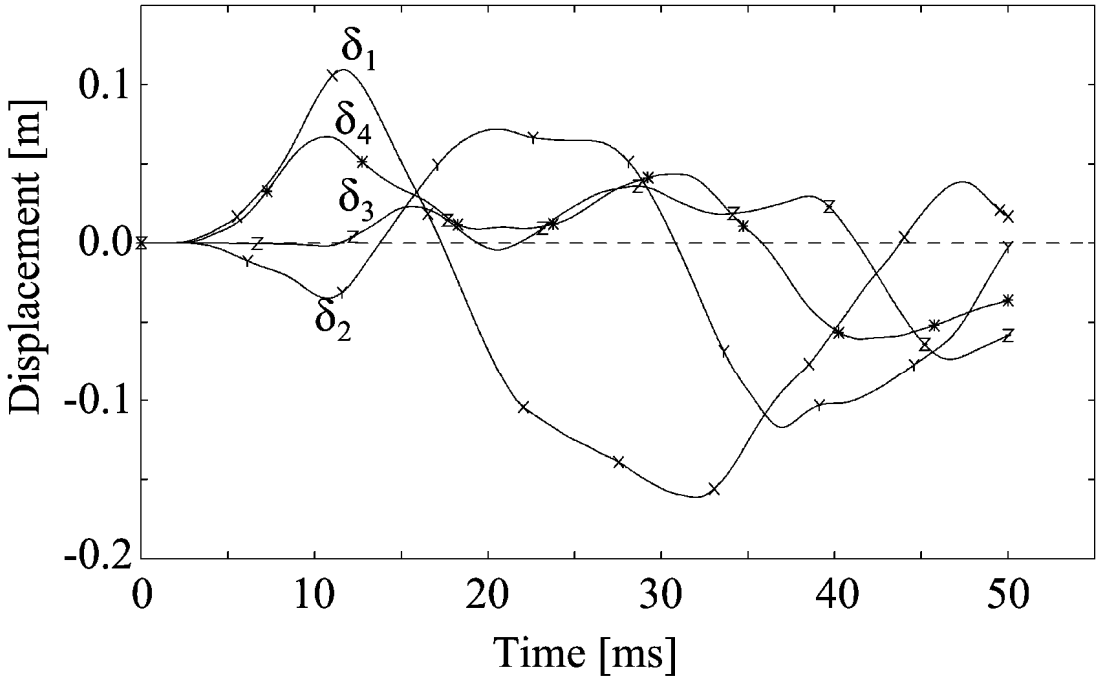
Some results comparisons

Resume of calculations (without partitioning)

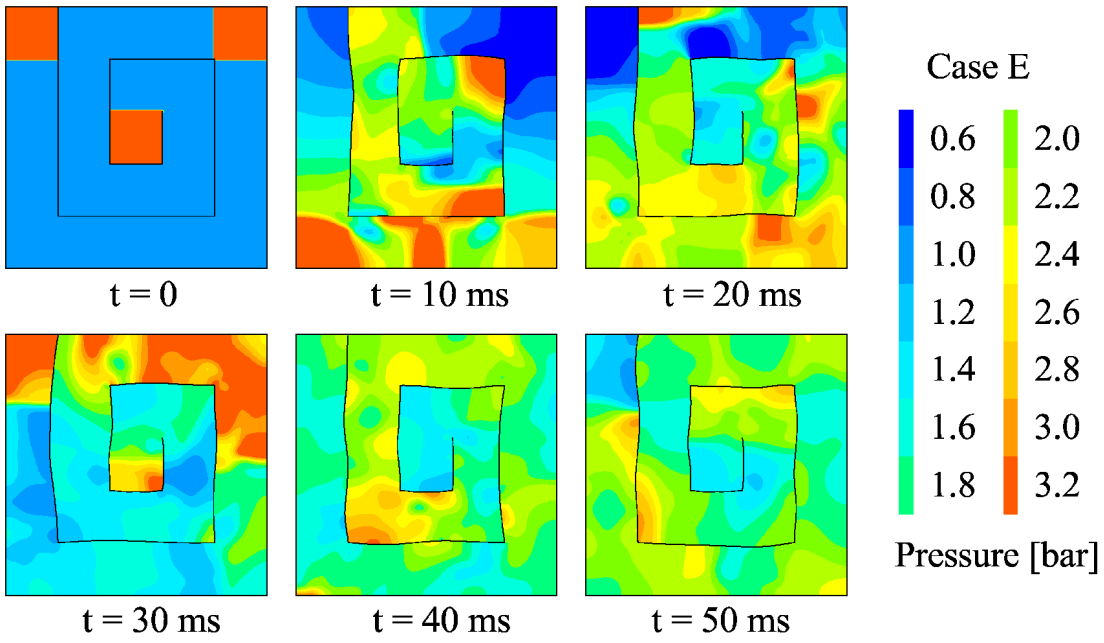
Case	Mesh refinement Φ (F/S)	Number of elements (F/S)	Time steps	CPU time [s]	CPU time ratio	Speed-up factor
A	1x/1x	100/32	1050	2.6	1.0	-
B	2x/2x	400/64	2100	11.7	4.5	-
C	4x/4x	1600/128	4200	77.5	29.8	-
D	8x/8x	6400/256	8400	587.3	225.9	-
E	16x/16x	25600/512	16789	4747.7	1826.0	-
F	8x/1x	6400/32	1416	110.1	42.3	5.3
G	16x/2x	25600/64	3063	933.7	359.1	5.1
H	16x/1x	25600/32	3087	960.2	369.3	4.9



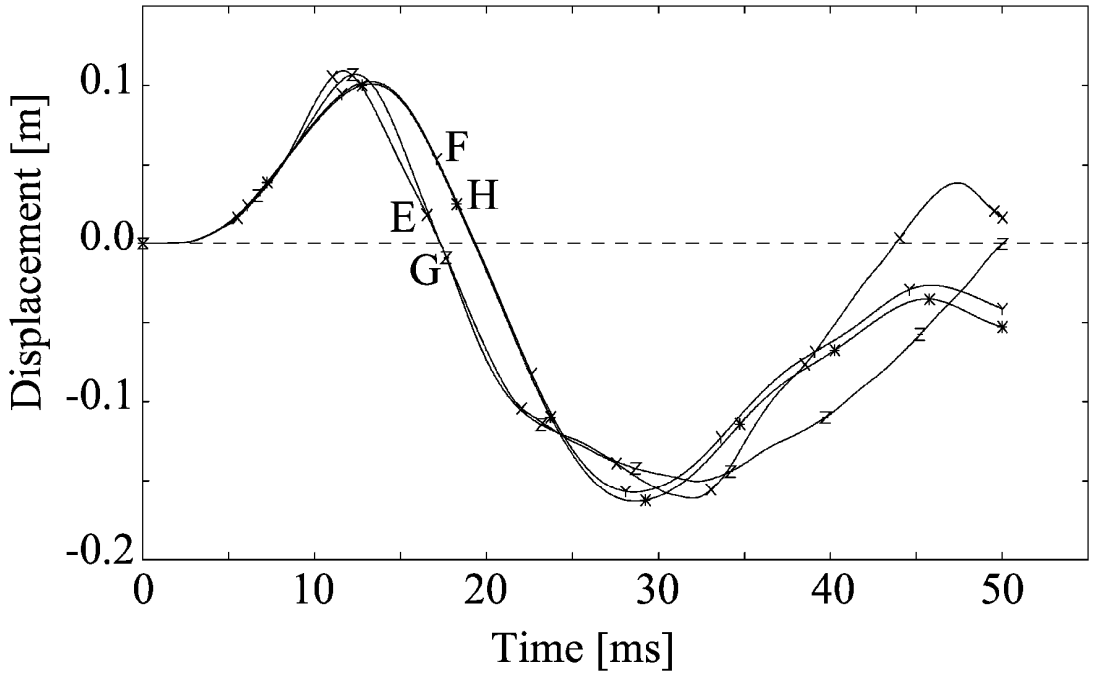
Labyrinth: displacement δ_1 in cases A to E (progressive mesh refinement)



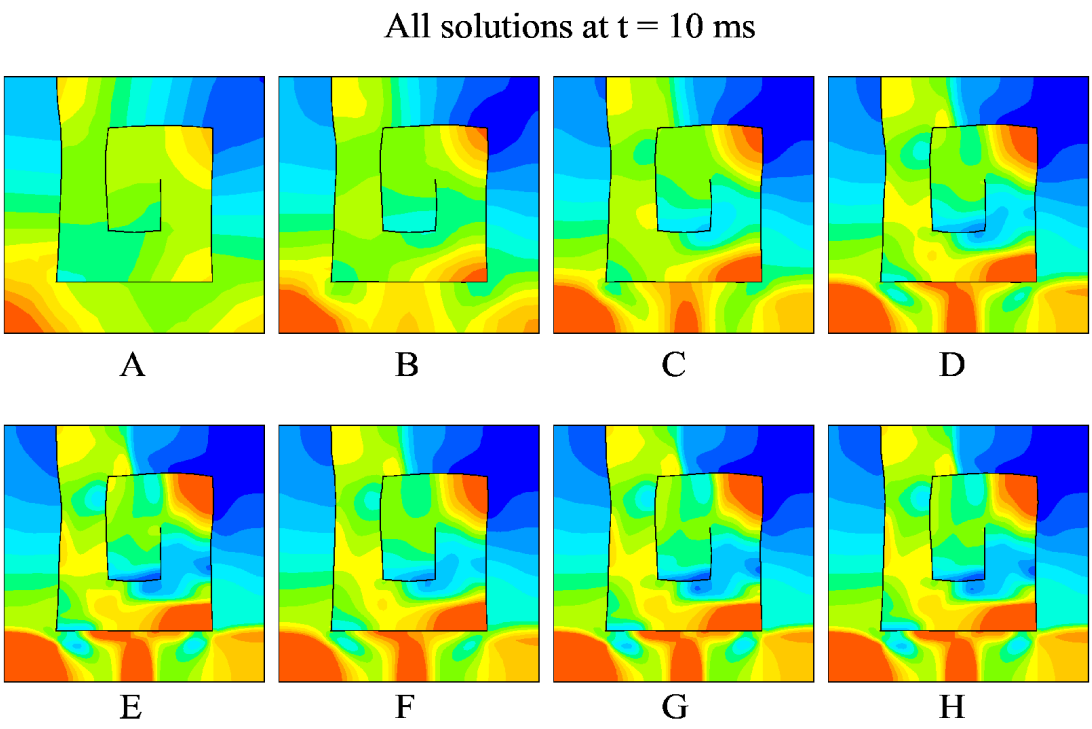
Labyrinth: displacements δ_1 to δ_4 in case E (reference solution)



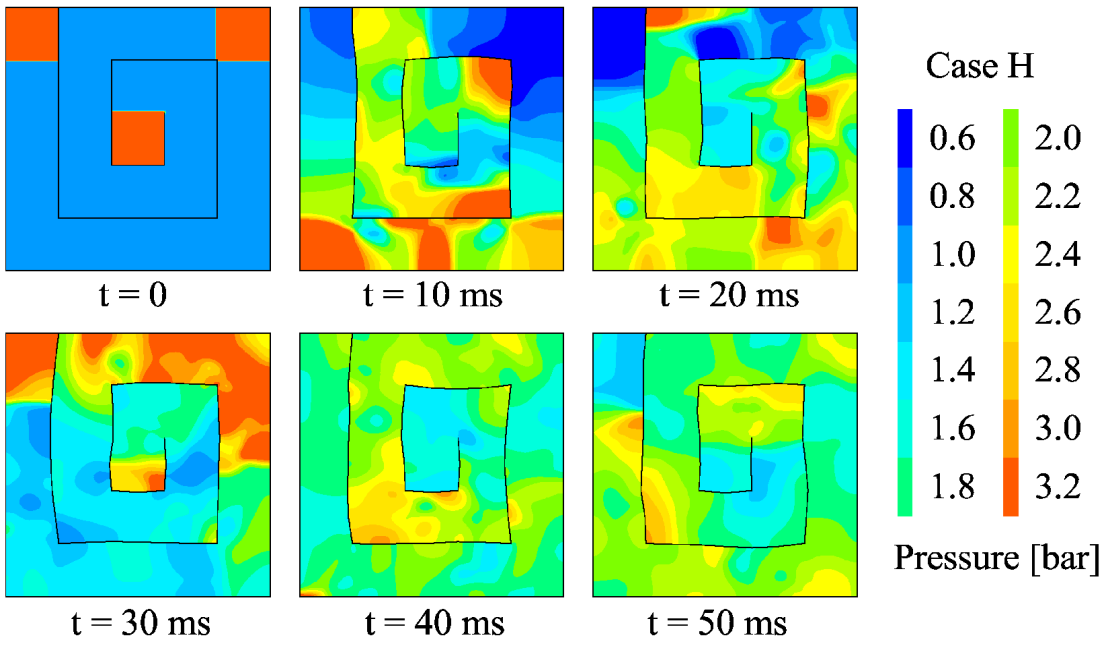
Labyrinth: fluid pressures in case E (reference solution)



Labyrinth: displacement δ_1 in cases E (reference) to H (nonconforming mesh solutions)

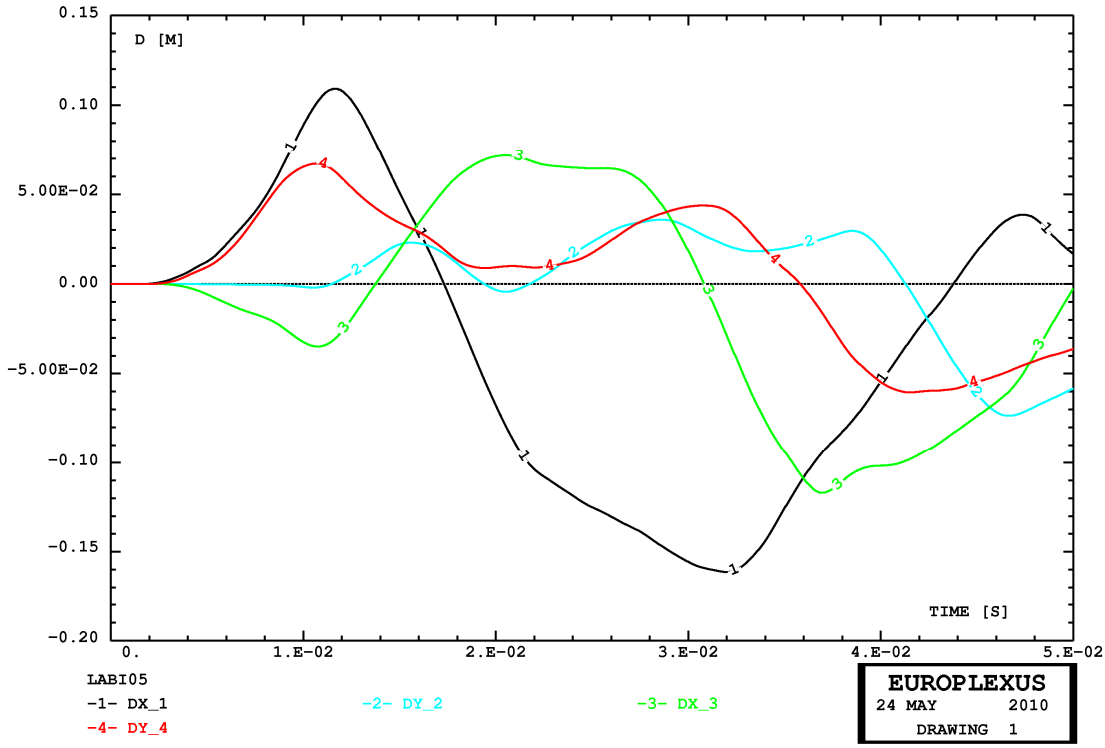


Labyrinth: fluid pressures at 10 ms in all test cases

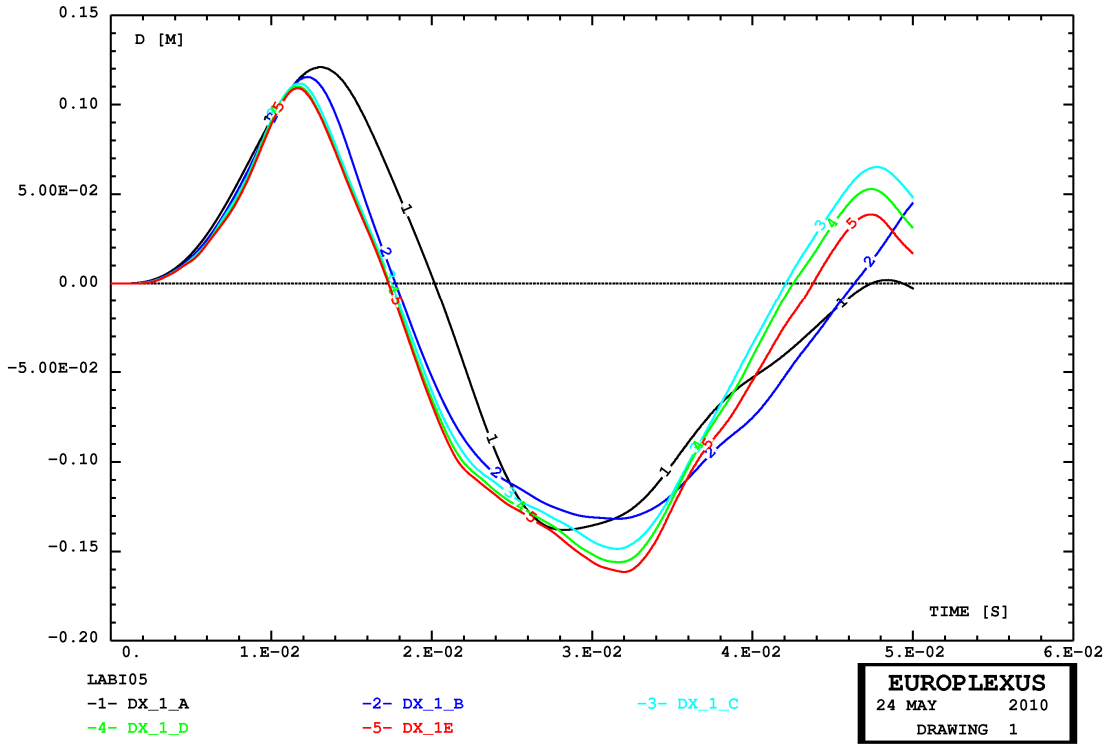


Labyrinth: fluid pressures in case H

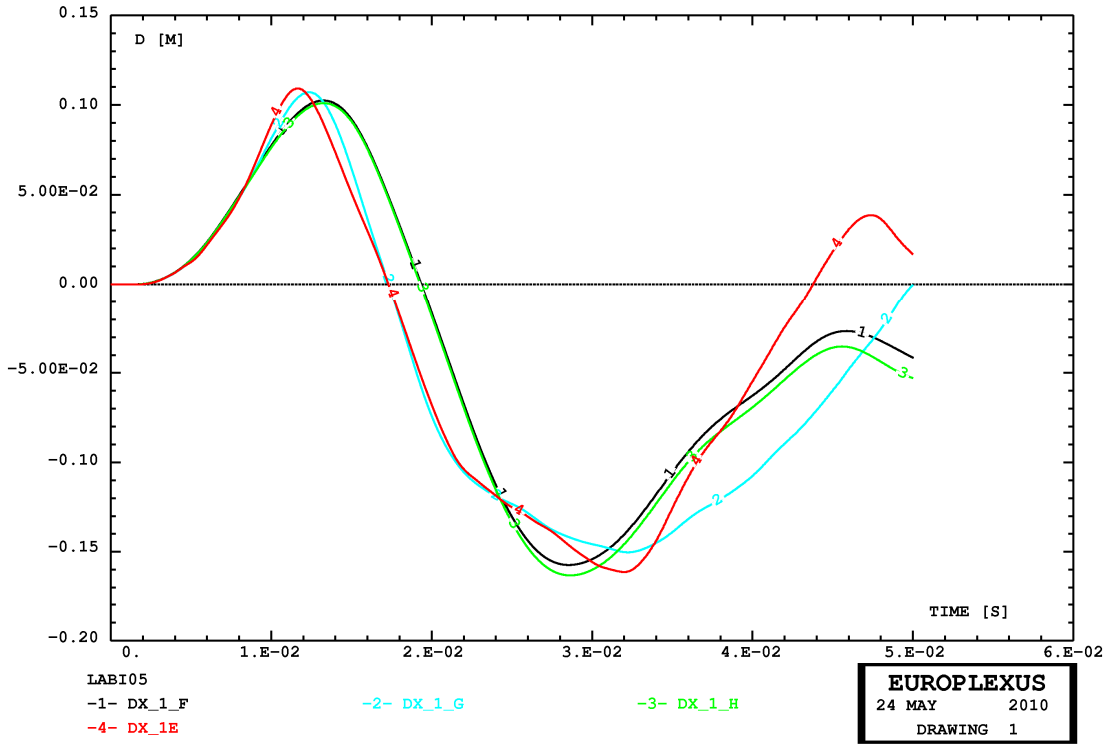
Displacements in the reference solution (case E).



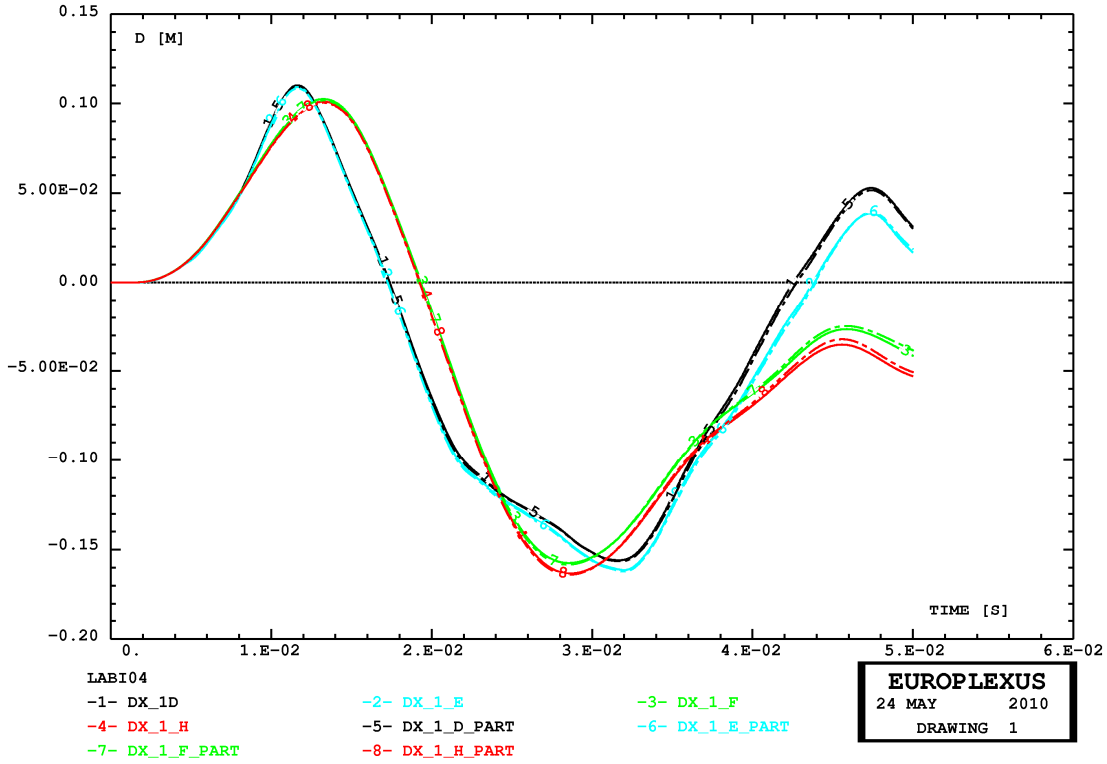
Displacement 1 in solutions A to E:

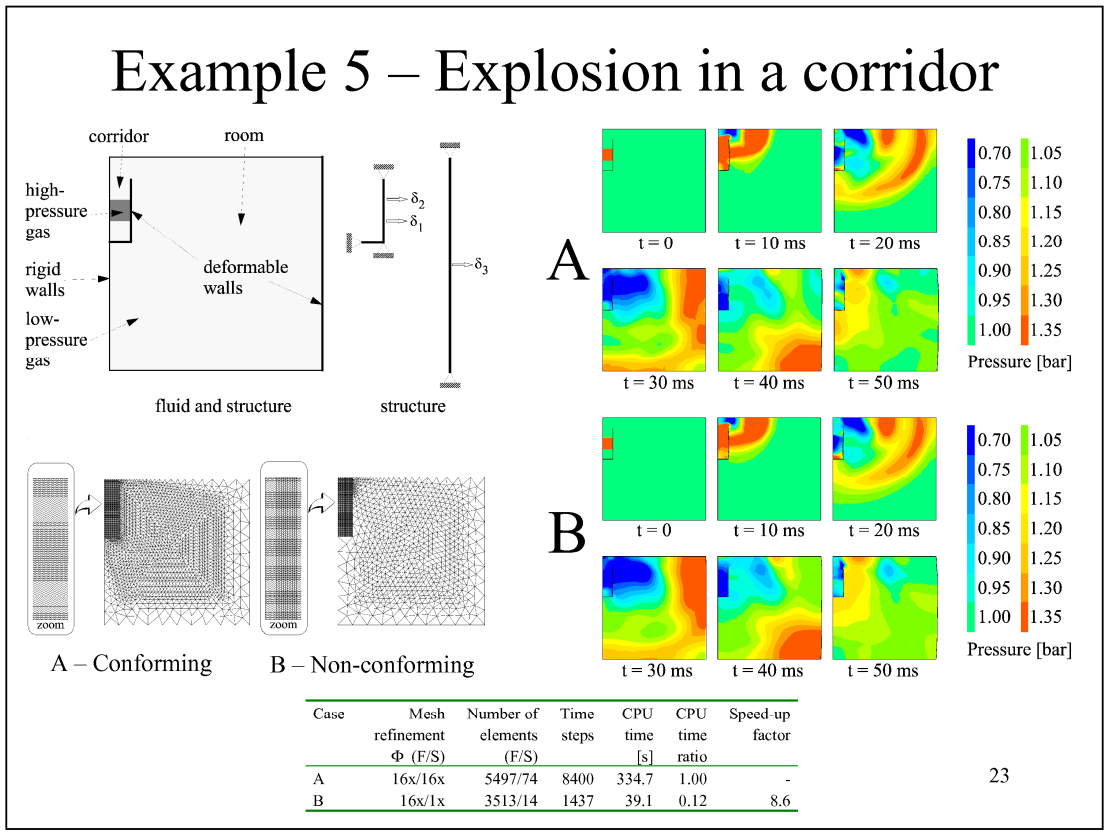


Displacement 1 in solutions E (reference), F, G and H.



Comparison of solutions without and with partitioning





Case	Mesh refinement Φ (F/S)	Number of elements (F/S)	Time steps	CPU time [s]	CPU time ratio	Speed-up factor
A	16x/16x	5497/74	8400	334.7	1.00	-
B	16x/1x	3513/14	1437	39.1	0.12	8.6

Geometric data and materials:

The domain is 10 units wide and 10 units high. The bubble is square in shape and has unit sides. The walls are rigid except the corridor and the rightmost wall.

The fluids are perfect gases. The structure is steel with an elasto-plastic law.

Numerical Solutions

DENS01

This model uses conforming FSI. The mesh generation file is:

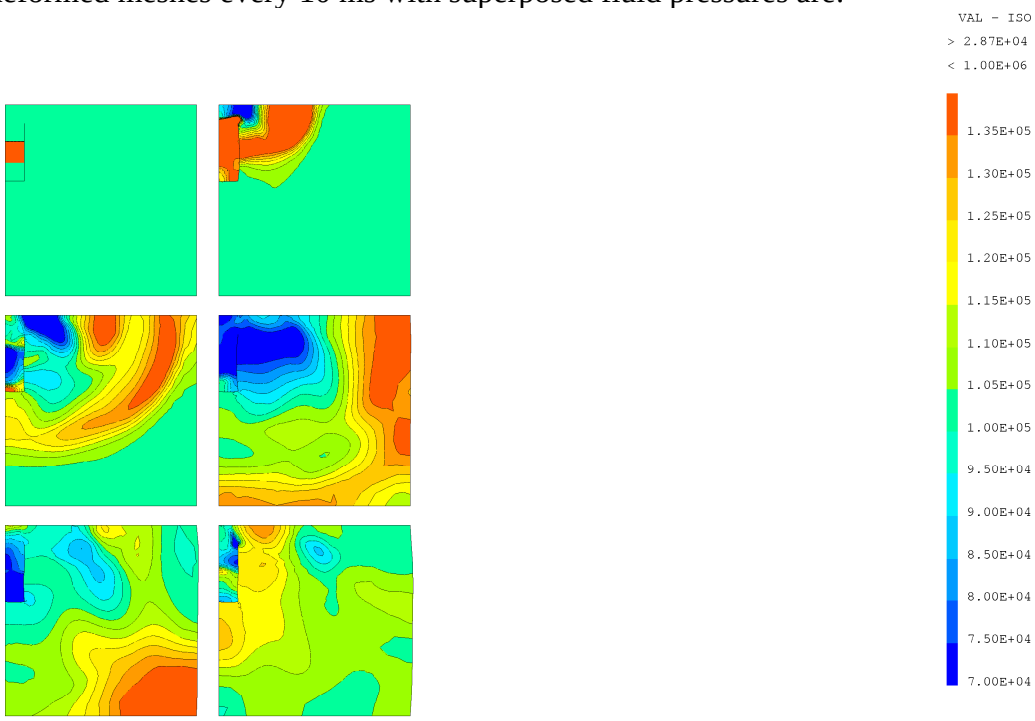
```
*%siz 4000
opti echo 1;
opti titr 'DENS - 01';
opti sauv form 'dens01.msh';
opti dime 2 elem tri3;
opti trac psc ftra 'dens01_mesh.ps';
tol = 0.0001;
dmax = 1.0;
dmin = 1.0 / 16.0;
p1 = 0 0;
p2 = 10 0;
p3 = 10 10;
p4 = 0 10;
p5 = 0 6;
p6 = 1 6;
p7 = 0 9;
p8 = 1 9;
p9 = 1 10;
p10 = 0 8;
p11 = 1 8;
p12 = 0 7;
p13 = 1 7;
c1 = p1 d 10 p2;
c2 = p2 d 10 p3;
fsan = c2;
c3 = p3 d p9 dini dmax dfin dmin;
c4a = p9 d p8 dini dmin dfin dmin;
c4b = p8 d p6 dini dmin dfin dmin;
fsan = fsan et c4b;
c4c = p6 d p5 dini dmin dfin dmin;
fsan = fsan et c4c;
c4 = c4a et c4b et c4c;
c5 = p5 d p1 dini dmin dfin dmax;
s1 = surf (c1 et c2 et c3 et c4 et c5) plan;
p5b = p5 plus p1;
p6b = p6 plus p1;
c1 = p5b d p6b dini dmin dfin dmin;
fsan = fsan et c1;
c2 = p6b d p13 dini dmin dfin dmin;
fsan = fsan et c2;
c3 = p13 d p12 dini dmin dfin dmin;
c4 = p12 d p5b dini dmin dfin dmin;
s2 = dall c1 c2 c3 c4 plan;
c1 = p12 d p13 dini dmin dfin dmin;
c2 = p13 d p11 dini dmin dfin dmin;
fsan = fsan et c2;
c3 = p11 d p10 dini dmin dfin dmin;
c4 = p10 d p12 dini dmin dfin dmin;
s3 = dall c1 c2 c3 c4 plan;
elim tol (s2 et s3);
c1 = p10 d p11 dini dmin dfin dmin;
c2 = p11 d p8 dini dmin dfin dmin;
fsan = fsan et c2;
c3 = p8 d p7 dini dmin dfin dmin;
c4 = p7 d p10 dini dmin dfin dmin;
s4 = dall c1 c2 c3 c4 plan;
elim tol (s3 et s4);
c1 = p7 d p8 dini dmin dfin dmin;
c2 = p8 d p9 dini dmin dfin dmin;
c3 = p9 d p4 dini dmin dfin dmin;
c4 = p4 d p7 dini dmin dfin dmin;
s5 = dall c1 c2 c3 c4 plan;
elim tol (s4 et s5);
elim tol (s5 et s1);
flui = s1 et s2 et s3 et s4 et s5;
p5s = p5 plus p1;
p6s = p6 plus p1;
p8s = p8 plus p1;
p2s = p2 plus p1;
p3s = p3 plus p1;
stru1 = p5s d p6s dini dmin dfin dmin;
stru2 = p6s d p8s dini dmin dfin dmin;
stru3 = p2s d 10 p3s;
stru = stru1 et stru2 et stru3;
bloc = p5s et p6s et p8s et p2s et p3s;
fsrn = flui poin droi p1 p4 tol;
fsrn = fsrn et (flui poin droi p1 p2 tol);
fsrn = fsrn et (flui poin droi p4 p3 tol);
fsrn = chan poi1 fsrn;
fsan = chan poi1 fsan;
fsan = fsan diff (fsan inte fsrn);
d1 = stru poin proc p13;
d2 = stru poin proc p11;
d3 = stru poin proc (10 5);
tpln = d1 et d2 et d3;
e1 = s2 elem cont p5b;
e2 = s5 elem cont p4;
e3 = s1 elem cont p3;
e4 = s1 elem cont p2;
e5 = s1 elem cont p1;
tple = e1 et e2 et e3 et e4 et e5;

mesh = flui et stru et fsan et fsrn et tple et tpln et bloc;
tass mesh;
trac flui;
trac stru;
trac fsrn;
trac fsan;
coco = cont flui;
trac qual (coco et tpln et tple);
sauv form mesh;
list (nbno flui);
list (nbno stru);
list (nbno fsan);
list (nbno fsrn);
list (nbel flui);
list (nbel stru);
opti trac mif;
trac s1;
trac (s2 et s3 et s4 et s5);
trac flui;
trac stru;
trac fsrn;
trac fsan;
trac qual (coco et tpln et tple);
fin;
```

The input file is:

```
DENS01
ECHO
!CONV win
CAST mesh
DPLA ALE
DIME
  NALE 54 NBLE 1
  BLOQ 1200
  FSA 136 IFSA 534
  LIAI 833
  ndvc 16172
TERM
GEOM FL23 flui ED01 stru TERM
COMP EPAI 0.01 LECT stru TERM
GRIL LAGR LECT stru TERM
     EULE LECT fsrn fsan TERM
     MEAN AUTR
OPTI REZO MVRE MODU LIAI
MATE VM23 RO 8000 YOUNG 2.E11 NU 0.3 ELAS 4.E8
          TRAC 3 4.E8 2.E-3 2.4E9 1.002E0 2.4E9 10.
          LECT stru TERM
     FLUT RO 10. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT s3 TERM
     FLUT RO  1. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT s1 s2 s4 s5 TERM
LIAI freq 1
     BLOQ 123 LECT bloc TERM
     FSR LECT fsrn TERM
     FSA LECT fsan TERM
ECRI DEPL VITE ECRO TFRE 10.E-3
     POIN LECT tpln TERM
     ELEM LECT tple TERM
     TRAC TPLO DESC 'DENS01' TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
     fich alic temp TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
     FICH FORM K200 TFRE 2.E-3
          POIN TOUS
          VARI DEPL VITE ECRO ECRC LECT 1 3 TERM
OPTI NOTE
  CSTA 0.6D0
* MOMT 2
  FSCR
  DTML
  LOG 1
CALCUL TINI 0. TEND 50.E-3
*
SUIT
Post-treatment
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dx_1'  DEPL COMP 1 POIN LECT d1 TERM
COUR  2 'dx_2'  DEPL COMP 1 POIN LECT d2 TERM
COUR  3 'dx_3'  DEPL COMP 1 POIN LECT d3 TERM
COUR  4 'p_e1'  ECRO COMP 1 ELEM LECT e1 TERM
COUR  5 'p_e2'  ECRO COMP 1 ELEM LECT e2 TERM
COUR  6 'p_e3'  ECRO COMP 1 ELEM LECT e3 TERM
COUR  7 'p_e4'  ECRO COMP 1 ELEM LECT e4 TERM
COUR  8 'p_e5'  ECRO COMP 1 ELEM LECT e5 TERM
*
trac 1 2 3 axes 1.0 'D [M]'
trac 4 5 6 7 8 axes 1.0 'P [PA]'
list 1 2 3 axes 1.0 'D [M]'
list 4 5 6 7 8 axes 1.0 'P [PA]'
*
*QUAL VITE comp 1 lect 51 term REFE 8.25539E+2 TOLE 5.E-3
*     ECRO comp 1 lect 50 term REFE 3.41392E+5 TOLE 5.E-3
FIN
```

The deformed meshes every 10 ms with superposed fluid pressures are:



DENS01

DENS02

We use a sixteen times coarser structural mesh. The F-S interface is non-conforming. The mesh generation file is:

```
*%siz 4000
opti echo 1;
opti titr 'DENS - 02';
opti sauv form 'dens02.msh';
opti dime 2 elem tri3;
opti trac psc ftra 'dens02_mesh.ps';
tol = 0.0001;
dmax = 1.0;
dmin = 1.0 / 16.0;
p1 = 0 0;
p2 = 10 0;
p3 = 10 10;
p4 = 0 10;
p5 = 0 6;
p6 = 1 6;
p7 = 0 9;
p8 = 1 9;
p9 = 1 10;
p10 = 0 8;
p11 = 1 8;
p12 = 0 7;
p13 = 1 7;
c1 = p1 d 10 p2;
c2 = p2 d 10 p3;
fsan = c2;
c3 = p3 d p9 dini dmax dfin dmin;
c4a = p9 d p8 dini dmin dfin dmin;
c4b = p8 d p6 dini dmin dfin dmax;
fsan = fsan et c4b;
c4c = p6 d p5 dini dmax dfin dmax;
fsan = fsan et c4c;
c4 = c4a et c4b et c4c;
c5 = p5 d p1 dini dmax dfin dmax;
s1 = surf (c1 et c2 et c3 et c4 et c5) plan;
p5b = p5 plus p1;
p6b = p6 plus p1;
c1 = p5b d p6b dini dmin dfin dmin;
fsan = fsan et c1;
c2 = p6b d p13 dini dmin dfin dmin;
fsan = fsan et c2;
c3 = p13 d p12 dini dmin dfin dmin;
c4 = p12 d p5b dini dmin dfin dmin;
s2 = dall c1 c2 c3 c4 plan;
c1 = p12 d p13 dini dmin dfin dmin;
c2 = p13 d p11 dini dmin dfin dmin;
fsan = fsan et c2;
c3 = p11 d p10 dini dmin dfin dmin;
c4 = p10 d p12 dini dmin dfin dmin;
s3 = dall c1 c2 c3 c4 plan;
elim tol (s2 et s3);
c1 = p10 d p11 dini dmin dfin dmin;
c2 = p11 d p8 dini dmin dfin dmin;
```

```
fsan = fsan et c2;
c3 = p8 d p7 dini dmin dfin dmin;
c4 = p7 d p10 dini dmin dfin dmin;
s4 = dall c1 c2 c3 c4 plan;
elim tol (s3 et s4);
c1 = p7 d p8 dini dmin dfin dmin;
c2 = p8 d p9 dini dmin dfin dmin;
c3 = p9 d p4 dini dmin dfin dmin;
c4 = p4 d p7 dini dmin dfin dmin;
s5 = dall c1 c2 c3 c4 plan;
elim tol (s4 et s5);
elim tol (s5 et s1);
flui = s1 et s2 et s3 et s4 et s5;
p5s = p5 plus p1;
p6s = p6 plus p1;
p8s = p8 plus p1;
p2s = p2 plus p1;
p3s = p3 plus p1;
stru1 = p5s d p6s dini dmax dfin dmax;
stru2 = p6s d p8s dini dmax dfin dmax;
stru3 = p2s d 10 p3s;
stru = stru1 et stru2 et stru3;
bloc = p5s et p6s et p8s et p2s et p3s;
fsrn = flui poin droi p1 p4 tol;
fsrn = fsrn et (flui poin droi p1 p2 tol);
fsrn = fsrn et (flui poin droi p4 p3 tol);
fsrn = chan poi1 fsrn;
fsan = chan poi1 fsan;
fsan = fsan diff (fsan inte fsrn);
d1 = stru poin proc p13;
d2 = stru poin proc p11;
d3 = stru poin proc (10 5);
```

```
tpln = d1 et d2 et d3;
e1 = s2 elem cont p5b;
e2 = s5 elem cont p4;
e3 = s1 elem cont p3;
e4 = s1 elem cont p2;
e5 = s1 elem cont p1;
tple = e1 et e2 et e3 et e4 et e5;

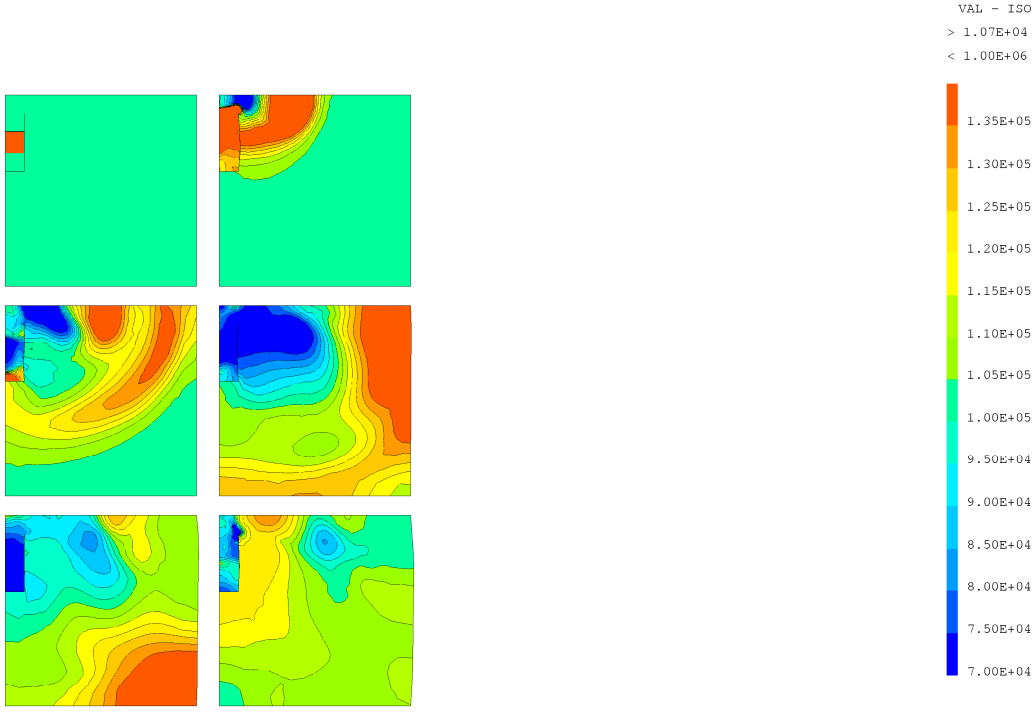
mesh = flui et stru et fsan et fsrn et tple et tpln et bloc;
tass mesh;
trac flui;
trac stru;
trac fsrn;
trac fsan;
coco = cont flui;
trac qual (coco et tpln et tple);
sauv form mesh;
list (nbno flui);
list (nbno stru);
list (nbno fsan);
list (nbno fsrn);
list (nbel flui);
list (nbel stru);
opti trac mif;
trac s1;
trac (s2 et s3 et s4 et s5);
trac flui;
trac stru;
trac fsrn;
trac fsan;
trac qual (coco et tpln et tple);
fin;
```

The input file:

```
DENS02
ECHO
!CONV win
CAST mesh
DPLA ALE
DIME
  NALE 46 NBLE 1
  BLOQ 1200
  FSA 85 IFSA 316
  LIAI 729
  ndvc 9913
TERM
GEOM FL23 flui ED01 stru TERM
COMP EPAI 0.01 LECT stru TERM
GRIL LAGR LECT stru TERM
     EULE LECT fsrn fsan TERM
     MEAN AUTR
OPTI REZO MVRE MODU LIAI
MATE VM23 RO 8000 YOUNG 2.E11 NU 0.3 ELAS 4.E8
          TRAC 3 4.E8 2.E-3 2.4E9 1.002E0 2.4E9 10.
          LECT stru TERM
     FLUT RO 10. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT s3 TERM
     FLUT RO  1. EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1
          BET0 1 KINT 1 AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          pref 1.e5
          LECT s1 s2 s4 s5 TERM
LIAI freq 1
     BLOQ 123 LECT bloc TERM
     FSR LECT fsrn TERM
     FSA NCFS LECT fsan TERM
ECRI DEPL VITE ECRO TFRE 10.E-3
     POIN LECT tpln TERM
     ELEM LECT tple TERM
     TRAC TPLO DESC 'DENS02' TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
     fich alic temp TFRE 51.E-6
               POIN LECT tpln TERM
               ELEM LECT tple TERM
     FICH FORM K200 TFRE 2.E-3
          POIN TOUS
          VARI DEPL VITE ECRO ECRC LECT 1 3 TERM
```

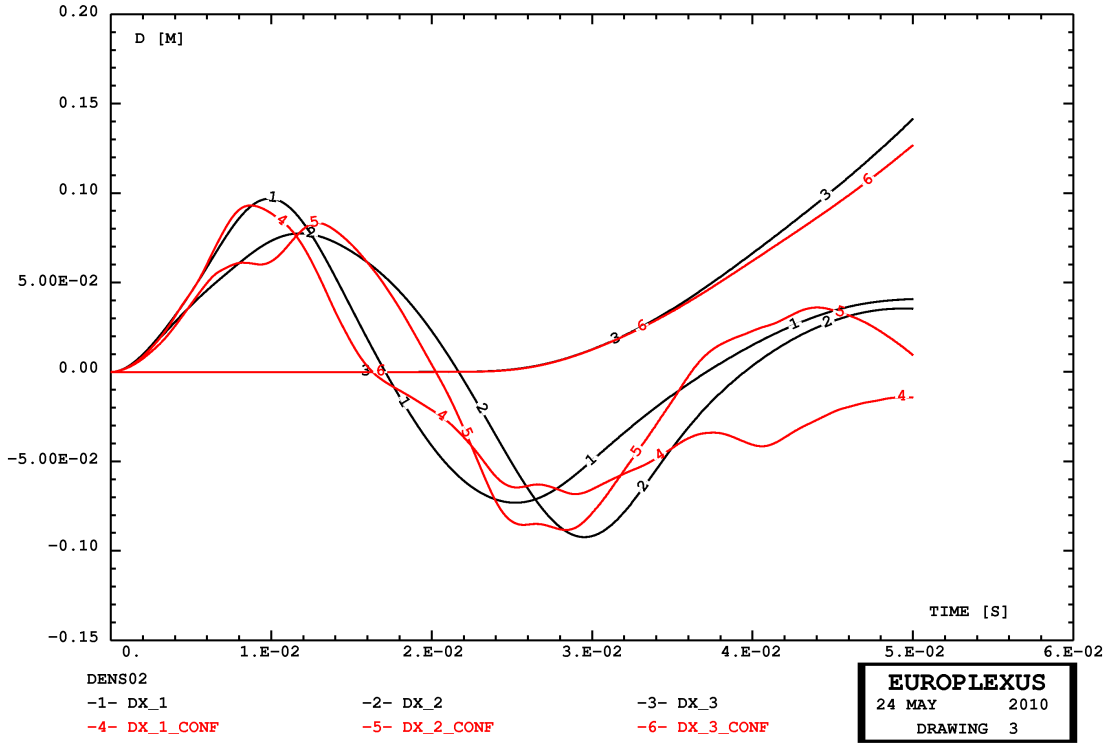
```
OPTI NOTE
  CSTA 0.60D0
* MOMT 2
  FSCR
  DTML
  LOG 1
CALCUL TINI 0. TEND 50.E-3
*
SUIT
Post-treatment
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dx_1'  DEPL COMP 1 POIN LECT d1 TERM
COUR  2 'dx_2'  DEPL COMP 1 POIN LECT d2 TERM
COUR  3 'dx_3'  DEPL COMP 1 POIN LECT d3 TERM
COUR  4 'p_e1'  ECRO COMP 1 ELEM LECT e1 TERM
COUR  5 'p_e2'  ECRO COMP 1 ELEM LECT e2 TERM
COUR  6 'p_e3'  ECRO COMP 1 ELEM LECT e3 TERM
COUR  7 'p_e4'  ECRO COMP 1 ELEM LECT e4 TERM
COUR  8 'p_e5'  ECRO COMP 1 ELEM LECT e5 TERM
RCOU 11 'dx_1'  FICH 'dens01.pun' RENA 'dx_1_conf'
RCOU 12 'dx_2'  FICH 'dens01.pun' RENA 'dx_2_conf'
RCOU 13 'dx_3'  FICH 'dens01.pun' RENA 'dx_3_conf'
RCOU 14 'p_e1'  FICH 'dens01.pun' RENA 'p_e1_conf'
RCOU 15 'p_e2'  FICH 'dens01.pun' RENA 'p_e2_conf'
RCOU 16 'p_e3'  FICH 'dens01.pun' RENA 'p_e3_conf'
RCOU 17 'p_e4'  FICH 'dens01.pun' RENA 'p_e4_conf'
RCOU 18 'p_e5'  FICH 'dens01.pun' RENA 'p_e5_conf'
*
trac 1 2 3 axes 1.0 'D [M]'
trac 4 5 6 7 8 axes 1.0 'P [PA]'
trac 1 2 3 11 12 13 axes 1.0 'D [M]'
     COLO noir noir noir roug roug roug
trac 4 5 6 7 8 14 15 16 17 18 axes 1.0 'P [PA]'
     COLO noir noir noir noir noir roug roug roug roug roug
*
*QUAL VITE comp 1 lect 51 term REFE 8.25539E+2 TOLE 5.E-3
*     ECRO comp 1 lect 50 term REFE 3.41392E+5 TOLE 5.E-3
FIN
```

The deformed meshes every 10 ms with superposed fluid pressures are:

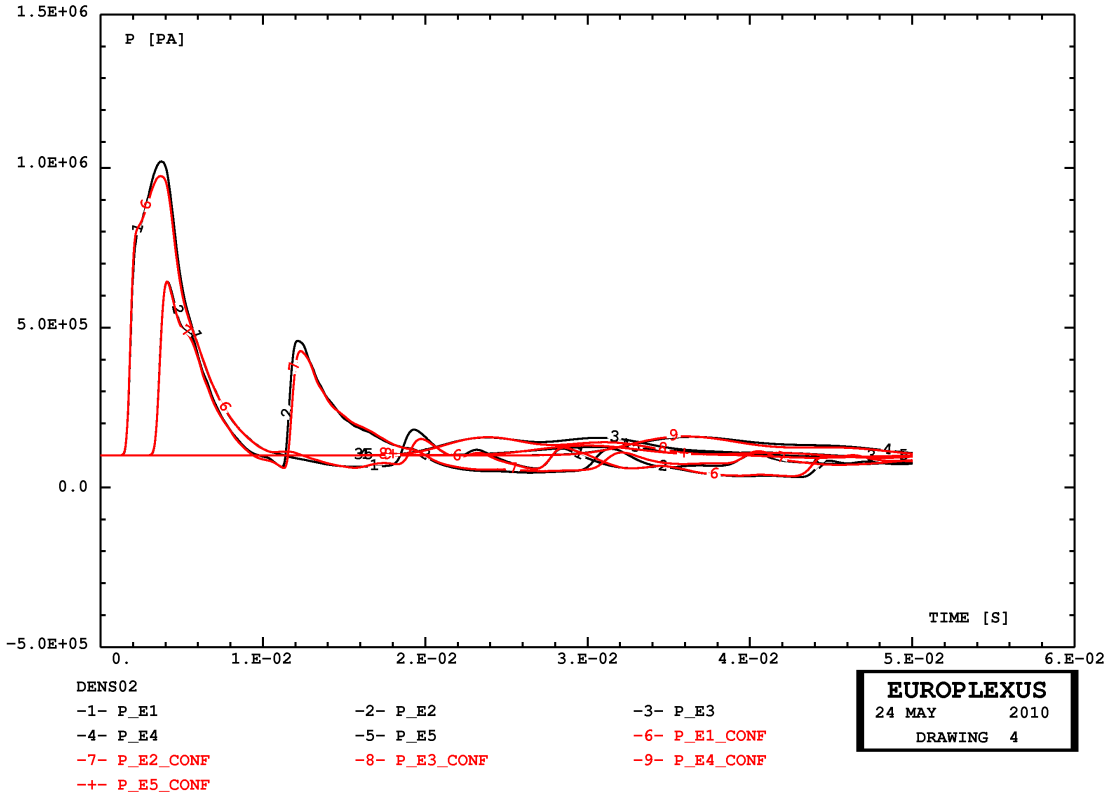


DENS02

Comparison of structural displacements in the conforming (in red) and non-conforming (in black) solutions:

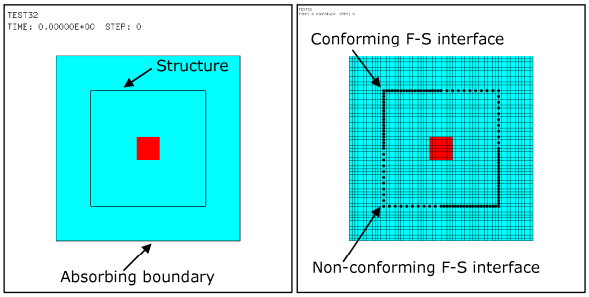


Comparison of fluid pressures in the conforming (in red) and non-conforming (in black) solutions:



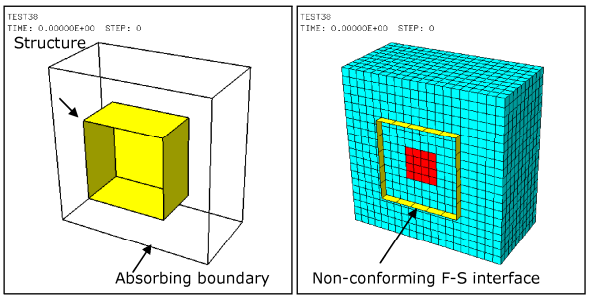
Example 6bis – Non-conforming FSI with CCVF

(Weak coupling, without or with structural failure)



2D case

(the dots indicate the structure nodes)



3D case

(half model shown for clarity)

32

Geometric data and materials:

See picture above for the geometry in 2D and 3D.

The fluids are perfect gases. The structure is steel with an elasto-plastic law.

Numerical Solutions (2D)

TEST32

This model uses conforming and non-conforming FSI together in the same calculation. The structure is deformable but is not allowed to fail. The mesh generation file is:

```
*
opti echo 1;
TITRE 'TEST32' ;
*
* creation du fluide (pour elements VFCC)
* - - - - - - - - - -
*
opti dime 2 elem qua4;
*
* une seule densite pour le maillage fluide
dens1= 0.025;
dens dens1;
*
p1= -0.5 -0.5;
p2= 0.5 -0.5;
p3= 0.5 0.5;
p4= -0.5 0.5;
p5= -0.1 -0.1;
p6= 0.1 -0.1;
p7= 0.1 0.1;
p8= -0.1 0.1;
p9= -0.1 -0.5;
p10= -0.1 0.5;
p11= 0.1 -0.5;
p12= 0.1 0.5;
p13= -0.8 -0.8;
p14= -0.5 -0.8;
p15= 0.5 -0.8;
p16= 0.8 -0.8;
p19= -0.5 0.8;
p17= 0.8 0.8;
p18= 0.5 0.8;
p20= -0.8 0.8;
p22= 0 -0.5;
p24= 0.5 0;
p26= 0 0.5;
p28= -0.5 0;
p33= 0 -0.1;
p34= 0.1 0;
p35= 0 0.1;
p36= -0.1 0;
*
* creation des surfaces
*
s1=dall (p1 d p9) (p9 d p36) (p36 d p28) (p28 d p1);
s2=dall (p11 d p2) (p2 d p24) (p24 d p34) (p34 d p11);
s3=dall (p8 d p35) (p35 d p26) (p26 d p10) (p10 d p8);
s4=dall (p9 d p22) (p22 d p33) (p33 d p5) (p5 d p9);
s6=dall (p13 d p14) (p14 d p19) (p19 d p20) (p20 d p13);
s7=dall (p15 d p16) (p16 d p17) (p17 d p18) (p18 d p15);
s8=dall (p14 d p15) (p15 d p2) (p2 d p1) (p1 d p14);
s9=dall (p4 d p3) (p3 d p18) (p18 d p19) (p19 d p4);
s10=dall (p28 d p36) (p36 d p10) (p10 d p4) (p4 d p28);
s11=dall (p34 d p24) (p24 d p3) (p3 d p12) (p12 d p34);
s12=dall (p35 d p7) (p7 d p12) (p12 d p26) (p26 d p35);
s13=dall (p22 d p11) (p11 d p6) (p6 d p33) (p33 d p22);
cha0=dall (p5 d p6) (p6 d p7) (p7 d p8) (p8 d p5);
*
* assemblage de toutes les surfaces sans la charge
*
a1= s11 et s12 et s1 et s4;
air0= s1 et s2 et s3 et s4 et s10 et s11 et s12 et s13;
air1= s6 et s7 et s8 et s9;
*
* assemblage du fluide par fusion des noeuds communs
*
flu1= cha0 et air0 et air1;
elim (flu1) (dens1/1000);
*
* noeuds pour la declaration de la frontiere externe: eulerienne
*
pflu1=chan 'POI1' flu1;
*trac pflu1;
seg1 = pflu1 POIN 'DROIT' p13 p16;
seg2 = pflu1 POIN 'DROIT' p16 p17;
seg3 = pflu1 POIN 'DROIT' p17 p20;
seg4 = pflu1 POIN 'DROIT' p20 p13;
eul0= seg1 et seg2 et seg3 et seg4;
*
* construction frontiere exterieure absorbante
*
abs0= (p13 d p16) et (p16 d p17) et (p17 d p20) et (p20 d p13);
*
flu0= flu1 et eul0 et abs0;
elim (flu0) (dens1/1000);
*
* creation de la structure
* - - - - - - - - - -
*
* deux densites pour le maillage de la structure
```

```
* correspondant aux cas conforme et non-conforme
*
* dens1 = dens conforme
* dens2 = dens non conforme
*
dens2= 2*dens1;
*
dens dens2;
p21 = -0.5 -0.5;
p25 = 0.5 0.5;
p29 = 0 -0.5;
p30 = 0.5 0;
p31 = 0 0.5;
p32 = -0.5 0;
*
dens dens1;
p23 = 0.5 -0.5;
p27 = -0.5 0.5;
p37 = 0 -0.5;
p38 = 0.5 0;
p39 = 0 0.5;
p40 = -0.5 0;
*
* creation de la structure
* - - - - - - - - - - - - - - - - - - - -
* 3 cas: structure conforme, structure non conforme, cas mixte
* cas mixte: 1 partie de la structure conforme 1 autre non conforme
* - - - - - - - - - - - - - - - - - - - -
*
* partie conforme dans le cas mixte
conf0= (p37 d p23) et (p23 d p38) et (p39 d p27) et (p27 d p40);
elim (conf0) (dens1/1000);
* partie non conforme dans le cas mixte
nconf0= (p21 d p29) et (p25 d p31) et (p32 d p21) et (p30 d p25);
elim (nconf0) (dens1/1000);
*
** cas conforme: on fusionne les noeuds de la structure (entre eux) et avec
** ceux du maillage fluide
*stru0= conf0 et nconf0;
*elim (stru0) (dens1/1000);
*mesh0= stru0 et flu0;
*elim (mesh0) (dens1/1000);
*
** cas non conforme: on fusionne les noeuds de la structure (entre eux) et on
** recupere la liste des noeuds fluide correspondant
*stru0= conf0 et nconf0;
*elim (stru0) (dens1/1000);
** noeuds correspondants a l'ensemble de la structure
*pair0=chan 'POI1' air0;
*seg5 = pair0 POIN 'DROIT' p1 p2;
*seg6 = pair0 POIN 'DROIT' p2 p3;
*seg7 = pair0 POIN 'DROIT' p3 p4;
*seg8 = pair0 POIN 'DROIT' p4 p1;
*noeF0= seg5 et seg6 et seg7 et seg8;
*mesh0= stru0 et flu0 et noeF0;
*elim (mesh0) (dens1/1000);
**
* cas mixte: on fusionne les noeuds des parties conformes avec les noeuds
fluide
* et on recupere la liste des noeuds fluides des parties correspondant aux
* parties non conformes
pa1=chan 'POI1' a1;
seg5 = pa1 POIN 'DROIT' p28 p1;
seg6 = pa1 POIN 'DROIT' p1 p9;
seg7 = pa1 POIN 'DROIT' p24 p3;
seg8 = pa1 POIN 'DROIT' p3 p12;
noeF0= seg5 et seg6 et seg7 et seg8;
mesh0= conf0 et flu0 et noeF0;
elim (mesh0) (dens1/1000);
mesh0= mesh0 et nconf0;
elim (nconf0 et conf0) (dens1/1000);
*
* post-traitement: VF ou l'on regarde la pression
*
e1 = air0 elem cont p1;
e2 = air0 elem cont p2;
e3 = air0 elem cont p3;
e4 = air0 elem cont p4;
e22 = air0 elem cont p22;
e24 = air0 elem cont p24;
e26 = air0 elem cont p26;
e28 = air0 elem cont p28;
ealic = e1 et e2 et e3 et e4 et e22 et e24 et e26 et e28;
mesh = mesh0 et ealic;
*
tass mesh;
opti sauv form 'TEST32.msh';
sauv form mesh;
opti trac psc ftra 'TEST32_mesh.ps';
trac qual mesh;
Fin;
```

The input file is:

```
TEST32
*------------------------------------------------------------------------
ECHO
$VERI
!CONV win
CAST MESH
*-------------------------------------------------------------Problem type
DPLA ALE
*-------------------------------------------------------------Dimensioning
DIME
 NALE 2000 NBLE 3887
TERM
*----------------------------------------------------------------Geometry
GEOM
  Q4VF air0 air1 cha0 ED01 conf0 nconf0 CL2D abs0
TERM
*-----------------------------------------------Geometrical complements
COMP COUL roug LECT cha0 TERM
          turq LECT air0 air1 TERM
     EPAI 0.01 LECT conf0 nconf0 TERM
     NGRO 1 'nstru' LECT conf0 nconf0 TERM
*-------------------------------------------------------------------ALE
GRIL LAGR LECT conf0 nconf0 TERM
     EULE LECT eul0 TERM
     AUTO AUTR
*-----------------------------------------------------------Material data
MATE
$ high-pressure perfect gas (explosive bubble)
          GAZP RO 1.3 GAMMA 1.4 PINI 100.E5 PREF 1.E5
          LECT cha0 TERM
$ air
          GAZP RO 1.3 GAMMA 1.4 PINI 1.E5 PREF 1.E5
          LECT air0 air1 TERM
$ structure
          VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT conf0 nconf0 TERM
$ absorbing boundary
          CLVF absorbant ro 1.4
          lect abs0 term
*----------------------------------------------------------------Outputs
ECRI
     VITE ECRO TFRE 100.E-3
     FICH ALIC TFRE 1.E-4
     FICH ALIC TEMP FREQ 1
          ELEM LECT ealic TERM
*-----------------------------------------------------------------Options
OPTI NOTEST
 csta 0.5e0
 step io
 log 1
 VFCC DUMP NCFS LECT noeF0 TERM
*-----------------------------------------------Transient calculation
CALCUL TINI 0 TEND 0.01E0
*=============================================================POST-TREATMENT
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
PLAY
CAME   1 EYE   0.00000E+00  0.00000E+00  4.50000E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.7E5 pas 0.4E5 5.9E5 term
          SUPP LECT air0 air1 cha0  TERM
     text isca
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air0 air1 cha0 TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
RESU ALIC GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
*
COUR  1 'dx_21'  DEPL COMP 1 NOEU LECT p21 TERM
COUR  2 'dx_23'  DEPL COMP 1 NOEU LECT p23 TERM
COUR  3 'dx_25'  DEPL COMP 1 NOEU LECT p25 TERM
COUR  4 'dx_27'  DEPL COMP 1 NOEU LECT p27 TERM
COUR  5 'dx_30'  DEPL COMP 1 NOEU LECT p30 TERM
COUR  6 'dx_32'  DEPL COMP 1 NOEU LECT p32 TERM
COUR  7 'dy_21'  DEPL COMP 2 NOEU LECT p21 TERM
COUR  8 'dy_23'  DEPL COMP 2 NOEU LECT p23 TERM
COUR  9 'dy_25'  DEPL COMP 2 NOEU LECT p25 TERM
COUR  10 'dy_27'  DEPL COMP 2 NOEU LECT p27 TERM
COUR  11 'dy_29'  DEPL COMP 2 NOEU LECT p29 TERM
COUR  12 'dy_31'  DEPL COMP 2 NOEU LECT p31 TERM
*
COUR 20 'pr_1'   ECRO COMP 1 ELEM LECT e1 TERM
COUR 21 'pr_2'   ECRO COMP 1 ELEM LECT e2 TERM
COUR 22 'pr_3'   ECRO COMP 1 ELEM LECT e3 TERM
COUR 23 'pr_4'   ECRO COMP 1 ELEM LECT e4 TERM
COUR 24 'pr_5'   ECRO COMP 1 ELEM LECT e22 TERM
COUR 25 'pr_6'   ECRO COMP 1 ELEM LECT e24 TERM
COUR 26 'pr_7'   ECRO COMP 1 ELEM LECT e26 TERM
COUR 27 'pr_8'   ECRO COMP 1 ELEM LECT e28 TERM
*
TRAC 1 2 3 4 5 6 7 8 9 10 11 12 AXES 1.0 'DISPL. [M]'
TRAC 20 21 22 23 24 25 26 27 AXES 1.0 'PRESS [PA]'
LIST 1 2 3 4 5 6 7 8 9 10 11 12 AXES 1.0 'DISPL. [M]'
LIST 20 21 22 23 24 25 26 27 AXES 1.0 'PRESS [PA]'
*
FIN
```

TEST35

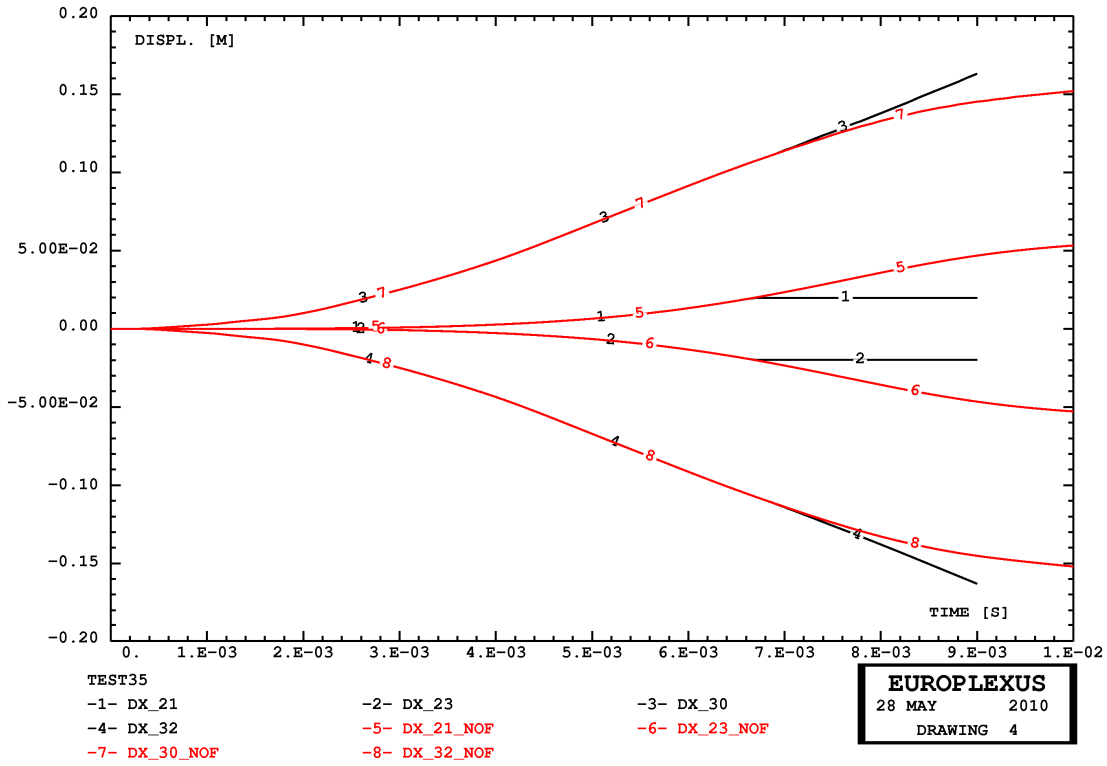
This test is identical to TEST32 but now the structure is allowed to fail. Erosion is applied upon structural failure. The mesh generation file is the same as in the previous case. The input file is:

```
TEST35
*------------------------------------------------------------------------
ECHO
$VERI
!CONV win
CAST MESH
*-------------------------------------------------------------Problem type
DPLA ALE EROS 0.0
*-------------------------------------------------------------Dimensioning
DIME
 NALE 2000 NBLE 3887
TERM
*----------------------------------------------------------------Geometry
GEOM
  Q4VF air0 air1 cha0 ED01 conf0 nconf0 CL2D abs0
TERM
*-----------------------------------------------Geometrical complements
COMP COUL roug LECT cha0 TERM
          turq LECT air0 TERM
     EPAI 0.01 LECT conf0 nconf0 TERM
     NGRO 1 'nstru' LECT conf0 nconf0 TERM
*-------------------------------------------------------------------ALE
GRIL LAGR LECT conf0 nconf0 TERM
     EULE LECT eul0 TERM
     AUTO AUTR
*-----------------------------------------------------------Material data
MATE
$ high-pressure perfect gas (explosive bubble)
          GAZP RO 1.3 GAMMA 1.4 PINI 100.E5 PREF 1.E5
          LECT cha0 TERM
$ air
          GAZP RO 1.3 GAMMA 1.4 PINI 1.E5 PREF 1.E5
          LECT air0 air1 TERM
$ structure
```

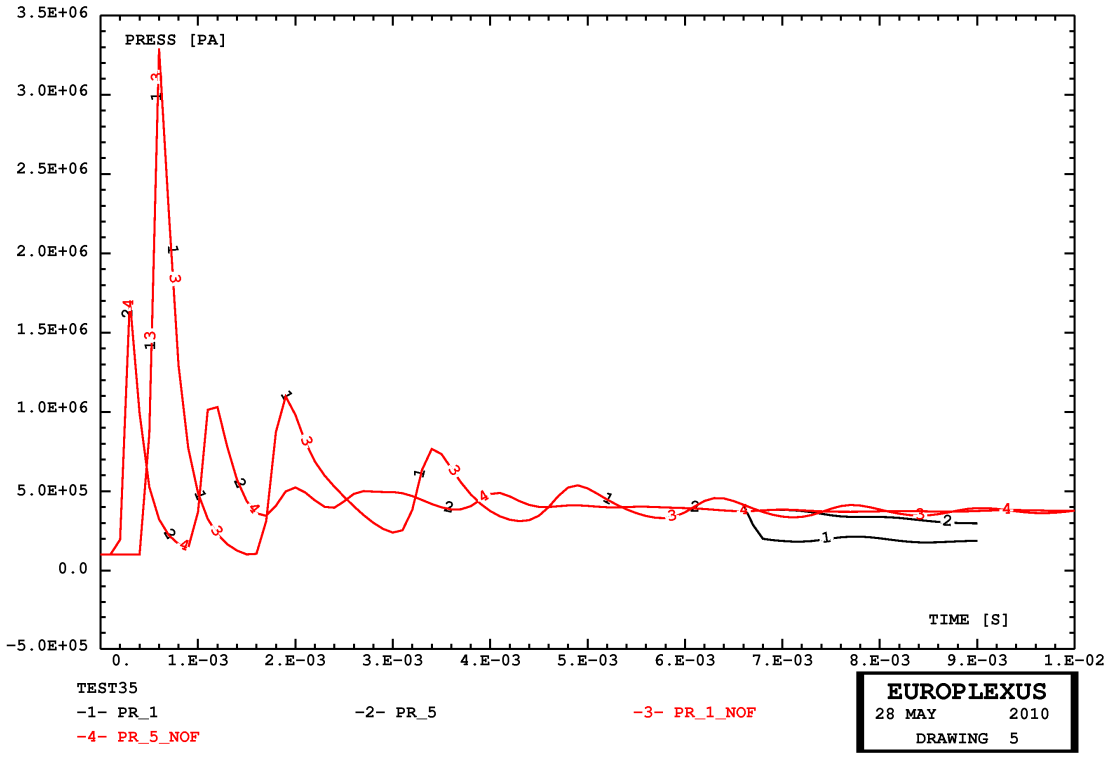
```
          VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          FAIL PEPS LIMI 0.038
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT conf0 TERM
          VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          FAIL PEPS LIMI 0.035
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT nconf0 TERM
$ absorbing boundary
          CLVF absorbant ro 1.4
          lect abs0 term
*-------------------------------------------------------------------Outputs
ECRI
     VITE ECRO TFRE 100.E-3
     FICH ALIC TFRE 1.E-4
     FICH ALIC TEMP FREQ 1
          ELEM LECT ealic TERM
*-------------------------------------------------------------------Options
OPTI NOTEST
 csta 0.5e0
 step io
 log 1
 VFCC DUMP NCFS LECT noeF0 TERM
*-----------------------------------------------------Transient calculation
CALCUL TINI 0 TEND 0.009E0
*============================================================POST-TREATMENT
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
PLAY
CAME   1 EYE   0.00000E+00  0.00000E+00  4.50000E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.7E5 pas 0.4E5 5.9E5 term
          SUPP LECT air0 air1 cha0  TERM
     text isca
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air0 air1 cha0 TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 91 fps 10 kfre 10 comp -1
     obje nfai lect tous term rend
freq 1
gotr loop 89 offs fich avi cont nocl
     obje nfai lect tous term rend
go
trac offs fich avi cont
     obje nfai lect tous term rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
RESU ALIC GARD PSCR
```

```
SORT GRAP
AXTE 1.0 'Time [s]'
*
* points structure
COUR  1 'dx_21'  DEPL COMP 1 NOEU LECT p21 TERM
COUR  2 'dx_23'  DEPL COMP 1 NOEU LECT p23 TERM
COUR  3 'dx_25'  DEPL COMP 1 NOEU LECT p25 TERM
COUR  4 'dx_27'  DEPL COMP 1 NOEU LECT p27 TERM
COUR  5 'dx_30'  DEPL COMP 1 NOEU LECT p30 TERM
COUR  6 'dx_32'  DEPL COMP 1 NOEU LECT p32 TERM
COUR  7 'dy_21'  DEPL COMP 2 NOEU LECT p21 TERM
COUR  8 'dy_23'  DEPL COMP 2 NOEU LECT p23 TERM
COUR  9 'dy_25'  DEPL COMP 2 NOEU LECT p25 TERM
COUR  10 'dy_27'  DEPL COMP 2 NOEU LECT p27 TERM
COUR  11 'dy_29'  DEPL COMP 2 NOEU LECT p29 TERM
COUR  12 'dy_31'  DEPL COMP 2 NOEU LECT p31 TERM
*
RCOU 101 'dx_21'  FICH 'test32.pun' RENA 'dx_21_nof'
RCOU 102 'dx_23'  FICH 'test32.pun' RENA 'dx_23_nof'
RCOU 105 'dx_30'  FICH 'test32.pun' RENA 'dx_30_nof'
RCOU 106 'dx_32'  FICH 'test32.pun' RENA 'dx_32_nof'
*
* points fluide
COUR  13 'dx_1'  DEPL COMP 1 NOEU LECT p1 TERM
COUR  14 'dx_2'  DEPL COMP 1 NOEU LECT p2 TERM
COUR  15 'dx_3'  DEPL COMP 1 NOEU LECT p3 TERM
COUR  16 'dx_4'  DEPL COMP 1 NOEU LECT p4 TERM
COUR  17 'dy_1'  DEPL COMP 2 NOEU LECT p1 TERM
COUR  18 'dy_2'  DEPL COMP 2 NOEU LECT p2 TERM
COUR  19 'dy_3'  DEPL COMP 2 NOEU LECT p3 TERM
COUR  20 'dy_4'  DEPL COMP 2 NOEU LECT p4 TERM
*
COUR 21 'pr_1'   ECRO COMP 1 ELEM LECT e1 TERM
COUR 22 'pr_2'   ECRO COMP 1 ELEM LECT e2 TERM
COUR 23 'pr_3'   ECRO COMP 1 ELEM LECT e3 TERM
COUR 24 'pr_4'   ECRO COMP 1 ELEM LECT e4 TERM
COUR 25 'pr_5'   ECRO COMP 1 ELEM LECT e22 TERM
COUR 26 'pr_6'   ECRO COMP 1 ELEM LECT e24 TERM
COUR 27 'pr_7'   ECRO COMP 1 ELEM LECT e26 TERM
COUR 28 'pr_8'   ECRO COMP 1 ELEM LECT e28 TERM
*
RCOU 121 'pr_1'   FICH 'test32.pun' RENA 'pr_1_nof'
RCOU 125 'pr_5'   FICH 'test32.pun' RENA 'pr_5_nof'
*
TRAC 1 2 3 4 5 6 7 8 9 10 11 12 AXES 1.0 'DISPL. [M]'
TRAC 13 14 15 16 17 18 19 20 AXES 1.0 'DISPL. [M]'
TRAC 21 22 23 24 25 26 27 28 AXES 1.0 'PRESS [PA]'
LIST 1 2 3 4 5 6 7 8 9 10 11 12 AXES 1.0 'DISPL. [M]'
LIST 13 14 15 16 17 18 19 20 AXES 1.0 'DISPL. [M]'
LIST 21 22 23 24 25 26 27 28 AXES 1.0 'PRESS [PA]'
TRAC 1 2 5 6 101 102 105 106 AXES 1.0 'DISPL. [M]'
     COLO noir noir noir noir roug roug roug roug
TRAC 21 25 121 125 AXES 1.0 'PRESS [PA]'
     COLO noir noir roug roug
*
*QUAL DEPL COMP 2 LECT 4    TERM REFE  1.77751E-3 TOLE 5.E-3
*     DEPL COMP 2 LECT 5    TERM REFE  1.77751E-3 TOLE 5.E-3
*     DEPL COMP 2 LECT 6    TERM REFE  1.77751E-3 TOLE 5.E-3
*     DEPL COMP 2 LECT 7    TERM REFE  1.77751E-3 TOLE 5.E-3
*     DEPL COMP 2 LECT 8    TERM REFE  1.77751E-3 TOLE 5.E-3
*     ECRO COMP 1 LECT 1    TERM REFE  9.97520E+4 TOLE 5.E-3
*     ECRO COMP 1 LECT 2    TERM REFE  9.97520E+4 TOLE 5.E-3
FIN
```

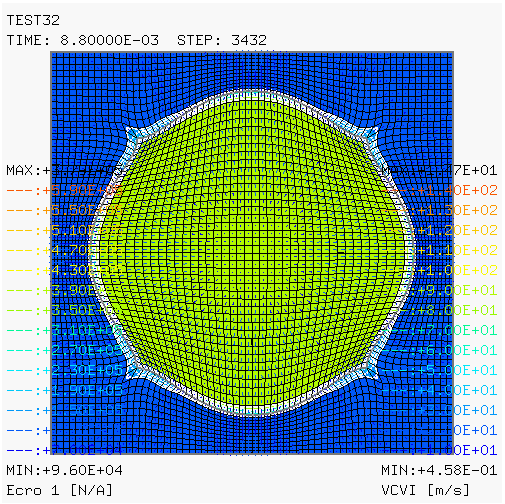
The structural displacements are (in red the case without failure, in black the case with failure):

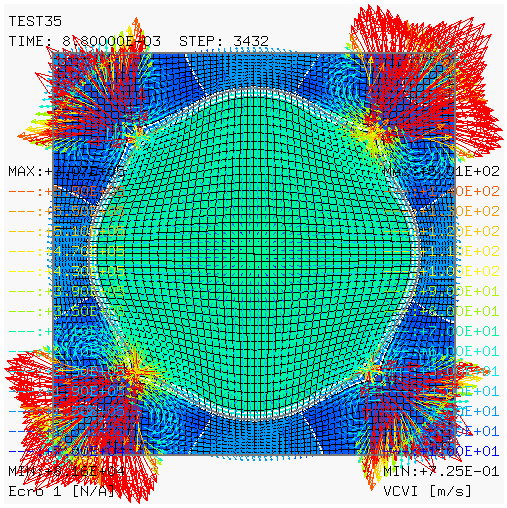


The fluid pressures are (in red the case without failure, in black the case with failure):



The final pressure and velocity maps for the cases without and with failure are:





Numerical Solutions (3D)

TEST38

This model uses non-conforming FSI. The structure is deformable but is not allowed to fail. The mesh generation file is:

```
*$siz 100
opti echo 1;
*
opti titr 'TEST38';
opti dime 3 elem cub8;
opti trac psc;
opti ftra 'TEST38_mesh.ps';
*
dens1= 0.5;
dens2=1.0;
```

```
*
dens dens1;
p0 = 0 0 0;
p1 = -5 -5 -5;
p2 = 5 -5 -5;
p3 = 5 5 -5;
p4 = -5 5 -5;
p5 = -5 -5 5;
p6 = 5 -5 5;
p7 = 5 5 5;
```

```
p8 = -5 5 5;
p91 = -2.5 -2.5 -2.5;
p151= 2.5 2.5 2.5;
tol = 0.01;
*
c1 = p1 d p2;
c2 = p2 d p3;
c3 = p3 d p4;
c4 = p4 d p1;
*
base = dall c1 c2 c3 c4 plan;
flu0 = base volu tran 20 (0 0 10);
abs0 = enve flu0;
elim tol (flu0 et p0 et p5 et p6 et p7 et p8);
expl1 = flu0 elem 'APPU' 'LARG' p0;
air1 = diff flu0 expl1;
expl2 = air1 elem 'APPU' 'LARG' expl1;
expl = expl1 et expl2;
air = diff flu0 expl;
*trak air;
*trak expl;
*
r1 = air elem 'APPU' 'LARG' expl;
r3 = (air elem 'APPU' 'LARG' r1) diff r1;
r2 = air diff (r1 et r3);
r1 = expl et r1;
r5 = air elem 'APPU' 'LARG' r3;
elim tol (p91 et p151 et r5);
r6= r5 et expl;
eflu1=enve r6;
noef0=chan 'POI1' eflu1;
*trak eflu1;
*trac noef0;
*
dens dens2;
p9 = -2.5 -2.5 -2.5;
p10= 2.5 -2.5 -2.5;
p11= 2.5 2.5 -2.5;
p12= -2.5 2.5 -2.5;
p13= -2.5 -2.5 2.5;
p14= 2.5 -2.5 2.5;
p15= 2.5 2.5 2.5;
p16= -2.5 2.5 2.5;
*
p17= 2.5 -0.5 -0.5;
p18= 0.5 2.5 0.5;
p19= 0.5 0.5 2.5;
*
stru1 = dall (p9 d p10) (p10 d p11) (p11 d p12) (p12 d p9)
plan;
stru2 = dall (p13 d p16) (p16 d p15) (p15 d p14) (p14 d p13)
plan;
```

```
stru3 = dall (p9 d p13) (p13 d p14) (p14 d p10) (p10 d p9)
plan;
stru4 = dall (p11 d p10) (p10 d p14) (p14 d p15) (p15 d p11)
plan;
stru5 = dall (p12 d p11) (p11 d p15) (p15 d p16) (p16 d p12)
plan;
stru6 = dall (p9 d p12) (p12 d p16) (p16 d p13) (p13 d p9)
plan;
stru0 = stru1 et stru2 et stru3 et stru4 et stru5 et stru6;
elim tol stru0;
elim tol (stru0 et p17 et p18 et p19);
*
pcx1 = -2.5 0 0;
pcx2 =  2.5 0 0;
pcy1 =  0 -2.5 0;
pcy2 =  0  2.5 0;
pcz1 =  0 0 -2.5;
pcz2 =  0 0  2.5;
elim tol (pcx1 et pcx2 et pcy1 et pcy2 et pcz1 et pcz2 et stru0);
tpln = pcx1 et pcx2 et pcy1 et pcy2 et pcz1 et pcz2;
*
ex1 = r5 elem cont pcx1;
ex2 = r5 elem cont pcx2;
ey1 = r5 elem cont pcy1;
ey2 = r5 elem cont pcy2;
ez1 = r5 elem cont pcz1;
ez2 = r5 elem cont pcz2;
e9 = r5 elem cont p91;
e15 = r5 elem cont p151;
ealic = ex1 et ex2 et ey1 et ey2 et ez1 et ez2 et e9 et e15;
*
mesh0= flu0 et abs0 et noef0 et tpln et ealic;
elim tol mesh0;
mesh=mesh0 et stru0;
*
tass mesh;
trac cach qual mesh;
trac cach (expl et stru0 et abs0);
trac cach (r1 et stru0);
trac cach (r2 et stru0);
trac cach (r3 et stru0);
*
opti sauv form 'TEST38.msh';
sauv form mesh;
*
list (nbel flu0);
list (nbno flu0);
list (nbel abs0);
list (nbno abs0);
list (nbel stru0);
list (nbno stru0);
fin;
```

The input file is:

```
TEST38
*------------------------------------------------------------------------
ECHO
!CONV win
CAST MESH
*-------------------------------------------------------------Problem type
TRID ALE
*-------------------------------------------------------------Dimensioning
DIME
 NALE 2000 NBLE 6859 ZONE 4
TERM
*-----------------------------------------------------------------Geometry
GEOM
  CUVF flu0 Q4GS stru0 CL3D abs0
TERM
*-----------------------------------------------Geometrical complements
COMP EPAI 0.01 LECT stru0 TERM
     GROU 3 'fy_gt_0' LECT flu0 TERM COND YB GT 0
            'sy_gt_0' LECT stru0 TERM COND YB GT -0.01
            'y_gt_0' LECT fy_gt_0 sy_gt_0 TERM
     COUL roug LECT expl TERM
          turq LECT air TERM
          jaun LECT stru0 TERM
          jaun LECT sy_gt_0 TERM
*-------------------------------------------------------------------------ALE
GRIL LAGR LECT stru0 TERM
     EULE LECT abs0 TERM
     AUTO AUTR
*-----------------------------------------------------------------Material data
MATE
$ air
          GAZP RO 1.3 GAMMA 1.4 PINI 1.E5 PREF 1.E5
          LECT air TERM
$ high-pressure perfect gas (explosive bubble)
          GAZP RO 1.3 GAMMA 1.4 PINI 100.E5 PREF 1.E5
          LECT expl TERM
$ structure
          VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru0 TERM
$ absorbing boundary
          CLVF absorbant ro 1.4
          lect abs0 term
*-----------------------------------------------------------------Liaison
LINK COUP
 REGI 'r_in' TOUT LECT r1 TERM
      'r_out' TOUT LECT r2 TERM
      'r_mid' TOUT LECT r3 TERM
      'r_abs' TOUT LECT abs0 TERM
*-------------------------------------------------------------------Outputs
ECRI
 DEPL VITE ACCE FINT FEXT TFRE 0.01D0 !FREQ 10
 FICH ALIC FREQ 1
*-----------------------------------------------------------------Options
OPTI NOTE
 csta 0.5 log 1
 VFCC DUMP NCFS LECT noef0 TERM
*-----------------------------------------------Transient calculation
CALCUL TINI 0. TEND 0.02D0
*=====================================================================
SUIT
Post treatment
ECHO
 conv win
```

```
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
PLAY
CAME 1 EYE 2.08771E+01 -2.07253E+01 3.17743E+01
       VIEW -4.82136E-01 4.78631E-01 -7.33796E-01
       RIGH 8.29814E-01 5.18117E-01 -2.07274E-01
       UP -2.80985E-01 7.08849E-01 6.46978E-01
       FOV 2.48819E+01
SCEN GEOM NAVI FREE
FACE SBAC
REFE FRAM
     ISO FELE FIEL ECRO 1
          SCAL USER PROG 0.9E5 PAS 0.5E5 7.4E5 TERM
     SUPP LECT fy_gt_0 TERM
     TEXT ISCA
     VECT SCCO SCAL USER PROG 5. PAS 5. 70. TERM
     TEXT VSCA
     COLO PAPE
LIMA ON
SLER CAM1 1 NFRA 1
TRAC OFFS FICH AVI NOCL NFTO 201 FPS 15 KFRE 10 COMP -1
OBJE LECT fy_gt_0 sy_gt_0 TERM REND
FREQ 1
GOTR LOOP 199 OFFS FICH AVI CONT NOCL
OBJE LECT fy_gt_0 sy_gt_0 TERM REND
GO
TRAC OFFS FICH AVI CONT
OBJE LECT fy_gt_0 sy_gt_0 TERM REND
ENDPLAY
*=====================================================================
SUIT
Post-treatment
ECHO
*
RESU ALIC GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 1 'dx_pcx1' DEPL COMP 1 NOEU LECT pcx1 TERM
COUR 2 'dx_pcx2' DEPL COMP 1 NOEU LECT pcx2 TERM
COUR 3 'dx_pcy1' DEPL COMP 2 NOEU LECT pcy1 TERM
COUR 4 'dx_pcy2' DEPL COMP 2 NOEU LECT pcy2 TERM
COUR 5 'dx_pcz1' DEPL COMP 3 NOEU LECT pcz1 TERM
COUR 6 'dx_pcz2' DEPL COMP 3 NOEU LECT pcz2 TERM
*
COUR 20 'pr_ex1'   ECRO COMP 1 ELEM LECT ex1 TERM
COUR 21 'pr_ex2'   ECRO COMP 1 ELEM LECT ex2 TERM
COUR 22 'pr_ey1'   ECRO COMP 1 ELEM LECT ey1 TERM
COUR 23 'pr_ey2'   ECRO COMP 1 ELEM LECT ey2 TERM
COUR 24 'pr_ez1'   ECRO COMP 1 ELEM LECT ez1 TERM
COUR 25 'pr_ez2'   ECRO COMP 1 ELEM LECT ez2 TERM
COUR 26 'pr_e9'    ECRO COMP 1 ELEM LECT e9  TERM
COUR 27 'pr_e15'   ECRO COMP 1 ELEM LECT e15 TERM
*
TRAC 1 2 3 4 5 6 axes 1.0 'DISPL. [M]' yzer
TRAC 20 21 22 23 24 25 26 27 AXES 1.0 'PRESS [PA]'
LIST 1 2 3 4 5 6 axes 1.0 'DISPL. [M]' yzer
LIST 20 21 22 23 24 25 26 27 AXES 1.0 'PRESS [PA]'
*=====================================================================
FIN
```

TEST40

This test is identical to TEST38 but now the structure is allowed to fail. Erosion is applied upon structural failure. The mesh generation file is the same as in the previous case. The input file is:

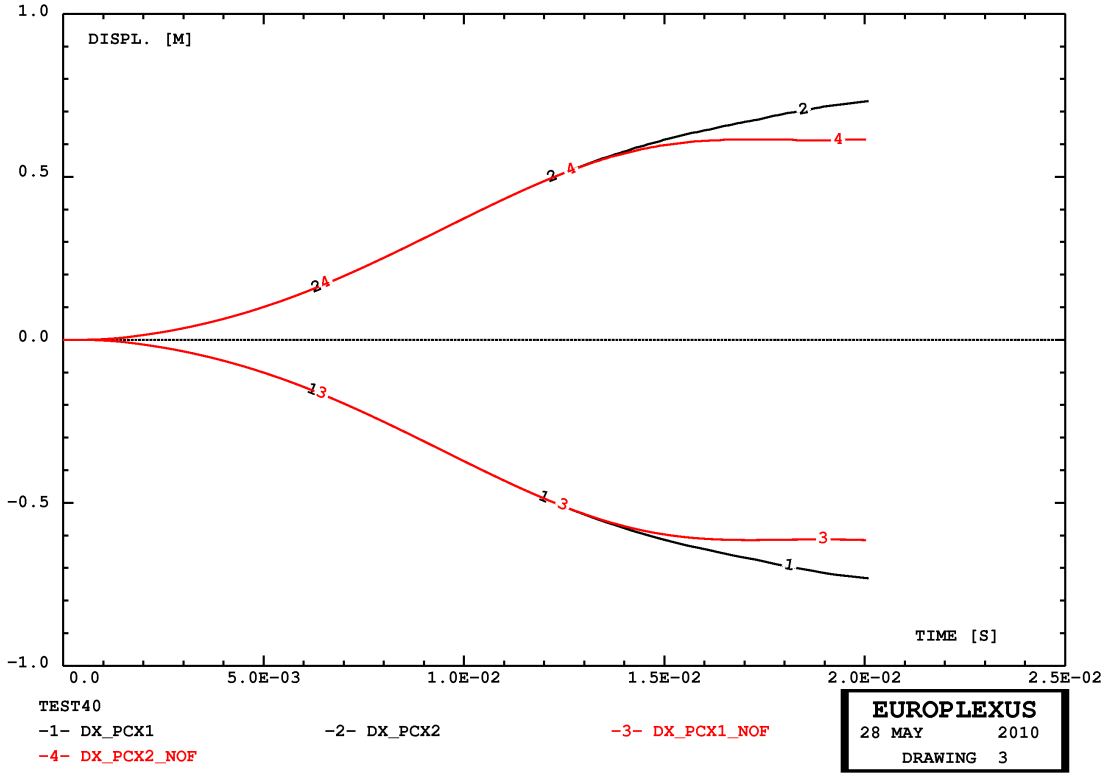
```
TEST40
*------------------------------------------------------------------------
ECHO
!CONV win
CAST MESH
*-------------------------------------------------------------Problem type
TRID ALE EROS 0.0
```

```
*-------------------------------------------------------------Dimensioning
DIME
 NALE 2000 NBLE 6859
TERM
*-----------------------------------------------------------------Geometry
GEOM
  CUVF flu0 Q4GS stru0 CL3D abs0
```

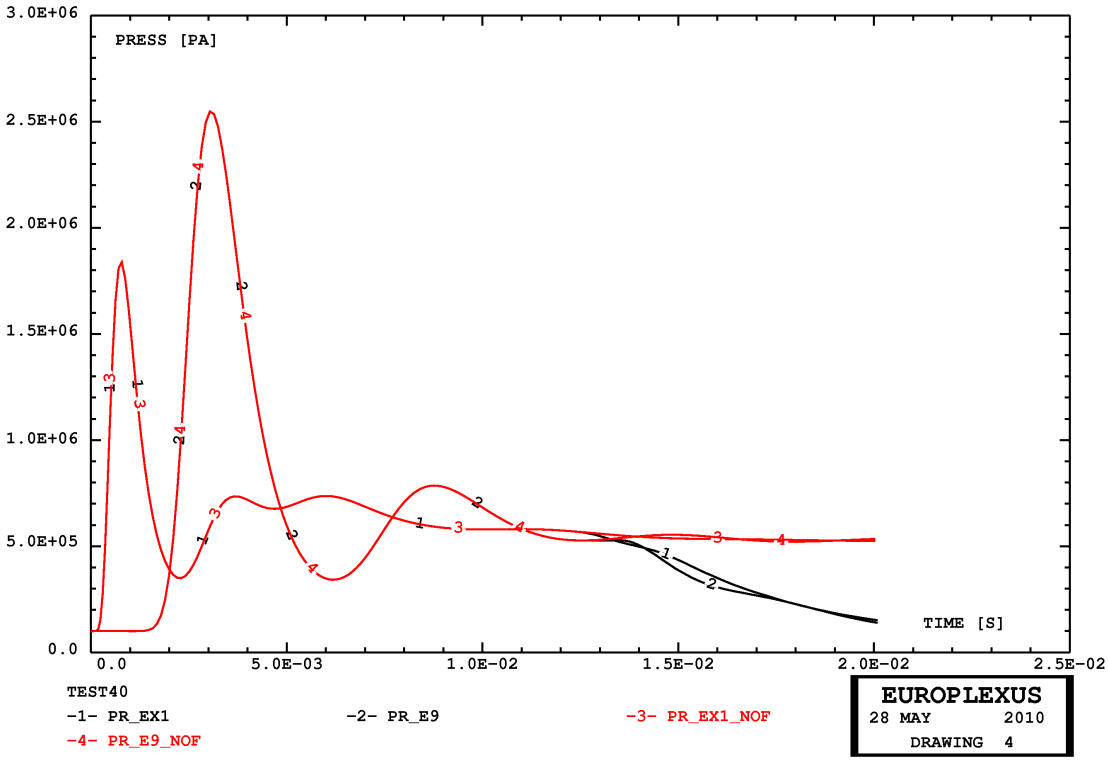
```
TERM
*-------------------------------------------------Geometrical complements
COMP EPAI 0.01 LECT stru0 TERM
     GROU 3 'fy_gt_0' LECT flu0 TERM COND YB GT 0
            'sy_gt_0' LECT stru0 TERM COND YB GT -0.01
            'y_gt_0' LECT fy_gt_0 sy_gt_0 TERM
     COUL roug LECT expl TERM
          turq LECT air TERM
          jaun LECT stru0 TERM
          jaun LECT sy_gt_0 TERM
*-------------------------------------------------------------------------ALE
GRIL LAGR LECT stru0 TERM
     EULE LECT abs0 TERM
     AUTO AUTR
*-----------------------------------------------------------Material data
MATE
$ air
          GAZP RO 1.3 GAMMA 1.4 PINI 1.E5 PREF 1.E5
          LECT air TERM
$ high-pressure perfect gas (explosive bubble)
          GAZP RO 1.3 GAMMA 1.4 PINI 100.E5 PREF 1.E5
          LECT expl TERM
$ structure
          VMZ3 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          FAIL PEPS LIMI 0.035
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru0 TERM
$ absorbing boundary
          CLVF absorbant ro 1.4
          lect abs0 term
*-------------------------------------------------------------------Liaison
LINK COUP
 REGI 'r_in' TOUT LECT r1 TERM
      'r_out' TOUT LECT r2 TERM
      'r_mid' TOUT LECT r3 TERM
      'r_abs' TOUT LECT abs0 TERM
*-------------------------------------------------------------------Outputs
ECRI
 DEPL VITE ACCE FINT FEXT TFRE 0.01D0 !FREQ 10
 FICH ALIC FREQ 1
*-------------------------------------------------------------------Options
OPTI NOTE
 csta 0.5 log 1
 VFCC DUMP NCFS LECT noef0 TERM
*-----------------------------------------------Transient calculation
CALCUL TINI 0. TEND 0.02D0
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
PLAY
CAME 1 EYE 2.08771E+01 -2.07253E+01 3.17743E+01
       VIEW -4.82136E-01 4.78631E-01 -7.33796E-01
       RIGH 8.29814E-01 5.18117E-01 -2.07274E-01
       UP -2.80985E-01 7.08849E-01 6.46978E-01
       FOV 2.48819E+01
SCEN GEOM NAVI FREE
```

```
FACE SBAC
REFE FRAM
     ISO FELE FIEL ECRO 1
          SCAL USER PROG 0.9E5 PAS 0.5E5 7.4E5 TERM
     SUPP LECT fy_gt_0 TERM
     TEXT ISCA
     VECT SCCO SCAL USER PROG 5. PAS 5. 70. TERM
     TEXT VSCA
     COLO PAPE
LIMA ON
SLER CAM1 1 NFRA 1
TRAC OFFS FICH AVI NOCL NFTO 201 FPS 15 KFRE 10 COMP -1
OBJE nfai LECT fy_gt_0 sy_gt_0 TERM REND
FREQ 1
GOTR LOOP 199 OFFS FICH AVI CONT NOCL
OBJE nfai LECT fy_gt_0 sy_gt_0 TERM REND
GO
TRAC OFFS FICH AVI CONT
OBJE nfai LECT fy_gt_0 sy_gt_0 TERM REND
ENDPLAY
*=================================================================
SUIT
Post-treatment
ECHO
*
RESU ALIC GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 1 'dx_pcx1' DEPL COMP 1 NOEU LECT pcx1 TERM
COUR 2 'dx_pcx2' DEPL COMP 1 NOEU LECT pcx2 TERM
COUR 3 'dx_pcy1' DEPL COMP 2 NOEU LECT pcy1 TERM
COUR 4 'dx_pcy2' DEPL COMP 2 NOEU LECT pcy2 TERM
COUR 5 'dx_pcz1' DEPL COMP 3 NOEU LECT pcz1 TERM
COUR 6 'dx_pcz2' DEPL COMP 3 NOEU LECT pcz2 TERM
RCOU 101 'dx_pcx1' FICH 'test38.pun' RENA 'dx_pcx1_nof'
RCOU 102 'dx_pcx2' FICH 'test38.pun' RENA 'dx_pcx2_nof'
*
COUR 20 'pr_ex1'   ECRO COMP 1 ELEM LECT ex1 TERM
COUR 21 'pr_ex2'   ECRO COMP 1 ELEM LECT ex2 TERM
COUR 22 'pr_ey1'   ECRO COMP 1 ELEM LECT ey1 TERM
COUR 23 'pr_ey2'   ECRO COMP 1 ELEM LECT ey2 TERM
COUR 24 'pr_ez1'   ECRO COMP 1 ELEM LECT ez1 TERM
COUR 25 'pr_ez2'   ECRO COMP 1 ELEM LECT ez2 TERM
COUR 26 'pr_e9'    ECRO COMP 1 ELEM LECT e9  TERM
COUR 27 'pr_e15'   ECRO COMP 1 ELEM LECT e15 TERM
RCOU 120 'pr_ex1' FICH 'test38.pun' RENA 'pr_ex1_nof'
RCOU 126 'pr_e9'  FICH 'test38.pun' RENA 'pr_e9_nof'
*
TRAC 1 2 3 4 5 6 axes 1.0 'DISPL. [M]' yzer
TRAC 20 21 22 23 24 25 26 27 AXES 1.0 'PRESS [PA]'
LIST 1 2 3 4 5 6 axes 1.0 'DISPL. [M]' yzer
LIST 20 21 22 23 24 25 26 27 AXES 1.0 'PRESS [PA]'
TRAC 1 2 101 102 axes 1.0 'DISPL. [M]' yzer
     COLO noir noir roug roug
TRAC 20 26 120 126 AXES 1.0 'PRESS [PA]'
     COLO noir noir roug roug
*=================================================================
FIN
```

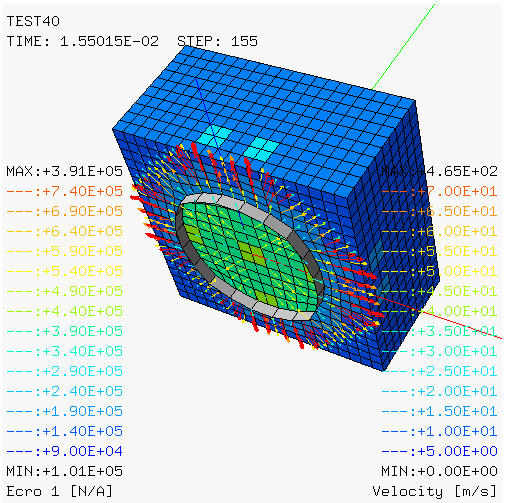
The structural displacements are (in red the case without failure, in black the case with failure):

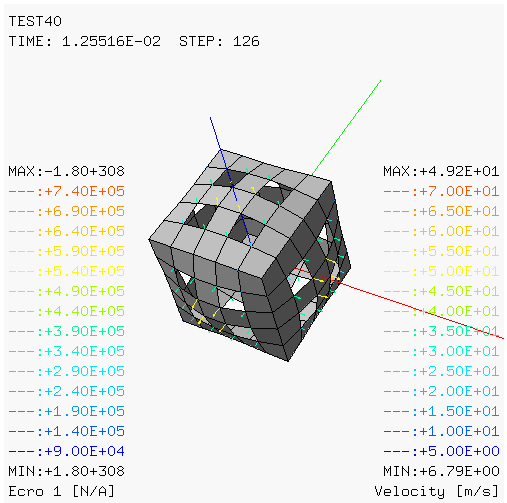


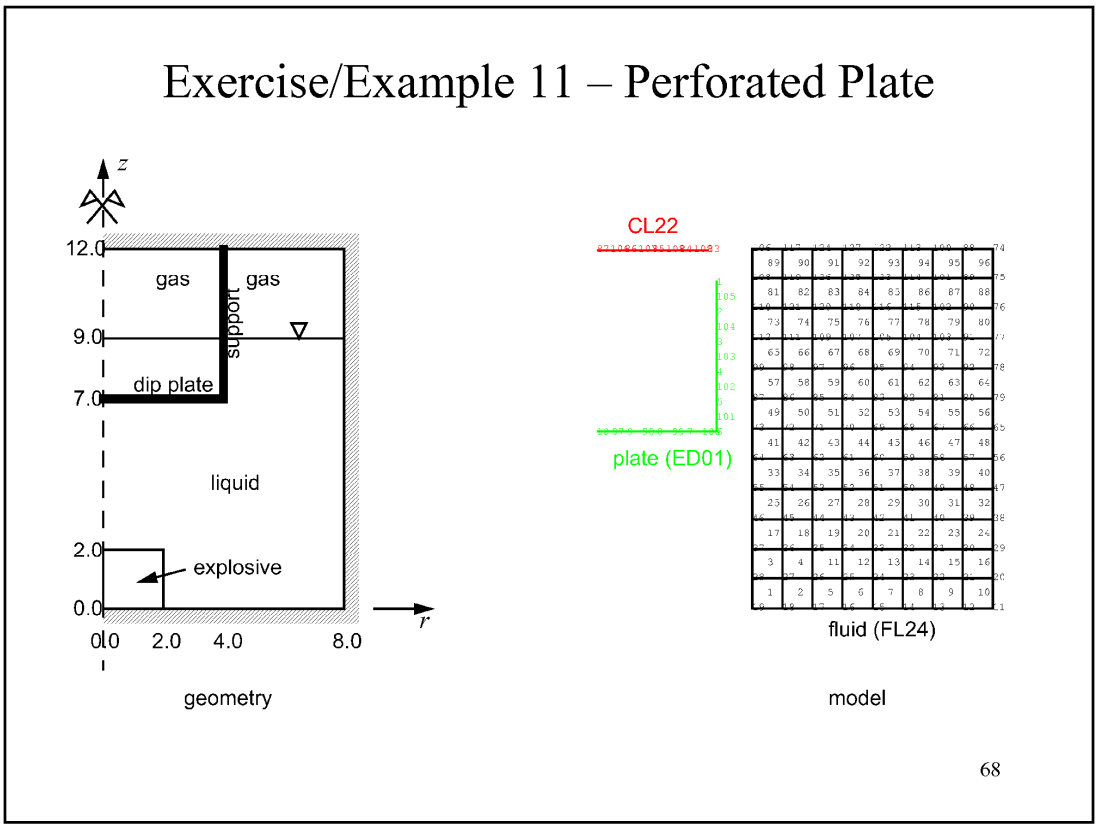
The fluid pressures are (in red the case without failure, in black the case with failure):



The final pressure and velocity maps and the structural failure (for the case with failure) are:







TITLE:
PPLA04: unsteady flow through a deformable perforated plate.

PROBLEM:
An explosion takes place in a rigid tank containing a deformable perforated plate. The plate is submerged below an initial liquid head and is supported along the circumference by elastoplastic supports. A cover gas is initially located in the upper part of the tank. The calculation is axisymmetric.

MESH:
The fluid is meshed by FL24 elements, the plate and its support by ED01 conical shell elements. Special CL22 boundary condition elements are used to represent the coupling between the fluid and the plate. Note that the fluid may freely flow across the support, since there is no coupling between them.

MATERIALS:
FLUT fluid materials are used for the three fluids involved (explosive, liquid and cover gas). The deformable structures use an elasto-plastic material law. An impedance material (IMPE PPLA) is assigned to the boundary condition elements. This represents the pressure drop across the plate, with a given (constant) resistance coefficient.

BOUNDARY CONDITIONS:
The tank is rigid but the inner structures (plate, support) are deformable. Coupling between the plate and the fluid is realized by CL22 elements.

LOADING:
The event is initiated by the expansion of the high-pressure explosive gas bubble.

CALCULATION:
The calculation is performed up to a final time of 80 ms.

RESULTS:
They are analyzed in the reference cited below.

POST-TREATMENT
An animation is produced.

REFERENCES:
This problem is detailed, and the results are analyzed, in the following reference:
1) F. Casadei: “New Boundary Condition Models for Compressible Fluid Flows in PLEXIS-3C.” Technical Note N. I.94.75, May 1994.

Numerical Solution

PPLA04

The mesh generation file reads:

```
*%siz 50
opti echo 1;
*
opti titr 'PPLA - 04';
opti dime 2 elem qua4;
*
p0=0 0;
p1=2 0;
p2=8 0;
p3=0 7;p3p=p3 plus p0;
p4=4 7;p4p=p4 plus p0;
p5=0 9;
p6=8 9;
p7=0 12;
p8=4 12;
p9=8 12;
p10=0 2;
p11=2 2;
p12=8 2;
*
tol=0.01;
*
c1=p0 d 2 p1;
c2=p1 d 2 p11;
c3=p11 d 2 p10;
c4=p10 d 2 p0;
expl=daller c1 c2 c3 c4 plan;
lag=chan poi1 c2;
lag=lag et (chan poi1 c3);
*
c1=p1 d 6 p2;
c2=p2 d 2 p12;
c3=p12 d 6 p11;
c4=p11 d 2 p1;
liq1=daller c1 c2 c3 c4 plan;
*
c1=p10 d 8 p12;
c2=p12 d 7 p6;
c3=p6 d 8 p5;
c4=p5 d 7 p10;
liq2=daller c1 c2 c3 c4 plan;
lag=lag et (chan poi1 c3);
*
c1=p5 d 8 p6;
c2=p6 d 3 p9;
c3=p9 d 8 p7;
c4=p7 d 3 p5;
gas=daller c1 c2 c3 c4 plan;
*
liqu=liq1 et liq2;
flui=expl et liqu et gas;
*
clim=p3 d 4 p4;
*
elim tol (flui et clim);
*
plat=p3p d 4 p4p;
supp=p4p d 5 p8;
stru=plat et supp;
lag=lag et (chan poi1 stru);
lag=lag et p0 et p2 et p7 et p9;
*
mesh=flui et clim et stru;
*
blocx=mesh poin droi p0 p7 tol;
blocx=blocx et (mesh poin droi p2 p9 tol);
blocy=mesh poin droi p0 p2 tol;
blocy=blocy et (mesh poin droi p7 p9 tol);
blocr=p3p et p8;
*
mesh=mesh et blocx et blocy et blocr et lag;
tass mesh;
*
opti sauv form 'ppla04.msh';
sauv form mesh;
opti trac ps ftra 'ppla04_mesh.ps';
trac qual mesh;
fin;
```

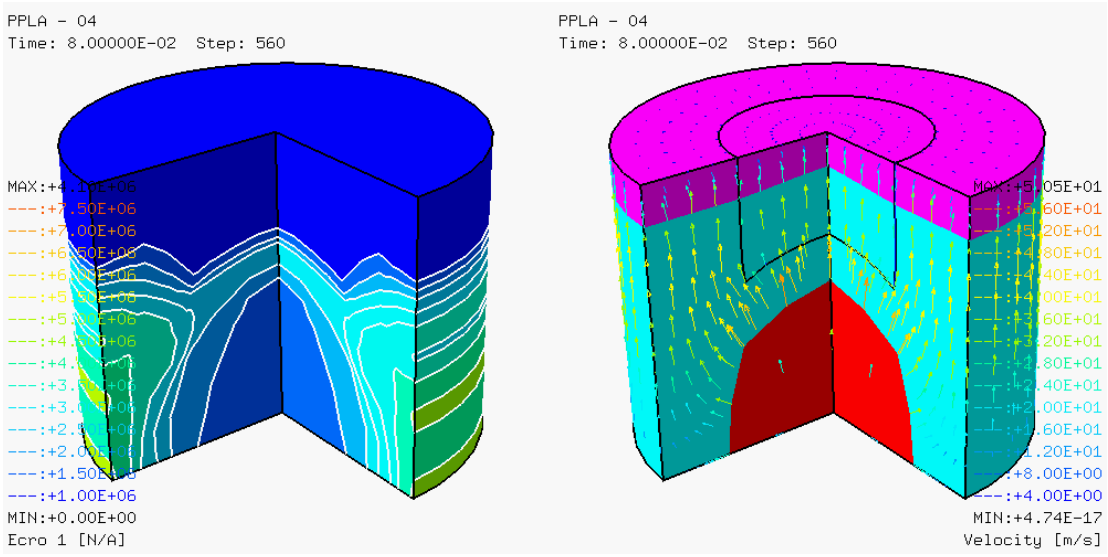
The EUROPLEXUS input file reads:

```
PPLA - 04
$
ECHO
*CONV win
AXIS NONL ALE
CAST MESH
$
DIME
PT2L 117 PT3L 10 FL24 96 ED01 9 CL22 4 ZONE 3
NALE 5 BLOQ 48
 mtpo 2 mtel 2
TERM
$
GEOM FL24 FLUI ED01 STRU CL22 CLIM TERM
$
COMPL
EPAI 0.05  LECT PLAT TERM
     0.10  LECT SUPP TERM
$
GRIL LAGR LECT LAG TERM
     ALE  LECT FLUI TERM
     AUTO AUTR
$
MATE VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT STRU TERM
     FLUT RO 832. EINT 98.68 GAMM 7.15D0 CL 0.5
          CQ 2.56 PB 2.71E5 PMIN 0. AHGF 0. ITER 2
          ALF0 1. BET0 1. KINT 0 NUM 5
          LECT LIQU TERM
     FLUT RO 2.4278E3 EINT 0. GAMM 0.75D0 CL 0.5
          CQ 2.56 PB 0. PMIN 0. AHGF 0. ITER 2
          ALF0 1. BET0 1. KINT 0 NUM 4
          LECT EXPL TERM
     FLUT RO .242777373 EINT 6.865E5 GAMM 1.6 CL 0.5
          CQ 2.56 PB 0. PMIN 0. AHGF 0. ITER 2
          ALF0 1. BET0 1. KINT 0 NUM 1
          LECT  GAS TERM
     IMPE PPLT ZETA 10.0
          LECT CLIM TERM
$
LIAI freq 1
     BLOQ 1 LECT BLOCX TERM
     BLOQ 2 LECT BLOCY TERM
     BLOQ 3 LECT BLOCR TERM
$
ECRI VITE ECRO TFRE 40.E-3
     FICH K200 TFRE 10.E-3
               POIN TOUS CHAM
     TRAC TPLO DESC 'PPLA04' TFRE 10.5E-6
                POIN LECT 9 118 TERM
                ELEM LECT 1 106 TERM
     fich alic temp FREQ 1
                 poin lect 9 118 term
                 elem lect 1 106 term
     fich alic tfre 1.e-3
$
OPTI NOTEST
 log 1
$
CALCUL TINI 0. TEND 80.E-3
*
SUIT
Post-treatment
```

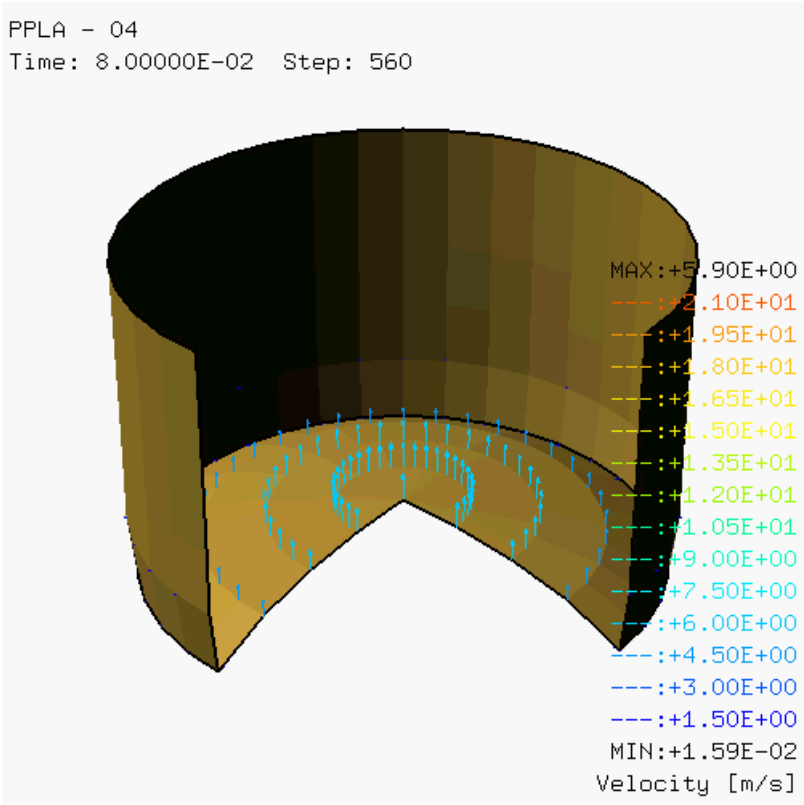
```
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR 1 'dx_9'   DEPL COMP 1 NOEU LECT 9   TERM
COUR 2 'dy_9'   DEPL COMP 2 NOEU LECT 9   TERM
COUR 3 'dy_118' DEPL COMP 2 NOEU LECT 118 TERM
COUR 4 'p_1'    ECRO COMP 1 ELEM LECT 1   TERM
COUR 5 'dp_106' ECRO COMP 1 ELEM LECT 106 TERM
*
```

```
trac 1 2 3 axes 1.0 'DISPL. [M]'
trac 4     axes 1.0 'P [PA]'
trac 5     axes 1.0 'DELTAP [PA]'
*
QUAL DEPL COMP 1 LECT   9 TERM REFE  2.09508E+0 TOLE 5.E-3
     DEPL COMP 2 LECT   9 TERM REFE  2.41317E+0 TOLE 5.E-3
     DEPL COMP 2 LECT 118 TERM REFE  8.67547E-1 TOLE 5.E-3
     ECRO COMP 1 LECT   1 TERM REFE  1.17908E+6 TOLE 5.E-3
     ECRO COMP 1 LECT 106 TERM REFE  2.85752E+6 TOLE 5.E-3
*
FIN
```

Some results: final fluid pressure and velocity:

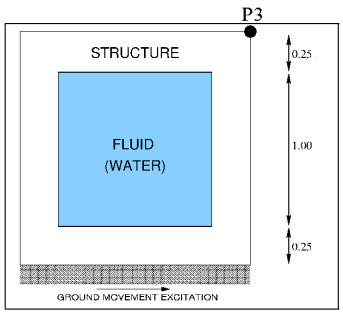


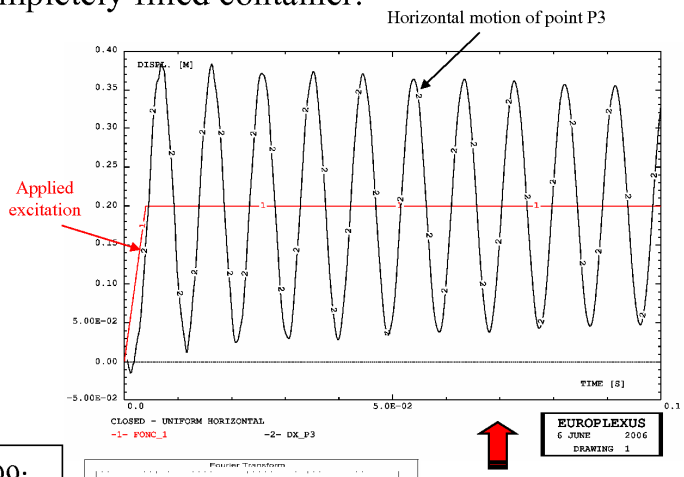
Final structure velocities:



Exercise/Example 12 – Sloshing (Courtesy of CRS4)

• A - Vibration of a completely filled container:

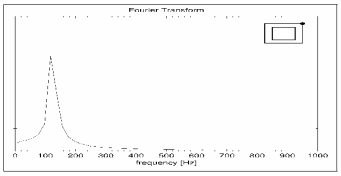




Bermudez & Rodriguez, 1999:

• 1st mode frequency : 117 Hz

• Estimated frequency : 102 Hz



Computed frequency: 106 Hz

71

PROBLEM:
A deformable tank completely filled with a liquid is accelerated by a linear ramp-like excitation in the horizontal direction applied to the base.

MESH:
The fluid is meshed by CAR1 elements, the deformable tank also by CAR1 elements. The calculation is plane strain (DPLA) and is declared of the NAVI type. In this way, incompressibility is automatically enforced for all CAR1 elements that are associated with a LIQU material (the fluid mesh, in this case).

MATERIALS:
The fluid is modelled by the LIQU material (density 1000), while the tank uses a linear elastic material (LINE).

BOUNDARY CONDITIONS:
The motion of the tank base is imposed in the horizontal direction. FSA fluid-structure interaction is used along the whole fluid-structure interface.

LOADING:
An imposed horizontal displacement with a ramp-like shape (20 cm in 4 ms) is imposed at the tank base.

CALCULATION:
The calculation is performed up to a final time of 100 ms. The NAVI condition would allow a very large stability step in the fluid elements, but in this case the integration step is dictated by the structural part.

RESULTS:
A paper by Bermudez and Rodriguez (1999) predicts a 1st mode oscillation frequency of 117 Hz according to a linearized theory, and an estimated frequency of 102 Hz. The numerically computed frequency is 106 Hz, in good agreement with the estimation.

POST-TREATMENT
Animations are produced.

Numerical Solution

CLOSED4

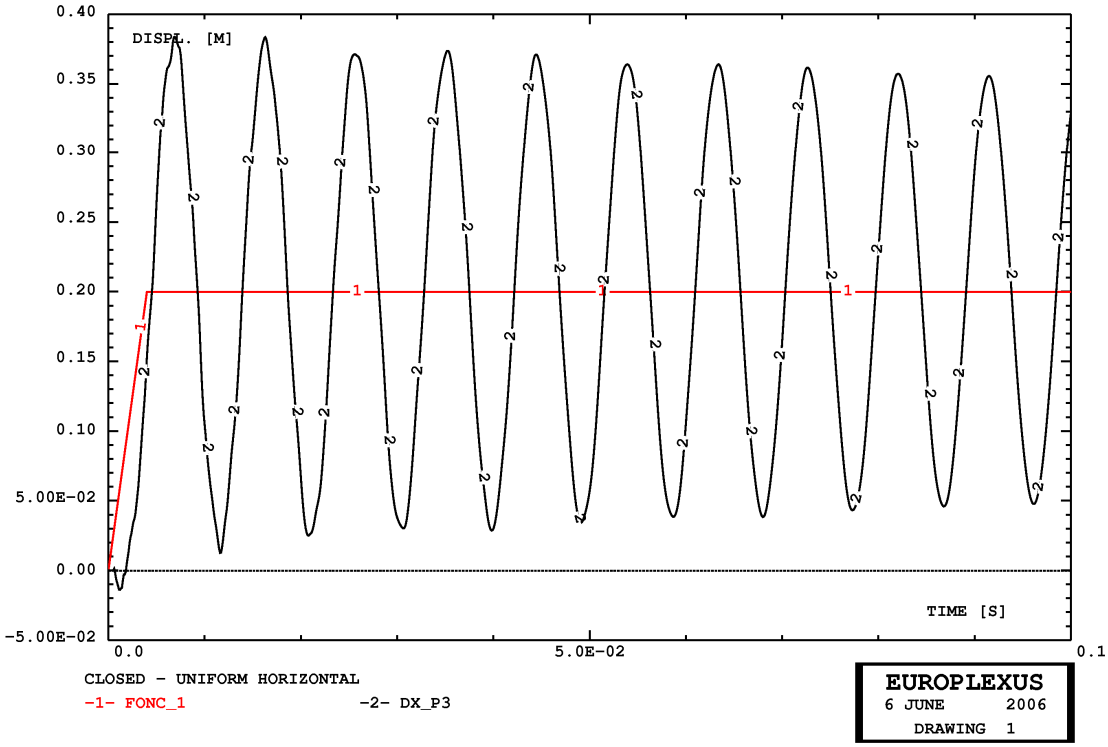
The Cast3m mesh generation file reads:

```
*%siz 200
*
opti echo 1;
opti titr 'CLOSE - D4';
*
opti trac psc ftra 'closed4_mesh.ps';
*
opti dime 2 elem qua4;
p1 = 0.00 0.00;
p2 = 1.50 0.00;
p3 = 1.50 1.50;
p4 = 0.00 1.50;
p5 = 0.00 0.25;
p6 = 1.50 0.25;
p7 = 0.00 1.25;
p8 = 1.50 1.25;
p9 = 0.25 0.25;
p10= 1.25 0.25;
p11= 1.25 1.25;
p12= 0.25 1.25;
*
p9f = p9 plus (0 0);
p10f = p10 plus (0 0);
p11f = p11 plus (0 0);
p12f = p12 plus (0 0);
*
fl1 = p9f d 16 p10f;
fl2 = p10f d 16 p11f;
fl3 = p11f d 16 p12f;
fl4 = p12f d 16 p9f;
flmesh = dall fl1 fl2 fl3 fl4 plan;
*
tol=0.001;
*
sel1 = p1 d 24 p2;
s2 = p2 d 4 p6;
s3 = p6 d 4 p10 d 16 p9 d 4 p5;
s4 = p5 d 4 p1;
stmesh1 = dall sel1 s2 s3 s4 plan;
*
s1 = p3 d 24 p4;
s2 = p4 d 4 p7;
s3 = p7 d 4 p12 d 16 p11 d 4 p8;
s4 = p8 d 4 p3;
stmesh2 = dall s1 s2 s3 s4 plan;
*
s1 = p10 d 4 p6;
s2 = p6 d 16 p8;
s3 = p8 d 4 p11;
s4 = p11 d 16 p10;
stmesh3 = dall s1 s2 s3 s4 plan;
*
s1 = p5 d 4 p9;
s2 = p9 d 16 p12;
s3 = p12 d 4 p7;
s4 = p7 d 16 p5;
stmesh4 = dall s1 s2 s3 s4 plan;
*
stmesh = stmesh1 et stmesh2 et stmesh3 et stmesh4;
elim tol stmesh;
*
* obstacles
*
op1 = 0.00 0.25;
op2 = -0.10 0.30;
op3 = -0.10 0.20;
ob1 = manu tri3 op1 op2 op3;
op4 = 1.70 0.25;
op5 = 1.80 0.20;
op6 = 1.80 0.30;
ob2 = manu tri3 op4 op5 op6;
*
mesh = flmesh et stmesh et ob1 et ob2;
*
tass mesh;
*
opti sauv form 'closed4.msh';
sauv form mesh;
*
trac mesh;
trac qual mesh;
*
opti donn 5;
```

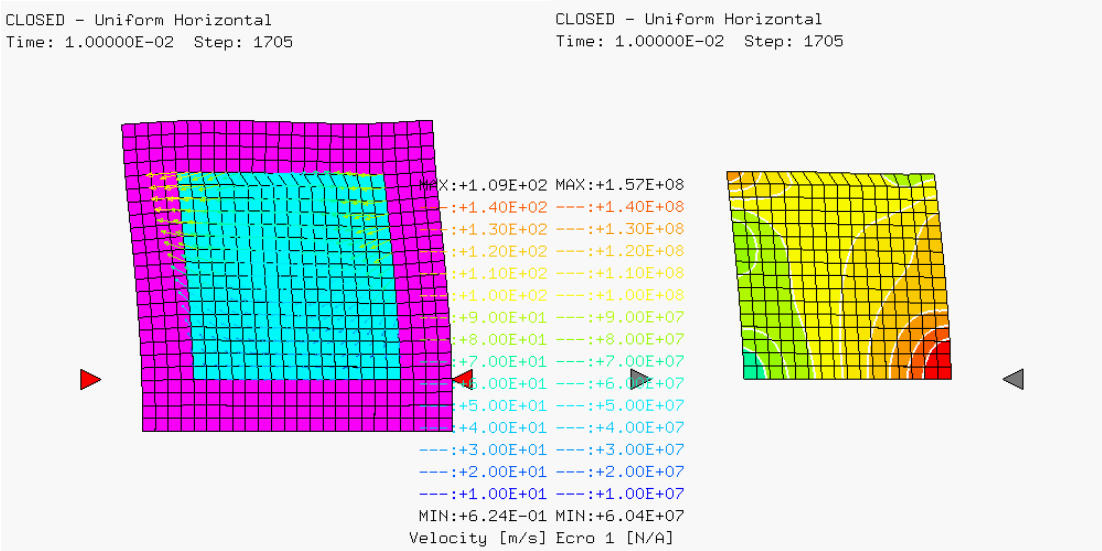
The EUROPLEXUS input file reads:

```
CLOSED - Uniform Horizontal
ECHO
!CONV win
DPLA NONL NAVI ALE
CAST MESH
DIME
 PT2L 695 CAR1 576 TRIA 2 ZONE 3
 NALE 25 NBLE 1
 FSA  68 IFSA 240
 TABL 1 3
 NDVC 900
 DEPL 25
 BLOQ 25
TERM
GEOM CAR1 FLMESH CAR1 STMESH TRIA OB1 OB2 TERM
COMP COUL TURQ LECT FLMESH TERM
          ROSE LECT STMESH TERM
          ROUG LECT OB1 OB2 TERM
GRIL LAGR LECT STMESH OB1 OB2 TERM
     ALE  LECT FLMESH TERM
     MEAN NOEU LECT FLMESH TERM
MATE LINE RO 7700. YOUNG 144.E9 NU 0.35
          LECT STMESH TERM
     LIQU RO 1000.
          LECT FLMESH TERM
     FANT 1.0 LECT OB1 OB2 TERM
LIAI BLOQ 2 LECT SEL1 TERM
     FSA  LECT FL1 FL2 FL3 FL4 TERM
CHAR 1 FACT 2 DEPL 1 0.20
       LECT SEL1 TERM
       TABL 3 0.0 0.0 0.0040 1.0 2.0 1.0
ECRI DEPL ECRO TFRE 0.005
     FICH ALIC TFRE 0.0001
OPTI NOTE CSTA 0.5
 LOG 100
CALC TINI 0 TEND 0.10 NMAX 10000000
FIN
```

The applied displacement and the computed oscillation of point P3 are presented below:

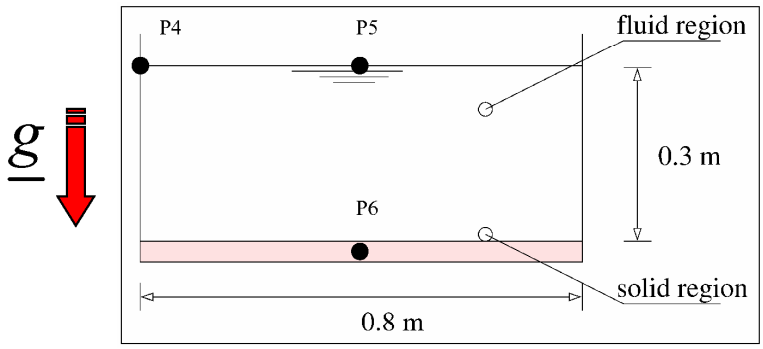


The final distribution of velocity and pressure in the fluid are shown below:



Exercise/Example 12 – Sloshing (3) (Courtesy of CRS4)

• B - Vibration of a partially filled container:



• Excitation : gravity starting at initial time

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PROBLEM:
A rigid tank with a deformable bottom is partially filled with a liquid. At the initial time, gravity is applied and we want to compute the oscillations of the tank bottom and the sloshing waves produced at the liquid free surface.
MESH:
The fluid is meshed by CAR1 elements, the flexible tank bottom by ED01 elements. The calculation is plane strain (DPLA) and is declared of the NAVI type. In this way, incompressibility is automatically enforced for all CAR1 elements that are associated with a LIQU material (the fluid mesh, in this case).
MATERIALS:
The fluid is modelled by the LIQU material (density 1000), while the tank uses a linear elastic material (VM23).
BOUNDARY CONDITIONS:
FSA fluid-structure interaction is used along the fluid-structure interface between the liquid and the tank bottom. SLIP is prescribed along the free fluid surface.
LOADING:
Gravity starts to act at the initial time.
CALCULATION:
The calculation is performed up to a final time of 2 s. The NAVI condition would allow a very large stability step in the fluid elements, but in this case the integration step is dictated by the deformable structural part (tank bottom).
RESULTS:
Linear theory predicts a 1st symmetric sloshing mode with a frequency of 1.41 Hz for a rigid tank. All monitored points (P4, P5, P6) show a numerically computed harmonic component at 11.7 Hz (driven by the flexible bottom oscillations). In addition, surface points (P4, P5) also exhibit a lower harmonic component at 1.3 Hz.

This result is in good agreement with the linear theory, if one cosiders that a flexible bottom is expected to somewhat reduce the value of the first sloshing frequency.
POST-TREATMENT
Animations are produced.

Numerical Solution

GRAV05

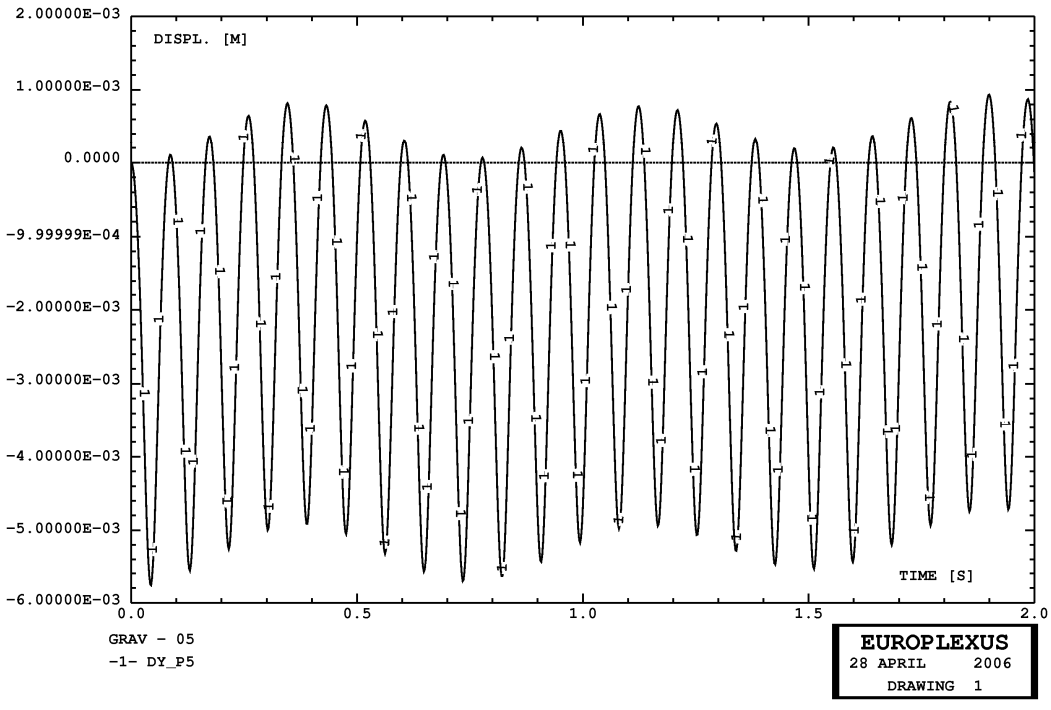
The Cast3m mesh generation file reads:

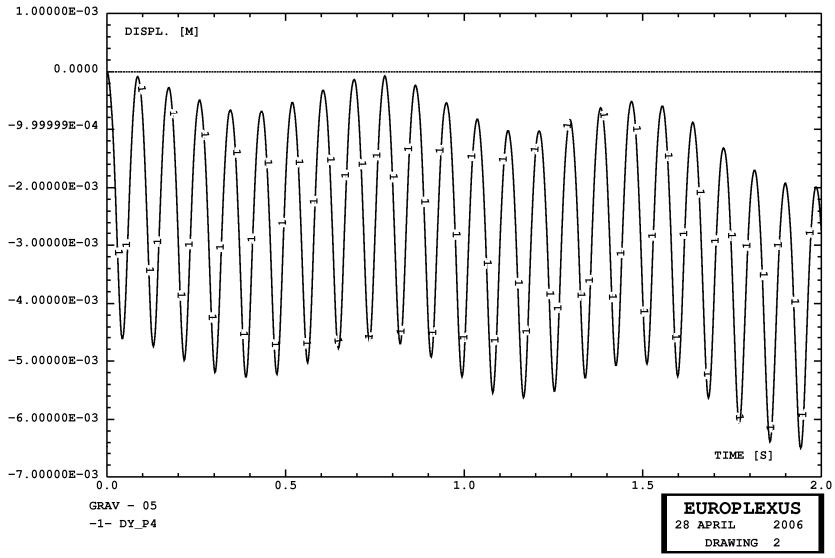
```
*%siz 200
*
opti echo 1;
opti donn 'D:\Users\Folco\Plexis3c\Proc\Pxordpoi.proc';
opti titr 'GRAV - 05';
*
opti trac psc ftra 'grav05_mesh.ps';
*
opti dime 2 elem qua4;
p1 = 0.00 0.00;
p2 = 0.80 0.00;
p3 = 0.80 0.30;
p4 = 0.00 0.30;
p5 = 0.40 0.30;
p6 = 0.40 0.00;
*
p1s = p1 plus (0 0);
p2s = p2 plus (0 0);
*
fl1 = p1 d 5 p6 d 5 p2;
fl2 = p2 d 4 p3;
fl3 = p3 d 5 p5 d 5 p4;
fl4 = p4 d 4 p1;
flmesh = dall fl1 fl2 fl3 fl4 plan;
*
tol=0.001;
*
stmesh = p1s d 10 p2s;
*
* obstacles
*
op1 = 0.00 -0.05;
op2 = 0.00 0.40;
ob1 = manu seg2 op1 op2;
op4 = 0.80 -0.05;
op5 = 0.80 0.40;
ob2 = manu seg2 op4 op5;
*
pfl3 = chan 'POI1' fl3;
surf = pxordpoi pfl3 p3;
*
mesh = flmesh et stmesh et ob1 et ob2 et surf;
*
tass mesh;
*
opti sauv form 'grav05.msh';
sauv form mesh;
*
trac mesh;
trac qual mesh;
*
opti donn 5;
```

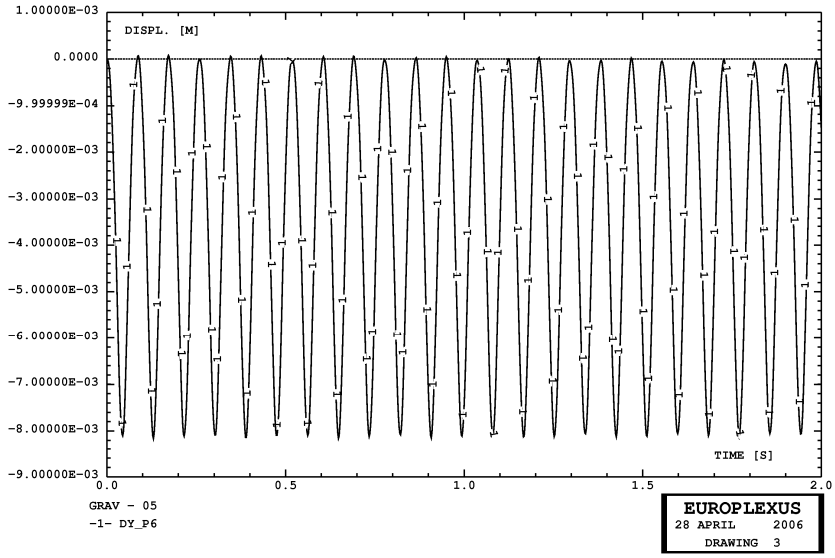
The EUROPLEXUS input file reads:

```
GRAV - 05
ECHO
!CONV win
DPLA NONL NAVI ALE
CAST MESH
DIME
 PT2L 55 PT3L 15 CAR1 40 ED01 12 ZONE 2
 NALE 4 NBLE 1
 FSA  13 IFSA 36
 NDVC 157
 BLOQ 14
 SLPC 1
 SLPN 11
TERM
GEOM CAR1 flmesh ED01 stmesh ob1 ob2 TERM
COMP EPAI 0.005 LECT stmesh  TERM
          1.0   LECT ob1 ob2 TERM
     COUL TURQ LECT flmesh TERM
          ROSE LECT stmesh TERM
          ROUG LECT ob1 ob2 TERM
GRIL LAGR LECT stmesh surf ob1 ob2 TERM
     EULE LECT fl1 TERM
     ALE  LECT flmesh TERM
     SLIP EQUI LECT surf TERM
     MEAN AUTR
MATE VM23 RO 2700. YOUNG 70.E9 NU 0.30 ELAS 70.E9
          TRAC 1 70.E9 1.E0
          LECT stmesh TERM
     LIQU RO 1000.
          LECT flmesh TERM
     FANT 1.0 LECT ob1 ob2 TERM
LIAI BLOQ 2 LECT p1s p2s ob1 ob2 TERM
     BLOQ 1 LECT p1s p2s fl2 fl4 TERM
     FSA  LECT fl1 TERM
CHAR CONST GRAV 0.0 -9.81
ECRI DEPL ECRO TFRE 0.02
     FICH ALIC TFRE 0.002
OPTI NOTE CSTA 0.5
 LOG 100
CALC TINI 0 TEND 2.0 NMAX 10000000
FIN
```

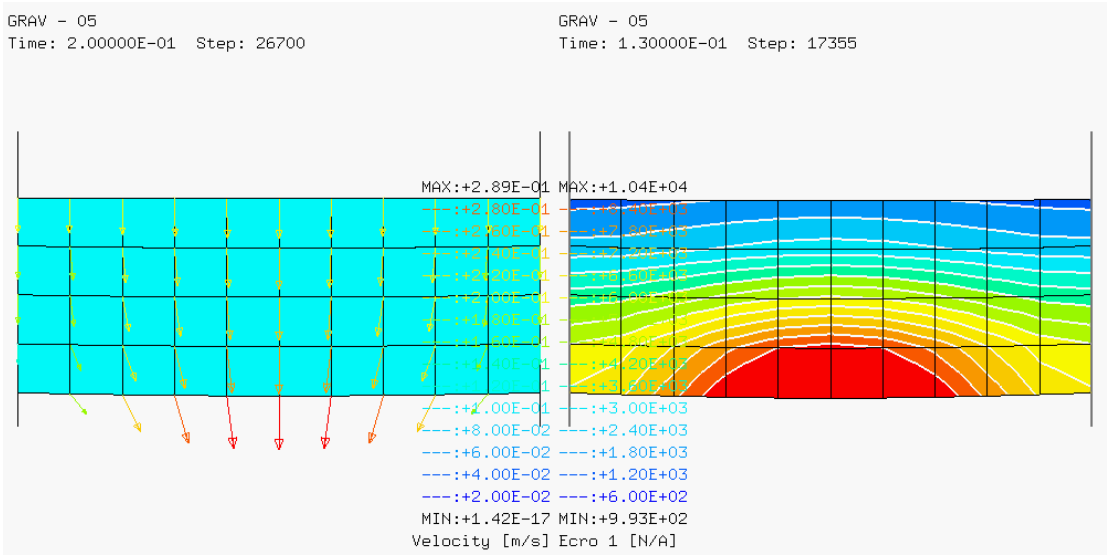
The vertical motions of points P5, p4 and P6 are presented below:





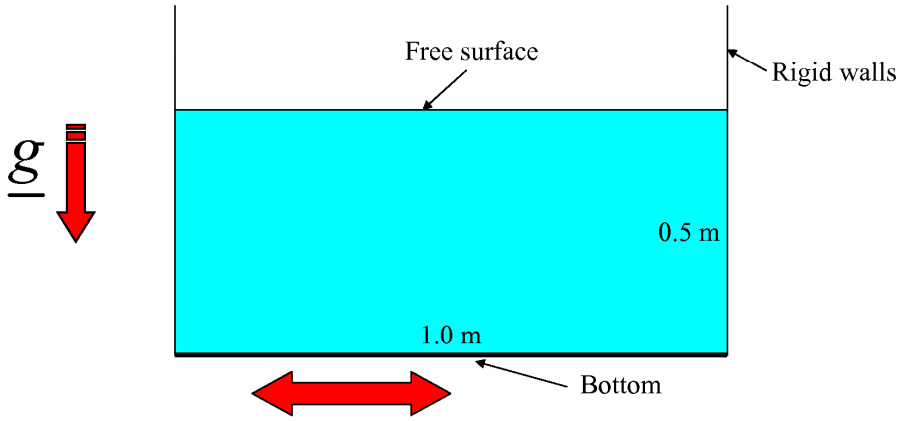


The velocity at 200 ms and the fluid pressure at 130 ms are presented below:



Exercise/Example 12 – Sloshing (7) (Courtesy of CRS4)

• C - Vibration of a partially filled container:



• Excitation : imposed harmonic horizontal displacement

• Container bottom may be either rigid or flexible

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PROBLEM:
A rigid tank with rigid or deformable bottom and partially filled with a liquid is subjected to gravity and accelerated by a harmonic excitation in the horizontal direction applied to the base.
MESH:
The fluid is meshed by CAR1 elements, the tank by COQU elements. The calculation is plane strain (DPLA) and is declared of the NAVI type. In this way, incompressibility is automatically enforced for all CAR1 elements that are associated with a LIQU material (the fluid mesh, in this case).
MATERIALS:
The fluid is modelled by the LIQU material (density 1000), while the tank uses a linear elastic material (LINE).
BOUNDARY CONDITIONS:
The motion of the tank base is imposed in the horizontal direction. FSA fluid-structure interaction is used along the whole fluid-structure interface. SLIP sliding conditions are prescribed along the free fluid surface.
LOADING:
An imposed horizontal displacement with a harmonic shape (9.3 mm aplitude) is imposed at the tank base. This imposed displacement starts at t = 1 s. Gravity acts on the system starting at t = 0. The initial 1 s of the calculation is used to let the code compute a reasonable initial distribution of pressure and deformation (in the elastic bottom case) before starting the forced oscillations.
The chosen frequency for the imposed displacement is 5.311 Hz, which is very close to the first sloshing frequency of the completely rigid tank predicted by the linear theory (5.316 Hz)
CALCULATION:

The calculation is performed up to a final time of 6 s. The NAVI condition would allow a very large stability step in the fluid elements, but in the case with flexible bottom the integration step is dictated by the structural part.
RESULTS:
Sloshing is computed for the rigid and flexible bottom cases..
POST-TREATMENT
Animations are produced.

Numerical Solution (rigid bottom)

TANK6R

The EUROPLEXUS input file reads:

```
TANK - 5mm Uniform Horizontal
$
$ FONDO RIGIDO, TABELLA DETTAGLIATA,
$ AMPIEZZA DI OSCILLAZIONE 9.3mm
$
 ECHO
!CONV win
$ 2D Plane Strain + NonLinear + ALE
 DPLA NONL NAVI ALE
$
DIME
 PT2L 256
 PT3L 4
 CAR1 200
 COQU 30
 TRIA 2
 ED01 2
$obsolete:    MATE 20
 NALE 100 NBLE 500
 FSA  100 IFSA 500
 SLPN 200
 SLPC 100
 NDVC 400
 TABL 200 200
 MTPO 200
 BLOQ 100
 DDLI 100
 FCOE 100
 FNOM 10
 FTAB 800
 FORC 24
 ZONE 10
TERM
$
GEOM LIBR POIN 157 CAR1 100 COQU 20 TRIA 2 ED01 2 TERM
$
$ 1
0.00 0.00
 . . . (skip for brevity)

$
COMP EPAI 0.005 LECT 101 102 103 104 105
                    106 107 108 109 110
                    111 112 113 114 115
                    116 117 118 119 120 TERM
         1.0   LECT 123 124 TERM
$
GRIL LAGR LECT 127 128 129 130 131
               132 133 134 135 136
               137 138 139 140 141
               142 143 144 145 146 147
                   107 108 109 110
               111 112 113 114 115
               116 117 118 119 120
               121 122 123 124 125
               1  21 106 126
               148 PAS 1 157
               TERM
$
     ALE  LECT 1  2  3  4  5  6  7  8  9  10
               11 12 13 14 15 16 17 18 19 20
               21 22 23 24 25 26 27 28 29 30
               31 32 33 34 35 36 37 38 39 40
               41 42 43 44 45 46 47 48 49 50
               51 52 53 54 55 56 57 58 59 60
               61 62 63 64 65 66 67 68 69 70
               71 72 73 74 75 76 77 78 79 80
               81 82 83 84 85 86 87 88 89 90
               91 92 93 94 95 96 97 98 99 100 TERM
$
     SLIP EQUI LECT 126 125 124 123 122 121
                    120 119 118 117 116
                    115 114 113 112 111
                    110 109 108 107 106 TERM
$
     SLIP EQUI LECT 1   22  43  64  85  106 TERM
     SLIP EQUI LECT 21  42  63  84  105 126 TERM
$
     MEAN NOEU LECT 23 24 25 26 27 28 29 30 31 32
                    33 34 35 36 37 38 39 40 41
                    44 45 46 47 48 49 50 51 52 53
                    54 55 56 57 58 59 60 61 62
                    65 66 67 68 69 70 71 72 73 74
                    75 76 77 78 79 80 81 82 83
                    86 87 88 89 90 91 92 93 94 95
                    96 97 98 99 100 101 102 103 104
                    TERM
$
MATE LINE RO 7800. YOUNG 200.E9 NU 0.3
         LECT 101 102 103 104 105
              106 107 108 109 110
              111 112 113 114 115
              116 117 118 119 120 TERM
$
     LIQU RO 1000.
          LECT 1  2  3  4  5  6  7  8  9  10
               11 12 13 14 15 16 17 18 19 20
               21 22 23 24 25 26 27 28 29 30
               31 32 33 34 35 36 37 38 39 40
               41 42 43 44 45 46 47 48 49 50
               51 52 53 54 55 56 57 58 59 60
               61 62 63 64 65 66 67 68 69 70
               71 72 73 74 75 76 77 78 79 80
               81 82 83 84 85 86 87 88 89 90
               91 92 93 94 95 96 97 98 99 100 TERM
     FANT 1.0 LECT 121 PAS 1 124 TERM
$
LIAI FREQ 1
     BLOQ 2 LECT 1 21 127 PAS 1 147
                   148 PAS 1 157
            TERM
$
     DEPL 1 -0.0093 FONC 1
            LECT 1   21  22  42  43  63  64
                 84  85  105 106 126 127 147
                 154 155 156 157
                 TERM
$
     FSA  LECT    2  3  4  5  6  7  8  9  10 11
               12 13 14 15 16 17 18 19 20     TERM
$
FONC 1 TABL 642
    0    0
 . . . (skip for brevity)
    12.8304    -0.0006
$
$ Carichi
$
CHAR
     1 FACT 2 FORCE 2 264
            LECT 127 128 129 130 131 132 133
                 134 135 136 137 138 139 140
                 141 142 143 144 145 146 147 TERM
       TABL 3 0.0 1.0 1.0 0.0 20.0 0.0
$
     CONST GRAV 0.0 -9.81
$
ECRI
     DEPL POINT LECT 127 128 129 130 131 132 133
                     134 135 136 137 138 139 140
                     141 142 143 144 145 146 147
                TERM TFRE 0.25
!    FICH FORM AVS TFRE 0.025
!    VARI DEPL VITE ECRO
!    fich alic temp TFRE 5.E-5
!                   poin lect 11 106 126 term
!                   elem lect 1 term
     FICH ALIC TFRE 10.E-3
OPTI NOTEST
  log 100
CALCUL TINI 0 TEND 6.0 NMAX 50000000
*=================================================================
SUIT
Post-treatment
ECHO
*
!RESU ALIC TEMP GARD PSCR
 RESU ALIC      GARD PSCR
*
FONC 1 TABL 642
    0    0
    1    0
    1.018485    0.098016
 . . . (skip for brevity)
    12.8304    -0.0006
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 1 'dx_11'    DEPL COMP 1 NOEU LECT 11  TERM
COUR 2 'dy_11'    DEPL COMP 2 NOEU LECT 11  TERM
COUR 3 'dx_106'   DEPL COMP 1 NOEU LECT 106 TERM
COUR 4 'dy_106'   DEPL COMP 2 NOEU LECT 106 TERM
COUR 5 'dx_126'   DEPL COMP 1 NOEU LECT 126 TERM
COUR 6 'dy_126'   DEPL COMP 2 NOEU LECT 126 TERM
DCOU 7 'fonc_1'   FONC 1
*
trac 1 2 3 4 5 6    axes 1.0 'DISPL. [M]'
trac 7              axes 1.0 'FUNCTION 1'
*
QUAL DEPL COMP 1 LECT  11 TERM REFE  0.00000E+0 TOLE 5.E-3
     DEPL COMP 2 LECT  11 TERM REFE -2.97067E-4 TOLE 5.E-3
     DEPL COMP 1 LECT 106 TERM REFE  0.00000E+0 TOLE 5.E-3
     DEPL COMP 2 LECT 106 TERM REFE -1.81780E-4 TOLE 5.E-3
     DEPL COMP 1 LECT 126 TERM REFE  0.00000E+0 TOLE 5.E-3
     DEPL COMP 2 LECT 126 TERM REFE -1.81780E-4 TOLE 5.E-3
*=================================================================
FIN
```

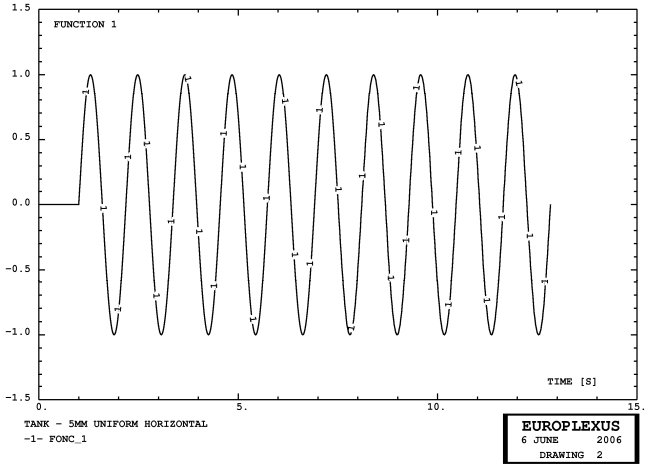
Numerical Solution (flexible bottom)

TANK6F

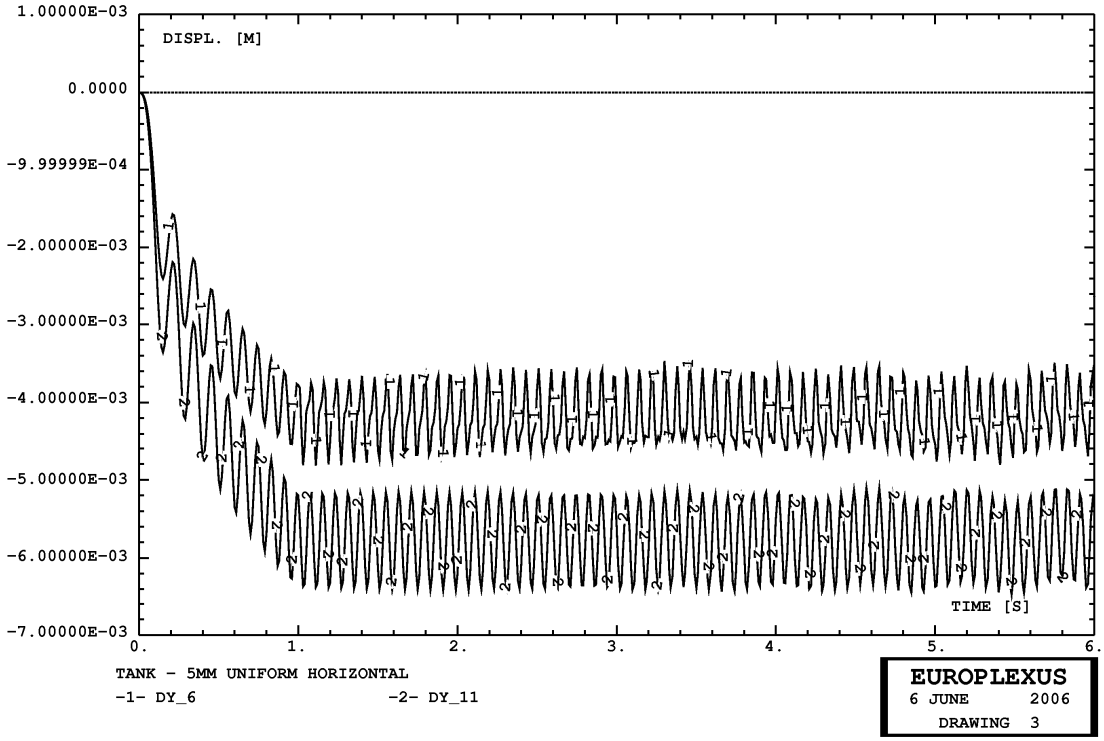
The EUROPLEXUS input file reads:

```
TANK - 5mm Uniform Horizontal
$
$ FONDO FLESSIBILE, TABELLA DETTAGLIATA,
$ AMPIEZZA DI OSCILLAZIONE 9.3mm
$
 ECHO
!CONV win
$ 2D Plane Strain + NonLinear + ALE
 DPLA NONL NAVI ALE
$
DIME
 PT2L 256
 PT3L 4
 CAR1 200
 COQU 30
 TRIA 2
 ED01 2
$obsolete:    MATE 20
 NALE 100 NBLE 500
 FSA  100 IFSA 500
 SLPN 200
 SLPC 100
 NDVC 400
 TABL 200 200
 MTPO 200
 BLOQ 100
 DDLI 100
 FCOE 100
 FNOM 10
 FTAB 800
 FORC 24
 ZONE 10
TERM
$
GEOM LIBR POIN 157 CAR1 100 COQU 20 TRIA 2 ED01 2 TERM
$
$ 1
0.00 0.00
 . . . (skip for brevity)
$
COMP EPAI 0.005 LECT 101 102 103 104 105
                    106 107 108 109 110
                    111 112 113 114 115
                    116 117 118 119 120 TERM
          1.0   LECT 123 124 TERM
$
GRIL LAGR LECT 127 128 129 130 131
               132 133 134 135 136
               137 138 139 140 141
               142 143 144 145 146 147
                   107 108 109 110
               111 112 113 114 115
               116 117 118 119 120
               121 122 123 124 125
               1  21 106 126
               148 PAS 1 157
               TERM
$
     ALE  LECT 1  2  3  4  5  6  7  8  9  10
               11 12 13 14 15 16 17 18 19 20
               21 22 23 24 25 26 27 28 29 30
               31 32 33 34 35 36 37 38 39 40
               41 42 43 44 45 46 47 48 49 50
               51 52 53 54 55 56 57 58 59 60
               61 62 63 64 65 66 67 68 69 70
               71 72 73 74 75 76 77 78 79 80
               81 82 83 84 85 86 87 88 89 90
               91 92 93 94 95 96 97 98 99 100 TERM
$
     SLIP EQUI LECT 126 125 124 123 122 121
                    120 119 118 117 116
                    115 114 113 112 111
                    110 109 108 107 106 TERM
$
     SLIP EQUI LECT 1   22  43  64  85  106 TERM
     SLIP EQUI LECT 21  42  63  84  105 126 TERM
$
     MEAN NOEU LECT 23 24 25 26 27 28 29 30 31 32
                    33 34 35 36 37 38 39 40 41
                    44 45 46 47 48 49 50 51 52 53
                    54 55 56 57 58 59 60 61 62
                    65 66 67 68 69 70 71 72 73 74
                    75 76 77 78 79 80 81 82 83
                    86 87 88 89 90 91 92 93 94 95
                    96 97 98 99 100 101 102 103 104
                    TERM
$
MATE LINE RO 7800. YOUNG 200.E9 NU 0.3
          LECT 101 102 103 104 105
               106 107 108 109 110
               111 112 113 114 115
               116 117 118 119 120 TERM
$
     LIQU RO 1000.
          LECT 1  2  3  4  5  6  7  8  9  10
               11 12 13 14 15 16 17 18 19 20
               21 22 23 24 25 26 27 28 29 30
               31 32 33 34 35 36 37 38 39 40
               41 42 43 44 45 46 47 48 49 50
               51 52 53 54 55 56 57 58 59 60
               61 62 63 64 65 66 67 68 69 70
               71 72 73 74 75 76 77 78 79 80
               81 82 83 84 85 86 87 88 89 90
               91 92 93 94 95 96 97 98 99 100 TERM
     FANT 1.0 LECT 121 PAS 1 124 TERM
$
LIAI FREQ 1
     BLOQ 2 LECT 1 21 127 147
                 148 PAS 1 157
            TERM
$
     DEPL 1 -0.0093 FONC 1
            LECT 1   21  22  42  43  63  64
                 84  85  105 106 126 127 147
                 154 155 156 157
                 TERM
$
     FSA  LECT    2  3  4  5  6  7  8  9  10 11
               12 13 14 15 16 17 18 19 20     TERM
$
FONC 1 TABL 642
     0    0
     1    0
     1.018485    0.098016
 . . . (skip for brevity)
     12.8304    -0.0006
$
$ Carichi
$
CHAR
     1 FACT 2 FORCE 2 264
            LECT 127 128 129 130 131 132 133
                 134 135 136 137 138 139 140
                 141 142 143 144 145 146 147 TERM
       TABL 3 0.0 1.0 1.0 0.0 20.0 0.0
$
     CONST GRAV 0.0 -9.81
$
ECRI
     DEPL POINT LECT 127 128 129 130 131 132 133
                     134 135 136 137 138 139 140
                     141 142 143 144 145 146 147
                TERM TFRE 0.25
!    FICH FORM AVS TFRE 0.025
!    VARI DEPL VITE ECRO
!    fich alic temp TFRE 5.E-5
!                   poin lect 11 106 126 term
!                   elem lect 1 term
     FICH ALIC TFRE 10.E-3
OPTI NOTEST
  log 100
CALCUL TINI 0 TEND 6.0 NMAX 50000000
*=================================================================
SUIT
Post-treatment
ECHO
*
!RESU ALIC TEMP GARD PSCR
 RESU ALIC      GARD PSCR
*
FONC 1 TABL 642
     0    0
     1    0
     1.018485    0.098016
 . . . (skip for brevity)
     12.8304    -0.0006
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 1 'dx_11'    DEPL COMP 1 NOEU LECT 11  TERM
COUR 2 'dy_11'    DEPL COMP 2 NOEU LECT 11  TERM
COUR 3 'dx_106'   DEPL COMP 1 NOEU LECT 106 TERM
COUR 4 'dy_106'   DEPL COMP 2 NOEU LECT 106 TERM
COUR 5 'dx_126'   DEPL COMP 1 NOEU LECT 126 TERM
COUR 6 'dy_126'   DEPL COMP 2 NOEU LECT 126 TERM
DCOU 7 'fonc_1'   FONC 1
*
trac 1 2 3 4 5 6    axes 1.0 'DISPL. [M]'
trac 7              axes 1.0 'FUNCTION 1'
*
QUAL DEPL COMP 1 LECT  11 TERM REFE  0.00000E+0 TOLE 5.E-3
     DEPL COMP 2 LECT  11 TERM REFE -2.97067E-4 TOLE 5.E-3
     DEPL COMP 1 LECT 106 TERM REFE  0.00000E+0 TOLE 5.E-3
     DEPL COMP 2 LECT 106 TERM REFE -1.81780E-4 TOLE 5.E-3
     DEPL COMP 1 LECT 126 TERM REFE  0.00000E+0 TOLE 5.E-3
     DEPL COMP 2 LECT 126 TERM REFE -1.81780E-4 TOLE 5.E-3
*=================================================================
FIN
```

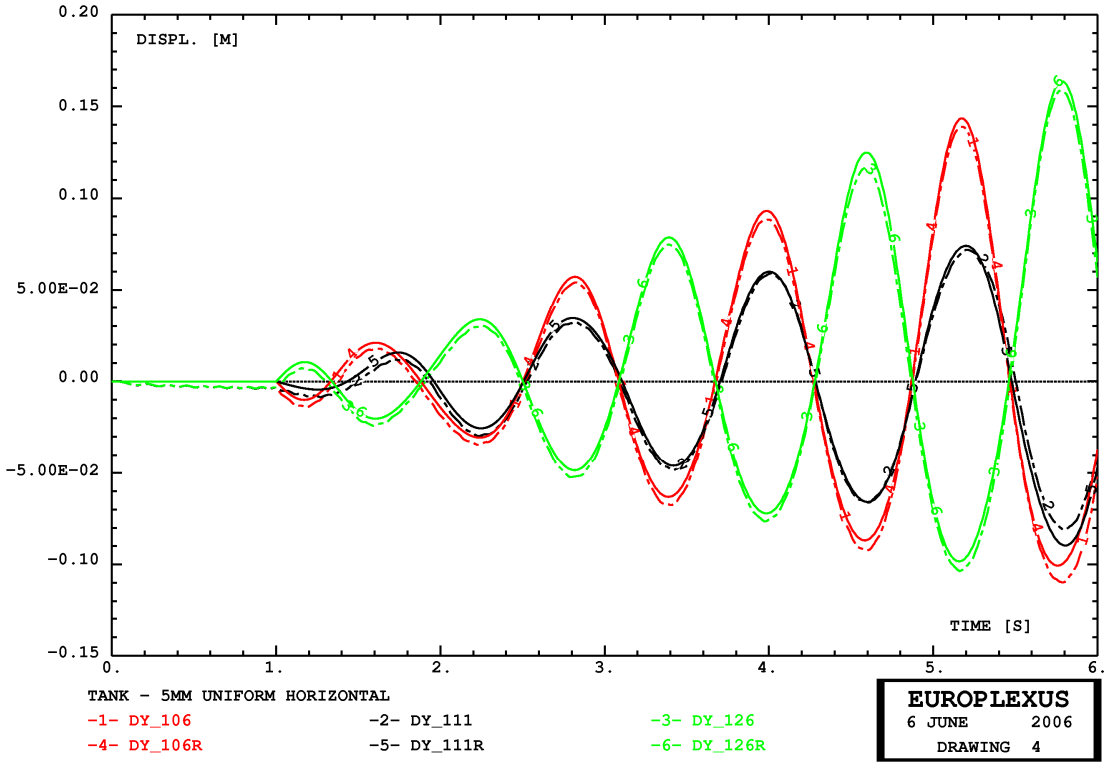
The applied displacement time function is presented below:



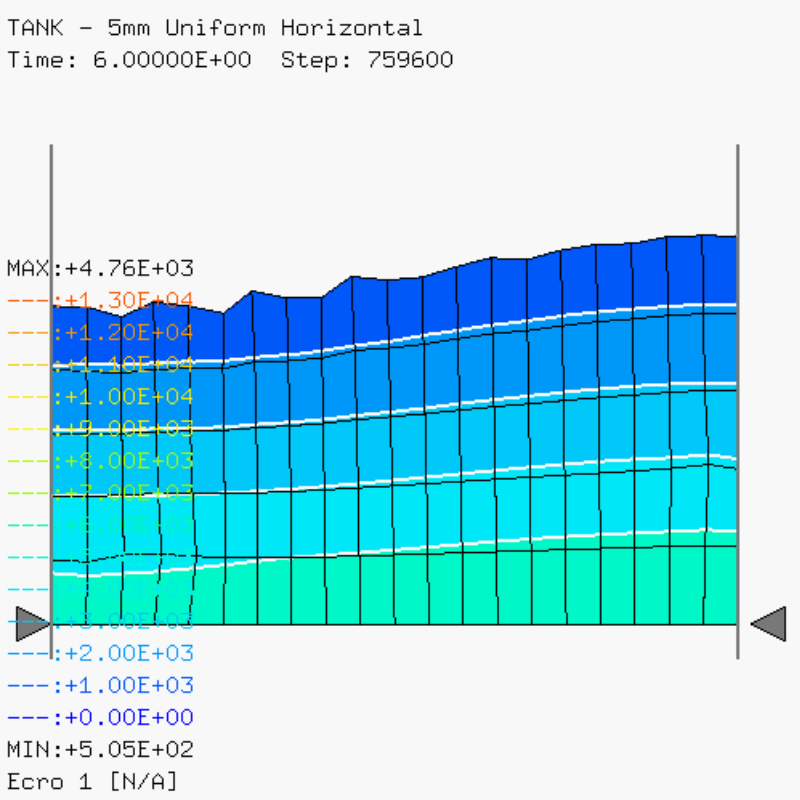
The computed displacements of the tank bottom (at ¼ length and ½ length, respectively) for the flexible bottom case are shown below:

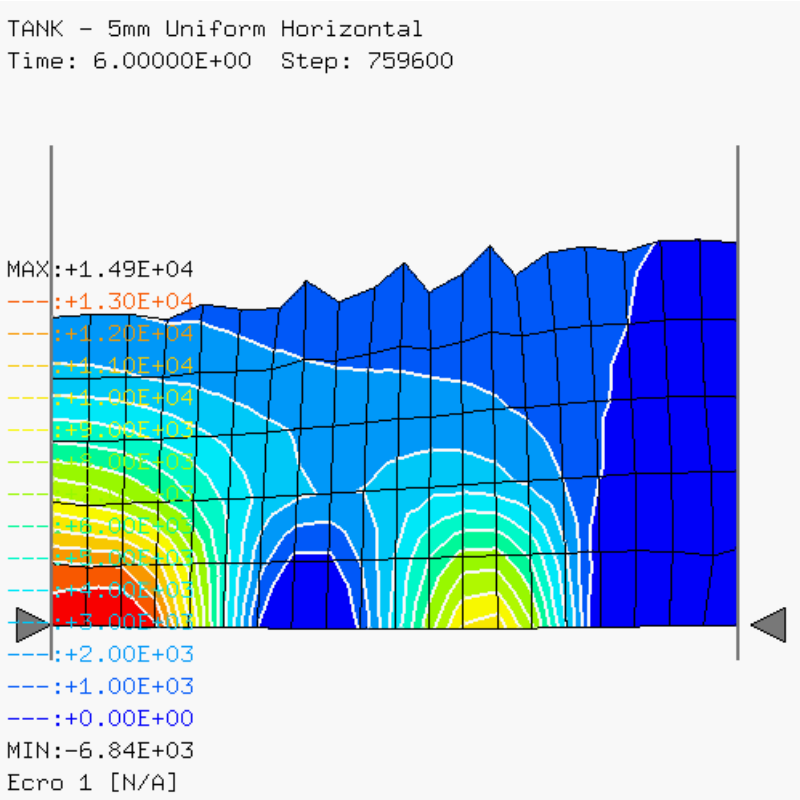


The computed displacements of the free surface (at both extremities and at the mid-point) as computed for the rigid bottom case (solid lines) and for the deformable bottom case (dashed lines) are shown below:



The final pressures in the rigid and flexible case, respectively, are shown below:

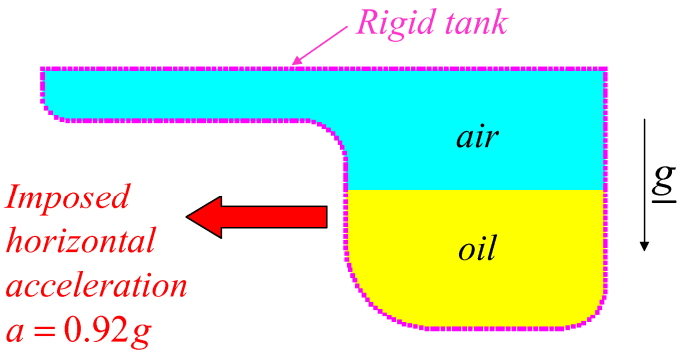




Exercise/Example 12 – Sloshing (11)

(Courtesy of Samtech)

• D – Accelerated oil cup:



95

TITLE:
OILCUP2: uniformly accelerated oil cup.

PROBLEM:
A rigid oil tank partially filled with mineral oil is accelerated uniformly at 0.92 g in the horizontal direction and is under the action of gravity in the vertical direction.

MESH:
The fluid is meshed by FL23/FL24 elements, the rigid tank by PMAT elements. These latter elements are used to impose a uniform acceleration to the container, while the FSA model takes care of prescribing suitable fluid velocities along the walls in a completely automatic way. Note that this is not the same as prescribing uniform acceleration directly to the fluid outer surface.

MATERIALS:
A multi-phase multi-component model (FLMP) is used for the two fluids, to avoid problems in representing a Lagrangian oil/air interface that is expected to undergo very large motions and deformations (formation of waves that successively break up). The oil is treated as a liquid with constant bulk modulus and the air as a perfect gas.

BOUNDARY CONDITIONS:
The tank is rigid so the same horizontal motion (constant acceleration) is prescribed to all its nodes. To model fluid-structure interaction appropriately, FSA conditions are associated with all fluid nodes on the fluid outer surface.

LOADING:
A constant gravity in the vertical direction acts on the fluids, while a constant horizontal acceleration directed leftwards is applied to the structure.

CALCULATION:
The calculation is performed up to a final time of 650 ms. Since we do not use the NAVI condition (incompressible fluid), unlike in the previous sloshing examples, the time step (driven by stability in the fluid mesh) is short and a lot of time steps are required to arrive to the final time (about 1 million). This is because we are modeling wave propagation in the problem, although these phenomena are negligible in reality. Using NAVI would require a multi-component fluid model compatible with this constraint, which is not currently available.

RESULTS:
They are analyzed below.

POST-TREATMENT
Animations are produced.

Numerical Solution

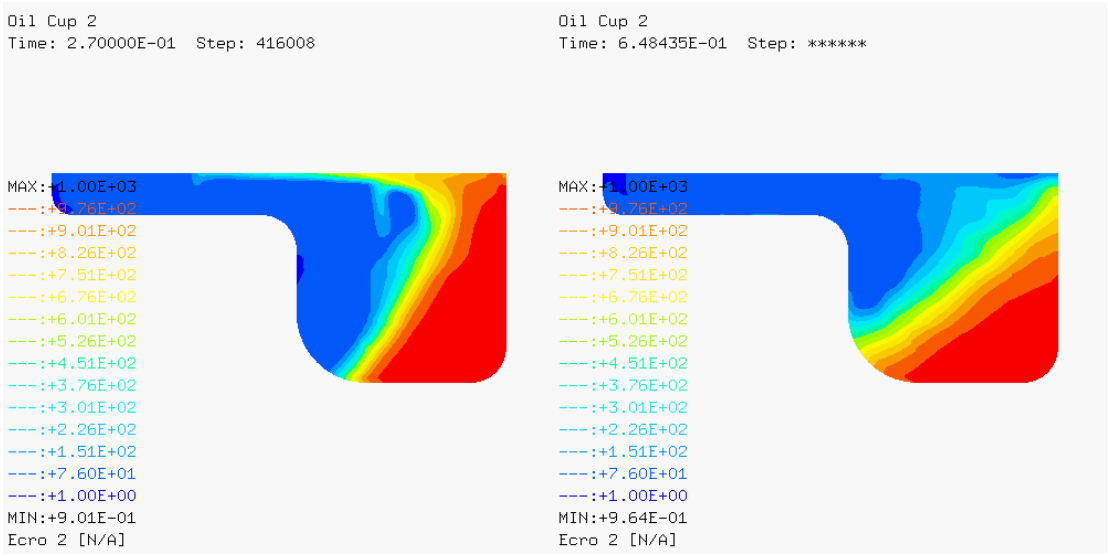
OILCUP2

The EUROPLEXUS input file reads:

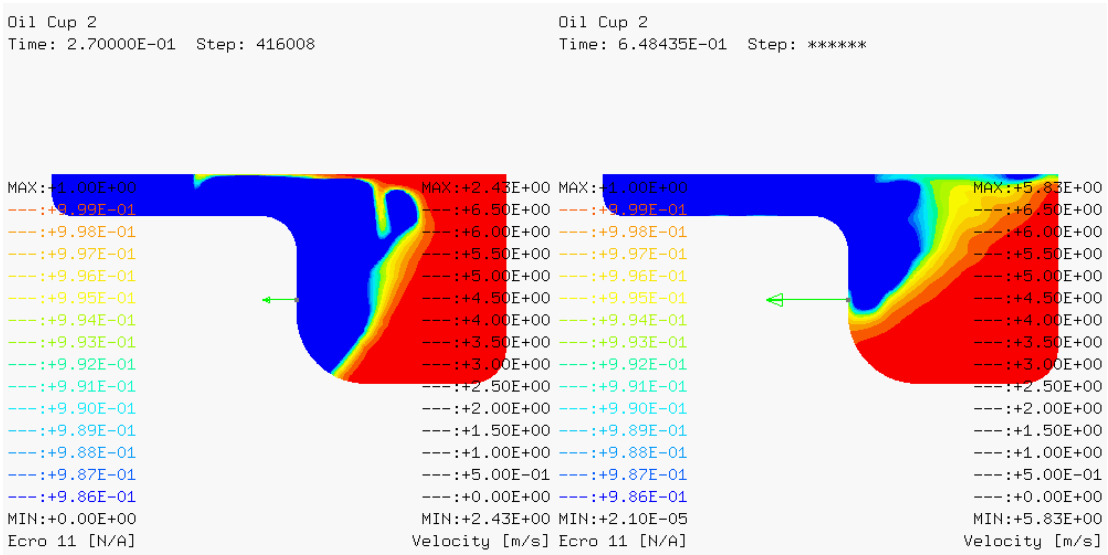
```
Oil Cup 2
*-----------------------------------------------------------Kind of problem
!conv win
 DPLA NONL ALE
 AMOR
*-------------------------------------------------------------------Sizing
DIME
 PTZL 4324 FL23 3 FL24 3900 PMAT 281 ZONE 3
 NALE 1617 NBLE 1
 BLOQ 281 LIAI 1686
 DDLI 843 FCOE 843
 FSA  283 IFSA 1116
 TABL 1 2 FNOM 1 FTAB 2
 MTPO 281 MTEL 1
 ECRO 134388
TERM
*-----------------------------------------------------------Geometry (Mesh)
GEOM '(2E22.15)' '(7I10)' POIN 4324
  FL23 3 FL24 3900 PMAT 281
TERM
*-----------------------------------------------------------Nodal Coordinates
 0.000000000000000E+00-1.500000000000000E-02
  … (skip)
 3.250000000000000E-01-7.323529411764707E-02
      3661      3662      1821      3764      3765       339      3782
  … (skip)
      4317      4318      4319      4320      4321      4322      4323
      4324
*-------------------------------------------------------------------Options
OPTI REZO GAM0 0.5
     amor line 0.01
     log  100
*-----------------------------------------------Additional geometrical data
COMP GROU 3
     'air' LECT
           1         4         5         6         7         8
  … (skip)

      2526      2527      2528      2529      2530      2531      2532
      2533
     TERM
     'oil' LECT
           2         3      1051      1052      1053      1054
  … (skip)
      3892      3893      3894      3895      3896      3897      3898
      3899      3900      3901      3902      3903
     TERM
     'stru' LECT 3904 PAS 1 4184 TERM
     NGRO 1
     'fsan' LECT
            1 PAS 1    6
           16 PAS 1   76
          141 PAS 1  203
          237 PAS 1  249
          274 PAS 1  281
         3616 PAS 1 3723
         3772 PAS 1 3793
     TERM
     COUL jaun LECT oil  TERM
          turq LECT air  TERM
          rose LECT stru TERM
*-----------------------------------------------------Mesh motion in ALE
GRIL LAGR LECT 4044 PAS 1 4324 TERM
     ALE  LECT 1 4 PAS 1 1050 1384 PAS 1 2533 TERM
     suiv base lect 4044 term list lect    7 term
  … (skip)
     suiv base lect 4044 term list lect 4043 term
*-------------------------------------------------------------Materials
MATE FLMP NLIQ 1 NGAS 1
     FLUT RO 1.E3 EINT 0 GAMM 2.E9 PB 1.e05 ITER 1 ALF0 1 BET0 1 KINT 0
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 9
          LECT oil TERM
     FLUT RO 1.E0 EINT 2.5E5 GAMM 1.4 PB 0 ITER 1 ALF0 1 BET0 1 KINT 0
          AHGF 0 CL 0.5 CQ 2.56 PMIN 0 NUM 1
          LECT air TERM
     MASS 0.1E-03
          LECT stru TERM
*-----------------------------------------------------------------Couplings
LIAI BLOQ 2               LECT stru TERM
     VITE 1 0.1E+01 FONC 1 LECT stru TERM
     FSA                   LECT fsan TERM
*-------------------------------------------------------------------Functions
FONC 1 TABL 2 0.0     0.0
              4.001  -36.0
*-----------------------------------------------------------External loads
CHAR CONS GRAV 0. -9.81 LECT oil air TERM
*-------------------------------------------------------------------Storage
ECRI VITE TFRE 0.05
     FICH ALIC TFRE 1.E-03
*-----------------------------------------------------------------Time Steps
CALC TINI 0.0E+00 TFIN 0.65
FIN
```

Some results: intermediate and final average fluid density:



Intermediate and final oil mass fraction:



Universitat Politècnica de Catalunya, Barcelona, 15 – 19 April 2013

Numerical Simulation of Fast Transient Phenomena in Fluid-Structure Systems

A Short Course by F. Casadei
Retired from European Commission, Joint Research Centre
Institute for the Protection and Security of the Citizen
T.P. 480, I-21027 Ispra (VA), Italy.
E-mail: casadeifolco@gmail.com

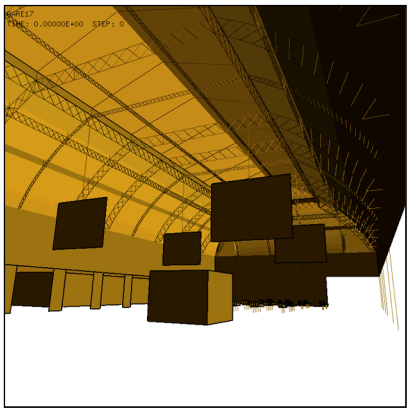
1

Contents

- I – Introduction (Structures)
- II – ALE formulation (Fluids)
- III – Classical Fluid-Structure Interaction
- IV – Advanced FSI (Failure/Fragmentation)
- V – Further topics and applications

2

FSI in the presence of structural failure/fragmentation



Motivation: extreme crashes or explosions (accident, attack) leading to severe structural damage / collapse

3

Detailed Contents (1/2)

- Structural failure and element erosion
- Fragmentation and flying debris
  - Modeling of glass
- Treatment of failure with CCFV (conforming, weak FSI)
- Embedded FSI models
  - The FLSR method (strong approach)
  - The FLSW method (weak approach)

4

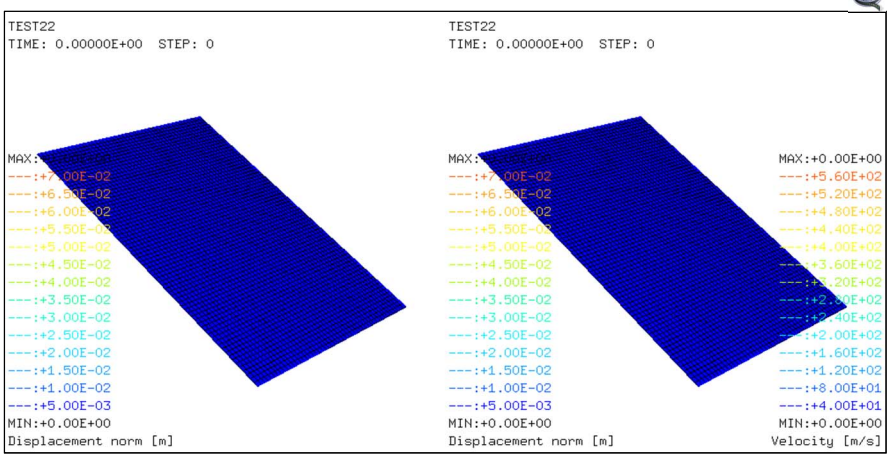
Detailed Contents (2/2)

- Advanced FSI example : Structure Vulnerability
  - Scenarios
  - Geometry reconstruction
  - Simplified building vulnerability study
  - Accounting for dead (static) weight
  - Modelling the explosive charge (AIRB, BUBB, JWLS)
  - Risk evaluation
  - Case study 1 : Railway Station
  - Case study 2 : Metro Station
  - Case study 3 : Metro Carriage
  - Complete Metro/Railway Station Simulation

5

Structural Failure/Fragmentation

- Example : glass rupture



Displacement *Velocity*

6

Structural Failure/Fragmentation (2)

- Element erosion:
  - Element is eroded (fails completely) and is no longer computed when a certain criterion (related to its material) is reached
- Input directives:
  - Choose a global erosion parameter:

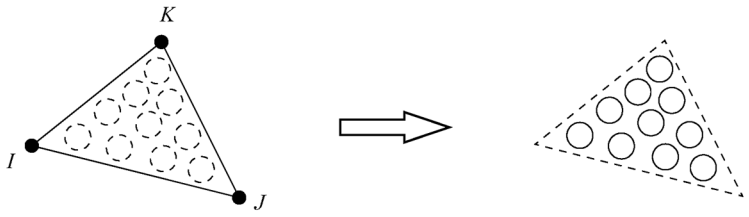
    ```
    EROS e
    ```
  - Choose a material possessing a failure criterion:

    ```
    MATE VM23 … FAIL PEPR LIMI 0.1 …
    ```
- The `EROS` global parameter `e` is : $0 \le e \le 1$. If e = 0 the element is eroded when any of its G.P.s fails, if e = 1 the element is eroded when all its G.P.s fail
- For example, the `PEPR` criterion is based on principal strains if the hydrostatic stress is positive (traction). There is no failure in compression
- Also possible to define local (element-specific) erosion parameter or displacement-based failure/erosion (e.g. for glass)

7

Modeling of Flying Debris

- Element erosion can only generate macroscopic fragments (i.e. groups of unfailed elements)
- To model microscopic fragments, replace each failed element by a cloud of particles (spheres)



a) Before fragmentation

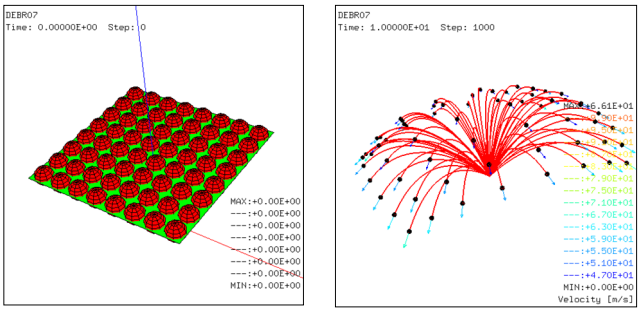
b) After fragmentation

- In this simplistic model, micro fragments are pre-defined

8

Modeling of Flying Debris (2)

- Given the number (density) of particles per element, particle size is automatically computed so that mass is conserved
- At failure, particles velocity is determined by velocity field in the eroded element (kinetic energy approximately conserved)



- Particles trajectories can be saved/visualized

Modeling of Flying Debris (3)

- Input directives:
  - Dimension (exactly) for total number of debris particles:

    DIME … DEBR 3500 …
  - Do not define debris elements in the geometry:

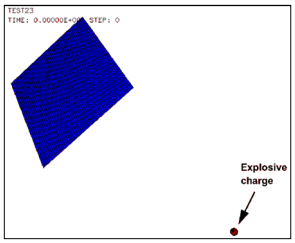
    GEOM …
  - Define elements that can generate debris in geometry complements:

    COMP … DEBR ROF 1.0 FILL PLEV 0
    RO 2500 DRAG 1.0 TRAJ
    OBJE /LECT/

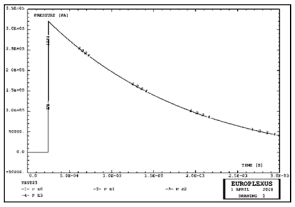
- The **FILL PLEV** parameter defines the level of recursion in filling by particles the eroded elements. E.g., **PLEV 3** generates $2^3 = 8$ particles per element in each spatial direction
- The **OBJE** parameter defines the geometrical object to be filled

Modeling of Flying Debris (4)

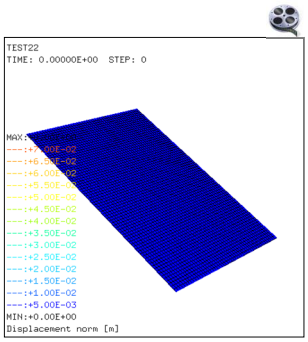
- Glass rupture revisited:



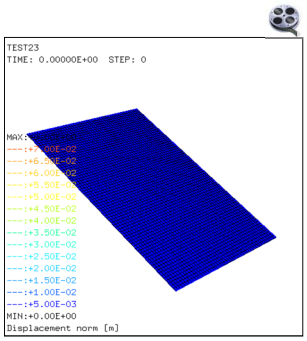
Geometry



Pressure (AIRB)



Erosion (Macro fragments)

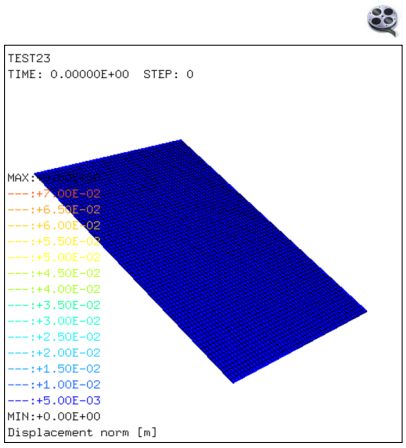


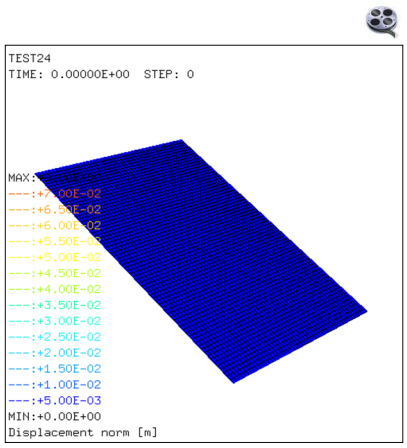
Erosion + Debris (Macro and micro fragments)

11

Modeling of Flying Debris (5)

- These solutions are quite sensitive to failure parameters:

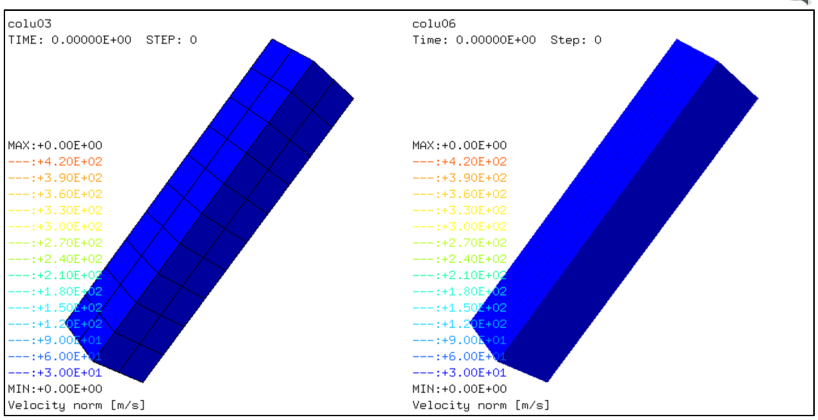




12

Modeling of Flying Debris (6)

- Fragmentation model can also be applied to bulky structures (e.g. a column made of unreinforced concrete)

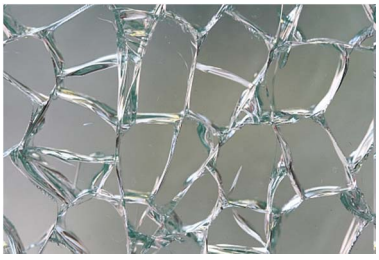


Coarse mesh, PLEV 1
320 particles

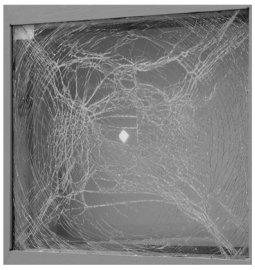
Fine mesh (4x), PLEV 2
163,840 particles

Modeling of Glass

- **Glass is used very often for structures and vehicles**
- **Glass can protect the interior from external air blast waves**
- **Glass can prevent an internal air blast wave from releasing**
- **Failure results in fragments and splinters**
- **Failure also results in internal pressure release**



Source: www.zdnet.com

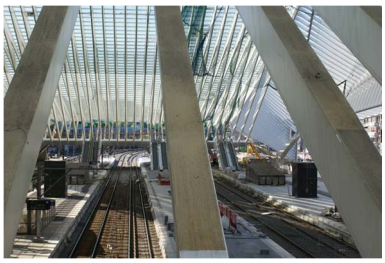


Source: www.glassfiles.com

Glazing of Stations and other Buildings



Broadgate Tower, London (under construction)



Railway station Liège



European Parliament, Strasbourg



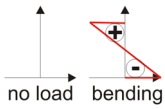
Railway station Berlin

15

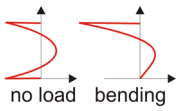
Source: wikipedia.org

Types of Glass

- **Annealed glass (brittle failure, small failure strength)**



- **Tempered glass (prestressed, small splinters)**



- **Laminated glass (splinters glued together)**
  Interlayer: Polyvinylbutyral (PVB)

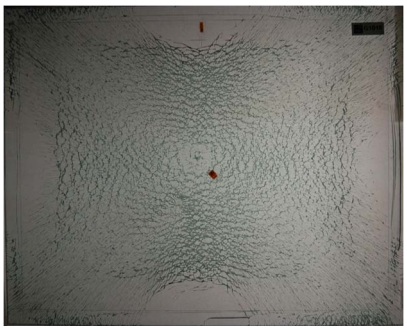


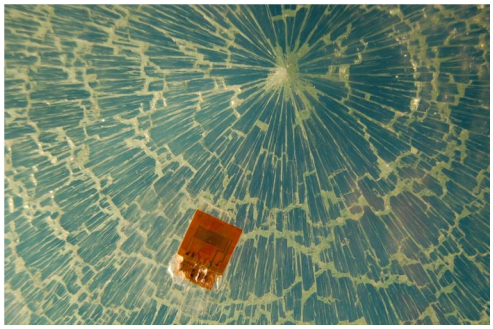
16

Complex Failure - Laminated Glass

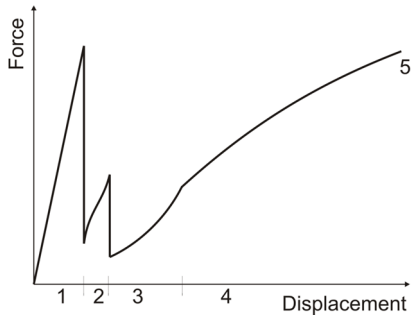


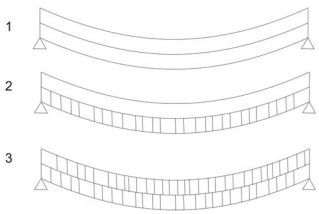
- Interlayer: Polyvinylbutyral (**PVB**)
- Interlayer keeps the glass plies **bonded** even when **cracked**
- Used very often for structures and vehicles
- Thickness: 6.4 – 100 mm, PVB: 0.4 mm and higher





Failure of Laminated Glass





5 phases (high strain rate):

- 1. Elastic behaviour of both glass layers
- 2. First layer is broken, the other one is still intact, interlayer is not damaged
- 3. Second glass layer fails
- Interlayer reacts elastically
- 4. Interlayer reacts plastically
- 5. Interlayer fails (tearing)

Laminated glass is replaced by debris particles after failure of the interlayer

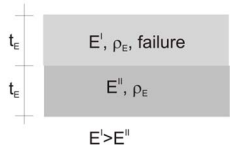
Failure of the interlayer is complex

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Modelling of Laminated Glass

Smeared model

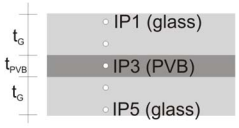
Two coincident shell elements
Stiffness before failure = Shell I+II
Stiffness after failure = Shell II



Phase 1 to 2
No shearing of the glass layers

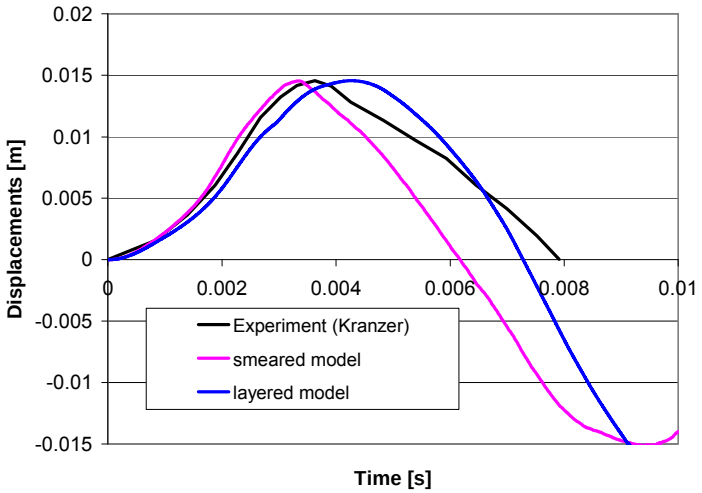
Layered model

After failure of a layer, still resists to compression



Phase 1 to 3 (5)
Better material law for PVB
Tearing of the PVB foil
No shearing of the glass layers

Modelling of Laminated Glass



1.0 x 0.8 m, 125 g C4 @ 2 m

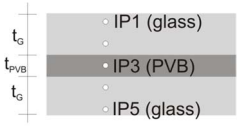
E_{PVB} = 3 10^6 N/m^2
n = 0.46
Failure strain 300%

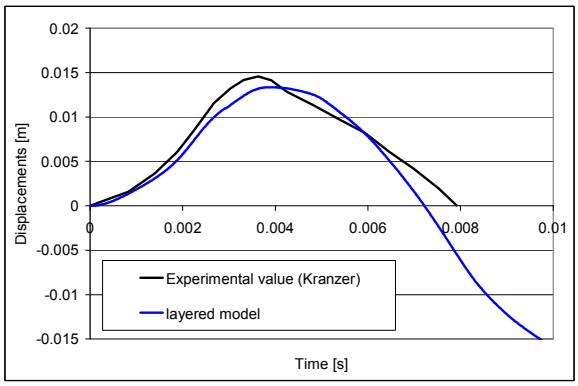
Experimental data: Kranzer 2005

Modelling of Laminated Glass

Layered glass model (LSGL material) :

Failure of a layer,
resistant against compression
Elastic-plastic material law for PVB





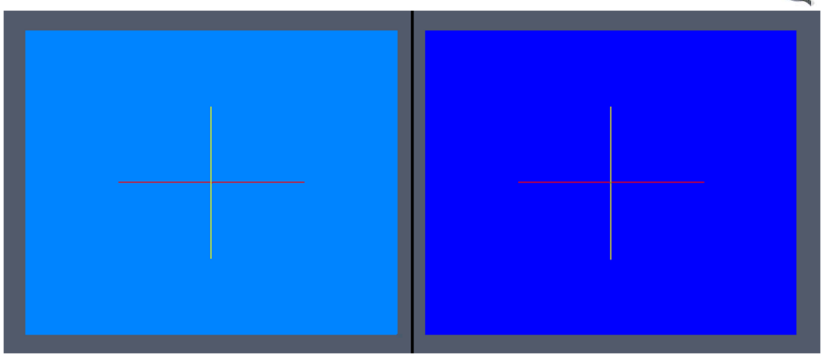
1.0 x 0.8 m, 7.5 mm thick LSG
125 g C4 @ 2 m

Experimental data: Kranzer et al. 2005

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Glass Blast Simulation

(glass failure only)



Displacements **Failure**

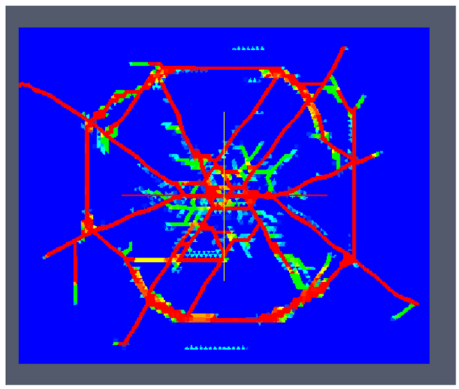
22

Comparison



Kranzer et al. 2005

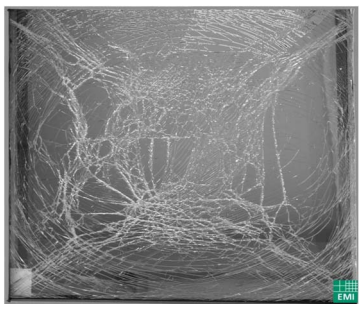
Experiment



Numerical failure

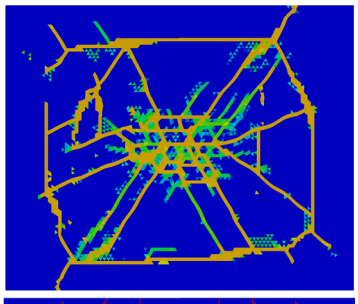
23

Crack Pattern (glass failure only)

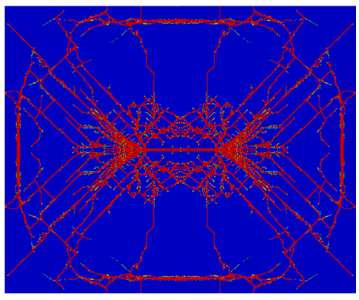


Kranzer et al. 2005

Experiment



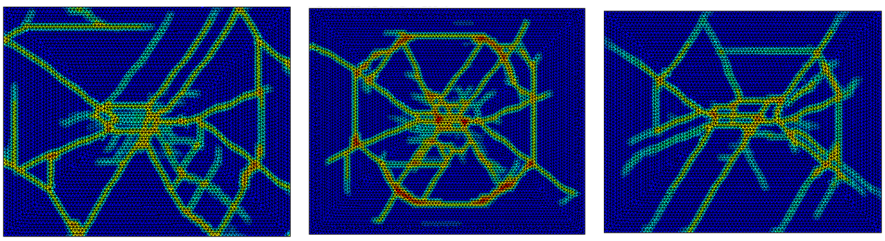
layered shell model
mesh 12.5 mm



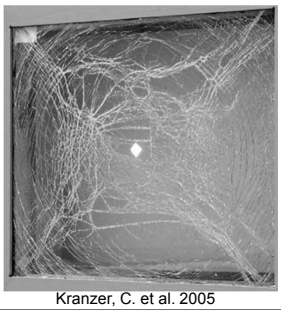
3D solid model
mesh 2.5 mm

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Influence of Boundary Conditions



sliding elastic fixed

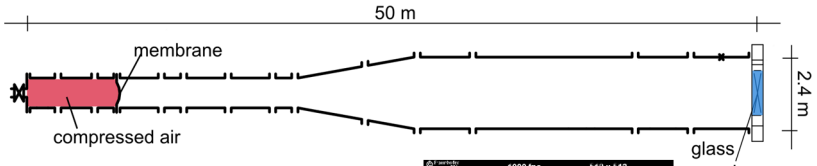


Kranzer, C. et al. 2005

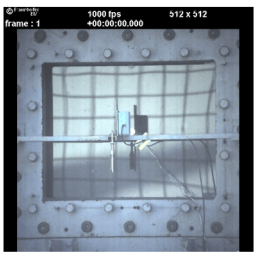
25

Experiments (complete failure)

- Full scale test at Ernst-Mach-Institut, Fraunhofergesellschaft, Germany
- Shock tube using compressed air, laminated glass 14 mm thickness
- Overpressures: 82 – 150 kPa (430 – 2300 kg TNT; 40-55 m distance)
- Measurement of the overpressure, displacements, strains



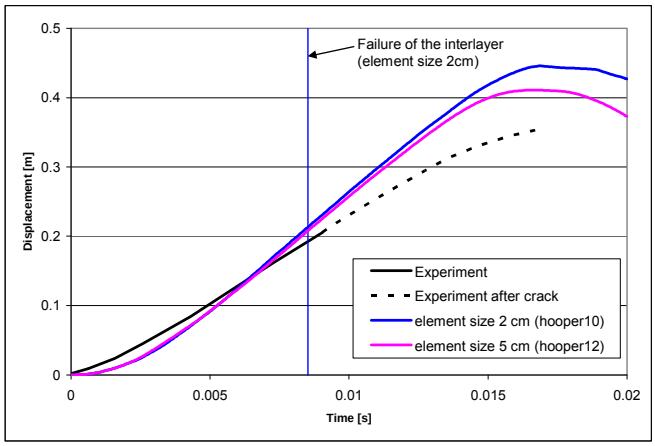






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Failure of the Interlayer



1.5 x 1.2 m, 7.5 mm LSG, 17 kg TNT @ 10 m

Experimental data: Hooper et al. 2008

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Simulation – Complete failure

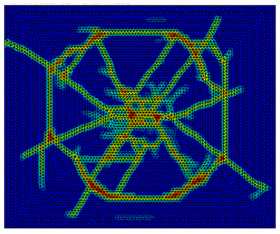


1.0 x 0.8 m, 14 mm LSG, 434 kg TNT, dist 41.9 m

28

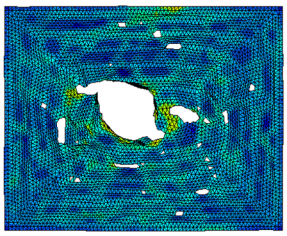
Failure of the Interlayer

Influence of charge size & distance on failure mode :



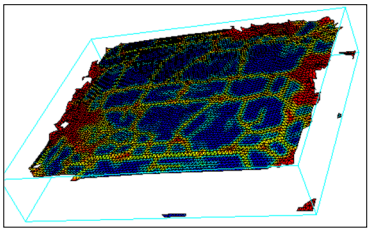
1.0 x 0.8 m
90 g TNT @ 1.8 m

No failure of the interlayer



1.5 x 1.2 m
17 kg TNT @ 13 m

Interlayer fails centrally (large displacements)



1.0 x 0.8 m
5 kg TNT @ 1.8 m

Interlayer fails early along the support

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Glazing Simulation : Summary

Laminated glass

- Layered model (LSGL material)
- Failure criteria: max. displacements (30% of span)
- Global criteria -> local failure of the border of the glass sheet
- Fragmentation of the interlayer is not considered

Tempered Glass

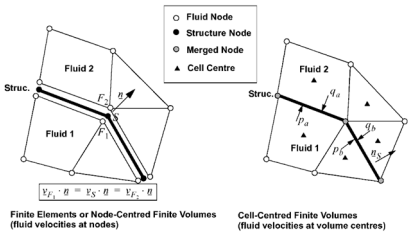
- GLAS material
- Failure stress of $159.6 \cdot 10^6$ N/mm^2
- Leads to complete failure of the glass
- Particles (debris) should be considered

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Structural failure with C-C Finite Volumes

(for a conforming FS mesh)

The **FLSR** model **cannot** be used with **CCFV** at the moment. However:



Finite Elements or Node-Centred Finite Volumes (fluid velocities at nodes)

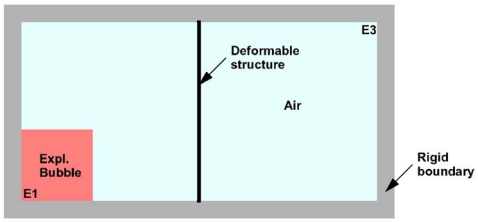
Cell-Centred Finite Volumes (fluid velocities at volume centres)

- To represent a deformable structural boundary, just merge the structure and fluid nodes (no need to use FSA condition)
- The program automatically detects the presence of the structure and transmits pressure forces to it (weak coupling)
- When the structure fails:
  - pressure forces are no longer transmitted
  - the two fluid volumes become "neighbors" of each other so that fluxes are computed (the fluid starts to flow across the failing structure)
  - Fluid nodes attached to a completely failed structure become Eulerian (not optimal …)

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Exercise/Example 12c – Failure with CCFV

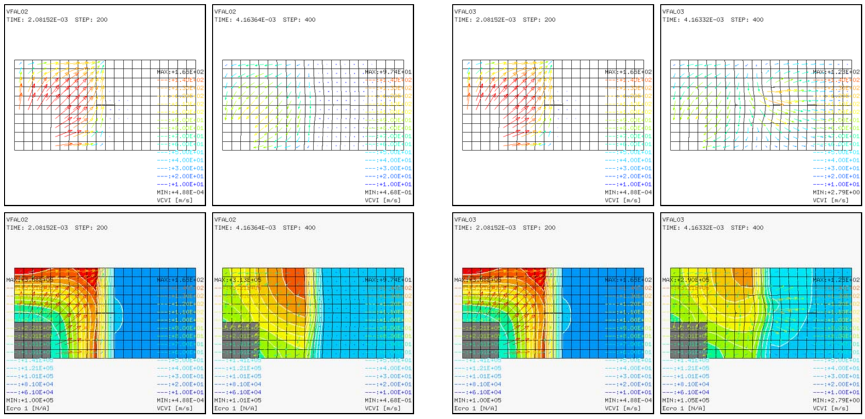
- Solve a FSI problem with failure and fragmentation by the CCFV fluid model (conforming meshes)



- Compare solutions without and with structural failure of the internal deformable wall

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Exercise/Example 12c – Failure with CCFV (2)

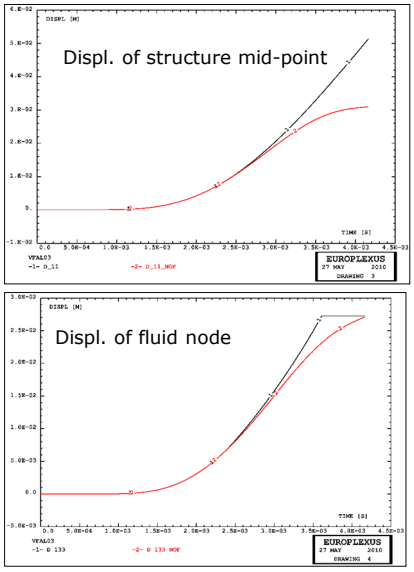


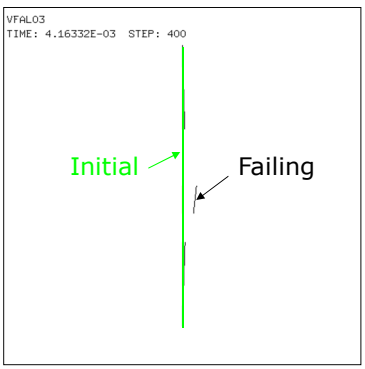
No failure

Failure

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Exercise/Example 12c – Failure with CCFV (3)



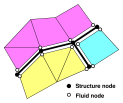
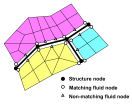
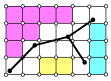


Failure

No Failure

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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

A Summary of FSI Algorithms

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Fluid-Structure Interaction

(in Fast Transient Dynamics)

One can distinguish <u>two classes</u> of problems :

- Large motions but moderate strains (**no structural failure**)
  - **ALE formulation** for treatment of F-S interfaces
  - Suitable **constraints** (compatibility conditions) on fluid (F) and structure (S) velocities at the interface (**FSA** model [2]):

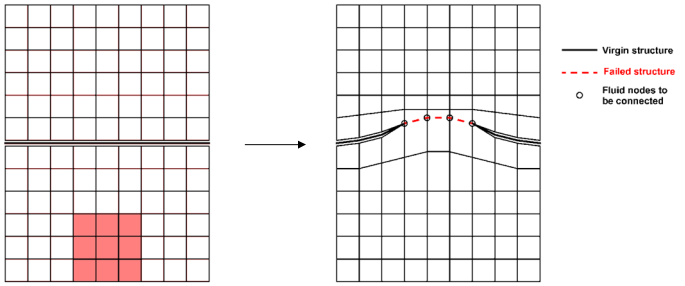
    $v_F \cdot n - v_S \cdot n = 0$ (n is the F-S normal)
  - Solution e.g. by **Lagrange multipliers** (<u>implicit</u>)
- Large motions and extreme strains (**structural failure**)
  - Failure in the structure is treated by suitable **failure criteria** and by **element erosion + flying debris model**
  - Special FSI technique required, based on **embedded** fluid and structure meshes (**FLSR / FLSW** models)

[2] Casadei F, Potapov S, <u>CMAME</u> **193** (2004) 4157-4194, *and references therein*.

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Issues in FSI with failure/fragmentation

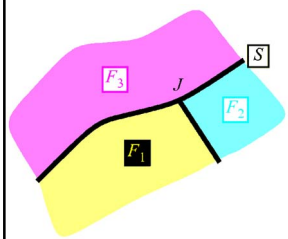
- When structure fails and is eroded, the FSI models seen so far are no longer applicable, because:
  - Difficult to "sew" the fluid meshes on either side of the failing structure
  - Automatic fluid mesh rezoning algorithms fail because the master domain (structure) "disappears"
  - Possible rotating macro fragments create rezoning problems
  - Etc. etc.



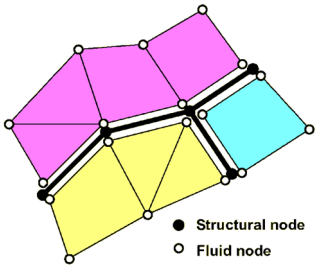
37

Issues in FSI with failure/fragmentation (2)

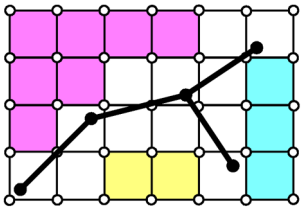
- Alternative approach : decouple structure from fluid at <u>topological</u> level (FLSR):



Continuous F/S Interface



Discretized F/S Interface (FSA, conforming)



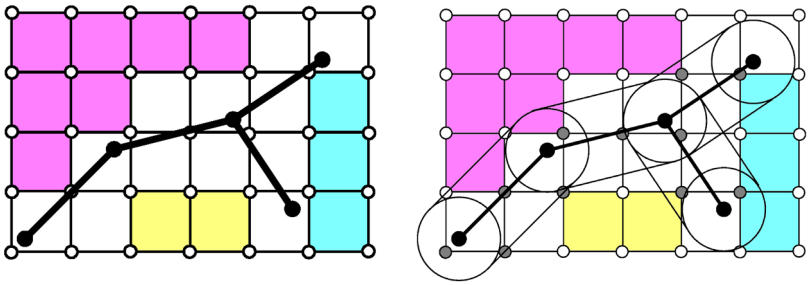
*Discretized F/S Interface (**FLSR**)*

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FLSR Model (outline)

- Automatically build up an "**influence domain**" around the structure (a sphere at each S node, then more complex shapes)
- Identify (fast search) **fluid nodes** F currently located within the influence domain
- Impose suitable constraints on velocities : $v_F \cdot n_{S^*} - v_{S^*} \cdot n_{S^*} = 0$

  (n_{S^*} is the normal to the structure, S* is **closest structural point** to fluid node)



The grayed fluid nodes are coupled with the structure

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The FLSR Model

- Build influence domain around the structure
- Identify fluid nodes *F* within the influence domain
- For each such fluid node *F*, identify the corresponding structural point S^*
- Write the coupling conditions
- Note that each coupling condition involves a different fluid node, by construction

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The FLSR Model (2)

- Fluid mesh can be Eulerian (and even structured!)
- No fluid mesh entanglement (by construction)
- F-S interaction imposed by suitable LINKs (Lag. Mul.) :

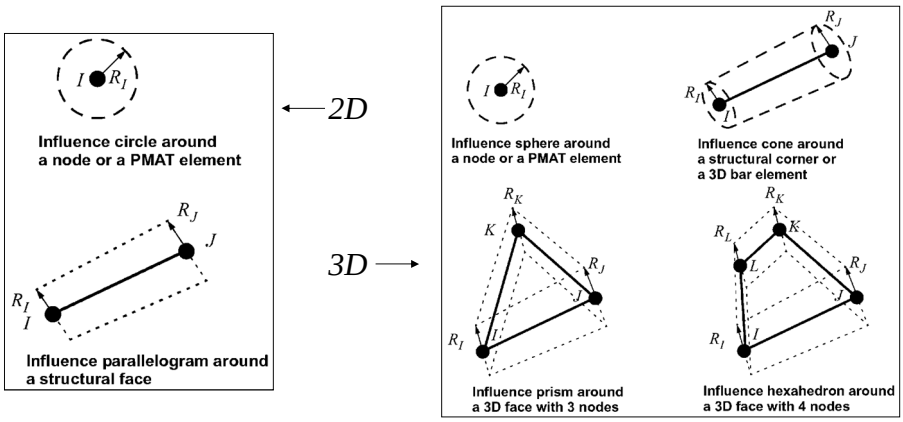
$$\underline{v}_F \cdot \underline{n} - \underline{v}_{S^*} \cdot \underline{n} = 0$$

- F is a fluid node, S^* is a structure point (not a node in general)
- $\underline{n}$ is unit normal (defined by the structure!)
- Some numerical diffusion is to be expected (less accurate than FSA)

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The FLSR Model (3)

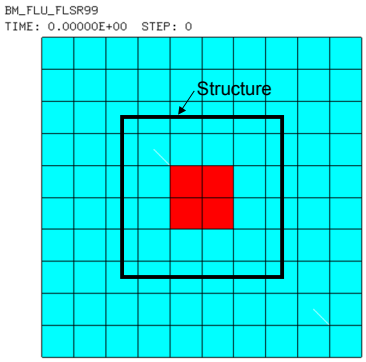
- The influence domain is the union of various entities:



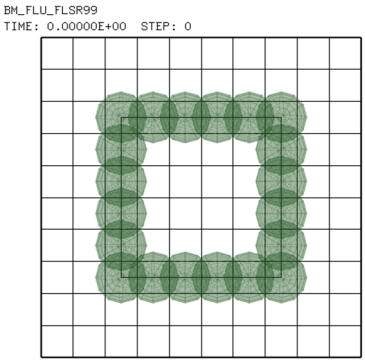
- Apply suitable precedence rules when a fluid node F belongs to more than one entity

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FLSR Example

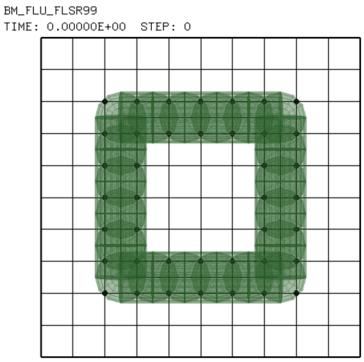


Initial mesh

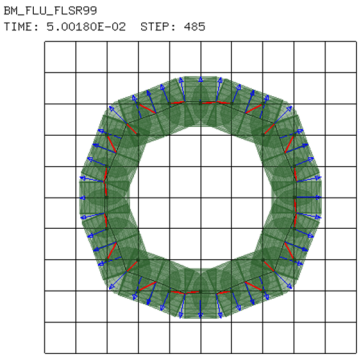


Initial FLSR nodal spheres

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Initial FLSR domain and coupled fluid nodes

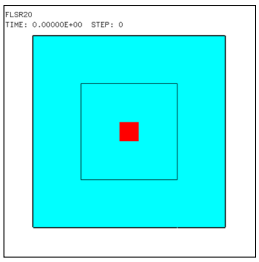


Final FLSR domain and coupled fluid nodes

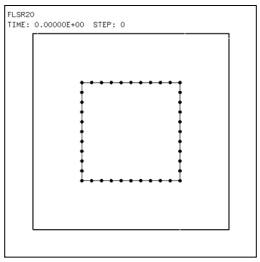
44

The FLSR Model (4)

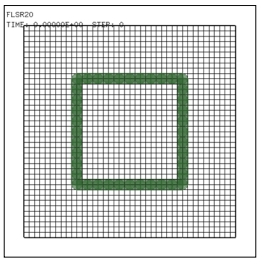
- Test FLSR model vs. FSA (without failure)



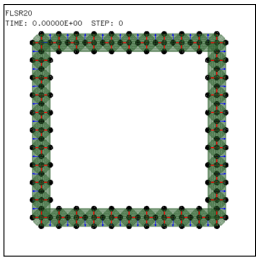
Outline



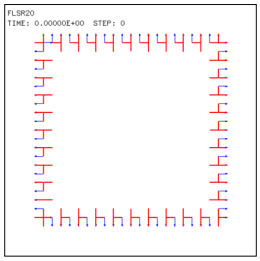
Structural nodes



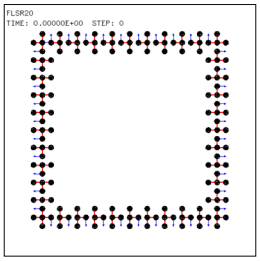
FLSR influence domain



FLSR fluid nodes

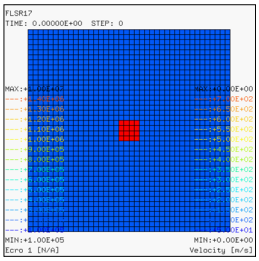


FLSR normals/links

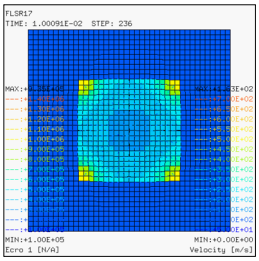


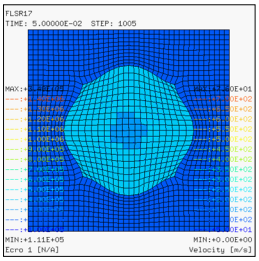
45

The FLSR Model (5)

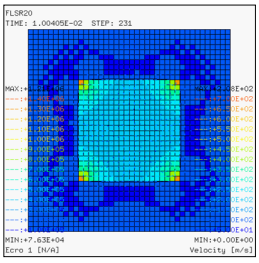


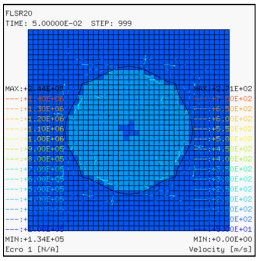
t = 0





FSA





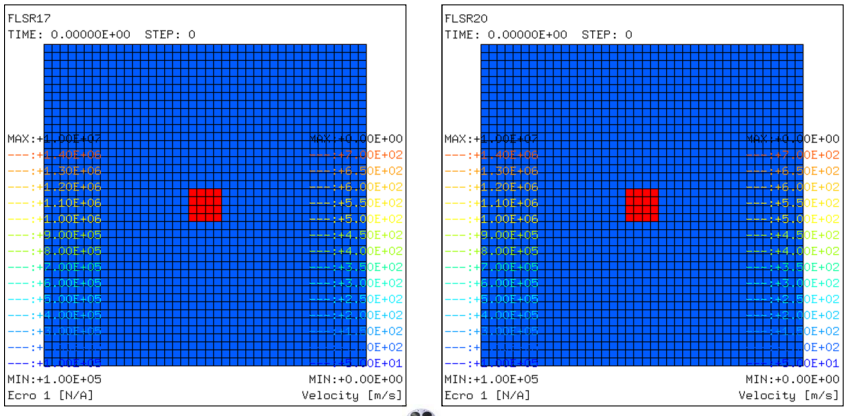
FLSR

t = 10 ms

t = 50 ms

46

The FLSR Model (5)



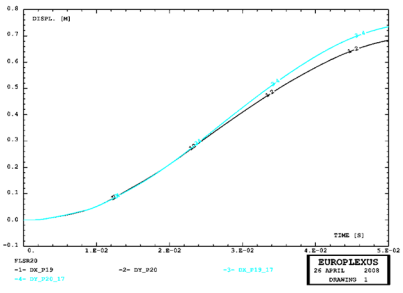
FSA *FLSR*

Comparison

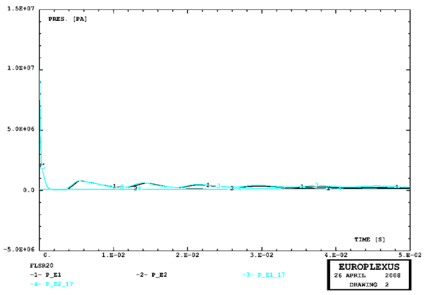
47

The FLSR Model (6)

- Compare FLSR model vs. FSA (without failure)



Structure displacements

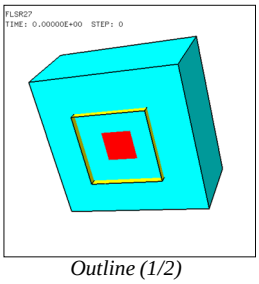


Fluid pressures

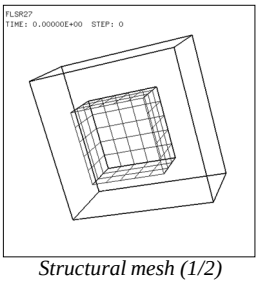
48

The FLSR Model (7)

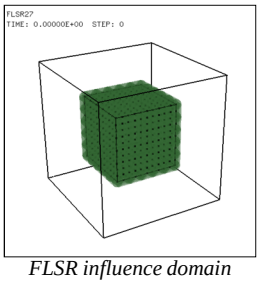
- Test FLSR model vs. FSA (without failure) in 3D



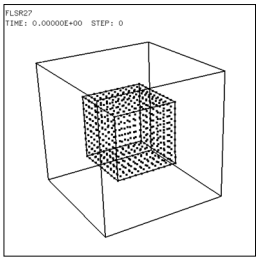
Outline (1/2)



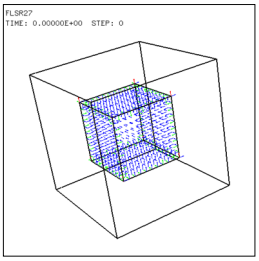
Structural mesh (1/2)



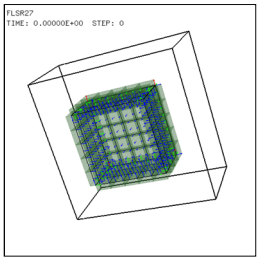
FLSR influence domain



FLSR fluid nodes



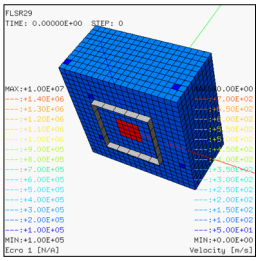
FLSR normals/links



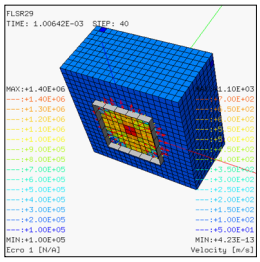
FLSR influence hexahedra (1/2)

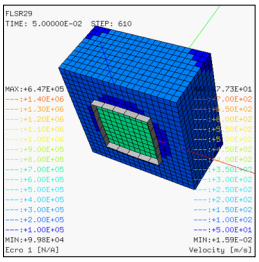
49

The FLSR Model (8)

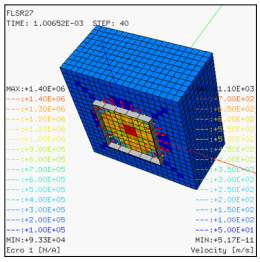


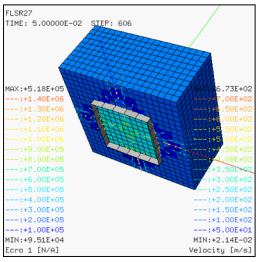
t = 0





FSA



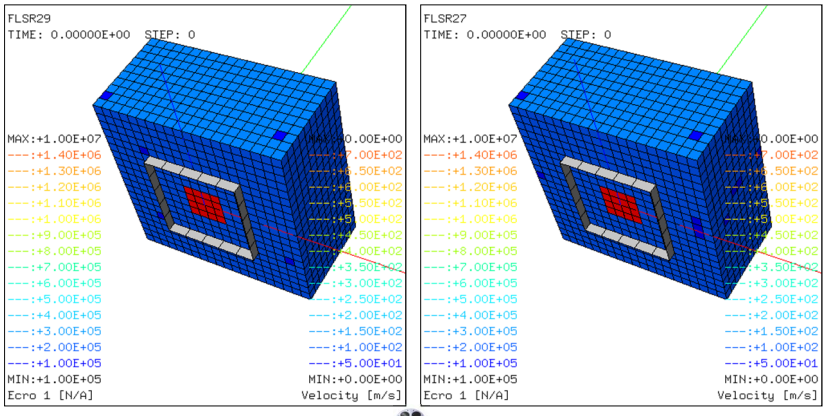


FLSR

t = 1 ms *t = 50 ms*

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The FLSR Model (9)

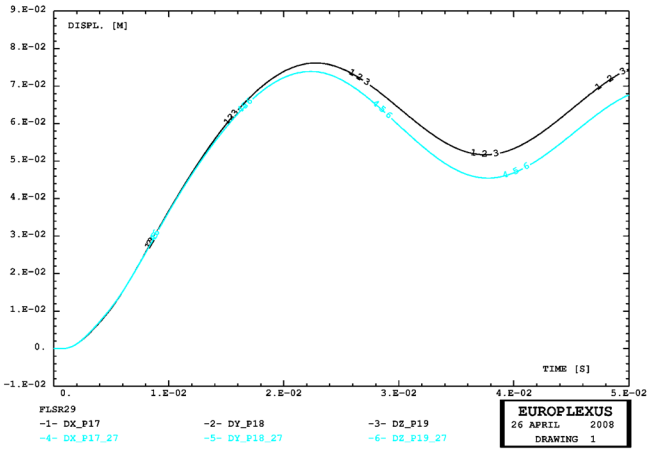


FSA *FLSR*

Comparison

The FLSR Model (10)

- Compare FLSR model vs. FSA (without failure) in 3D



Structure displacements

The FLSR Model with NCFV

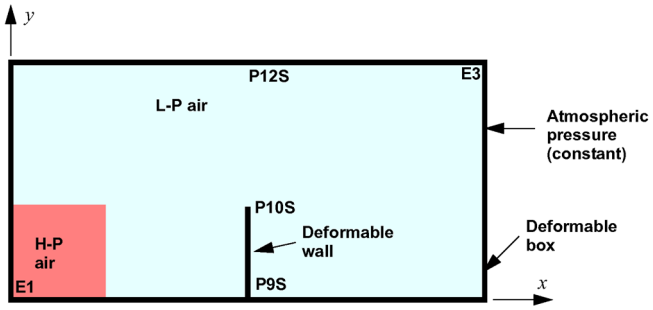
- The basic FLSR model described above does not work well with NCFV : large spurious passages of fluid (mass and energy fluxes) across the structure are observed
- Unlike in FE, blocking the momentum flux alone (through velocity constraints) does not ensure blocking of the other fluxes (mass, energy) in the NCFV formulation, due to the way in which such fluxes are computed
- To solve this problem, add an optional keyword **MCFL mcfl** to the **FLSR** directive (where **mcfl** is 1 or 2, see User's manual)

```
LINK COUP … FLSR … MCFL mcfl
```

- For the same reason, using a link to constrain an internal NCFV node (not on the fluid boundary) does not work as expected

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Exercise 12b – FLSR with NCFV

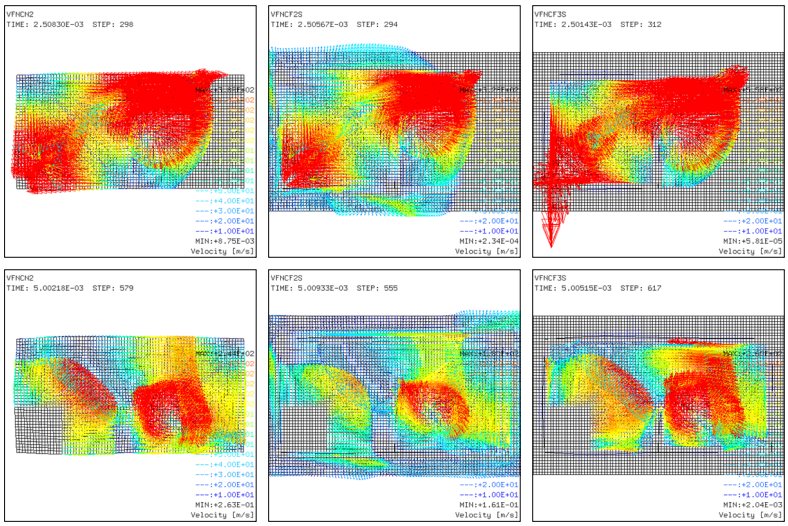


- The box problem of exercise 10b (Part 3) is solved with NCFV using the FLSR model for Fluid-Structure Interaction
  - Obtain solution with NCFV and FSA (reference solution) by using a fine fluid mesh and non-conforming FSA model (see Part 5)
  - Obtain solution with NCFV and basic FLSR : large spurious fluid leakage is observed
  - Add keyword **MCFL 1** : the spurious leakage disappears

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Exercise 12b – FLSR with NCFV

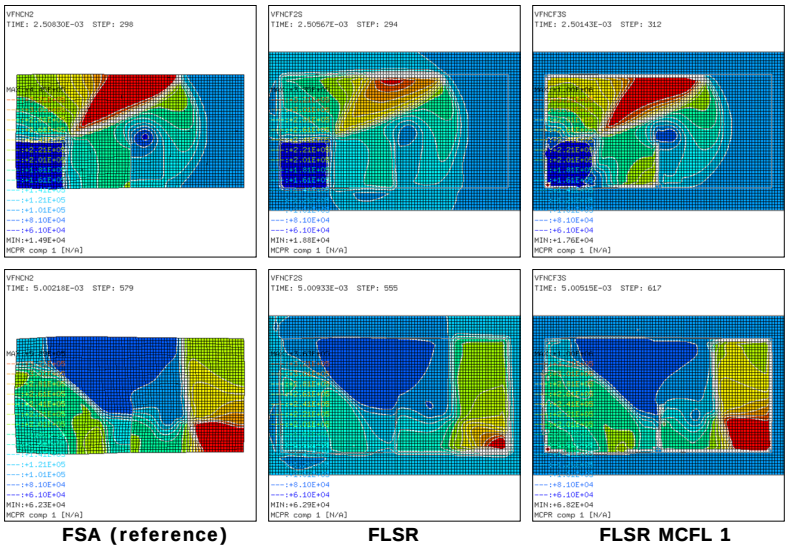
- Fluid velocities :



55

Exercise 12b – FLSR with NCFV

- Fluid pressures :

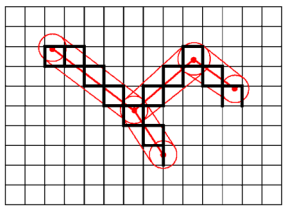


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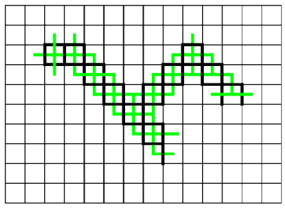
FLSW Model : a "weak" variant of FLSR

for use especially with CCFV

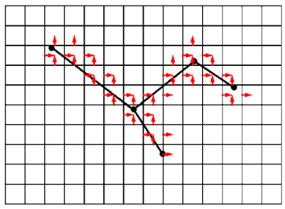
- Automatically build up an "**influence domain**" around the structure (exactly like for **FLSR**)
- Identify (fast search) **fluid volume centres** C **or fluid faces** F currently located within the influence domain
- Transmit **pressure drop forces** to the structure and block associated mass and energy **fluxes** (**weak** approach)



Influence domain of structure (in red) and associated FV faces (thick lines)



Blocked fluxes (in green)

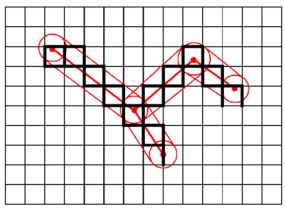


F) Forces to be applied to the structure (closest point)

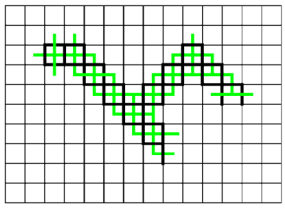
Strategy 1 : detect directly fluid faces (CCFV only)

57

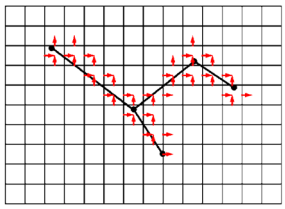
FLSW Model (2)



Influence domain of structure (in red) and associated FV faces (thick lines)

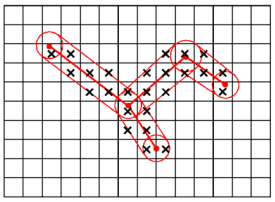


Blocked fluxes (in green)

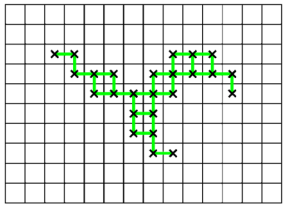


F) Forces to be applied to the structure (closest point)

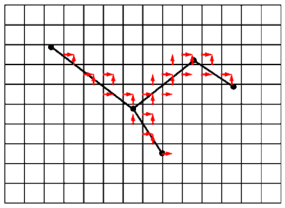
Strategy 1 : detect directly fluid faces (CCFV only)



Influence domain of structure (in red) and associated element centres (crosses)



Blocked fluxes (in green)

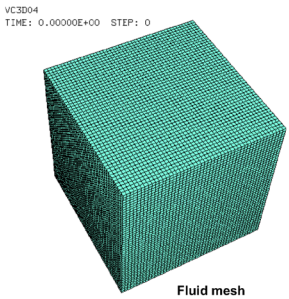


Forces to be applied to the structure (closest point

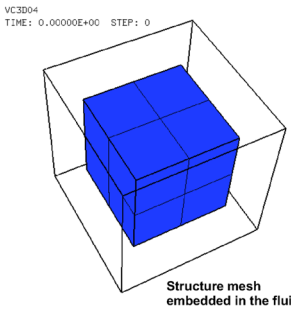
Strategy 2 : detect fluid elements, then faces

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FLSW Model (3) : practical advantages



Fluid mesh



Structure mesh embedded in the fluid

- **Fluid** mesh **much finer** than structure (in view of **adaptivity**)

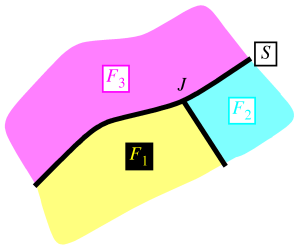
- **Strong** approach (**FLSR**, implicit) slow due to large bandwidth of constraints matrix
- **Weak** approach (**FLSW**) much faster in this case

Case	Mesh	FSI model	Steps	CPU [s]	Elms * steps
VC3D04	110592 CUVF, 24 Q4GS (2nd order)	Fixed ext. boundary (no condition). FLSW 1 0.0541875 HGRI 1.1 BFLU 2 FSCP 1	139	271	1.6×10^{7}
EF3D05	110592 FL38, 24 Q4GS	FSR on ext. boundary. FLSR 1 0.0541875 HGRI 1.1 BFLU 2 FSCP 1 SOLV SPLI SPLT NONE	125	7,885	1.4×10^{7}

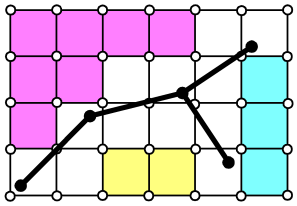
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Summary of Embedded FSI algorithms

- Structure is discretized **independently** from fluid and its mesh is **embedded** (or immersed) in the fluid mesh
- Fluid can be Eulerian, with regular mesh : no mesh entanglement for large structure **rotations**
- Treatment of structural **failure** is greatly facilitated
- Less accurate : (locally) **fine** fluid mesh is needed



a) Continuous F-S domain.

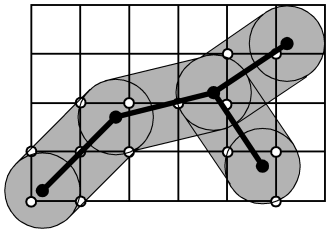

b) Structure mesh embedded in the fluid.

Sample FSI problem and its **embedded** discretization

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Strong embedded approach (FLSR)

- Detection via **influence domain** around structure
- **Fast** search of **coupled fluid nodes**
- Strong coupling with **closest** structure **point**

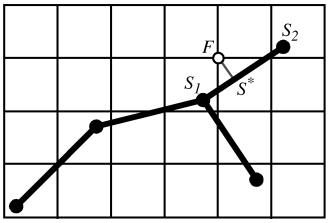


a) Influence domain (shaded) of the structure.

$$\mathbf{v}_F \cdot \mathbf{n}_S = \mathbf{v}_{S^*} \cdot \mathbf{n}_S = (N_1 \mathbf{v}_{S_1} + N_2 \mathbf{v}_{S_2}) \cdot \mathbf{n}_S$$

or more simply :

$$\mathbf{v}_F = \mathbf{v}_{S^*} = N_1 \mathbf{v}_{S_1} + N_2 \mathbf{v}_{S_2}$$



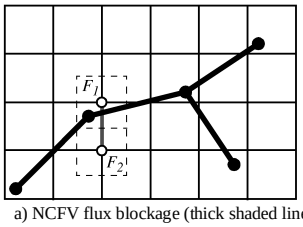
b) F-S coupling.

The **FLSR** embedded algorithm with a **strong** approach

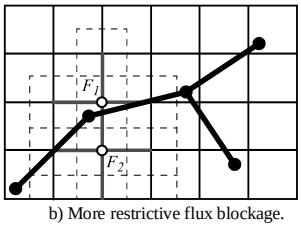
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Application to NCFV

- The **FLSR** embedded algorithm can be applied also to **NCFV**. However, **spurious** fluid passage across solid structure (**leakage**) is observed (**not** with **FE**!)
- Necessary to **block numerical fluxes** between volumes **close** to the structure (various possible strategies)



a) NCFV flux blockage (thick shaded line).

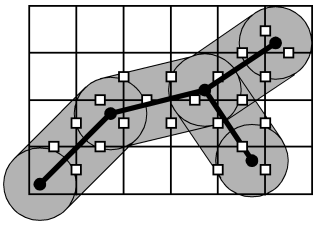


b) More restrictive flux blockage.

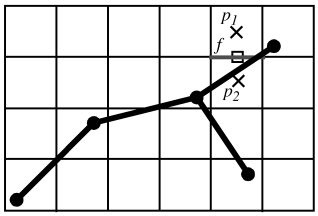
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Weak embedded approach (FLSW)

- Detection via **influence domain** around structure (= FLSR)
- Fast search of coupled fluid **faces (for CCFV)**
- Weak coupling : pressure force to **closest** structure **point**
- Necessary to **block numerical fluxes** (= NCFV)



a) CCFV faces in the influence domain.



b) Pressure drop force calculation.

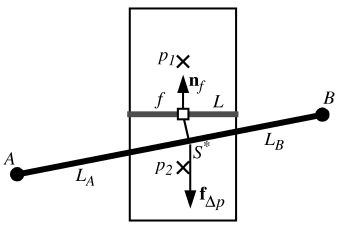
The **FLSW** embedded algorithm with a **weak** approach

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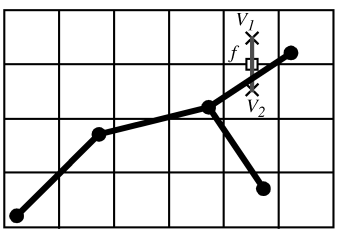
Weak embedded approach (2)

$$\mathbf{f}_{\Delta p} = (p_1 - p_2) L \mathbf{n}_f$$

$$\mathbf{f}_{\Delta p,A} = (L_B / L_S)\mathbf{f}_{\Delta p} \quad ; \quad \mathbf{f}_{\Delta p,B} = (L_A / L_S)\mathbf{f}_{\Delta p}$$

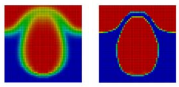


a) F-S coupling force.

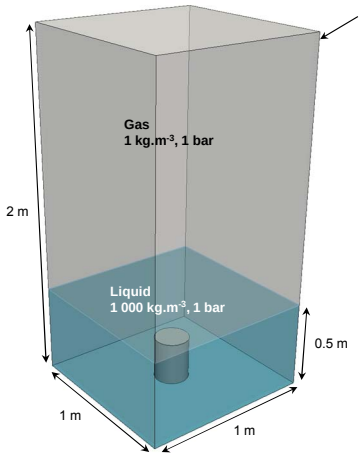


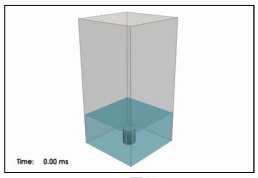
b) CCFV flux blockage (thick shaded line).

64



Under-water barrel explosion with anti-diffusion (Courtesy of CEA)







Barrel mesh: DKT3 elements
Elasto-plastic steel
Failure model: ε_p max
Explosive gas inside

Coupled Euler-Lagrange FSI

65

Conclusions and perspectives on anti-diffusivity

Explosive multicomponent flows with EUROPLEXUS Software

- **Robust approach** with no interface reconstruction
- **Necessary anti-dissipation** achieved with:
  - Downwind scheme with constraints for 1D and 2D/3D structured meshes
  - VOFIRE algorithm for unstructured meshes
- **Several illustrations** performed for non-linear liquid-gas flows with free surface and fluid-structure interaction

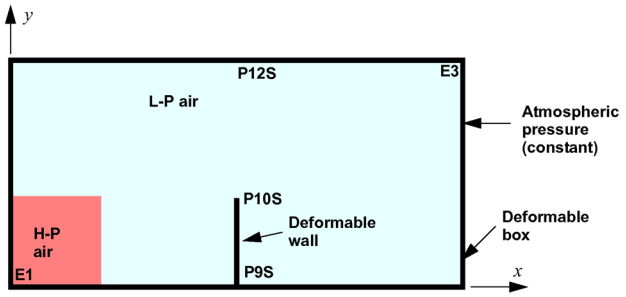
Residual limitations and prospects

- Anti-dissipative approach currently limited to **two-components flows** (one scalar concentration advected with anti-dissipation)
- **Slower mesh convergence** observed for simulations with anti-dissipation
- **Further validation in progress** for liquid-gas interface behaviour, correlated with experimental results:
  - Sloshing within a decelerated tank
  - Pulse frequency of an immersed gas bubble

66

Exercise 6ter – Résumé of FSI models

(All available non-conforming techniques)



- Revisit the box problem of Exercise III-10b (**coarse** solutions with **conforming** FSI) and obtain more **accurate** solutions using all the available **non-conforming FSI** techniques:
  - With **FE** (**JRC** formulation) and either **FSA** or **FLSR**
  - With **FE** (**CEA** formulation) and either **FSA** or **FLSR**
  - With **NCFV** and either **FSA** or **FLSR** (see also Exercise IV-12b)
  - With **CCFV** and non-conforming **weak** FSI coupling or **FLSW**

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Exercise 6ter – Résumé of FSI models (2)

(All available non-conforming techniques)

- Resume of the 8 obtained solutions :

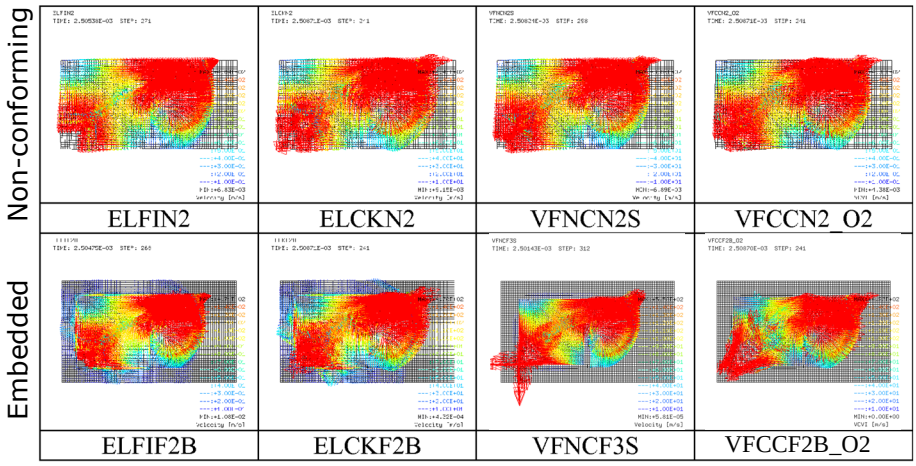
Fluid model / FSI model	FSA or weak (for CCFV)	Embedded: FLSR/FLSW
FE-JRC	ELFIN2	ELFIF2B
FE-CEA	ELCKN2	ELCKF2B
NCFV	VFNCN2S	VFNCF3S
CCFV	VFCCN2_O2	VFCCF2B_O2

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Exercise 6ter – Résumé of FSI models (3)

(All available non-conforming techniques)

- Fluid velocities at 2.5 ms in the 8 solutions :

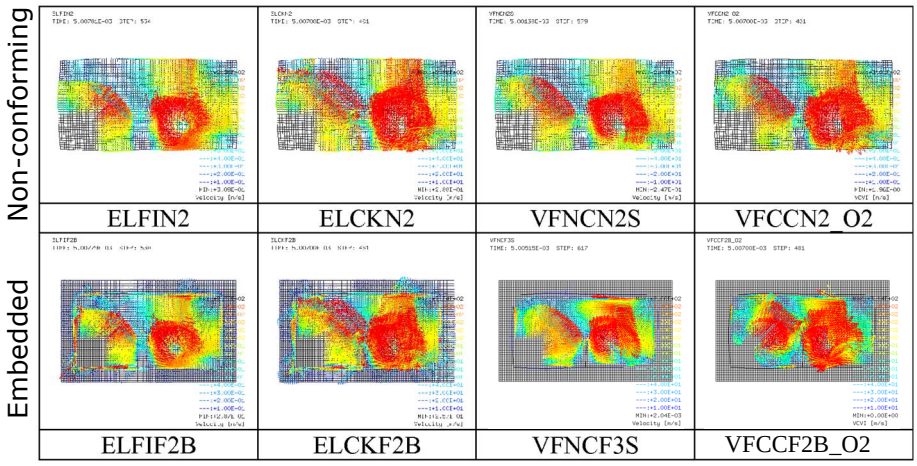


69

Exercise 6ter – Résumé of FSI models (4)

(All available non-conforming techniques)

- Fluid velocities at 5.0 ms in the 8 solutions :

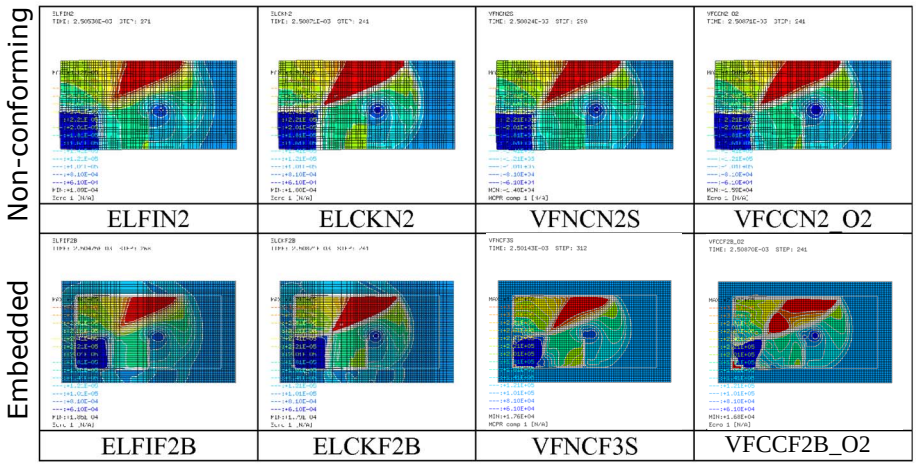


70

Exercise 6ter – Résumé of FSI models (5)

(All available non-conforming techniques)

- Fluid pressures at 2.5 ms in the 8 solutions :

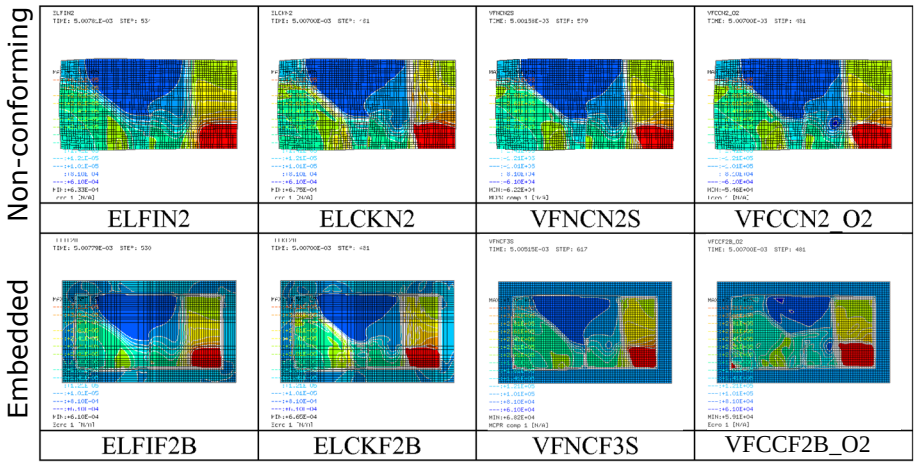


71

Exercise 6ter – Résumé of FSI models (6)

(All available non-conforming techniques)

- Fluid pressures at 5.0 ms in the 8 solutions :

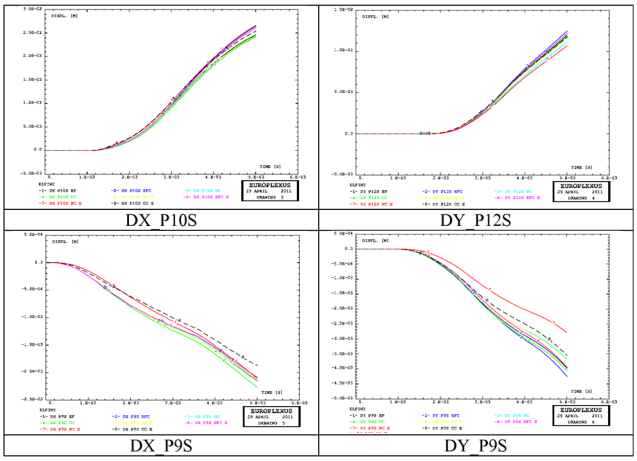


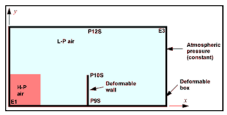
72

Exercise 6ter – Résumé of FSI models (7)

(All available non-conforming techniques)

- Structural displacements in the 8 solutions :

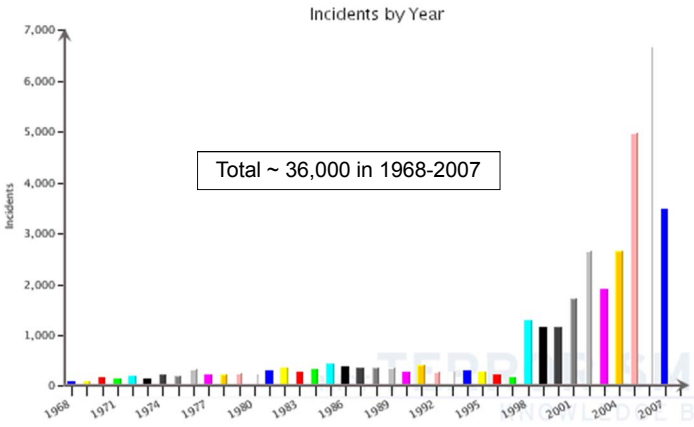




73

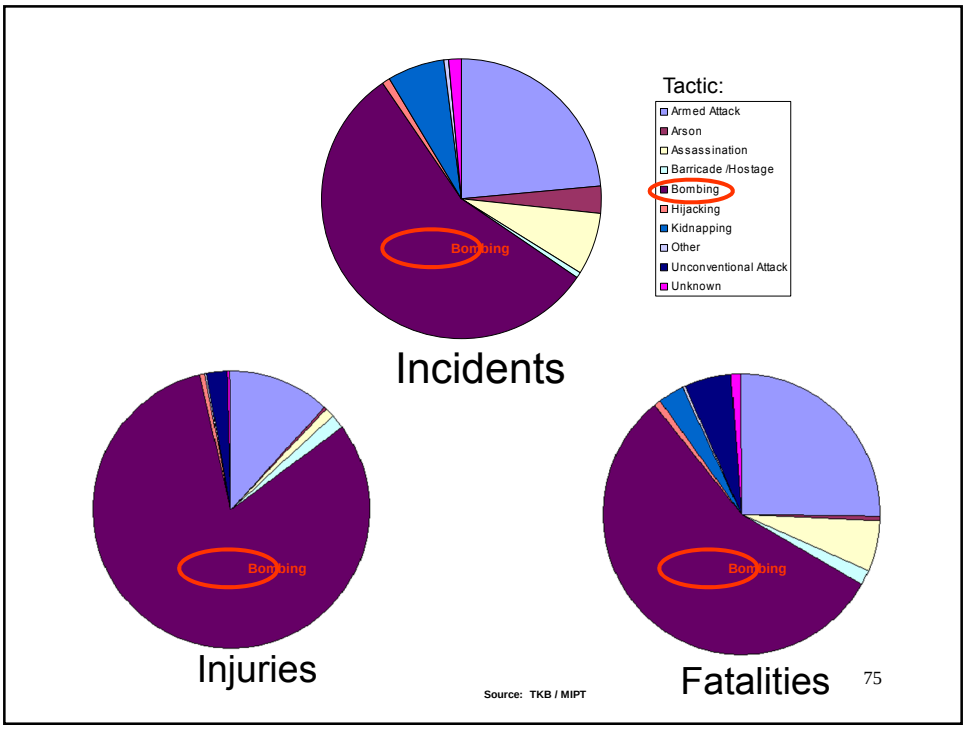
Land Transport Vulnerability: attack on train/metro stations / rolling stock – Background & motivation

Terrorist Incidents Pattern



Source: Terrorism Knowledge Base (TKB), Memorial Institute for the Prevention of Terrorism (MIPT), Last updated on Jan. 29, 2008

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Terrorist Attacks against Land Transport System



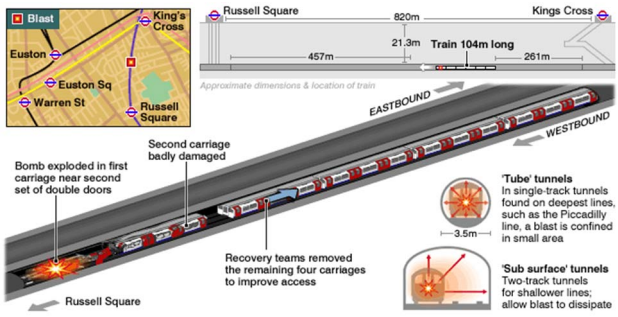
Madrid, 11 March 2004



London, 7 July 2005



Barajas Madrid, 30 Dec. 2006



Characteristics of land mass passenger transport:

- Accessible, dynamic, with **open** security **architecture** and widely dispersed assets
- No measures comparable to those of civil **aviation** or maritime transport
- Not possible to completely eliminate the hazard by **prevention** / **intelligence**

➢ System is INHERENTLY VULNERABLE TO TERRORIST ATTACKS

- **Numerical simulation** may help in designing safer new infrastructures and in retrofitting most critical existing infrastructures
- Same **vulnerability assessment** techniques may be used also for other **critical infrastructures**: buildings, bridges, power plants, dams, etc.

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The starting point:

- **RAILPROTECT** project (2007-2009)
  - Funded by DG-TREN
  - Focus on **railway/metro stations** and **rolling stock**
  - Involving several national experts/authorities
- Main tool : **EUROPLEXUS** computer code
  - Developed jointly by CEA (F) and JRC (EU)
  - Commercial version distributed by SamTech
  - FE / FV **explicit** code for **fast transient dynamic** analysis (impact, crash, explosion, …)
  - Sophisticated FSI modelling
  - Decades of experience in industrial safety studies
  - Many specialized developments were needed (see below)
- Main Contributors at JRC:
  - F. Casadei, G. Solomos, M. Larcher, G. Giannopoulos

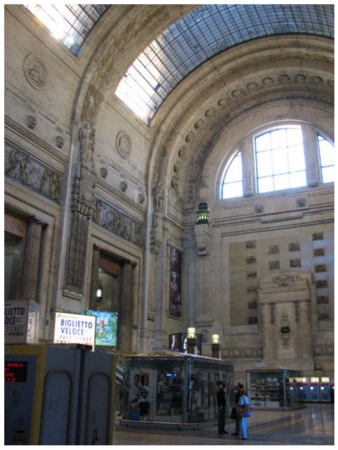
78

Land Transport Vulnerability: attack on train/metro stations and rolling stock

Old stations …



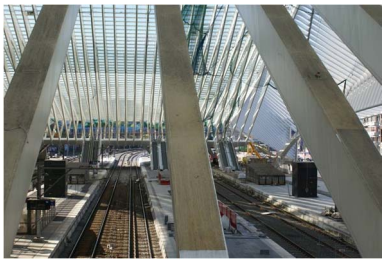
Milan Central station



Glazing of Stations and other Buildings



Broadgate Tower, London (under construction)



Railway station Liège



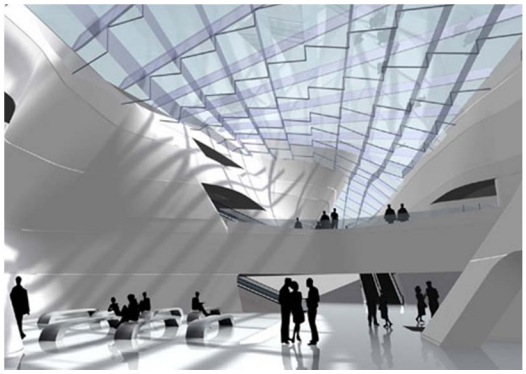
European Parliam Strasbourg



Railway station Berlin

80

Source: wikipedia.org



Naples, Afragola

Future stations …

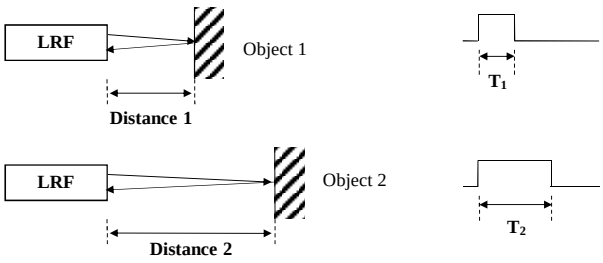
Florence, Belfiore



Are explosion effects considered ?

Getting the Real Geometry (JRC 3D Reconstructor)

- Laser scanner and digital camera





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Getting the Geometry (2)

- Tripod and/or vehicle

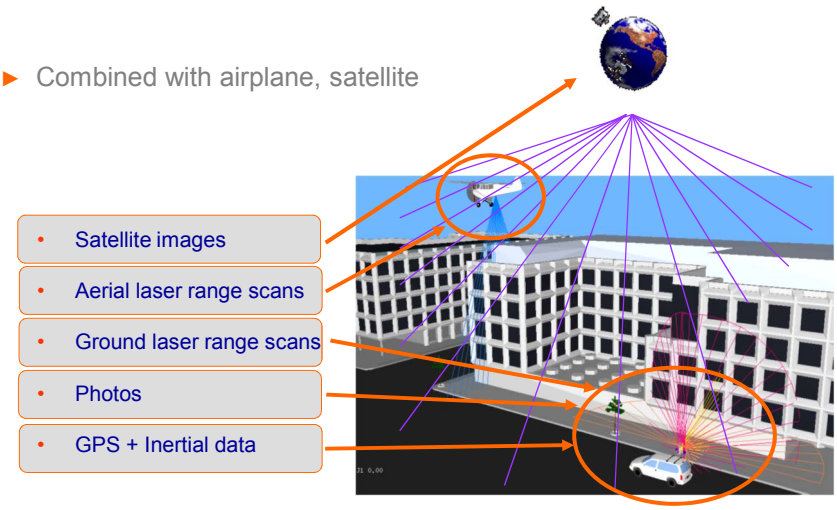




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Getting the Geometry (3)

- Combined with airplane, satellite

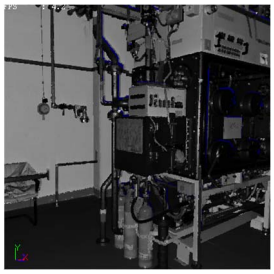


Computer simulation of the data acquisition system

Example : detecting changes



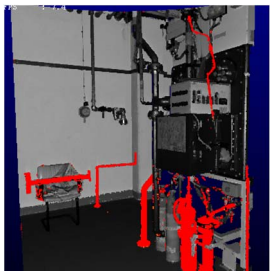
Reference



Verification

Differences

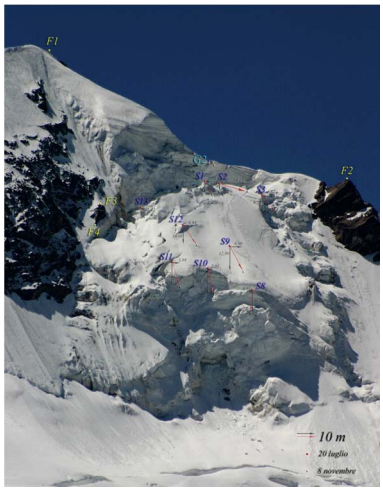
highlighted by JRC 3D Reconstructor software

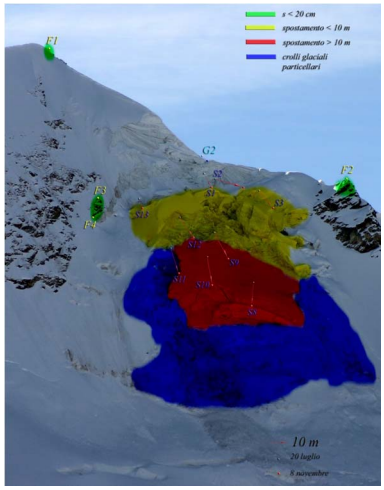


85

Example : detecting changes (2)

- Evaluate possible damage in case of the ice fall collapse



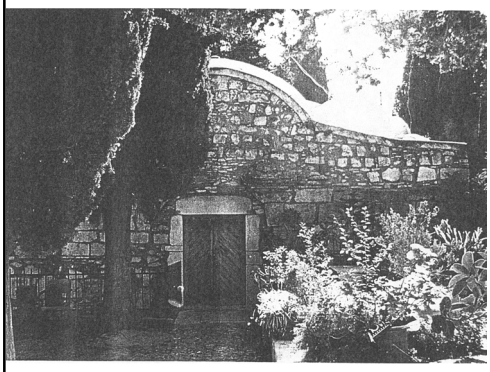


Source: InnTec, University of Brescia, Servizio Glaciologico Lombardo Arpa

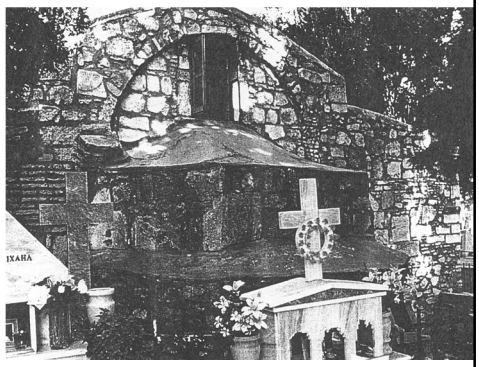
86

Exercise/Example 13 – Building Vulnerability

- Internal blast in a (deformable) building (but no failure yet!):



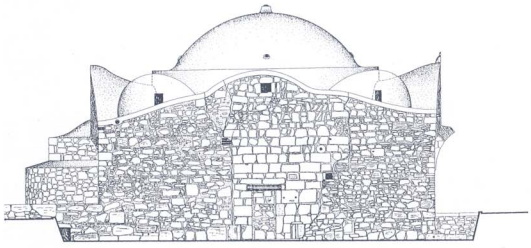
Front View



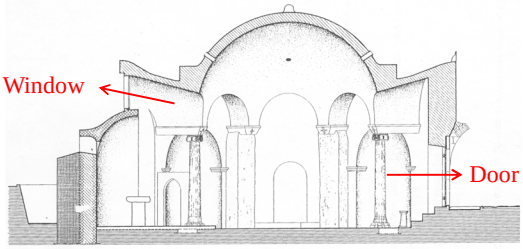
Back View

87

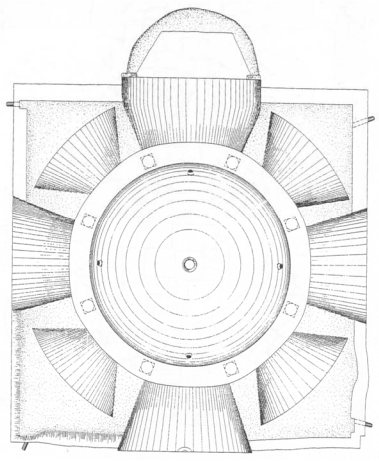
Exercise/Example 13 – Building Vulnerability (2)



Side View



Sectioned View

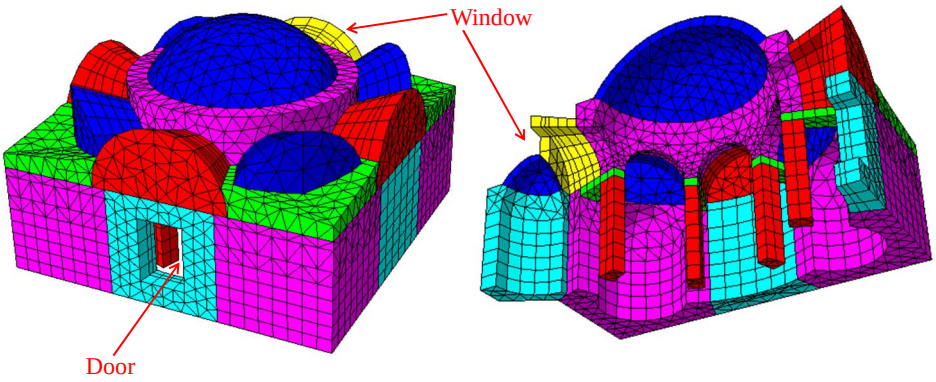


Top View

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Exercise/Example 13 – Building Vulnerability (3)

• Structural mesh:



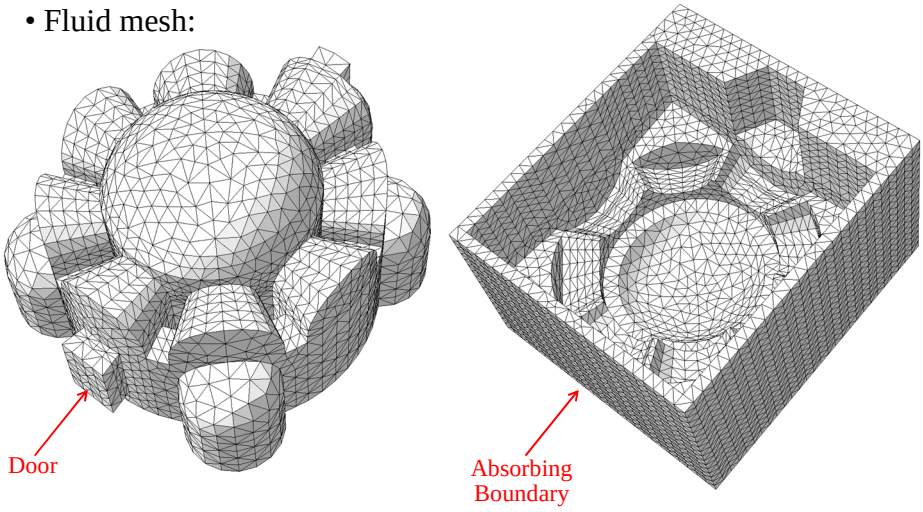
Complete View

Sectioned View Along Symmetry Plane

89

Exercise/Example 13 – Building Vulnerability (4)

• Fluid mesh:



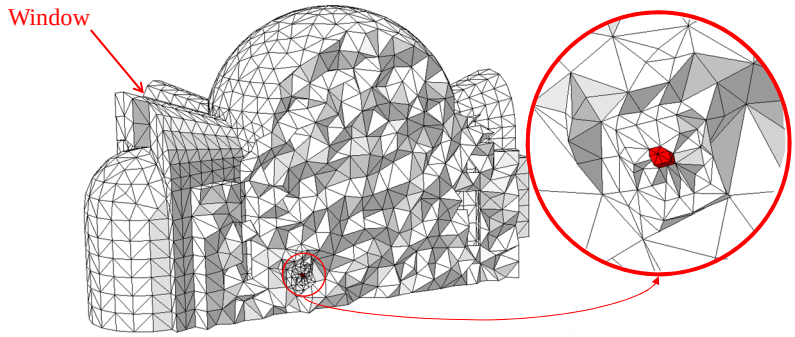
Internal Fluid (from top)

External Fluid (from bottom)

90

Exercise/Example 13 – Building Vulnerability (5)

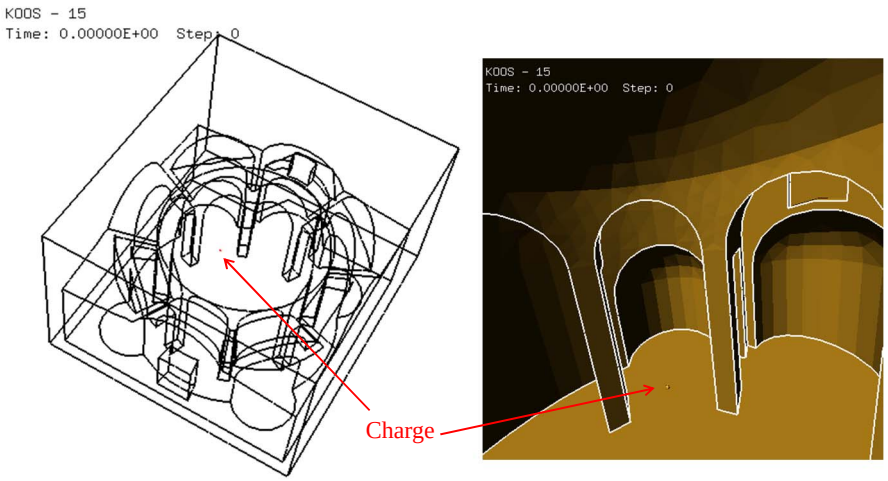
• Explosive charge (solid TNT):



91

Exercise/Example 13 – Building Vulnerability (6)

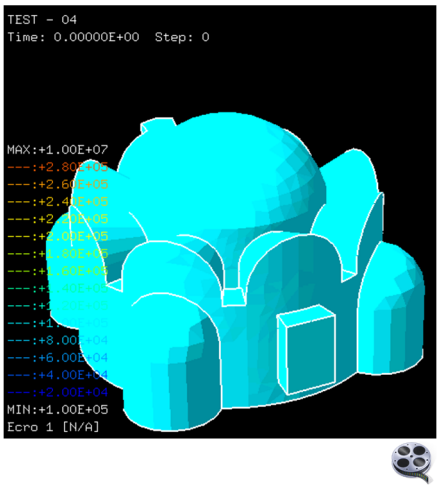
• Explosive charge (solid TNT):

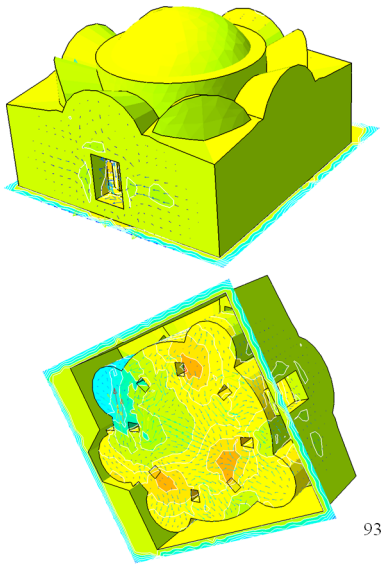


92

Exercise/Example 13 – Building Vulnerability (7)

- Pressures/velocities in fluid:

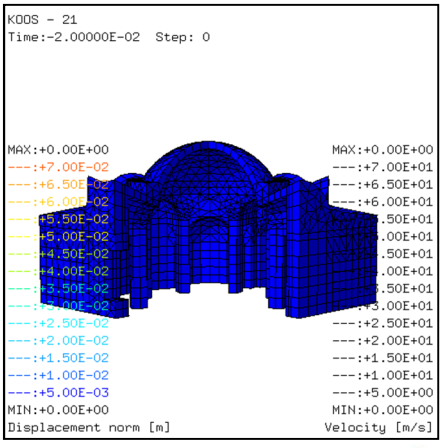


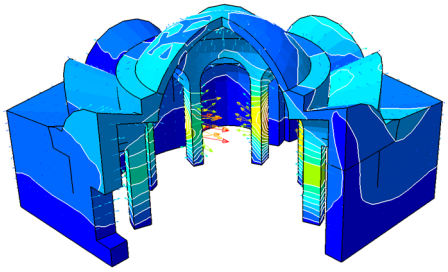


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Exercise/Example 13 – Building Vulnerability (8)

- Structural deformations and velocities:





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Exercise/Example 13 – Building Vulnerability (9)

• Benefits of spatial partitioning:

Solution	Description	Steps (N_p)	Cycles (M_s)	Max level frequency (Φ_d)	Elements × cycles	CPU (s)	Speed-up (theor)/ actual
1 (test14)	uniform step	16060	—	—	1449248274	11648	—/—
2 (test13)	spatial partitioning	100	25600	256	112280998	1650	12.9/7.1

Table 5 - Numerical solutions for the explosion in the building

95

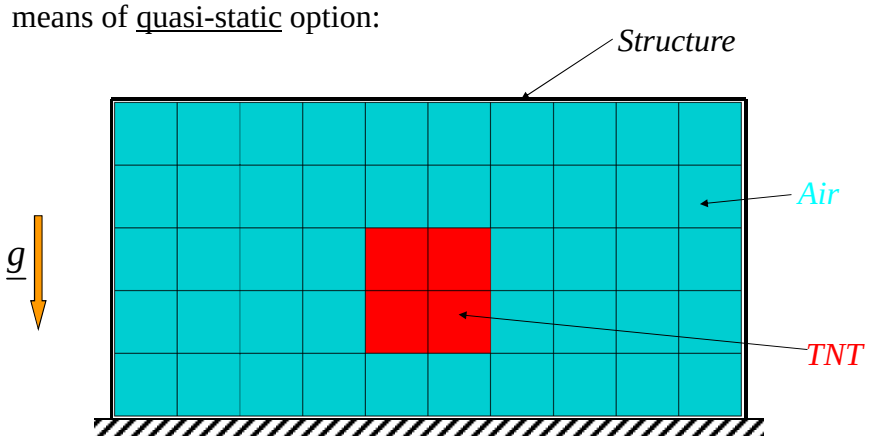
Exercise/Example 13 – Building Vulnerability (10)



96

Exercise 14 – Improving Initial Conditions

• Take into account static loading (gravity, fluid pressure) by means of quasi-static option:



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Exercise 14 – Improving Initial Conditions (2)

• Take into account static loading (gravity, fluid pressure) by means of quasi-static option:

```
OPTI QUAS STAT fsys beta <FROM t1> <UPTO t2>
```

• Add a viscous force proportional to momentum for each dof:

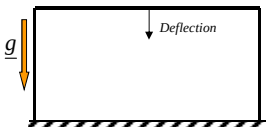
$$F_{iQS} = -4\pi\beta f_{sys} M_i v_i$$

• $\beta = 1$ corresponds to critical damping for the frequency f_{sys}.

98

Exercise 14 – Improving Initial Conditions (3)

- Compute system frequency under gravity load:



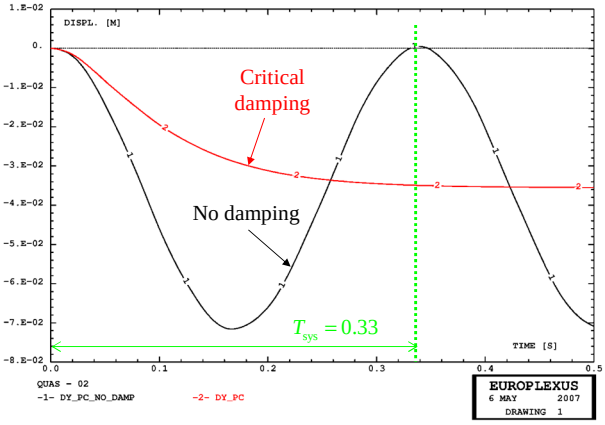
$T_{sys} = 0.33$

$\Downarrow$

$f_{sys} = 1/T_{sys} = 3$

$\Downarrow$

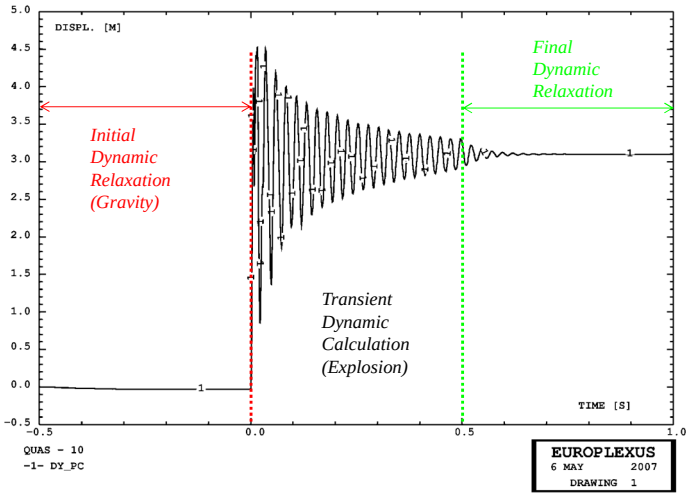
OPTI QUAS STAT 3.0 1.0



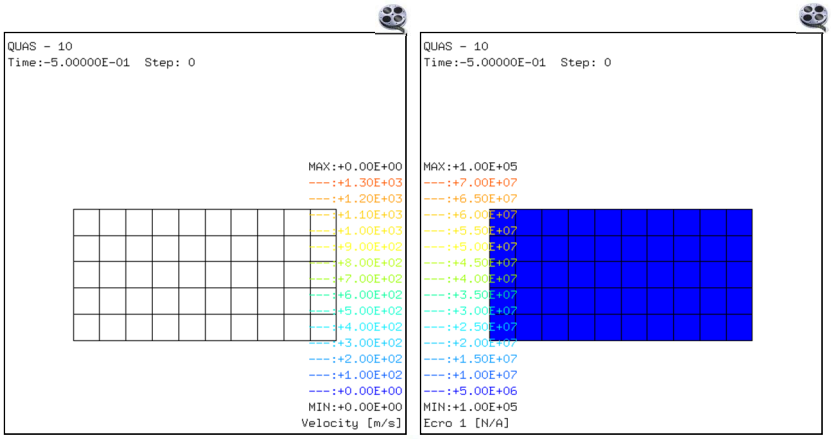
Exercise 14 – Improving Initial Conditions (4)

- Transient calculation with initial and final quasistatic option:

OPTI QUAS STAT 3. 1. UPTO 0. FROM .5



Exercise 14 – Improving Initial Conditions (5)



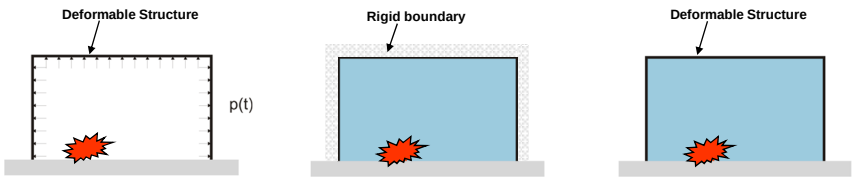
Velocities *Pressures*

Comparison

101

Three approaches to simulate an explosion :

- **Structure only (AIRB) :** no reflections!
- **Fluid only (FSR) :** valid only for very heavy / stiff structures!
- **Fluid-Structure (FLSR) :** all effects included



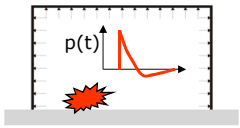
Pressure-time curve (AIRB) | Fluid + Rigid boundary (FSR) | Fluid / Structure (FLSR)

Realism / Difficulty / Cost

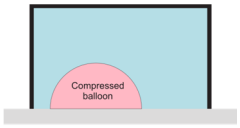
102

Three ways to model the explosive charge :

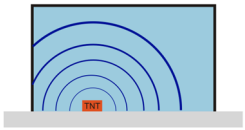
- **Pressure-time empirical function (AIRB)**
- **Compressed Bubble (BUBB) :** calibration needed
- **Solid TNT (JWLS) :** requires fine mesh (CPU-expensive)



Pressure-time curve (AIRB)



Compressed bubble (BUBB)



Solid TNT (JWLS)

Realism / Difficulty / Cost

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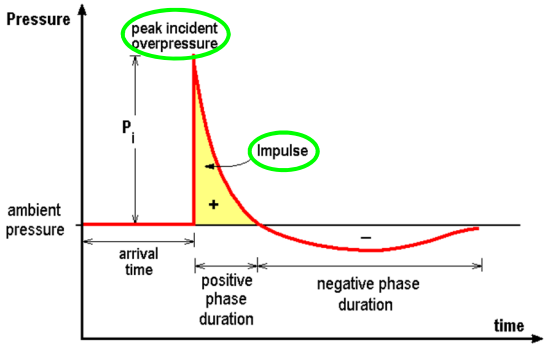
Air Blast Simulation

Experimental results for free-air explosions (idealized) :

- Explosion: rapid **chemical** conversion of solid or liquid to gas with **energy** release
- The peak **overpressure** and the positive phase **impulse** are correlated to **damage** induced
- Low explosives…, High explosives…, (IEDs) → **TNT equivalent**
- "Modified **Friedlander" equation** (scaled **m**ass, **d**istance, **t**ime)

p = p (m, d, t)

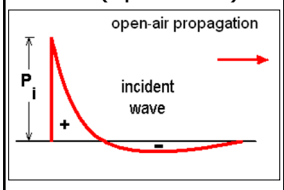
- Parameter tables in the literature (Baker, Kinney, Kingery, …)



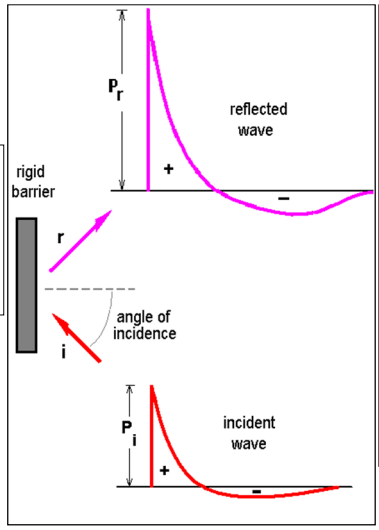
104

Pressure Wave Propagation

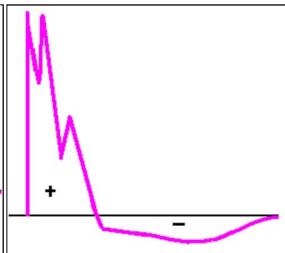
Free (spherical)



Simple reflection



Complex geometry



- Terrain
- Urban areas
- Confined spaces
- Interiors

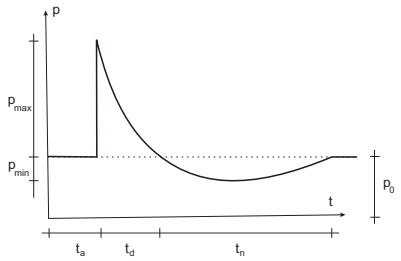
Multiple reflections, **channeling**, **shadowing**

105

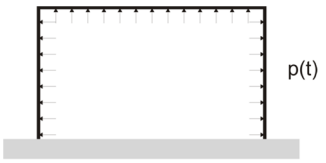
Simple "AIRB" model

- Modified Friedlander equation:

$$p = p(m, d, t)$$



- This pressure can be directly applied to a structure:
  - Fast calculation because only the structure is modelled (no fluid)
  - No problem with structural failure and fragmentation
  - However: no modeling of reflections, shadowing, street channeling etc. (works only for simple geometrical situations)



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AIRB model (3)

- Input directives:
  - **AIRB** pressure is applied by means of special CLxx elements
  - Use **IMPE AIRB** material associated with these elements :

```
MATE … IMPE AIRB
            $ X x Y y Z z ; NODE /LECT1/ $
            MASS m
            …
            /LECT2/
```

- The explosive charge position can be specified either by its coordinates **X Y Z** or by the initial position of a node **/LECT1/**
- The CLxx elements subjected to the **AIRB** blast wave are specified by **/LECT2/**

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The BUBB (explosive bubble) model

- A shorthand for defining an explosive bubble formed by compressed gas (**GAZP** or **FLUT** materials)
- Input directive:
  - Use **BUBB** material associated with a region composed by fluid elements :

```
MATE … BUBB MASS m /LECT/
```

- The initial conditions of the compressed gas are evaluated automatically by the code by means of the equivalent TNT mass **m** of the explosive charge and the initial volume of the bubble region **/LECT/**

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Risk evaluation

Newly developed risk analysis module

Aim : translate the computed values of physical parameters (overpressure…) into something more meaningful for decision makers and authorities and more directly applicable in areas involving human presence.

Background:

- **New technique that only recently is integrated in FE software**
- **Translate deterministic results into statistical data**
- **Statistical data based on standard (normal) distribution**

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Risk Estimation

Explosion effects (qualitative):

- **High pressure waves** : effects on the human body (*primary blast injuries*).
- **Flying debris** : generated from structural fragmentation, can substantially extend the dangerous area (*secondary blast injuries*).
- **Structural collapse** : can occur in multi-storey building with complex architecture (*progressive collapse*).

Overpressure Thresholds [bar]	
Eardrum Rupture	~ 0.33
Lung Damage	~ 1
Lethality	~ 2.5

Damage	Incident Overpressure [bar]
Typical window glass breakage	0.01-0.02
Minor damage to some buildings	0.03-0.08
Panels of sheet metal buckled	0.08-0.13
Failure of concrete block walls	0.13-0.20
Collapse of wood framed buildings	over 0.35
Serious damage to steel framed buildings	0.30-0.50
Severe damage to reinforced concrete structures	0.45-0.65
Probable total destruction of most buildings	0.70-0.85

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Mechanisms of Blast Injury



Primary blast injury (due to **overpressure** : eardrum rupture, lung injury …)

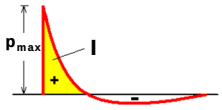
Secondary blast injury (due to **fragments** propelled by blast wave)

Tertiary blast injury (due to **impact** with environment)

Reference: *Blast Injuries - Physics vs. Physiology*, Jeffrey D. Ferguson, MD, NREMT-P, December 2004

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Risk evaluation (see Ferradás *et al.* [1])



- Risk depends on **peak overpressure p_{max}** (in Pa) and on the **positive impulse I** (in Pa·s) in the **fluid**
- Use is made of following **probit functions**

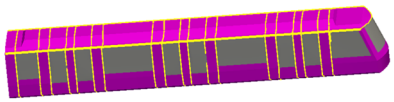
  Lethal blast injuries :
  - $Y_1 = 5.0 - 8.49 \ln [(2430/p_{max}) + 4.0E8/(p_{max}I)]$: **Head impact**
  - $Y_2 = 5.0 - 2.44 \ln [(7380/p_{max}) + 1.3E9/(p_{max}I)]$: **Body impact**
  - $Y_3 = - 77.1 \ln (p_{max})$: **Lung haemorrhage**
  - $Y_4 =$? (under investigation) : **Debris impact**

  Non-lethal blast injuries :
  - $Y_5 = - 12.6 + 1.524 \ln (p_{max})$: **Eardrum rupture**
- Probability of occurrence (or % of affected population) is :
  - $P_i = - 3.25\ Y_i^3 + 48.76\ Y_i^2 - 206.60\ Y_i + 270.35, \quad i = 1, ..., 5$
- Death risk is maximum of the above lethal risks :
  - $P_{death} = \max (P_1, P_2, P_3, P_4)$

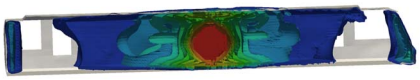
[1] Ferradás EG *et al.*, Process Safety and Environmental Protection **86** (2008) 121-129.

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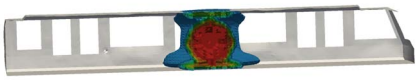
Risk maps are directly obtained in the **fluid** sub-domain :



Metro carriage



Eardrum rupture risk



Death risk

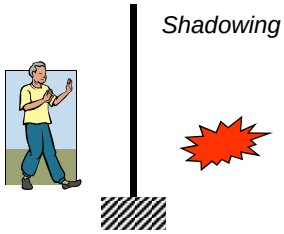
Risk evaluation requires **modeling of the fluid**

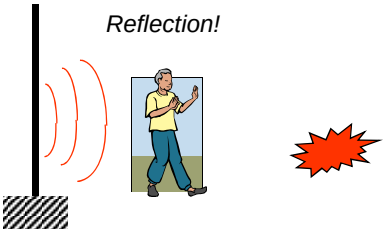
113

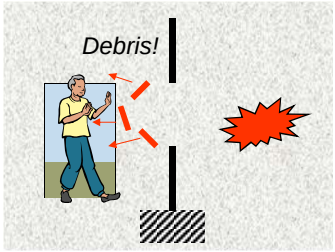
Explosion effects (qualitative)

One should consider the following **trade-offs**:

- Presence or not of a structure:
  - Shadowing
  - Reflections / channeling
  - Secondary debris
- Relative positioning

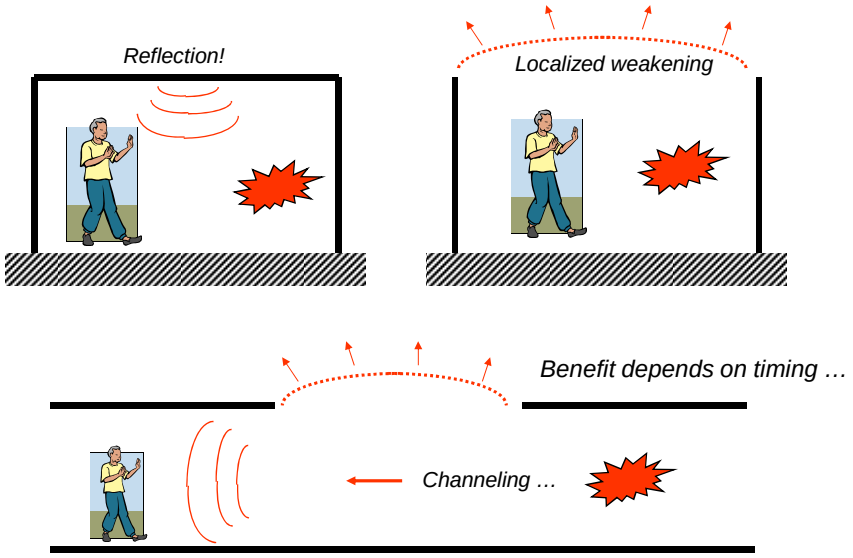






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Explosion effects (qualitative)



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Case Study 1 - Historic Railway Station





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Historic Railway Station (2)

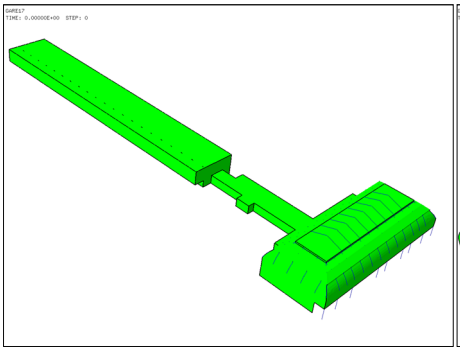




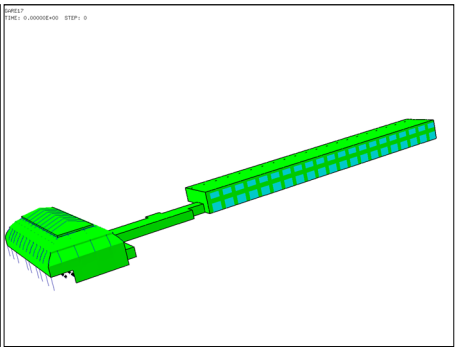
In-Situ Laser Scan + “JRC 3D-Reconstructor”

Historic Railway Station (3)

Structural model :



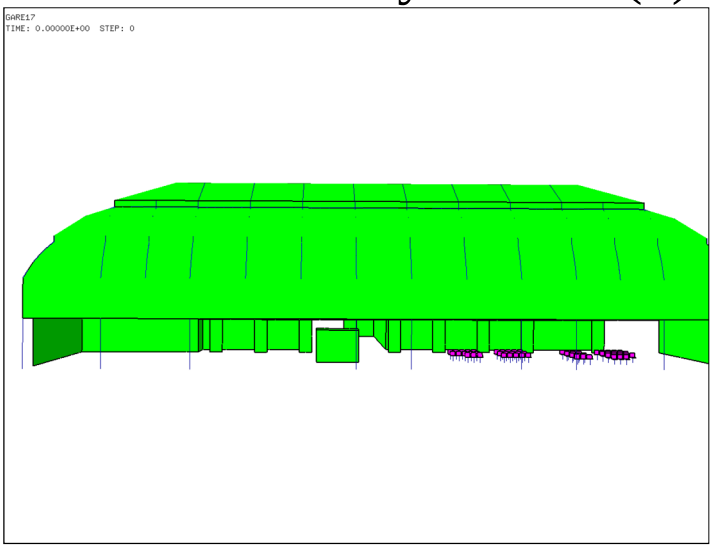
Left outside view



Right outside view

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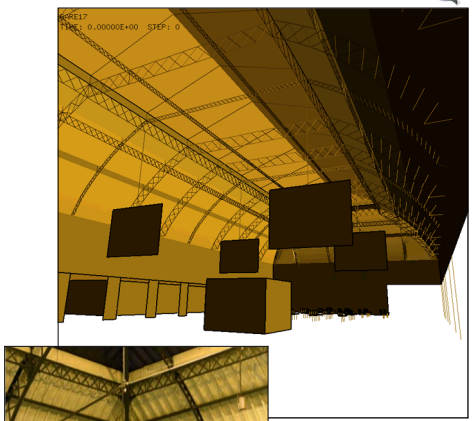
Historic Railway Station (4)

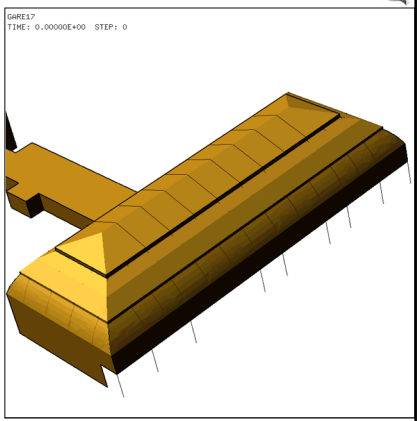


Front view

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Historic Railway Station (5)





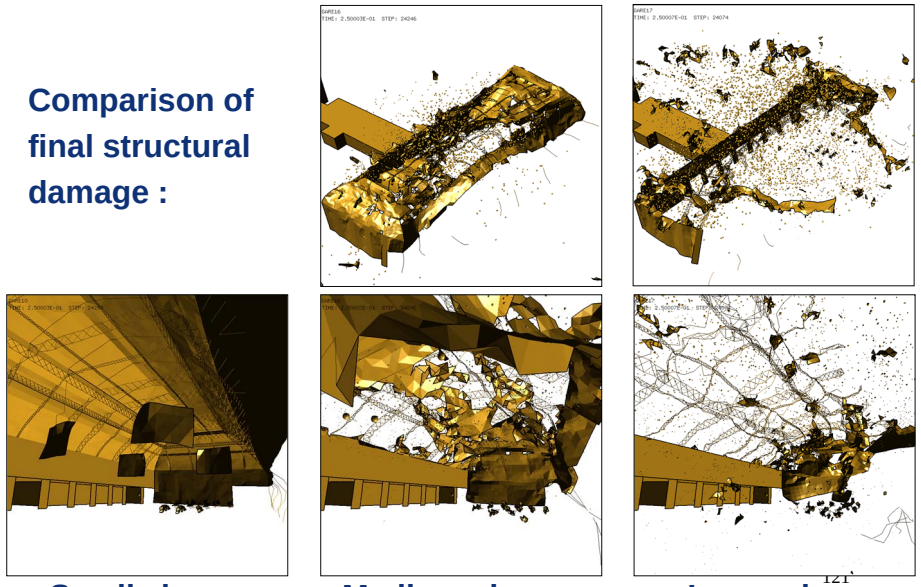


AIRB loading, large TNT mass

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Historic Railway Station (6)

Comparison of final structural damage :



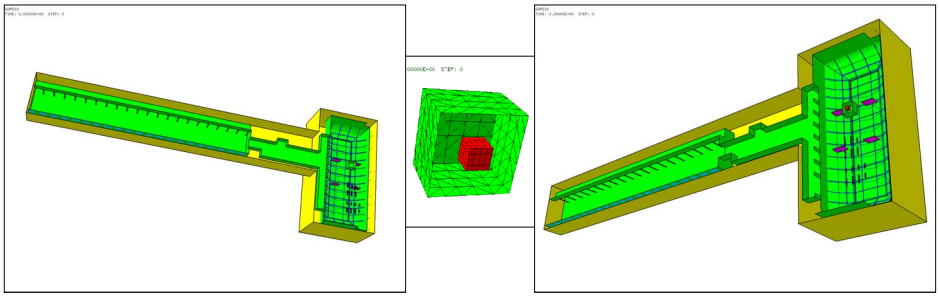
Small charge **Medium charge** **Large charge**

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Historic Railway Station (7)

Full FSI modeling : both Fluid and Structure are modeled

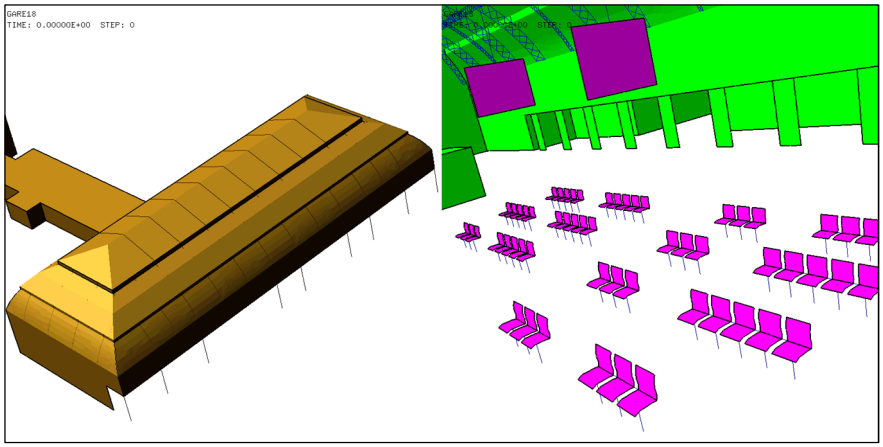
- Compressed bubble model (BUBB)
- Non-conforming Fluid-Structure Interaction (FLSR)
- Absorbing conditions around fluid domain



4.3 million elements (mostly fluid hexa.), 14.6 days CPU

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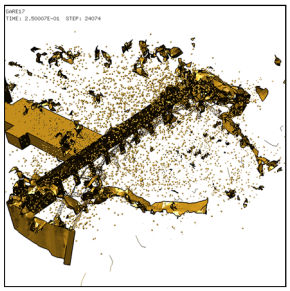
Historic Railway Station (8)

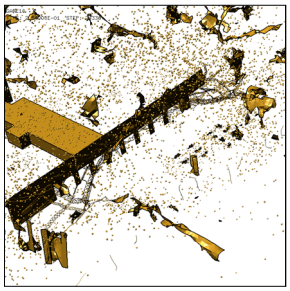


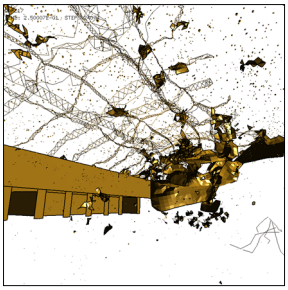
Large charge

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Historic Railway Station (9)









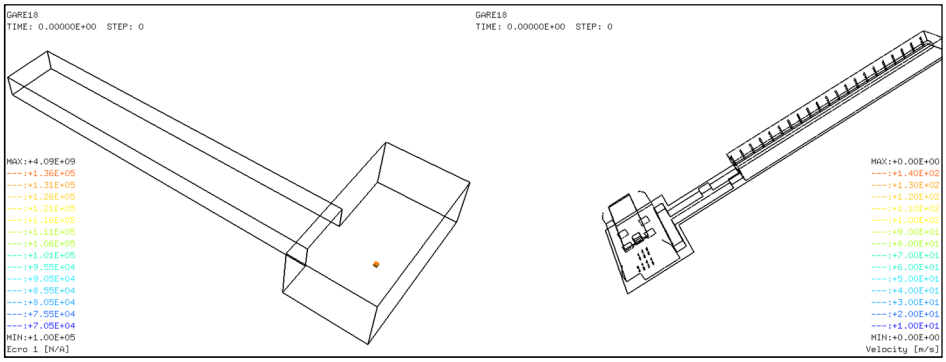
AIRB FLSR

Comparison of final structural damage for large charge

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Historic Railway Station (10)

Fluid Pressure **Fluid Velocity**

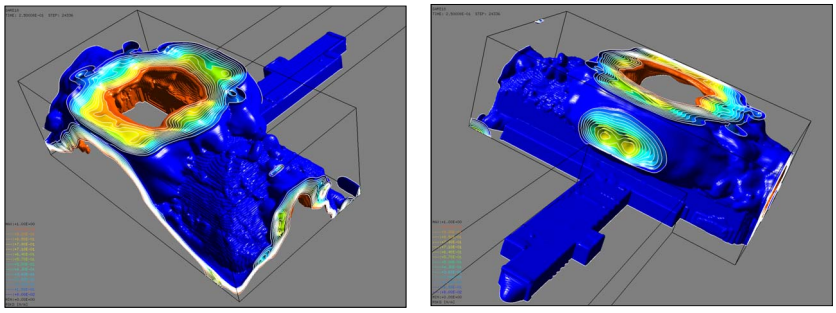


Large charge

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Historic Railway Station (11)

Final Death Risk

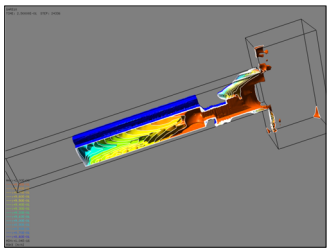


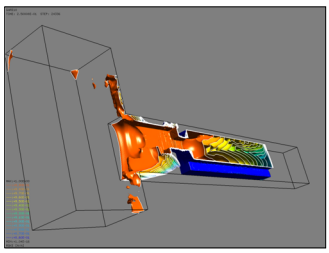
Large charge

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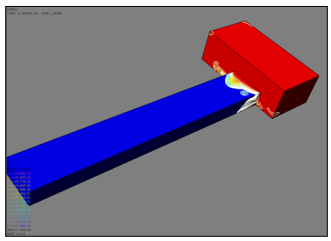
Historic Railway Station (12)

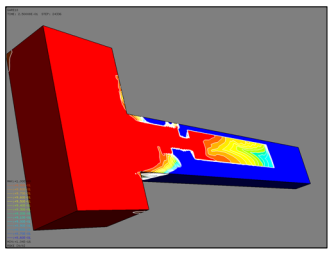
Final Eardrum Rupture Risk





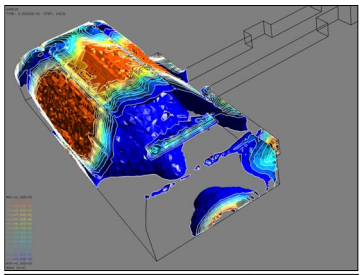
Large charge



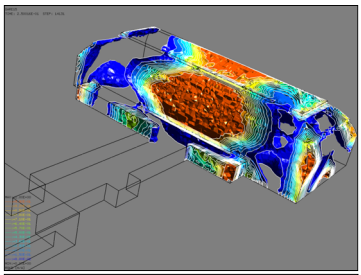


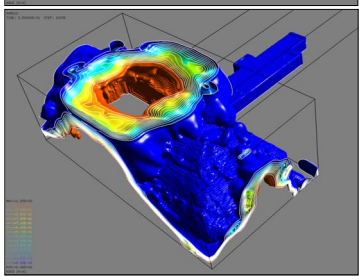
Historic Railway Station (13)

Comparison of Risk : Death Risk

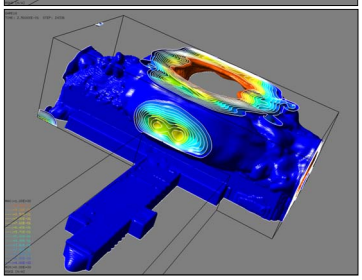


FSR, Small charge (rigid structure)





FLSR, Large charge (deformable Structure)

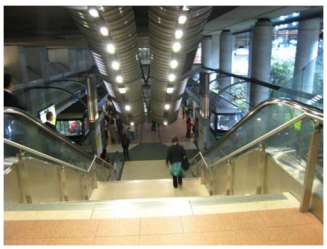


Summary of Approaches
to Severe Blast Simulation

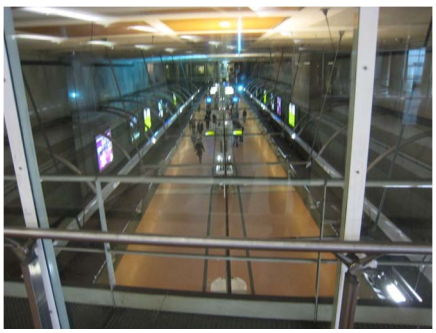
Approach	Model	Complexity / CPU / Memory	Advantages	Drawbacks
Structure alone	AIRB	Low / Minutes ÷ Hours / < 1GB	▪ Simple and fast	▪ Cannot represent wave reflections and channeling ▪ Wrong behavior with very large rotations ▪ Does not allow risk evaluation
Fluid alone	FSR	Medium / Hours ÷ Days / < 4GB	▪ Represents wave reflections and channeling effects ▪ Still fairly simple from user viewpoint ▪ Allows risk evaluation	▪ Does not model the structural behavior
Fluid and Structure	FLSR	High / Days ÷ Weeks / > 4 GB	▪ All effects are included	▪ Long CPU time and large memory ▪ More complex input set-up and post-processing

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Case Study 2 - Recent Metro Station







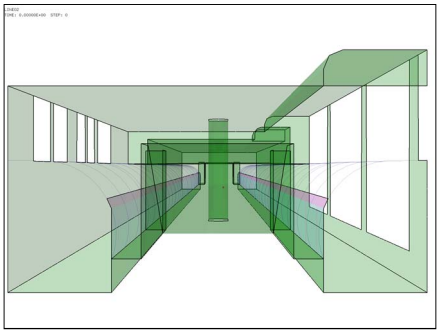
Corridor with sliding doors

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Metro Line Station (2)



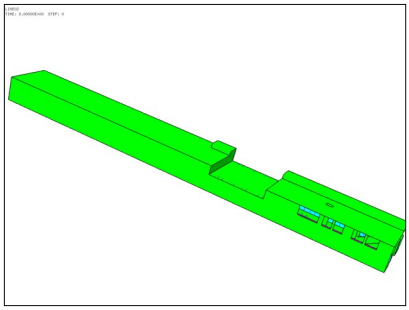
Laser Scan



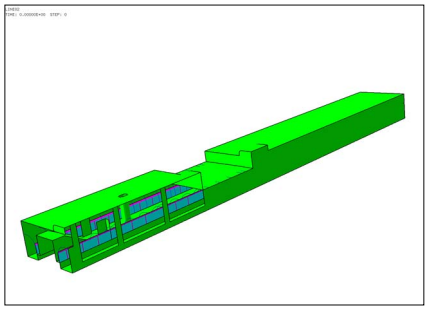
Numerical model

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Metro Line Station (3)



Left outside view



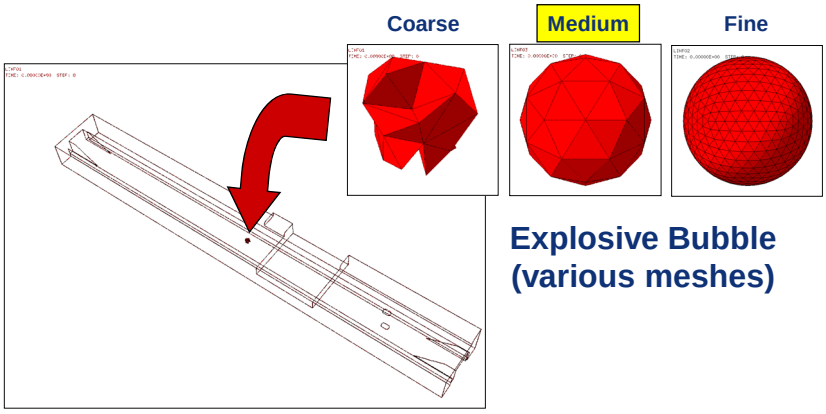
Right outside view

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Metro Line Station (4)

Second approach : only the Fluid is modeled

- Compressed bubble model (BUBB)
- Rigid inviscid boundary (FSR)



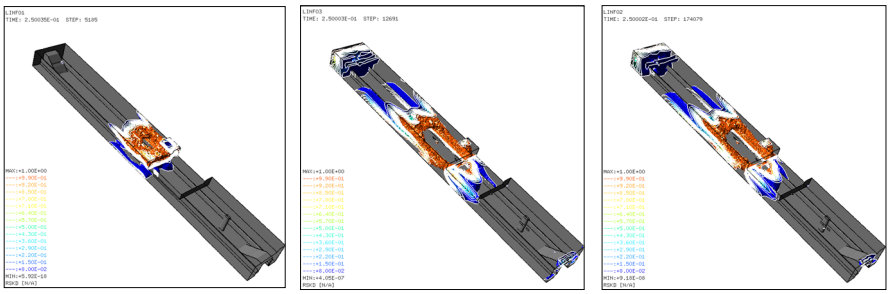
Explosive Bubble (various meshes)

133

Metro Line Station (5)

Influence of bubble discretization :

Final Death Risk for Large Charge



Coarse
(43 tetr.)
0.5 days CPU

Medium
(190 tetr.)
1.3 days CPU

Fine
(9564 tetr.)
18.3 days CPU

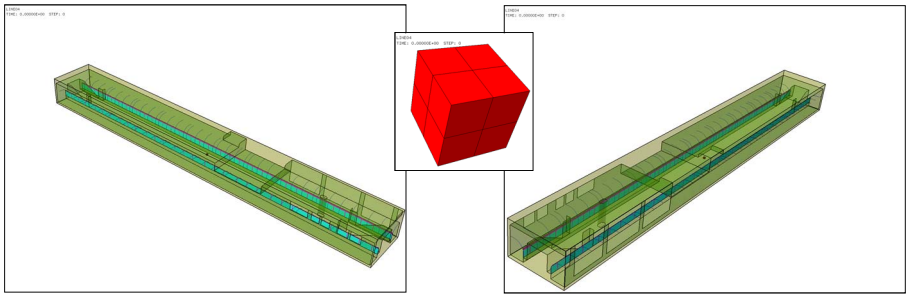
Total # of elements roughly identical : 1.1 million tetr.

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Metro Line Station (6)

Third approach : Both Fluid and Structure are modeled :

- Compressed bubble model (BUBB)
- Non-conforming Fluid-Structure Interaction (FLSR)
- Absorbing conditions around fluid domain
- Contact between debris particles and concrete walls

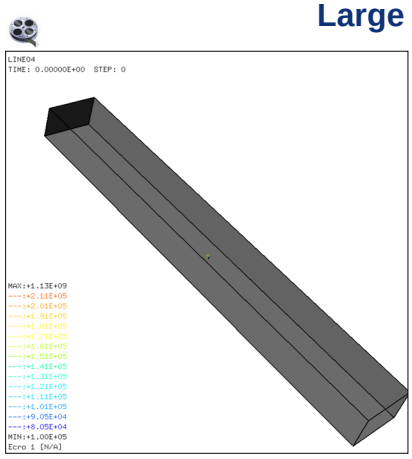


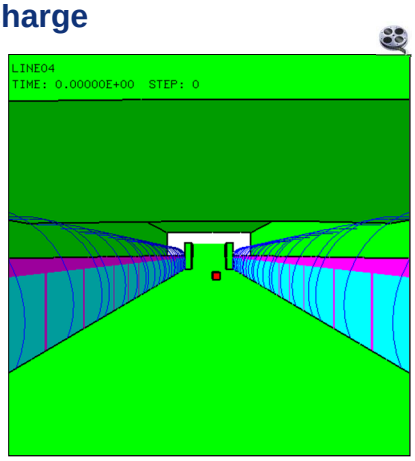
2.0 million elements (mostly fluid hexa.), 8.5 days CPU

135

Metro Line Station (7)

Large charge



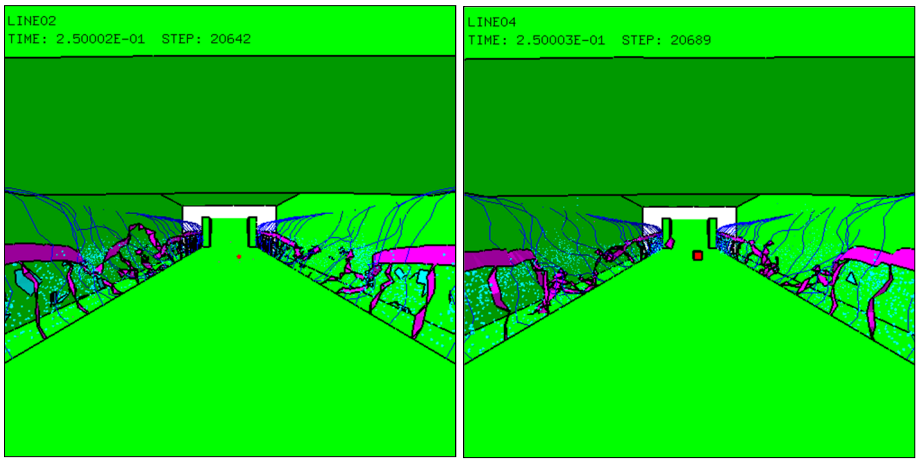


Fluid Pressure **Structural Failure**

136

Metro Line Station (8)

Large Charge



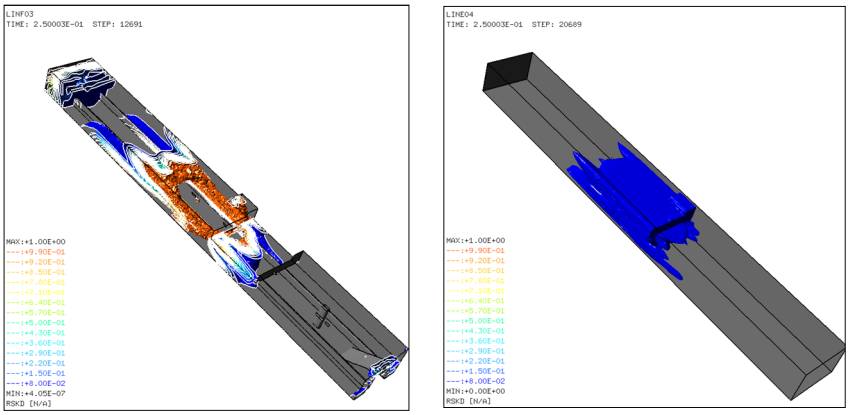
AIRB
156,000 elems, 0.9 days

FLSR
2,022,000 elements, 8.5 days

137

Metro Line Station (9)

Comparison of Final Death Risk



FSR
1.1 million elements
1.3 days CPU

Large Charge

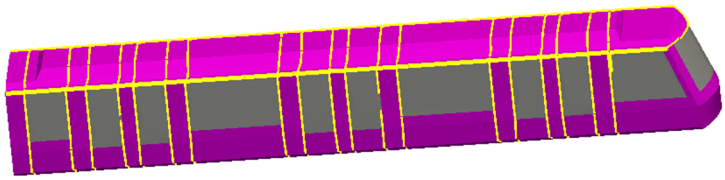
FLSR
2.0 million elements
8.5 days CPU

138

Case Study 3 – Metro Line Carriage







Geometry : JRC 3D Reconstructor

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Motivation

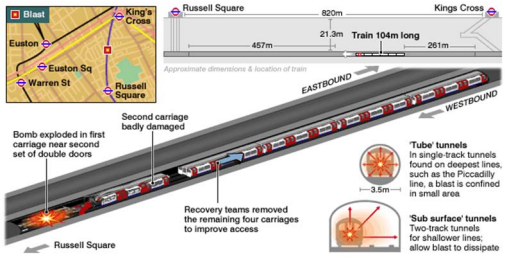


Madrid, 11 March 2004 :
Fatalities 191
Injured 1200



London, 7 July 2005:
Fatalities 50
Injured 700





140

Source: www.bbc.co.uk

Blast-related phenomena

Source: www.spiegel.de

Bag bomb : main effects

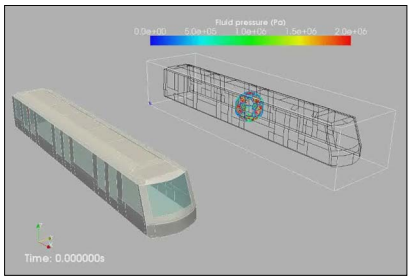


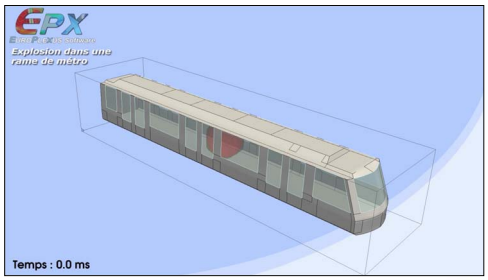
Simulation vs. reality



141

Example of metro carriage



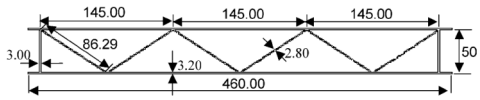


142

Carriage Structure

Honeycomb structure

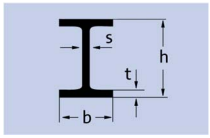
- Detailed model too expensive
- Sandwich element with same thickness, mass and stiffness



Zheng 2005

OR : Frame structure

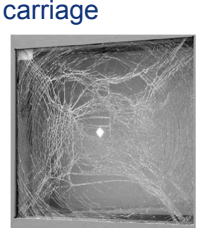
- IPE80
- 3 mm aluminum sheet welded on frame structure
- Floor fixed
- Explosive in the centre of the carriage

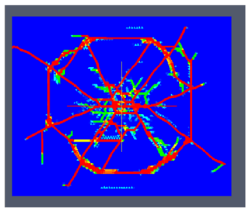


A [m^2]	7.60E-04
max I [m^4]	8.01E-07
h [m]	0.08
c [m/s]	5092

Windows: Laminated glass

- LSGL material

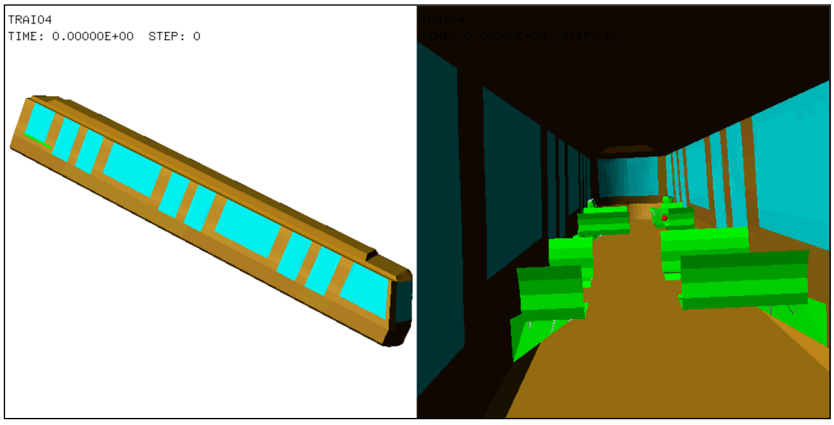




143

Train (AIRB)

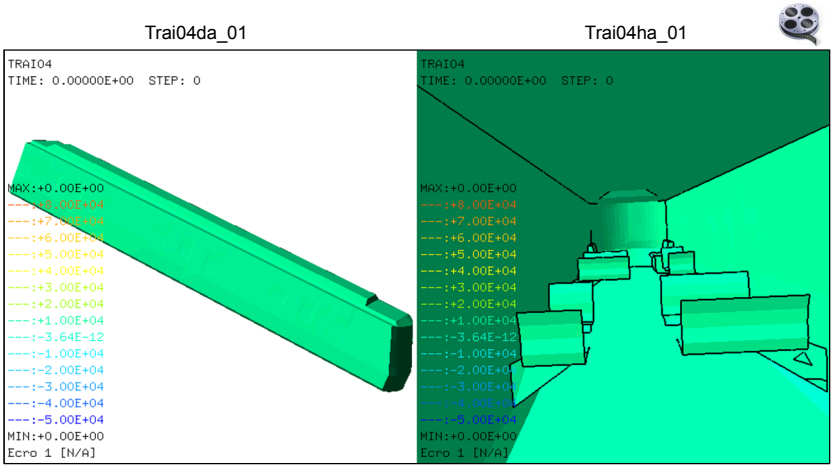
Trai04ba_01 Trai04fa_01



Structural deformation and failure

144

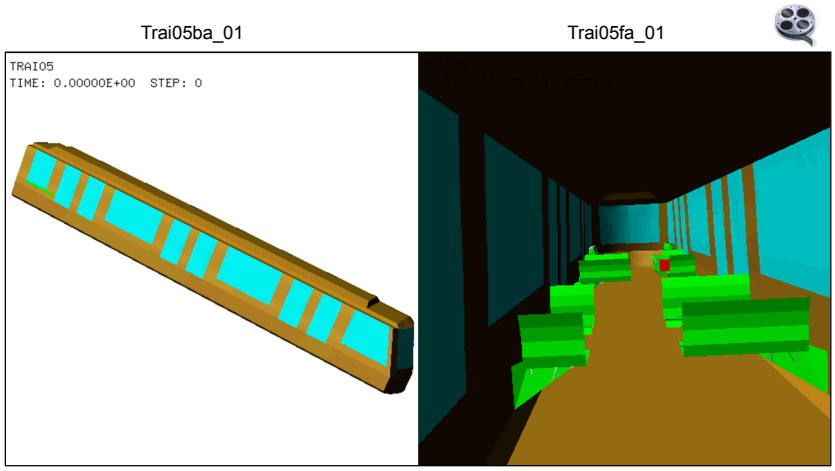
Train (AIRB) (2)



AIRB pressure

145

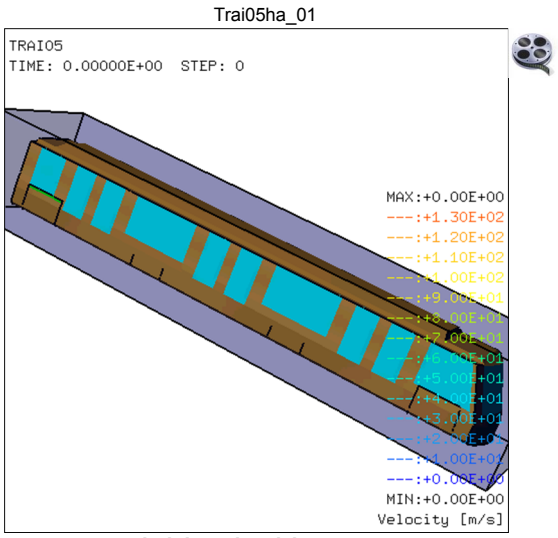
Train (Fluid/FLSR) (3)



Structural deformation and failure

146

Train (Fluid/FLSR) (4)



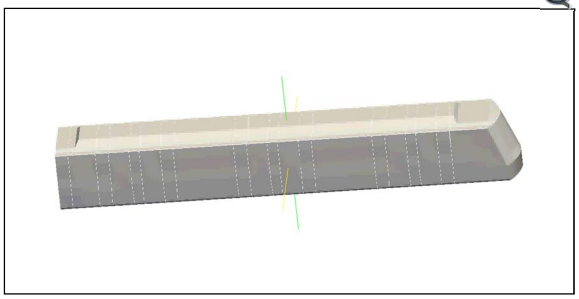
Fluid velocities

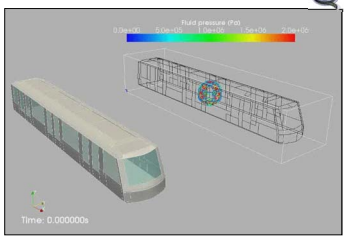
147

Blast Simulation



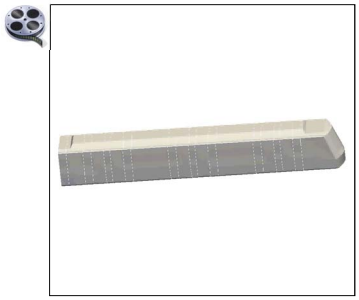
Bag bomb,
frame structure,
laminated glass

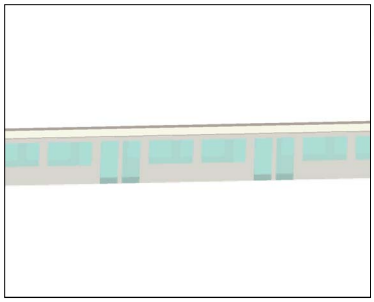


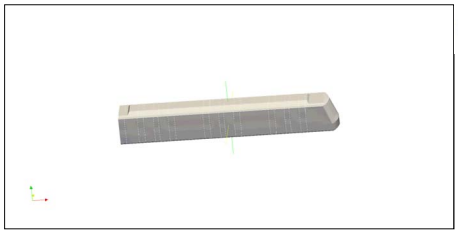


148

Example of metro carriage





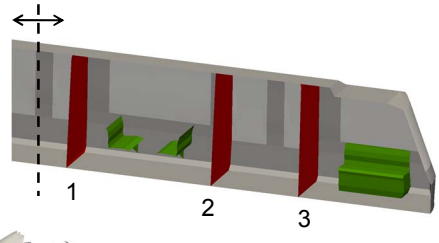


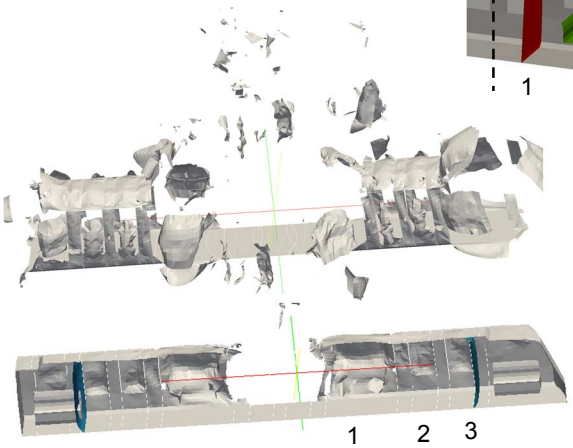
149

Effect of internal Structures

FSI, Laminated glass, frame structure, 10kg TNT:

- Internal walls
- Seats





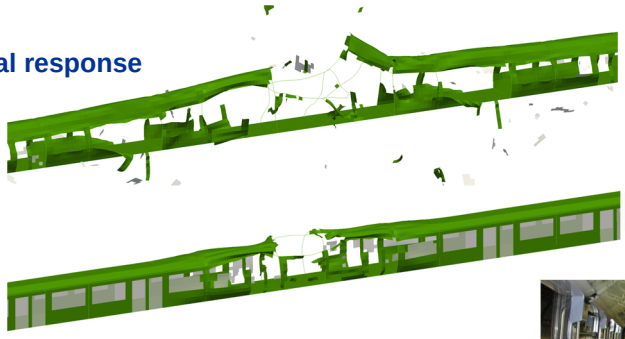
No internal walls

Internal walls : failure is **more localized**

150

Influence of a tunnel

Structural response

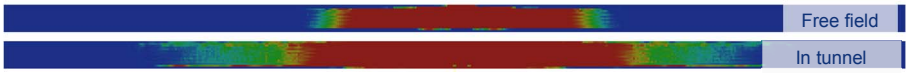


Free field

In tunnel



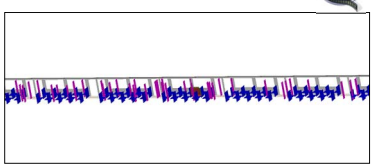
Human injuries

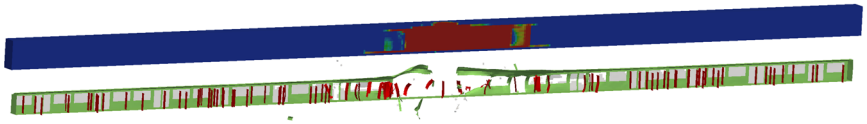


Probability of death

Influence of Passengers / Seats

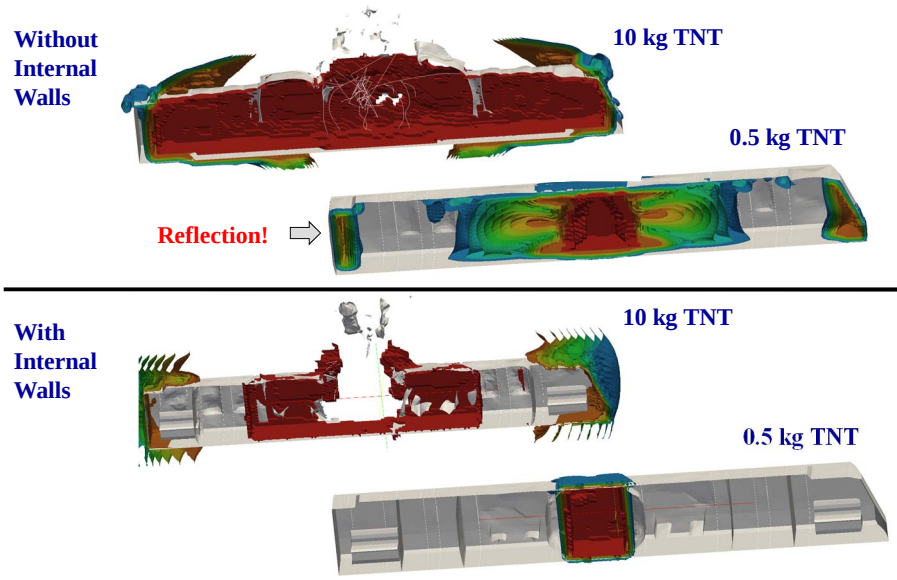
- Simple model with shell elements, thickness 10 cm
- Standard weight (~70 kg)
- 100/500 passengers randomly in the train
- No connection to floor
- Aluminium seats, thickness 3 mm



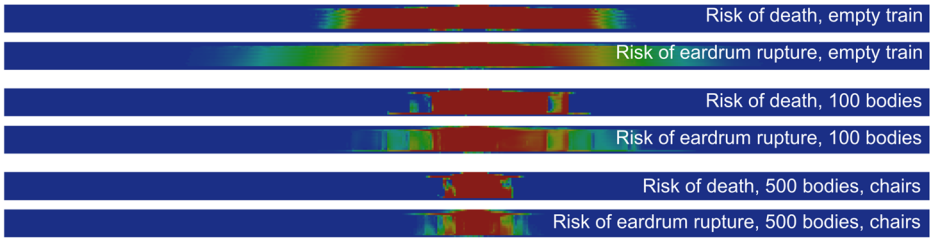


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Death Risk Maps

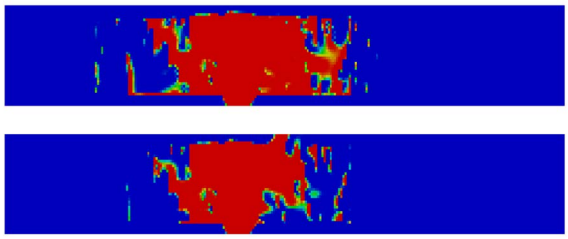


10 kg TNT, including passengers & seats



Seats	Number of passengers	Length of high-death-risk zone [m]	Number of affected passengers
No seats	—	27.4	—
No seats	100	13.2	12.7
No seats	500	7.9	41.1
Seats	—	17.6	—
Seats	100	10.0	9.6
Seats	500	7.6	36.5

Effect of Open Doors



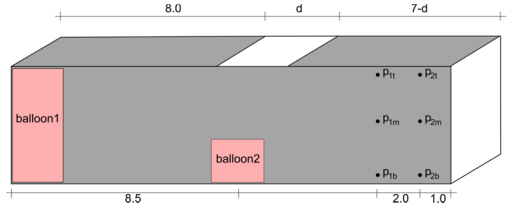
Closed doors

Open doors

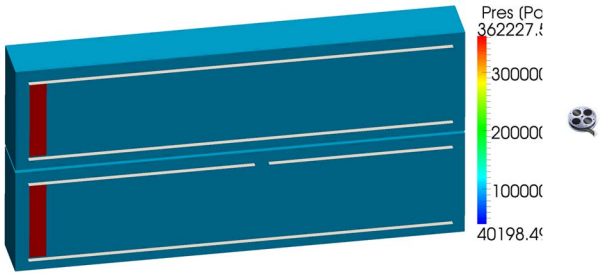
155

Effect of Venting Areas

Calculations with d = 0.5, 1.0, 2.0 m and 2 x 1.0 m



d = 0.5



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However : **roof hatches** are very useful in case of crash (**rescue**)

Nosaby, Sweden (2004)







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Complete Station Simulation

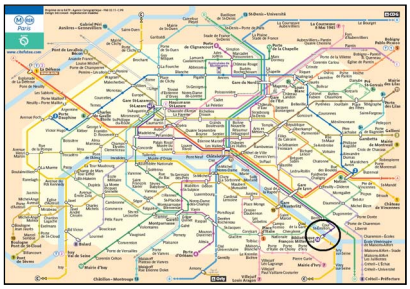
The starting point:

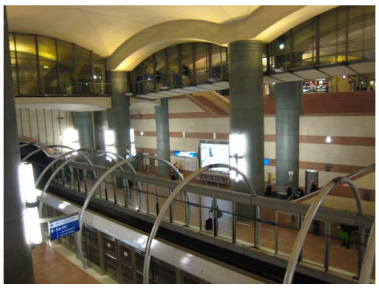
- **SECUR-ED** project (2012-ongoing)
  - Coordinated by THALES
  - Enhance **urban transport** security
  - SP3/WP32 involves JRC, TNO, RATP and others
- Main contributors at JRC:
  - G. Solomos, G. Valsamos, F. Casadei

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Complete Station Simulation (2)

- "Bibliothèque François Mitterrand" Station
  - Transfer point between Metro "Line 14" and Railway "RER C"
  - No major openings to the atmosphere
  - Numerous fragile glass panels

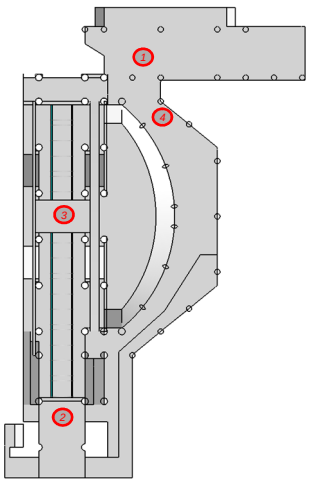




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Complete Station Simulation (3)

- Blast Scenarios (courtesy RATP)
  - Avenue de France (1)
  - Rue de Chevaleret (2)
  - Footbridge (3)
  - Hemicycle (4)



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Complete Station Simulation (4)

Numerical Simulation Approach

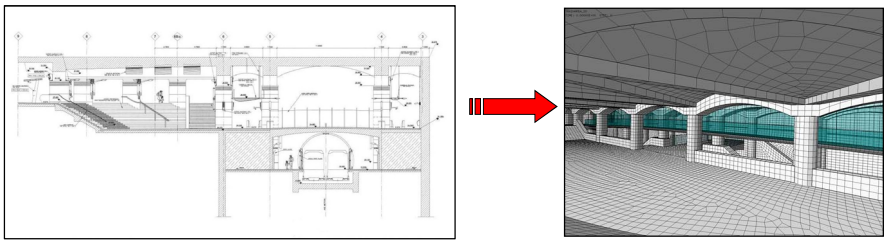
- Set up **geometric model**
  - Structural mesh from blueprints and photos (by Cast3m)
  - Regular fluid mesh (“embedded” FSI technique: essential!!!)
- Main modeling **assumptions**
  - Rigid structural walls (thick reinforced concrete)
  - Deformable glass panels and metallic components
- Main calculation **parameters**
  - Material properties
  - Boundary conditions
  - Element types (for the fluid: either FE or CCFV)
  - Solution methodology

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Complete Station Simulation (5)

Discretized **geometric model (Cast3m)**:

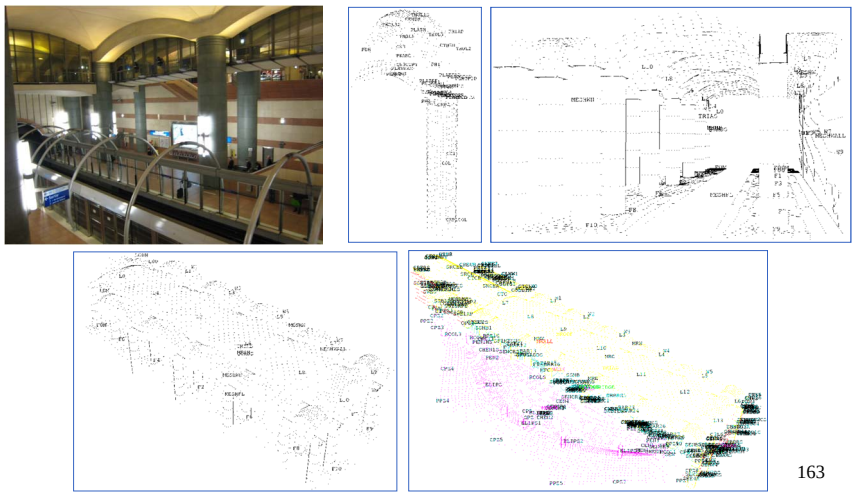
- ~ 20 Gibiane “procedures” (2500 lines of code)
- Structural mesh (4500 lines, 0.5M FE)
- Fluid mesh (100 lines, 4.0M FE/FV)
- CPU time for mesh generation : < 1 minute !
- Human time : a couple of months …



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Complete Station Simulation (6)

Cast3m model for the structure :

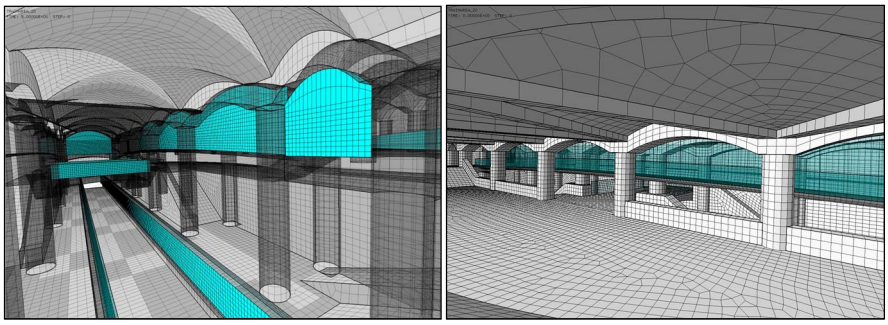


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Complete Station Simulation (7)

FE structural **model (Cast3m)**:

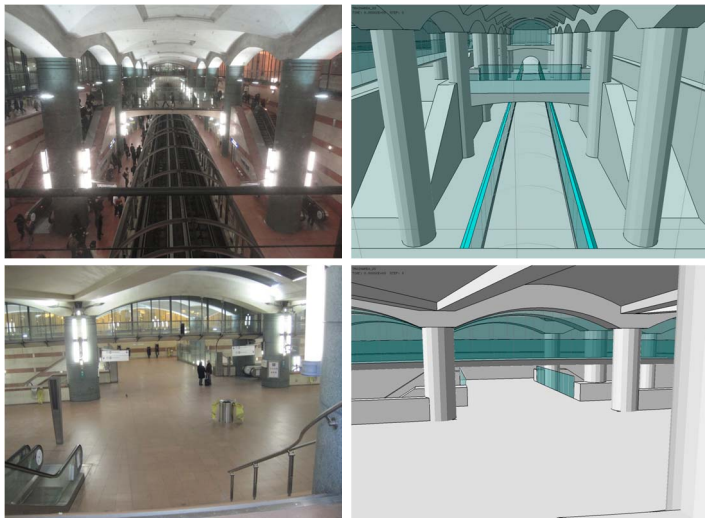
- Average element size for rigid parts : 0.50 m
- Min element size for deformable parts : 0.25 m



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Complete Station Simulation (8)

Model fidelity:



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Complete Station Simulation (9)

Virtual Tour of the Station:

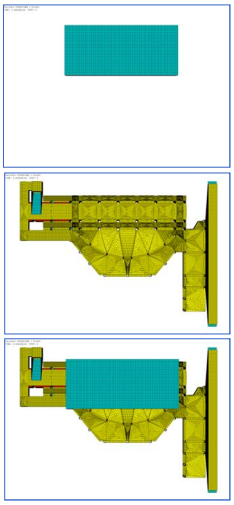


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Complete Station Simulation (10)

Fluid mesh (FE or CCFV) :

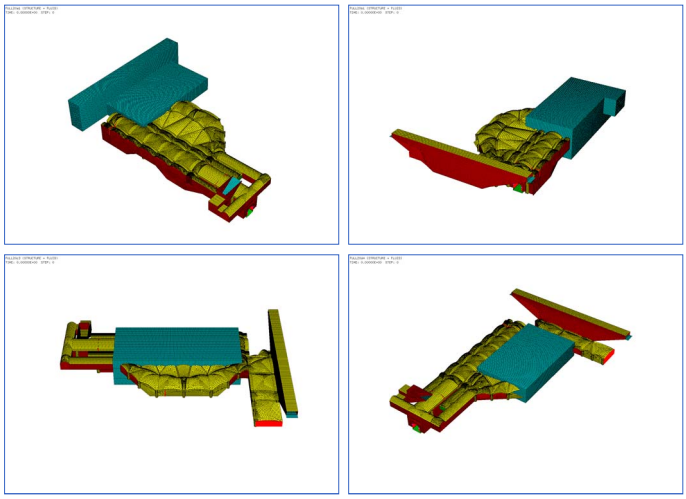
- **Regular** parallelepiped grid(s)
- **Non-conforming** with structure
- The meshes are simply **superposed**
- **Absorbing** fluid envelope



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Complete Station Simulation (11)

Examples of assembled F/S meshes :



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Complete Station Simulation (12)

Solution Parameters :

- TRID ALE
- Lagrangian structure
- Eulerian fluid
- FLSR / FLSW “embedded” FSI algorithms
- RISK
- DEBR
- BUBB
- PINB model for contact / impact
- NOCR for the rigid structure parts
- GRAV
- Final time : 250 ms
- Critical step ~ 30 μs (~ 8000 time steps)

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Complete Station Simulation (13)

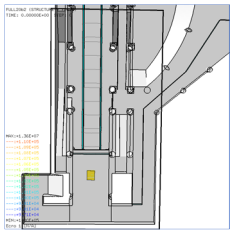
Solution data for some different scenarios :

Location	Mesh type	FL38	CL3Q	Num. of Points	Steps	CPU [sec]
Footbridge	Coarse	425600	39880	581262	8507	139347 (38.7h) (1.6d)
	Fine	3404800 (x8)	159520 (x4)	3627473 (x6.24)	8498	828771 (230h) (9.6d) (x5.9)
Avenue de France	Coarse	394256	51352	555846	8499	113027 (31.4h) (1.3d)
	Fine	3154048 (x8)	205408 (x4)	3399809 (x6.12)	8507	634173 (176.2h) (7.3d) (x5.6)
Rue de Chevaleret	Coarse	467648	41152	630875	8500	141834 (39.4h) (1.6d)
	Fine	3741184 (x8)	164608 (x4)	3966413 (x6.29)	8498	791896 (220h) (9.2d) (x5.6)

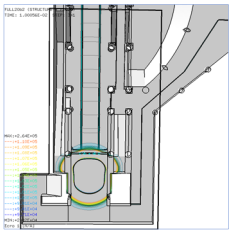
170

Complete Station Simulation (14)

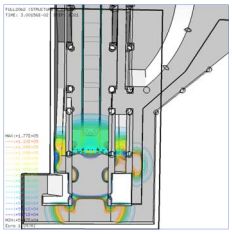
Typical numerical results (pressures, debris …) :



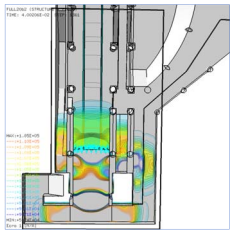
0ms



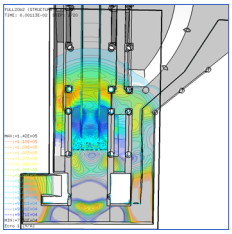
10ms



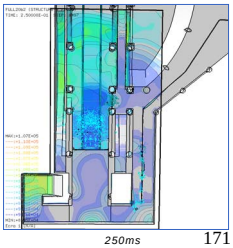
30ms



40ms



80ms

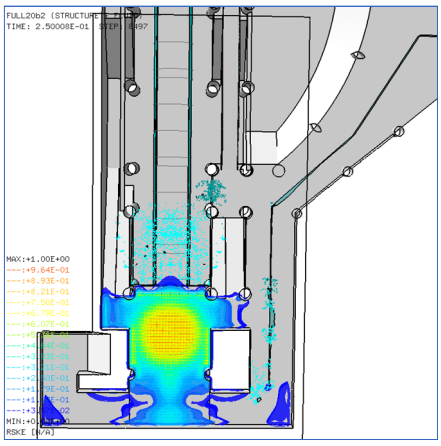


250ms

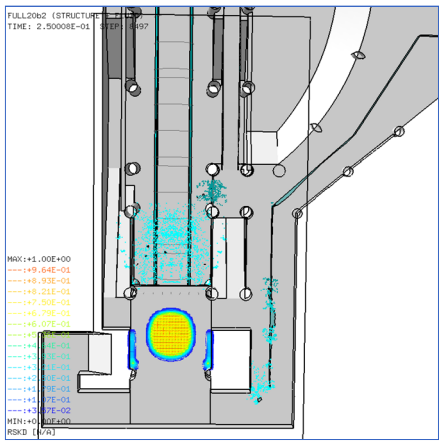
171

Complete Station Simulation (15)

Typical numerical results (risk) :



Eardrum rupture RISK

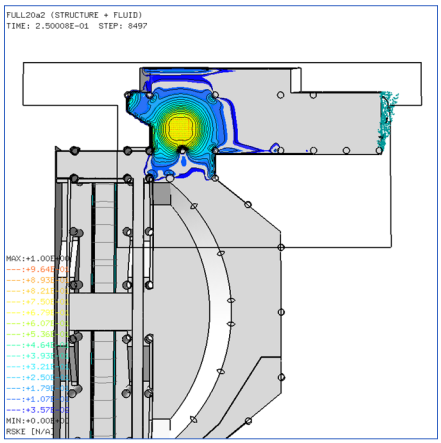


Death RISK

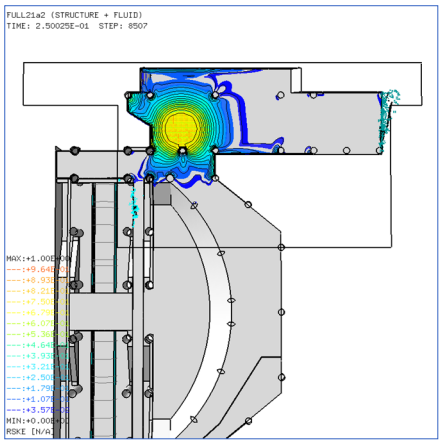
172

Complete Station Simulation (16)

Accuracy assessment (coarse and fine solutions) :



Coarse model

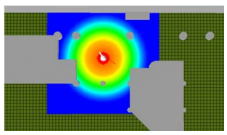


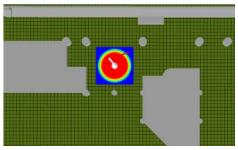
Fine model

173

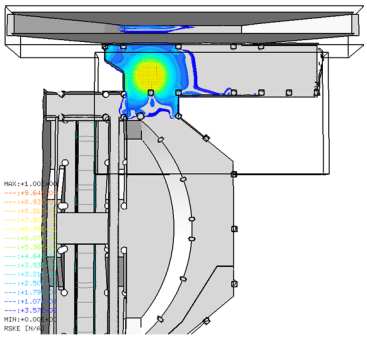
Complete Station Simulation (17)

Comparison with another risk assessment methodology:

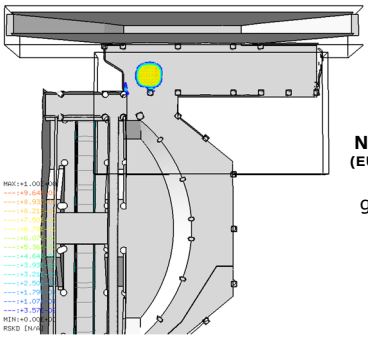




Analytical (empirical)
No reflections!



Eardrum rupture RISK



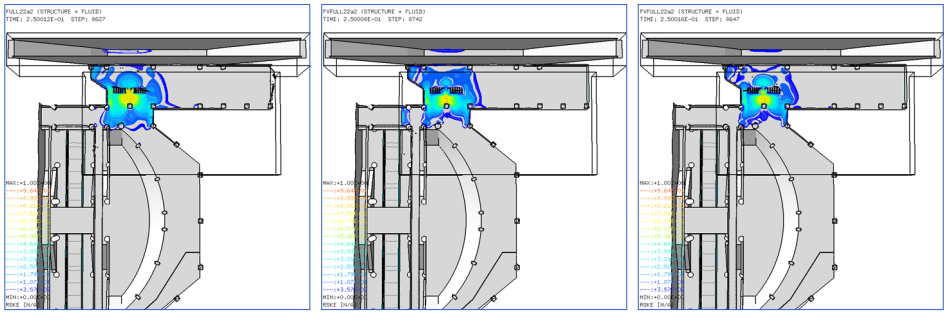
Death RISK

Numerical
(EUROPLEXUS)
Full geometric effects

174

Complete Station Simulation (18)

Comparison of different fluid formulations :



FE *VFCC 1st order* *VFCC 2nd order*

175

Complete Station Simulation (19)

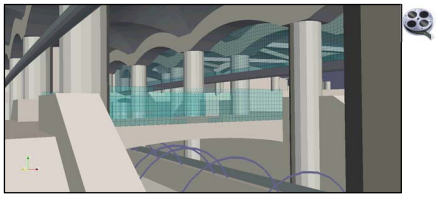
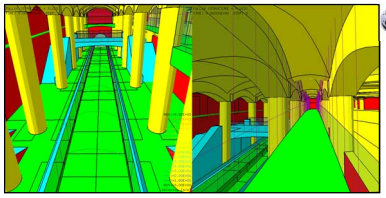
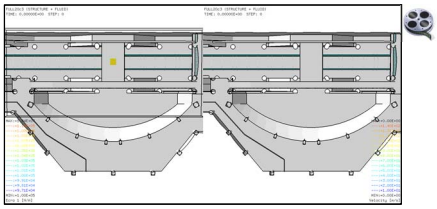
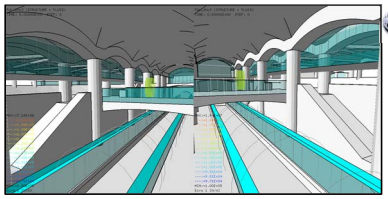
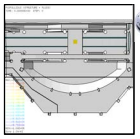
Solution data - Comparison FE / VFCC :

File name	Formulation	Coupling	Ali size [MB]	Memory peak [GB]	Time step	CPU per time step [sec]	Steps	Total time [days]
full22a2	FE	FLSR BLOQ COUP	396	2.84	2.94E-5	14.13	8627	1.41
FVfull22a2	FE+FV 1st order	FLSW BLOQ COUP	488 (23%)	5.08 (78%)	2.94E-5	18.01	8742	1.83 (30%)
FV2full22a2	FE+FV 2nd order	FLSW BLOQ COUP	488 (23%)	5.43 (92%)	2.94E-5	21.63	8647	2.16 (53%)
DECfull22a2	FE	FLSR BLOQ DECO	395 (-)	2.26 (-20%)	2.94E-5	12.46	8630	1.24 (-12%)
DECFV2full22a2	FV+FE 2nd order	FLSW BLOQ DECO	488 (23%)	4.89 (72%)	2.94E-5	20.53	8647	2.05 (45%)

176

Complete Station Simulation (20)

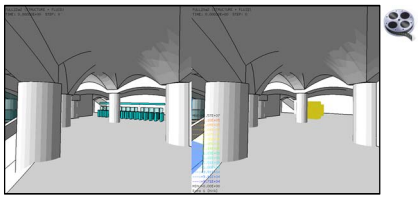
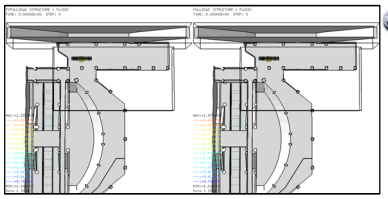
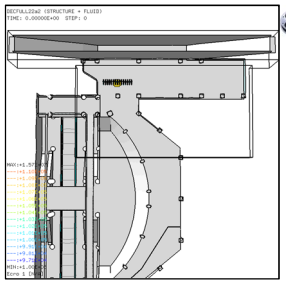
Footbridge:

177

Complete Station Simulation (21)

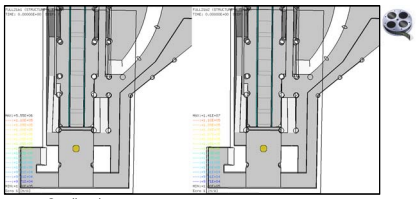
Avenue de France:

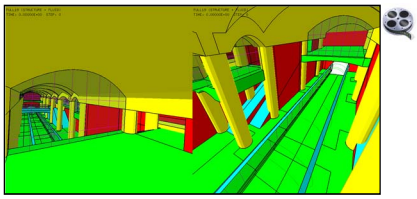
178

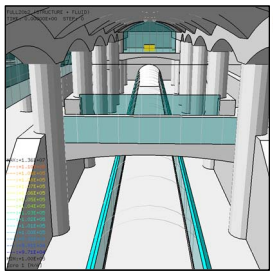
Complete Station Simulation (22)

Rue de Chevaleret:



Smaller charge *Larger charge*

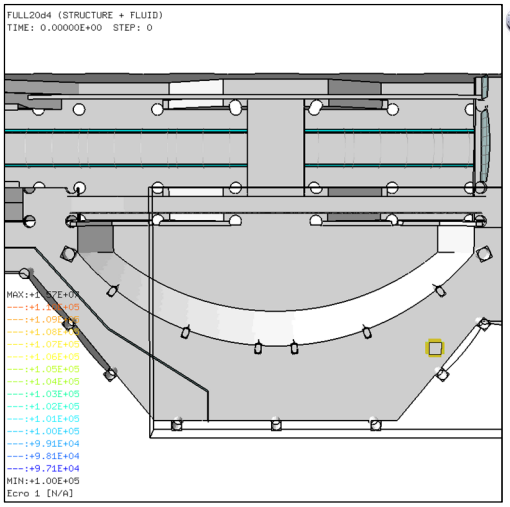




179

Complete Station Simulation (23)

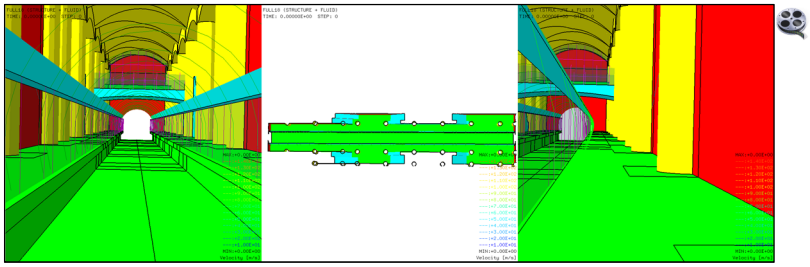
Hemicycle :



180

Complete Station Simulation (24)

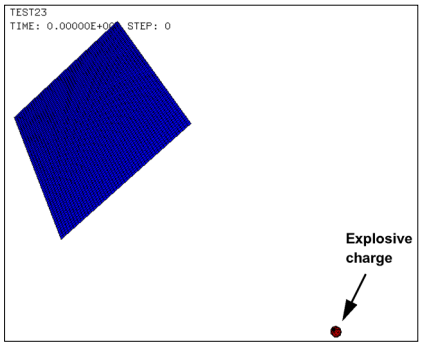
Metro Platform :



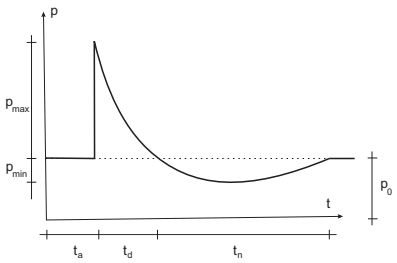
181

Exercise 15 – Blast on a glass sheet

Simulate the fragmentation of a glass sheet subjected to a blast wave using the AIRB model



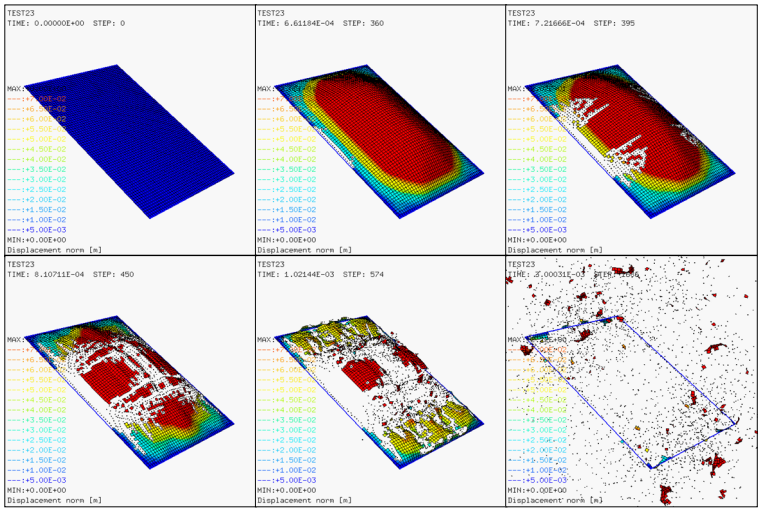
Geometry



Pressure (AIRB)

182

Exercise 15 – Blast on a glass sheet (2)

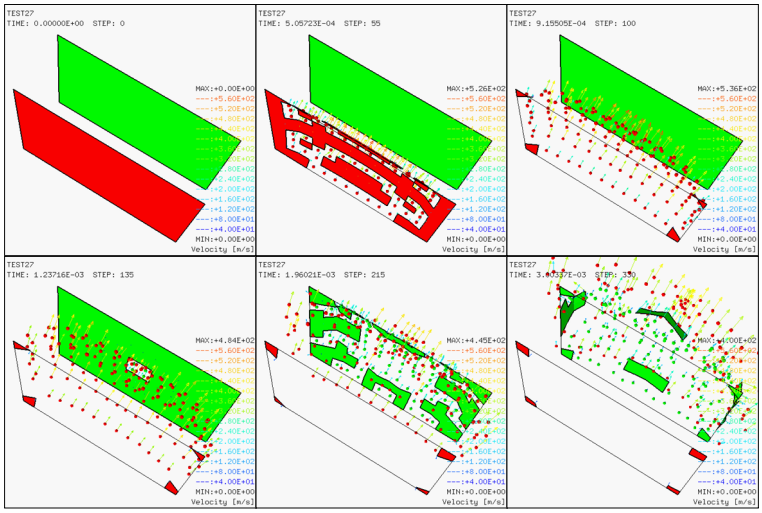


Fragmentation

183

Exercise 15b – Secondary debris

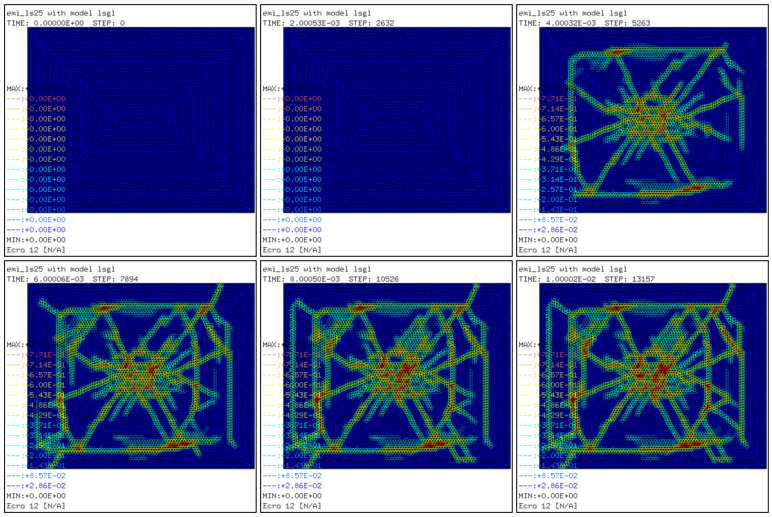
Simulate the formation of secondary debris due to impact of primary debris on a glass sheet :



184

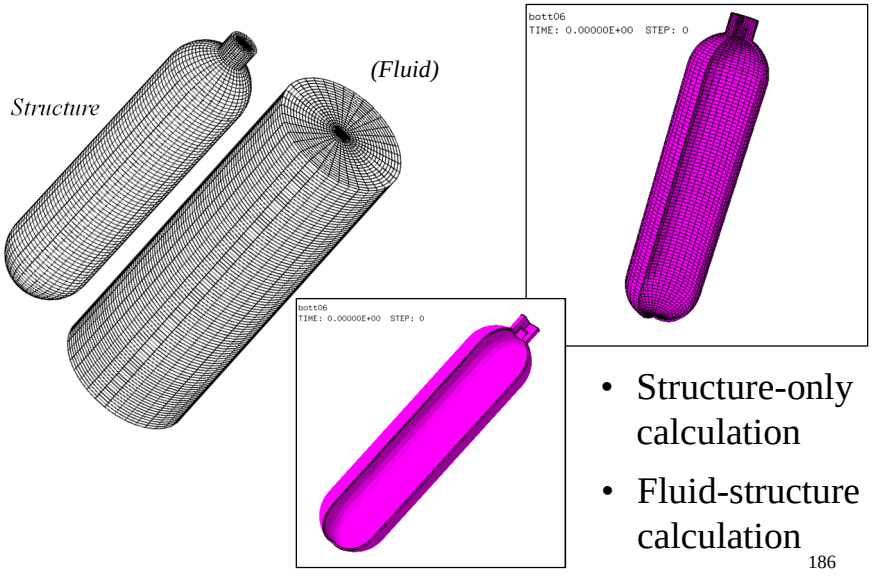
Exercise 15c – Crack formation

in Laminated Glass



185

Exercise 16 – Explosion of an air bottle



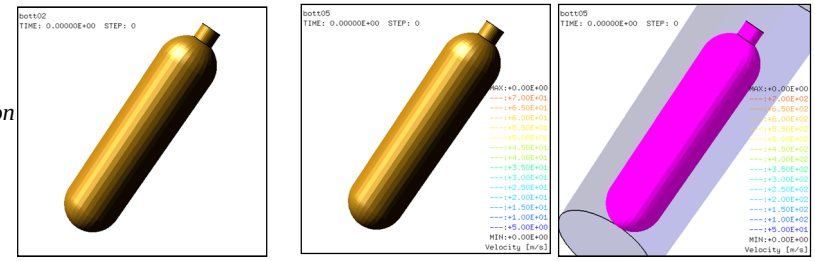
- Structure-only calculation
- Fluid-structure calculation

186

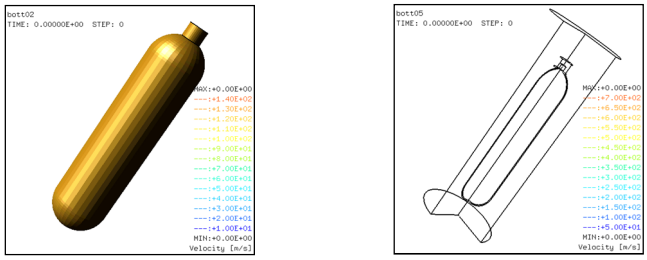
Exercise 16 – Explosion of an air bottle (2)

Structure-only solution Fluid-structure solution

Fragmentation



Velocities



187

Blast on ISO container (Courtesy NTNU)

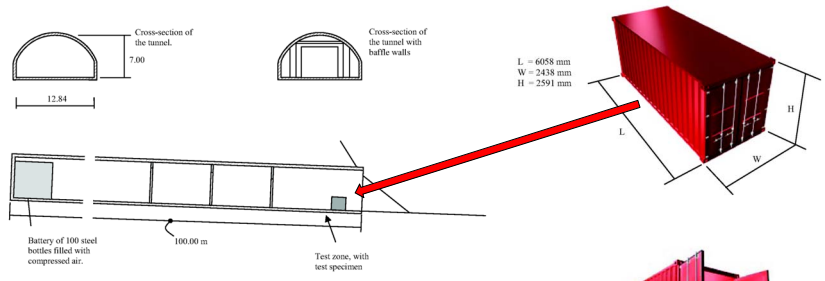
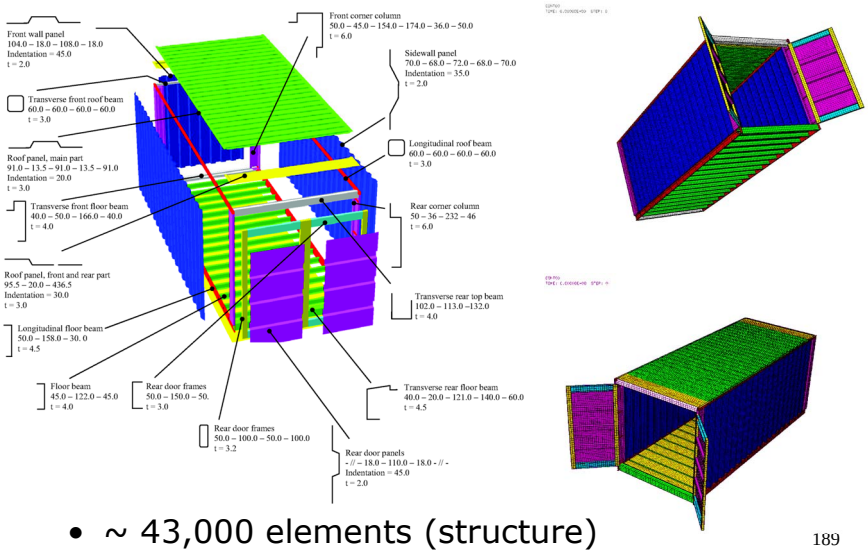


Figure 1 A schematic view of the Large Blast Simulator (LBS) at Bundeswehr Technical Center for Protective and Special Technologies (WTD 52) in Oberjettenberg, Germany /2/. Courtesy WTD 52 .

Standard 20 ft ISO container /1/

188

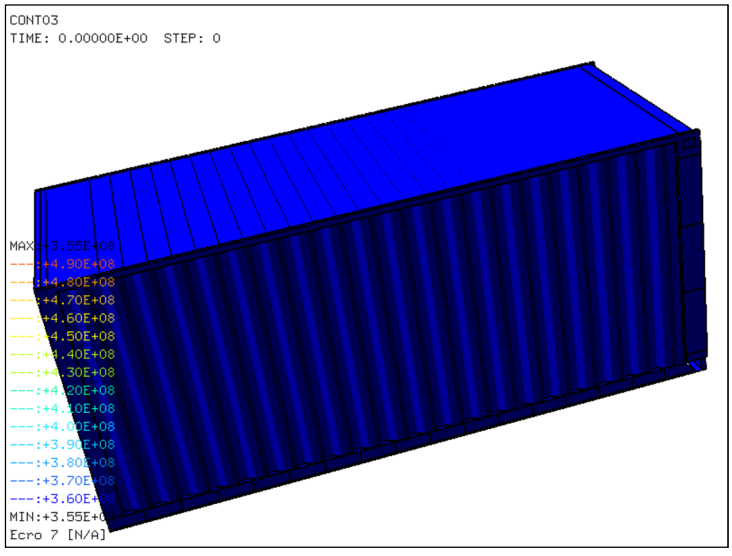
FE model



- ~ 43,000 elements (structure)

189

Preliminary simulation with AIRB



Current Yield stress (plasticity)

190

Simulation (applied test pressure) vs experiment



Blast test in tunnel



Simulation

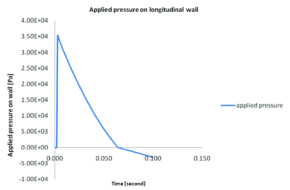


Figure 8 Pressure versus time function applied on the container.

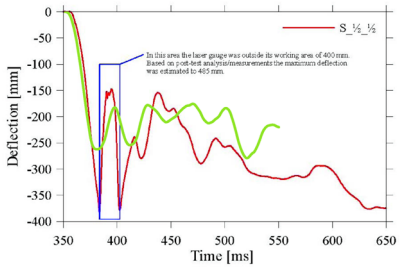
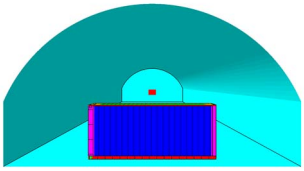


Figure 20 Displacement of the mid-point of the longitudinal wall of the container. Experimental results (red curve) compared with numerical results for the cont1000 model (green curve).

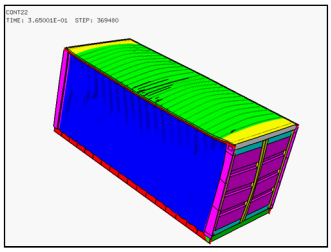
191

Predictive simulations require FSI

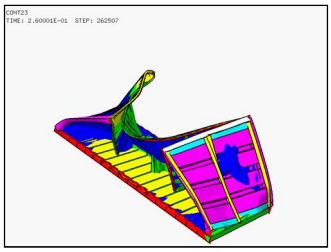




Model of container in tunnel



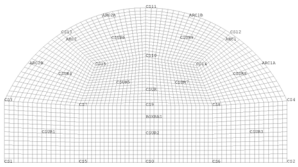
Load case 1: FE + FLSR



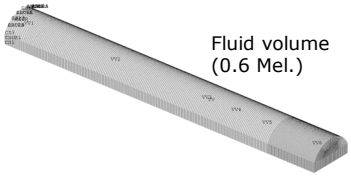
Load case 2: CCFV + FLSW

192

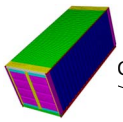
Full (Blind) Simulation with FSI



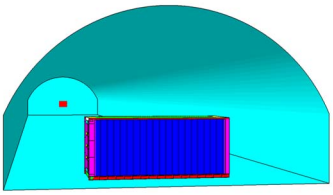
Fluid cross-section



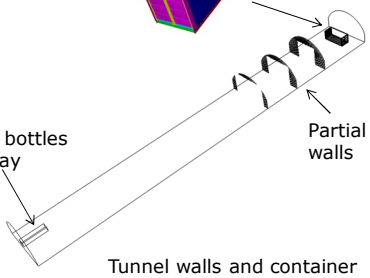
Fluid volume
(0.6 Mel.)



Container (43 kel.)



Container within tunnel



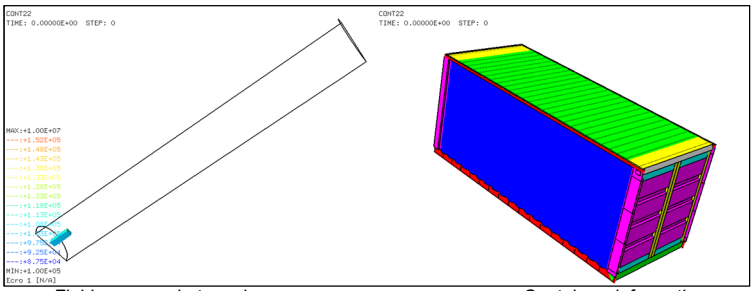
Air bottles
array

Partial
walls

Tunnel walls and container

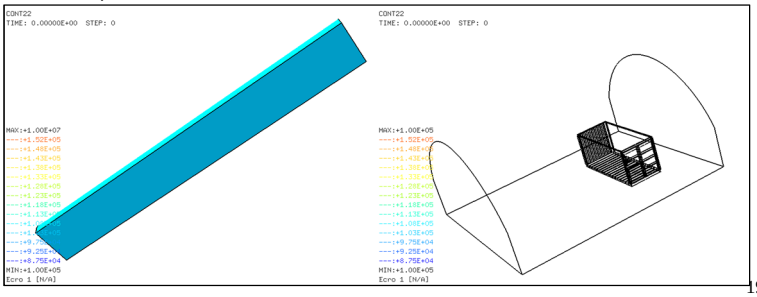
193

FE fluid with FLSR



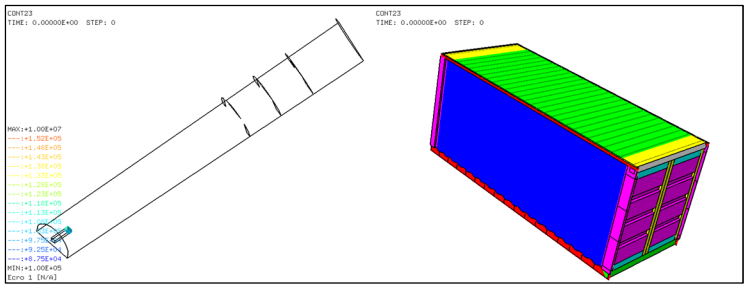
Fluid pressure in tunnel

Container deformation



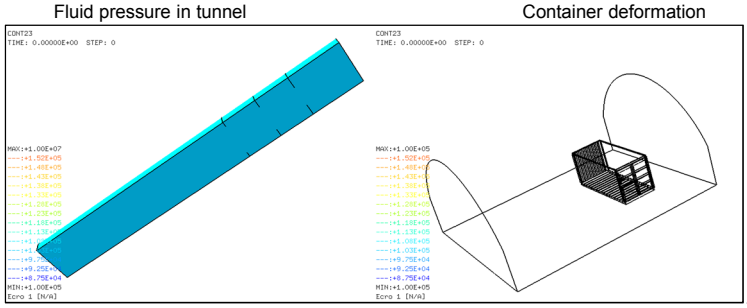
194

CCFV fluid with FLSW (preliminary)



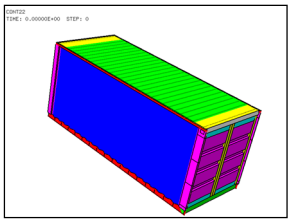
Fluid pressure in tunnel

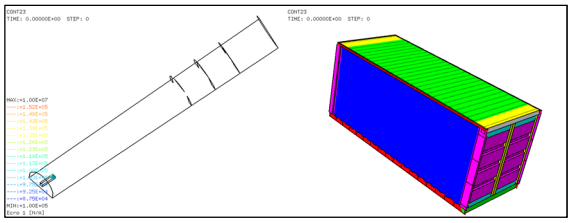
Container deformation



195

Container simulations with FSI





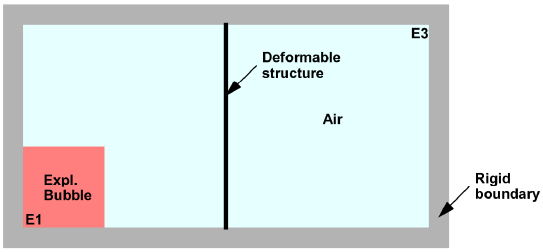
Load case 1:
FE + FLSR

Load case 2:
CCFV + FLSW

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Exercise/Example 12c – Failure with CCFV

- Solve a FSI problem with failure and fragmentation by the CCFV fluid model (conforming meshes)



- Compare solutions without and with structural failure of the internal deformable wall

43

PROBLEM:
An explosion takes place in a box. The xternal box walls are rigid. An internal deformable wall divides the box in two zones. The fluid domain is modelled by Cell-Centered Finite Volumes (CCFV) and a conforming F-S mesh is used.

The purpose is to show that in case of failure of the deformable wall the fluid flow across the failing wall can be modelled by the CCFV, thanks to the fact that fluid velocities are discretized at the cell centres, and not at nodes

Numerical Solutions

VFAL02
This is the solution without structural failure. The mesh generation file is:

```
opti echo 1;
opti titr 'VFAL02';
opti sauv form 'vfal02.msh';
opti trac psc ftra 'vfal02_mesh.ps';
*
opti dime 2 elem qua4;
*
p1 = 0 0;
p2 = 2 0;
p3 = 2 1;
p4 = 0 1;
p5 = 0.4 0;
p6 = 0.4 0.4;
p7 = 0 0.4;
p8 = 0.4 1;
*
tol = 0.001;
*
c1 = p1 d 4 p5;
c2 = p5 d 4 p6;
c3 = p6 d 4 p7;
c4 = p7 d 4 p1;
expl = dall c1 c2 c3 c4 plan;
*
c1 = p5 d 16 p2;
c2 = p2 d 10 p3;
c3 = p3 d 16 p8;
c4 = p8 d 6 p6 d 4 p5;
air1 = dall c1 c2 c3 c4 plan;
*
c1 = p7 d 4 p6;
c2 = p6 d 6 p8;
c3 = p8 d 4 p4;
c4 = p4 d 6 p7;
air2 = dall c1 c2 c3 c4 plan;
*
air = air1 et air2;
flui = expl et air;
elim tol flui;
*
e1 = expl elem cont p1;
e3 = air1 elem cont p3;
*
p9 = 1 0;
p10 = 1 1;
p11 = 1 0.5;
p12 = 1 0.3;
p13 = 1 0.7;
stru1 = p9 d 3 p12;
stru2 = p13 d 3 p10;
stru3 = p12 d 2 p11 d 2 p13;
stru = stru1 et stru2 et stru3;
elim tol (flui et stru);
*
contfl = cont flui;
*
mesh = flui et stru et e1 et e3;
*
sauv form mesh;
trac qual mesh;
*
list (nbel mesh);
list (nbno mesh);
*
fin;
```

The EUROPLEXUS input file reads:

```
VFAL02
ECHO
!conv win
CAST mesh
DPLA ALE
DIME
 NALE 1 NBLE 162
TERM
GEOM Q4VF flui ED01 stru TERM
COMP EPAI 0.02  LECT stru1 stru2 TERM
          0.002 LECT stru3 TERM
     COUL roug LECT expl TERM
          turq LECT air  TERM
GRIL LAGR LECT stru TERM
     EULE LECT contfl DIFF p9 p10 TERM
     AUTO AUTR
MATE GAZP RO 13. GAMMA 1.4 CV 720. PINI 1.E6 PREF 1.E5
          LECT expl TERM
     GAZP RO 1.3 GAMMA 1.4 CV 720. PINI 1.E5 PREF 1.E5
          LECT air TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
LINK COUP
     BLOQ 12 LECT p9 p10 TERM
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO VFCC FREQ 100
          POIN LECT p1 p5 p6 p7 p3 p11 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC FREQ 2
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p5 p6 p7 p3 p11 SUIT 133 TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
     VFCC FCON 1 ! rusanov
CALC TINI 0.0 PAS1 1.E-5 NMAX 400 TFIN 1.0
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 200
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT air  TERM
     text isca
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 201 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 199 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text isca
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 201 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 199 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'vcvi_e1' VCVI NORM ELEM LECT e1 TERM
COUR  2 'vcvi_e3' VCVI NORM ELEM LECT e3 TERM
COUR  3 'p_e1'    ECRO COMP 1 ELEM LECT e1 TERM
COUR  4 'p_e3'    ECRO COMP 1 ELEM LECT e3 TERM
COUR  5 'd_l1'    DEPL COMP 1 NOEU LECT p11 TERM
COUR  6 'd_l33'   DEPL COMP 1 NOEU LECT 133 TERM
*
trac 1 2 axes 1.0 'VELOC. [M/S]'
trac 3 4 axes 1.0 'PRESS [PA]'
trac 5 axes 1.0 'DISPL [M]'
trac 6 axes 1.0 'DISPL [M]'
LIST 1 2 axes 1.0 'VELOC. [M/S]'
LIST 3 4 axes 1.0 'PRESS [PA]'
LIST 5 axes 1.0 'DISPL [M]'
LIST 6 axes 1.0 'DISPL [M]'
*
! J'ai l'impression che la qualification de VCVi ne marche pas ...
!QUAL VCVI COMP 1 LECT e1 TERM REFE  0.00000E+0 TOLE 5.E-3
!     VCVI COMP 2 LECT e3 TERM REFE  0.00000E+0 TOLE 5.E-3
!qual ECRO COMP 1 LECT e1 TERM REFE  2.20444E+5 TOLE 5.E-3
!     ECRO COMP 1 LECT e3 TERM REFE  1.55334E+5 TOLE 5.E-3
*=================================================================
FIN
```

VFAL03

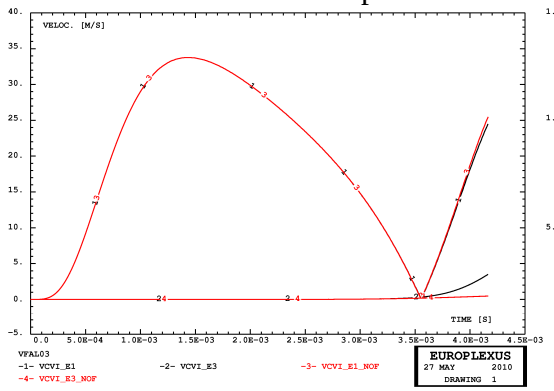
This is identical to the previous test but the deformable wall may undergo failure. Failing elements are eroded. The Cast3m mesh generation file is identical to the previous case. The EUROPLEXUS input file reads:

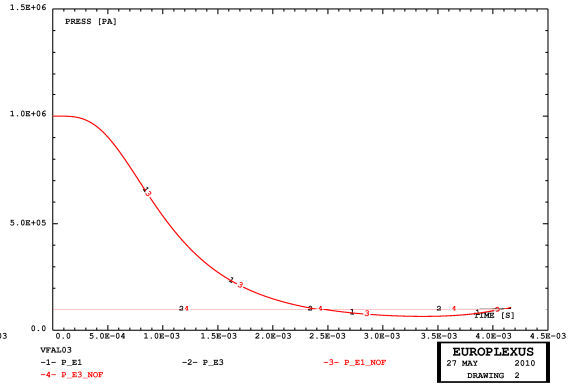
```
VFAL03
ECHO
!conv win
CAST mesh
DPLA ALE EROS 0.0
DIME
 NALE 1 NBLE 162
TERM
GEOM Q4VF flui ED01 stru TERM
opti dump
COMP EPAI 0.02  LECT stru1 stru2 TERM
          0.002 LECT stru3 TERM
     COUL roug LECT expl TERM
          turq LECT air  TERM
GRIL LAGR LECT stru TERM
     EULE LECT contfl DIFF p9 p10 TERM
     AUTO AUTR
MATE GAZP RO 13. GAMMA 1.4 CV 720. PINI 1.E6 PREF 1.E5
          LECT expl TERM
     GAZP RO 1.3 GAMMA 1.4 CV 720. PINI 1.E5 PREF 1.E5
          LECT air TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          FAIL PEPS LIMI 0.002
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
LINK COUP
     BLOQ 12 LECT p9 p10 TERM
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO VFCC FAIL FREQ 100
          POIN LECT p1 p5 p6 p7 p3 p11 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC FREQ 2
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p5 p6 p7 p3 p11 SUIT 133 TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
     VFCC dump FCON 1 ! rusanov
CALC TINI 0.0 PAS1 1.E-5 NMAX 400 TFIN 1.0
!fin
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 200
go
trac offs fich bmp obje nfai lect tous term rend
go
trac offs fich bmp obje nfai lect tous term rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT air  TERM
     text isca
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 201 fps 10 kfre 10 comp -1
     obje nfai lect tous term rend
freq 1
gotr loop 199 offs fich avi cont nocl obje nfai lect tous term rend
go
trac offs fich avi cont obje nfai lect tous term rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
```

```
*===============================================================
PLAY
CAME    1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
:         Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
          VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
          RIGH  1.00000E+00  0.00000E+00  0.00000E+00
          UP    0.00000E+00  1.00000E+00  0.00000E+00
          FOV   2.48819E+01
sler caml 1 nfra 1
scen geom navi free
     iso  fili fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text isca
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 201 fps 10 kfre 10 comp -1
     obje nfai lect tous term rend
freq 1
gotr loop 199 offs fich avi cont nocl
     obje nfai lect tous term rend
go
trac offs fich avi cont
     obje nfai lect tous term rend
ENDPLAY
*===============================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
```

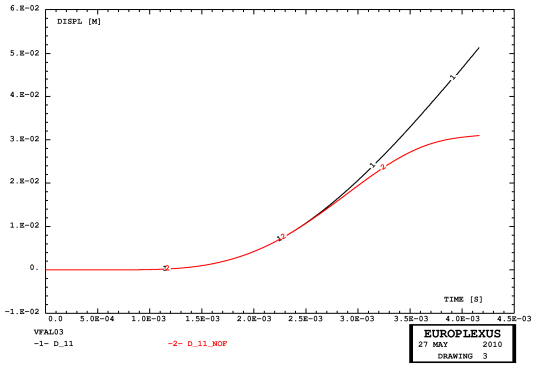
```
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'vcvi_e1' VCVI NORM ELEM LECT e1 TERM
COUR  2 'vcvi_e3' VCVI NORM ELEM LECT e3 TERM
COUR  3 'p_e1'    ECRO COMP 1 ELEM LECT e1 TERM
COUR  4 'p_e3'    ECRO COMP 1 ELEM LECT e3 TERM
COUR  5 'd_11'    DEPL COMP 1 NOEU LECT p11 TERM
COUR  6 'd_133'   DEPL COMP 1 NOEU LECT 133 TERM
RCOU 11 'vcvi_e1' FICH 'vfal02.pun' RENA 'vcvi_e1_nof'
RCOU 12 'vcvi_e3' FICH 'vfal02.pun' RENA 'vcvi_e3_nof'
RCOU 13 'p_e1'    FICH 'vfal02.pun' RENA 'p_e1_nof'
RCOU 14 'p_e3'    FICH 'vfal02.pun' RENA 'p_e3_nof'
RCOU 15 'd_11'    FICH 'vfal02.pun' RENA 'd_11_nof'
RCOU 16 'd_133'   FICH 'vfal02.pun' RENA 'd_133_nof'
*
trac 1 2 11 12 axes 1.0 'VELOC. [M/S]'
     COLO noir noir roug roug
trac 3 4 13 14 axes 1.0 'PRESS [PA]'
     COLO noir noir roug roug
trac 5 15 axes 1.0 'DISPL [M]'
     COLO noir roug
trac 6 16 axes 1.0 'DISPL [M]'
     COLO noir roug
*
! J'ai l'impression che la qualification de VCVi ne marche pas ...
!QUAL VCVI COMP 1 LECT e1 TERM REFE  0.00000E+0 TOLE 5.E-3
!     VCVI COMP 2 LECT e3 TERM REFE  0.00000E+0 TOLE 5.E-3
!qual ECRO COMP 1 LECT e1 TERM REFE  2.20444E+5 TOLE 5.E-3
!     ECRO COMP 1 LECT e3 TERM REFE  1.55334E+5 TOLE 5.E-3
*===============================================================
FIN
```

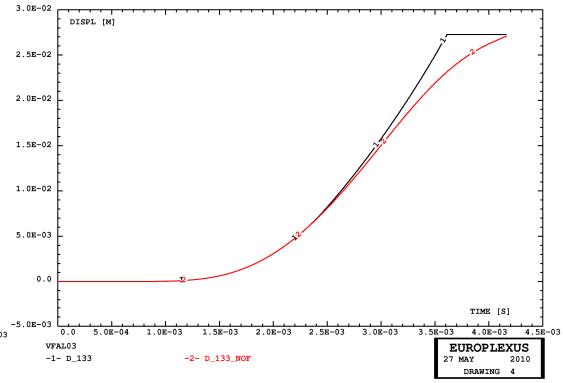
Here are some results: in red the solution without failure, in black the solution with failure. Fluid velocities and pressures:



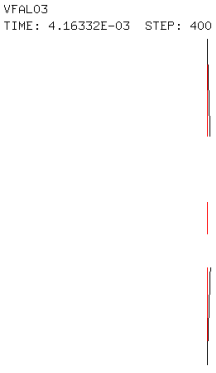


Displacement of central point of the structure and displacement of the initially attached fluid node:

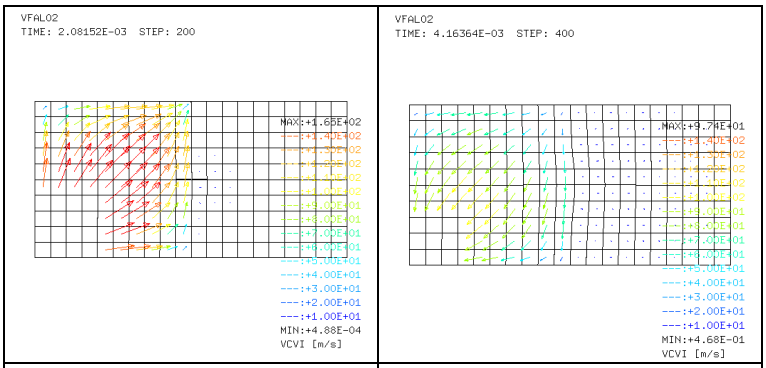




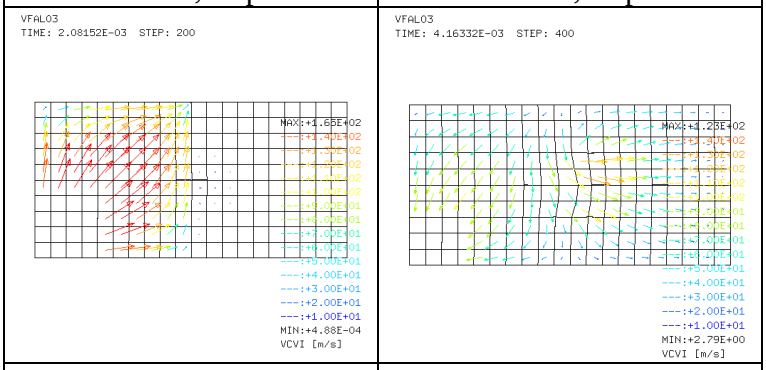
Detail of structural failure:



Fluid velocity maps

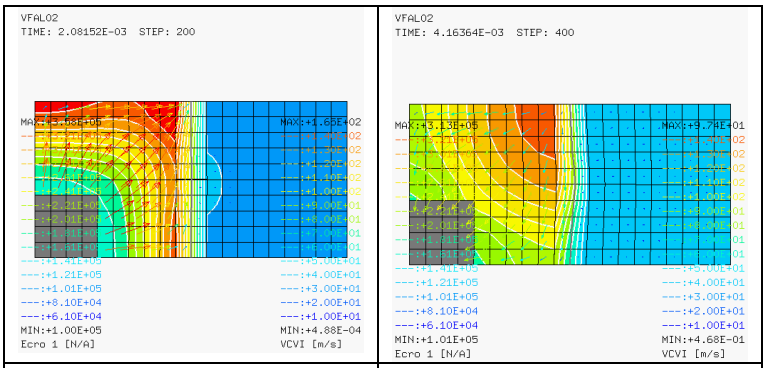


No failure, step 200 | No failure, step 400

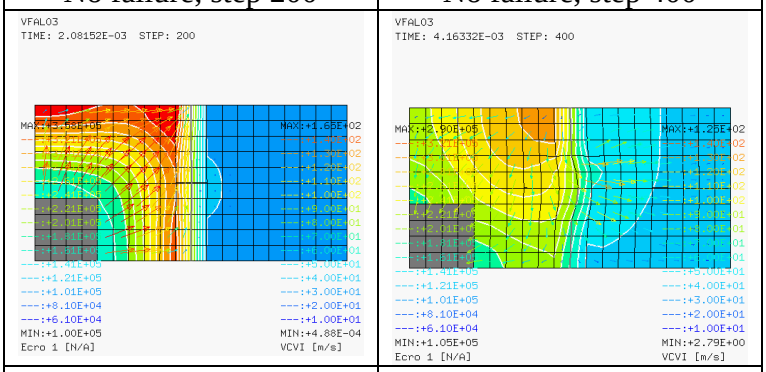


Failure, step 200 | Failure, step 400

Fluid pressure maps:

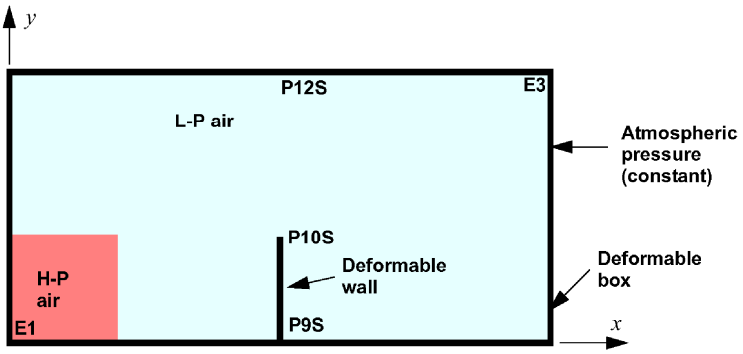


No failure, step 200 | No failure, step 400



Failure, step 200 | Failure, step 400

Exercise 12b – FLSR with NCFV



- The box problem of exercise 10b (Part 3) is solved with NCFV using the FLSR model for Fluid-Structure Interaction
  - Obtain solution with NCFV and FSA (reference solution) by using a fine fluid mesh and non-conforming FSA model (see Part 5)
  - Obtain solution with NCFV and basic FLSR : large spurious fluid leakage is observed
  - Add keyword **`MCFL 1`** : the spurious leakage disappears

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PROBLEM:
This is the same box problem already studied in Part 3 (exercise 10b). Now the problem is solved by NCFV using either FSA (reference solution) or FLSR. The use of optional keyword FLSR … MCFL 1 ito block spurious fluxes is illustrated.

Numerical Solutions

VFNCN2
This is the reference solution, obtained with FSA (non conforming mesh, see Part 5). The Cast3m mesh generation file reads:

```
opti echo 1;
opti titr 'VFNCN2';
opti sauv form 'vfncn2.msh';
opti trac psc ftra 'vfncn2_mesh.ps';
*
opti dime 2 elem qua4;
*
p1 = 0 0;
p2 = 2 0;
p3 = 2 1;
p4 = 0 1;
p5 = 0.4 0;
p6 = 0.4 0.4;
p7 = 0 0.4;
p8 = 0.4 1;
*
tol = 0.001;
*
c1 = p1 d 16 p5;
c2 = p5 d 16 p6;
c3 = p6 d 16 p7;
c4 = p7 d 16 p1;
expl = dall c1 c2 c3 c4 plan;
*
p9l = 1 0;
p9r = 1 0;
p10 = 1 0.4;
p11 = 2 0.4;
*
c1 = p5 d 24 p9l;
c2 = p9l d 16 p10;
c3 = p10 d 24 p6;
c4 = p6 d 16 p5;
air1a = dall c1 c2 c3 c4 plan;
*
c1 = p9r d 40 p2;
c2 = p2 d 16 p11;
c3 = p11 d 40 p10;
c4 = p10 d 16 p9r;
air1b = dall c1 c2 c3 c4 plan;
*
c1 = p6 d 24 p10 d 40 p11;
c2 = p11 d 24 p3;
c3 = p3 d 64 p8;
c4 = p8 d 24 p6;
air1c = dall c1 c2 c3 c4 plan;
*
elim tol (air1a et air1c);
elim tol (air1b et air1c);
air1 = air1a et air1b et air1c;
*
c1 = p7 d 16 p6;
c2 = p6 d 24 p8;
c3 = p8 d 16 p4;
c4 = p4 d 24 p7;
air2 = dall c1 c2 c3 c4 plan;
elim tol (air1c et air2);
elim tol (expl et air2);
elim tol (expl et air1a);
*
air = air1 et air2;
flui = expl et air;
*
e1 = expl elem cont p1;
e3 = air1 elem cont p3;
*
p1s = p1 plus p1;
p2s = p2 plus p1;
p3s = p3 plus p1;
p4s = p4 plus p1;
p9s = p9l plus p1;
p10s = p10 plus p1;
p12s = 1 1;
c1s = p1s d 10 p9s d 10 p2s;
c2s = p2s d 10 p3s;
c3s = p3s d 10 p12s d 10 p4s;
c4s = p4s d 10 p1s;
c5s = p9s d 4 p10s;
stru = c1s et c2s et c3s et c4s et c5s;
*
c1p = p2s d 10 p9s d 10 p1s;
c2p = p3s d 10 p2s;
c3p = p4s d 10 p12s d 10 p3s;
c4p = p1s d 10 p4s;
pext = c4p et c3p et c2p et c1p;
elim tol (stru et pext);
*
nfsa = cont flui;
*
mesh = flui et stru et pext et e1 et e3 et nfsa;
*
sauv form mesh;
trac qual mesh;
*
list (nbel mesh);
list (nbno mesh);
```

```
*
fin;
```

The EUROPLEXUS input file reads:

```
VFNCN2
ECHO
!conv win
CAST mesh
DPLA ALE
DIME
 NALE 148 NBLE 3065 NDVC 13072
TERM
GEOM MC24 flui ED01 stru CL22 pext TERM
COMP EPAI 0.01 LECT stru TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
          jaun LECT pext TERM
GRIL LAGR LECT stru TERM
     EULE LECT nfsa TERM
     AUTO AUTR
MATE MCGP NCOM 1 R 8.3143E3
          COMP 'Air' PM 29.0 CV1 2.07585E4 CV2 0 CV3 0
          LECT flui TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
     IMPE PIMP RO 1.1897 PRES 1.E5 PREF 0
          LECT pext TERM
INIT MCOM COMP 'Air' MFRA 1.0 LECT flui TERM
          PRES 1.E6 LECT expl TERM
          PRES 1.E5 LECT air  TERM
          TEMP 586.36 LECT expl TERM
          TEMP 293.16 LECT air  TERM
          VEL1 0.0 LECT flui TERM
          VEL2 0.0 LECT flui TERM
LINK COUP FSA NCFS LECT nfsa TERM
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO MCVA TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p4 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
     MC ORDR 2 NUFL ROE
CALC TINI 0.0 TFIN 5.E-3
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
```

```
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dt1'     DT1
COUR  3 'p_e1'    MCPR COMP 1 NOEU LECT p1 TERM
COUR  4 'p_e3'    MCPR COMP 1 NOEU LECT p3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
COUR 101 'p_p4'    MCPR COMP 1 NOEU LECT p4 TERM
COUR 102 'r_p4'    MCRO COMP 1 NOEU LECT p4 TERM
COUR 103 't_p4'    MCTE COMP 1 NOEU LECT p4 TERM
COUR 104 'yl_p4'   MCMF COMP 1 NOEU LECT p4 TERM
*
TRAC 1   AXES 1.0 'DELTAT [S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
TRAC 101 AXES 1.0 'PRESS. [PA]'
TRAC 102 AXES 1.0 'DENS. [KG/M3]'
TRAC 103 AXES 1.0 'TEMP. [K]'
TRAC 104 AXES 1.0 'FRAC. [-]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
QUAL MCPR COMP 1 LECT p1 TERM REFE  1.56554E+5 TOLE 5.E-3
     MCPR COMP 1 LECT p3 TERM REFE  2.02150E+5 TOLE 5.E-3
*=================================================================
FIN
```

VFNCF2S

This is the solution with (basic) FLSR. The Cast3m mesh generation file reads:

```
opti echo 1;
opti titr 'VFNCF2S';
opti sauv form 'vfncf2s.msh';
opti trac psc ftra 'vfncf2s_mesh.ps';
*
opti dime 2 elem qua4;
*
p1 = 0 0;
p2 = 2 0;
p3 = 2 1;
p4 = 0 1;
p5 = 0.4 0;
p6 = 0.4 0.4;
p7 = 0 0.4;
p8 = 0.4 1;
*
pa = -0.2 -0.2;
pb =  2.2 -0.2;
pc =  2.2  1.2;
pd = -0.2  1.2;
*
tol = 0.001;
*
c1 = pa d 96 pb;
c2 = pb d 56 pc;
c3 = pc d 96 pd;
c4 = pd d 56 pa;
flui = dall c1 c2 c3 c4 plan;
elim tol (flui et p1 et p2 et p3 et p4 et p5 et p6 et p7 et p8);
```

```
abso = c1 et c2 et c3 et c4;
*
el1 = flui elem appu larg p1;
el3 = flui elem appu larg p3;
*
p9s = 1 0;
p10s = 1 0.4;
p11s = 2 0.4;
p12s = 1 1;
p1s = p1 plus p1;
p2s = p2 plus p1;
p3s = p3 plus p1;
p4s = p4 plus p1;
c1s = p1s d 10 p9s d 10 p2s;
c2s = p2s d 10 p3s;
c3s = p3s d 10 p12s d 10 p4s;
c4s = p4s d 10 p1s;
c5s = p9s d 4 p10s;
stru = c1s et c2s et c3s et c4s et c5s;
*
mesh = flui et stru et abso et el1 et el3;
*
sauv form mesh;
trac qual mesh;
*
list (nbel mesh);
list (nbno mesh);
*
fin;
```

The EUROPLEXUS input file reads:

```
VFNCF2S
ECHO
 conv win
CAST mesh
DPLA ALE
DIME
 NALE 148 NBLE 3065 NDVC 21808
TERM
GEOM MC24 flui ED01 stru CL22 abso TERM
COMP EPAI 0.01 LECT stru TERM
     GROU 3 'expl' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 0.4 DY 0.4
            'flin' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 2.0 DY 1.0
            'air'  LECT flui TERM COND COMP LECT expl TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
          jaun LECT abso TERM
GRIL LAGR LECT stru TERM
MATE MCGP NCOM 1 R 8.3143E3
          COMP 'Air' PM 29.0 CV1 2.07585E4 CV2 0 CV3 0
          LECT flui TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
     MCFF BDFO 1 TEMP 293.16 PRES 1.E5
          VEL1 0. VEL2 0.
          COMP 'Air'      MFRA 1.
          LECT abso TERM
INIT MCOM COMP 'Air' MFRA 1.0 LECT flui TERM
          PRES 1.E6 LECT expl TERM
          PRES 1.E5 LECT air  TERM
          TEMP 586.36 LECT expl TERM
          TEMP 293.16 LECT air  TERM
          VEL1 0.0 LECT flui TERM
          VEL2 0.0 LECT flui TERM
LINK COUP FLSR STRU LECT stru TERM
               FLUI LECT flui TERM
               R    0.036 ! = gamma*delta*h_fluide = 1.01*1.41*0.025
!fc            R    0.018 ! = gamma*delta*h_fluide = 1.01*1.41*0.025
                          !   [delta = sqrt(2) en 2D, = sqrt(3) en 3D]
               HGRI 0.110
               DGRI
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO
     MCVC MCVS MCFL MCEF MCMU MCVM TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p4 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
OPTI NOTE LOG 1
     CSTA 0.5
     MC ORDR 2 NUFL ROE SYNC 1
CALC TINI 0.0 TFIN 5.E-3
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     face hfro
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dt1'     DT1
COUR  3 'p_e1'    MCPR COMP 1 NOEU LECT p1 TERM
COUR  4 'p_e3'    MCPR COMP 1 NOEU LECT p3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
COUR 101 'p_p4'    MCPR COMP 1 NOEU LECT p4 TERM
COUR 102 'r_p4'    MCRO COMP 1 NOEU LECT p4 TERM
COUR 103 't_p4'    MCTE COMP 1 NOEU LECT p4 TERM
COUR 104 'yl_p4'   MCMF COMP 1 NOEU LECT p4 TERM
*
TRAC 1   AXES 1.0 'DELTAT [S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
TRAC 101 AXES 1.0 'PRESS. [PA]'
TRAC 102 AXES 1.0 'DENS. [KG/M3]'
TRAC 103 AXES 1.0 'TEMP. [K]'
TRAC 104 AXES 1.0 'FRAC. [-]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
QUAL MCPR COMP 1 LECT p1 TERM REFE  1.10708E+5 TOLE 5.E-3
     MCPR COMP 1 LECT p3 TERM REFE  1.36705E+5 TOLE 5.E-3
*=================================================================
FIN
```

VFNCF3S

This is the solution with FLSR and MCFL 1. The Cast3m mesh generation file is identical to the previous case. The EUROPLEXUS input file reads:

```
VFNCF3S
ECHO
 conv win
CAST mesh
DPLA ALE
DIME
 NALE 148 NBLE 3065 NDVC 21808
TERM
GEOM MC24 flui ED01 stru CL22 abso TERM
COMP EPAI 0.01 LECT stru TERM
     GROU 3 'expl' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 0.4 DY 0.4
            'flin' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 2.0 DY 1.0
            'air'  LECT flui TERM COND COMP LECT expl TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
          jaun LECT abso TERM
GRIL LAGR LECT stru TERM
MATE MCGP NCOM 1 R 8.3143E3
          COMP 'Air' PM 29.0 CV1 2.07585E4 CV2 0 CV3 0
          LECT flui TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
     MCFF BDFO 1 TEMP 293.16 PRES 1.E5
          VEL1 0. VEL2 0.
          COMP 'Air'      MFRA 1.
          LECT abso TERM
INIT MCOM COMP 'Air' MFRA 1.0 LECT flui TERM
          PRES 1.E6 LECT expl TERM
          PRES 1.E5 LECT air  TERM
          TEMP 586.36 LECT expl TERM
          TEMP 293.16 LECT air  TERM
          VEL1 0.0 LECT flui TERM
          VEL2 0.0 LECT flui TERM
LINK COUP FLSR STRU LECT stru TERM
               FLUI LECT flui TERM
               R    0.036 ! = gamma*delta*h_fluide = 1.01*1.41*0.025
!fc            R    0.018 ! = gamma*delta*h_fluide = 1.01*1.41*0.025
                          !   [delta = sqrt(2) en 2D, = sqrt(3) en 3D]
               HGRI 0.110
               DGRI
               MCFL 1 MCCP 1
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO
     MCVC MCVS MCFL MCEF MCMU MCVM TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p4 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
OPTI NOTE LOG 1
     CSTA 0.5
     MC ORDR 2 NUFL ROE SYNC 1
CALC TINI 0.0 TFIN 5.E-3
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
```

```
        RIGH  1.00000E+00  0.00000E+00  0.00000E+00
        UP    0.00000E+00  1.00000E+00  0.00000E+00
        FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
freq 50
```

```
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dt1'     DT1
COUR  3 'p_e1'    MCPR COMP 1 NOEU LECT p1 TERM
COUR  4 'p_e3'    MCPR COMP 1 NOEU LECT p3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
COUR 101 'p_p4'    MCPR COMP 1 NOEU LECT p4 TERM
COUR 102 'r_p4'    MCRO COMP 1 NOEU LECT p4 TERM
COUR 103 't_p4'    MCTE COMP 1 NOEU LECT p4 TERM
COUR 104 'yl_p4'   MCMF COMP 1 NOEU LECT p4 TERM
*
TRAC 1   AXES 1.0 'DELTAT [S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
TRAC 101 AXES 1.0 'PRESS. [PA]'
TRAC 102 AXES 1.0 'DENS. [KG/M3]'
TRAC 103 AXES 1.0 'TEMP. [K]'
TRAC 104 AXES 1.0 'FRAC. [-]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
QUAL MCPR COMP 1 LECT p1 TERM REFE  1.00000E+5 TOLE 5.E-3
     MCPR COMP 1 LECT p3 TERM REFE  1.00000E+5 TOLE 5.E-3
*================================================================
FIN
```

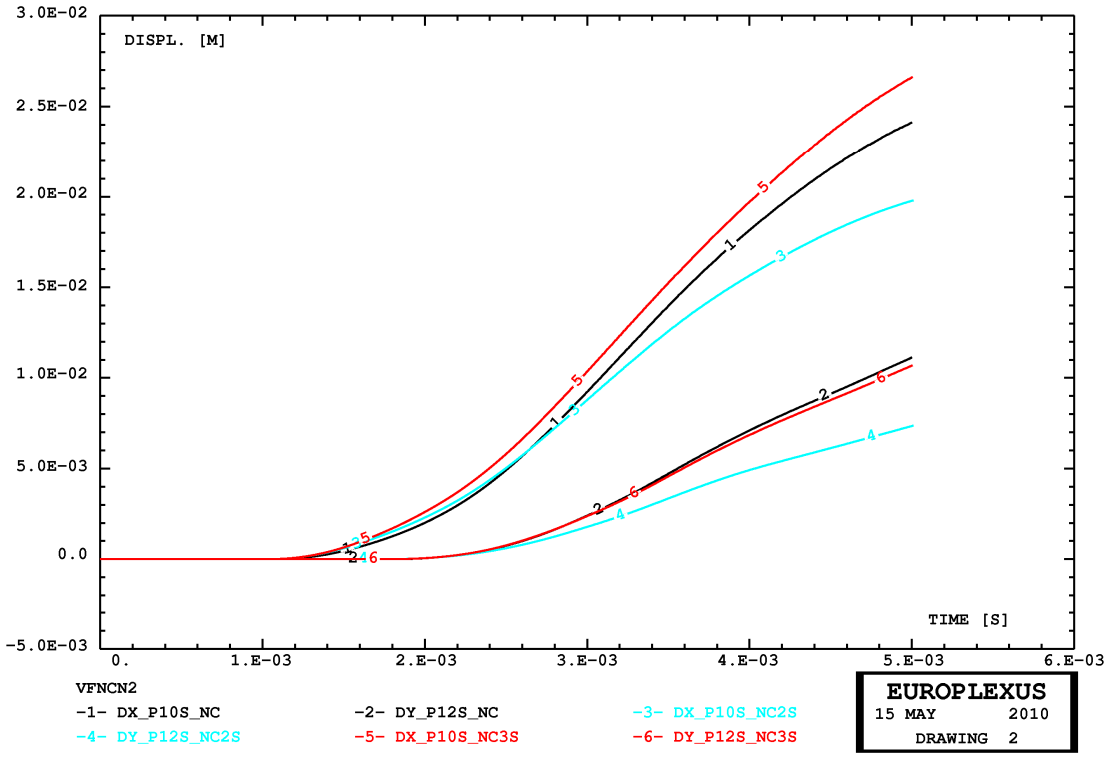
EFVFC2

This is an input file used to compare the various solutions:

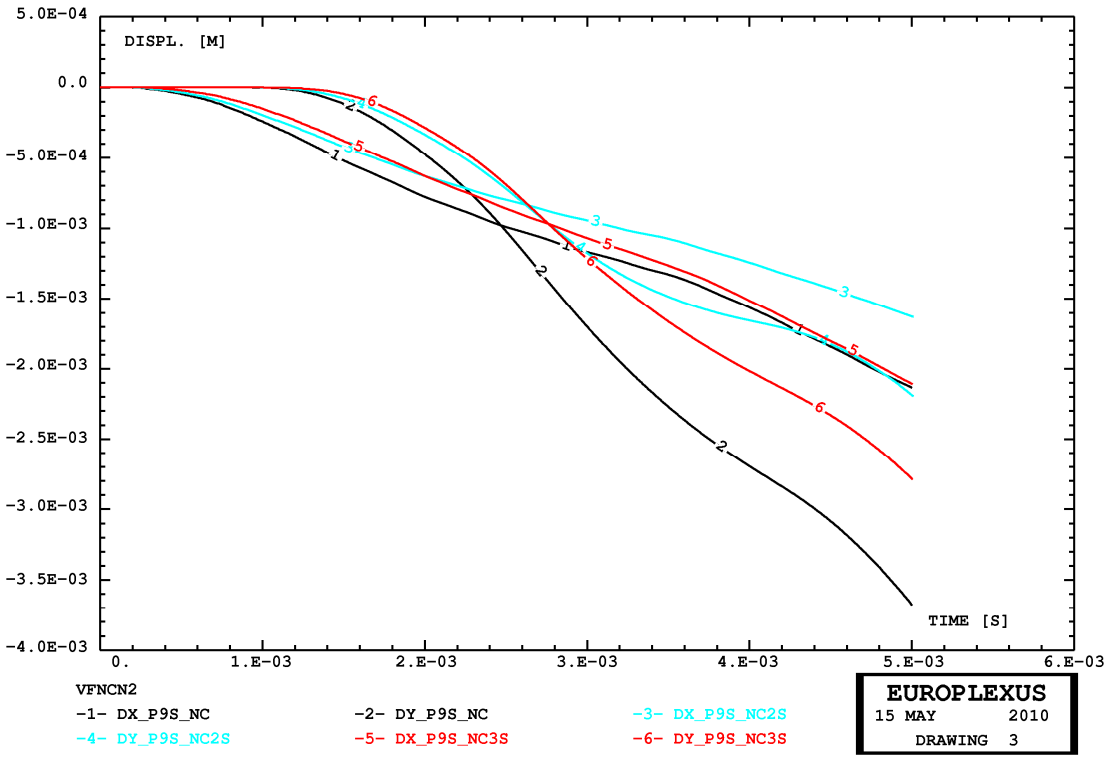
```
EFVFC2
ECHO
*
RESU ALIC TEMP 'vfncn2.alt' GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 13 'p_e1_nc'    MCPR COMP 1 NOEU LECT p1 TERM
COUR 14 'p_e3_nc'    MCPR COMP 1 NOEU LECT p3 TERM
COUR 15 'dx_p10s_nc' DEPL COMP 1 POIN LECT p10s TERM
COUR 16 'dy_p12s_nc' DEPL COMP 2 POIN LECT p12s TERM
COUR 17 'dx_p9s_nc'  DEPL COMP 1 POIN LECT p9s TERM
COUR 18 'dy_p9s_nc'  DEPL COMP 2 POIN LECT p9s TERM
*
RCOU 23 'p_e1'    FICH 'vfncf2s.pun' RENA 'p_e1_nc2s'
RCOU 24 'p_e3'    FICH 'vfncf2s.pun' RENA 'p_e3_nc2s'
RCOU 25 'dx_p10s' FICH 'vfncf2s.pun' RENA 'dx_p10s_nc2s'
```

```
RCOU 26 'dy_p12s' FICH 'vfncf2s.pun' RENA 'dy_p12s_nc2s'
RCOU 27 'dx_p9s'  FICH 'vfncf2s.pun' RENA 'dx_p9s_nc2s'
RCOU 28 'dy_p9s'  FICH 'vfncf2s.pun' RENA 'dy_p9s_nc2s'
*
RCOU 43 'p_e1'    FICH 'vfncf3s.pun' RENA 'p_e1_nc3s'
RCOU 44 'p_e3'    FICH 'vfncf3s.pun' RENA 'p_e3_nc3s'
RCOU 45 'dx_p10s' FICH 'vfncf3s.pun' RENA 'dx_p10s_nc3s'
RCOU 46 'dy_p12s' FICH 'vfncf3s.pun' RENA 'dy_p12s_nc3s'
RCOU 47 'dx_p9s'  FICH 'vfncf3s.pun' RENA 'dx_p9s_nc3s'
RCOU 48 'dy_p9s'  FICH 'vfncf3s.pun' RENA 'dy_p9s_nc3s'
*
TRAC 13 14 23 24 43 44 AXES 1.0 'PRESS [PA]'
     COLO noir noir turq turq roug roug
TRAC 15 16 25 26 45 46 AXES 1.0 'DISPL. [M]'
     COLO noir noir turq turq roug roug
TRAC 17 18 27 28 47 48 AXES 1.0 'DISPL. [M]'
     COLO noir noir turq turq roug roug
*================================================================
FIN
```

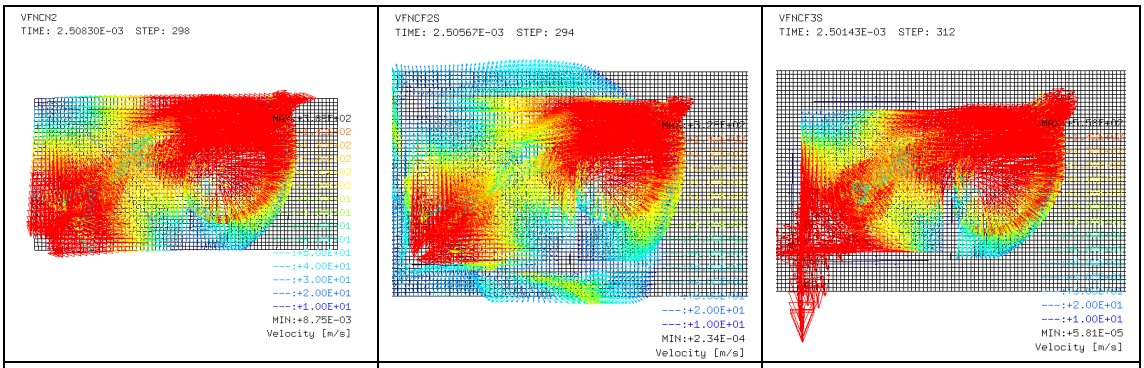
Here are some results. Structural displacements at points P10S and P12S



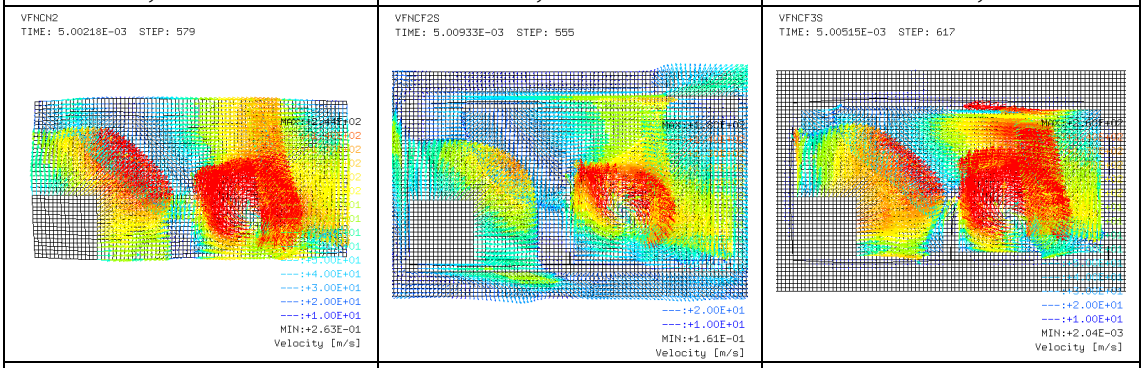
Structural displacements at point P9s:



Fluid velocities:

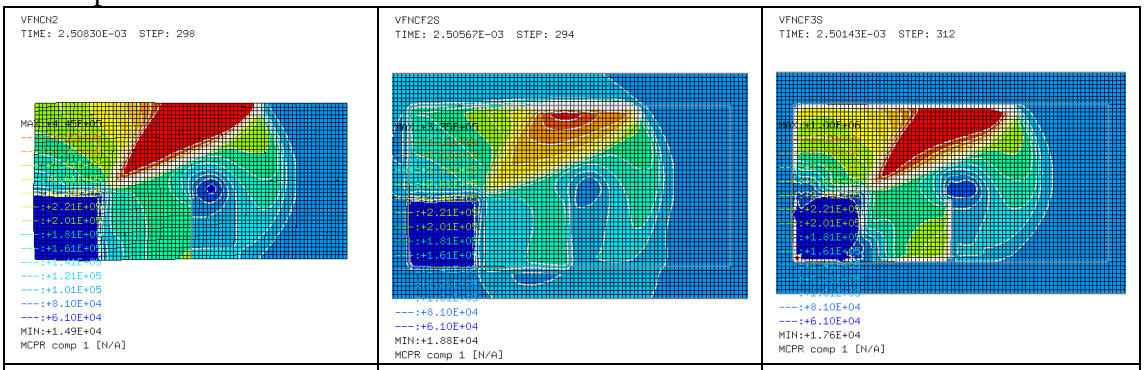


FSA, t = 2.5 ms	FLSR, t = 2.5 ms	FLSR MCFL 1, t = 2.5 ms

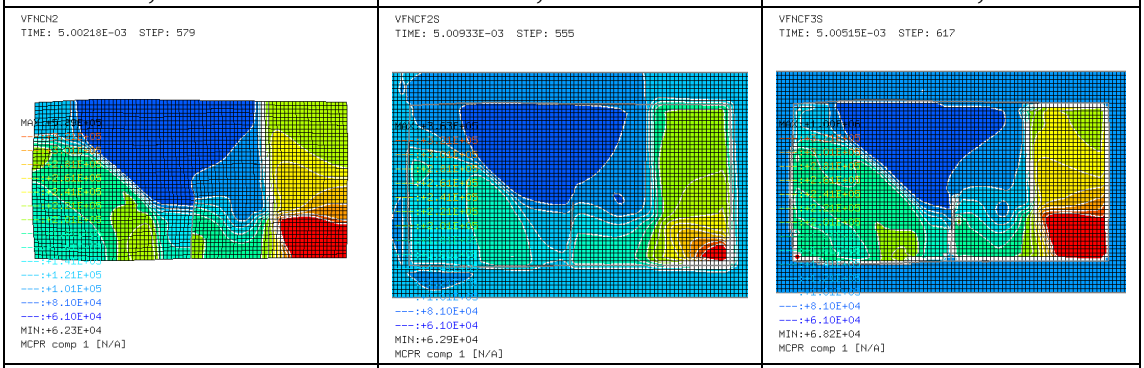


FSA, t = 5.0 ms	FLSR, t = 5.0 ms	FLSR MCFL 1, t = 5.0 ms

Fluid pressures:



FSA, t = 2.5 ms	FLSR, t = 2.5 ms	FLSR MCFL 1, t = 2.5 ms

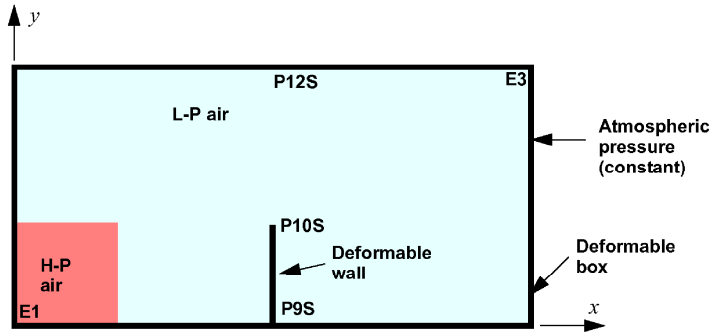


FSA, t = 5.0 ms	FLSR, t = 5.0 ms	FLSR MCFL 1, t = 5.0 ms

The large leakages observed with the standard FLSR model disappear when MCFL 1 is added, and the solution is overall in good agreement with the reference.

Exercise 6ter – Résumé of FSI models

(All available non-conforming techniques)



- Revisit the box problem of Exercise III-10b (**coarse** solutions with **conforming** FSI) and obtain more **accurate** solutions using all the available **non-conforming FSI** techniques:
  - With **FE** (**JRC** formulation) and either **FSA** or **FLSR**
  - With **FE** (**CEA** formulation) and either **FSA** or **FLSR**
  - With **NCFV** and either **FSA** or **FLSR** (see also Exercise IV-12b)
  - With **CCFV** and non-conforming **weak** FSI coupling or **FLSW**

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Problem description:

Revisit the box problem of Exercise III-10b (coarse solutions with conforming FSI) and obtain more accurate solutions using all the available non-conforming FSI techniques:

- With FE (JRC formulation) and either FSA or FLSR
- With FE (CEA formulation) and either FSA or FLSR
- With NCFV and either FSA or FLSR (see also Exercise IV-12b)
- With CCFV and non-conforming weak FSI coupling or FLSW

Numerical Solutions

All obtained solutions are listed in the following Table:

Fluid model / FSI model	FSA or weak (for CCFV)	Embedded: FLSR/FLSW
FE-JRC	ELFIN2	ELFIF2B
FE-CEA	ELCKN2	ELCKF2B
NCFV	VFNCN2S	VFNCF3S
CCFV	VFCCN2_O2	VFCCF2B_O2

ELFIN2

Solution with FE (JRC formulation) and FSA (non conforming). The fluid mesh is made of 3200 quadrilateral elements while the structure is made of 64 shell elements. The mesh generation file is:

```
opti echo 1;
opti titr 'ELFIN2';
opti sauv form 'elfin2.msh';
opti trac psc ftra 'elfin2_mesh.ps';
*
opti dime 2 elem qua4;
*
p1 = 0 0;
p2 = 2 0;
p3 = 2 1;
p4 = 0 1;
p5 = 0.4 0;
p6 = 0.4 0.4;
p7 = 0 0.4;
p8 = 0.4 1;
*
tol = 0.001;
*
c1 = p1 d 16 p5;
c2 = p5 d 16 p6;
c3 = p6 d 16 p7;
c4 = p7 d 16 p1;
expl = dall c1 c2 c3 c4 plan;
*
p9l = 1 0;
p9r = 1 0;
p10 = 1 0.4;
p11 = 2 0.4;
*
c1 = p5 d 24 p9l;
c2 = p9l d 16 p10;
c3 = p10 d 24 p6;
c4 = p6 d 16 p5;
air1a = dall c1 c2 c3 c4 plan;
*
c1 = p9r d 40 p2;
c2 = p2 d 16 p11;
c3 = p11 d 40 p10;
c4 = p10 d 16 p9r;
air1b = dall c1 c2 c3 c4 plan;
*
c1 = p6 d 24 p10 d 40 p11;
c2 = p11 d 24 p3;
c3 = p3 d 64 p8;
c4 = p8 d 24 p6;
air1c = dall c1 c2 c3 c4 plan;
*
elim tol (air1a et air1c);
elim tol (air1b et air1c);
air1 = air1a et air1b et air1c;
*
c1 = p7 d 16 p6;
c2 = p6 d 24 p8;
c3 = p8 d 16 p4;
c4 = p4 d 24 p7;
air2 = dall c1 c2 c3 c4 plan;
elim tol (air1c et air2);
elim tol (expl et air2);
elim tol (expl et air1a);
*
air = air1 et air2;
flui = expl et air;
*
e1 = expl elem cont p1;
e3 = air1 elem cont p3;
*
p1s = p1 plus p1;
p2s = p2 plus p1;
p3s = p3 plus p1;
p4s = p4 plus p1;
p9s = p9l plus p1;
p10s = p10 plus p1;
p12s = 1 1;
c1s = p1s d 10 p9s d 10 p2s;
c2s = p2s d 10 p3s;
c3s = p3s d 10 p12s d 10 p4s;
c4s = p4s d 10 p1s;
c5s = p9s d 4 p10s;
stru = c1s et c2s et c3s et c4s et c5s;
*
nfsa = cont flui;
*
mesh = flui et stru et e1 et e3 et nfsa;
*
sauv form mesh;
trac qual mesh;
*
list (nbel mesh);
list (nbno mesh);
*
fin;
```

The input file is:

```
ELFIN2
ECHO
!conv win
CAST mesh
DPLA ALE
DIME
 NALE 148 NBLE 3065
TERM
GEOM FL24 flui ED01 stru TERM
COMP EPAI 0.01 LECT stru TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
GRIL LAGR LECT stru TERM
     EULE LECT nfsa TERM
     AUTO AUTR
MATE FLUT RO 5.9485 EINT 4.20274E5 GAMM 1.4 PB 0 PREF 1.E5
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT expl TERM
     FLUT RO 1.1897 EINT 2.10137E5 GAMM 1.4 PB 0 PREF 1.E5
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT air TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
LINK COUP FSA NCFS LECT nfsa TERM
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
CALC TINI 0.0 TFIN 5.E-3
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
         face hfro
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
```

```
COUR  1 'dt1'     DT1
COUR  3 'p_e1'    ECRO COMP 1 ELEM LECT e1 TERM
COUR  4 'p_e3'    ECRO COMP 1 ELEM LECT e3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
*
TRAC 1   AXES 1.0 'DELTAT [S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
QUAL ECRO COMP 1 LECT e1 TERM REFE  1.56327E+5 TOLE 5.E-3
     ECRO COMP 1 LECT e3 TERM REFE  2.04496E+5 TOLE 5.E-3
*=================================================================
FIN
```

ELCKN2

Solution with FE (CEA formulation) and FSA (non conforming). The mesh is identical to the previous example. The input file is:

```
ELCKN2
ECHO
!conv win
CAST mesh
DPLA ALE
DIME
 NALE 148 NBLE 3065
TERM
GEOM CAR1 flui ED01 stru TERM
COMP EPAI 0.01 LECT stru TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
GRIL LAGR LECT stru TERM
     EULE LECT nfsa TERM
     AUTO AUTR
MATE GAZP RO 5.9485 GAMMA 1.4 CV 716.75 PINI 1.E6 PREF 1.E5
          LECT expl TERM
     GAZP RO 1.1897 GAMMA 1.4 CV 716.75 PINI 1.E5 PREF 1.E5
          LECT air TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
LINK COUP FSA NCFS LECT nfsa TERM
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
     KFLU 1000
CALC TINI 0.0 TFIN 5.E-3
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dt1'     DT1
COUR  3 'p_e1'    ECRO COMP 1 ELEM LECT e1 TERM
COUR  4 'p_e3'    ECRO COMP 1 ELEM LECT e3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
*
TRAC 1   AXES 1.0 'DELTAT [S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
QUAL ECRO COMP 1 LECT e1 TERM REFE  1.62924E+5 TOLE 5.E-3
     ECRO COMP 1 LECT e3 TERM REFE  2.16846E+5 TOLE 5.E-3
*=================================================================
FIN
```

VFNCN2S

Solution with NCFV (new SYNC 1 time integration strategy) and FSA (non conforming). The mesh is identical to the previous example, except from the presence of an external layer of CLxx elements used to impose the external atmospheric pressure (there is no PREF parameter in the material of NCFV). The input file is:

```
VFNCN2S
ECHO
!conv win
CAST mesh
DPLA ALE
DIME
 NALE 148 NBLE 3065 NDVC 13072
TERM
GEOM MC24 flui ED01 stru CL22 pext TERM
COMP EPAI 0.01 LECT stru TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
          jaun LECT pext TERM
GRIL LAGR LECT stru TERM
     EULE LECT nfsa TERM
     AUTO AUTR
MATE MCGP NCOM 1 R 8.3143E3
          COMP 'Air' PM 29.0 CV1 2.07585E4 CV2 0 CV3 0
          LECT flui TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
     IMPE PIMP RO 1.1897 PRES 1.E5 PREF 0
```

```
          LECT pext TERM
INIT MCOM COMP 'Air' MFRA 1.0 LECT flui TERM
          PRES 1.E6 LECT expl TERM
          PRES 1.E5 LECT air  TERM
          TEMP 586.36 LECT expl TERM
          TEMP 293.16 LECT air  TERM
          VEL1 0.0 LECT flui TERM
          VEL2 0.0 LECT flui TERM
LINK COUP FSA NCFS LECT nfsa TERM
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO MCVA TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p4 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
     MC ORDR 2 NUFL ROE SYNC 1
CALC TINI 0.0 TFIN 5.E-3
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dt1'     DT1
COUR  3 'p_e1'    MCPR COMP 1 NOEU LECT p1 TERM
COUR  4 'p_e3'    MCPR COMP 1 NOEU LECT p3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
COUR 101 'p_p4'    MCPR COMP 1 NOEU LECT p4 TERM
COUR 102 'r_p4'    MCRO COMP 1 NOEU LECT p4 TERM
COUR 103 't_p4'    MCTE COMP 1 NOEU LECT p4 TERM
COUR 104 'yl_p4'   MCMF COMP 1 NOEU LECT p4 TERM
*
TRAC 1   AXES 1.0 'DELTAT [S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
TRAC 101 AXES 1.0 'PRESS. [PA]'
TRAC 102 AXES 1.0 'DENS. [KG/M3]'
TRAC 103 AXES 1.0 'TEMP. [K]'
TRAC 104 AXES 1.0 'FRAC. [-]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
QUAL MCPR COMP 1 LECT p1 TERM REFE  1.56554E+5 TOLE 5.E-3
     MCPR COMP 1 LECT p3 TERM REFE  2.02150E+5 TOLE 5.E-3
*=================================================================
FIN
```

VFCCN2_O2

Solution with CCFV (second-order in space and time) and weak FSI coupling (non conforming). The mesh generation file is:

```
opti echo 1;
opti titr 'VFCCN2_O2';
opti sauv form 'vfccn2_o2.msh';
opti trac psc ftra 'vfccn2_o2_mesh.ps';
*
opti dime 2 elem qua4;
*
p1 = 0 0;
p2 = 2 0;
p3 = 2 1;
p4 = 0 1;
p5 = 0.4 0;
p6 = 0.4 0.4;
p7 = 0 0.4;
p8 = 0.4 1;
*
tol = 0.001;
*
c1 = p1 d 16 p5;
c2 = p5 d 16 p6;
c3 = p6 d 16 p7;
c4 = p7 d 16 p1;
expl = dall c1 c2 c3 c4 plan;
*
c1 = p5 d 64 p2;
c2 = p2 d 40 p3;
c3 = p3 d 64 p8;
c4 = p8 d 24 p6 d 16 p5;
air1 = dall c1 c2 c3 c4 plan;
*
c1 = p7 d 16 p6;
c2 = p6 d 24 p8;
c3 = p8 d 16 p4;
c4 = p4 d 24 p7;
air2 = dall c1 c2 c3 c4 plan;
*
air = air1 et air2;
flui = expl et air;
elim tol flui;
*
p9 = 1 0;
p10 = 1 0.4;
ndia = p9 d 16 p10;
elim tol (ndia et flui);
*
e1 = expl elem cont p1;
e3 = air1 elem cont p3;
*
p1s = p1 plus p1;
p2s = p2 plus p1;
p3s = p3 plus p1;
p4s = p4 plus p1;
p9s = 1 0;
p10s = 1 0.4;
p12s = 1 1;
c1s = p1s d 10 p9s d 10 p2s;
c2s = p2s d 10 p3s;
c3s = p3s d 10 p12s d 10 p4s;
c4s = p4s d 10 p1s;
c5s = p9s d 4 p10s;
stru = c1s et c2s et c3s et c4s et c5s;
*
*elim tol (flui et stru);
elim tol stru;
*
nfsa = cont flui;
nfsa = nfsa et ndia;
*
mesh = flui et stru et e1 et e3 et nfsa;
*
sauv form mesh;
trac qual mesh;
*
list (nbel mesh);
list (nbno mesh);
*
fin;
```

The input file is:

```
VFCCN2_O2
ECHO
!conv win
CAST mesh
```

```
DPLA ALE
DIME
 NALE 154 NBLE 3321
TERM
GEOM Q4VF flui ED01 stru TERM
COMP EPAI 0.01 LECT stru TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
GRIL LAGR LECT stru TERM
     AUTO AUTR
MATE GAZP RO 5.9485 GAMMA 1.4 CV 716.75 PINI 1.E6 PREF 1.E5
          LECT expl TERM
     GAZP RO 1.1897 GAMMA 1.4 CV 716.75 PINI 1.E5 PREF 1.E5
          LECT air TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00666
          LECT stru TERM
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
     VFCC FCON 6    ! Solveur HLLC
          ORDR 2    ! Ordre 2 en espace
          OTPS 2    ! Ordre 2 en temps
          RECO 1    ! Reconstruction de type Green-Gauss
          LMAS 3    ! k-limiteur de Dubois (eq. masse)
          LQDM 3    ! k-limiteur de Dubois (eq. QDM)
          LENE 3    ! k-limiteur de Dubois (eq. energie)
          KMAS 0.75 ! Coefficient de limitation (eq. masse)
          KQDM 0.75 ! Coefficient de limitation (eq. QDM)
          KENE 0.75 ! Coefficient de limitation (eq. energie)
          CRNE      ! Correction de l'energie interne
          NCFS LECT nfsa TERM
CALC TINI 0.0 TFIN 5.E-3
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
SUIT
Post treatment
```

```
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 11 'dt1'     DT1
COUR  1 'vcvi_e1' VCVI NORM ELEM LECT e1 TERM
COUR  2 'vcvi_e3' VCVI NORM ELEM LECT e3 TERM
COUR  3 'p_e1'    ECRO COMP 1 ELEM LECT e1 TERM
COUR  4 'p_e3'    ECRO COMP 1 ELEM LECT e3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
*
TRAC 11  AXES 1.0 'DELTAT [S]'
TRAC 1 2 AXES 1.0 'VELOC. [M/S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
LIST 1 2 AXES 1.0 'VELOC. [M/S]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
! J'ai l'impression che la qualification de VCVi ne marche pas ...
!QUAL VCVI COMP 1 LECT e1 TERM REFE  0.00000E+0 TOLE 5.E-3
!     VCVI COMP 2 LECT e3 TERM REFE  0.00000E+0 TOLE 5.E-3
QUAL ECRO COMP 1 LECT e1 TERM REFE  1.59613E+5 TOLE 5.E-3
     ECRO COMP 1 LECT e3 TERM REFE  2.08017E+5 TOLE 5.E-3
*=================================================================
FIN
```

ELFIF2B

Solution with FE (JRC formulation) and FLSR (embedded structural mesh). The “extended” fluid mesh is made of 5376 quadrilateral elements while the structure is made of 64 shell elements. A layer of 304 elements CLxx is used around the external fluid boundary to specify absorbing conditions. The mesh generation file is:

```
opti echo 1;
opti titr 'ELFIF2B';
opti sauv form 'elfif2b.msh';
opti trac psc ftra 'elfif2b_mesh.ps';
*
opti dime 2 elem qua4;
*
p1 = 0 0;
p2 = 2 0;
p3 = 2 1;
p4 = 0 1;
p5 = 0.4 0;
p6 = 0.4 0.4;
p7 = 0 0.4;
p8 = 0.4 1;
*
pa = -0.2 -0.2;
pb =  2.2 -0.2;
pc =  2.2  1.2;
pd = -0.2  1.2;
*
tol = 0.001;
*
c1 = pa d 96 pb;
c2 = pb d 56 pc;
c3 = pc d 96 pd;
c4 = pd d 56 pa;
flui = dall c1 c2 c3 c4 plan;
elim tol (flui et p1 et p2 et p3 et p4 et p5 et p6 et p7 et p8);
```

```
abso = c1 et c2 et c3 et c4;
*
el1 = flui elem appu larg p1;
el3 = flui elem appu larg p3;
*
p9s = 1 0;
p10s = 1 0.4;
p11s = 2 0.4;
p12s = 1 1;
p1s = p1 plus p1;
p2s = p2 plus p1;
p3s = p3 plus p1;
p4s = p4 plus p1;
c1s = p1s d 10 p9s d 10 p2s;
c2s = p2s d 10 p3s;
c3s = p3s d 10 p12s d 10 p4s;
c4s = p4s d 10 p1s;
c5s = p9s d 4 p10s;
stru = c1s et c2s et c3s et c4s et c5s;
*
mesh = flui et stru et abso et el1 et el3;
*
sauv form mesh;
trac qual mesh;
*
list (nbel mesh);
list (nbno mesh);
*
fin;
```

The input file is:

```
ELFIF2B
ECHO
!conv win
CAST mesh
DPLA ALE
DIME
 NALE 148 NBLE 3065
TERM
GEOM FL24 flui ED01 stru CL22 abso TERM
COMP EPAI 0.01 LECT stru TERM
     GROU 5 'expl' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 0.4 DY 0.4
            'flin' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 2.0 DY 1.0
            'air'  LECT flui TERM COND COMP LECT expl TERM
            'e1'   LECT flin INTR el1 TERM
            'e3'   LECT flin INTR el3 TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
          jaun LECT abso TERM
GRIL LAGR LECT stru TERM
MATE FLUT RO 5.9485 EINT 4.20274E5 GAMM 1.4 PB 0 PREF 1.E5
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT expl TERM
     FLUT RO 1.1897 EINT 2.10137E5 GAMM 1.4 PB 0 PREF 1.E5
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1
          LECT air TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
     IMPE ABSI LECT abso TERM
LINK COUP FLSR STRU LECT stru TERM
               FLUI LECT flui TERM
               R    0.018
               HGRI 0.110
               DGRI
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
CALC TINI 0.0 TFIN 5.E-3
*=====================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=====================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=====================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=====================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=====================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=====================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=====================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=====================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dt1'     DT1
COUR  3 'p_e1'    ECRO COMP 1 ELEM LECT e1 TERM
COUR  4 'p_e3'    ECRO COMP 1 ELEM LECT e3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
*
TRAC 1   AXES 1.0 'DELTAT [S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
!QUAL ECRO COMP 1 LECT e1 TERM REFE  1.56327E+5 TOLE 5.E-3
!     ECRO COMP 1 LECT e3 TERM REFE  2.04496E+5 TOLE 5.E-3
*=====================================================================
FIN
```

ELCKF2B

Solution with FE (CEA formulation) and FLSR (embedded structural mesh). The mesh is identical to the previous example. The input file is:

```
ELCKF2B
ECHO
!conv win
CAST mesh
DPLA ALE
DIME
 NALE 148 NBLE 3065
TERM
GEOM CAR1 flui ED01 stru CL22 abso TERM
COMP EPAI 0.01 LECT stru TERM
     GROU 5 'expl' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 0.4 DY 0.4
            'flin' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 2.0 DY 1.0
            'air'  LECT flui TERM COND COMP LECT expl TERM
            'e1'   LECT flin INTR el1 TERM
            'e3'   LECT flin INTR el3 TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
          jaun LECT abso TERM
GRIL LAGR LECT stru TERM
MATE GAZP RO 5.9485 GAMMA 1.4 CV 716.75 PINI 1.E6 PREF 1.E5
          LECT expl TERM
     GAZP RO 1.1897 GAMMA 1.4 CV 716.75 PINI 1.E5 PREF 1.E5
          LECT air TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
     IMPE ABSI LECT abso TERM
LINK COUP FLSR STRU LECT stru TERM
               FLUI LECT flui TERM
               R    0.018
               HGRI 0.110
               DGRI
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
     KFLU 1000
CALC TINI 0.0 TFIN 5.E-3
*=====================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=====================================================================
SUIT
Post treatment
```

```
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*===============================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*===============================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*===============================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
```

```
*===============================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*===============================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*===============================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dt1'     DT1
COUR  3 'p_e1'    ECRO COMP 1 ELEM LECT e1 TERM
COUR  4 'p_e3'    ECRO COMP 1 ELEM LECT e3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
*
TRAC 1   AXES 1.0 'DELTAT [S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
!QUAL ECRO COMP 1 LECT e1 TERM REFE  1.56327E+5 TOLE 5.E-3
!     ECRO COMP 1 LECT e3 TERM REFE  2.04496E+5 TOLE 5.E-3
*===============================================================
FIN
```

VFNCF3S

Solution with NCFV and FLSR (embedded structural mesh). The mesh is identical to the previous example. The input file is:

```
VFNCF3S
ECHO
 conv win
CAST mesh
DPLA ALE
DIME
 NALE 148 NBLE 3065 NDVC 21808
TERM
GEOM MC24 flui ED01 stru CL22 abso TERM
COMP EPAI 0.01 LECT stru TERM
     GROU 3 'expl' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 0.4 DY 0.4
            'flin' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 2.0 DY 1.0
            'air'  LECT flui TERM COND COMP LECT expl TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
          jaun LECT abso TERM
GRIL LAGR LECT stru TERM
MATE MCGP NCOM 1 R 8.3143E3
          COMP 'Air' PM 29.0 CV1 2.07585E4 CV2 0 CV3 0
          LECT flui TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
     MCFF BDFO 1 TEMP 293.16 PRES 1.E5
          VEL1 0. VEL2 0.
          COMP 'Air'       MFRA 1.
          LECT abso TERM
INIT MCOM COMP 'Air' MFRA 1.0 LECT flui TERM
          PRES 1.E6 LECT expl TERM
          PRES 1.E5 LECT air  TERM
          TEMP 586.36 LECT expl TERM
          TEMP 293.16 LECT air  TERM
          VEL1 0.0 LECT flui TERM
          VEL2 0.0 LECT flui TERM
LINK COUP FLSR STRU LECT stru TERM
               FLUI LECT flui TERM
               R    0.036 ! = gamma*delta*h_fluide = 1.01*1.41*0.025
!fc            R    0.018 ! = gamma*delta*h_fluide = 1.01*1.41*0.025
                          !   [delta = sqrt(2) en 2D, = sqrt(3) en 3D]
               HGRI 0.110
               DGRI
               MCFL 1 MCCP 1
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO
     MCVC MCVS MCFL MCEF MCMU MCVM TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p4 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
OPTI NOTE LOG 1
     CSTA 0.5
     MC ORDR 2 NUFL ROE SYNC 1
CALC TINI 0.0 TFIN 5.E-3
*===============================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*===============================================================
SUIT
```

```
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*===============================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*===============================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*===============================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vite scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*===============================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*===============================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  5.03115E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
```

```
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel mcpr scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dt1'     DT1
COUR  3 'p_e1'    MCPR COMP 1 NOEU LECT p1 TERM
COUR  4 'p_e3'    MCPR COMP 1 NOEU LECT p3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
COUR 101 'p_p4'    MCPR COMP 1 NOEU LECT p4 TERM
COUR 102 'r_p4'    MCRO COMP 1 NOEU LECT p4 TERM
COUR 103 't_p4'    MCTE COMP 1 NOEU LECT p4 TERM
COUR 104 'yl_p4'   MCMF COMP 1 NOEU LECT p4 TERM
*
TRAC 1   AXES 1.0 'DELTAT [S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
TRAC 101 AXES 1.0 'PRESS. [PA]'
TRAC 102 AXES 1.0 'DENS. [KG/M3]'
TRAC 103 AXES 1.0 'TEMP. [K]'
TRAC 104 AXES 1.0 'FRAC. [-]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
QUAL MCPR COMP 1 LECT p1 TERM REFE  1.00000E+5 TOLE 5.E-3
     MCPR COMP 1 LECT p3 TERM REFE  1.00000E+5 TOLE 5.E-3
*=================================================================
FIN
```

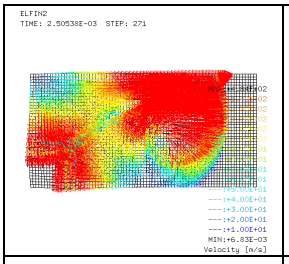
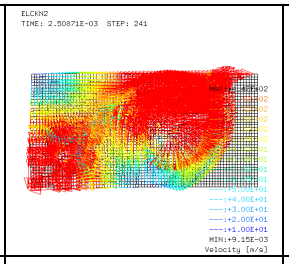
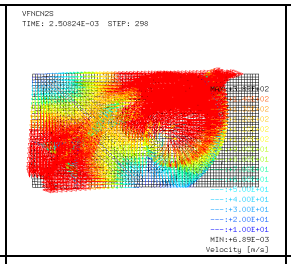
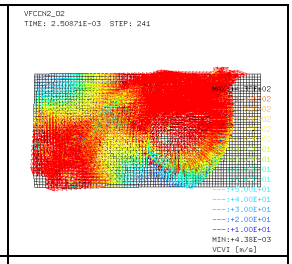
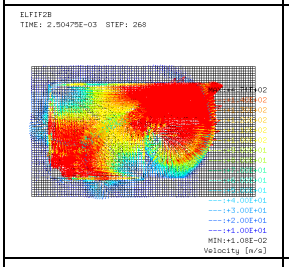
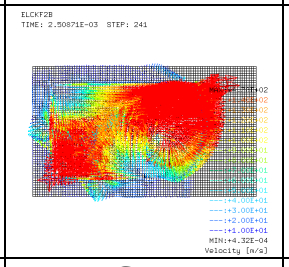
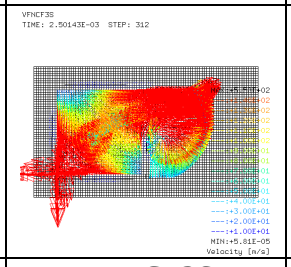
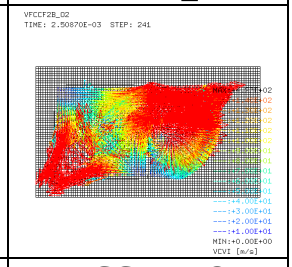
VFCCF2B_O2

Solution with CCFV and FLSW (embedded structural mesh, weak formulation). The mesh is identical to the previous example. The input file is:

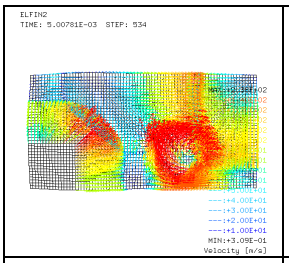
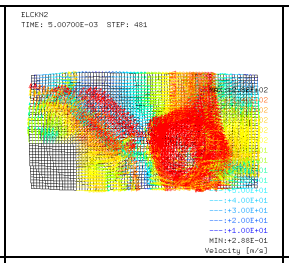
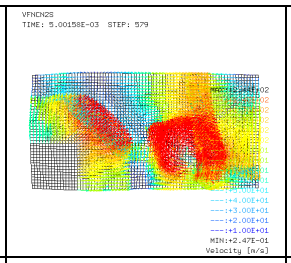
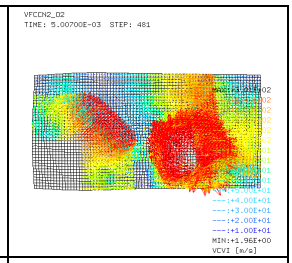
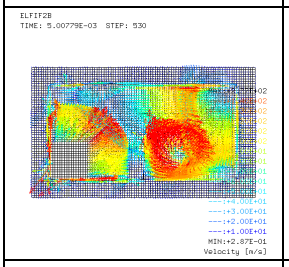
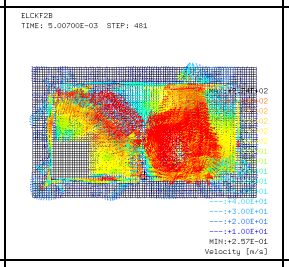
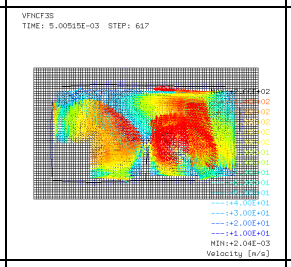
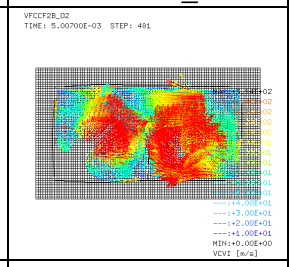
```
VFCCF2B_O2
ECHO
!conv win
CAST mesh
DPLA ALE
DIME
 NALE 148 NBLE 3065
TERM
GEOM Q4VF flui ED01 stru CL22 abso TERM
COMP EPAI 0.01 LECT stru TERM
     GROU 5 'expl' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 0.4 DY 0.4
            'flin' LECT flui TERM COND BOX X0 0.0 Y0 0.0 DX 2.0 DY 1.0
            'air'  LECT flui TERM COND COMP LECT expl TERM
            'e1'   LECT flin INTR el1 TERM
            'e3'   LECT flin INTR el3 TERM
     COUL turq LECT air  TERM
          roug LECT expl TERM
          bleu LECT stru TERM
          jaun LECT abso TERM
GRIL LAGR LECT stru TERM
MATE GAZP RO 5.9485 GAMMA 1.4 CV 716.75 PINI 1.E6 PREF 1.E5
          LECT expl TERM
     GAZP RO 1.1897 GAMMA 1.4 CV 716.75 PINI 1.E5 PREF 1.E5
          LECT air TERM
     VM23 RO 7800. YOUNG 1.6E11 NU 0.333 ELAS 1.05E8
          TRAC 2 1.05E8 .656256E-3 1.6105E10 1.00066
          LECT stru TERM
     IMPE ABSI LECT abso TERM
LINK DECO FLSW STRU LECT stru TERM
               FLUI LECT flui TERM
               R    0.018
               HGRI 0.110
               DGRI
               BFLU 2 FSCP 1
ECRI DEPL VITE ACCE FINT FEXT CONT ECRO TFRE 1.E-3
          POIN LECT p1 p5 p6 p7 p3 TERM
          ELEM LECT e1 e3 TERM
     FICH ALIC TFRE 5.E-5
     FICH ALIC TEMP FREQ 1
          POIN LECT p1 p5 p6 p7 p3 p1s p2s p3s p4s p9s p10s p12s TERM
          ELEM LECT e1 e3 TERM
OPTI NOTE LOG 1
     CSTA 0.5
     VFCC FCON 6    ! Solveur HLLC
          ORDR 2    ! Ordre 2 en espace
          OTPS 2    ! Ordre 2 en temps
          RECO 1    ! Reconstruction de type Green-Gauss
          LMAS 3    ! k-limiteur de Dubois (eq. masse)
          LQDM 3    ! k-limiteur de Dubois (eq. QDM)
          LENE 3    ! k-limiteur de Dubois (eq. energie)
          KMAS 0.75 ! Coefficient de limitation (eq. masse)
          KQDM 0.75 ! Coefficient de limitation (eq. QDM)
          KENE 0.75 ! Coefficient de limitation (eq. energie)
          CENE      ! Correction de l'energie interne
CALC TINI 0.0 TFIN 5.E-3
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
          face hfro
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT air  TERM
     text vsca
     colo pape
freq 0 tfre 2.5e-3
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
trac offs fich avi     nocl nfto 101 fps 10 kfre 10 comp -1 rend
freq 1
gotr loop 99 offs fich avi cont nocl rend
go
trac offs fich avi cont rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     vect scco fiel vcvi scal user prog 10 pas 10 140 term
          SUPP LECT flui TERM
     text vsca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post treatment
ECHO
 conv win
RESU ALIC GARD PSCR
OPTI PRIN
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE   1.00000E+00  5.00000E-01  6.11268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
sler cam1 1 nfra 1
scen geom navi free
     iso  fili fiel ecro 1 scal user prog 0.61E5 pas 0.2E5 3.21E5 term
          SUPP LECT flui TERM
     text isca
     colo pape
freq 50
go
trac offs fich bmp rend
go
trac offs fich bmp rend
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 11 'dt1'     DT1
COUR  1 'vcvi_e1' VCVI NORM ELEM LECT e1 TERM
COUR  2 'vcvi_e3' VCVI NORM ELEM LECT e3 TERM
COUR  3 'p_e1'    ECRO COMP 1 ELEM LECT e1 TERM
COUR  4 'p_e3'    ECRO COMP 1 ELEM LECT e3 TERM
COUR  5 'dx_p10s' DEPL COMP 1 POIN LECT p10s TERM
COUR  6 'dy_p12s' DEPL COMP 2 POIN LECT p12s TERM
COUR  7 'dx_p9s'  DEPL COMP 1 POIN LECT p9s TERM
COUR  8 'dy_p9s'  DEPL COMP 2 POIN LECT p9s TERM
TRAC 11  AXES 1.0 'DELTAT [S]'
TRAC 1 2 AXES 1.0 'VELOC. [M/S]'
TRAC 3 4 AXES 1.0 'PRESS [PA]'
TRAC 5 6 AXES 1.0 'DISPL. [M]'
TRAC 7 8 AXES 1.0 'DISPL. [M]'
LIST 1 2 AXES 1.0 'VELOC. [M/S]'
LIST 3 4 AXES 1.0 'PRESS [PA]'
LIST 5 6 AXES 1.0 'DISPL. [M]'
LIST 7 8 AXES 1.0 'DISPL. [M]'
*
!QUAL ECRO COMP 1 LECT e1 TERM REFE  1.56327E+5 TOLE 5.E-3
!     ECRO COMP 1 LECT e3 TERM REFE  2.04496E+5 TOLE 5.E-3
*=================================================================
FIN
```

Comparison of solutions

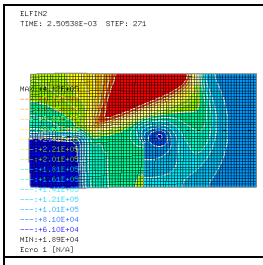
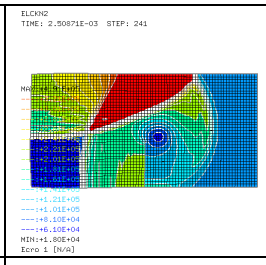
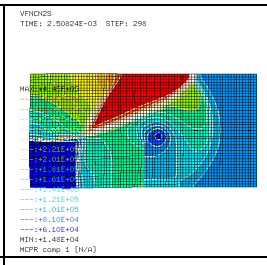
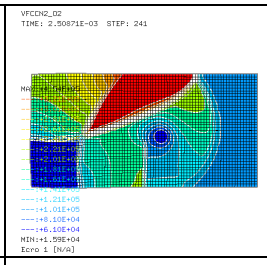
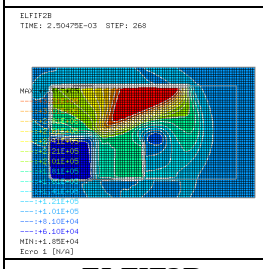
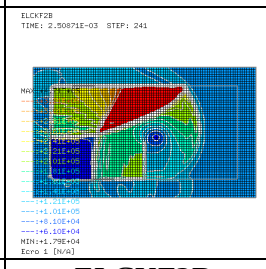
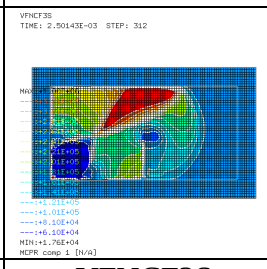
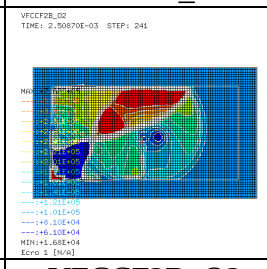
The fluid velocity fields at 2.5 ms in the various solutions are:

			
ELFIN2	ELCKN2	VFNCN2S	VFCCN2_O2
			
ELFIF2B	ELCKF2B	VFNCF3S	VFCCF2B_O2

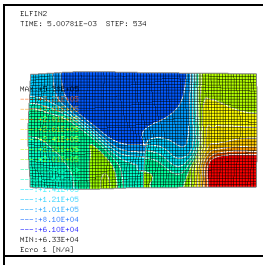
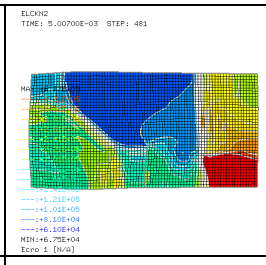
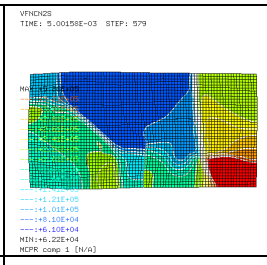
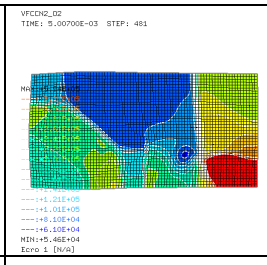
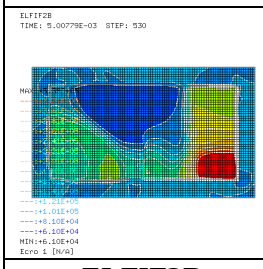
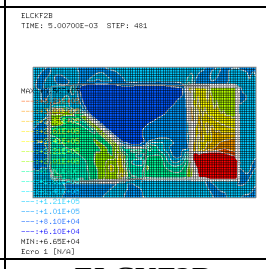
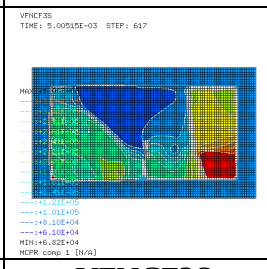
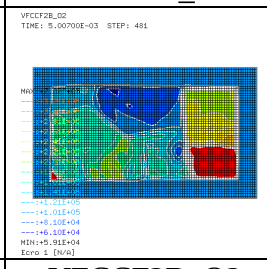
The fluid velocity fields at 5.0 ms in the various solutions are:

			
ELFIN2	ELCKN2	VFNCN2S	VFCCN2_O2
			
ELFIF2B	ELCKF2B	VFNCF3S	VFCCF2B_O2

The fluid pressure fields at 2.5 ms in the various solutions are:

			
ELFIN2	ELCKN2	VFNCN2S	VFCCN2_O2
			
ELFIF2B	ELCKF2B	VFNCF3S	VFCCF2B_O2

The fluid pressure fields at 5.0 ms in the various solutions are:

			
ELFIN2	ELCKN2	VFNCN2S	VFCCN2_O2
			
ELFIF2B	ELCKF2B	VFNCF3S	VFCCF2B_O2

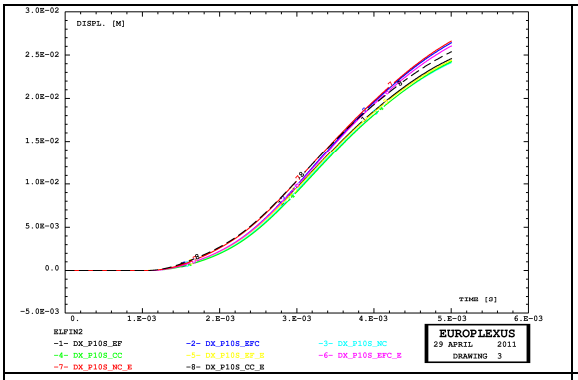
Comparison of structural displacements

EFVFC1

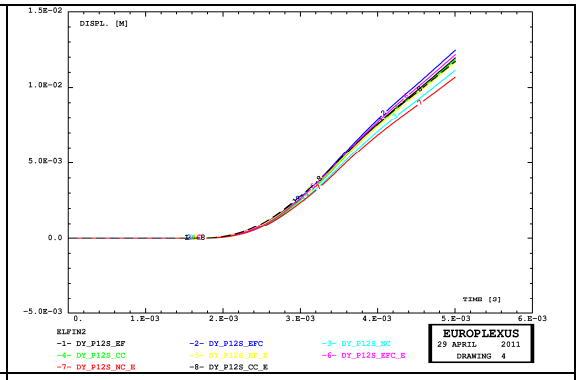
This input is used to compare the different solutions:

```
EFVFC1
ECHO
*
RESU ALIC TEMP 'elfin2.alt' GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 13 'p_e1_ef'    ECRO COMP 1 ELEM LECT e1 TERM
COUR 14 'p_e3_ef'    ECRO COMP 1 ELEM LECT e3 TERM
COUR 15 'dx_p10s_ef' DEPL COMP 1 POIN LECT p10s TERM
COUR 16 'dy_p12s_ef' DEPL COMP 2 POIN LECT p12s TERM
COUR 17 'dx_p9s_ef'  DEPL COMP 1 POIN LECT p9s TERM
COUR 18 'dy_p9s_ef'  DEPL COMP 2 POIN LECT p9s TERM
*
RCOU 23 'p_e1'    FICH 'elckn2.pun' RENA 'p_e1_efc'
RCOU 24 'p_e3'    FICH 'elckn2.pun' RENA 'p_e3_efc'
RCOU 25 'dx_p10s' FICH 'elckn2.pun' RENA 'dx_p10s_efc'
RCOU 26 'dy_p12s' FICH 'elckn2.pun' RENA 'dy_p12s_efc'
RCOU 27 'dx_p9s'  FICH 'elckn2.pun' RENA 'dx_p9s_efc'
RCOU 28 'dy_p9s'  FICH 'elckn2.pun' RENA 'dy_p9s_efc'
*
RCOU 33 'p_e1'    FICH 'vfncn2s.pun' RENA 'p_e1_nc'
RCOU 34 'p_e3'    FICH 'vfncn2s.pun' RENA 'p_e3_nc'
RCOU 35 'dx_p10s' FICH 'vfncn2s.pun' RENA 'dx_p10s_nc'
RCOU 36 'dy_p12s' FICH 'vfncn2s.pun' RENA 'dy_p12s_nc'
RCOU 37 'dx_p9s'  FICH 'vfncn2s.pun' RENA 'dx_p9s_nc'
RCOU 38 'dy_p9s'  FICH 'vfncn2s.pun' RENA 'dy_p9s_nc'
*
RCOU 43 'p_e1'    FICH 'vfccn2_o2.pun' RENA 'p_e1_cc'
RCOU 44 'p_e3'    FICH 'vfccn2_o2.pun' RENA 'p_e3_cc'
RCOU 45 'dx_p10s' FICH 'vfccn2_o2.pun' RENA 'dx_p10s_cc'
RCOU 46 'dy_p12s' FICH 'vfccn2_o2.pun' RENA 'dy_p12s_cc'
RCOU 47 'dx_p9s'  FICH 'vfccn2_o2.pun' RENA 'dx_p9s_cc'
RCOU 48 'dy_p9s'  FICH 'vfccn2_o2.pun' RENA 'dy_p9s_cc'
*
RCOU 53 'p_e1'    FICH 'elfif2b.pun' RENA 'p_e1_ef_e'
RCOU 54 'p_e3'    FICH 'elfif2b.pun' RENA 'p_e3_ef_e'
RCOU 55 'dx_p10s' FICH 'elfif2b.pun' RENA 'dx_p10s_ef_e'
RCOU 56 'dy_p12s' FICH 'elfif2b.pun' RENA 'dy_p12s_ef_e'
RCOU 57 'dx_p9s'  FICH 'elfif2b.pun' RENA 'dx_p9s_ef_e'
RCOU 58 'dy_p9s'  FICH 'elfif2b.pun' RENA 'dy_p9s_ef_e'
*
RCOU 63 'p_e1'    FICH 'elckf2b.pun' RENA 'p_e1_efc_e'
RCOU 64 'p_e3'    FICH 'elckf2b.pun' RENA 'p_e3_efc_e'
RCOU 65 'dx_p10s' FICH 'elckf2b.pun' RENA 'dx_p10s_efc_e'
RCOU 66 'dy_p12s' FICH 'elckf2b.pun' RENA 'dy_p12s_efc_e'
RCOU 67 'dx_p9s'  FICH 'elckf2b.pun' RENA 'dx_p9s_efc_e'
RCOU 68 'dy_p9s'  FICH 'elckf2b.pun' RENA 'dy_p9s_efc_e'
*
RCOU 73 'p_e1'    FICH 'vfncf3s.pun' RENA 'p_e1_nc_e'
RCOU 74 'p_e3'    FICH 'vfncf3s.pun' RENA 'p_e3_nc_e'
RCOU 75 'dx_p10s' FICH 'vfncf3s.pun' RENA 'dx_p10s_nc_e'
RCOU 76 'dy_p12s' FICH 'vfncf3s.pun' RENA 'dy_p12s_nc_e'
RCOU 77 'dx_p9s'  FICH 'vfncf3s.pun' RENA 'dx_p9s_nc_e'
RCOU 78 'dy_p9s'  FICH 'vfncf3s.pun' RENA 'dy_p9s_nc_e'
*
RCOU 83 'p_e1'    FICH 'vfccf2b_o2.pun' RENA 'p_e1_cc_e'
RCOU 84 'p_e3'    FICH 'vfccf2b_o2.pun' RENA 'p_e3_cc_e'
RCOU 85 'dx_p10s' FICH 'vfccf2b_o2.pun' RENA 'dx_p10s_cc_e'
RCOU 86 'dy_p12s' FICH 'vfccf2b_o2.pun' RENA 'dy_p12s_cc_e'
RCOU 87 'dx_p9s'  FICH 'vfccf2b_o2.pun' RENA 'dx_p9s_cc_e'
RCOU 88 'dy_p9s'  FICH 'vfccf2b_o2.pun' RENA 'dy_p9s_cc_e'
*
TRAC 13 23 33 43 53 63 73 83 AXES 1.0 'PRESS [PA]'
     COLO noir bleu turq vert jaun rose roug noir
     DASH 0    0    0    0    0    0    0    1
TRAC 14 24 34 44 54 64 74 84 AXES 1.0 'PRESS [PA]'
     COLO noir bleu turq vert jaun rose roug noir
     DASH 0    0    0    0    0    0    0    1
TRAC 15 25 35 45 55 65 75 85 AXES 1.0 'DISPL. [M]'
     COLO noir bleu turq vert jaun rose roug noir
     DASH 0    0    0    0    0    0    0    1
TRAC 16 26 36 46 56 66 76 86 AXES 1.0 'DISPL. [M]'
     COLO noir bleu turq vert jaun rose roug noir
     DASH 0    0    0    0    0    0    0    1
TRAC 17 27 37 47 57 67 77 87 AXES 1.0 'DISPL. [M]'
     COLO noir bleu turq vert jaun rose roug noir
     DASH 0    0    0    0    0    0    0    1
TRAC 18 28 38 48 58 68 78 88 AXES 1.0 'DISPL. [M]'
     COLO noir bleu turq vert jaun rose roug noir
     DASH 0    0    0    0    0    0    0    1
*=============================================================
FIN
```

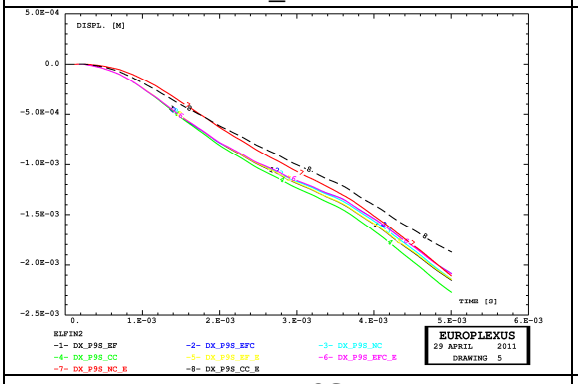
The structural displacements at the various points indicated in the problem definition figure are (all 8 solutions are shown together):



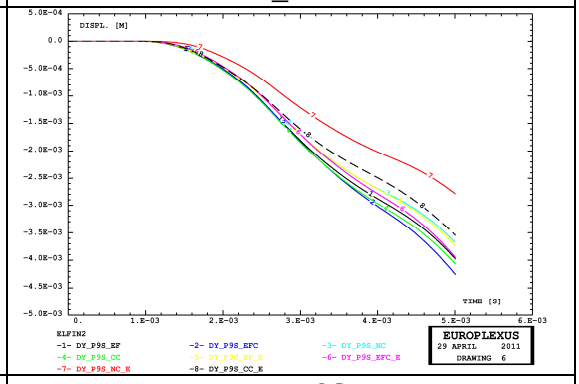
DX_P10S



DY_P12S



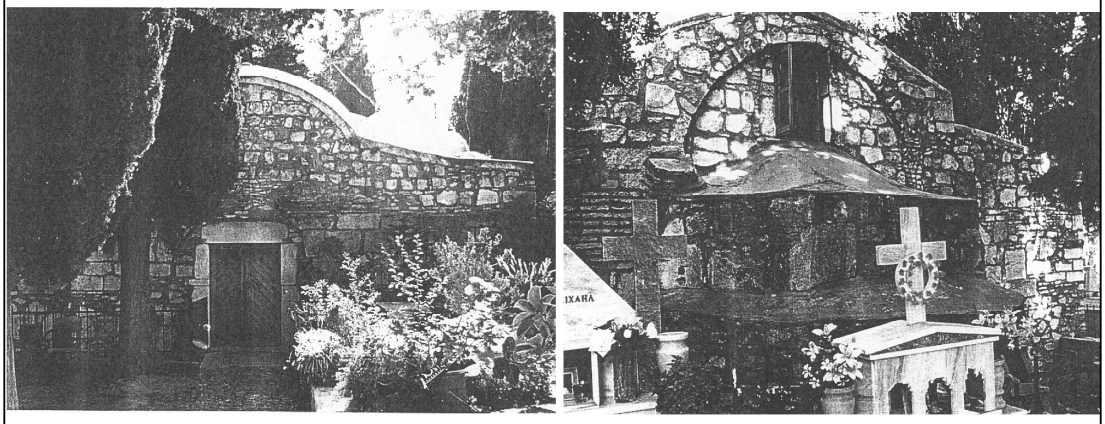
DX_P9S



DY_P9S

Exercise/Example 13 – Building Vulnerability

• Internal blast in a (deformable) building:



Front View *Back View*

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PROBLEM:
A deformable building (an ancient Greek baptistery in the island of Kos) undergoes an internal explosion. This particular building has nothing to do with explosions in reality, but has been chosen because a detailed numerical model of the building was available from previous seismic studies.
MESH:
The fluid (both internal and external to the building) is meshed by 72748 FL34 tetrahedral elements, the deformable structure by 6894 TETR elements and by 5378 PRIS elements. The calculation is 3D (TRID) and is declared of the ALE type. An absorbing boundary made of 5214 CL3I elements is placed along the outer envelope of the fluid mesh to simulate an infinite atmosphere.
MATERIALS:
Both the air and the initially solid TNT charge are modelled by the FLUT JWLS material (perfect gas and Jones-Wilkins-Lee model), the structure uses a linear elastic material (VM23). The absorbing boundary elements have the IMPE ABSI material.
BOUNDARY CONDITIONS:
The structure is clamped at the base. FSA and FSR fluid-structure interaction is used along the fluid-structure interface as appropriate.
LOADING:
Gravity loading in the vertical direction is imposed on the whole model.
OPTIONS:
The QUAS STAT option is used to introduce an initial dynamic relaxation phase which allows to take into account approximately the static stresses generated in the structure by the gravity. This phase goes from t = -20 ms to t = 0. Then follows the explosion and the usual transient calculation, until the final time t = 50 ms.
CALCULATIONS:

Preliminary calculations involving only the structure are used to estimate the system's frequency under static loading (gravity). Then follows the real calculation as described in the previous point.
RESULTS:
The initial oscillations are effectively damped out by the quasi-static option.
POST-TREATMENT
Animations are produced.

Numerical Solutions

KOOS21

The Cast3m mesh generation file reads:

```
* The Kws Baptistery:
* tota0: 3D mesh of the structure (qua8, pri6, pyr5, tet4)
* etota0: 2D mesh of the external face including holes (qua4, tri3)
* itota0: 2D mesh of the internal face including holes (qua4, tri3)
* btota0: 2D mesh of the base (qua4, tri3)
* ttota0: 2D mesh of both faces and base without holes (qua4, tri3)
* eair0: 3D mesh of the external space (tet4)
* iair0: 3D mesh of the internal space (tet4)
* tair0: 3D mesh of both spaces (tet4)
* Axe x -> South
* Axe y -> East
* Axe z -> Up
*
ele1 = cub8;
ele1 = tet4;
ele2 = tet4;
opti echo 1 dime 3 elem ele1;
l0 = 0.25;
l0 = 0.50;
dens l0;
eps0 = 1.d-6;
*
*Dimensions
*Internal radius of the central dome
r1 = 3.35;
*External radius of the central dome
r2 = 3.70;
*Position of the dome centre (with respect to the cone apex)
dh0 = 0.35;
*Height of the cone apex
h1 = 3.75;
*Half angle of the external cones
f0 = 45./2.;
*Half angle of the internal cones
g0 = (45.-8.)/2.;
*External radius of the first ring
r4 = 3.90;
*Internal radius of the secong ring
r5 = 5.00;
*External radius of the second ring (or external half side)
r6 = 5.75;
*Internal radius of the lateral domes
r7 = 1.50;
*Height of the lateral domes base
h7 = h1-r7;
*Internal radius of the choir dome
r8 = r7;
*Height of the choir dome base
h8 = 2.65;
h8 = 2.75;
*Thickness of the choir wall
dr8 = 0.60;
*Height of the chapiteau
dh1 = 0.30;
*Height of the scale
he0 = 0.75;
*Height of the front door
hd0 = 2.25;
*Width of the front door
wd0 = 1.60;
*Angle of the infill on the big cone
ai0 = 22.5;
*Thickness of the infill at the corner
ti0 = 0.50;
*
*Useful quantities
c45 = cos 45.;
ca0 = cos ai0;
sa0 = sin ai0;
cf0 = cos f0;
sf0 = sin f0;
tf0 = sf0/cf0;
cg0 = cos g0;
sg0 = sin g0;
tg0 = sg0/cg0;
*Internal radius of the first ring
r3 = (((r1*r1)-(dh0*dh0*cf0*cf0))**0.5 + (dh0*sf0))*cf0;
*External height of the first ring
h2 = ((r2*r2)-(r3*r3))**0.5 + dh0 + h1;
*Intersection sphere r7 / cylindre r5 -> point p2
k0 = ((2.*r5*r5)-(r7*r7))*c45/r5;
r0 = ((2.*r5*r5)-(k0*k0))**0.5;
*External radius of the choir dome
r9 = (((h1-h8)*(h1-h8))+(r8*r8))**0.5;
*Half width of the choir window (~square window)
ww0 = (r6*tg0)+h1-(h8+(((r9*r9)-(r6*r6*(1.-cf0)*(1.-cf0)))**0.5))/2.;
*Mean radius (where the density will be l0)
rm0 = (r3+r6)/2.;
*
*Definitions of points
*Axes
o0 = 0. 0. 0.;
x0 = 1. 0. 0.;
y0 = 0. 1. 0.;
z0 = 0. 0. 1.;
*
*Group u: points of the cones at distance rm0
u0 = rm0 (rm0*tf0) h1;
u1 = rm0 (rm0*tg0) h1;
u2 = rm0 0.  h1;
u3 = rm0 0. (rm0*tg0+h1);
u4 = rm0 0. (rm0*tf0+h1);
u5 = rm0 (rm0*tf0*ca0) (rm0*tf0*sa0+h1);
u6 = (rm0*c45*(1.+(tf0*ca0))) (rm0*c45*(1.-(tf0*ca0))) (rm0*tf0*sa0+h1);
u7 = (rm0*c45) (rm0*c45) (rm0*tf0+h1);
u8 = (rm0*c45) (rm0*c45) (rm0*tg0+h1);
u9 = (rm0*c45) (rm0*c45) h1;
u10= (rm0*c45*(1.+tg0)) (rm0*c45*(1.-tg0)) h1;
u11= (rm0*c45*(1.+(tg0*ca0))) (rm0*c45*(1.-(tg0*ca0))) (rm0*tg0*sa0+h1);
u12= (rm0*c45) (rm0*c45) (ti0*rm0*c45/r6+h1);
u13= rm0 (ww0*rm0*tf0/r6/tg0) ((1.-(ww0/r6/tg0**2))**0.5*rm0*tf0+h1);
*Group t: points of dome and top of first ring
zt0 = h1+dh0;
t0 = 0. 0. zt0;
t1 = (r3*r1/r2) 0. ((h2-zt0)*r1/r2 + zt0);
t2 = 0. 0. (zt0+r1);
t3 = (r3*c45*r1/r2) (r3*c45*r1/r2) ((h2-zt0)*r1/r2 + zt0);
t4 = r3 0. h2;
t6 = (r3*c45) (r3*c45) h2;
t7 = r4 0. h2;
t8 = (r4*c45) (r4*c45) h2;
*Group a: points of the internal first ring (r3)
a0 = 0. 0. h1;
a1 = (r3*cg0) (r3*sg0) h1;
a4 = r3 0. (r3*tf0+h1);
a7 = (r3*c45) (r3*c45) (r3*tf0+h1);
*Group b: points of the external first ring (r4)
b4 = r4 0. (r4*tf0+h1);
b7 = (r4*c45) (r4*c45) (r4*tf0+h1);
*Group c: points of the internal second ring (r5)
c1 = (r5*cg0) (r5*sg0) h1;
c9 = (r5*c45) (r5*c45) h1;
c10= (r5*c45*(cg0+sg0)) (r5*c45*(cg0-sg0)) h1;
*Group d: points of the external second ring (r6)
d0 = (r6*cf0) (r6*sf0) h1;
d1 = (r6*cf0) (r6*cf0*tg0) h1;
d2 = (r6*cf0) 0. h1;
d9 = (r6*c45) (r6*c45) h1;
*Group e: points of the external side (r6)
e0 = r6 (r6*tf0) h1;
e1 = r6 (r6*tg0) h1;
e9 = r6 r6 h1;
e10= r6 (r6*(cg0-sg0)/(cg0+sg0)) h1;
e12= r6 r6 (ti0+h1);
e13= r6 ww0 (((r6*r6*tg0*tg0)-(ww0*ww0))**0.5+h1);
*Group q: points at level (h1-dh1)
zq0 = h1-dh1;
q0 = 0. 0. zq0;
q1 = (r5*cg0) (r5*sg0) zq0;
q2 = (r5*c45*(cg0+sg0)) (r5*c45*(cg0-sg0)) zq0;
q7 = r6 (r6*tg0) zq0;
q8 = (r6*cf0) (r6*cf0*tg0) zq0;
*Group p: points at level (h1-r7)
zp0 = h1-r7;
p0 = 0. 0. zp0;
p1 = (r5*cg0) (r5*sg0) zp0;
p2 = ((k0+r0)/2.) ((k0-r0)/2.) zp0;
p3 = (r5*c45) (r5*c45) zp0;
p4 = ((r5+r7)*c45) ((r5+r7)*c45) zp0;
p5 = r6 r6 zp0;
p7 = r6 (r6*tg0) zp0;
*Group i,j,k relative to the choir
i0 = 0. 0. h8;
i1 = (r6*cf0) 0. h8;
i2 = (r6*cf0) 0. (h8+r8);
i3 = ((r6*cf0)+(r8*r8/r9)) 0. (((h1-h8)*r8/r9)+h8);
i5 = ((r6*cf0)+r8) 0. h8;
i6 = (r6*cf0) r8 h8;
i7 = r6 (r6*tg0) h8;
j1 = r6 0. h8;
j3 = ((r6*cf0)+r8) 0. h1;
j6 = (r6*cf0) (r6*cf0*tg0) h8;
j7 = r6 0.  (((r9*r9)-(r6*r6*(1.-cf0)*(1.-cf0)))**0.5+h8);
j78= r6 ww0 (((r9*r9)-(r6*r6*(1.-cf0)*(1.-cf0))-(ww0*ww0))**0.5+h8);
j8 = r6 (((r8*r8)-(r6*r6*(1.-cf0)*(1.-cf0)))**0.5) h1;
k3 = ((r6*cf0)+r8+dr8) 0. h1;
k4 = ((r6*cf0)+r8+dr8) (r6*tg0/2.) h1;
k5 = ((r6*cf0)+r8+dr8) 0. h8;
*Group w relative to the opening
*Front door
w0 = r6 0. 0.;
w1 = r6 0. he0;
w2 = r6 (wd0/2.) he0;
w3 = r6 (wd0/2.) (hd0+he0);
w4 = r6 0. (hd0+he0);
w7 = r6 (r6*tg0) 0.;
*Number of elements generated between two homeomorphic lines/surfaces
*Within the cone thickness
nn0 = 1+(enti (tf0-tg0*rm0/10));
*Within the first ring
nn1 = 1+(enti (r4-r3/10));
*Between the first and second ring
nn2 = 1+(enti (r5-r4/10));
*Within the second ring
nn3 = 1+(enti (r6-r5/10));
*Within the choir wall thicness
nn4 = 1+(enti (r6/cf0-r6/10));
*within the choir dome thickness
nn5 = 1+(enti (r9-r8/10));
*
*Reference lines
u0u1 = d u0 u1 dini l0 dfin l0;
u1u2 = d u1 u2 dini l0 dfin l0;
u2u3 = d u2 u3 dini l0 dfin l0;
u0u5 = cerc u0 u2 u5 dini l0 dfin l0;
u5u13= cerc u5 u2 u13 dini l0 dfin l0;
u13u4= cerc u13 u2 u4 dini l0 dfin l0;
u5u4 = u5u13 et u13u4;
u0u4 = u0u5 et u5u4;
u1u13= (u0u5 et u5u13) homo (tg0/tf0) u2;
u13u3= u13u4 homo (tg0/tf0) u2;
u1u3 = u0u4 homo (tg0/tf0) u2;
u3u4 = d u3 u4 dini l0 dfin l0;
u5u6 = d u5 u6 dini l0 dfin l0;
u6u7 = cerc u6 u9 u7 dini l0 dfin l0;
u11u8= u6u7 homo (tg0/tf0) u9;
u8u7 = d u8 u7 dini l0 dfin l0;
u12u8= d u12 u8 dini l0 dfin l0;
u9u12= d u9 u12 dini l0 dfin l0;
u10u9= d u10 u9 dini l0 dfin l0;
u11u12=d u11 u12 dini l0 dfin l0;
u0u10= d u0 u10 dini l0 dfin l0;
u6u11= d u6 u11 dini l0 dfin l0;
u0u6 = cerc u0 u9 u6 dini l0 dfin l0;
u0u7 = u0u6 et u6u7;
u10u11=u0u6 homo (tg0/tf0) u9;
u10u8= u0u7 homo (tg0/tf0) u9;
u1u10= d u1 u10 dini l0 dfin l0;
*Reference surfaces
elim eps0 (u0u1 et u1u2 et u2u3 et u0u5 et u5u4 et u0u4 et
           u1u13 et u1u3 et u3u4 et u5u6 et u6u7 et u11u8 et
           u8u7 et u12u8 et u9u12 et u10u9 et u11u12 et
           u0u10 et u0u6 et u10u11 et u10u8 et u1u10);
sur1 = (u1u2 et u2u3 et u1u3) surf plan coul bleu;
```

```
sur2 = u0u4 regl nn0 u1u3 coul roug;
opti elem ele2;
sur3 =((u5u6 et u0u5 et u0u6) proj coni a0 cyli a0 t0 u2)
                              surf cylindrique a0 t0 coul vert;
opti elem ele1;
sur4 = u10u11 regl nn0 u0u6 coul turq;
sur5 = u11u8 regl nn0 u6u7 coul rose;
sur6 = (u10u11 et u11u12 et u9u12 et u10u9) surf plan coul jaun;
sur7 = (u11u8 et u11u12 et u12u8) surf plan coul blan;
*trak (sur1 et sur2 et sur3 et sur4 et sur5 et sur6 et sur7);
*
*Construction of the conjunction between the dome and the cones (named truc0
here)
opti elem ele2;
a1a10= u1u10 proj coni a0 cyli a0 t0 a4;
a1a3 = u1u3 proj coni a0 cyli a0 t0 a4;
a3a4 = u3u4 proj coni a0 cyli a0 t0 a4;
a4a7 = cerc a4 (0. 0. (r3*tf0+h1)) a7 dini l0 dfin l0;
a8a7 = u8u7 proj coni a0 cyli a0 t0 a4;
a10a8= u10u8 proj coni a0 cyli a0 t0 a4;
tru1 = a1a10 et a1a3 et a3a4 et a4a7 et a8a7 et a10a8;
elim eps0 tru1;
tru1 = tru1 surf cylindrique a0 t0;
*
a4t1 = cerc a4 t0 t1 dini l0 dfin l0;
t1t3 = cerc t1 (0. 0. ((h2-zt0)*r1/r2 + zt0)) t3 dini l0 dfin l0;
a7t3 = cerc a7 t0 t3 dini l0 dfin l0;
tru2 = a4a7 et a4t1 et t1t3 et a7t3;
elim eps0 tru2;
tru2 = tru2 surf spherique a0;
*
t1t4 = d t1 t4 dini l0 dfin l0;
*t4t6 = cerc t4 (0. 0. h2) t6 dini l0 dfin l0;
t4t6 = t1t3 homo (r2/r1) t0;
t3t6 = d t3 t6 dini l0 dfin l0;
tru3 = t1t3 et t1t4 et t4t6 et t3t6;
elim eps0 tru3;
tru3 = tru3 surf conique t0 a0;
tru3 = t1t3 regl t4t6 dini l0 dfin l0;
*
t4t7 = d t4 t7 dini l0 dfin l0;
t7t8 = cerc t7 (0. 0. h2) t8 dini l0 dfin l0;
t6t8 = d t6 t8 dini l0 dfin l0;
tru4 = t4t6 et t4t7 et t7t8 et t6t8;
elim eps0 tru4;
tru4 = tru4 surf plan;
*
b7t8 = d b7 t8 dini l0 dfin l0;
b4t7 = d b4 t7 dini l0 dfin l0;
b6b7 = u6u7 proj coni a0 cyli a0 t0 b4;
b5b6 = u5u6 proj coni a0 cyli a0 t0 b4;
b5b4 = u5u4 proj coni a0 cyli a0 t0 b4;
tru5 = t7t8 et b7t8 et b6b7 et b5b6 et b5b4 et b4t7;
elim eps0 tru5;
tru5 = tru5 surf cylindrique a0 t0;
*
b3b4 = u3u4 proj coni a0 cyli a0 t0 b4;
tru6 = a3a4 regl nn1 b3b4;
a4b4 = tru6 cote 2;
elim eps0 (t1t4 et t4t7 et b4t7 et a4b4 et a4t1);
tru6 = ((t1t4 et t4t7 et b4t7 et a4b4 et a4t1) surf plan) et tru6;
*
b8b7 = u8u7 proj coni a0 cyli a0 t0 b4;
tru7 = b8b7 regl nn1 a8a7;
a7b7 = tru7 cote 2;
elim eps0 (t3t6 et t6t8 et b7t8 et a7b7 et a7t3);
tru7 = ((t3t6 et t6t8 et b7t8 et a7b7 et a7t3) surf plan) et tru7;
*
b1b3 = u1u3 proj coni a0 cyli a0 t0 b4;
tru8 = a1a3 regl nn1 b1b3;
*
b10b8= u10u8 proj coni a0 cyli a0 t0 b4;
tru9 = a10a8 regl nn1 b10b8;
*
a1b1 = tru8 cote 4;
a10b10=tru9 cote 4;
b0b10= u0u10 proj coni a0 cyli a0 t0 b4;
b0b1 = u0u1 proj coni a0 cyli a0 t0 b4;
tru10= a1b1 et b0b1 et b0b10 et a10b10 et a1a10;
elim eps0 tru10;
tru10= tru10 surf plan;
*
tru11 =((sur2 et sur4 et sur5) chan ele2) proj coni a0 cyli a0 t0 b4;
tru12 = sur3 proj coni a0 cyli a0 t0 b4;
truc0 = tru1 et tru2 et tru3 et tru4 et tru5 et tru6 et
        tru7 et tru8 et tru9 et tru10 et tru11 et tru12;
elim eps0 truc0;
truc0 = truc0 volu coul rose;
*trak truc0;
itruc0 = tru1 et tru2 et tru8 et tru9 coul rose;
etruc0 = tru4 et tru5 coul rose;
*trak (itruc0 et etruc0);
*
*Construction of the central dome (named calo0 here);
opti elem ele1;
t1t2 = cerc t1 t0 t2 dini l0 dfin l0;
t3t2 = cerc t3 t0 t2 dini l0 dfin l0;
cal1 = t1t3 et t3t2 et t1t2;
elim eps0 cal1;
cal1 = cal1 surf spherique t0;
cal2 = cal1 homo (r2/r1) t0;
calo0 = cal1 volu cal2 dini l0 dfin l0 coul bleu;
*trak calo0;
icalo0 = cal1 coul bleu;
ecalo0 = cal2 coul bleu;
*trak (icalo0 et ecalo0);
*
*Contruction of the small cone (named scon0 here)
sco1 = (sur4 et sur5) proj coni a0 cyli a0 t0 b4;
sco2 = sco1 homo (r5/r4) a0;
sco3 = sco2 homo (r6/r5) a0;
sco4 = (sur6 et sur7) proj coni a0 cyli a0 t0 c1;
sco5 = sco4 homo (r6/r5) a0;
scon0 = (sco1 volu nn2 sco2
                volu nn3 sco3) et
        (sco4 volu nn3 sco5) coul bleu;
elim eps0 scon0;
*trak scon0;
sco6 = regl nn2 (u10u8 proj coni a0 cyli a0 t0 b4)
                (u10u8 proj coni a0 cyli a0 t0 c1);
sco7 = regl nn2 (u6u7 proj coni a0 cyli a0 t0 b4)
                (u6u7 proj coni a0 cyli a0 t0 c1)
       regl nn3 (u6u7 proj coni a0 cyli a0 t0 d0);
sco8 = (sur5 et sur7) proj coni a0 cyli a0 t0 d0;
iscon0 = sco4 et sco6 coul bleu;
escon0 = sco7 et sco8 coul bleu;
elim eps0 (iscon0 et escon0);
*trak (iscon0 et escon0);
*
*Contruction of the big cone (named bcon0 here)
bco1 = sur2 proj coni a0 cyli a0 t0 b4;
bco2 = bco1 homo (r5/r4) a0;
bco3 = bco2 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
bco4 = bco3 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
bco5 = sur1 proj coni a0 cyli a0 t0 c1;
bco6 = bco5 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
bco7 = bco5 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
bcon0 = (bco1 volu nn2 bco2
                volu nn3 bco3
                volu nn4 bco4) et
        (bco5 volu nn3 bco6
                volu nn4 bco7) coul roug;
elim eps0 bcon0;
*trak bcon0;
bco8 = regl nn2 (u1u3 proj coni a0 cyli a0 t0 b4)
                (u1u3 proj coni a0 cyli a0 t0 c1);
bco9 = regl nn2 (u5u4 proj coni a0 cyli a0 t0 b4)
                (u5u4 proj coni a0 cyli a0 t0 c1)
       regl nn3 (u5u4 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0))
       regl nn4 (u5u4 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0));
ibcon0 = bco5 et bco8 coul roug;
ebcon0 = bco4 et bco7 et bco9 coul roug;
elim eps0 (ibcon0 et ebcon0);
*trak (ibcon0 et ebcon0);
*
*Construction of the filling (named fill0 here)
fil1 = sur3 proj coni a0 cyli a0 t0 b4;
fil2 = fil1 homo (r5/r4) a0;
fil3 = fil2 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
fil4 = fil3 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
d0d6 = u0u6 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
elim eps0 (fil3 et d0d6);
depl d0d6 proj coni a0 cyli a0 t0 d0;
fil5 = sur4 proj coni a0 cyli a0 t0 d0;
fil6 = fil5 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
opti elem ele2;
si (sur6 elem type dime neg 1);
  sur6 = (sur6 elem tri3) et (sur6 elem qua4 'NOVERIF' chan tri3);
fins;
fil7 = sur6 proj coni a0 cyli a0 t0 d0;
e10e11 = u10u11 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
e9e12 = u9u12 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
e10e9 = d e10 e9 dini l0 dfin l0;
e11e12= d (e10e11 poin final) e12 dini l0 dfin l0;
fil8 = e10e9 et e10e11 et e11e12 et e9e12;
elim eps0 fil8;
fil8 = fil8 surf plan;
d10d11= u10u11 proj coni a0 cyli a0 t0 d0;
e10e11 = u10u11 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
fil9 = d10d11 regl nn4 e10e11;
d9d12= u9u12 proj coni a0 cyli a0 t0 d0;
e9e12= u9u12 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
fill0 = d9d12 regl e9e12 dini l0 dfin l0;
d12e12= fil10 cote 2;
d11e11= fil9 cote 2;
d11d12= u11u12 proj coni a0 cyli a0 t0 d0;
fill1 = d11e11 et d11d12 et d12e12 et e11e12;
elim eps0 fill1;
fill1 = fill1 surf plan;
d9e9 = fil10 cote 4;
d10e10 = fil9 cote 4;
d10d9 = u10u9 proj coni a0 cyli a0 t0 d0;
fill2 = d9e9 et d10e10 et d10d9 et e10e9;
elim eps0 fill2;
fill2 = fill2 surf plan;
fill0 = fil7 et fil8 et fil9 et fil10 et fill1 et fill2;
elim eps0 fill0;
fill0 = fill0 volu;
opti elem ele1;
fill0 = fill0 et (fil1 volu nn2 fil2
                        volu nn3 fil3
                        volu nn4 fil4) et
                (fil5 volu nn4 fil6) coul vert;
elim eps0 fill0;
*trak fill0;
c5c6 = b5b6 homo (r5/r4) a0;
d5d6 = c5c6 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
d6 = u6 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
elim eps0 (d5d6 et d6);
depl d6 proj coni a0 cyli a0 t0 d0;
e5e6 = d5d6 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
fil13 = b5b6 regl nn2 c5c6 regl nn3 d5d6 regl nn4 e5e6;
fil14 = regl (u6u11 proj coni a0 cyli a0 t0 d0) nn4
             (u6u11 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0));
efill0 = fil4 et fil6 et fil8 et fill1 et fil13 et fil14 coul vert;
elim eps0 efill0;
*trak efill0;
*
*Construction of the chapiteau (named chap0 here)
c1c10= (b0b10 et b0b1) homo (r5/r4) a0;
cha1 = (b0b10 et b0b1) regl nn2 c1c10;
chap0 = tru10 et cha1;
elim eps0 chap0;
chap0 = chap0 volu tran (q0 moin a0) dini l0 dfin l0 coul vert;
*trak chap0;
cha2 = cha1 plus (q0 moin a0);
cha3 = (c1 droi nn2 a1b1) et a1a10 et (c10 droi nn2 a10b10)
       tran (q0 moin a0) dini l0 dfin l0;
ichap0 = cha2 et cha3 coul vert;
elim eps0 ichap0;
*trak ichap0;
*
*Construction of the column (named colo0 here)
col1 = tru10 moin a0;
colo0 = col1 volu tran q0 dini l0 dfin l0 coul roug;
*trak colo0;
icolo0 = cont col1 tran q0 dini l0 dfin l0 coul roug;
bcolo0 = col1 coul roug;
elim eps0 (icolo0 et bcolo0);
*trak (bcolo0 et icolo0);
*
*Construction of the wall under the big cone (named bwal0 here)
c1c2 = u1u2 proj coni a0 cyli a0 t0 c1;
d1d2 = u1u2 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
e1e2 = u1u2 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
bwa1 = c1c2 regl nn3 d1d2 regl nn4 e1e2;
bwal0 = bwa1 volu tran (q0 moin a0) dini l0 dfin l0
             volu tran (i0 moin q0) dini l0 dfin l0
             volu tran (p0 moin i0) dini l0 dfin l0
             volu tran (o0 moin p0) dini l0 dfin l0 coul turq;
*trak bwal0;
ibwal0 = c1c2 tran (q0 moin a0) dini l0 dfin l0
              tran (i0 moin q0) dini l0 dfin l0
              tran (p0 moin i0) dini l0 dfin l0
              tran (o0 moin p0) dini l0 dfin l0 coul turq;
ebwal0 = e1e2 tran (q0 moin a0) dini l0 dfin l0
              tran (i0 moin q0) dini l0 dfin l0
              tran (p0 moin i0) dini l0 dfin l0
              tran (o0 moin p0) dini l0 dfin l0 coul turq;
bbwal0 = bwa1 plus o0 moin a0 coul turq;
elim eps0 (ibwal0 et ebwal0 et bbwal0);
*trak (ibwal0 et ebwal0 et bbwal0);
*
*Construction of the wall under the small cone+chapiteau (named swal0 here)
opti elem ele2;
d1d10=(u0u10 proj coni a0 cyli a0 t0 d0) et
      (u0u1 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0));
elim eps0 d1d10;
e1e10= c1c10 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
swa1 = c1c10 regl nn3 d1d10 regl nn4 e1e10;
c10c9 = u10u9 proj coni a0 cyli a0 t0 c1;
d10d9 = u10u9 proj coni a0 cyli a0 t0 d0;
swa2 = fil12 et (c10c9 regl nn3 d10d9);
swa3 = c1c10 tran (q0 moin a0) dini l0 dfin l0;
c1d1 = c1 d nn3 d1;
swa4 = c1d1 tran (q0 moin a0) dini l0 dfin l0
            tran (i0 moin q0) dini l0 dfin l0
            tran (p0 moin i0) dini l0 dfin l0;
d1e1 = d1 d nn4 e1;
swa5 = d1e1 tran (q0 moin a0) dini l0 dfin l0
            tran (i0 moin q0) dini l0 dfin l0
            tran (p0 moin i0) dini l0 dfin l0;
e1e9 = e1e10 et e10e9;
elim eps0 e1e9;
swa6 = e1e9 tran (q0 moin a0) dini l0 dfin l0
            tran (i0 moin q0) dini l0 dfin l0
            tran (p0 moin i0) dini l0 dfin l0;
c9e9 = (d nn3 c9 d9) et d9e9;
p5e9 = swa6 cote 2;
p4p5 = d p4 p5 dini l0 dfin l0;
c9p4 = cerc c9 p3 p4 dini l0 dfin l0;
swa7 = c9e9 et p5e9 et p4p5 et c9p4;
elim eps0 swa7;
swa7 = swa7 surf plan;
q2c10= d q2 c10 dini l0 dfin l0;
q1q2 = c1c10 plus (q0 moin a0);
q1p1 = d q1 (q1 plus i0 moin q0) dini l0 dfin l0 d p1 dini l0 dfin l0;
p1p2 = d p1 p2 dini l0 dfin l0;
p2c9 = cerc p2 p3 c9 dini l0 dfin l0;
p2p3 = (p2c9 proj cyli a0 plan p2 p3 p4)
            proj coni p0 cyli p0 a0 p3;
p2c9 = (p2p3 proj cyli a0 sphe p3 p2) syme plan p0 p2 p3;
swa8 = c10c9 et q2c10 et q1q2 et q1p1 et p1p2 et p2c9;
elim eps0 swa8;
swa8 = swa8 surf cylindrique a0 t0;
p2p4 = cerc p2 p3 p4 dini l0 dfin l0;;
p7p5 = ele9 plus (p0 moin a0);
p1p7 = (c1d1 et d1e1) plus (p0 moin a0);
```

```
swa9 = p1p2 et p2p4 et p4p5 et p7p5 et p1p7;
elim eps0 swa9;
swa9 = swa9 surf plan;
swa0 = c9p4 et p2c9 et p2p4;
elim eps0 swa0;
swa0 = swa0 surf spherique p3;
swal0 = swa1 et swa2 et swa3 et swa4 et swa5 et
        swa6 et swa7 et swa8 et swa9 et swa0;
elim eps0 swal0;
swal0 = swal0 volu;
opti elem ele1;
swal0 = swal0 et
       (swa9 volu tran (o0 moin p0) dini l0 dfin l0) coul rose;
elim eps0 swal0;
*trak swal0;
iswal0 =((p1p2 et p2p4) tran (o0 moin p0) dini l0 dfin l0)
         et swa8 et swa0 coul rose;
eswal0 =( p7p5          tran (o0 moin p0) dini l0 dfin l0)
         et swa6 coul rose;
bswal0 = swa9 plus o0 moin p0 coul rose;
elim eps0 (iswal0 et eswal0 et bswal0);
*trak (iswal0 et eswal0 et bswal0);
*
*Construction of the alternative of bcon0 (named bcon1 here)
ele13= u1u13 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
j8j78= cerc j8 j1 j78 dini l0 dfin l0;
e1j8 = d e1 j8 dini l0 dfin l0;
e13j78 = d e13 j78 dini l0 dfin l0;
bco11 = j8j78 et e13j78 et e1e13 et e1j8;
elim eps0 bco11;
dens 1.d-6;
bco11 = bco11 surf plan;
bco12 = bco11 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
bcon1 = (bco1 volu nn2 bco2
              volu nn3 bco3
              volu nn4 bco4) et
        (bco11 volu nn4 bco12) coul jaun;
*trak bcon1;
bco18 = bco8 regl nn3
        (u1u3 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0));
d13j78 = e13j78 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
d13d3 = u13u3 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
e13e3 = u13u3 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
bco19 = (e13j78 et e13e3) regl nn4 (d13j78 et d13d3);
ibcon1 = bco18 et bco19 et bco12 coul jaun;
ebcon1 = bco4 et bco9 et bco11 coul jaun;
elim eps0 (ibcon1 et ebcon1);
*Window
e2e3 = u2u3 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
j78j7= j78 cerc j1 j7 dini l0 dfin l0;
e3 = u3 proj coni a0 plan e0 (e0 plus y0) (e0 plus z0);
j7e3 = j7 droi e3 dini l0 dfin l0;
void1 = e13j78 et j78j7 et j7e3 et e13e3;
elim eps0 void1;
void1 = void1 surf plan coul blan;
elim eps0 (ibcon1 et ebcon1 et void1);
*trak (ibcon1 et ebcon1 et void1);
*
*Construction of the choir (named choi0 here)
j8j7 = j8j78 et j78j7;
j2j4 = j8j7 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
cho1 = j8j7 regl nn4 j2j4;
cho2 = cho1 proj coni i1 sphe i1 i2;
j3j7 = cerc j3 i1 j7 dini l0 dfin l0;
j3j8 = cerc j3 d2 j8 dini l0 dfin l0;
cho3 = j8j7 et j3j7 et j3j8;
elim eps0 cho3;
cho3 = cho3 surf spherique i1;
cho4 = cho3 proj coni i1 sphe i1 i2;
choi0 = (cho1 volu nn5 cho2) et
        (cho3 volu nn5 cho4) coul bleu;
elim eps0 choi0;
*trak choi0;
j78j7bi = j78j7 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
cho5 = j78j7 regl nn4 j78j7bi;
j2j4bi = j2j4 proj coni i1 sphe i1 i2;
cho6 = j2j4 regl nn5 j2j4bi;
ichoi0 = cho2 et cho4 et cho5 et cho6 coul bleu;
echoi0 = cho3 coul bleu;
elim eps0 (ichoi0 et echoi0);
*trak echoi0;
*
*Construction of the first alternative of bwal0 (named bwal1 here)
opti elem ele2;
d1j4 = e1j8 proj coni a0 plan d0 (d0 plus y0) (d0 plus z0);
bwa11 = e1j8 regl nn4 d1j4;
j8j4 = bwa11 cote 2;
i8i4 = j8j4 proj coni i1 sphe i1 i2;
bwa12 = j8j4 regl nn5 i8i4;
i3i8 = j3j8 homo i1 (r8/r9);
bwa13 = j3j8 regl nn5 i3i8;
j3k3 = d j3 k3 dini l0 dfin l0;
k3k4 = d k3 k4 dini l0 dfin l0;
e1k4 = d e1 k4 dini l0 dfin l0;
bwa14 = e1j8 et j3j8 et j3k3 et k3k4 et e1k4;
elim eps0 bwa14;
bwa14 = bwa14 surf plan;
j4i4 = bwa12 cote 2;
j4i6 = cerc j4i4 i1 i6 dini l0 dfin l0;
i6j6 = d i6 j6 dini l0 dfin l0;
d1j6 = d d1 q8 dini l0 dfin l0 d j6 dini l0 dfin l0;
bwa15= d1j4 et j4i6 et i6j6 et d1j6;
elim eps0 bwa15;
bwa15= bwa15 surf plan;
d1e1 = bwa11 cote 4;
bwa16= d1e1 tran (q0 moin a0) dini l0 dfin l0
            tran (i0 moin q0) dini l0 dfin l0;
e1k3 = e1k4 et k3k4;
elim eps0 e1k3;
bwa17= e1k3 tran (q0 moin a0) dini l0 dfin l0
            tran (i0 moin q0) dini l0 dfin l0;
k3k5 = d1j6 plus k3 moin d1;
k5i5 = d k5 i5 dini l0 dfin l0;
i3i5 = cerc i3 i1 i5 dini l0 dfin l0;
i3j3 = bwa13 cote 4;
bwa18 = j3k3 et k3k5 et k5i5 et i3i5 et i3j3;
elim eps0 bwa18;
bwa18 = bwa18 surf plan;
j6k5 = (d1e1 et e1k3) plus i0 moin a0;
i5i6 = cerc i5 i1 i6 dini l0 dfin l0;
bwa19 = i6j6 et j6k5 et k5i5 et i5i6;
elim eps0 bwa19;
bwa19 = bwa19 surf plan;
i8i6 = cerc i8i4 i1 i6 dini l0 dfin l0;
bwa10 = i5i6 et i3i5 et i3i8 et i8i6;
elim eps0 bwa10;
bwa10 = bwa10 surf spherique i1;
bwa11 = bwa11 et bwa12 et bwa13 et bwa14 et bwa15 et
        bwa16 et bwa17 et bwa18 et bwa19 et bwa10;
elim eps0 bwa11;
bwa11 = bwa11 volu;
opti elem ele1;
bwa11 = bwa11 et
       (bwa19 volu tran (p0 moin i0) dini l0 dfin l0
              volu tran (o0 moin p0) dini l0 dfin l0) coul turq;
elim eps0 bwa11;
*trak bwa11;
e1k3bi= e1k3 plus i0 moin a0;
swa14 =((c1d1 plus p0 moin a0) tran (o0 moin p0) dini l0 dfin l0)
       et swa4 coul rose;
ibwa11=((i5i6 et i6j6) tran (p0 moin i0) dini l0 dfin l0
                       tran (o0 moin p0) dini l0 dfin l0) et
         bwa10 et bwa15 coul turq et swa14;
ebwa11= (e1k3bi tran (p0 moin i0) dini l0 dfin l0
                tran (o0 moin p0) dini l0 dfin l0) et
         bwa14 et bwa17 coul turq;
bbwa11=  bwa19 plus o0 moin i0 coul turq;
elim eps0 (ibwa11 et ebwa11 et bbwa11);
*trak (ibwa11 et ebwa11 et bbwa11);
*
*Construction of the entrance under the big cone (named bwal2 here)
por1 = w4 droi w3 dini l0 dfin l0 droi w2 dini l0 dfin l0
          droi w1 dini l0 dfin l0;
ele2bi = (ele2 plus o0 moin a0) inve;

bwa21 = ele2 droi por1 dini l0 dfin l0 droi ele2bi dini l0 dfin l0
            droi p7   dini l0 dfin l0 droi i7     dini l0 dfin l0
            droi q7   dini l0 dfin l0 droi        dini l0 dfin l0;
bwa21 = bwa21 surf plan;
coo1 coo2 coo3 = coor bwa21;
de12 = (nomc ux ((cf0-1.)*coo1)) + (nomc uy ((cf0-1.)*coo2));
bwa22 = bwa21 plus de12;
ra13 = ((coo2/r6)**2+1.)**(-0.5)*r5;
de13 = (nomc ux (ra13-coo1)) + (nomc uy (ra13*coo2/r6-coo2));
bwa23 = bwa21 plus de13;
bwa12 = bwa21 volu nn4 bwa22 volu nn3 bwa23 coul turq;
*trak bwa12;
por2 = por1 plus de12;
por3 = por1 plus de13;
bwa24 = por1 regl nn4 por2 regl nn3 por3;
ibwa12 = bwa23 et bwa24 coul turq;
ebwa12 = bwa21 coul turq;
bbwa12 = bbwa10;
elim eps0 (ibwa12 et ebwa12 et bbwa12);
*Door
void2 = por1 droi dini l0 dfin l0;
void2 = void2 surf plan coul blan;
*trak (ibwa12 et ebwa12 et bbwa12 et void2);
*
mesh0 = truc0 et calo0 et scon0 et bcon0 et fill0 et
        chap0 et colo0 et bwa10 et swa10;
elim eps0 mesh0;
*trak mesh0;
imesh0 = itruc0 et icalo0 et iscon0 et ibcon0 et
         ichap0 et icolo0 et ibwa10 et iswa10;
emesh0 = etruc0 et ecalo0 et escon0 et ebcon0 et
         efill0 et ebwa10 et eswa10;
bmesh0 = bcolo0 et bbwa10 et bswa10;
elim eps0 (imesh0 et emesh0 et bmesh0);
*trak (imesh0 et emesh0 et bmesh0);
*
mesh1 = truc0 et calo0 et scon0 et bcon1 et fill0 et
        chap0 et colo0 et bwa11 et swa10 et choi0;
elim eps0 mesh1;
*trak mesh1;
imesh1 = itruc0 et icalo0 et iscon0 et ibcon1 et ichap0 et
         icolo0 et ibwa11 et iswa10 et ichoi0 et void1;
emesh1 = etruc0 et ecalo0 et escon0 et ebcon1 et
         efill0 et ebwa11 et eswa10 et echoi0 et void1;
bmesh1 = bcolo0 et bbwa11 et bswa10;
elim eps0 (imesh1 et emesh1 et bmesh1);
*trak (imesh1 et emesh1 et bmesh1);
*
mesh2 = truc0 et calo0 et scon0 et bcon0 et fill0 et
        chap0 et colo0 et swa10 et bwa12;
elim eps0 mesh2;
*trak mesh2;
imesh2 = itruc0 et icalo0 et iscon0 et ibcon0 et
         ichap0 et icolo0 et iswa10 et ibwa12 et void2;
emesh2 = etruc0 et ecalo0 et escon0 et ebcon0 et
         efill0 et eswa10 et ebwa12 et void2;
bmesh2 = bcolo0 et bswa10 et bbwa12;
elim eps0 (imesh2 et emesh2 et bmesh2);
*trak (imesh2 et emesh2 et bmesh2);
*
demi0 = mesh1 et (mesh0 syme plan o0 (x0 plus y0) z0)
              et (mesh2 syme plan o0 y0 z0)
              et (mesh0 tour 90. o0 z0);
elim eps0 demi0;
*trak (enve demi0);
idemi0 = imesh1 et (imesh0 syme plan o0 (x0 plus y0) z0)
                et (imesh2 syme plan o0 y0 z0)
                et (imesh0 tour 90. o0 z0);
edemi0 = emesh1 et (emesh0 syme plan o0 (x0 plus y0) z0)
                et (emesh2 syme plan o0 y0 z0)
                et (emesh0 tour 90. o0 z0);
bdemi0 = bmesh1 et (bmesh0 syme plan o0 (x0 plus y0) z0)
                et (bmesh2 syme plan o0 y0 z0)
                et (bmesh0 tour 90. o0 z0);
elim eps0 (idemi0 et edemi0 et bdemi0);
*trak (idemi0 et edemi0 et bdemi0);
tota0 = demi0 et (demi0 syme plan o0 x0 z0);
elim eps0 tota0;
*trak (enve tota0);
itota0 = idemi0 et (idemi0 syme plan o0 x0 z0);
etota0 = edemi0 et (edemi0 syme plan o0 x0 z0);
btota0 = bdemi0 et (bdemi0 syme plan o0 x0 z0);
elim eps0 (itota0 et etota0 et btota0);
*trak (itota0 et etota0 et btota0);
ttota0 = (etota0 diff itota0) et btota0;
*
*Verifying the enveloppe
*ttota0 = ttota0 plus o0;
*list (nbno ttota0);
*elim eps0 (ttota0 et tota0);
*Trying to fill the enveloppe
*opti elem tet4;
*ttota1 = (ttota0 elem tri3) et (ttota0 elem qua4 chan tri3);
*tota1 = volu ttota1;
*and verifying the result
*ttota2 = enve tota1;
*dif12 = diff ttota1 ttota2;
*list dif12;
*
*Ground
cbase0 = cont (btota0 orie direction z0);
igrou0 = cbase0 elem appuye strictement itota0;
egrou0 = cbase0 elem appuye strictement etota0;
xma = maxi (coor 1 egrou0) + l0;
xmi = mini (coor 1 egrou0) - l0;
yma = maxi (coor 2 egrou0) + l0;
ymi = mini (coor 2 egrou0) - l0;
zma = maxi (coor 3 etota0) + l0;
opti elem seg2;
cexte0 = (xma yma 0) droi dini l0 dfin l0
         (xma ymi 0) droi dini l0 dfin l0
         (xmi ymi 0) droi dini l0 dfin l0
         (xmi yma 0) droi dini l0 dfin l0;
opti elem tri3;
igrou0 = igrou0 surf plane coul vert;
egrou0 = (egrou0 et cexte0) surf plane coul vert;
eexte0 = (cexte0 tran (0 0 zma) dini l0 dfin l0) et
         (cexte0 plus (0 0 zma) surf plane) coul blan;
*
*Internal space
opti elem tet4;
si (itota0 elem type dime neg 1);
  itota0 = (itota0 elem tri3) et (itota0 elem qua4 chan tri3);
fins;
iiair0 = itota0 et igrou0;
elim eps0 iiair0;
*trak iiair0;
iair0 = iiair0 volu;
*
*External space
si (etota0 elem type dime neg 1);
  etota0 = (etota0 elem tri3) et (etota0 elem qua4 chan tri3);
fins;
eeair0 = etota0 et egrou0 et eexte0;
elim eps0 eeair0;
*trak eeair0;
eair0 = eeair0 volu;
*
*Total space
tair0 = iair0 et eair0;
elim eps0 tair0;
*trak (enve tair0);
*
*Explosive bubble (center + radius)
ec0 = 2. 2. 1.;
er0 = 0.75;
*
*A partir d'un octaedre
*ep1 = (x0*er0) plus ec0;
*ep2 = (y0*er0) plus ec0;
*ep3 = (z0*er0) plus ec0;
*avec maillage sur une sphere
*sph0 = ep1 cerc ec0 ep2 dini l0 dfin l0
*           cerc ec0 ep3 dini l0 dfin l0
```

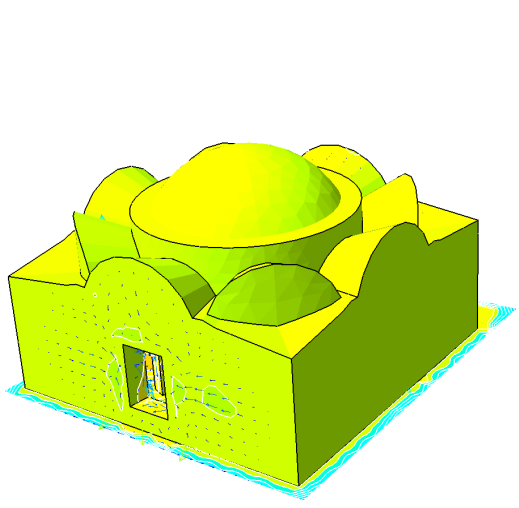
```
*           cerc ec0     dini 10 dfin 10;
*sph0 = sph0 surf spherique ec0;
*avec maillage sur un plan
*opti elem qua4;
*sph0 = ep1 droi ep2 dini 10 dfin 10
*           droi ep3 dini 10 dfin 10
*           droi     dini 10 dfin 10;
*l1 = mesu (elem 1 sph0);
*sph0 = sph0 (manu chpo sph0 1 scal l1) surf plane;
*sph0 = sph0 et (sph0 tour  90. ec0 ep3);
*sph0 = sph0 et (sph0 tour 180. ec0 ep3);
*sph0 = sph0 et (sph0 tour 180. ec0 ep1);
*elim eps0 sph0;
*sph0 = sph0 proj coni ec0 sphe ec0 ep1;
*opti elem cub8;
*sph0 = sph0 volu coul roug;
*
*A partir d'un icosaedre maille sur un plan (intersphere)
or0 = 5.**.5+1./2.;
ad0 = atg (-2./3.) (5.**.5/3.) + 180.;
ep1 = (x0*er0/2.) plus (y0*er0/or0/2.) plus ec0;
ep2 = (x0*er0/2.) moin (y0*er0/or0/2.) plus ec0;
ep3 = (z0*er0/2.) plus (x0*er0/or0/2.) plus ec0;
l1 = 10/2.;
sph0 = ep1 droi ep2 dini l1 dfin l1
           droi ep3 dini l1 dfin l1
           droi     dini l1 dfin l1;
l1 = mesu (elem 1 sph0);
*opti elem qua4;
opti elem tri3;
sph0 = sph0 (manu chpo sph0 1 scal l1) surf plane;
sph1 ep11 = sph0 (ep1 et ep1) tour ad0 ep2 ep3;
ep11 = ep11 poin 1;
sph2 ep22 = sph0 (ep2 et ep2) tour ad0 ep3 ep1;
ep22 = ep22 poin 1;
sph3 ep33 = sph0 (ep3 et ep3) tour ad0 ep1 ep2;
ep33 = ep33 poin 1;
sph0 = sph0 et sph1 et sph2 et sph3 et
      (sph1 tour ad0 ep2 ep11) et (sph1 tour ad0 ep11 ep3) et
      (sph2 tour ad0 ep3 ep22) et (sph2 tour ad0 ep22 ep1) et
      (sph3 tour ad0 ep1 ep33) et (sph3 tour ad0 ep33 ep2);
sph0 = sph0 et (sph0 syme poin ec0);
elim eps0 sph0;
sph0 = sph0 proj coni ec0 sphe ec0 (ep1 plus ep2 / 2.);
*opti elem cub8;
opti elem tet4;
sph0 = sph0 volu coul rose;
esp0 = tair0 incl sph0 volu larg coul roug;
*trak esp0;
tair0 = tair0 diff esp0 coul turq;
*trak tair0 nosm;
*
stru = tota0 plus o0;
stru6 = stru elem pri6;
stru4 = stru elem tet4;
aria = tair0;
```

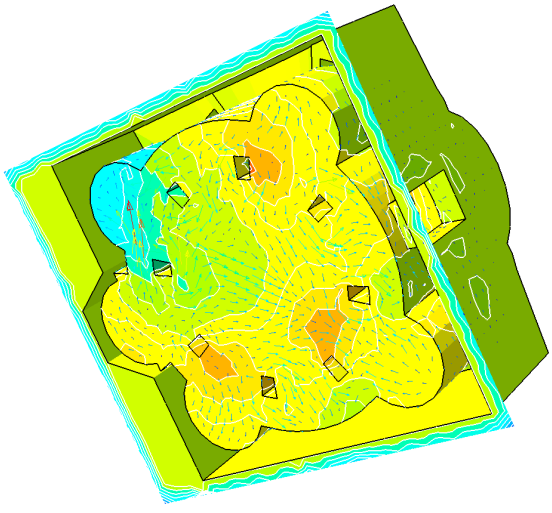
```
bull = esp0;
flui = aria et bull;
abso = exte0;
orie abso poin o0;
abso = inve abso;
*
list (nbel bull);
list (nbno bull);
list (mesu bull volu);
*
babul = bary bull;
pdet = bull poin proc babul;
list babul;
list pdet;
*
opti trac psc ftra 'koos21_mesh.ps';
trac qual bull;
trac cach bull;
*b1 = bull elem 1;
*b2 = diff bull b1;
*b1 = b1 coul roug;
*b2 = b2 coul vert;
*bb = b1 et b2;
*list (mesu b1 volu);
*list (mesu b2 volu);
*list (mesu bb volu);
*trac qual bb;
*trac cach bb;
*trac cach face bb;
*
blo123 = stru poin plan o0 x0 y0 eps0;
list (nbno blo123);
fsrn = flui poin plan o0 x0 y0 eps0;
list (nbno fsrn );
fsan = enve flui chan poi1;
list (nbno fsan);
pabso = abso chan poi1;
list (nbno pabso);
pabsoxy = pabso poin plan o0 x0 y0 eps0;
list (nbno pabsoxy);
pabso = diff pabso pabsoxy;
list (nbno pabso);
fsan = diff fsan (pabso et fsrn);
list (nbno fsan);
*
mesh = stru et flui et abso et blo123 et fsrn et fsan;
tass mesh;
opti sauv form 'koos21.msh';
sauv form mesh;
list (nbel bull);
list (mesu bull);
list (nbel mesh);
list (nbno mesh);
opti donn 5;
fin;
```

The EUROPLEXUS input file reads:

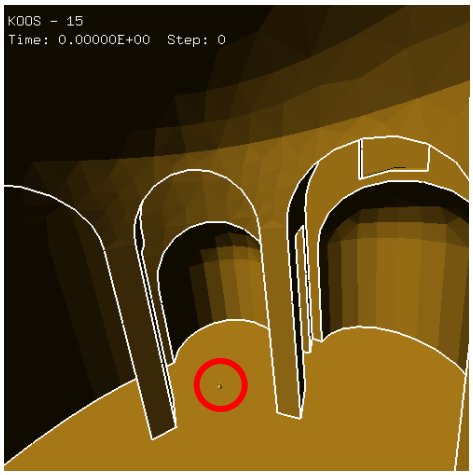
```
KOOS - 21
$
 ECHO
$VERI
!CONV win
CAST MESH
TRID NONL ALE
$
DIME
 PT3L 22605 FL34 78358 TETR 6894 PRIS 5378 CL3I 5214 ZONE 4
 NALE 1386 NBLE 8519
TERM
$
GEOM
   FL34 flui TETR stru4 PRIS stru6 CL3I abso
TERM
$
GRIL LAGR LECT stru TERM
     EULE LECT fsan fsrn abso TERM
     ALE  LECT flui TERM
     AUTO autr
$
MATE
**   l'air :  on calcule eint pour avoir P=1 bar (P=omeg*ro*eint)
    flut ro 1.3 eint 0.21978e6 gamm 1.35 PB 0
         ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
         CQ 2.56 PMIN 0 PREF 1.e5 NUM 11
         a 3.738e11 b 3.747e9 r1 4.15 r2 0.90
         ros 1630
         LECT aria TERM
**  Le TNT :   on donne directement ro = ros
*              avec ignition au point PDET a l'instant 0.0
*              la vitesse de detonation est celle de Chapman-Jouguet
    flut ro 1630 eint 3.68e6 gamm 1.35 PB 0
         ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
         CQ 2.56 PMIN 0 PREF 1.e5 NUM 11
         a 3.738e11 b 3.747e9 r1 4.15 r2 0.90
         d 6930 TDET 0.0 pini 1e5
         xdet 1.9971 ydet 2.2741 zdet 1.0700
         LECT bull TERM
$ structure
     LINE RO 2000 YOUN 3.E10 NU 0.2
          LECT stru TERM
$ absorbing
     IMPE ABSI
          LECT abso TERM
$
LINK COUP
     BLOQ 123 LECT blo123 TERM
     FSA      LECT fsan TERM
     FSR      LECT fsrn TERM
$
CHAR CONS GRAV 0 0 -9.80665D0 LECT tous TERM
$
ECRI VITE ECRO TFRE 10.E-3
     FICH K200 TFRE 2.0E-3 POIN TOUS
               VARI VITE ECRO ECRC LECT 1 2 TERM
     fich spli alic      tfre 1.e-3
$
OPTI NOTE
 QUAS STAT 100. 1. UPTO 0.
 csta 0.8e0
 log 1
 NF34 MOMT 2
CALCUL TINI -20.E-3 TEND 50.E-3
*=====================================================================
FIN
```

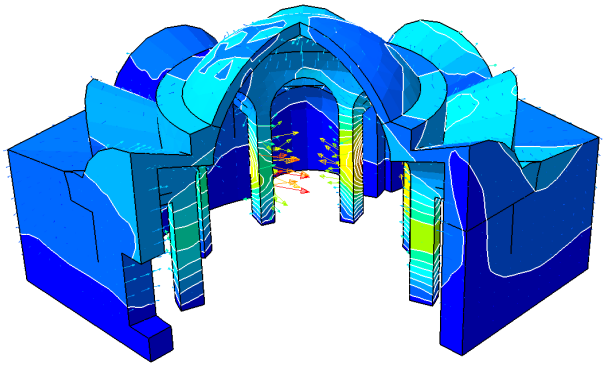
Some (qualitative) results are shown. The fluid flow out of the main door:



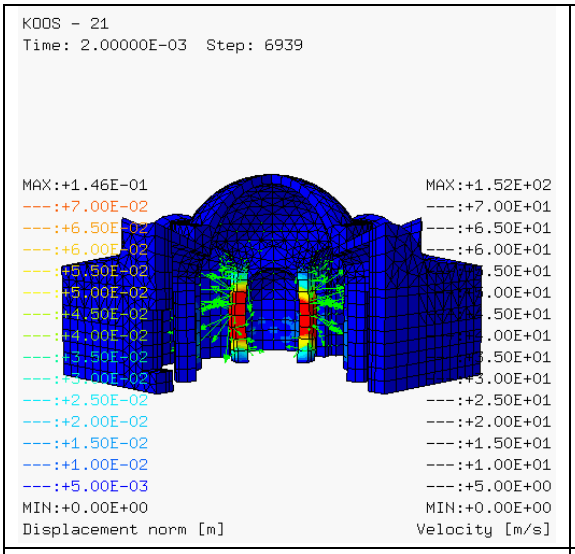


Location of the explosive charge and structural deformations/velocities:

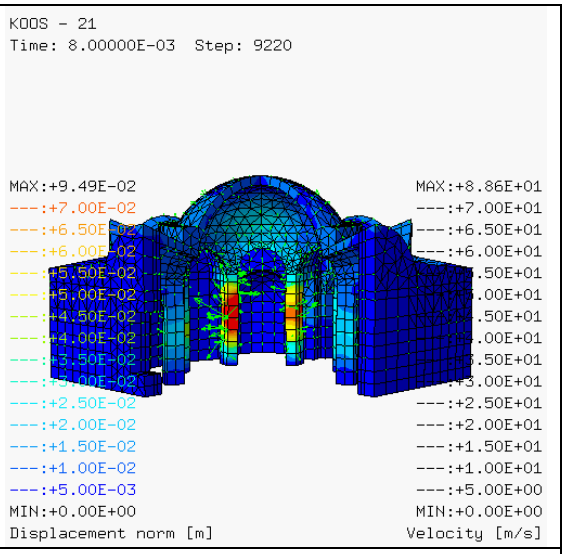




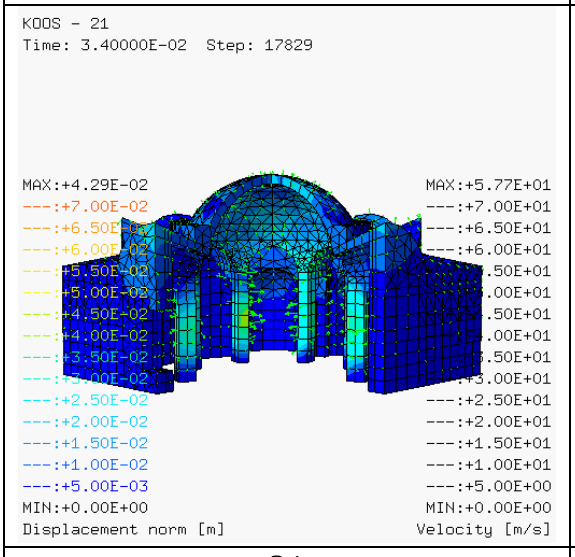
Some selected snapshots:



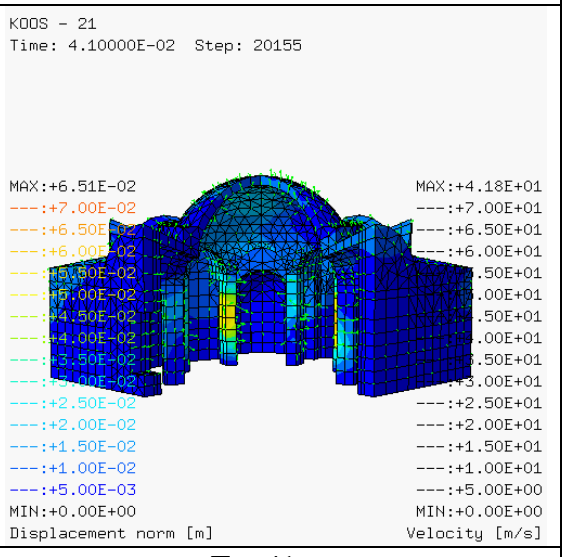
t = 2 ms



T = 8 ms



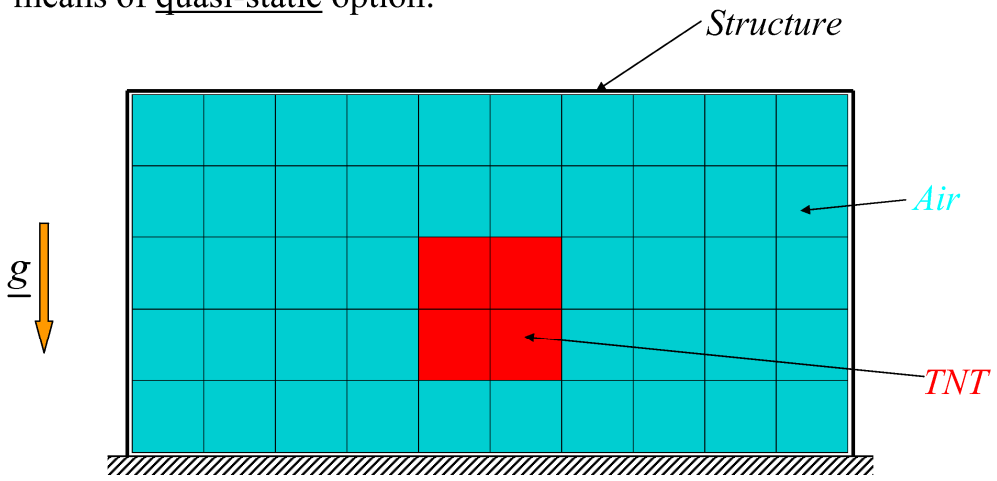
t = 34 ms



T = 41 ms

Exercise 14 – Improving Initial Conditions

• Take into account static loading (gravity, fluid pressure) by means of quasi-static option:



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PROBLEM:
A deformable C-shaped structure under gravity load undergoes an internal explosion.
MESH:
The fluid is meshed by Fl24 elements, the deformable structure by ED01 elements. The calculation is plane strain (DPLA) and is declared of the ALE type.
MATERIALS:
The air is modelled by the FLUT material (perfect gas), the explosive is solid TNT and the structure uses a linear elastic material (VM23).
BOUNDARY CONDITIONS:
The structure is clamped at the base. FSA fluid-structure interaction is used along the whole fluid-structure interface.
LOADING:
Gravity loading in the vertical direction is imposed on the whole model.
OPTIONS:
The QUAS STAT option is used to introduce an initial dynamic relaxation phase which allows to take into account approximately the static stresses generated in the structure by the gravity. This phase goes from t = -500 ms to t = 0. Then follows the explosion and the usual transient calculation. From t = 500 ms to the final time t = 1 s a second dynamic relaxation phase is introduced, which damps out the elastic oscillations of the system due to the explosion, and allows to compute the final, quasi-static configuration of the system.
CALCULATIONS:
Preliminary calculations involving only the structure are used to estimate the system's frequency under static loading (gravity). Then follows the real calculation as described in the previous point.
RESULTS:
The initial and final oscillations are effectively damped out by the quasi-static option.

POST-TREATMENT
Animations are produced.
Numerical Solutions

QUAS01

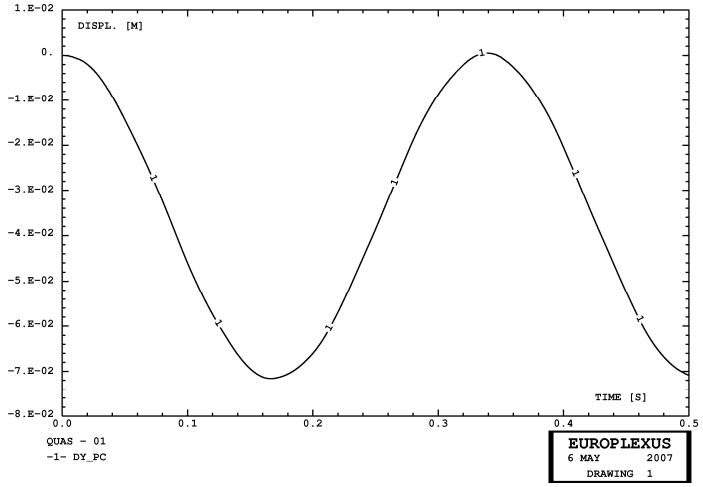
Preliminary calculation modelling only the structure under gravity load and without dynamic relaxation, used to estimate the system's oscillation frequency. The Cast3m mesh generation file reads:

```
*%siz 100
opti echo 1;
*
opti titr 'QUAS - 01';
opti dime 2 elem qua4;
*
p1p=0 0;
p2p=10 0;
p3p=10 5;
p4p=0 5;
pc = 5 5;
tol=0.001;
s1 = p2p d 5 p3p;
s2 = p3p d 10 p4p;
s3 = p4p d 5 p1p;
stru = s1 et s2 et s3;
elim tol (stru et pc);
bloqall = stru poin droi p1p p2p tol;
*
mesh=stru et bloqall;
*
tass mesh;
*
opti sauv form 'quas01.msh';
sauv form mesh;
opti trac psc ftra 'quas01_mesh.ps';
trac qual mesh;
fin;
```

The EUROPLEXUS input file reads:

```
QUAS - 01
$
 ECHO
$VERI
!CONV win
CAST MESH
DPLA NONL LAGR
$
DIME
 PT3L 21 ED01 20 ZONE 1
TERM
$
GEOM
   ED01 stru
TERM
$
COMP EPAI 0.1 LECT stru TERM
$
MATE
$ structure
     VM23 RO 2000 YOUN 3.E10 NU 0.2 ELAS 3.E10
          TRAC 1 3.E10 1.0
          LECT stru TERM
$
LINK COUP
     BLOQ 123 LECT bloqall TERM
$
CHAR CONS GRAV 0 -9.80665D0 LECT tous TERM
$
ECRI VITE ECRO TFRE 10.E-3
     FICH K200 TFRE 2.0E-3 POIN TOUS
               VARI VITE ECRO ECRC LECT 1 2 TERM
     fich      alic temp tfre 1.e-3
               poin lect pc term
     fich      alic      tfre 1.e-3
$
OPTI NOTE
!QUAS STAT 100. 1. UPTO 0.
 csta 0.8e0
 log 1
CALCUL TINI 0. TEND 500.E-3 pas1 1.e-5
*=====================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dy_pc'   DEPL COMP 2 NOEU LECT pc TERM
*
trac 1 axes 1.0 'DISPL. [M]'
LIST 1 axes 1.0 'DISPL. [M]'
*=====================================================================
FIN
```

By plotting the vertical displacement of the central point of the structure one estimates an oscillation period under gravity of about 0.33 s (i.e. a frequency of 3 Hz):



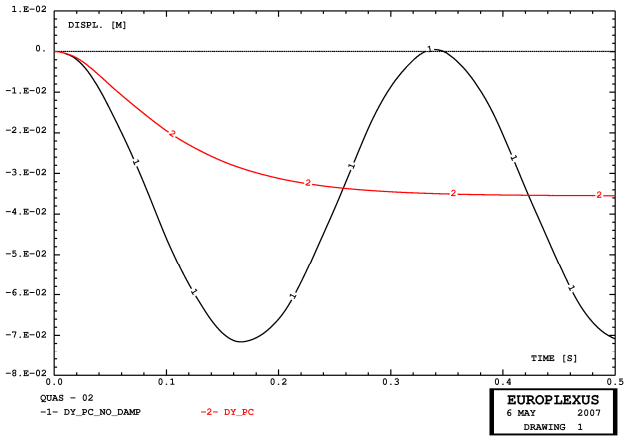
QUAS02

Further preliminary calculation modelling only the structure under gravity load with dynamic relaxation, to verify that the computed system frequency is correct:
The EUROPLEXUS input file reads:

```
QUAS - 02
$
 ECHO
$VERI
!CONV win
CAST 'quas01.msh' MESH
DPLA NONL LAGR
$
DIME
 PT3L 21 ED01 20 ZONE 1
TERM
$
GEOM
   ED01 stru
TERM
$
COMP EPAI 0.1 LECT stru TERM
$
MATE
$ structure
     VM23 RO 2000 YOUN 3.E10 NU 0.2 ELAS 3.E10
          TRAC 1 3.E10 1.0
          LECT stru TERM
$
LINK COUP
     BLOQ 123 LECT bloqall TERM
$
CHAR CONS GRAV 0 -9.80665D0 LECT tous TERM
$
ECRI VITE ECRO TFRE 10.E-3
     FICH K200 TFRE 2.0E-3 POIN TOUS
               VARI VITE ECRO ECRC LECT 1 2 TERM
     fich      alic temp tfre 1.e-3
               poin lect pc term
     fich      alic      tfre 1.e-3
$
OPTI NOTE
 QUAS STAT 3. 1. !UPTO 0.
 csta 0.8e0
 log 1
```

```
CALCUL TINI 0. TEND 500.E-3 pas1 1.e-5
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dy_pc'   DEPL COMP 2 NOEU LECT pc TERM
RCOU  2 'dy_pc'   FICH 'quas01.pun' RENA 'dy_pc_no_damp'
*
trac 2 1 axes 1.0 'DISPL. [M]' yzer
     COLO noir roug
*=================================================================
FIN
```

By comparing the results without and with initial dynamic relaxation one has:



The damping is indeed critical. In agreement with the linear theory, the “static” displacement is one half of the dynamic displacement.

QUAS10

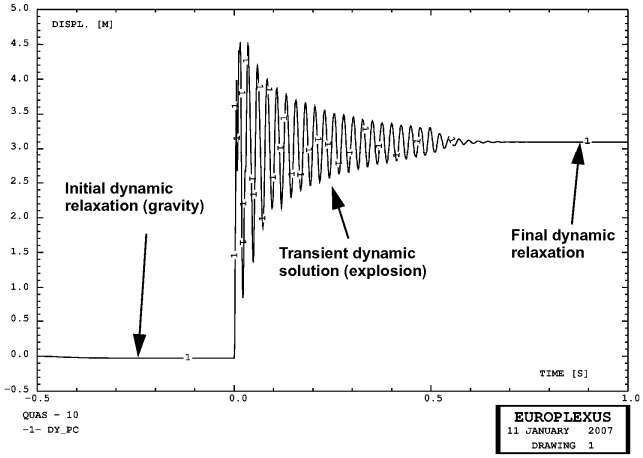
Final calculation modelling the complete system (fluid and structure) and containing an initial and a final dynamic relaxation phases, as explained above.
The Cast3m mesh generation file reads:

```
*%siz 100
opti echo 1;
*
opti titr 'QUAS - 10';
opti dime 2 elem qua4;
*
p1=0 0;
p2=10 0;
p3=10 5;
p4=0 5;
pb= 5 2;
pc= 5 5;
tol=0.001;
c1 = p1 d 10 p2;
c2 = p2 d 5 p3;
c3 = p3 d 10 p4;
c4 = p4 d 5 p1;
flui = dall c1 c2 c3 c4 plan;
elim tol (flui et pb et pc);
bull = flui elem appu larg pb;
air = diff flui bull;
p1p = p1 plus p1;
p2p = p2 plus p1;
p3p = p3 plus p1;
p4p = p4 plus p1;
s1 = p2p d 5 p3p;
s2 = p3p d 10 p4p;
s3 = p4p d 5 p1p;
stru = s1 et s2 et s3;
bloqall = stru poin droi p1 p2 tol;
fsan = cont flui;
fsan = chan poi1 fsan;
list (nbno fsan);
fsrn = flui poin droi p1 p2 tol;
list (nbno fsrn);
fsan = diff fsan fsrn;
list (nbno fsan);
*
mesh=flui et stru et bloqall et fsan et fsrn;
*
tass mesh;
*
opti sauv form 'quas10.msh';
sauv form mesh;
opti trac psc ftra 'quas10_mesh.ps';
*trac qual mesh;
bull = bull coul roug;
air = air coul turq;
trac face (bull et air);
fin;
```

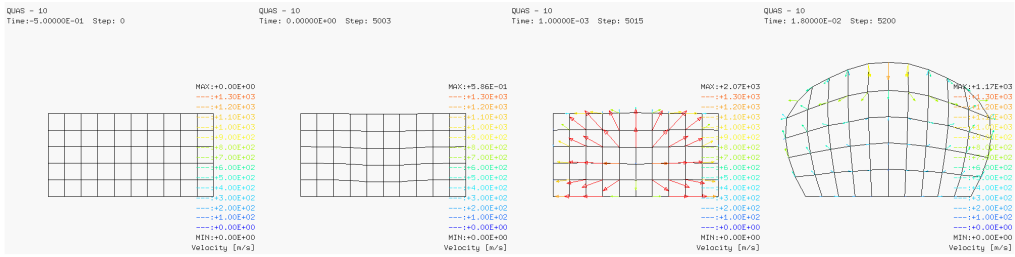
The EUROPLEXUS input file reads:

```
QUAS - 10
$
 ECHO
$VERI
!CONV win
CAST MESH
DPLA NONL ALE
$
DIME
 PT3L 21 PT2L 66 FL24 50 ED01 20 ZONE 2
 NALE 87 NBLE 87
TERM
$
GEOM
   FL24 flui ED01 stru
TERM
$
COMP EPAI 0.1 LECT stru TERM
$
opti rezo mvre modu
GRIL LAGR LECT stru TERM
     EULE LECT fsan fsrn TERM
     ALE  LECT flui TERM
     AUTO autr
$
MATE
**   l'air :  on calcule eint pour avoir P=1 bar (P=omeg*ro*eint)
    flut ro 1.3 eint 0.21978e6 gamm 1.35 PB 0
         ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
         CQ 2.56 PMIN 0 PREF 1.e5 NUM 11
         a 3.738e11 b 3.747e9 r1 4.15 r2 0.90
         ros 1630
         LECT air TERM
        !LECT air bull  TERM
**  Le TNT :   on donne directement ro = ros
*             avec ignition au point PDET a l'instant 0.0
*             la vitesse de detonation est celle de Chapman-Jouguet
    flut ro 1630 eint 3.68e6 gamm 1.35 PB 0
         ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
         CQ 2.56 PMIN 0 PREF 1.e5 NUM 11
         a 3.738e11 b 3.747e9 r1 4.15 r2 0.90
         d 6930 pini 1e5
         TDET 0.
         xdet 5.0 ydet 2.0
        LECT bull TERM
$ structure
     VM23 RO 2000 YOUN 3.E10 NU 0.2 ELAS 3.E10
          TRAC 1 3.E10 1.0
          LECT stru TERM
$
LINK COUP
     BLOQ 123 LECT bloqall TERM
     FSA      LECT fsan TERM
     FSR      LECT fsrn TERM
$
CHAR CONS GRAV 0 -9.80665D0 LECT tous TERM
$
ECRI VITE ECRO TFRE 10.E-3
     FICH K200 TFRE 2.0E-3 POIN TOUS
               VARI VITE ECRO ECRC LECT 1 2 TERM
     fich      alic temp tfre 1.e-3
               poin lect pc term
     fich      alic      tfre 1.e-3
$
OPTI NOTE
 QUAS STAT 3. 1. UPTO 0. FROM 500.E-3
 csta 0.4e0
 dtml
 stel
 log 1
CALCUL TINI -500.E-3 TEND 1000.E-3 pas1 1.e-5
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR  1 'dy_pc'   DEPL COMP 2 NOEU LECT pc TERM
*
trac 1 axes 1.0 'DISPL. [M]'
*=================================================================
FIN
```

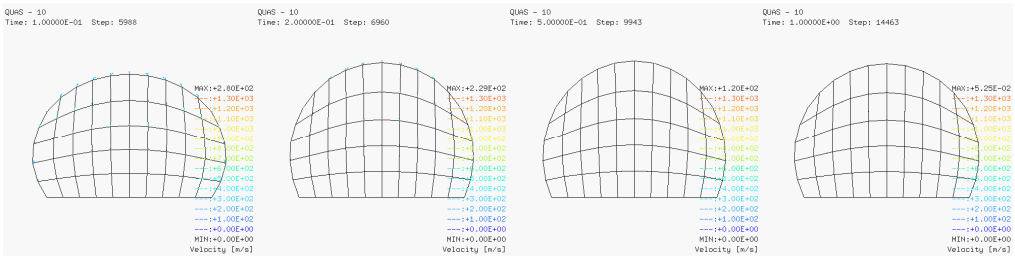
The deflection of the central point is (note the initial and final relaxations):



The velocities and pressures during the various phases are:

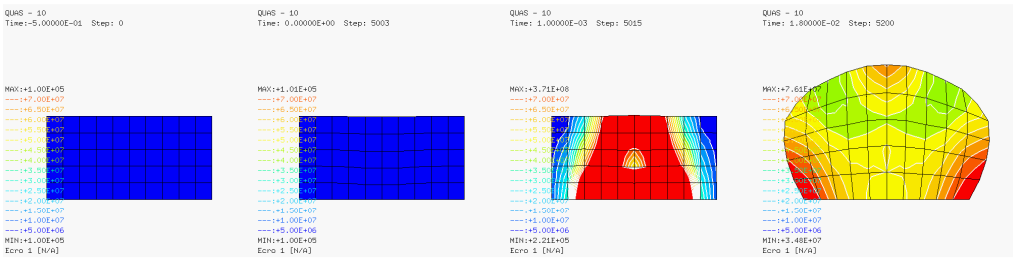


t = -500 ms t = 0 ms t = 1 ms t = 18 ms

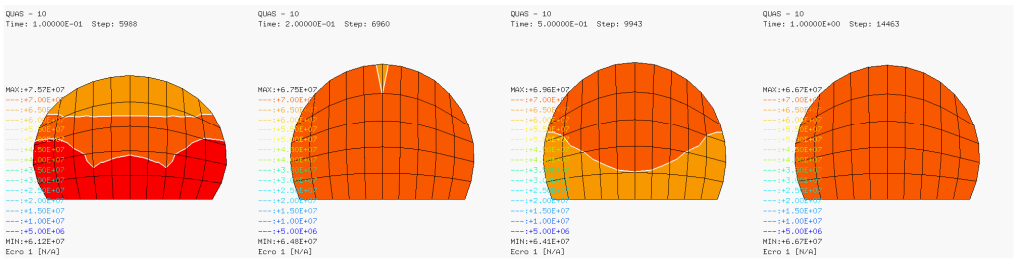


t = 100 ms t = 200 ms t = 500 ms t = 1000 ms

a) velocities and deformed shapes



t = -500 ms t = 0 ms t = 1 ms t = 18 ms

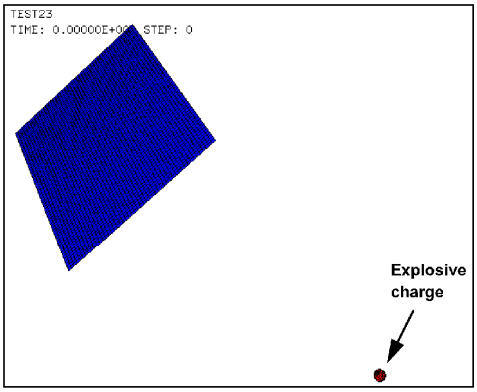


t = 100 ms t = 200 ms t = 500 ms t = 1000 ms

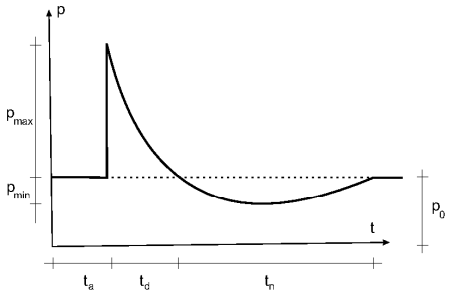
b) fluid pressures

Exercise 15 – Blast on a glass sheet

Simulate the fragmentation of a glass sheet subjected to a blast wave using the AIRB model



Geometry



Pressure (AIRB)

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PROBLEM:
A fragile glass sheet is hit by a an explosive blast wave and fails, generating a cloud of fragments.
MESH:
The sheet is meshed by Q4GS 4-node shell elements. The blast pressure wave is applied to the sheet by means of CL3Q boundary condition elements. A PMAT element is used to visualize the initial position of the explosive charge, and 4 FUN3 elements are used to visualize the external frame of the sheet, which is held fixed.
GEOMETRIC COMPLEMENTS
Debris elements (DEBR) are associated with the whole sheet. By using PLEV 0, just one spherical particle replaces each failing shell element.
MATERIALS:
The glass sheet uses a linear elastic material (VM23) with an associated failure criterion (FAIL PEPR). A special impedance material IMPE AIRB is associated with the CL3Q elements that are used to apply the blast pressure wave to the sheet. A phantom (FANT) material is associated with the FUN3 elements used to visualize the frame.
BOUNDARY CONDITIONS:
The sheet is clamped all around its perimeter.
LOADING:
AIRB pressure loading is applied.
CALCULATIONS:
A calculation is performed until a physical time of 3 ms, when the sheet is completely failed.
RESULTS:
The sheet fragments as expected. Some macro fragments survive until the end of the simulation, together with a cloud of DEBR particles.

POST-TREATMENT
Animations are produced.
Numerical Solutions

TEST23

The Cast3m mesh generation file reads:

```
OPTI echo 1;
opti titr 'test23';
OPTI sauv form 'test23.msh';
opti trac psc ftra 'test23.ps';
OPTI dime 3 elem qua4;
den=0.02;
DENS den;
sizx = 1.00;
sizy = 1.40;
p0 = 0 0 0;
p1 = sizx 0 0;
p2 = sizx sizy 0;
p3 = 0 sizy 0;
pairb = 0.5 0.7 -3.5;
glas = (dall (p0 d p1) (p1 d p2) (p2 d p3) (p3 d p0) plan) coul bleu;
pres = glas coul roug;
!pres = (dall (p0 d p3) (p3 d p2) (p2 d p1) (p1 d p0) plan) coul bleu;
e0 = pres elem cont p0;
e1 = pres elem cont p1;
e2 = pres elem cont p2;
e3 = pres elem cont p3;
tple = e0 et e1 et e2 et e3;
lbq = p0 d p1 d p2 d p3 d;
fram = p0 d 1 p1 d 1 p2 d 1 p3 d 1 p0;
bubb = (manu poi1 pairb) coul roug;
mesh = glas et lbq et pres et bubb et tple et fram;
elim mesh;
TASS mesh;
sauv form mesh;
trac qual mesh;
*
list(nbno glas);
list(nbel glas);
list(nbno pres);
list(nbel pres);
list(nbno bubb);
list(nbel bubb);
list(nbno mesh);
list(nbel mesh);
fin;$
```

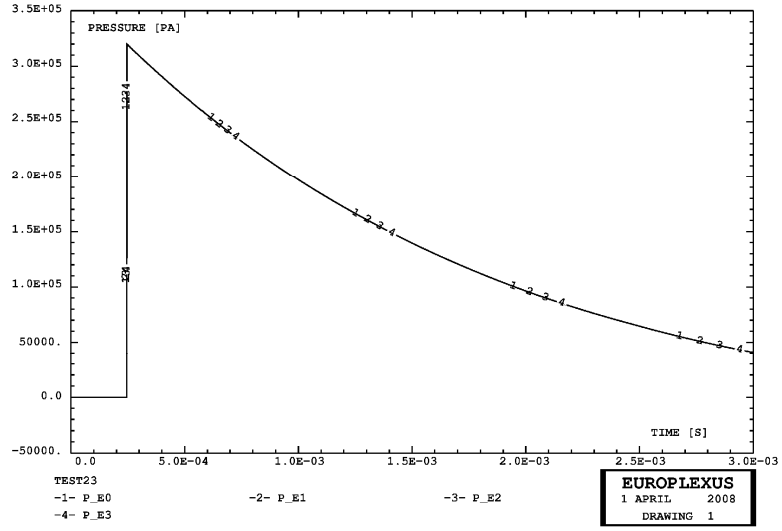
The EUROPLEXUS input file reads:

```
TEST23
ECHO
!CONV win
TRID LAGR FAIL 0.0
CAST FORM mesh
DIME
  PT6L 3622 PT3L 3500 Q4GS 3500 CL3Q 3500 PMAT 1 FUN3 4 DEBR 3500 ZONE 5
  FORC 100
  TABL 1 3
  PRES 33 26
TERM
GEOM
  Q4GS glas
  PMAT bubb
  FUN3 fram
  CL3Q pres
TERM
COMP EPAI 1.E-4 LECT glas TERM
          1.E-1 LECT bubb TERM
          1.E-4 LECT fram TERM
     DEBR ROF 1.0
          FILL PLEV 0
                RO 2500. DRAG 1.D0 TRAJ OBJE LECT glas TERM
     GROU 1 'part' LECT 7006 PAS 1 10505 TERM
     COUL roug LECT part  TERM
MATE VM23 RO 2500 YOUN 7E10 NU 0.23 ELAS 1.756E10
          FAIL PEPR LIMI 0.1
          TRAC 2 1.756E10 0.15 1.8E10 1.15
          LECT glas TERM
!    IMPE AIRB X 0.5 Y 0.7 Z -3.5 MASS 3 TINT -2.E-3
     IMPE AIRB NODE LECT bubb TERM MASS 3 TAUT
          LECT pres TERM
     MASS 1.0 LECT bubb TERM
     FANT 1.0 LECT fram TERM
LINK COUP FREQ 1
     BLOQ 123456 LECT lbq TERM
ECRI DEPL VITE TFRE 3.E-3
     FICH ALIC TEMP FREQ 1
          ELEM LECT tple TERM
     FICH SPLI ALIC TFRE 3.D-5
OPTI NOTE CSTA 0.5 LOG 1
CALC TINI 0. TEND 3.D-3
Fin
```

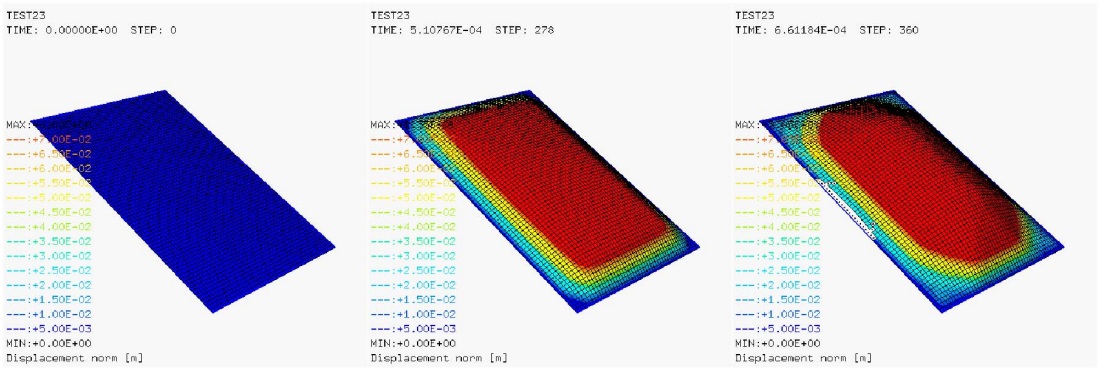
The EUROPLEXUS post-treatment file reads:

```
Post-treatment
ECHO
*
RESU SPLI ALIC 'test23.ali' GARD PSCR
COMP GROU 1 'part' LECT 7006 PAS 1 10505 TERM
*
SORT VISU NSTO 1
*=================================================================
PLAY
CAME   1 EYE  -2.51740E+00 -1.05337E+00  2.51415E+00
!        Q     8.50710E-01  3.34786E-01 -3.09280E-01 -2.61834E-01
         VIEW  7.01532E-01  4.07651E-01 -5.84529E-01
         RIGH  6.71577E-01 -6.52575E-01  3.50899E-01
         UP    2.38404E-01  6.38723E-01  7.31571E-01
         FOV   2.48819E+01
CAME   2 EYE   1.35836E+00 -3.40898E+00  2.68476E+00
!        Q     8.56960E-01  3.69966E-01  2.05747E-01 -2.93961E-01
         VIEW -1.35123E-01  7.55055E-01 -6.41587E-01
         RIGH  7.42511E-01 -3.51586E-01 -5.70145E-01
         UP    6.56064E-01  5.53425E-01  5.13129E-01
         FOV   2.48819E+01
SCEN GEOM NAVI FREE
          FACE SBAC
          POIN SPHP
     ISO  FILL FIEL DEPL SCAL USER PROG 0.5E-2 PAS 0.5E-2 7.E-2 TERM
     VECT SCCO FIEL VITE SCAL USER PROG 40. PAS 40. 560. TERM
     TEXT ISCA
     TEXT VSCA
     COLO PAPE
     LIMA ON
SLER CAM1 1 NFRA 1
FREQ 1
TRAC OFFS FICH AVI NOCL NFTO 101 FPS 10 KFRE 10 COMP -1
  OBJE NFAI LECT glas part fram TERM REND
GOTR LOOP 99 OFFS FICH AVI CONT NOCL
  OBJE NFAI LECT glas part fram TERM REND
GO
TRAC OFFS FICH AVI CONT
  OBJE NFAI LECT glas part fram TERM REND
ENDPLAY
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP 'test23.alt' GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 1 'p_e0' ECRO COMP 1 ELEM LECT e0 TERM
COUR 2 'p_e1' ECRO COMP 1 ELEM LECT e1 TERM
COUR 3 'p_e2' ECRO COMP 1 ELEM LECT e2 TERM
COUR 4 'p_e3' ECRO COMP 1 ELEM LECT e3 TERM
TRAC 1 2 3 4 AXES 1.0 'Pressure [Pa]'
FIN
```

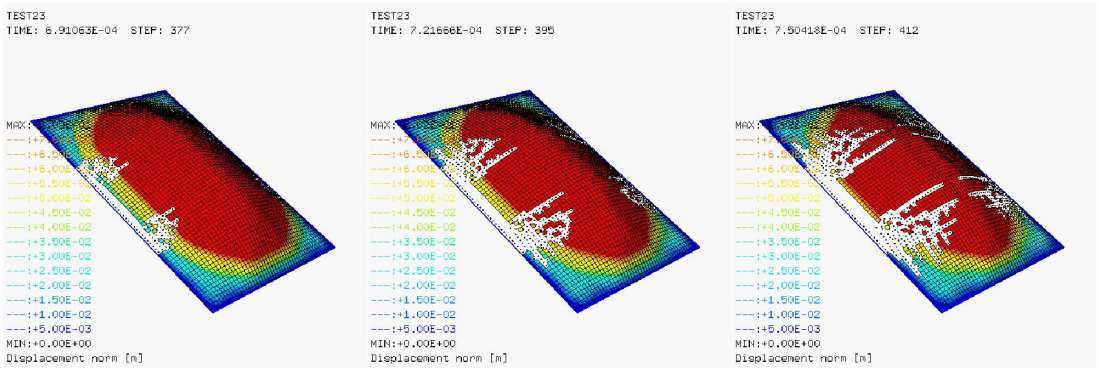
The resulting AIRB pressure at the four corners of the sheet is:



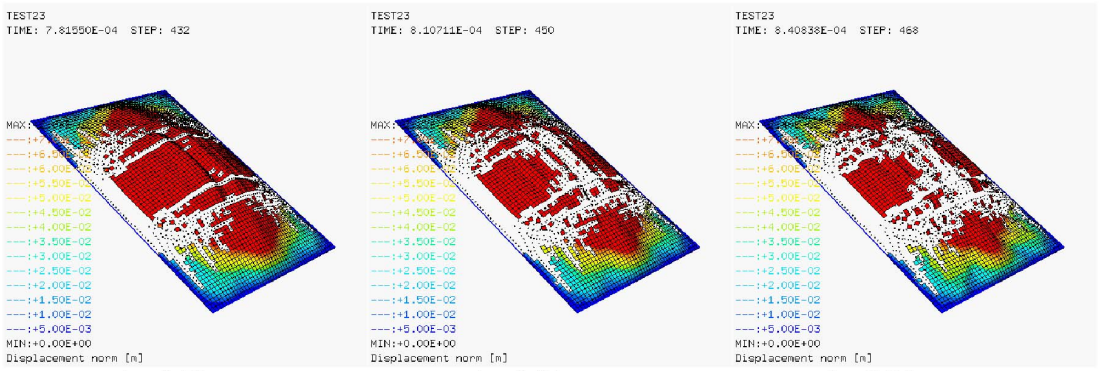
The fragmentation process and the velocities are shown in the next figures:



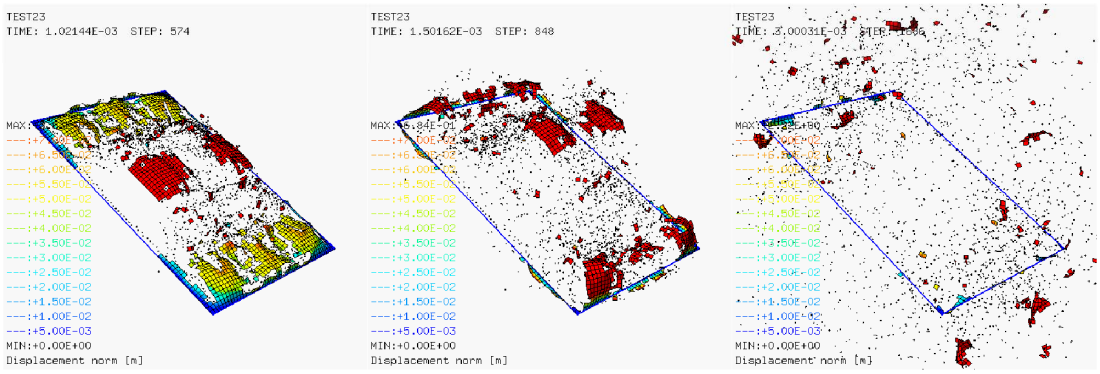
t = 0 t = 0.50 ms t = 0.66 ms



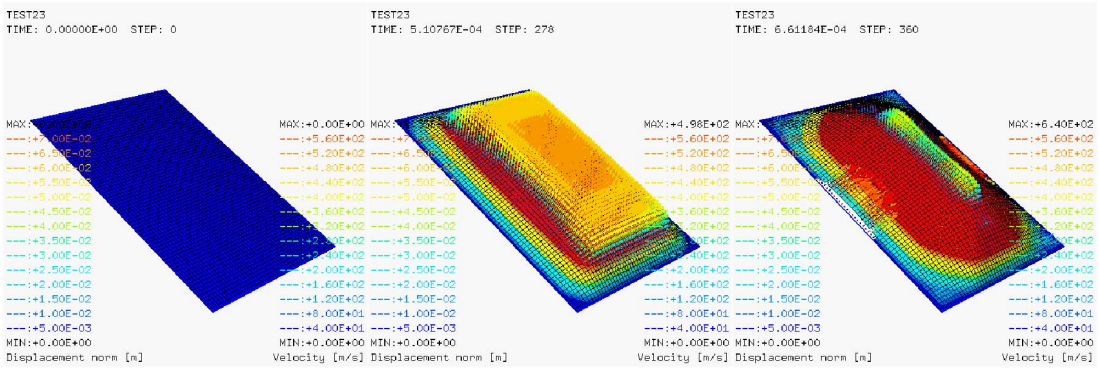
t = 0.69 ms t = 0.72 ms t = 0.75 ms



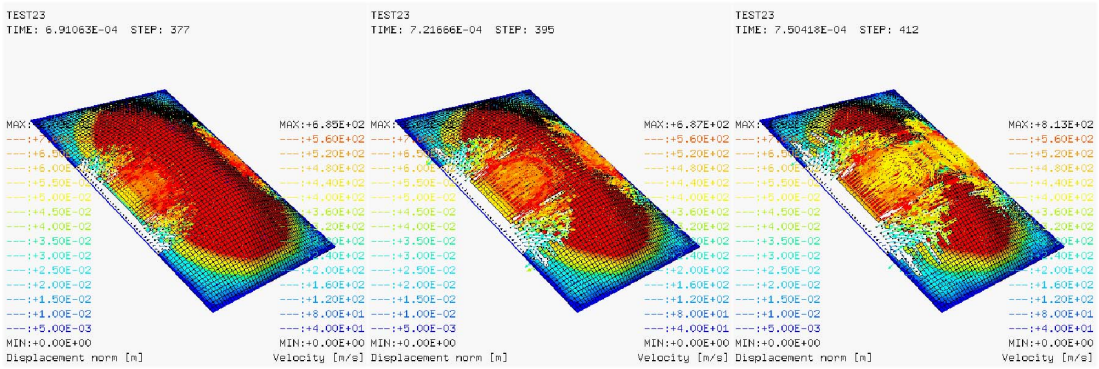
t = 0.78 ms t = 0.81 ms t = 0.84 ms



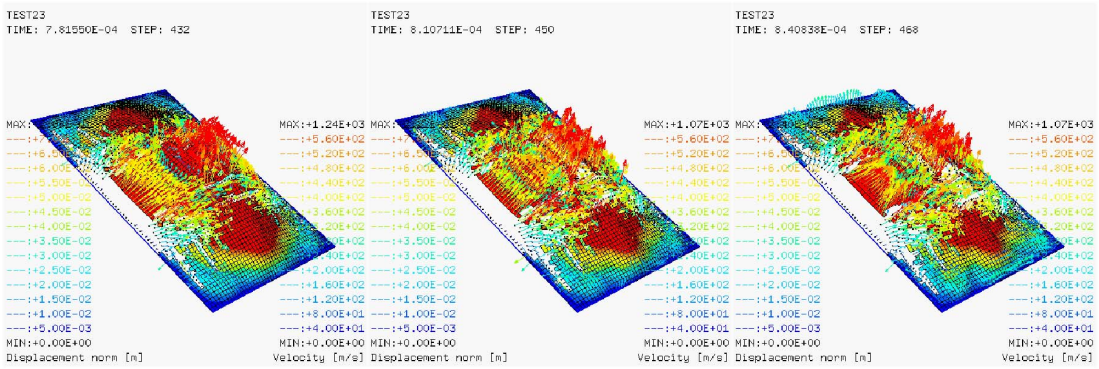
t = 1.02 ms t = 1.50 ms t = 3.00 ms



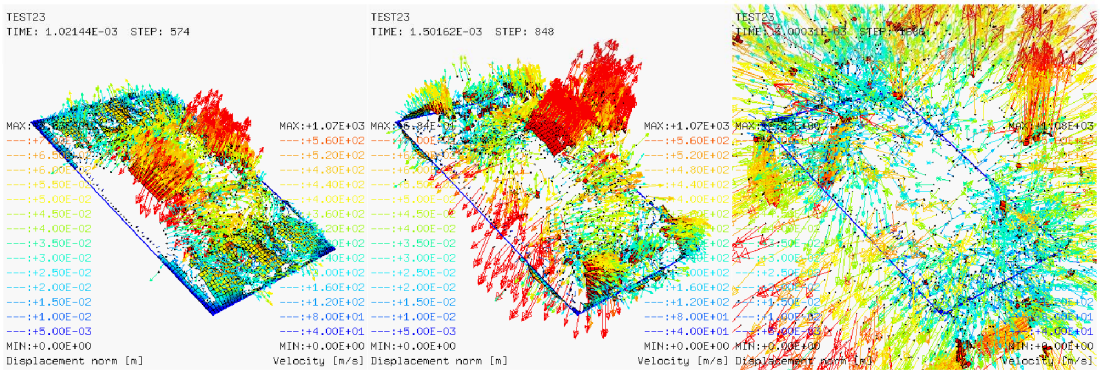
t = 0 t = 0.50 ms t = 0.66 ms



t = 0.69 ms t = 0.72 ms t = 0.75 ms



t = 0.78 ms t = 0.81 ms t = 0.84 ms

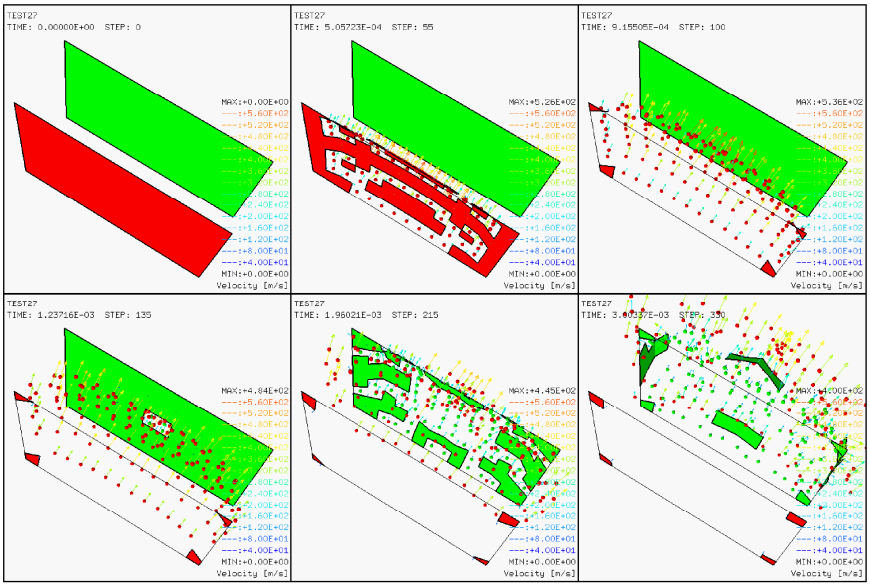


t = 1.02 ms t = 1.50 ms t = 3.00 ms

Formation of secondary debris

Exercise 15b – Secondary debris

Simulate the formation of secondary debris due to impact of primary debris on a glass sheet :



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A glass sheet is loaded by an air blast wave and breaks up into fragments (debris particles). These particles impact a second glass sheet nearby and break it up into secondary debris particles.

TEST27

The Cast3m mesh generation file reads:

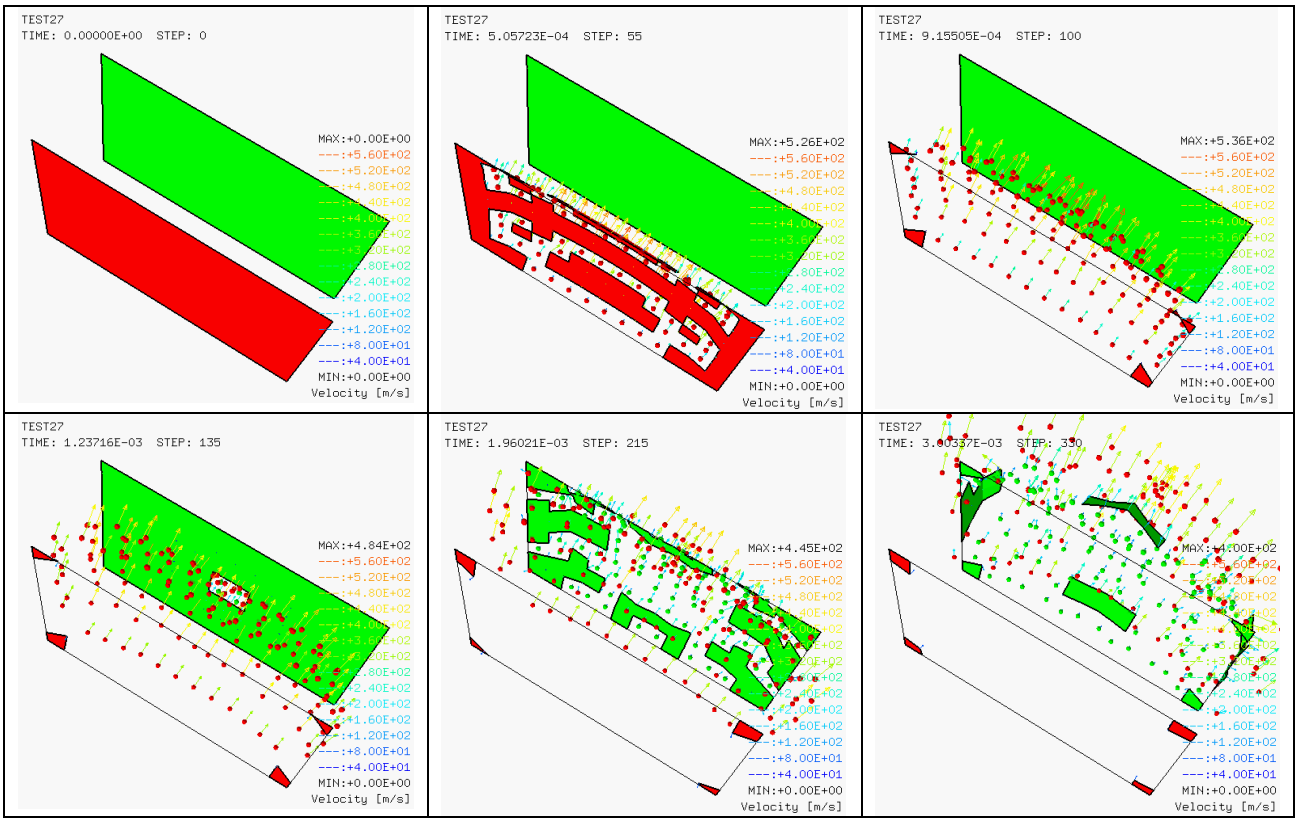
```
OPTI echo 1;
opti titr 'test27';
OPTI sauv form 'test27.msh';
opti trac psc ftra 'test27_mesh.ps';
OPTI dime 3 elem qua4;
den=0.10;
DENS den;
sizx = 1.00;
sizy = 1.40;
p0 = 0 0 0;
p1 = sizx 0 0;
p2 = sizx sizy 0;
p3 = 0 sizy 0;
pairb = 0.5 0.7 -3.5;
glas = (dall (p0 d p1) (p1 d p2) (p2 d p3) (p3 d p0) plan) coul roug;
glas2 = (glas plus (0 0 0.5)) coul vert;
pres = glas coul jaun;
e0 = pres elem cont p0;
e1 = pres elem cont p1;
e2 = pres elem cont p2;
e3 = pres elem cont p3;
tple = e0 et e1 et e2 et e3;
lbq = p0 d p1 d p2 d p3 d;
lbq = lbq et (cont glas2);
fram = p0 d 1 p1 d 1 p2 d 1 p3 d 1 p0;
fram = fram et (fram plus (0 0 0.5));
bubb = (manu poi1 pairb) coul roug;
mesh = glas et glas2 et lbq et pres et bubb et tple et fram;
elim mesh;
TASS mesh;
sauv form mesh;
trac qual mesh;
*
list(nbno glas);
list(nbel glas);
list(nbno glas2);
list(nbel glas2);
list(nbno pres);
list(nbel pres);
list(nbno bubb);
list(nbel bubb);
list(nbno mesh);
list(nbel mesh);
fin;
```

The EUROPLEXUS input file reads:

```
TEST27
ECHO
  CONV win
TRID LAGR EROS 0.0
CAST FORM mesh
DIME
  PT6L 330 PT3L 289 Q4GS 280 CL3Q 140 PMAT 1 FUN3 8 DEBR 280 ZONE 5
TERM
GEOM
  Q4GS glas glas2
  PMAT bubb
  FUN3 fram
  CL3Q pres
TERM
COMP EPAI 1.E-4 LECT glas glas2 TERM
          1.E-1 LECT bubb TERM
          1.E-4 LECT fram TERM
     DEBR ROP 1.0
          FILL PLEV 0
               RO 2500. DRAG 1.D0 TRAJ OBJE LECT glas TERM
          FILL PLEV 0
               RO 2500. DRAG 1.D0 TRAJ OBJE LECT glas2 TERM
     GROU 3 'part1' LECT 430 PAS 1 569 TERM
            'part2' LECT 570 PAS 1 709 TERM
            'part'  LECT part1 part2   TERM
     COUL roug LECT part1 TERM
          vert LECT part2 TERM
MATE VM23 RO 2500 YOUN 7E10 NU 0.23 ELAS 1.756E10
          !FAIL PEPR LIMI 0.1
          FAIL PEPR LIMI 0.05
          TRAC 2 1.756E10 0.15 1.8E10 1.15
          LECT glas glas2 TERM
     IMPE AIRB NODE LECT bubb TERM MASS 3 TAUT
          LECT pres TERM
     MASS 1.0 LECT bubb TERM
     FANT 1.0 LECT fram TERM
LINK COUP PREQ 1
     BLOQ 123456 LECT lbq TERM
     PINB BODY       DMIN 0.02 LECT glas2 TERM
          BODY MLEV 0 DIAM 0.02 LECT part1 TERM
```

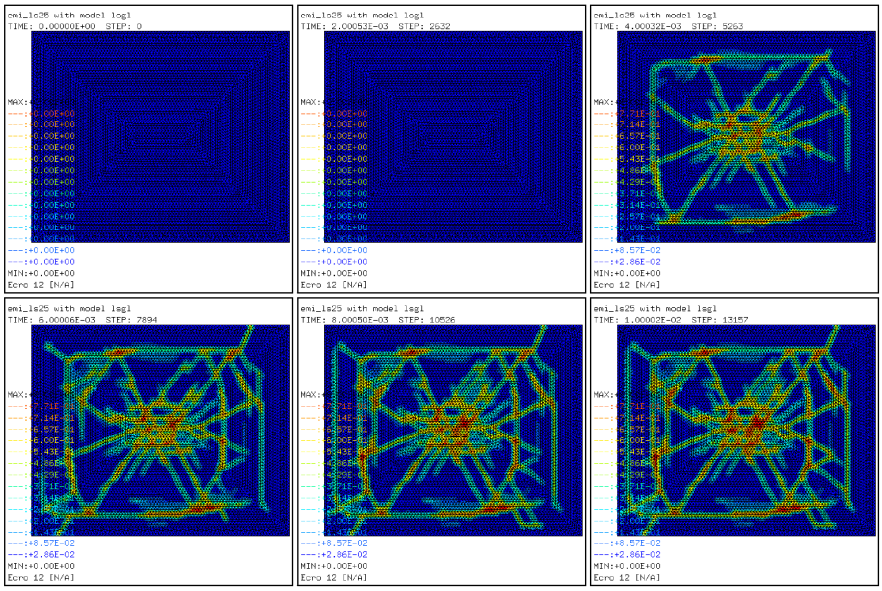
```
ECRI DEPL VITE TFRE 3.E-3
     FICH ALIC FREQ 1
OPTI NOTE CSTA 0.5 LOG 1
CALC TINI 0. TEND 3.D-3
*================================================================
PLAY
CAME   1 EYE  -3.25928E+00  1.61671E-01 -1.27078E+00 ! From below
!        Q     5.00268E-01  4.44242E-01 -7.09366E-01 -2.21768E-01
         VIEW  9.06783E-01  1.29851E-01  4.01102E-01
         RIGH -1.04761E-01 -8.52147E-01  5.12708E-01
         UP   -4.08374E-01  5.06935E-01  7.59109E-01
         FOV   2.48819E+01
SCEN GEOM NAVI FREE
          FACE SBAC
          LINE HEOU SFRE
          POIN SPHP FACT 2.0
          PINB CDES
     VECT SCCO FIEL VITE SCAL USER PROG 40. PAS 40. 560. TERM
     TEXT VSCA
     COLO PAPE
     LIMA ON
          LIGY -1
         !SELE BRAS
         !APPL MESH
SLER CAM1 1 NFRA 1
FREQ 1
TRAC OFFS FICH AVI NOCL NFTO 331 FPS 25 KFRE 10 COMP -1
     OBJE NFAI LECT glas glas2 part fram TERM REND
GOTR LOOP 329 OFFS FICH AVI CONT NOCL
     OBJE NFAI LECT glas glas2 part fram TERM REND
GO
TRAC OFFS FICH AVI CONT
     OBJE NFAI LECT glas glas2 part fram TERM REND
ENDPLAY
*================================================================
FIN
```

The fragmentation process is shown in the next figure:



Crack formation in Laminated Glass

Exercise 15c – Crack formation
in Laminated Glass



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A laminated glass sheet is loaded by an air blast wave. After va certain time, cracks are formed whose pattern resembles the experimentally observed one.

EMI_LS25_DKT3

The Cast3m mesh generation file reads:

```
OPTI echo 1;
OPTI dime 3 elem tet4;
den=0.0125;
DENS den;
sizx = 1.1;
sizy = 0.9;
rand = 0.05;
b11 = rand rand 0;
b12 = (sizx-rand) rand 0;
b13 = (sizx-rand) (sizy-rand) 0;
b14 = rand (sizy-rand) 0;
li1 = b11 d b12 d b13 d b14 d;
a_airb = surf li1 plan;

b31 = 0 0 0;
b32 = sizx 0 0;
li3 = b31 d b32 d b12 d b11 d;
a3 = surf li3 plan;

b41 = sizx sizy 0;
li4 = b32 d b41 d b13 d b12 d;
a4 = surf li4 plan;

b51 = 0 sizy 0;
li5 = b41 d b51 d b14 d b13 d;
a5 = surf li5 plan;

li6 = b31 d b11 d b14 d b51 d;
a6 = surf li6 plan;

a_rand = a3 et a4 et a5 et a6;
a_glass1 = a_airb et a_rand;

p1 = 0 0 0.004;
p2 = 0 0 -0.004;
v1 = a_rand volu 'TRAN' p1;
v1 = v1 et (a_rand volu 'TRAN' p2);

pch1 = ((sizx+rand)/2.) ((sizy+rand)/2.) 1.8;
ch1 = manu poi1 pch1;

pcent = ((sizx+rand)/2.) ((sizy+rand)/2.) 0;

pdis = a_glass1 poin 'PROC' pcent;

edis1 = a_glass1 ELEM CONTENANT pdis;

a_v1 = v1 enve;

kod1 = faux;
REPE I0 (NBEL (a_v1 ELEM TRI3));
  xx yy zz = coor (bary (a_v1 ELEM TRI3 &I0));
  SI ( zz ega 0.004 0.001);
     si (kod1);bound=bound et (a_v1 ELEM TRI3 &I0);
     sinon; bound = a_v1 ELEM TRI3 &I0;kod1 = vrai;
     fins;
  FINS;
  SI ( zz ega -0.004 0.001);
     si (kod1);bound=bound et (a_v1 ELEM TRI3 &I0);
     sinon; bound = a_v1 ELEM TRI3 &I0;kod1 = vrai;
     fins;
  FINS;
FIN I0;


modell = v1 et a_glass1 et a_airb et pdis et
         edis1 et ch1 et bound;
elim modell;

TASS modell;
OPTI sauv form 'emi_ls25_dkt3.msh';
sauv form modell;
```

The EUROPLEXUS input file reads:

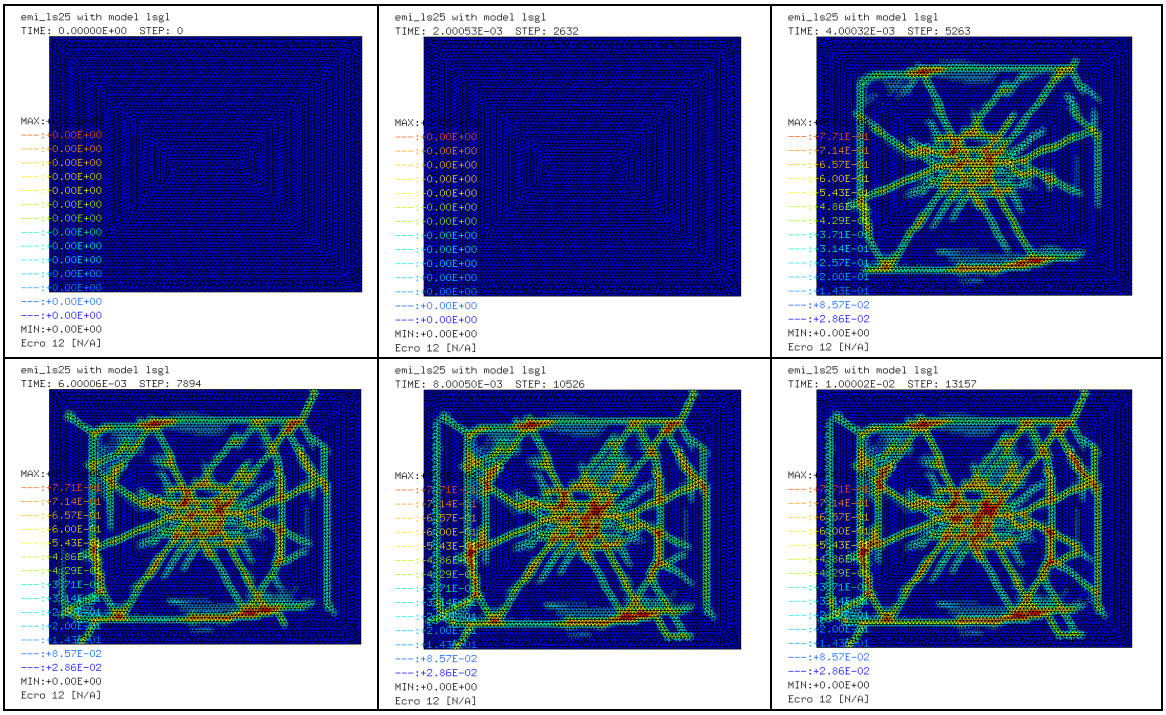
```
emi_ls25 with model lsgl
$
 ECHO
! VERI
! CONV WIN
CAST modell
TRID LAGR EROS 1.0
OPTI TOLC 1e-1
$
```

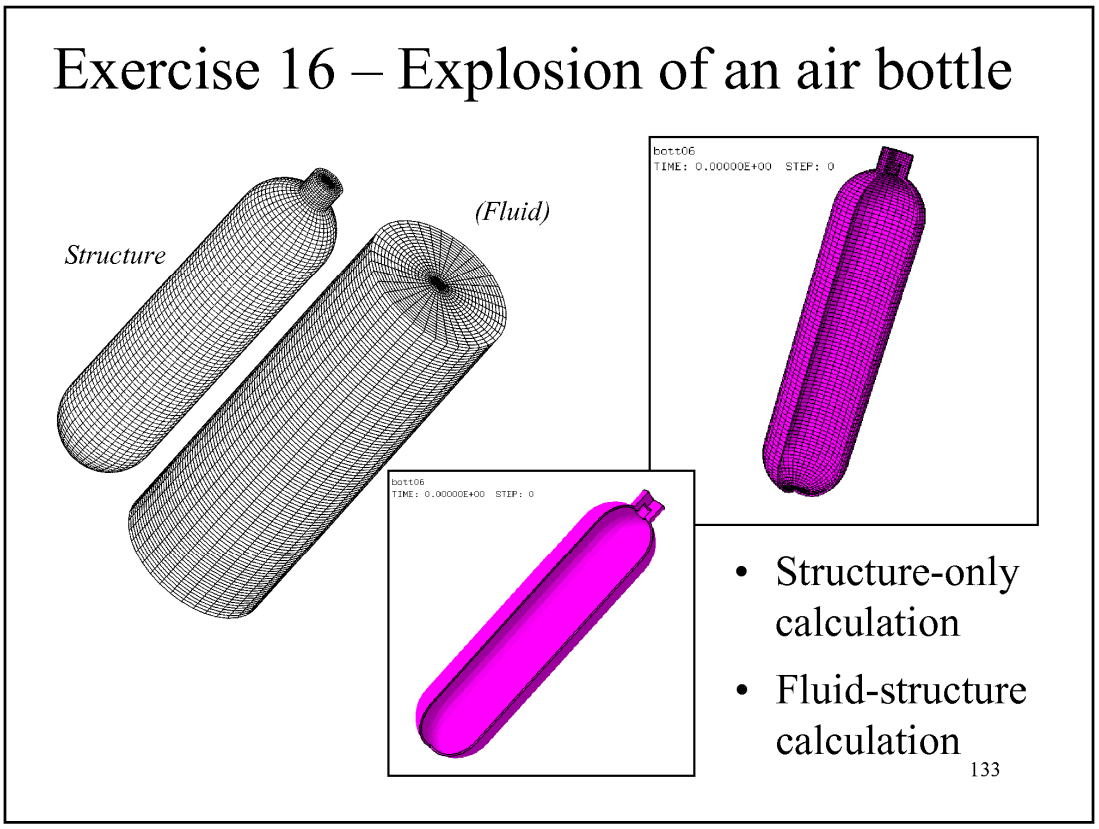
```
DIME
  PT6L       12000     ZONE  4
  PR6         5708     CL3T        14808     DKT3  14808
  PMAT 1
  ECRO     3373653
  LIAI       10400
  BLOQ       10400
  MNTI 102
  NGPZ 5
```

```
TERM
$
GEOM
   PR6 v1
  DKT3 a_glass1
  PMAT ch1
  CL3T a_airb
TERM
$
COMP
 EPAI 0.0075 LECT a_glass1 TERM
      0.05 LECT ch1 TERM ! only for visualization
 SAND    3
  FRAC 0.4 0.2 0.4
  NGPZ   2 1 2
  LECT a_glass1 term
 COUL roug LECT ch1 TERM
      turq LECT a_glass1 TERM
      jaun LECT a_airb TERM
      vert LECT v1 TERM
MATE
      LSGL RO 2500 YOUN 7E10 NU 0.23 CORR 16.0
           FAIL PEPR LIMI 0.0012
           LECT a_glass1 TERM
           laye lect 1 3 term
      VM23 RO 1100. YOUNG 3E6 NU 0.46 ELAS 3.45E9
           TRAC 1 3.45E9 15
           LECT a_glass1 TERM
           laye lect 2 term
      VM23 RO 2770. YOUNG 3.5e6 NU 0.42 ELAS 3.45E9
           TRAC 1 3.45E9 0.15
           LECT v1 TERM
      IMPE AIRB NODE LECT ch1 TERM CONF 1 MASS 0.09 TAUT
           LECT a_airb TERM
      FANT 1.E-3 LECT ch1 TERM
LIAI BLOQ 123 bound

ECRI DEPL VITE TFRE 5.E-3
     FICH SPLI ALIC tfreq 1e-4
     FICH ALIC TEMP tfreq 5e-5
               POIN LECT pdis TERM
               ELEM LECT 4148 1628 1698 edis1 TERM
$
OPTI NOTE LOG 1
$
CALC TINI 0 TEND 10e-3
*================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1.0 'Time [s]'
COUR 1 'sig_edis' CONT COMP 1 GAUZ 0 ELEM LECT 4148 TERM
COUR 2 'sig_edis' CONT COMP 2 GAUZ 0 ELEM LECT 4148 TERM
COUR 3 'sig_edis' ECRO COMP 12 GAUZ 0 ELEM LECT 4148 TERM
COUR 4 'sig_edis' ECRO COMP 9 GAUZ 0 ELEM LECT 4148 TERM
COUR 5 'sig_edis' ECRO COMP 4 GAUZ 0 ELEM LECT 4148 TERM
COUR 6 'sig_edis' ECRO COMP 5 GAUZ 0 ELEM LECT 4148 TERM
COUR 7 'sig_edis' ECRO COMP 8 GAUZ 0 ELEM LECT 4148 TERM
COUR 11 'sig_edis' CONT COMP 1 GAUZ 0 ELEM LECT 1628 TERM
COUR 12 'sig_edis' CONT COMP 2 GAUZ 0 ELEM LECT 1628 TERM
COUR 13 'sig_edis' ECRO COMP 12 GAUZ 0 ELEM LECT 1628 TERM
COUR 14 'sig_edis' ECRO COMP 9 GAUZ 0 ELEM LECT 1628 TERM
COUR 15 'sig_edis' ECRO COMP 4 GAUZ 0 ELEM LECT 1628 TERM
COUR 16 'sig_edis' ECRO COMP 5 GAUZ 0 ELEM LECT 1628 TERM
COUR 17 'sig_edis' ECRO COMP 8 GAUZ 0 ELEM LECT 1628 TERM
COUR 21 'sig_edis' CONT COMP 1 GAUZ 0 ELEM LECT 1698 TERM
COUR 22 'sig_edis' CONT COMP 2 GAUZ 0 ELEM LECT 1698 TERM
COUR 23 'sig_edis' ECRO COMP 12 GAUZ 0 ELEM LECT 1698 TERM
COUR 24 'sig_edis' ECRO COMP 9 GAUZ 0 ELEM LECT 1698 TERM
COUR 25 'sig_edis' ECRO COMP 4 GAUZ 0 ELEM LECT 1698 TERM
COUR 26 'sig_edis' ECRO COMP 5 GAUZ 0 ELEM LECT 1698 TERM
COUR 27 'sig_edis' ECRO COMP 8 GAUZ 0 ELEM LECT 1698 TERM
COUR 9 SOMME 3 5 1 6 1 7 1
COUR 19 SOMME 3 15 1 16 1 17 1
COUR 29 SOMME 3 25 1 26 1 27 1
COUR 99 'ds_pdis' DEPL COMP 3 NOEU LECT pdis TERM
trac 1 2  axes 1.0 'SIG'
trac 9  axes 1.0 'EPSHYD'
trac 3 4  axes 1.0 'FAIL'
trac 11 12  axes 1.0 'SIG'
trac 19  axes 1.0 'EPSHYD'
trac 13 14  axes 1.0 'FAIL'
trac 21 22  axes 1.0 'SIG'
trac 29  axes 1.0 'EPSHYD'
trac 23 24  axes 1.0 'FAIL'
trac 99 text axes 1.0 'DISPL. [M]'
SUIT
*================================================================
emi12_avi
 ECHO
 CONV WIN
RESU SPLI ALIC GARD PSCR
*
OPTI PRIN
*
SORT VISU NSTO 1
*================================================================
PLAY
CAME   1 EYE   5.00000E-01  4.00000E-01  6.42268E+00
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   1.08819E+01
SCEN GEOM NAVI FREE
          FACE SBAC
          POIN SPHP
     ISO  FILL FIEL ECRO 12 SCAL A14
     TEXT ISCA
     COLO PAPE
sler cam1 1        nfra 1
freq 200
go
trac offs fich bmp
     obje lect a_glass1 term   rend
ENDPLAY
*================================================================
FIN
```

The cracking process is shown in the next figure:





PROBLEM:
A metal bottle filled by pressurized air explodes. The bottle is axisymmetric but a full 3D model is used to simulate the fragmentation. Two simulations are performed. In the first one only the structure is modelled and the inner pressure is applied by an IMPE PIMP boundary condition by means of CL3d and CL3T elements. In the second simulation, the inner and outer air are modelled by means of FL38 and FL36 fluid elements and the fluid-structure interaction is modelled by the FLSR directive. In both calculations the fragmentation process is treated by means of DEBR particles.

MESH:
The bottle is meshed by CUB8 and PR6 solid elements. The fluid, when present, is modelled by means of FL38 and FL36 fluid elements.

GEOMETRIC COMPLEMENTS
Debris elements (DEBR) are associated with the whole bottle. By using PLEV 0, just one spherical particle replaces each failing element.

MATERIALS:
The metallic bottle uses a linear elastoplastic material (VM23) with an associated failure criterion (FAIL PEPS). For the fluid, the FLUT material is used. In the calculation with fluid, absorbing boundary conditions are applied on the external surface of the fluid domain by means of an IMPE ABSI material

BOUNDARY CONDITIONS:
The bottle is free in 3D space. Fluid-structure interaction in the second simulation uses the FLSR model.

LOADING:
In the first simulation an internal pressure raising in time is applied. In the second simulation, the loading is produced by the high initial pressure of the internal air.

CALCULATIONS:
Calculations are performed until a physical time of 0.35 ms, when the bottle is completely failed.

RESULTS:
The bottle fragments as expected. Some macro fragments survive until the end of the simulation, together with a cloud of DEBR particles.

POST-TREATMENT
Animations are produced.

Numerical Solutions

BOTT02

This is the first simulation, including only the structure. The Cast3m mesh generation file reads:

```
opti echo 0;
opti donn 'pxordpoi.proc';
opti donn 'pxvolu3d.proc';
opti donn 'pxrota3d.proc';
opti echo 1;
opti dime 3 elem cub8;
opti titr 'bott02';
opti trac psc ftra 'bott02_mesh.ps';
opti sauv form 'bott02.msh';
oeily = 0 -100000 0;
*
l = 0.6;
ri = 0.1;
h = 0.005;
re = ri + h;
*
p0 = 0 0 0;
p1 = 0 0 l;
p2 = 0 0 (0 - ri);
p3 = ri 0 0;
p4 = ri 0 l;
p8 = 0 0 (0 - ri - h);
p9 = (ri + h) 0 0;
p10 = (ri + h) 0 l;
p1y = p1 plus (0 -1 0);
p11 = p10 TOUR 70.0 p1 p1y;
p14 = p4 TOUR 70.0 p1 p1y;
x11 y11 z11 = coor p11;
x14 y14 z14 = coor p14;
p12 = x11 0 0.75;
p13 = 0 0 0.75;
p5 = p4 tour 80.0 p1 p1y;
x5 y5 z5 = coor p5;
p15 = x5 0 (z5 + h);
p16 = x5 0 0.75;
p6 = x5 0 0.725;
p7 = 0 0 0.725;
p17 = ri 0 (l*0.5);
tol = 1.E-4;
*
c1 = p2 d 1 p8;
p0y = p0 plus (0 -1 0);
bot1 = c1 ROTA 18 90.0 p0 p0y;
elim tol (bot1 et p3 et p9);
*
c2 = p3 d 1 p9;
bot2 = c2 TRAN 60 (0 0 l);
elim tol (bot2 et p10 et p4 et p17);
*
c3 = p4 d 1 p10;
bot3 = c3 ROTA 15 70.0 p1 p1y;
elim tol (bot3 et p11 et p14);
*
c4 = p5 c 3 p1 p14;
c5 = p14 d 1 p11;
c6 = p11 c 3 p1 p15;
c7 = p15 d 1 p5;
bot4 = DALL c4 c5 c6 c7 PLAN;
*
ca = p15 c 3 p1 p11;
cb = p11 d 10 p12;
cc = p12 d 3 p16;
cd = p16 d 5 p6 d 5 p15;
bot5 = DALL ca cb cc cd PLAN;
*
ce = p7 d 3 p6;
cf = p6 d 5 p16;
cg = p16 d 3 p13;
ch = p13 d 5 p7;
bot6 = DALL ce cf cg ch PLAN;
*
bott = bot1 et bot2 et bot3 et bot4 et bot5 et bot6;
elim tol bott;
*
bott1a ier s1n = pxvolu3d (bot1 et bot2) 9 -90.0 c1 tol;
list ier;
bott1b ier s1n = pxvolu3d (bot3 et bot4 et bot5 et bot6) 9 -90.0 ch tol;
list ier;
bott1 = bott1a et bott1b;
elim tol bott1;
*
bott2 = bott1 tour 90.0 p0 p1;
bott3 = bott2 tour 90.0 p0 p1;
bott4 = bott3 tour 90.0 p0 p1;
bottle = bott1 et bott2 et bott3 et bott4;
elim tol bottle;
*
trac cach bottle;
*
trac oeily bott;
trac oeily qual bott;
trac qual oeily (bot3 et bot4 et bot5 et bot6);
trac oeily (bot3 et bot4 et bot5 et bot6);
*
bott18 = bottle elem cub8;
bott16 = bottle elem pri6;
list (nbno bottle);
list (nbel bottle);
list (nbel bott18);
list (nbel bott16);
*
* internal surface (to apply the pressure)
*
icon1 = p2 c 18 p0 p3 d 60 p4;
*icon2 = p4 c 15 p1 p14 c 3 p1 p5 d 1 p15 d 5 p6 d 3 p7;
icon2 = p7 d 3 p6 d 5 p15 d 1 p5 c 3 p1 p14 c 15 p1 p4;
trac (icon1 et icon2);
isur1a ier = pxrota3d icon1 9 -90.0 c1 tol;
list ier;
ax = p7 d 1 p13;
isur1b ier = pxrota3d icon2 9 90.0 ax tol;
list ier;
isur1 = isur1a et isur1b;
isur2 = isur1 tour 90.0 p0 p1;
isur3 = isur2 tour 90.0 p0 p1;
isur4 = isur3 tour 90.0 p0 p1;
isurf = isur1 et isur2 et isur3 et isur4;
elim tol (isurf et bottle);
trac cach isurf;
*
isurf4 = isurf elem qua4;
isurf3 = isurf elem tri3;
list (nbno isurf);
list (nbel isurf);
list (nbel isurf4);
list (nbel isurf3);
e17 = (bott1 elem appu larg p17) elem 1;
list e17;
*
mesh = bottle et isurf;
tass mesh;
sauv form mesh;
*
fin;
```

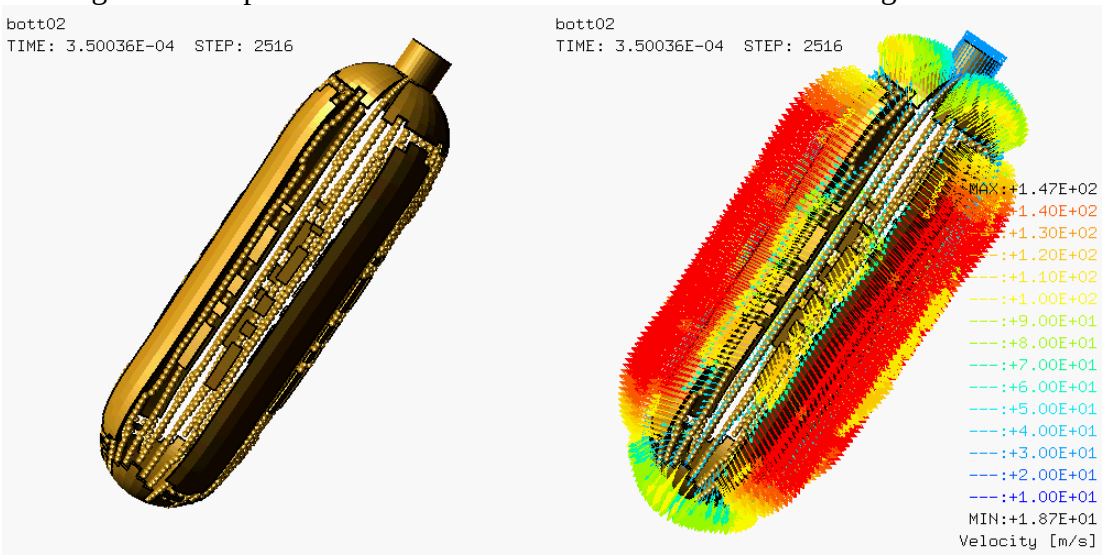
The EUROPLEXUS input file reads:

```
bott02
ECHO
!CONV win
TRID LAGR FAIL 0.0
CAST FORM mesh
DIME
  PT3L 13652 CUB8 4860 PR6 216 CL3D 3708 CL3T 72 DEBR 4860 ZONE 5
TERM
GEOM
  CUB8 bott18
  PR6  bott16
  CL3D isurf4
  CL3T isurf3
TERM
COMP COUL rose LECT bottle TERM
          vert LECT isurf  TERM
     DEBR ROF 1.0
          FILL PLEV 0
```

```
              RO 8000. DRAG 1.0 OBJE LECT bottl8 TERM
MATE VM23 RO 8000 YOUN 2.E11 NU 0.3 ELAS 2.E8
          FAIL PEPS LIMI 0.05
          TRAC 2 2.E8 0.001 2.02E8 1.001
          LECT bottle TERM
     IMPE PIMP RO 1.0 PRES 1.0 PREF 0.0 FONC 1
          LECT isurf TERM
FONC NUM 1 TABL 2 0.0 2.E7 1.0 2.E10
ECRI DEPL VITE TFRE 1.E-4
     FICH SPLI ALIC TFRE 1.E-6
     FICH ALIC TEMP TFRE 1.E-6
          POIN LECT p2 p3 p17 p4 p7 TERM
          ELEM LECT e17 TERM
OPTI NOTE LOG 1
CALC TINI 0. TEND 0.35E-3
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
```

```
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 1 'dy_p2' DEPL COMP 2 POIN LECT p2 TERM
COUR 2 'dx_p3' DEPL COMP 1 POIN LECT p3 TERM
COUR 3 'dx_p17' DEPL COMP 1 POIN LECT p17 TERM
COUR 4 'dx_p4' DEPL COMP 1 POIN LECT p4 TERM
COUR 5 'dy_p7' DEPL COMP 2 POIN LECT p7 TERM
COUR 6 'vm_e17' ECRO COMP 2 ELEM LECT e17 TERM
TRAC 1 2 3 4 5 AXES 1.0 'Displ. [M]'
TRAC 6 AXES 1.0 'Von Mises [Pa]'
FIN
```

The fragmentation process and the velocities are shown in the next figures:



BOTT05

This is the second silulation, including both the structure and the fluid. The Cast3m mesh generation file reads:

```
opti echo 0;
opti donn 'pxordpoi.proc';
opti donn 'pxvolu3d.proc';
opti donn 'pxrota3d.proc';
opti echo 1;
opti dime 3 elem cub8;
opti titr 'bott05';
opti trac psc ftra 'bott05_mesh.ps';
opti sauv form 'bott05.msh';
oeill = 100000 100000 100000;
oeily = 0 -100000 0;
*
l = 0.6;
ri = 0.1;
h = 0.005;
re = ri + h;
*
p0 = 0 0 0;
p1 = 0 0 l;
p2 = 0 0 (0 - ri);
p3 = ri 0 0;
p4 = ri 0 l;
p8 = 0 0 (0 - ri - h);
p9 = (ri + h) 0 0;
p10 = (ri + h) 0 l;
p1y = p1 plus (0 -1 0);
p11 = p10 TOUR 70.0 p1 p1y;
p14 = p4 TOUR 70.0 p1 p1y;
x11 y11 z11 = coor p11;
x14 y14 z14 = coor p14;
p12 = x11 0 0.75;
p13 = 0 0 0.75;
p5 = p4 tour 80.0 p1 p1y;
x5 y5 z5 = coor p5;
p15 = x5 0 (z5 + h);
p16 = x5 0 0.75;
p6 = x5 0 0.725;
p7 = 0 0 0.725;
p17 = ri 0 (l*0.5);
tol = 1.E-4;
*
c1 = p2 d 1 p8;
p0y = p0 plus (0 -1 0);
bot1 = c1 ROTA 18 90.0 p0 p0y;
elim tol (bot1 et p3 et p9);
*
c2 = p3 d 1 p9;
bot2 = c2 TRAN 60 (0 0 l);
elim tol (bot2 et p10 et p4 et p17);
*
c3 = p4 d 1 p10;
bot3 = c3 ROTA 15 70.0 p1 p1y;
elim tol (bot3 et p11 et p14);
*
c4 = p5 c 3 p1 p14;
c5 = p14 d 1 p11;
c6 = p11 c 3 p1 p15;
c7 = p15 d 1 p5;
bot4 = DALL c4 c5 c6 c7 PLAN;
*
ca = p15 c 3 p1 p11;
cb = p11 d 10 p12;
cc = p12 d 3 p16;
cd = p16 d 5 p6 d 5 p15;
bot5 = DALL ca cb cc cd PLAN;
*
```

```
ce = p7 d 3 p6;
cf = p6 d 5 p16;
cg = p16 d 3 p13;
ch = p13 d 5 p7;
bot6 = DALL ce cf cg ch PLAN;
*
bott = bot1 et bot2 et bot3 et bot4 et bot5 et bot6;
elim tol bott;
*
bott1a ier s1n = pxvolu3d (bot1 et bot2) 9 -90.0 c1 tol;
list ier;
bott1b ier s1n = pxvolu3d (bot3 et bot4 et bot5 et bot6) 9 -90.0 ch tol;
list ier;
bott1 = bott1a et bott1b;
elim tol bott1;
*
bott2 = bott1 tour 90.0 p0 p1;
bott3 = bott2 tour 90.0 p0 p1;
bott4 = bott3 tour 90.0 p0 p1;
bottle = bott1 et bott2 et bott3 et bott4;
elim tol bottle;
*
trac cach bottle;
*
trac oeily bott;
trac oeily qual bott;
trac qual oeily (bot3 et bot4 et bot5 et bot6);
trac oeily (bot3 et bot4 et bot5 et bot6);
*
bottl8 = bottle elem cub8;
bottl6 = bottle elem pri6;
list (nbno bottle);
list (nbel bottle);
list (nbel bottl8);
list (nbel bottl6);
*
* internal volume (to apply the pressure)
*
p2p = p2 plus p0;
p3p = p3 plus p0;
p4p = p4 plus p0;
p14p = p14 plus p0;
p5p = p5 plus p0;
p15p = p15 plus p0;
p6p = p6 plus p0;
p7p = p7 plus p0;
icon = p2p c 18 p0 p3p d 60 p4p c 15 p1 p14p c 3 p1 p5p d 1 p15p
       d 5 p6p d 3 p7p d 20 p1 d 60 p0 d 20 p2p;
isur = SURF icon plan;
trac isur;
*
p18 = 0 0 -0.2;
p19 = 0.2 0 -0.2;
p20 = 0.2 0  0.9;
p21 = 0   0  0.9;
p16p = p16 plus p0;
p13p = p13 plus p0;
p12p = p12 plus p0;
p11p = p11 plus p0;
p10p = p10 plus p0;
p9p = p9 plus p0;
p8p = p8 plus p0;
p22 = 0.2 0 0;
econ1 = p9p c 18 p0 p8p d 10 p18 d 20 p19 d 20 p22 d 10 p9p;
econ2 = p13p d 3 p16p d 3 p12p d 10 p11p c 15 p1 p10p d 60 p9p
        d 10 p22 d 80 p20 d 20 p21 d 14 p13p;
```

```
esur1 = SURF econ1 plan;
esur2 = SURF econ2 plan;
esur = esur1 et esur2;
elim tol esur;
trac esur;
trac (isur et esur);
*bsur = bott plus p0;
bsur1 = bot1 plus p0;
bsur2 = (bot2 et bot3 et bot4 et bot5 et bot6) plus p0;
bsur = bsur1 et bsur2;
elim tol (isur et bsur et esur);
trac bsur;
trac (isur et esur et bsur);
*
axis = p7p d 20 p1 d 60 p0 d 20 p2p;
elim tol (axis et isur);
ivol1 ier s1n = pxvolu3d isur 9 -90.0 axis tol;
list ier;
trac oeil1 cach ivol1;
ivol2 = ivol1 tour 90.0 p0 p1;
ivol3 = ivol2 tour 90.0 p0 p1;
ivol4 = ivol3 tour 90.0 p0 p1;
ivol = ivol1 et ivol2 et ivol3 et ivol4;
elim tol ivol;
trac oeil1 cach ivol;
*
besur1 = bsur1 et esur1;
axis1 = p2p d 1 p8p d 10 p18;
elim tol (axis1 et besur1);
besur2 = bsur2 et esur2;
axis2 = p21 d 14 p13p d 5 p7p;
elim tol (axis2 et besur2);
besur = besur1 et besur2;
*
bevol1a ier s1n = pxvolu3d besur1 9 -90.0 axis1 tol;
list ier;
```

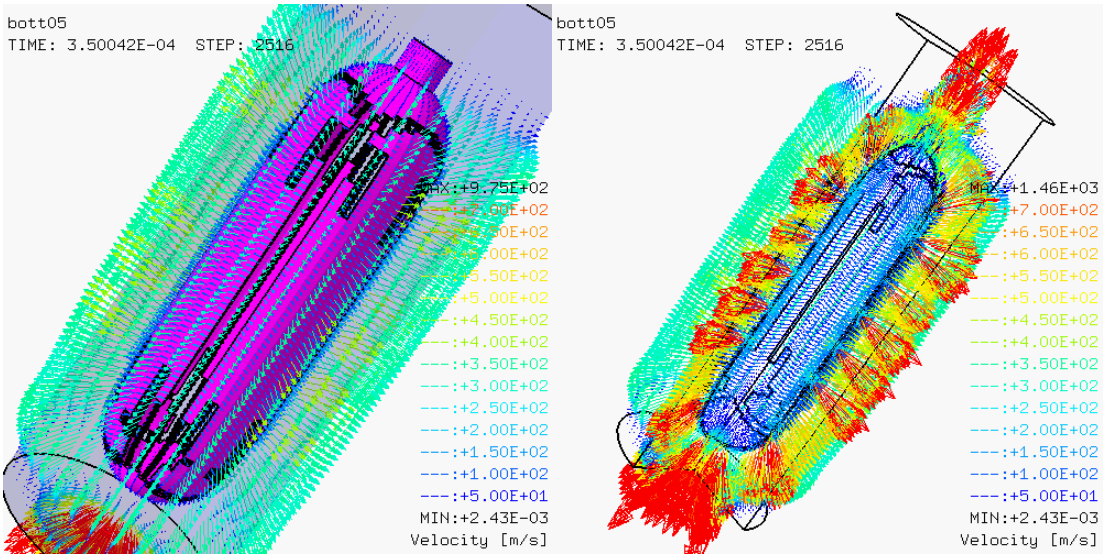
```
bevol2a ier s1n = pxvolu3d besur2 9 -90.0 axis2 tol;
list ier;
bevol1 = bevol1a et bevol2a;
elim tol bevol1;
trac oeil1 cach bevol1;
bevol2 = bevol1 tour 90.0 p0 p1;
bevol3 = bevol2 tour 90.0 p0 p1;
bevol4 = bevol3 tour 90.0 p0 p1;
bevol = bevol1 et bevol2 et bevol3 et bevol4;
elim tol bevol;
trac oeil1 cach bevol;
*
flui = ivol et bevol;
elim tol flui;
*
flui8 = flui elem CUB8;
flui6 = flui elem PRI6;
*
eabs = enve flui;
eabs4 = eabs elem QUA4;
eabs3 = eabs elem TRI3;
*
list (nbno flui);
list (nbel flui8);
list (nbel flui6);
list (nbel eabs4);
list (nbel eabs3);
*
e17 = (bott1 elem appu larg p17) elem 1;
list e17;
*
mesh = bottle et flui et eabs;
tass mesh;
sauv form mesh;
*
fin;
```

The EUROPLEXUS input file reads:

```
bott05
ECHO
!CONV win
TRID ALE FAIL 0.0
CAST FORM mesh
DIME
  PT3L 112531
  CUB8   4860 PR6   216
  FL38  92988 FL36 6480
  CL3Q   4968
  CL3I     72
  DEBR   4860
  ZONE 7
  NALE 1 NBLE 1
TERM
GEOM
  CUB8 bottl8
  PR6  bottl6
  FL38 flui8
  FL36 flui6
  CL3Q eabs4
  CL3I eabs3
TERM
COMP DEBR ROF 1.0
          FLUI LECT bevol TERM DGRI DELE 1.5
          FILL PLEV 0
               RO 8000. DRAG 1.0 OBJE LECT bottl8 TERM
     GROU 1 'part' LECT 109585 PAS 1 114444 TERM
     COUL rose LECT bottle TERM
          roug LECT ivol   TERM
          turq LECT bevol  TERM
          jaun LECT eabs   TERM
GRIL LAGR LECT bottle part TERM
MATE VM23 RO 8000 YOUN 2.E11 NU 0.3 ELAS 2.E8
          FAIL PEPS LIMI 0.05
          TRAC 2 2.E8 0.001 2.02E8 1.001
          LECT bottle TERM
     FLUT RO 1.0 EINT 2.5E5 GAMM 1.4 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1 PREF 1.E5
```

```
          LECT bevol TERM
     FLUT RO 100.0 EINT 5.0E5 GAMM 1.4 PB 0
          ITER 1 ALF0 1 BET0 1 KINT 0 AHGF 0 CL 0.5
          CQ 2.56 PMIN 0 NUM 1 PREF 1.E5
          LECT ivol TERM
     IMPE ABSI LECT eabs TERM
LINK COUP FLSR STRU LECT bottle TERM
               FLUI LECT flui   TERM
               PHIS 0.3D0
               PHIF 0.2D0
               HGRI 0.01D0
ECRI DEPL VITE TFRE 1.E-4
     FICH SPLI ALIC TFRE 1.E-6
     FICH ALIC TEMP TFRE 1.E-6
          POIN LECT p2 p3 p17 p4 p7 TERM
          ELEM LECT e17 TERM
OPTI NOTE LOG 1
CALC TINI 0. TEND 0.35E-3
fin
*=================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 1 'dy_p2' DEPL COMP 2 POIN LECT p2 TERM
COUR 2 'dx_p3' DEPL COMP 1 POIN LECT p3 TERM
COUR 3 'dx_p17' DEPL COMP 1 POIN LECT p17 TERM
COUR 4 'dx_p4' DEPL COMP 1 POIN LECT p4 TERM
COUR 5 'dy_p7' DEPL COMP 2 POIN LECT p7 TERM
COUR 6 'vm_e17' ECRO COMP 2 ELEM LECT e17 TERM
TRAC 1 2 3 4 5 AXES 1.0 'Displ. [M]'
TRAC 6 AXES 1.0 'Von Mises [Pa]'
FIN
```

The fragmentation process and the velocities are shown in the next figures:



Universitat Politècnica de Catalunya, Barcelona, 15 – 19 April 2013

Numerical Simulation of Fast Transient Phenomena in Fluid-Structure Systems

A Short Course by F. Casadei
Retired from European Commission, Joint Research Centre
Institute for the Protection and Security of the Citizen
T.P. 480, I-21027 Ispra (VA), Italy.
E-mail: casadeifolco@gmail.com

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Contents

- I – Introduction (Structures)
- II – ALE formulation (Fluids)
- III – Classical Fluid-Structure Interaction
- IV – Advanced FSI (Failure/Fragmentation)
- V – Further topics and applications

2

Detailed contents (1/2)

- ALE description for structures
- Lagrangian contact:
  - Classical methods
  - Pinballs
  - SPH (for fluid-like materials)
- Meshless methods:
  - SPH for structures
  - DEM

3

Detailed contents (2/2)

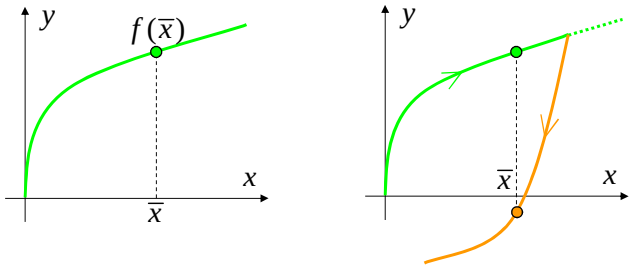
- Spectral elements
- Spatial time step partitioning
- Domain decomposition
- Mesh adaptivity:
  - Application to solids
  - Application to fluids
  - FSI

4

ALE description of structures

Donea, Huerta, Casadei (early 1990s)

- Extend ALE formulation to materials with memory, namely, non-linear path-dependent materials



No memory Memory

5

ALE description of structures (2)

- Major extra difficulty w/r to Newtonian fluids: necessity to transport stresses and stress-related quantities across inter-element boundaries. Fields are usually discontinuous and evaluated only at Gauss Points
- Previous attempts had used implicit interpolation techniques: too expensive in the present explicit fast transient context
- Two distinct strategies, borrowed from the fluid dynamic experience: a) a Lax-Wendroff scheme based on nodal averaging and smoothing of the stress gradients, and b) a Godunov scheme inspired by methods often used for conservation laws in finite volumes
- Both techniques implemented in 2D quadrilateral finite elements using single-point as well as multiple-point spatial numerical integration

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ALE description of structures (3)

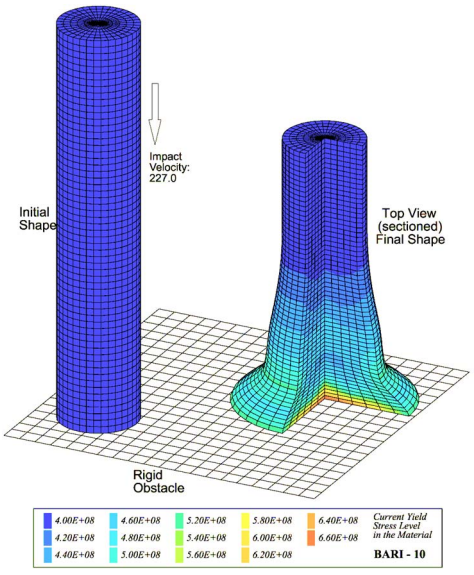
- When ALE is applied to nonlinear path-dependent materials, three conservation equations basically similar to Euler equations are obtained and therefore the same techniques (time integration strategy, rezoning algorithms, treatment of boundary conditions, etc.) developed for the fluids can be directly applied, with the important exception, however, of the stress transport algorithm

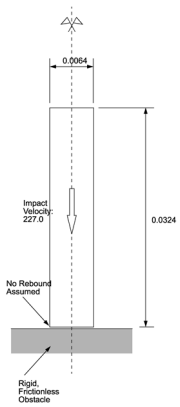
- Time integration is achieved by same fractional step strategy seen above for fluids: 1) Lagrangian phase, in which it is assumed that the mesh follows the material particles and transport terms vanish; 2) Convective flux calculation (transport terms only)

- The time integration procedure still remains completely explicit and only an extra loop over the elements to deal with transport is required at each time step, compared with the Lagrangian case

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Example 1 – Taylor bar impact

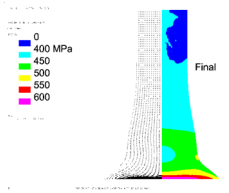


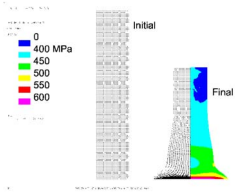


Material Data	
Density	8930
Young's Modulus	1.17×10^{11}
Yield Stress	4.0×10^{8}
Plastic Modulus	1.0×10^{8}
Poisson's Ratio	0.35

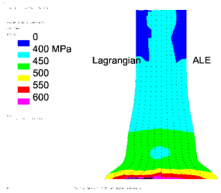
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Example 1 – Taylor bar impact (2)

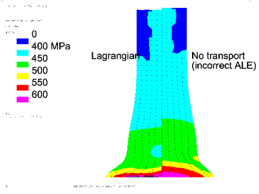




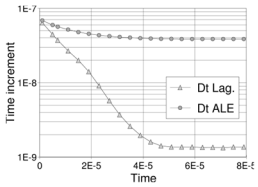
Reference solution: Lagrangian, 12 x 120 quadratic elements

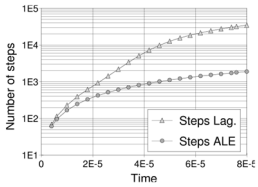


Comparison Lagrangian/ALE, 5 x 50 linear elements



Effect of transport terms

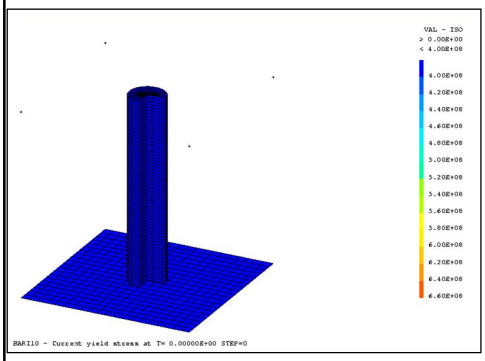


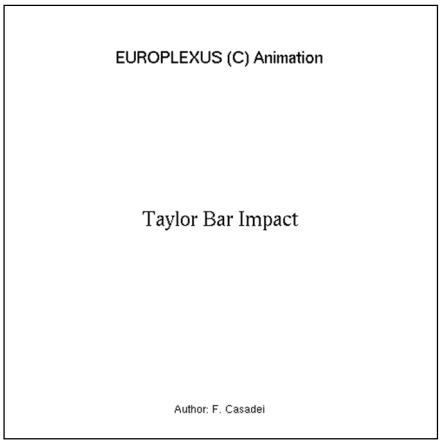


Formulation effects on time increment

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Example 1 – Taylor bar impact (3)

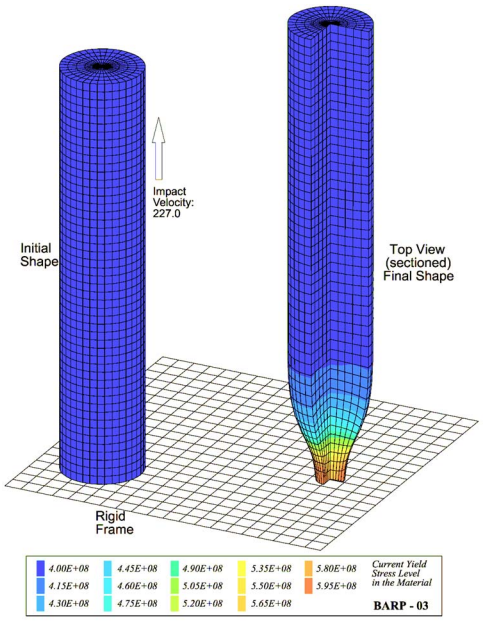


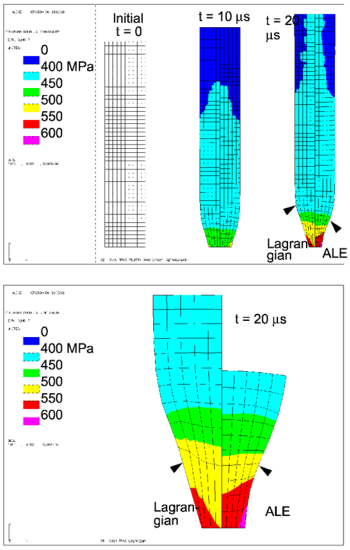


BARI10: ALE solution, 6 x 60 linear elements, Lax-Wendroff stress transport

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Example 2 – Bar pulling



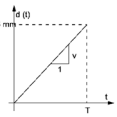


Comparison Lagrangian/ALE, 5 x 50 linear elements

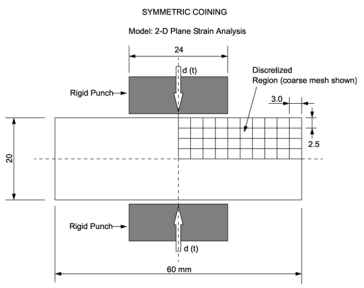
11

Example 3 – Coining

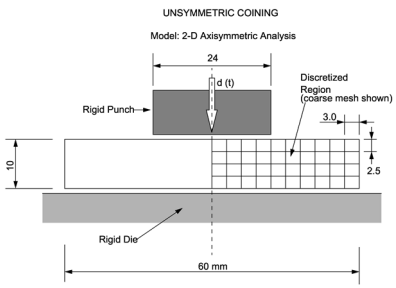
Material Data	
Density	8930
Young's Modulus	$2.\times10^{11}$
Yield Stress	2.5×10^{8}
Plastic Modulus	$1.\times10^{9}$
Poisson's Ratio	0.3



Punching Time T [ms]	Punching Velocity v [m/s]
40.00	0.15
2.00	3.00
0.10	60.00
0.02	300.00



Bilateral, Plane strain

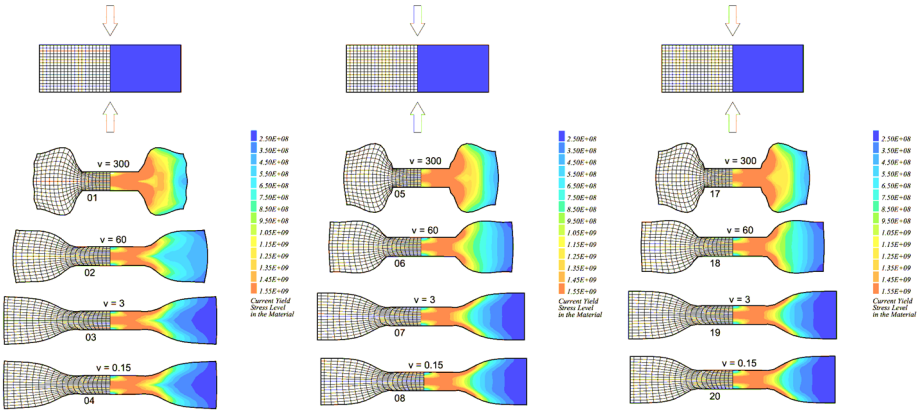


Unilateral, Axisymmetric

12

Example 3 – Coining (2)

Influence of punch velocity:



Lax-Wendroff
2 x 2

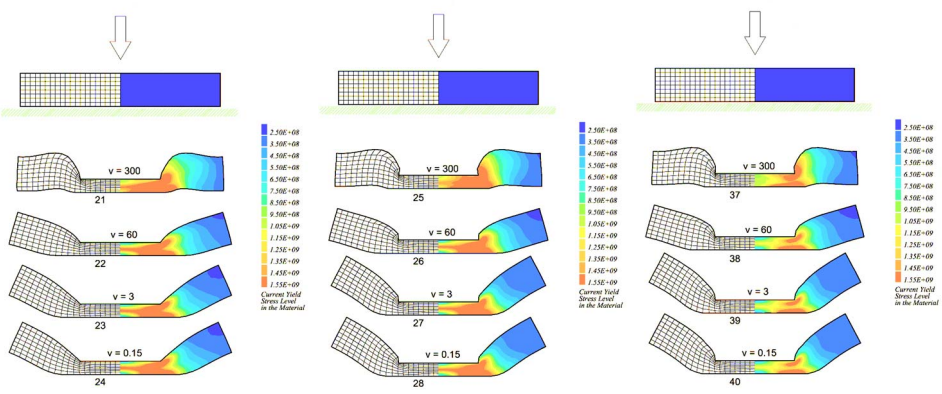
Godunov "B"
2 x 2

Godunov "A"
2 x 2

13

Example 3 – Coining (3)

Influence of punch velocity:



Lax-Wendroff
2 x 2

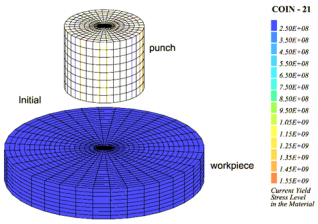
Godunov "B"
2 x 2

Godunov "A"
2 x 2

14

Example 3 – Coining (4)

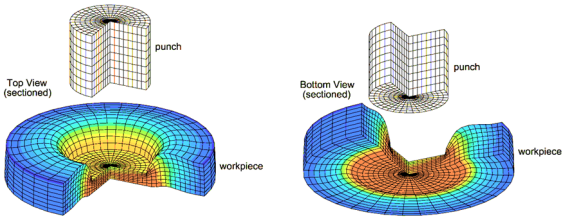
Initial:



Unilateral, 2 x 2

L-W, v = 300

Final:



15

Example 3 – Coining (5)

Bilateral, 2 x 2

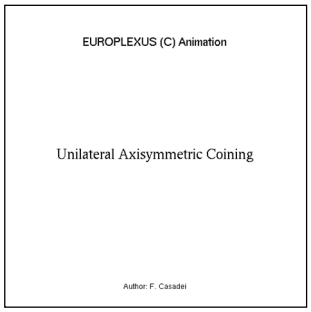
GDV "B", v = 300



Bilateral,
Plane strain (**COIN05**)

Unilateral, 2 x 2

GDV "B", v = 300

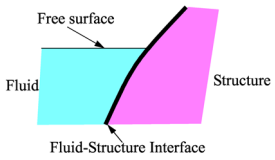


Unilateral,
Axisymmetric (**COIN25**)

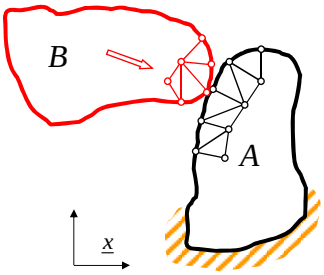
16

Lagrangian contact

- Non-permanent FSI



- Contact-impact between solids



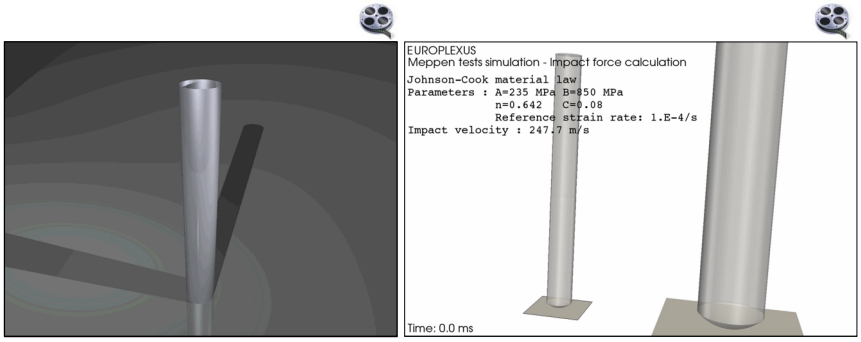
17

A contact-impact example (crash)



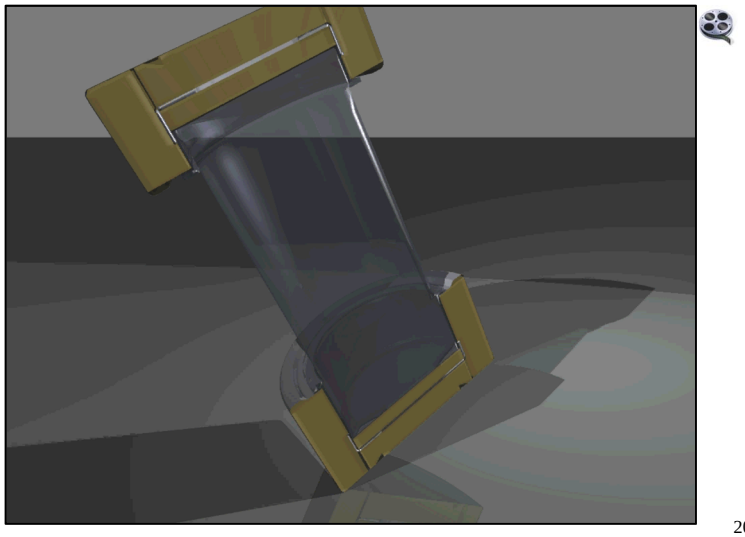
18

Example : tube crash



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Example : container drop



20

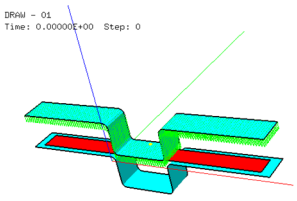
Contact-Impact Classification

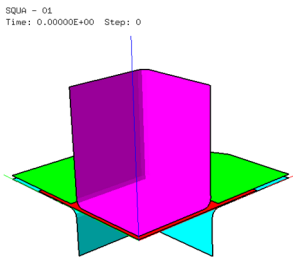
- Slow, e.g. metal forming
  - Slow loading, smooth contact, friction
- Fast, e.g. impact or crash test
  - Fast loading, friction not too important
  - Large deformations, but typically no fragments
- Very fast, e.g. perforation
  - Complete failure, fragmentation

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Examples of “Slow” Transient Contact

- A - Deep drawing of an elasto-plastic strip (no friction)

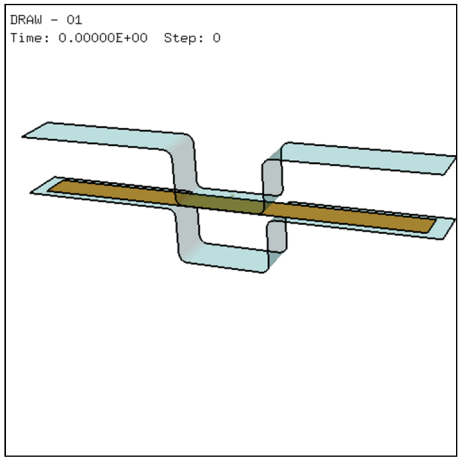




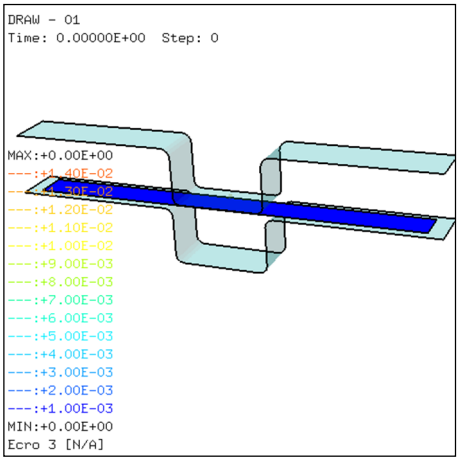
- B - Deep drawing of a square box (with friction)

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Example 6a – Deep drawing A



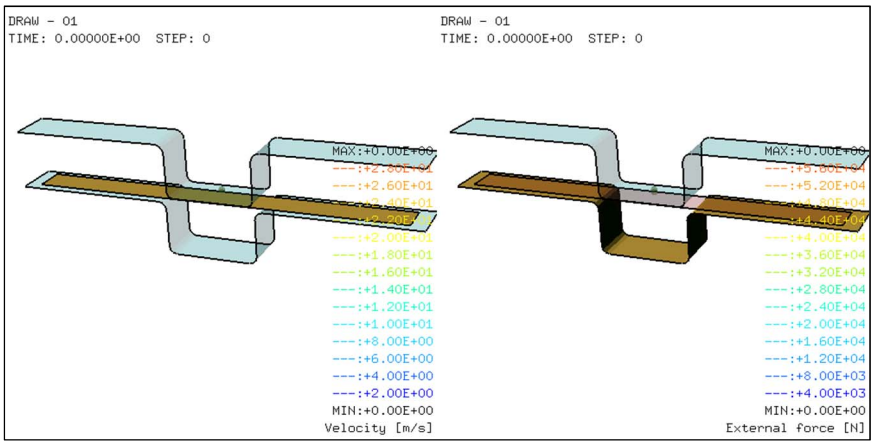
Deformation



Plastic strain

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Example 6a – Deep drawing A (2)

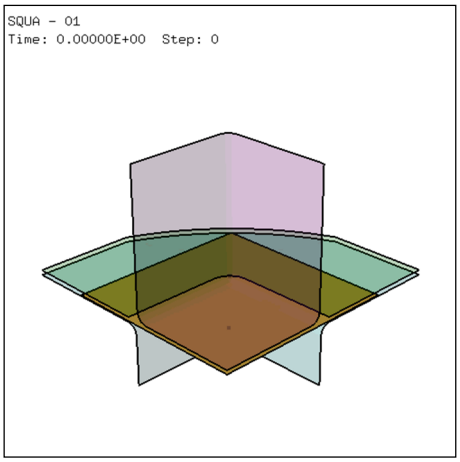


Velocities

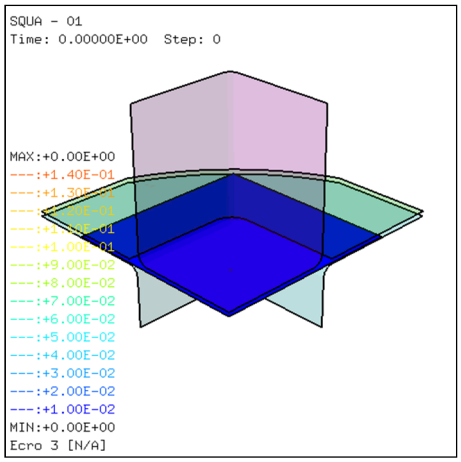
Force on the die

24

Example 6b – Deep drawing B



Deformation

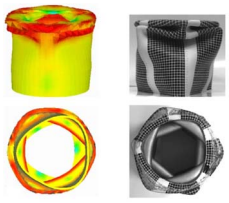


Plastic strain

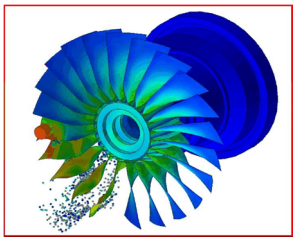
25

Examples of Fast Transient Impact

- Crash of a metallic tube (self-contact)
  [Courtesy of CEA]

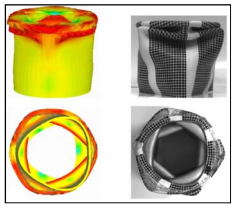


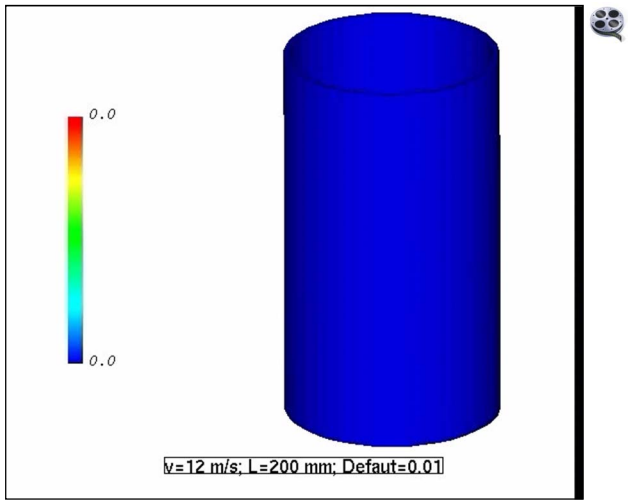
- Bird strike on jet fan by the SPH method
  [Courtesy of Snecma/CEA]



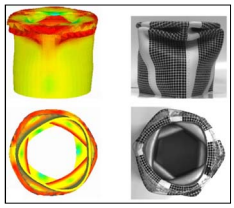
26

Tube Crash [Courtesy of CEA]

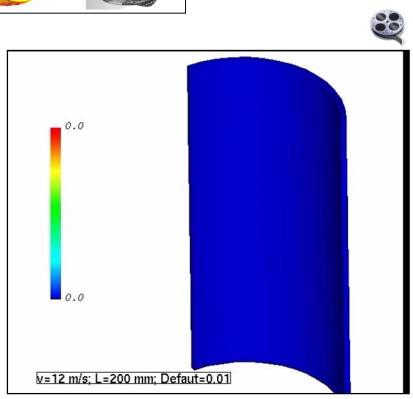


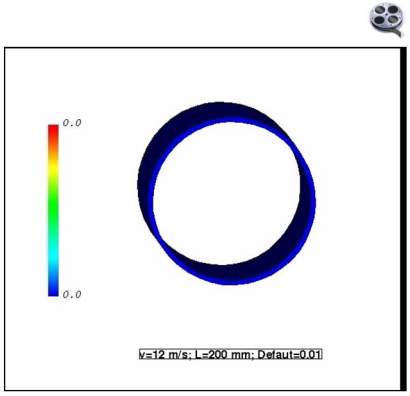


27

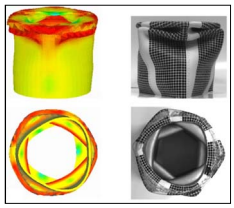


Tube Crash (2)

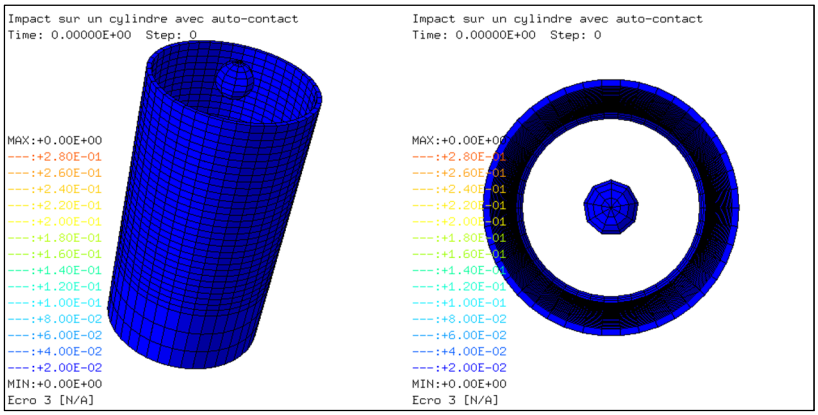




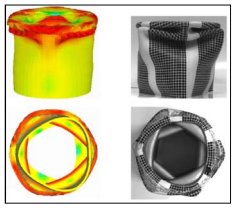
28



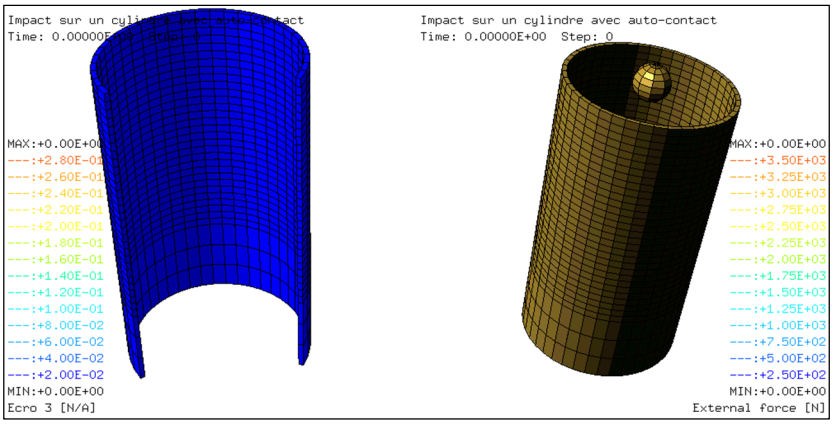
Tube Crash (3)



Plastic strain



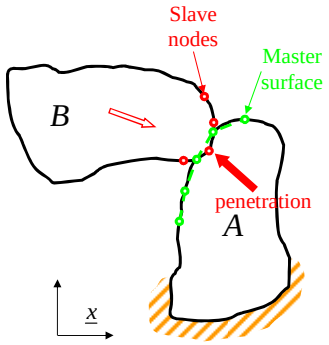
Tube Crash (4)



Plastic strain *External forces*

Conventional contact-impact methods

- Slide-line (2D) or slide-surface (3D) [Hallquist, Benson, mid-'80s]
  - "Slave" nodes
  - "Master" surfaces
  - Contact detected as node-through-surface penetration



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Components of Contact-Impact Methods

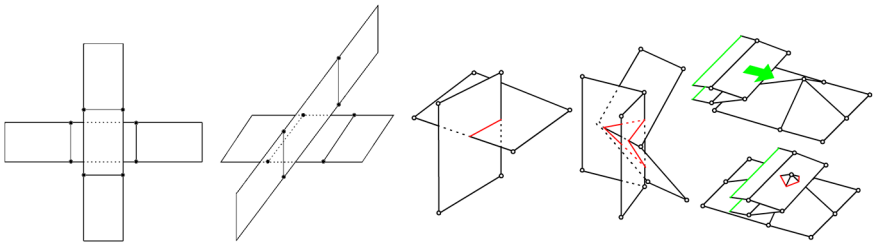
Contact-impact algorithms usually consist of two main components:

- Contact detection module, e.g. penetration detector (~heavy geometrical computations)
- Contact enforcement technique, e.g. penalty, Lagrange multipliers, …

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Some Drawbacks of Conventional Techniques

- Lack of symmetry (master/slave)
- Geometrically complex (contact detection)
- Complicated input data
- Ambiguous contact cases:



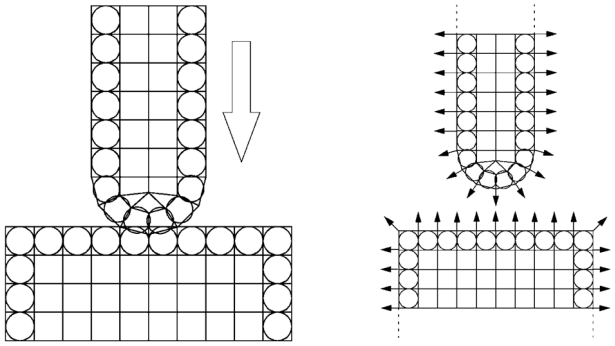
Surface-to-surface Edge-to-surface Edge-to-edge …

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The Basic Pinball Method

[Belytschko & Neal, 1991]

- Embed a sphere (pinball) in each element

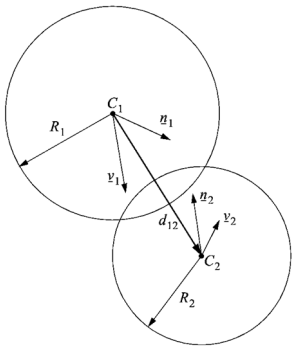


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The Basic Pinball Method (2)

- Contact occurs between elements when:

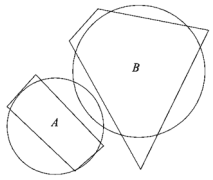
$$d_{12} < (R_1 + R_2)$$



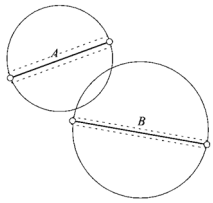
35

Shortcomings

- Slender or distorted continuum elements



- Zero-thickness beam/shell elements

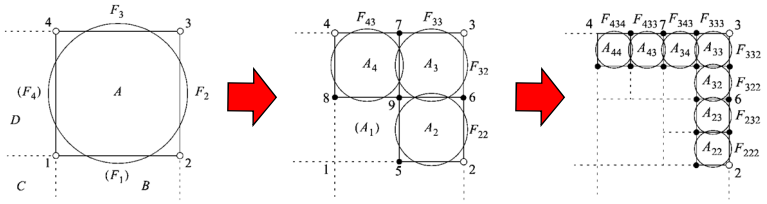


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The Hierarchic Pinball Method

[Belytschko & Yeh, 1993]

- Embed a parent pinball in each element
- Recursively generate descendent pinballs as long as contact holds

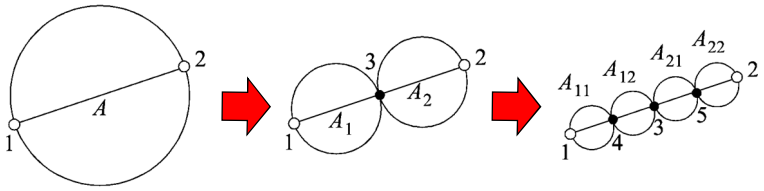


Level 0 (parent) Level 1 Level 2

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Hierarchic Pinball Method (2)

- Hierarchy stops when:
  - Continuum: min size or max level is reached
  - Shells: size equals physical element thickness



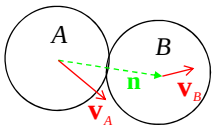
Level 0 (parent) Level 1 Level 2

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Contact Force Computation

- Constraints on velocities:

$$\mathbf{v}_A \cdot \hat{\mathbf{n}} - \mathbf{v}_B \cdot \hat{\mathbf{n}} \leq 0$$



- By expanding the velocities:

$$\left[\sum_{i=1}^{n_A} N_{Ai}(A)\mathbf{v}_{Ai}\right]\cdot\hat{\mathbf{n}} - \left[\sum_{i=1}^{n_B} N_{Bi}(B)\mathbf{v}_{Bi}\right]\cdot\hat{\mathbf{n}} \leq 0$$

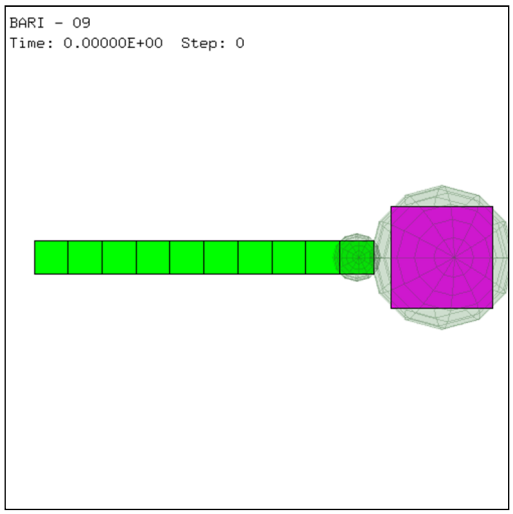
- These inequalities are of the generic form:

$$\boxed{\mathbf{Cv} \leq \mathbf{b}}$$

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Example – Bar impact

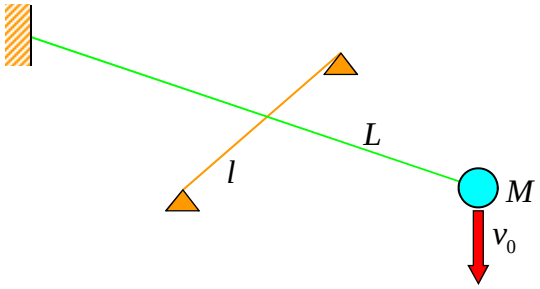
- (See Part 1)



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Example 7 – Cable impact

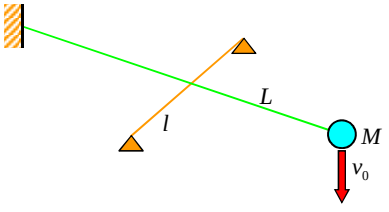
- A cable is fixed at one end and has a concentrated mass at the other end. The mass has an initial velocity. In its motion, the cable impacts on a second cable fixed at both extremities.
- Cables have <u>no resistance to bending or compression</u> (only to traction).



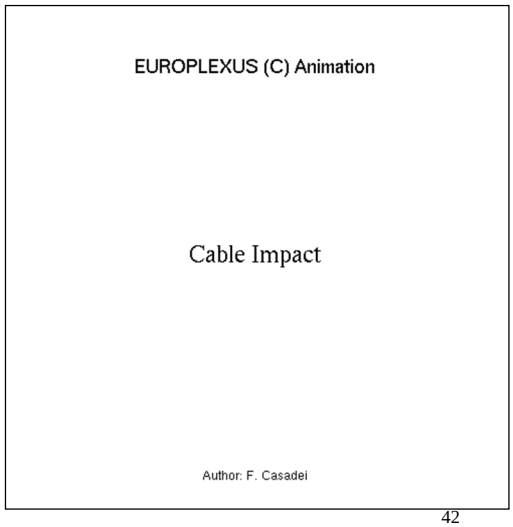
$L = 10$
$l = 2$
$M = 100$
$v_0 = -100$

41

Example 7 – Cable impact (2)



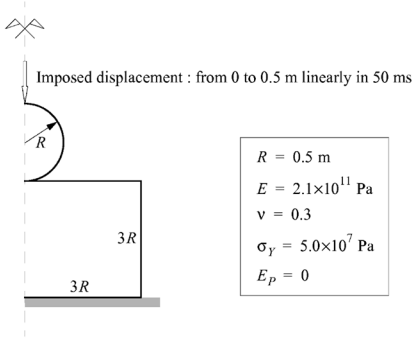
WRAP06



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Example 7b – Indentation

- A rigid spherical indenter is pushed at constant speed of 10 m/s into a ductile block of material

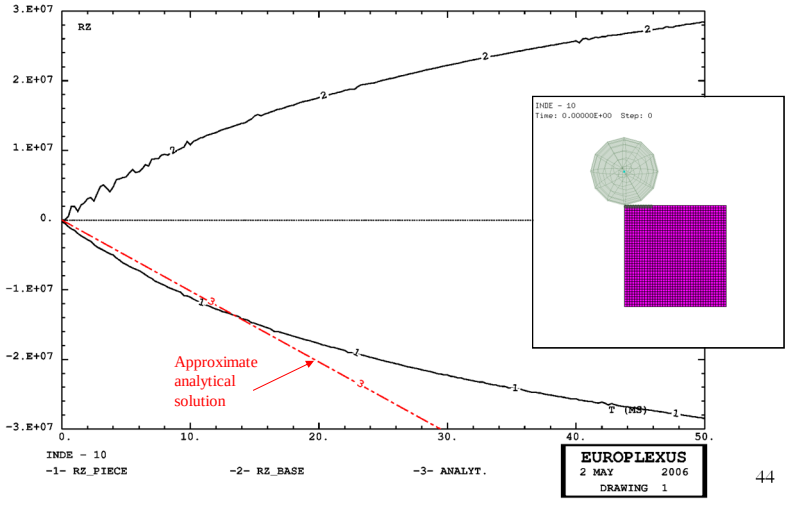


- Compute the indentation force as a function of displacement
  - 2D axisymmetric solution
  - 3D solution(s)

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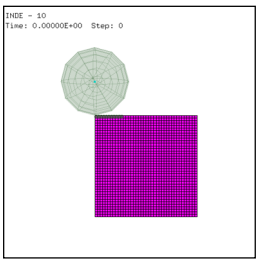
Example 7b – Indentation (2)

- 2D axisymmetric solution:

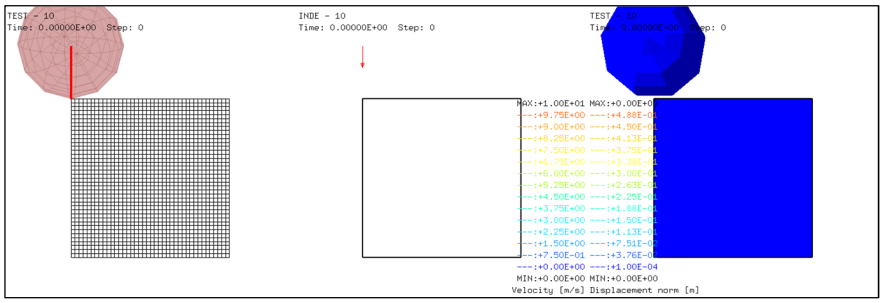


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Example 7b – Indentation (3)



- 2D axisymmetric solution:

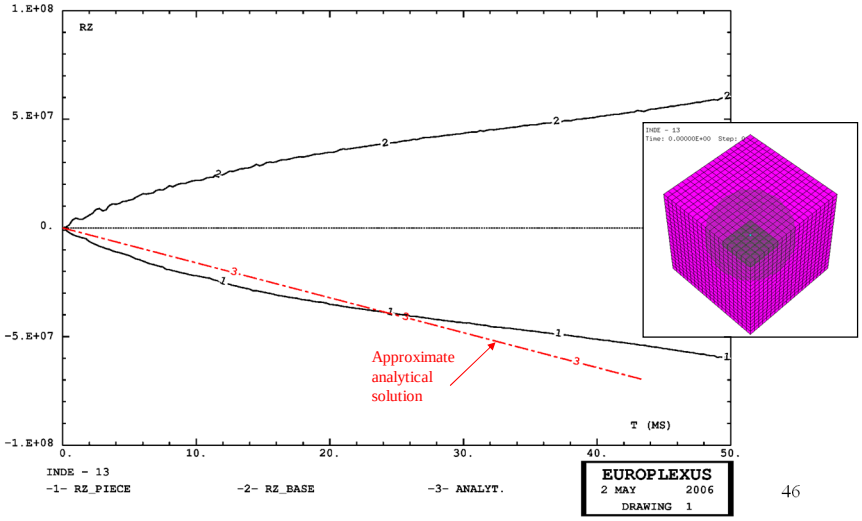


Contact and deformations | Velocities | Displacement norm

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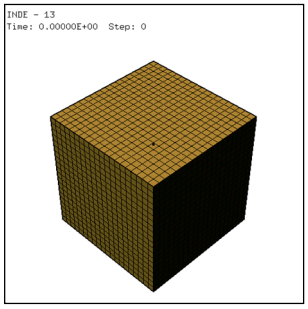
Example 7b – Indentation (4)

- 3D hexahedra-only solution:

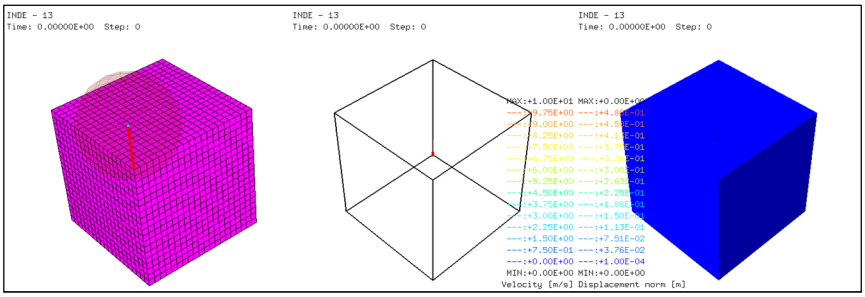


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Example 7b – Indentation (5)



- 3D hexahedra-only solution:

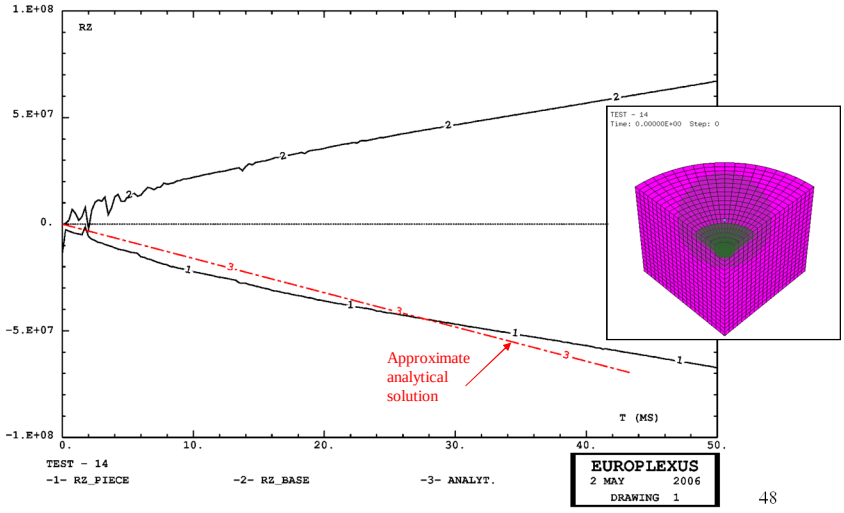


Contact and deformations | Velocities | Displacement norm

47

Example 7b – Indentation (6)

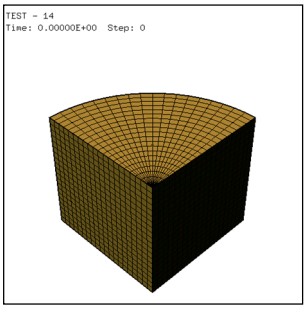
- 3D symmetric mesh solution:

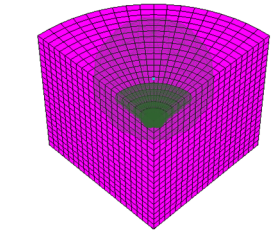


48

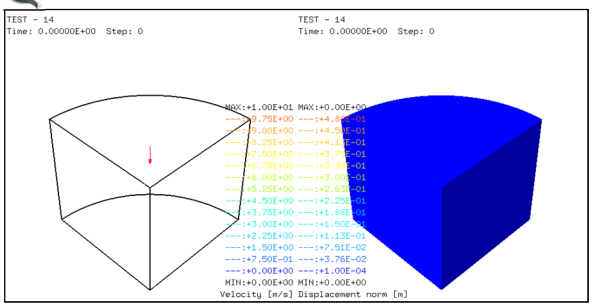
Example 7b – Indentation (7)

- 3D symmetric mesh solution:





Initial mesh and pinballs

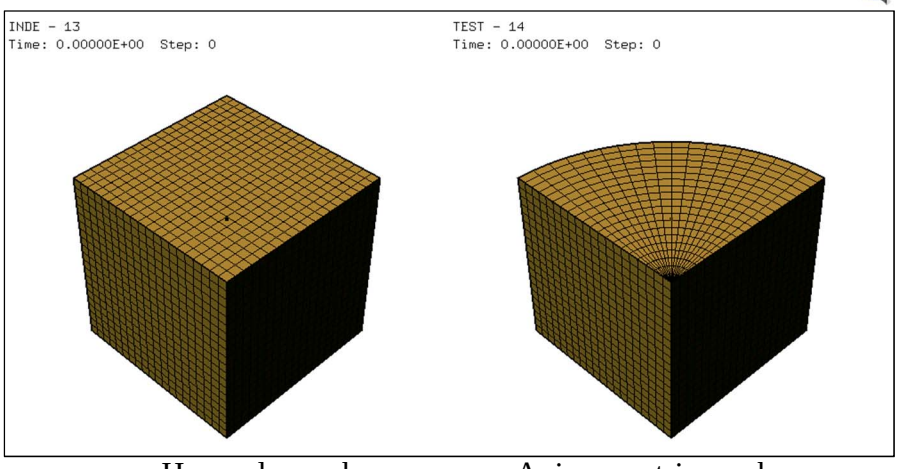


Velocities Displacement norm

49

Example 7b – Indentation (8)

- Comparison of 3D solutions:

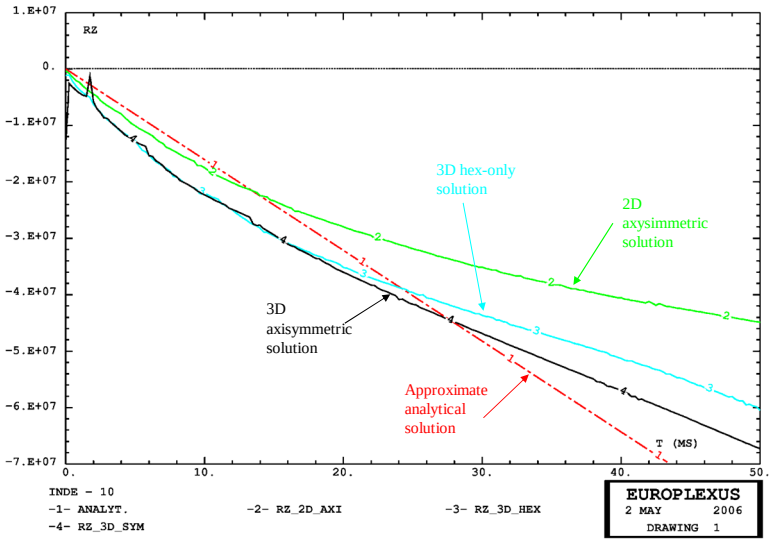


Hex-only mesh Axisymmetric mesh

50

Example 7b – Indentation (9)

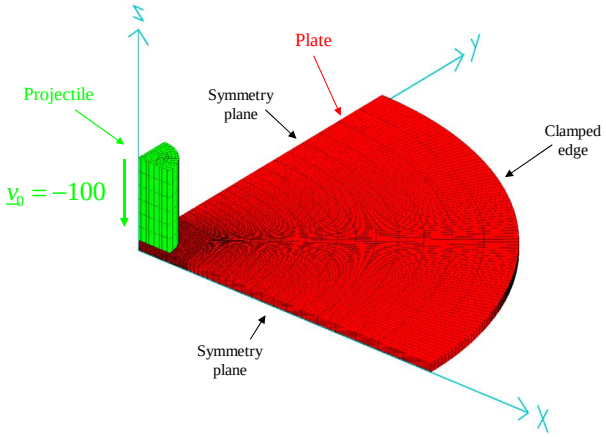
- Comparison of all solutions:



51

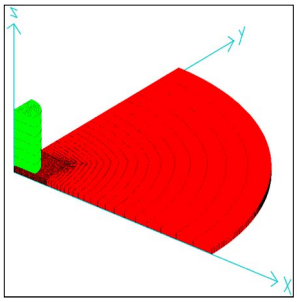
Example 7c – Plate perforation (Courtesy of CEA)

- A tough cylindrical projectile impacts a ductile circular plate at the initial velocity of 100 m/s and completely perforates it



52

Example 7c – Plate perforation (2)

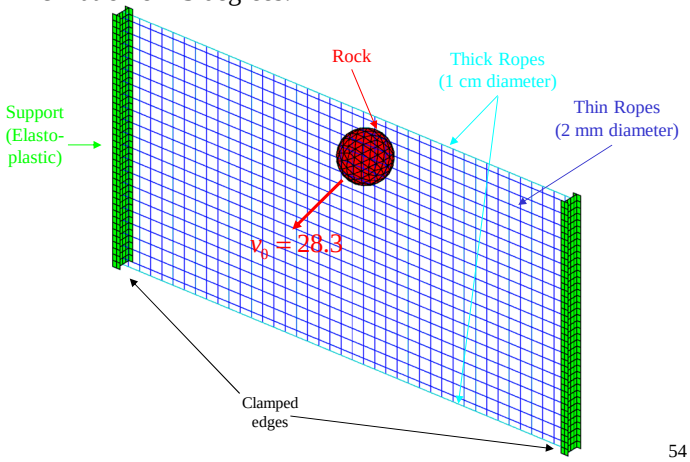




53

Example 7d – Falling Rock Catcher

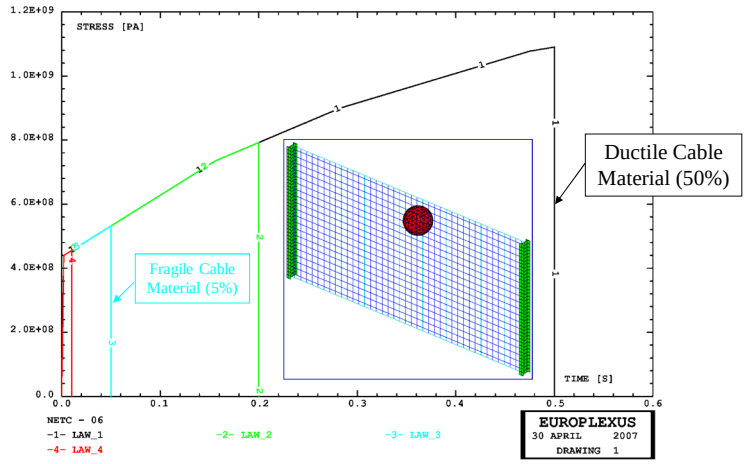
- A falling rock catcher of 6 m by 3 m is hit by a spherical rock of 0.6 m diameter and a mass of 283 kg, at a speed of 100 km/h (28.3 m/s) and with an inclination of 45 degrees:



54

Example 7d – Falling Rock Catcher (2)

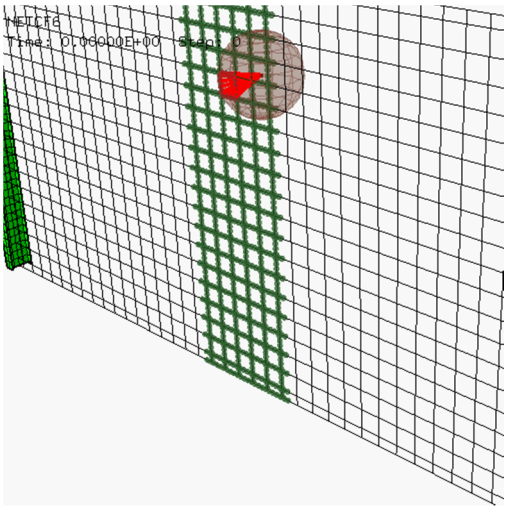
- Two solutions are presented, one with a ductile cable material (rupture strain 50%) and one with a fragile cable material (rupture strain 5%):



55

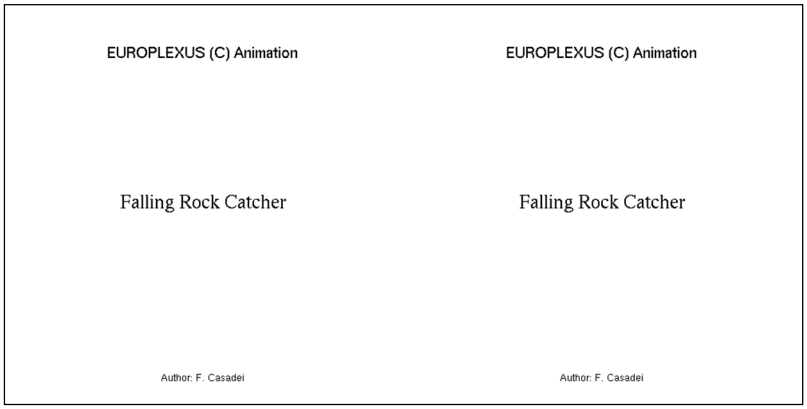
Example 7d – Falling Rock Catcher (3)

- View of pinballs used for contact calculations:



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Example 7d – Falling Rock Catcher (4)

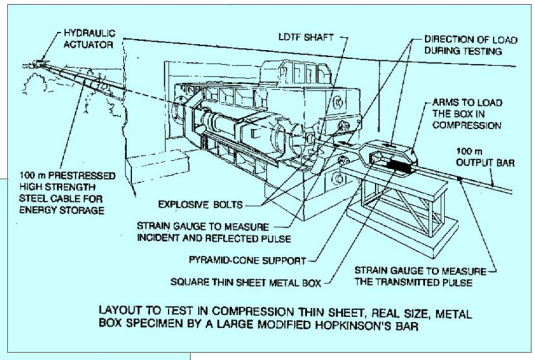


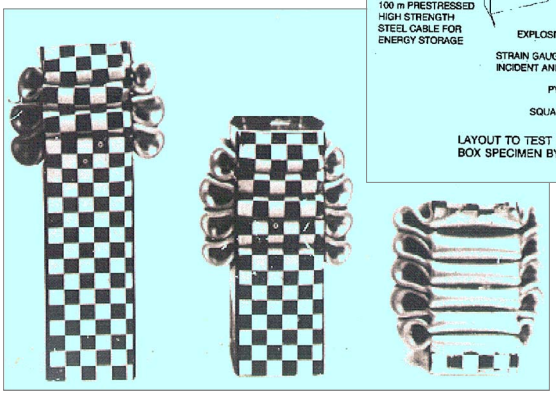
Ductile Fragile

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Example: impact tests of car crash absorbers

Test set-up for car crash absorbers

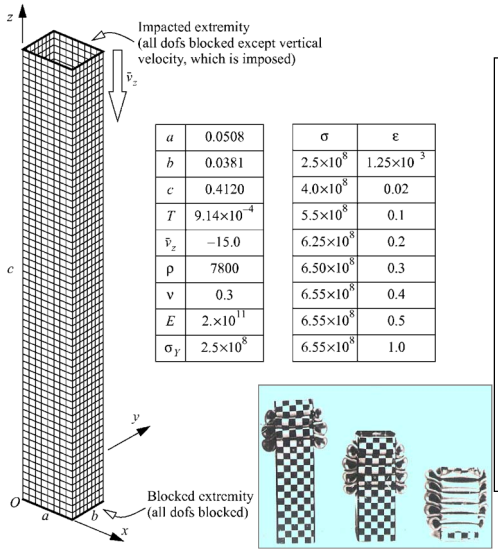




Car absorbers after crash tests

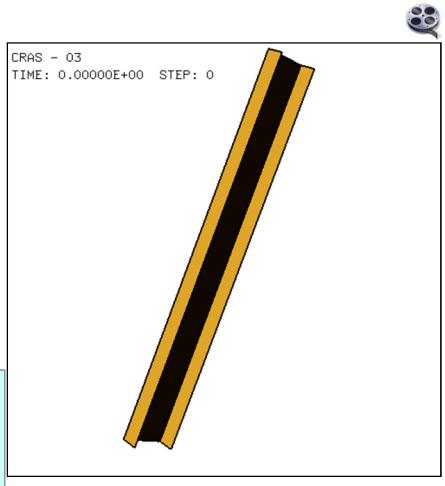
58

Tube Crash by the Pinball method



a	0.0508
b	0.0381
c	0.4120
T	9.14×10^{-4}
$\bar{v}_z$	−15.0
ρ	7800
ν	0.3
E	$2.\times10^{11}$
σ_y	2.5×10^{8}

σ	ε
2.5×10^{8}	1.25×10^{-3}
4.0×10^{8}	0.02
5.5×10^{8}	0.1
6.25×10^{8}	0.2
6.50×10^{8}	0.3
6.55×10^{8}	0.4
6.55×10^{8}	0.5
6.55×10^{8}	1.0

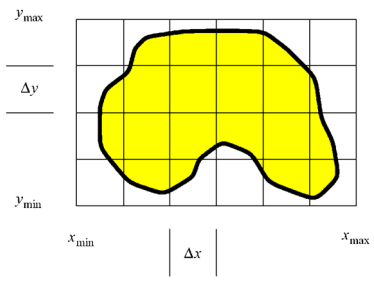


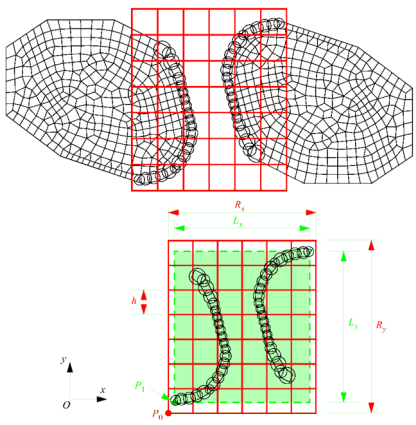
59

Tube Crash by the Pinball method (2)

- To speed up contact search, use bucket-sort algorithm:

Brute force	20.4 h CPU
Fast search	2.8 h CPU

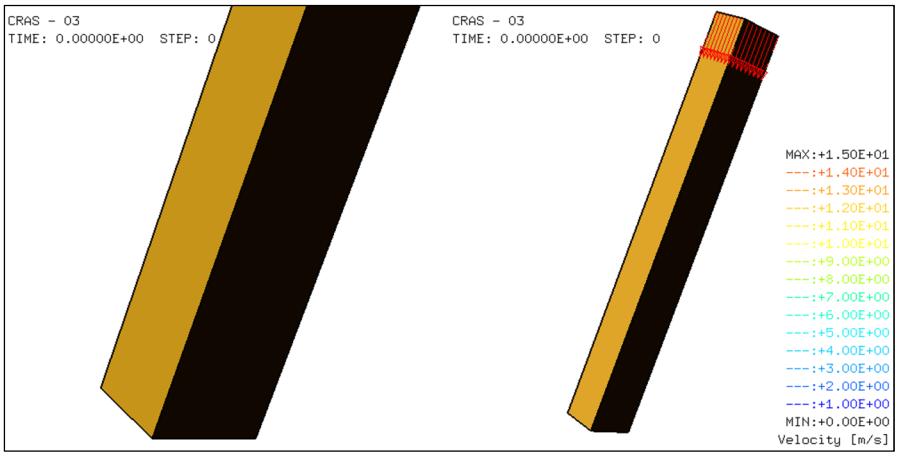




OPTI PINS …
GRID DPIN 1.5

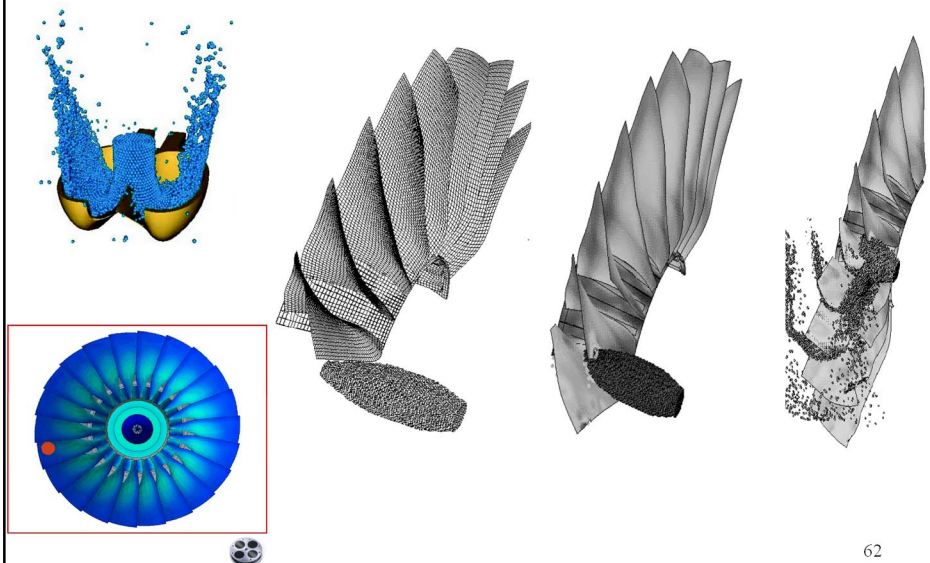
60

Tube Crash by the Pinball method (3)



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SPH (Courtesy of CEA / Snecma)



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Smoothed Particles Hydrodynamics

(Courtesy H.Bung, CEA Saclay)

- Application domain: impact of a relatively soft body (~fluid) onto a structure, typically with fragmentation:
  - Aeronautics: bird strike
  - Nuclear: various applications (e.g. corium slug impact)
  - …
- Goal: verify behaviour of the structure (not so much of the impacting body)
- Advantages: it allows to overcome the limitations of classical FE-based methods in problems where a constant mesh topology becomes a serious drawback

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Why a Particle-Based Method?

- FE Lagrangian formulation: the mesh follows the material
  - Well adapted for solid behaviour
  - Relatively easy treatment of B.C.s
  - Need to model only the real domain
- However: if deformations exceed a certain value, remeshing becomes necessary, else calculation stops
- FE Eulerian formulation: the mesh is fixed
  - Well adapted for fluid behaviour
  - No mesh distortions
  - More difficult treatment of B.C.s (e.g. free surface tracking)
  - In certain problems (e.g. rotating bodies) need to model more than the real domain
  - Longer and less accurate calculations due to transport terms

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Why a Particle-Based Method? (2)

- ALE formulation: the mesh moves arbitrarily
  - Simple and elegant treatment of Fluid-Structure Interaction (permanent!)
  - Combines advantages of Lag./Eul. without respective drawbacks
  - Mesh rezoning has limitations (e.g. with fragmentation) and is difficult to do e.g. in the presence of rotating bodies
- SPH formulation: the mesh is made of particles (no standard connectivity)
  - Same advantages as the Lagrangian formulation: easy B.C.s and only the real domain is modelled
  - Without the associated drawbacks: the mesh does not "deform"
  - Recalculation of connectivity at each step is costly
  - More difficult representation of material laws
  - Relatively "young" method

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SPH Formulation

- Developed in the '70s for astrophysical problems (Lucy, Gingold, Monaghan, 1977) involving the motion of compressible fluids in complex geometries
- It can be effectively coupled with standard FE to model impact phenomena with fragmentation
- The approach is Lagrangian and has the advantage of not using a mesh in the traditional sense, so that all problems related to excessive mesh distortions are avoided

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SPH Formulation (2)

- Basic idea: represent a continuum by a (large) set of particles, whose motion is governed by the conservation laws of continuum mechanics
- The method is based upon the following identity for a function f:

$$f(\vec{r}) = \int f(\vec{r}') \cdot \delta(\vec{r} - \vec{r}') dV'$$

$\vec{r}$ = position vector δ = Dirac's distribution

f = scalar or vectorial field ($\rho, \underline{v}, ...$)

- One tries to approximate the former integral by a "regularization", i.e. to replace Dirac's function by a kernel function $W(\vec{r}, h)$, where h is the characteristic length

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SPH Formulation (3)

- One can thus define an approximation $\langle f(\vec{r}) \rangle$ of the field as: $f(\vec{r})$

$$f(\vec{r}) \approx \langle f(\vec{r}) \rangle = \int f(\vec{r}) W(\vec{r} - \vec{r}', h) dV'$$

The kernel must satisfy the following properties:

- As the regularization length tends to 0, it tends to Dirac's distribution:

$$\lim_{h \to 0} W(\vec{r} - \vec{r}', h) = \delta(\vec{r} - \vec{r}')$$

- It is normalized:

$$\int W(\vec{r}, h) dV' = 1$$

- We use a cubic kernel (Monaghan's W4)

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SPH Formulation (4)

- To write the equations of continuum mechanics under the form of a particle approximation, it is necessary to estimate the various fields (density, energy, etc.) and their spatial gradients (gradient, divergence, …).

- Then, for each term:

Term of dynamic conservation equation at point $\vec{r}$

↓

Multiply by $W(\vec{r}-\vec{r}')$

↓

Integrate over the fluid domain (special attention to boundaries!)

↓

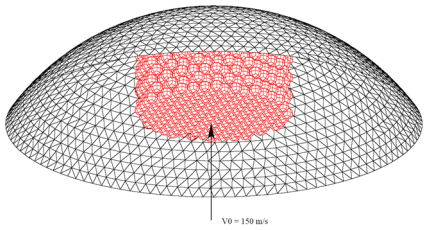
Approximate the integrals by discrete summations

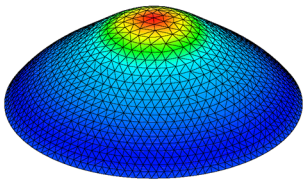
↓

Term of SPH equation at point $\vec{r}$

69

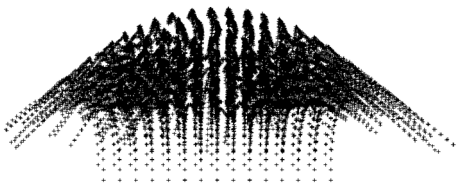
Slug impact [Courtesy of CEA Saclay]





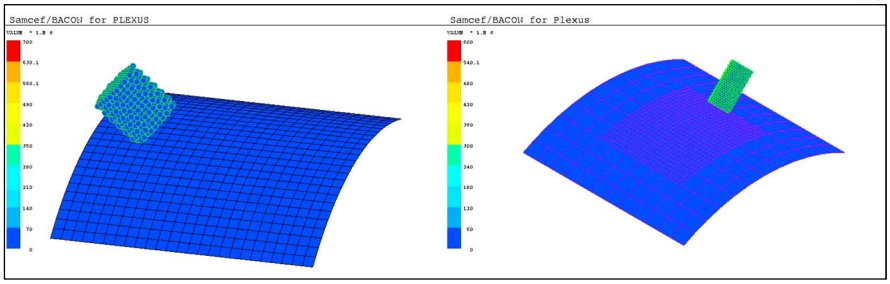


2648 triangular shells, 1180 particles



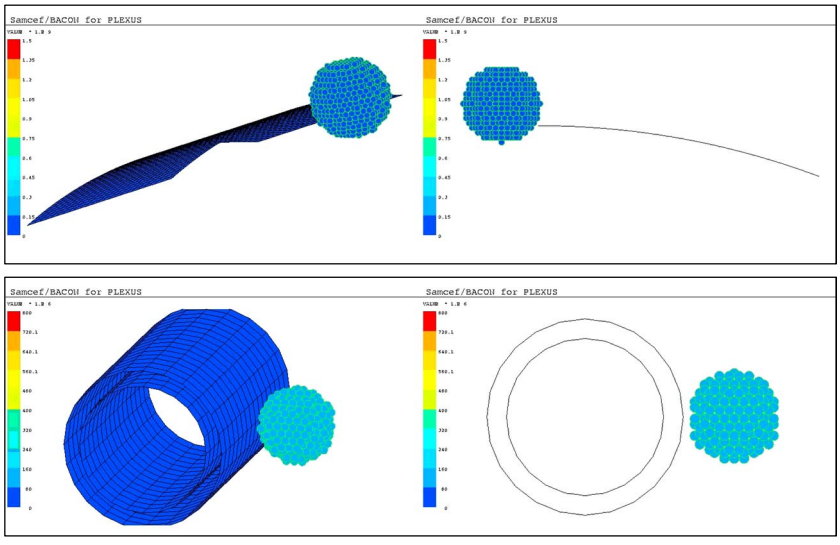
70

SPH impact [Courtesy of Samtech/Sonaca]



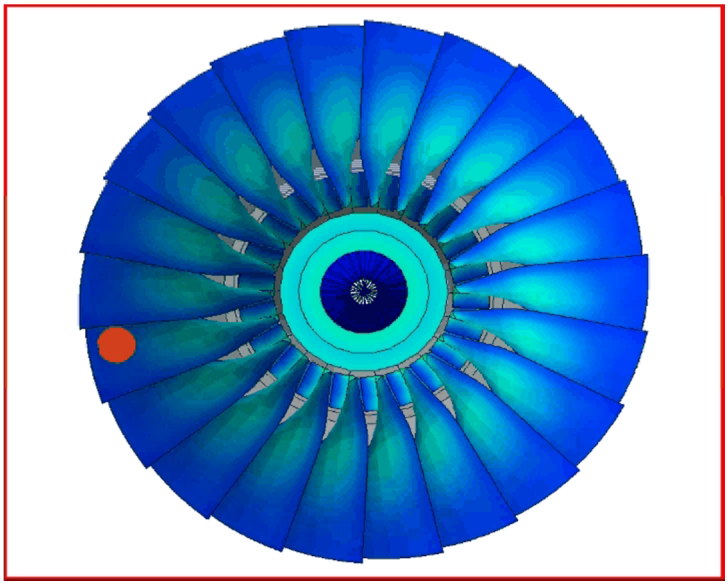
71

SPH impact [Courtesy of Samtech/Sonaca]



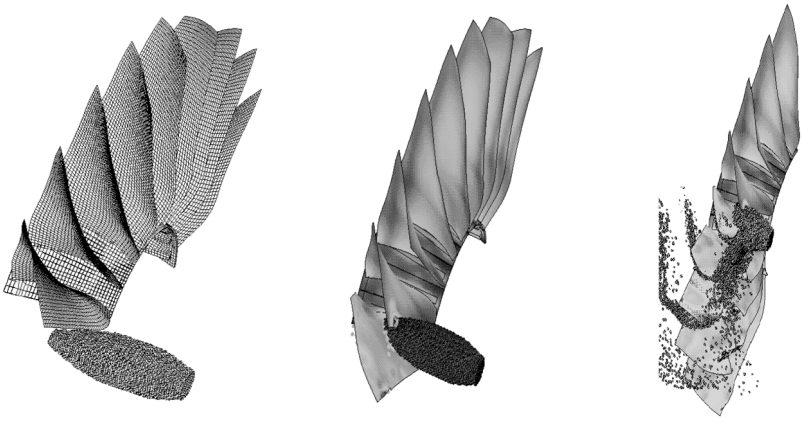
72

Bird Strike [Courtesy of Snecma/CEA]



73

Bird Strike [Courtesy of Snecma/CEA]

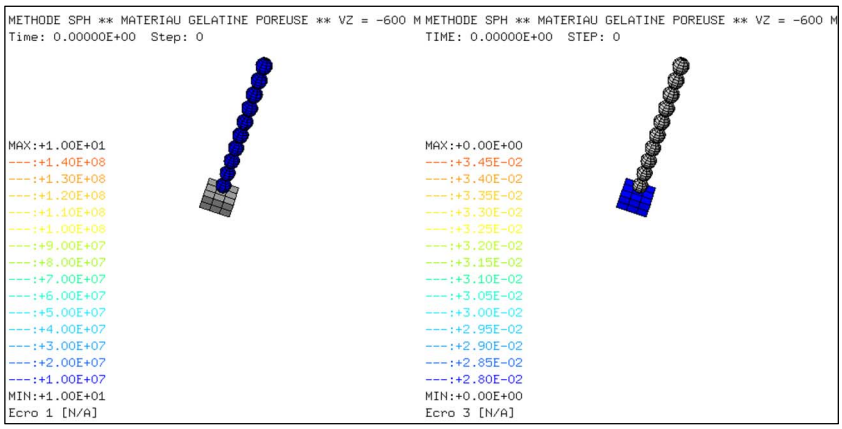


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Example 8 – SPH impacts

(Courtesy of CEA and Samtech S.A.)

PRGL01:



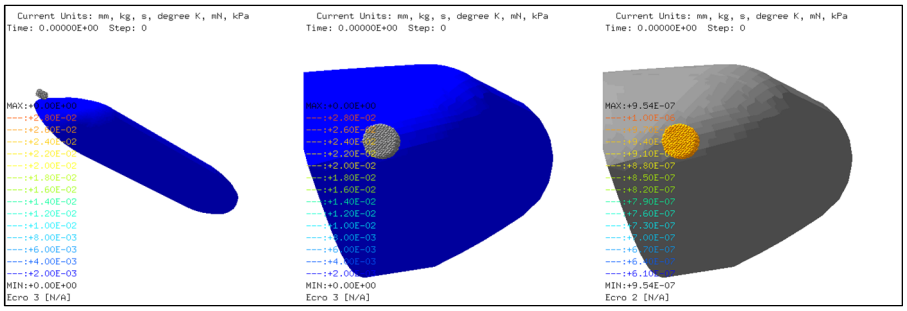
Absolute pressure in projectile Plastic strain in target

75

Example 8 – SPH impacts

(Courtesy of CEA and Samtech S.A.)

ROMA01:

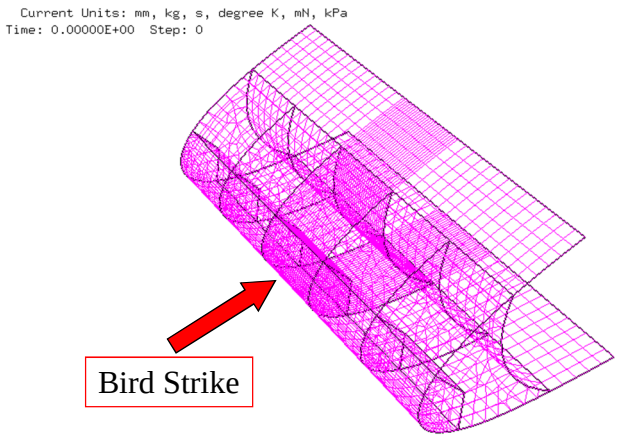


Plastic strain in structure Plastic strain in structure (zoom) Density in projectile

76

Example 8 – SPH impacts (2)

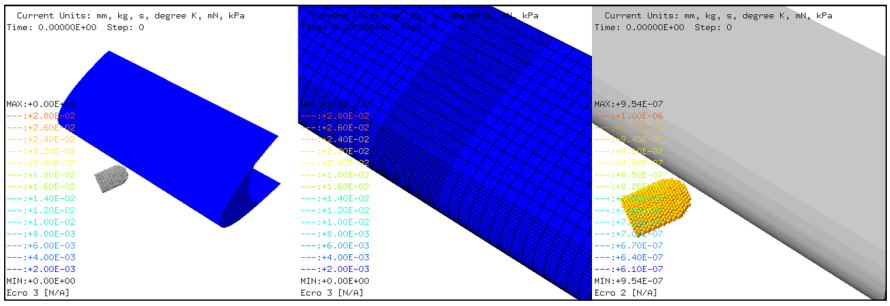
SONA01:



77

Example 8 – SPH impacts (3)

SONA01:



Plastic strain in structure | Plastic strain in structure (zoom) | Density in the projectile

78

SPH for structures

(Courtesy INSA-Lyon / EDF) Implemented in EUROPLEXUS by B. Maurel

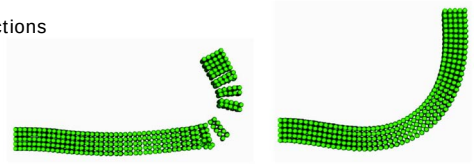
Application of SPH to **structural mechanics:** 3 major difficulties

Lack of spatial **precision/convergence** :

⟶ Use Moving Least Square (**MLS**) functions

Instability in the presence of **traction** :

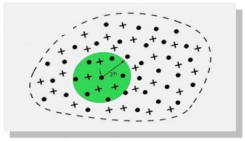
⟶ Use **Total Lagrangian** formulation



Classical SPH | Total Lagrangian

Zero-energy modes :

⟶ Introduce "**stress points**"



Introduce « Stress Points »

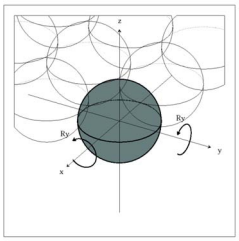


Traction instability

79

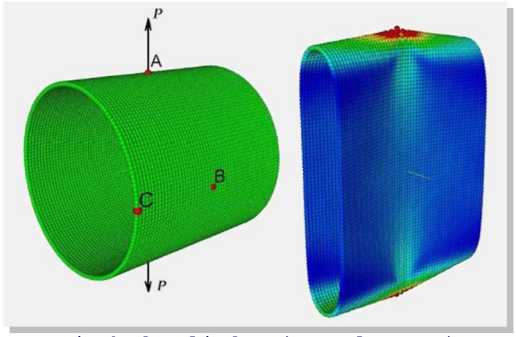
SPH for shells

(Courtesy INSA-Lyon / EDF)



Rotational dofs added

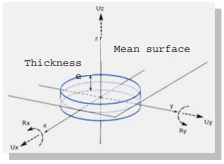
- Challenge: use **just one layer** of spheres through the shell thickness

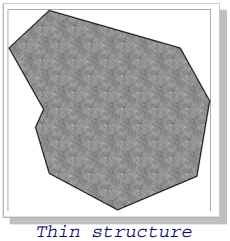


Pinched cylinder (Maurel, 2008)

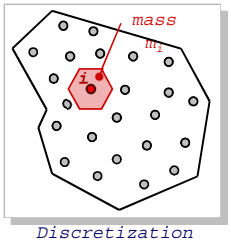
80

SPH for shells

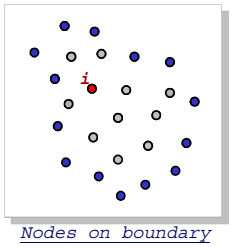




Thin structure



Discretization



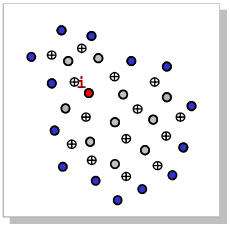
Nodes on boundary

SPH shell node

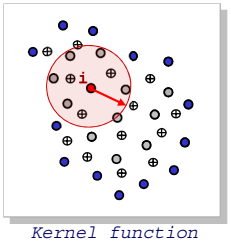
SPH Node

Boundary SPH node

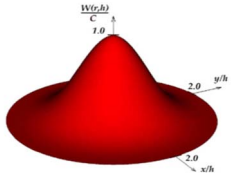
« Stress Point »



« Stress points »



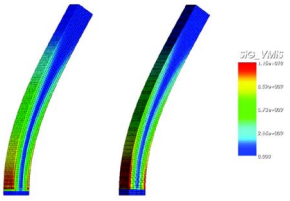
Kernel function domain



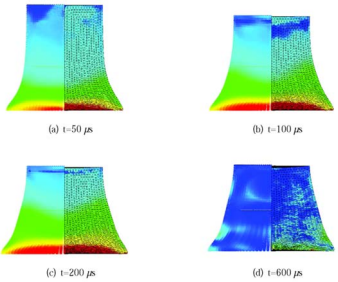
Cubic spline kernel W

81

SPH *vs.* FE

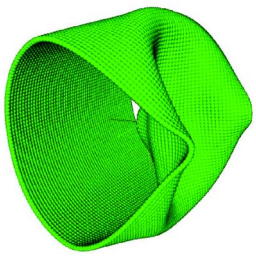


Solid bending

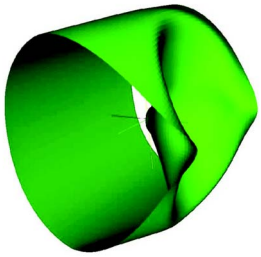


Solid impact

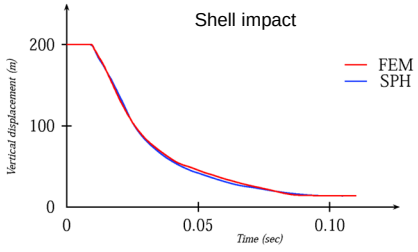
SPH



FE

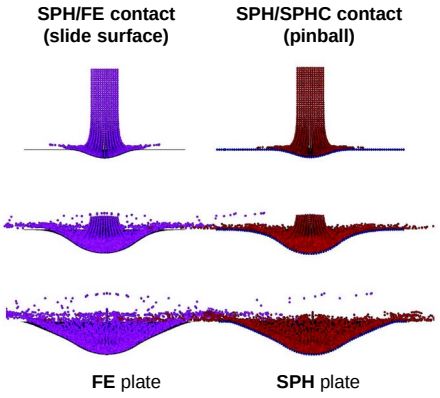


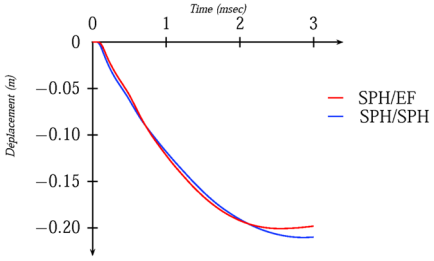
Shell impact



82

SPH : Lagrangian contact

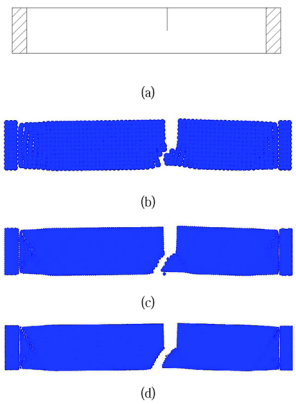




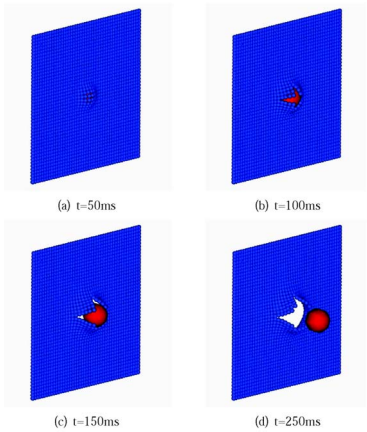
Water jet on plate

83

SPH facilitates treatment of rupture



Specimen with crack



Shell perforation

84

Impact on Fluid-filled Tanks by SPH

(Courtesy of **F. Caleyron**, A. Combescure, V. Faucher, S. Potapov)
[INSA Lyon, CEA Saclay, EDF Clamart]

→ **Protection** of **citizens** and of **installations** against **plane crash**

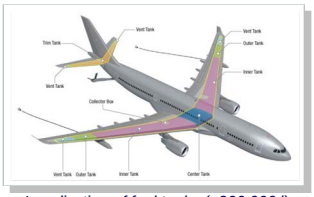
→ Thermal effects due to **dispersion** and **combustion** of **fuel** within the structure



WTC 2: impact (9h03)



WTC 2: collapse (9h59)



Localization of fuel tanks (~200 000 l)

→ Accounting for the presence of **fuel** **mandatory** in the analysis of **effects** of a plane crash

→ **Experiments** are difficult, expensive et dangerous: partial failure of CID project (NASA, 1984)











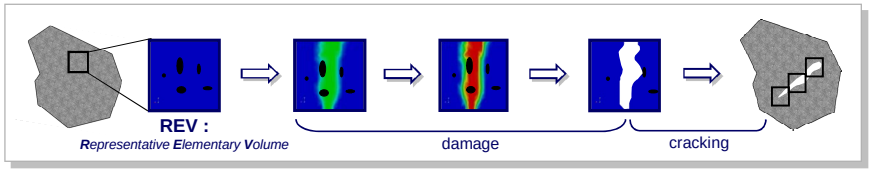
Dryden Flight Research Center EC84-31809 Photographed 1984
Remotely piloted Boeing 720 Controlled Impact Demonstration
aircraft following impact with iron cutter posts. NASA photo

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SPH Failure Model

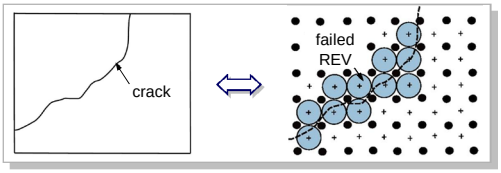
According to: Mécanique des Matériaux Solides, (***Lemaitre & Chaboche**, 2004)*:

« The theory of **damage** allows to foresee the **onset of a macroscopic crack** (*i.e.* at REV size).
The theory of **cracking** allows to foresee **its evolution** until complete failure of the structure »



Philosophy of the method:

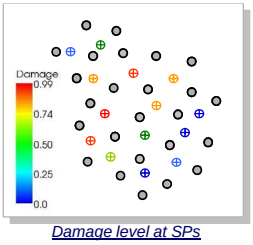
- **onset** of a crack when **critical damage** is reached in a REV
- **propagation** by cracking of **neighboring REVs**



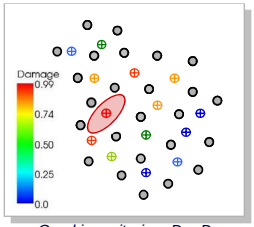
⇨ REV: - supported by « stress points »
- size given by spatial discretization

86

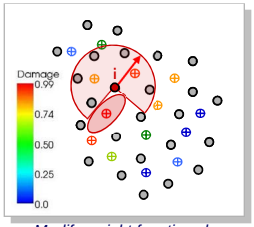
Damage – Cracking Transition



Damage level at SPs

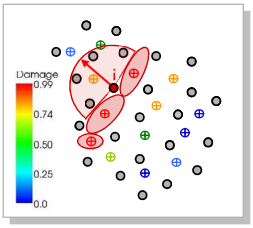


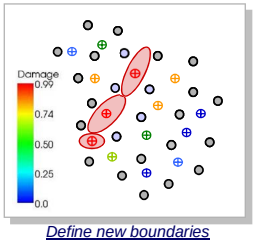
Cracking criterion: $D = D_c$



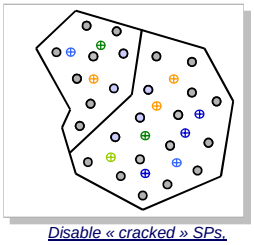
Modify weight functions by « visibility method »

SPH Node
Boundary SPH node
« Stress Point »





Define new boundaries



Disable « cracked » SPs, treat « fragments »

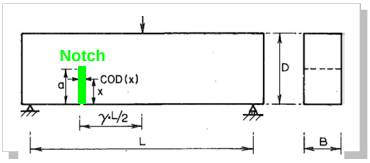
- Energy & mass are **conserved**
- **Simple** but **coarse** crack representation
- **Fine** SPH mesh is needed

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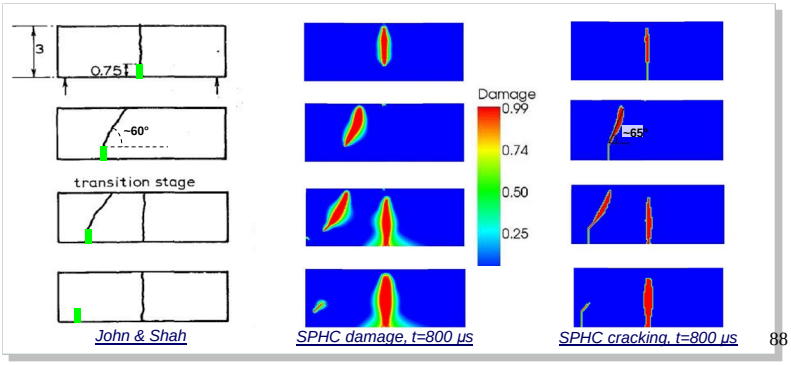
Crack propagation in mixed mode

(John & Shah 1988)

- **Concrete:** linear elastic
- **Mazars** damage model
- **Loading:** impact
- Assume **plane stress**



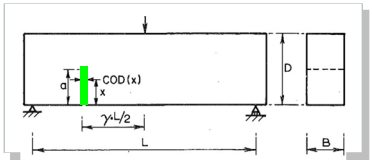
Scheme of experimental setup (John & Shah)



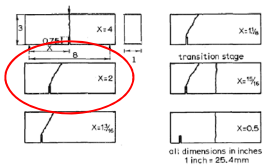
John & Shah | SPHC damage, t=800 µs | SPHC cracking, t=800 µs

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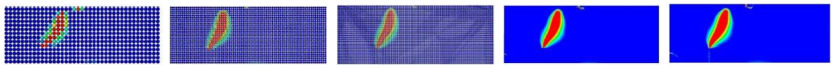
Convergence study



Scheme of experimental setup (John & Shah)



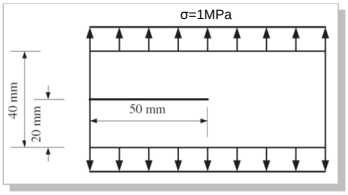
Experimental results

Mesh size →	10	5	3	2	1
D →					
L_{crack} →	20 +/- 10	20 +/- 5	15 +/-3	16 +/-2	17 +/-1

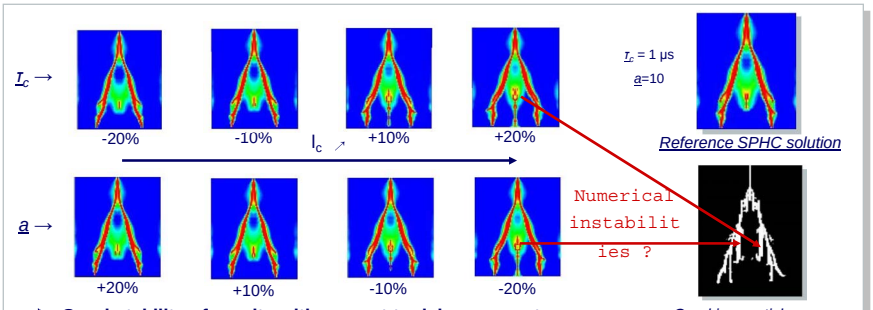
⇨ **Low dependency** upon mesh size: **localization limiter is effective**

Crack branching in 2D

(Belytsckho *et al.* 2006)



- Concrete: linear elastic, **Mazars** damage model
- **Loading:** traction ramp from 0 to σ
- **Plane stress**
- **Sensitivity** study to parameters τ_c and a

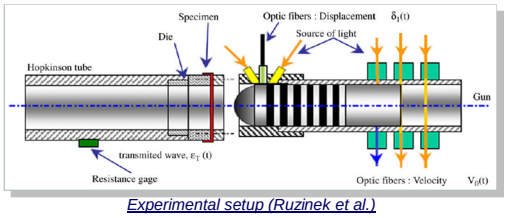


⇨ **Good stability of results with respect to delay parameter**

Petaling of a plate (Rusinek *et al.* 2009)

→ **Experimental conditions**

- Plates in mild steel ES
- Hemispherical projectile
- V_{imp}< 100 m/s
- Lubricated or dry contacy



Experimental setup (Ruzinek et al.)



Dry contact (Rusinek et al.)



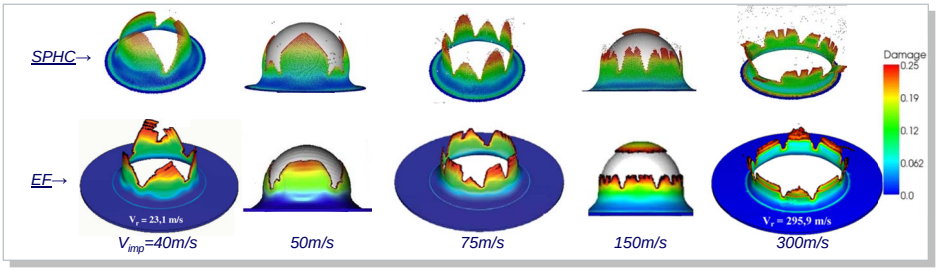
Lubricated contact (Ruzinek et al.)

⇨ The **petaling** mode depends upon **impact velocity** and upon **lubrication**

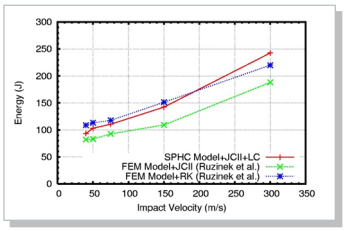
→ **Computational model**

- Steel: visco-plastic Johnson-Cook model with Lemaître & Chaboche damage model
- Spherical projectile: rigid
- Contact: pinball method

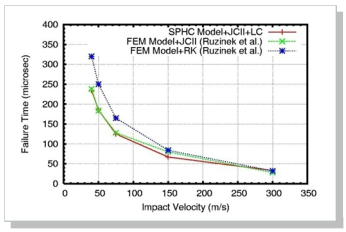
Petaling of a plate



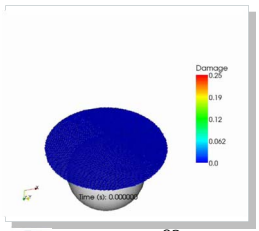
Comparison of SPHC (EuroPlexus) and EF (Ruzinek et al.) simulations



Kinetic energy « lost » by projectile



Time of plate rupture

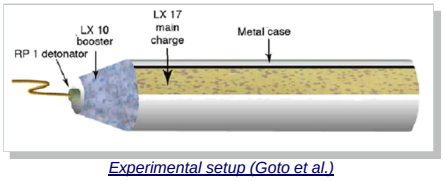


V_{imp}=300m/s

Fragmentation of a cylinder (Goto *et al.* 2008)

→ Experimental conditions

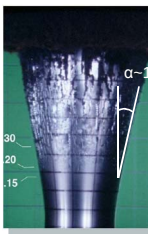
- Cylinder of AISI 1018 steel
- LX-17 explosive charge



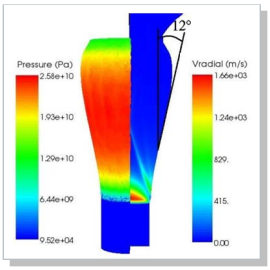
Experimental setup (Goto et al.)

→ Computational model

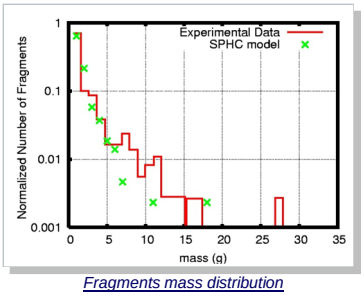
- Explosive: FEF, JWL equation of state
- Steel: SPHC, visco-plasticitic Johnson-Cook material, Lemaître & Chaboche damage model
- Contact: sliding surfaces



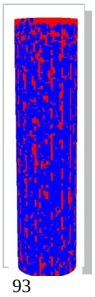
t=25 µs (Goto et al.)



t=25 µs (SPHC)



Fragments mass distribution



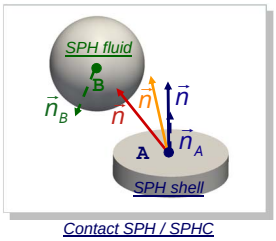
t=100 µs

SPH / SPHC Contact by Pinballs (Maurel 2008, Caleyron 2011)

→ **Fits naturally into SPH formulation**: 1 SPH particle = 1 « Pinball »

→ Treatment of a contact

- Compute the **normal** $\vec{n}$ **on contact**
  - Critical for effectiveness of the method: centres, mean, shell …
  - Choose the **normal to the shell**
  - Introduces a **pathological** case

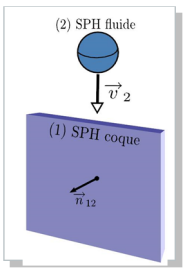


Contact SPH / SPHC

- Detect contact by **interpenetration sphere/cylinder**
- **Unilateral condition (inequality)** $(\vec{v}_A - \vec{v}_B)\cdot\vec{n} \le 0$
  - **Detection of rebound** by virtual configuration * w/out contact

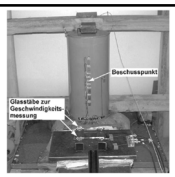
$$d^*_{AB} > d_{AB} \ ?$$

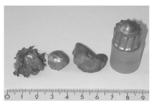
  - Impenetrability **condition** $(\vec{v}_A^{\,n+3/2} - \vec{v}_B^{\,n+3/2})\cdot\vec{n}^{n+1} = 0 \Rightarrow \underline{\underline{C}}\,\vec{V} = \vec{0}$
- Contact force by **Lagrange multipliers** $\vec{F}_c = \underline{\underline{C}}^t\vec{\lambda}$



Pathological case

Perforation of a Tank (Timm 2003)





→ **Experiment**

- perforation of a cylinder
- empty ou full
- 300 m/s < V_{imp} < 730 m/s
- H/D & *e* variable



« Hydrodynamic ram » phenomenon

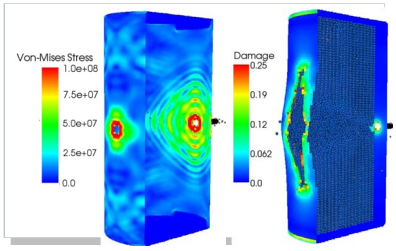


Empty (Timm, 2003) *Full (Timm, 2003)*

→ **Model**

- **Steel:** SPHC, visco-plasticity of JC, damage model of Lemaître & Chaboche, CT
- **Fluid:** SPH, perfect, slightly compressible
- **Impactor:** rigid
- **Contact:** « pinballs » method

⇨ Reproduction of the rupture mode

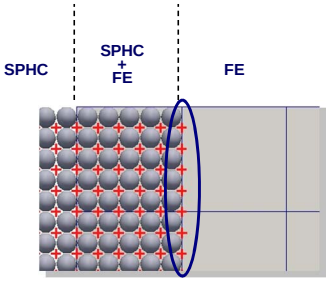


Empty (SPHC) *Full (SPHC)*

95

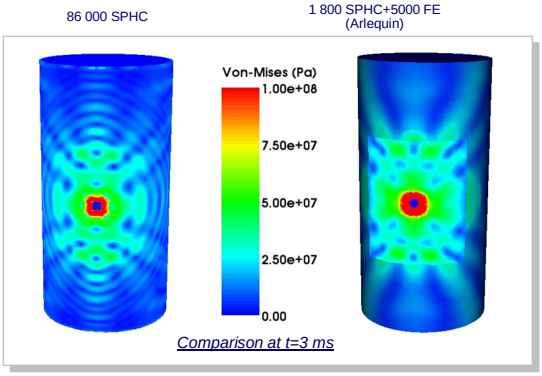
SPHC/FE Coupling ("Arlequin" Method, Ben Dhia 1998)

→ **Superposition zone**



Additional « Stress Points »

→ **Empty tank:** equivalent SPH mesh sizes



Comparison at t=3 ms

- CPU speed-up factor 5
- Exit velocities ~ equivalent
- Loss of resolution on high frequencies

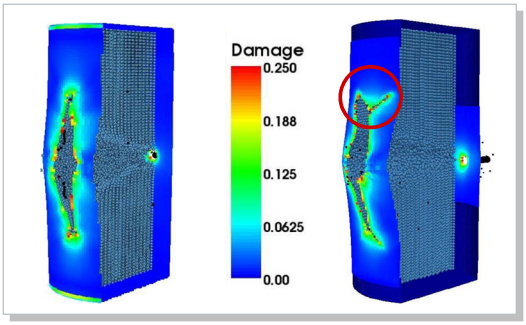
96

SPHC/FE Coupling in Tank Perforation

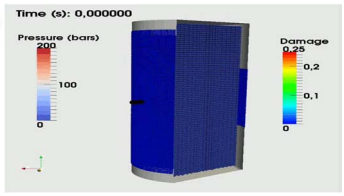
→ **Full tank:** refined SPH mesh

19 000 SPHC +
104 000 SPH

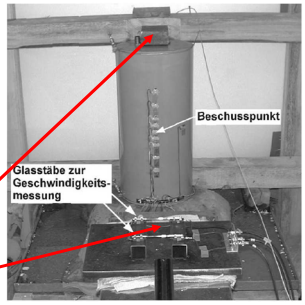
31 800 SPHC+2200 FE
(Arlequin)



Comparison at t=1.8 ms



Tank rupture and fluid jet until 20 ms

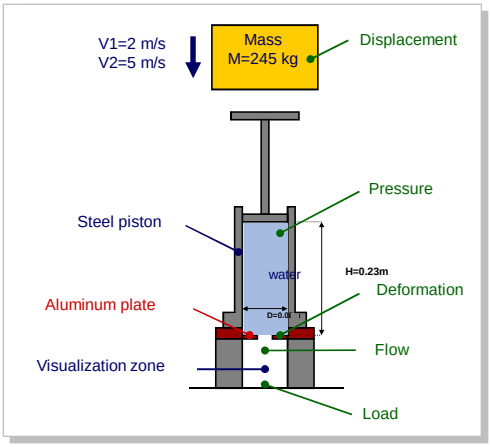


- The entire transient can be computed thks to coupling
- Exit velocities ~ equivalent
- Bifurcation of the crack (~ boundary conditions)

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Plate Rupture / Jet Simulation (J. Fabis, ONERA Lille)

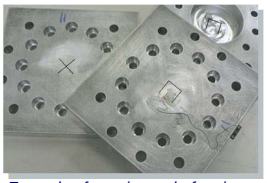
→ A **simple** but **representative** test of tank impact: **shock pressure on a plate**



Scheme of the test rig

→ Specimens characteristics

- **Thickness:** 25 mm, 2 mm, 1 mm
- circular **hole**, **notch** U, I, X



Example of specimens before impact

→ Physical phenomena

- **shock pressure** in the fluid
- **fluid jet**
- **deformation**, **cracking**, **rupture** depending on cases

98

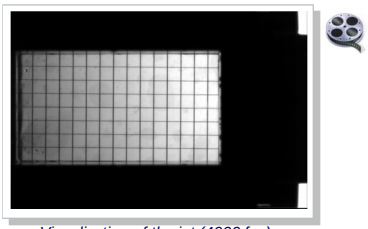
Sample Test (courtesy J. Fabis, ONERA Lille)



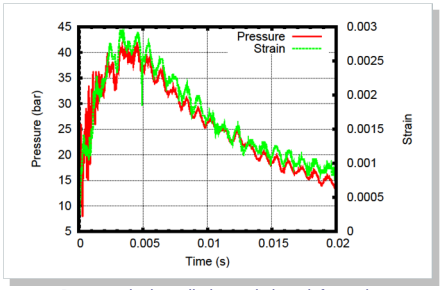
A test

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Plate with Circular Hole



Visualization of the jet (4000 fps)



Pressure in the cylinder and plate deformation

→ **Observations**

- **periodic pattern** in the jet
- **pressure** peak then **sinusoidal decrease**
- similar variation of **deformation**

frequencies are reproducible for a given specimen

→ **Interpretation**

- **turbulent instability** (Plateau-Rayleigh)
- excitation frequency = **eigenmode of device**

⇨ strongly coupled **fluid-structure** oscillator

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Types of Notches and Failure Modes

→ **U-Notch**

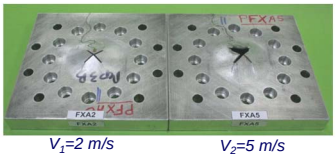


V_1=2 m/s



V_2=5 m/s

→ **X-Notch**

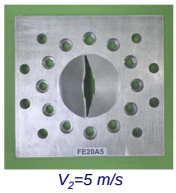


V_1=2 m/s V_2=5 m/s



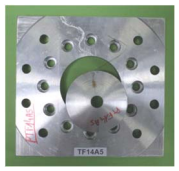
zoom

→ **I-Notch**



V_2=5 m/s

→ **Design Fault**



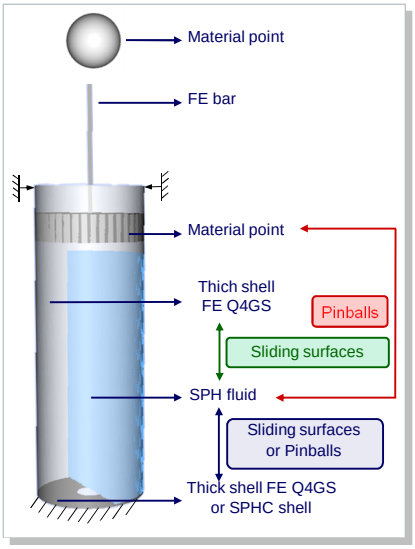
V_2=5 m/s

⇨ A variety of strongly non-linear phenomena in addition to FSI:

- **large deformations**
- **plasticity**
- **cracking**
- **full rupture**

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Numerical Model



→ Explicit **representation** of the **device**

→ Model of the **structure**

- cylinder: - FE thick shell
  - APX: linear elastic
- plate: - FE thick shell **(+ SPHC if cracking)**
  - AL4G: élasto-plastic with damage

→ **Fluid model**

- SPH
- Water: slightly compressible, acoustic, perfect

→ **Fluid-structure interaction**

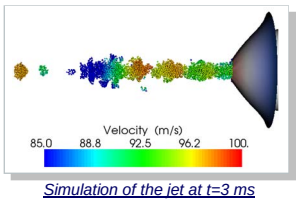
- FE-SPH: **sliding surface** without parasitic forces
- SPH-SPHC: **pinballs**

→ ~1 700 FE, ~112 000 SPH , ~15 000 SPHC

→ **parallel calculations** on 4 CPUs

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Results for Thick Plate with Circular Hole



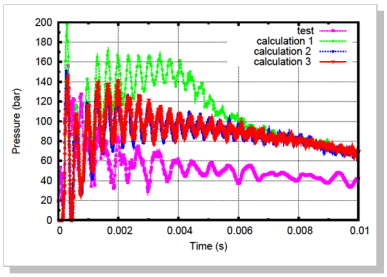
Simulation of the jet at t=3 ms

→ **Comparison** simulation/experiment

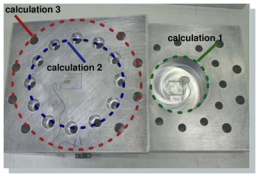
- **patterns** in the jet
- **ejection speed** of the fluid
- **peak** and **variation** of **pressure** after impact

- **overestimation of pressure** and its variation beyond 2 ms
  - state equation slightly compressible
  - SPH discretisation too coarse in the fluid
  - too rigid idealised model

⇨ **Predictive simulation** of response just **after impact**
Model is inaccurate once the flow develops



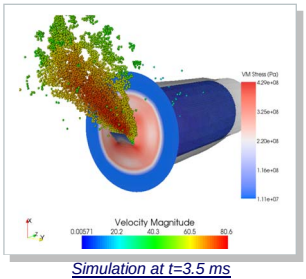
Pressure in the cylinder



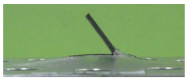
Influence of boundary conditions

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Results for Thin Plate with U-Notch



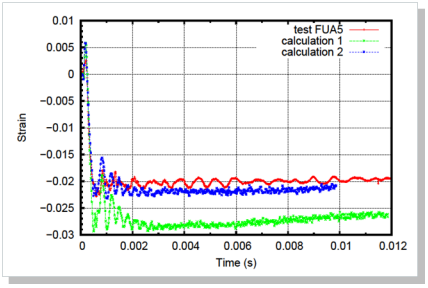
Simulation at t=3.5 ms



Experimental deformation α~50°



Numerical deform. t=10 ms, α~50°



Deformation of the lid

→ **Comparison** simulation/experiment

- **ejection speed** of the fluid
- **opening** of the lid
- **peak** and **variation** of **pressure** after impact
- **variations of deformation**

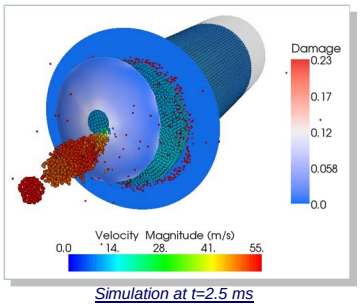
- **overestimation of pressure** and its variation beyond 2 ms

⇨ **FSI** is treated correctly

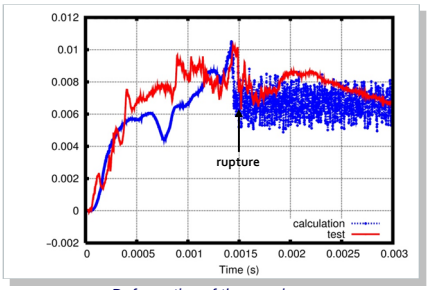
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Results for Badly Designed Specimen

→ Rupture by **stress concentration**: erosion & debris



Simulation at t=2.5 ms



Deformation of the specimen

→ **Comparison** simulation/experiment

- **rupture mode**
- **pressure peak** and **variation**
- **rupture time**
- **variations** of **deformation**

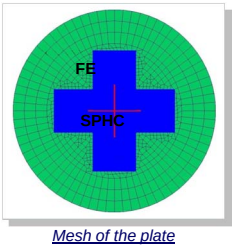


Rupture mode

⇨ **Predictive simulation** of impacted tank **rupture**

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Results for Thin Plate with X-Notch



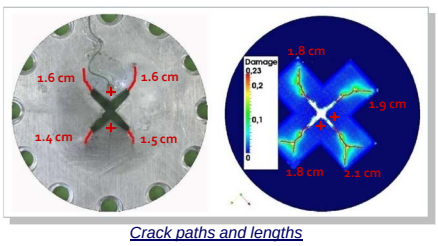
Mesh of the plate

→ **Crack propagation:** SPHC model

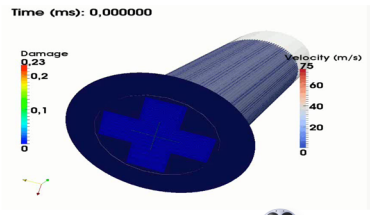
→ **Comparison** simulation/experiment

- **ejection speed** of the fluid
- **rupture mode**
- **crack propagation**
- **parasitic ruptures**
- **overestimation of the length** of cracks
- **bifurcation** of cracks

⇨ **The simulation of crack propagation with FSI is feasible**



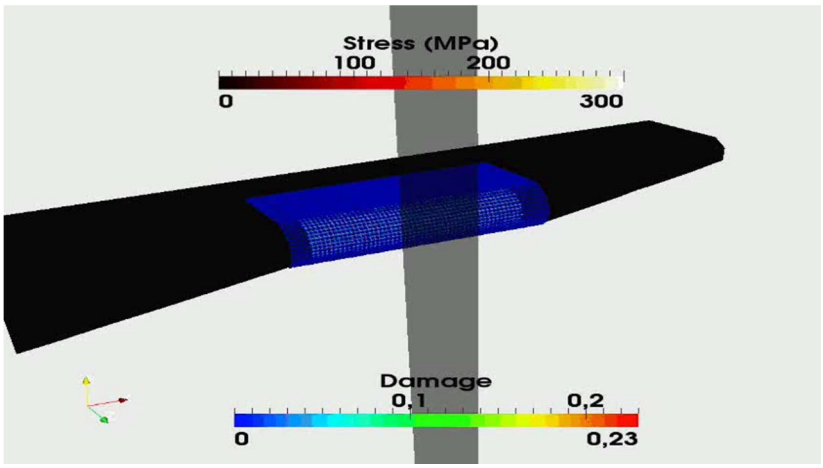
Crack paths and lengths



Simulation

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Towards Industrial Simulations

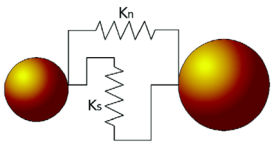


Simplified plane wing (P.Yard)

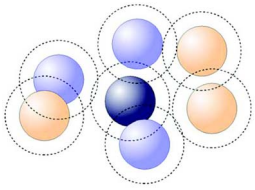
107

DEM (Courtesy of EDF)

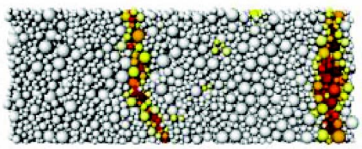
- "Discrete Element" Method from L3S-R UJF Grenoble, implemented in EUROPLEXUS by EDF (J. Rousseau)



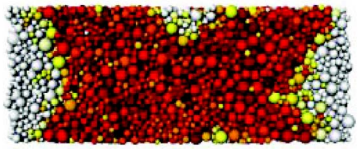
Interactions between "elements"



Interaction radius



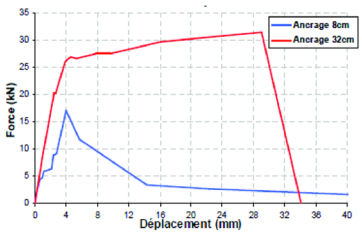
"Specimen" in traction



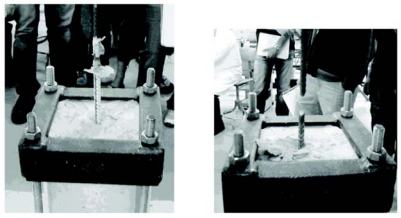
"Specimen" in compression

108

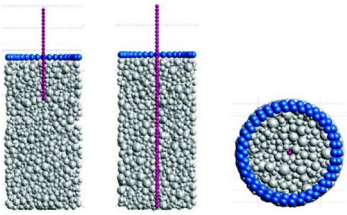
DEM : Pull-out tests



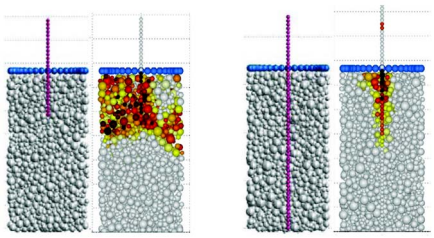
Experimental force



"Short" vs. "long" pull-out



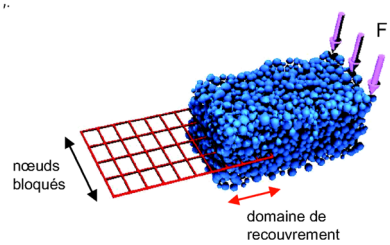
Numerical "specimens"



Numerical results

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DEM : Impact tests on R/C plate



DEM-FE (shell) coupling

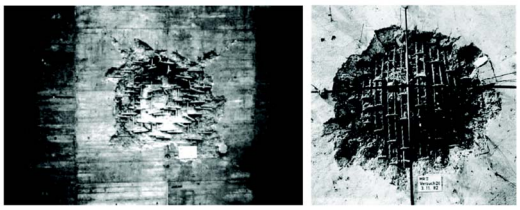
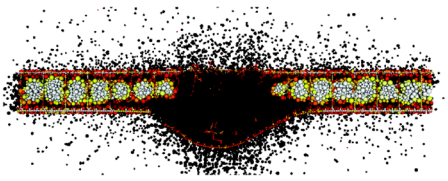
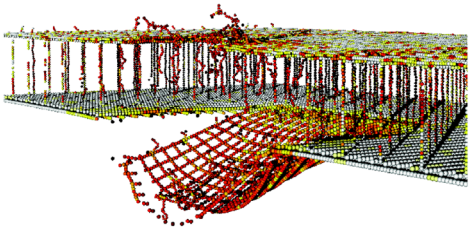


Plate impact experiment



Numerical result



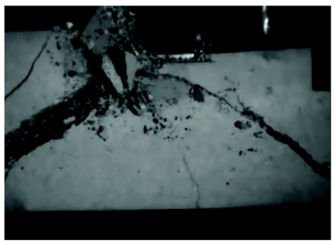
Detail of reinforcement

110

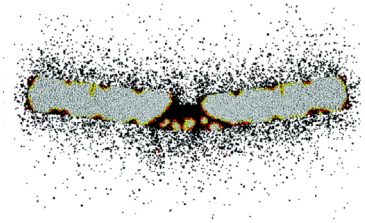
DEM : Impact tests on R/C beam



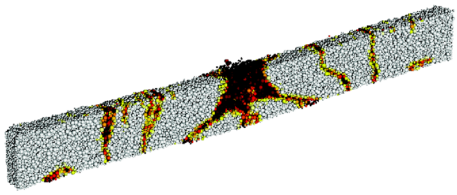
“Long” beam



“Short” beam



Numerical result (excessive spalling)

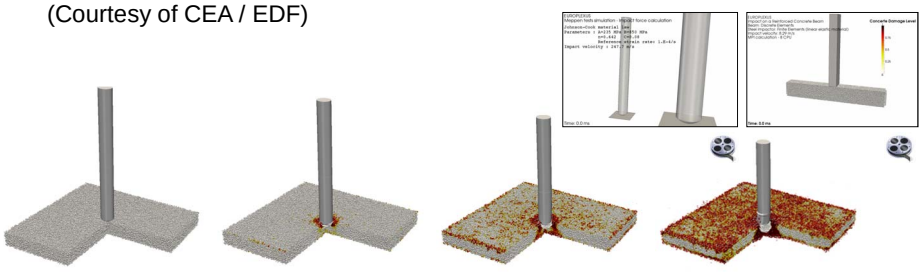


Without reinforcement

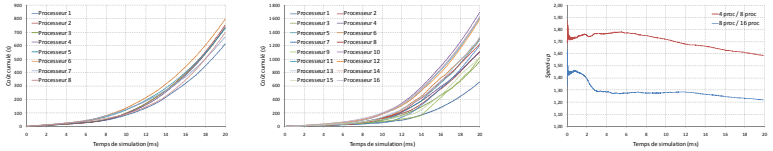
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Simulation of the Meppen Test

(Courtesy of CEA / EDF)



(a) t = 0 ms *(b) t = 2 ms* *(c) t = 5 ms* *(d) t = 10 ms*



(e) Cost of identifying the global links *(f) Evolution of the speed-up*

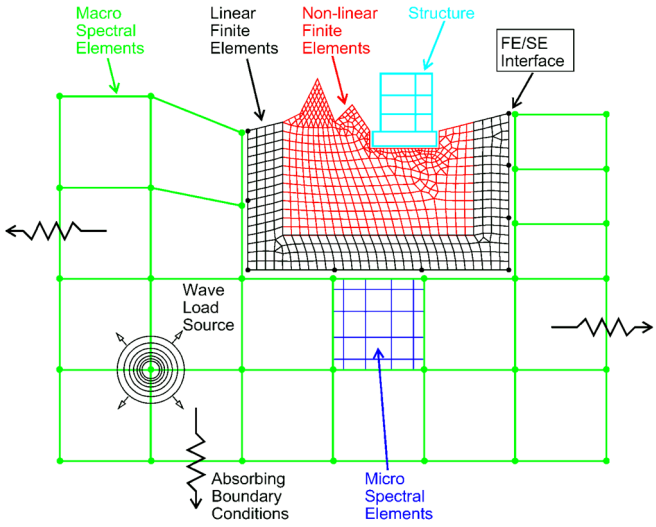
Interpretation:

- **Bad distribution of entities** (cf. Ponderation of domain decomposition)
- **Evolution of costs during the run** with loss of structure of the plate
- **Progressive degradation of the *speed-up***

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Spectral Elements

- Motivation: locally linear wave propagation (no singularities)



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Spectral Elements (2)

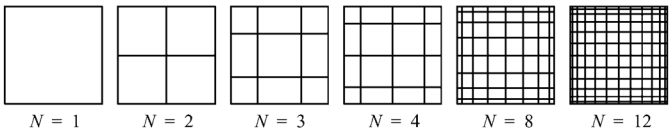
Various approaches for numerical solution of PDEs :

- Finite-element methods:
  - Discrete approximating function is a polynomial of low degree
  - Well suited to complex geometry and full non-linearities
  - Accuracy limited by low degree of polynomials
- Spectral-type methods:
  - Discrete approximating function is a polynomial of high degree
  - Very accurate ("spectral" accuracy) when exact solution is smooth
  - Currently limited to linear problems (and no singularities)
  - Difficult to treat complicated boundaries: use domain decomposition
- *p*-version of FEM:
  - Shape functions are polynomials of high degree
  - Bases & quadrature formulas completely different from spectral methods

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Spectral Elements (3)

- To obtain spectral convergence, nodes are placed at special Legendre-Gauss-Lobatto (LGL) positions ξ_P:



$N \doteq$ degree of polynomial

- These correspond, in 1-D, to the zeroes of L_N', the first space derivative of L_N, the Legendre polynomial of degree N:

$$\{\xi_P\} = \{\text{zeroes of } L_N'\} \cup \{-1,1\}$$

$N+1$ points

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Spectral Elements (4)

- Solution is then interpolated by Lagrange polynomials through the LGL points:

$$\psi_I = \frac{(\xi-\xi_1)\cdots(\xi-\xi_{I-1})(\xi-\xi_{I+1})\cdots(\xi-\xi_{N+1})}{(\xi_I-\xi_1)\cdots(\xi_I-\xi_{I-1})(\xi_I-\xi_{I+1})\cdots(\xi_I-\xi_{N+1})} \Rightarrow \begin{cases} 1 \text{ in } \xi_I \\ 0 \text{ in } \xi_J, J \neq I \end{cases}$$

- For numerical integrations, use is made of LGL rule instead of the Gauss rule typical of FEM:
  - All quantities, including stresses, are expressed at “nodes”
  - Considerable simplifications in programming: very efficient implementation!
  - For a given accuracy, one more sampling point is needed by LGL rule compared with Gauss rule

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Spectral Elements (5)

Convergence properties:

- In the FEM, let *h* be the element size and *k* the degree of the piecewise polynomial in each element, then the convergence of the method, obtained for $h \to 0$, is:

$$\|u - u_h\|_{L^2(\Omega)} = Ch^{k+1}$$

- In the SEM, let *N* be the degree of the piecewise polynomial in each element, then the convergence of the method, obtained now for $N \to \infty$, is:

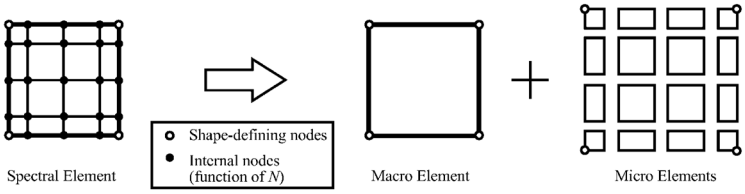
$$\|u - u_N\|_{L^2(\Omega)} = Ce^{-\alpha N}$$

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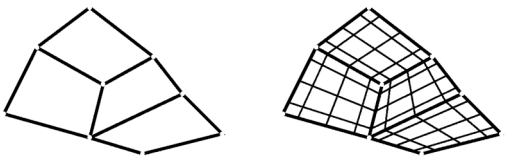
Spectral Elements (6)

Generation of spectral mesh and implementation in FEM code

- A dual mesh composed of *macro* and *micro* elements is used:



- The macro elements are built first, then the micro mesh is generated according to the chosen N:



e.g. in Cast3m mesh generator:

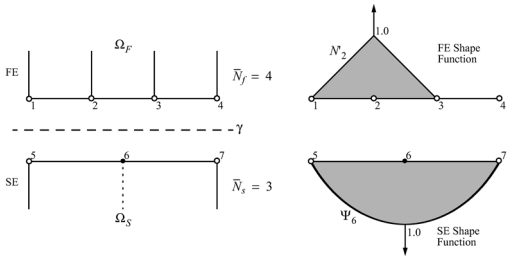
```
micro = pxspect2
      macro n tol;
```

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Spectral Elements (7)

Coupling between FE and SE

- We use an ***integral*** form of continuity condition at the non-conforming FE/SE interface (***mortar*** method):



$$\int_{\gamma} (\underline{\dot{u}}_F - \underline{\dot{u}}_S) \cdot N_F' \, d\gamma = 0 \qquad F = 1, \cdots, \bar{N}_F$$

$\gamma \doteq$ FE/SE interface $\qquad \underline{\dot{u}} \doteq$ velocity

$N_F' \doteq$ FE surface shape function $\qquad \bar{N}_F \doteq$ FE nodes on γ

- These conditions are of the usual form $\underline{C}\underline{v} = \underline{b}$ and are solved via the method of Lagrange multipliers.
- More accurate than with ***local*** conditions (node-by-node basis).

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Spectral Elements (8)

Absorbing boundary conditions (ABCs)

- We use first-order ***Stacey*** ABCs:

$$\frac{\partial}{\partial \underline{n}}(\underline{u} \cdot \underline{n}) = -\frac{1}{\alpha} \cdot \frac{\partial}{\partial t}(\underline{u} \cdot \underline{n}) + \frac{\beta - \alpha}{\alpha} \cdot \frac{\partial}{\partial \tau}(\underline{u} \cdot \underline{\tau})$$

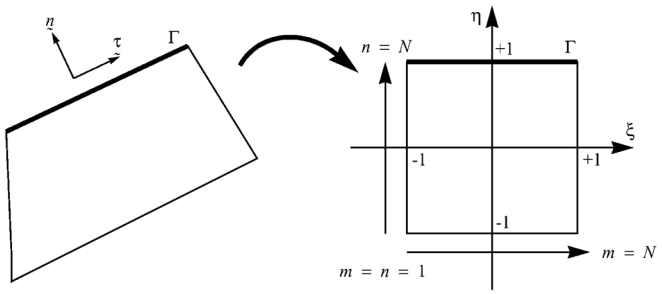
$$\frac{\partial}{\partial \underline{n}}(\underline{u} \cdot \underline{\tau}) = -\frac{1}{\beta} \cdot \frac{\partial}{\partial t}(\underline{u} \cdot \underline{\tau}) + \frac{\beta - \alpha}{\beta} \cdot \frac{\partial}{\partial \tau}(\underline{u} \cdot \underline{n})$$

$\underline{n} \doteq$ normal to boundary

$\underline{\tau} \doteq$ tangent to boundary

$\alpha \doteq$ longitudinal wave speed

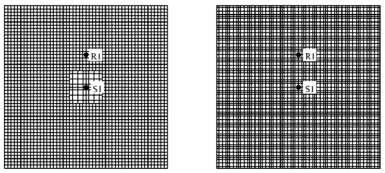
$\beta \doteq$ transversal wave speed

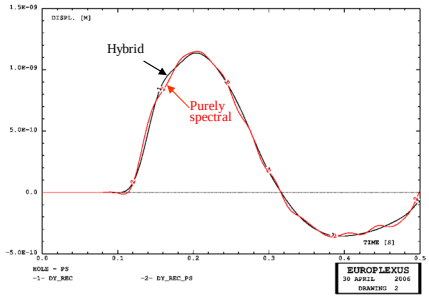


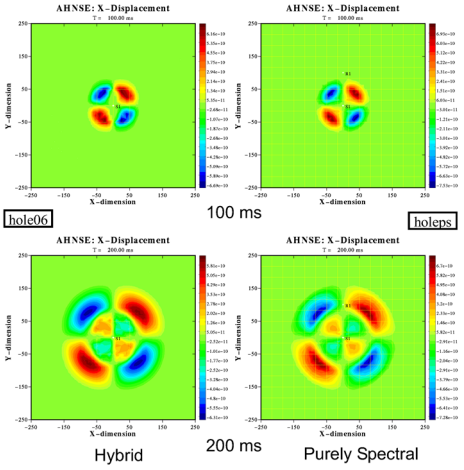
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Example 9 – Closed FE/SE interface

- Verification of coupling algorithm - closed interface test:

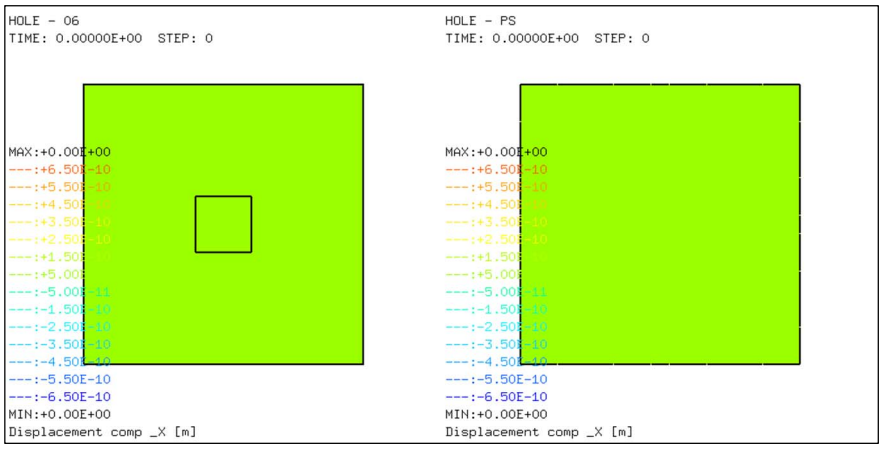






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Closed FE/SE interface (2)



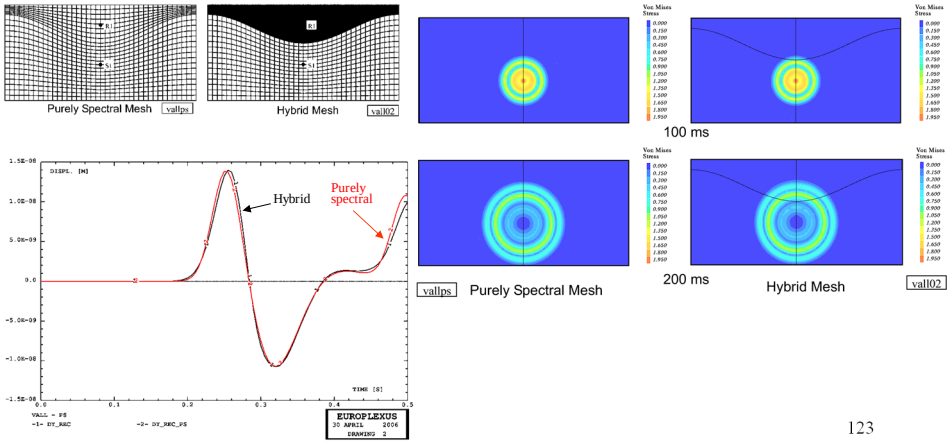
Coupled FE/SE solution

Purely Spectral solution

122

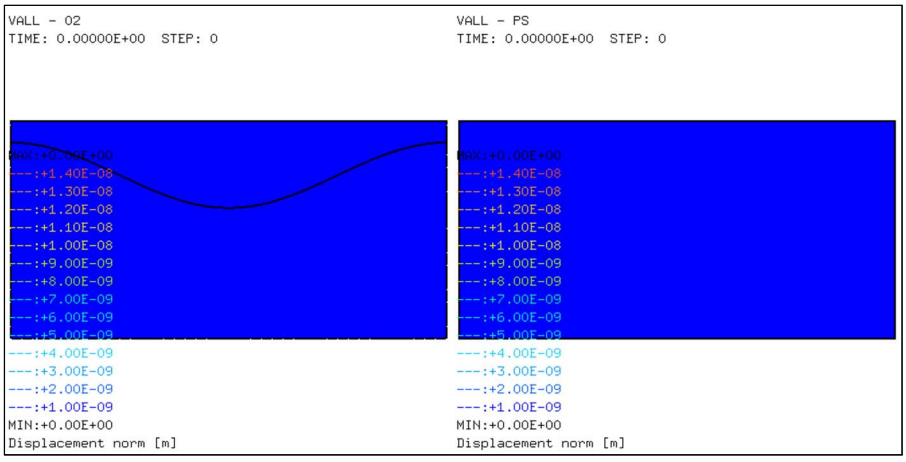
Example 10 – Sediment valley

- Verification of coupling algorithm - sediment valley test:



123

Sediment valley (2)

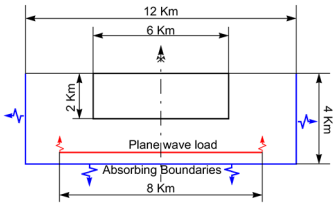


Coupled FE/SE solution

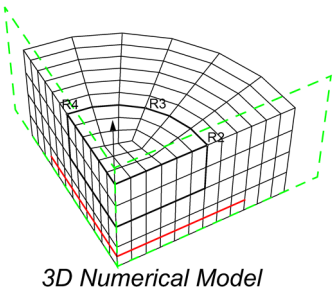
Purely Spectral solution

124

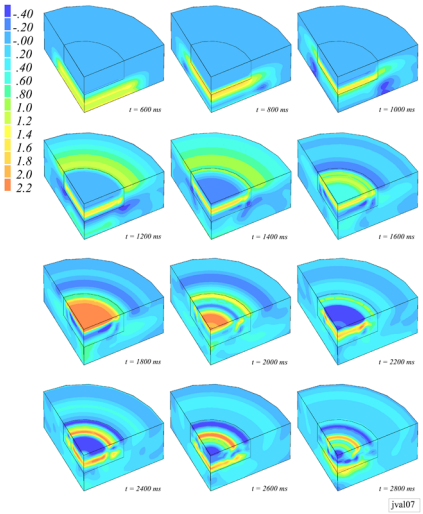
Example 11 - Cylindrical valley



Problem Definition



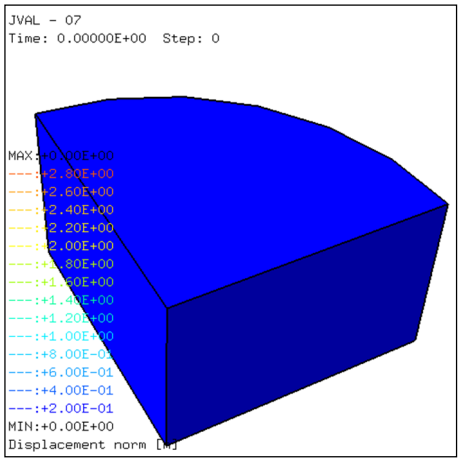
3D Numerical Model



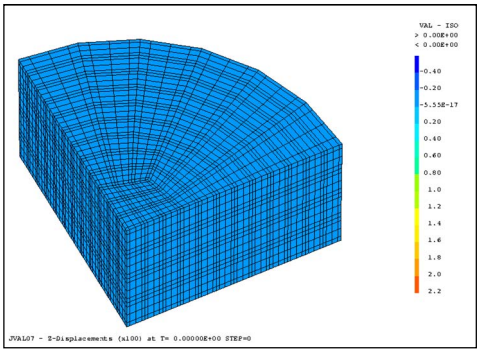
3D Numerical Solution (z-Displacement)

125

Cylindrical valley (2)



Total displacement



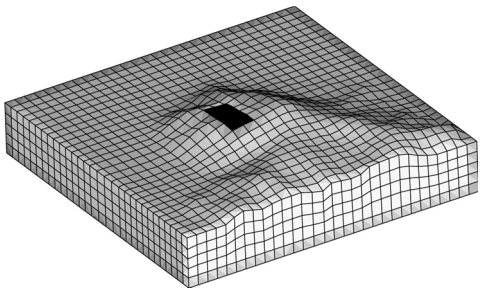
Vertical displacement

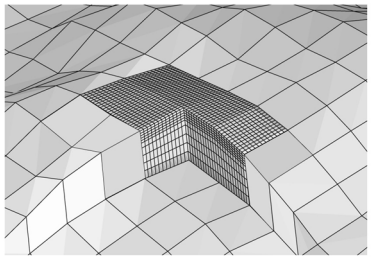
126

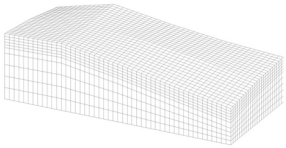
Example 12 - Matsuzaki valley

- Matsuzaki valley (Japan):

3D computational model (Spectral Elements for the bedrock, coupled with Finite Elements for the heterogeneous valley)



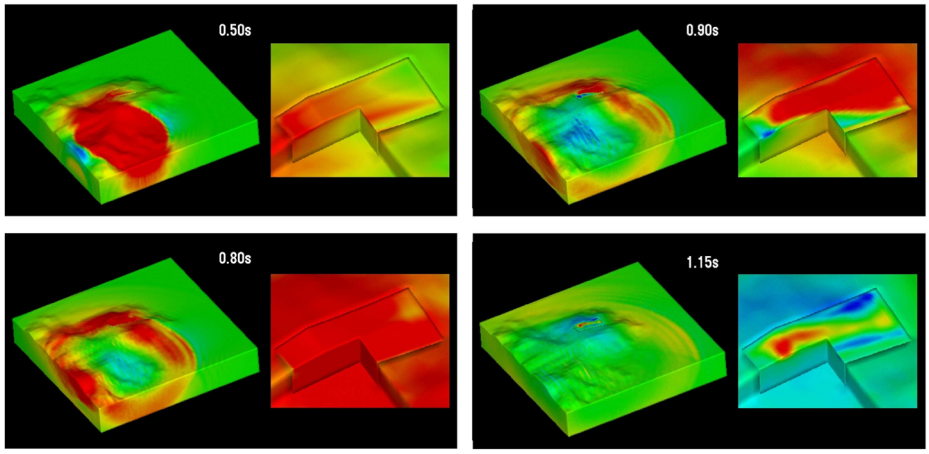




Detail of heterogeneous valley

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Matsuzaki valley [Courtesy of CRS4]



Wave propagation and detailed view of site effects due to localized soil heterogeneity

Numerical Model: 4492 Macro SE, 121284 Micro SE, 11520 FE, 145806 nodes

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Performance Optimization

- All examples seen so far used the same time increment $\Delta t(t)$ for all elements in the mesh.
- Can be penalizing in explicit methods, especially in 3D when mesh is locally very fine. The smallest element drives the calculation's time increment.

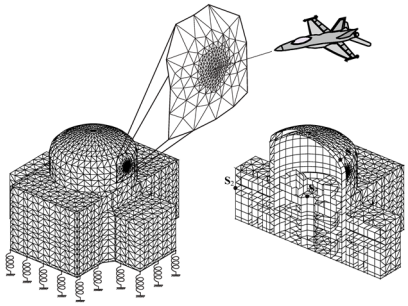


FIGURE [2.3.4.2] : *Ilot nucléaire - Maillage et conditions aux limites*

- Alternative strategies where the step varies both in time and in space: $\Delta t(x,t)$.
  - Spatial time step partitioning
  - Domain decomposition

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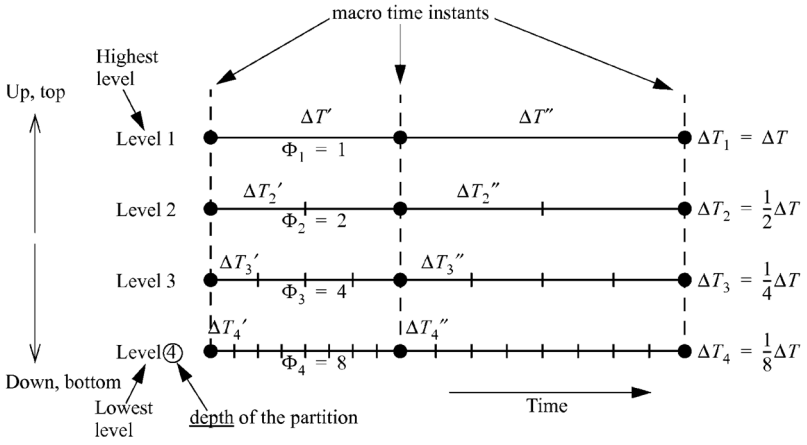
Time Step Partitioning

- Due to J.P. Halleux (1985!)
- Time step is automatically varied in space according to a binary partition (1, ½, ¼, etc.).
- Simple and elegant: activated by **OPTI PART**.
- Each element is integrated with a step much closer to its stability limit than usual (better accuracy!)
- Some complications in B.C.s: any nodes subjected to essential conditions are associated with the deepest partition level (smallest step) by default. A more efficient treatment is possible (see below), but also more complex to implement.

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Time Step Partitioning (2)

- Build up partition levels according to binary rule:

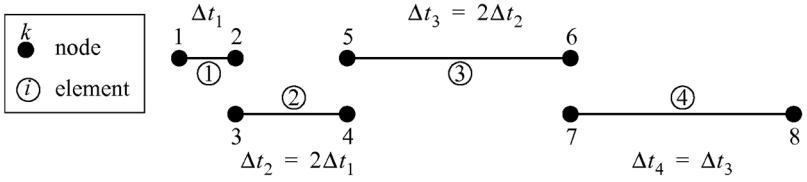


Example of two consecutive macro steps in a binary partition with 4 levels

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Time Step Partitioning (3)

- Partitioning trivial for unconnected mesh



A simple mesh of independent elements

- Complexity arises from element connections through nodes (or from boundary conditions!)

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Time Step Partitioning (4)

- Intrinsic element frequency:

$$\varphi_i = \Phi_l \quad \text{such that} \quad \Delta T_l \le \Delta t_i < \Delta T_{l-1} \ (*) \qquad i = 1, \ldots, N_e$$

(*) For $l = 1$ this is replaced by $\Delta T_1 = \Delta t_m$, where m are elements with maximum step.

- Intrinsic node frequency:

$$\psi_k^{\text{free}} = \max\,(\varphi_j) \qquad j = \text{any element sharing node } k \qquad k = 1, \cdots, N_n$$

Used to update *nodal accelerations and velocities*

- Neighbouring element frequency:

$$\bar{\varphi}_i = \max\,(\psi_m) \qquad m = \text{any node of element } i \qquad i = 1, \ldots, N_e$$

Used to update *element quantities*

- Neighbouring node frequency:

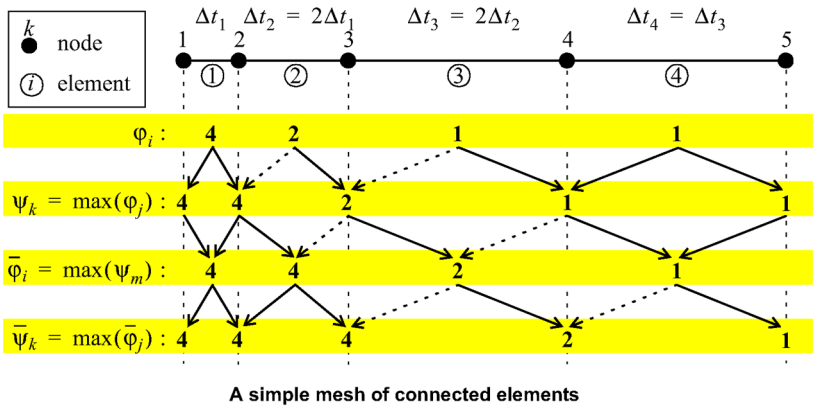
$$\bar{\psi}_k = \max\,(\bar{\varphi}_j) \qquad j = \text{any element sharing node } k \qquad k = 1, \cdots, N_n$$

Used to update *nodal configurations*

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Time Step Partitioning (5)

- Consider following simple example:

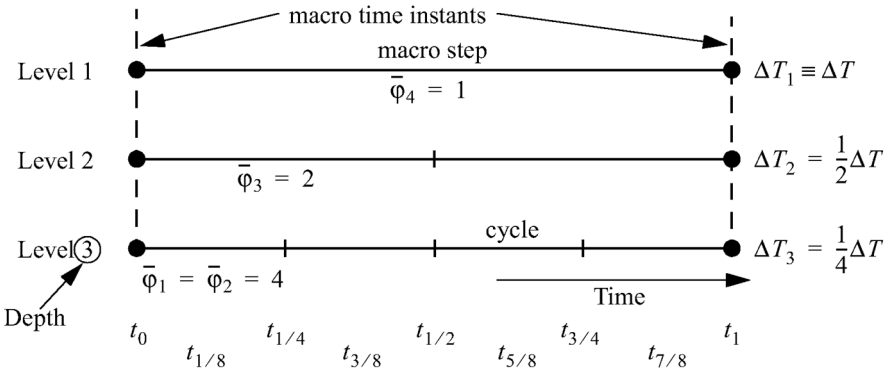


A simple mesh of connected elements

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Time Step Partitioning (6)

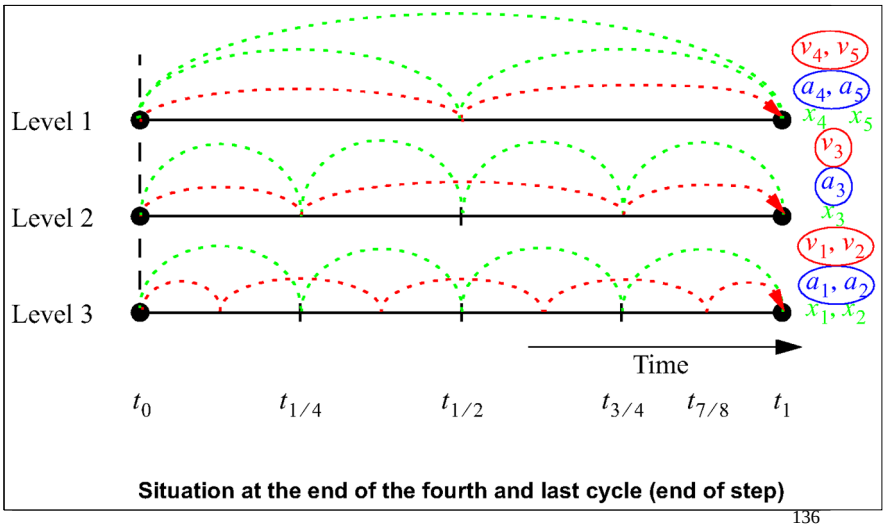
- This leads to the following partition:



Partition for the mesh shown in the previous Figure

Time Step Partitioning (7)

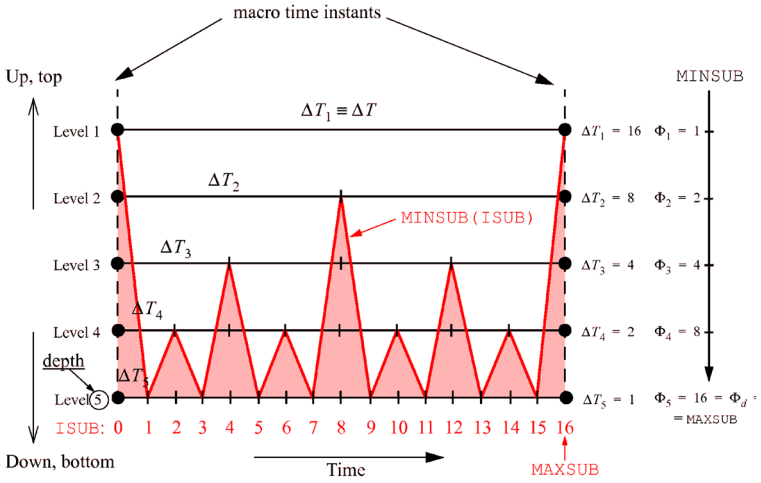
- Advancing solution in time:



Situation at the end of the fourth and last cycle (end of step)

Time Step Partitioning (8)

- Activity chart:



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Illustration of the meaning of MAXSUB and MINSUB

Treatment of links in partitioning (1)

- First method - assign any linked nodes to lowest partition level:

  $\psi_k^{\text{link}} = \Phi_d \equiv 2^{d-1}$ for any node k subjected to a link

- Then treat by standard Lagrange multipliers technique (recall Part 1)
- Advantages:
  - Extremely simple to implement (if limited to permanent links)
- Drawbacks:
  - Can reduce efficiency if there are many links
  - Deals only with permanent links (synchronization) if search for linked dofs is done just once

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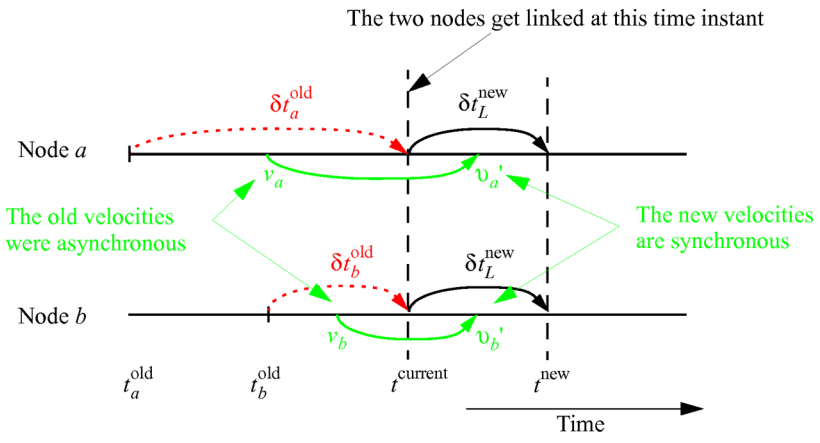
Treatment of links in partitioning (2)

- Second method (for a permanent link):
  - For nodes *k* subjected to a link compute: $\psi_{\max} = \max_k(\psi_k^{\text{free}})$
  - For the same nodes, set: $\psi_k^{\text{link}} = \psi_{\max}$
  - Consequently, all nodes affected by the link are time-integrated by the same time increment (synchronized): $\delta t_L = \Delta t_{\max} / \psi_k^{\text{link}} = \Delta t_{\max} / \psi_{\max}$
- Advantages:
  - Fully general (see below for non-permanent links)
  - More efficient than first method, at least potentially
- Drawbacks:
  - More difficult to implement

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Treatment of links in partitioning (3)

- For non-permanent links: synchronization issue



Lack of synchronization in a non-permanent link

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Treatment of links in partitioning (4)

- The Lagrange multipliers method (recall Part 1) can be generalized as follows $\underline{C}\underline{v} = \underline{b} \rightarrow \underline{A}\underline{\lambda} = \underline{z}$
- Synchronous case:

$$\underline{A} = \underline{C}\gamma\underline{m}^{-1}\underline{C}^T \qquad \underline{z} = \underline{b} - \underline{C}\underline{v}^{n+1/2} - \underline{C}\gamma\underline{m}^{-1}(\underline{f}^e - \underline{f}^i) \qquad \gamma = \frac{\Delta t^n + \Delta t^{n+1}}{2}$$

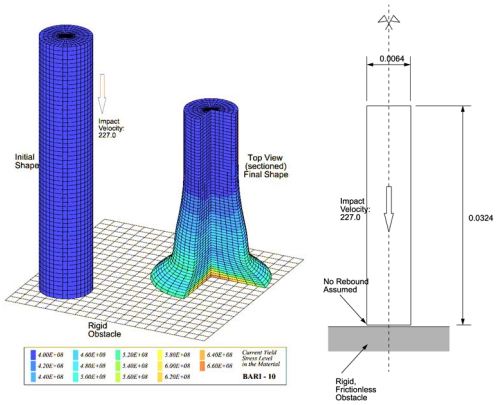
- Asynchronous case: just replace the scalar γ by the matrix:

$$\underline{\Gamma} = \text{diag}\,(\gamma_i) \qquad \gamma_i = \frac{\delta t_i^{\text{old}} + \delta t_L^{\text{new}}}{2}$$

- The connections matrix remains symmetric and positive definite like in the synchronous case.

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Example 12a – Taylor bar impact revisited



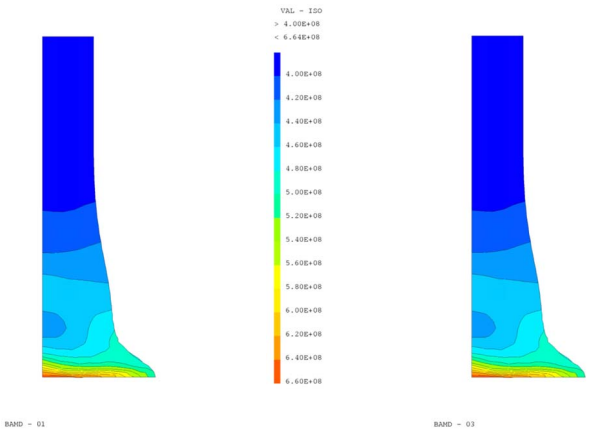
Material Data	
Density	8930
Young's Modulus	1.17×10^{11}
Yield Stress	4.0×10^{8}
Plastic Modulus	1.0×10^{8}
Poisson's Ratio	0.35

- A - Solution with spatially uniform time increment (BAMD01)
- B - Solution with space partitioning (BAMD03)

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Example 12a – Taylor bar impact revisited (2)

- Comparison of solutions (final yield stress):

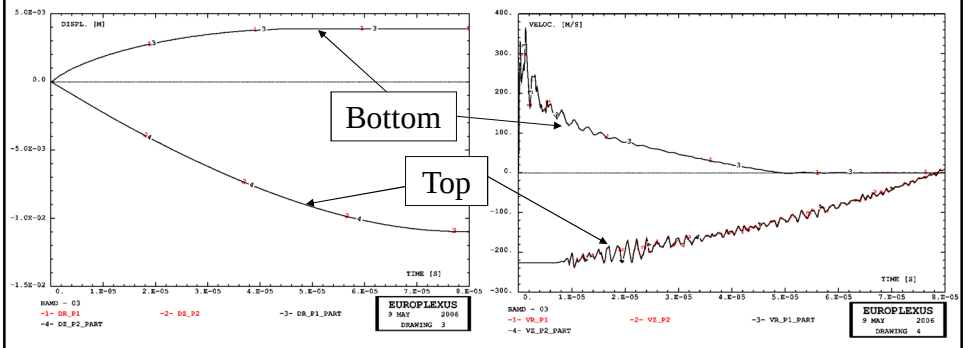


Standard Partition

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Example 12a – Taylor bar impact revisited (3)

- Comparison of solutions:

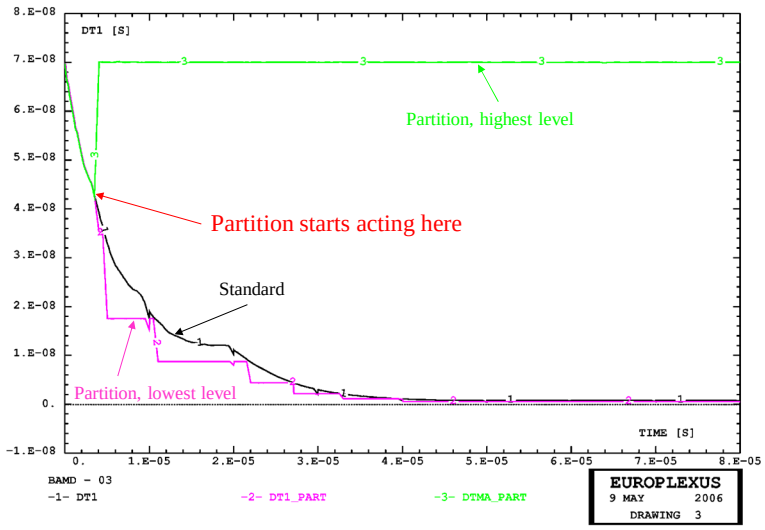


Displacements Velocities

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Example 12a – Taylor bar impact revisited (4)

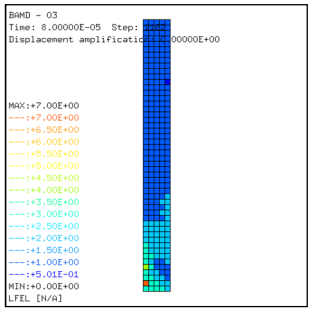
- Comparison of solutions (time increments):



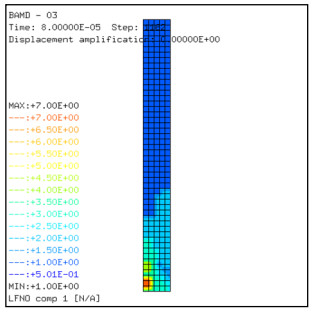
145

The partition at work (final time on initial geom):

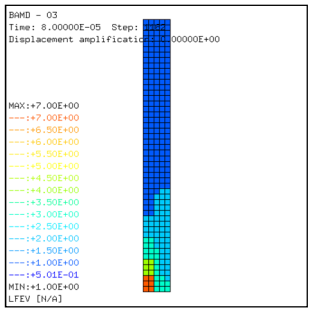
Element frequency



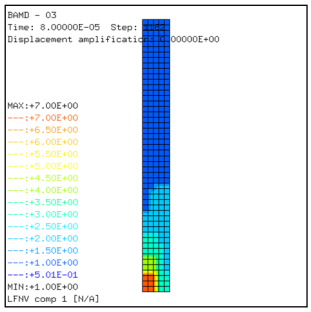
Node frequency



Element neighbour frequency



Node neighbour frequency



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Example 12a – Taylor bar impact revisited (6)

- Performance comparison:

Case	Time Integr.	Steps	Cycles	Maximum frequency	Elements * cycles	CPU (s)	Speedup (theor. / actual)
BAMD01	AUTO	59886	—	—	14,971,750	55.7	—
BAMD03	PART	1162	85537	128	1,296,171	6.6	11.6 / **8.4**

- To activate the partition, simply add:

OPTI PART

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Domain Decomposition

References: see A. Combescure (ENS Cachan), B. Herry, A. Gravouil, N. Bousquet, V. Faucher (2000-2004)

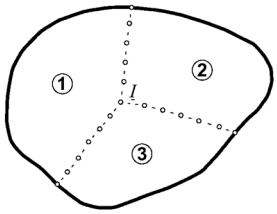
Goal: multi-scale problems in time and space.

- Use appropriate time integration step in each s/d:
  - Couple s/d's with different (and variable) time steps
- Use appropriate time integration scheme in each s/d:
  - Any of the Newmark "beta" time schemes can be coupled
  - Explicit-explicit or explicit-implicit coupling is possible
- Open the way to special techniques:
  - E.g.: combine modal analysis (linear vibrations) with direct time integration
  - Treat vibrating parts in large rotations (rotating machinery)

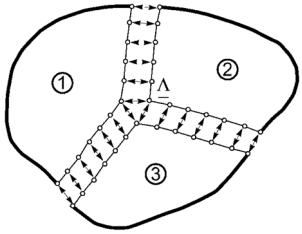
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Coupling at the Interfaces

- Two approaches possible: primal or dual



Continuity of kinematic quantities is satisfied *a priori* (same nodes)



Continuity of kinematic quantities is enforced by suitable conditions (different nodes)

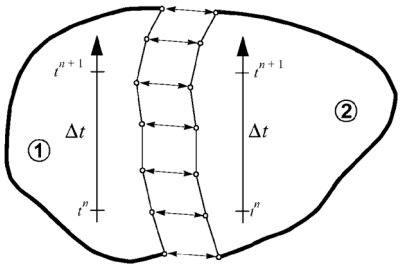
- We use a dual approach:
  - More general also in view of non-conforming interfaces

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Coupling at the Interfaces (2)

Dual approach (Gravouil & Combescure, 2001)

- Simplest case: 2 S/Ds, conforming interface, same Δt



- The coupled problem can be written as:

$$\begin{cases} \underline{M}_1\ddot{\underline{U}}_1 = \underline{F}_1 + \underline{R}_1 \\ \underline{M}_2\ddot{\underline{U}}_2 = \underline{F}_2 + \underline{R}_2 \\ \underline{C}_1\dot{\underline{U}}_1 + \underline{C}_2\dot{\underline{U}}_2 = \underline{0} \end{cases}$$

$\Leftarrow$ equilibrium

$\Leftarrow$ continuity at interface (constraint)

$\underline{F}_i \doteq \underline{F}_i^{\text{ext}} - \underline{F}_i^{\text{int}}$

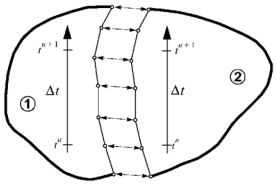
$i = 1,2$ (sub-domain index)

$\underline{R}_i \doteq$ interface reactions

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$$\begin{cases} \underline{M}_1\ddot{\underline{U}}_1 = \underline{F}_1 + \underline{R}_1 \\ \underline{M}_2\ddot{\underline{U}}_2 = \underline{F}_2 + \underline{R}_2 \\ \underline{C}_1\dot{\underline{U}}_1 + \underline{C}_2\dot{\underline{U}}_2 = \underline{0} \end{cases}$$

Coupling at the Interfaces (3)



- It can be useful to split the problem into a *free* and a *link* problem by an additive decomposition. Define:

$$\begin{aligned} \ddot{\underline{U}}_{i,\text{free}} &\doteq \underline{M}_i^{-1}\underline{F}_i \\ \ddot{\underline{U}}_{i,\text{link}} &\doteq \underline{M}_i^{-1}\underline{R}_i \end{aligned}$$

so that: $\ddot{\underline{U}}_i = \ddot{\underline{U}}_{i,\text{free}} + \ddot{\underline{U}}_{i,\text{link}}$

- The problem becomes:

Free problem (involves all dofs) $\begin{cases} \underline{M}_1\ddot{\underline{U}}_{1,\text{free}} = \underline{F}_1 \\ \underline{M}_2\ddot{\underline{U}}_{2,\text{free}} = \underline{F}_2 \end{cases}$ + $\begin{cases} \underline{M}_1\ddot{\underline{U}}_{1,\text{link}} = \underline{R}_1 \\ \underline{M}_2\ddot{\underline{U}}_{2,\text{link}} = \underline{R}_2 \\ \underline{C}_1\dot{\underline{U}}_1 + \underline{C}_2\dot{\underline{U}}_2 = \underline{0} \end{cases}$ *Link* problem (involves only dofs on interface)

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$$\begin{cases} \underline{M}_1\ddot{\underline{U}}_{1,\text{free}} = \underline{F}_1 \\ \underline{M}_2\ddot{\underline{U}}_{2,\text{free}} = \underline{F}_2 \end{cases}$$

Coupling at the Interfaces (4)

$$\begin{cases} \underline{M}_1\ddot{\underline{U}}_{1,\text{link}} = \underline{R}_1 \\ \underline{M}_2\ddot{\underline{U}}_{2,\text{link}} = \underline{R}_2 \\ \underline{C}_1\dot{\underline{U}}_1 + \underline{C}_2\dot{\underline{U}}_2 = \underline{0} \end{cases}$$

- The *free* problem can be solved directly to obtain $\ddot{\underline{U}}_{i,\text{free}}$
- To solve the *link* problem, we introduce as usual Lagrange multipliers and associated reaction (interaction) forces:

$$\underline{R}_i = \underline{C}_i^T\underline{\Lambda}$$

so that:

$$\begin{aligned} \underline{M}_1\ddot{\underline{U}}_{1,\text{link}} - \underline{C}_1^T\underline{\Lambda} &= \underline{0} \\ \underline{M}_2\ddot{\underline{U}}_{2,\text{link}} - \underline{C}_2^T\underline{\Lambda} &= \underline{0} \\ \underline{C}_1\dot{\underline{U}}_1 + \underline{C}_2\dot{\underline{U}}_2 &= \underline{0} \end{aligned}$$

Unknowns: $\ddot{\underline{U}}_{i,\text{link}}$, $\underline{\Lambda}$ and $\dot{\underline{U}}_i$

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Coupling at the Interfaces (5)

$$\underline{M}_1\ddot{\underline{U}}_{1,\text{link}} - \underline{C}_1^T\underline{\Lambda} = \underline{0}$$
$$\underline{M}_2\ddot{\underline{U}}_{2,\text{link}} - \underline{C}_2^T\underline{\Lambda} = \underline{0}$$
$$\underline{C}_1\dot{\underline{U}}_1 + \underline{C}_2\dot{\underline{U}}_2 = \underline{0}$$

- We express the unknown velocities $\dot{\underline{U}}_i$ in terms of the accelerations. By using CD time integration scheme (recall Part 1)

$$\dot{\underline{U}} = \dot{\underline{U}}^n + \frac{\Delta t}{2}(\ddot{\underline{U}}^n + \ddot{\underline{U}})$$

- By introducing the velocity predictor (or mid-step velocity):

$${}^p\dot{\underline{U}} \doteq \dot{\underline{U}}^n + \frac{\Delta t}{2}\ddot{\underline{U}}^n \equiv \dot{\underline{U}}^{n+1/2}$$

one gets:

$$\dot{\underline{U}} = {}^p\dot{\underline{U}} + \frac{\Delta t}{2}\ddot{\underline{U}}$$

- By splitting the acceleration this becomes:

$$\dot{\underline{U}} = {}^p\dot{\underline{U}} + \frac{\Delta t}{2}\ddot{\underline{U}}_{\text{free}} + \frac{\Delta t}{2}\ddot{\underline{U}}_{\text{link}}$$

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Coupling at the Interfaces (6)

$$\dot{\underline{U}} = {}^p\dot{\underline{U}} + \frac{\Delta t}{2}\ddot{\underline{U}}_{\text{free}} + \frac{\Delta t}{2}\ddot{\underline{U}}_{\text{link}}$$

$$\underline{M}_1\ddot{\underline{U}}_{1,\text{link}} - \underline{C}_1^T\underline{\Lambda} = \underline{0}$$
$$\underline{M}_2\ddot{\underline{U}}_{2,\text{link}} - \underline{C}_2^T\underline{\Lambda} = \underline{0}$$
$$\underline{C}_1\dot{\underline{U}}_1 + \underline{C}_2\dot{\underline{U}}_2 = \underline{0}$$

- We see therefore that also the velocities can be formally split into a *free* and a *link* part. By defining:

(known) $\rightarrow$ $\boxed{\dot{\underline{U}}_{\text{free}} \doteq {}^p\dot{\underline{U}} + \frac{\Delta t}{2}\ddot{\underline{U}}_{\text{free}}}$ $\qquad$ $\boxed{\dot{\underline{U}}_{\text{link}} \doteq \frac{\Delta t}{2}\ddot{\underline{U}}_{\text{link}}}$

so that:

$$\boxed{\dot{\underline{U}} = \dot{\underline{U}}_{\text{free}} + \dot{\underline{U}}_{\text{link}}}$$

one gets for the link problem:

$$\begin{cases} \underline{M}_1\ddot{\underline{U}}_{1,\text{link}} - \underline{C}_1^T\underline{\Lambda} = \underline{0} \\ \underline{M}_2\ddot{\underline{U}}_{2,\text{link}} - \underline{C}_2^T\underline{\Lambda} = \underline{0} \\ -\frac{\Delta t}{2}\underline{C}_1\ddot{\underline{U}}_{1,\text{link}} - \frac{\Delta t}{2}\underline{C}_2\ddot{\underline{U}}_{2,\text{link}} = \underline{C}_1\dot{\underline{U}}_{1,\text{free}} + \underline{C}_2\dot{\underline{U}}_{2,\text{free}} \end{cases}$$

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Coupling at the Interfaces (7)

$$\begin{cases} \underline{M}_1\ddot{\underline{U}}_{1,\text{link}} - \underline{C}_1^T\underline{\Lambda} = \underline{0} \\ \underline{M}_2\ddot{\underline{U}}_{2,\text{link}} - \underline{C}_2^T\underline{\Lambda} = \underline{0} \\ -\frac{\Delta t}{2}\underline{C}_1\ddot{\underline{U}}_{1,\text{link}} - \frac{\Delta t}{2}\underline{C}_2\ddot{\underline{U}}_{2,\text{link}} = \underline{C}_1\dot{\underline{U}}_{1,\text{free}} + \underline{C}_2\dot{\underline{U}}_{2,\text{free}} \end{cases}$$

- By condensing on the Lagrange multipliers one obtains formally:

$$\ddot{\underline{U}}_{1,\text{link}} = \underline{M}_1^{-1}\underline{C}_1^T\underline{\Lambda}$$

$$\ddot{\underline{U}}_{2,\text{link}} = \underline{M}_2^{-1}\underline{C}_2^T\underline{\Lambda}$$

$$-\frac{\Delta t}{2}\underline{C}_1\underline{M}_1^{-1}\underline{C}_1^T\underline{\Lambda} - \frac{\Delta t}{2}\underline{C}_2\underline{M}_2^{-1}\underline{C}_2^T\underline{\Lambda} = \underline{C}_1\dot{\underline{U}}_{1,\text{free}} + \underline{C}_2\dot{\underline{U}}_{2,\text{free}}$$

- By posing:

$$\boxed{\underline{H} \doteq \frac{\Delta t}{2}(\underline{C}_1\underline{M}_1^{-1}\underline{C}_1^T + \underline{C}_2\underline{M}_2^{-1}\underline{C}_2^T)} \qquad \text{(Steklov-Poincaré operator)}$$

$$\boxed{\underline{d} \doteq -(\underline{C}_1\dot{\underline{U}}_{1,\text{free}} + \underline{C}_2\dot{\underline{U}}_{2,\text{free}})}$$

one obtains the linear system: $\boxed{\underline{H}\underline{\Lambda} = \underline{d}}$

which upon solution yields the Lagrange multipliers $\underline{\Lambda}$, then the link accelerations $\ddot{\underline{U}}_{i,\text{link}}$

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Coupling at the Interfaces (8)

Summarizing, the problem can be written in matrix form:

- First, solve the problem <u>without</u> links (*free*). Symbolically:

$$\begin{bmatrix} \underline{M}_1 & 0 & 0 \\ 0 & \underline{M}_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} \ddot{\underline{U}}_{1,\text{free}} \\ \ddot{\underline{U}}_{2,\text{free}} \\ 0 \end{bmatrix} = \begin{bmatrix} \underline{F}_1 \\ \underline{F}_2 \\ 0 \end{bmatrix}$$

Standard problem! Use single-domain operators.

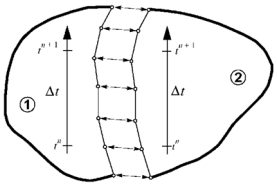
- Then, solve the problem <u>with</u> links (*link*). Symbolically:

$$\frac{\Delta t}{2}\begin{bmatrix} \underline{M}_1 & 0 & -\underline{C}_1^T \\ 0 & \underline{M}_2 & -\underline{C}_2^T \\ -\underline{C}_1 & -\underline{C}_2 & 0 \end{bmatrix}\begin{bmatrix} \ddot{\underline{U}}_{1,\text{link}} \\ \ddot{\underline{U}}_{2,\text{link}} \\ \underline{\Lambda} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \underline{C}_1\dot{\underline{U}}_{1,\text{free}} + \underline{C}_2\dot{\underline{U}}_{2,\text{free}} \end{bmatrix}$$

Thanks to diagonal mass matrix, the problem with links is confined only to the interfaces!

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Coupling at the Interfaces (9)



Time integration flowchart is as follows:

- Let complete solution be known at time t^n: $\underline{U}_i^n, \underline{\dot{U}}_i^n, \underline{\ddot{U}}_i^n$
- Compute mid-step velocities (i.e. predictors): ${}^p\underline{\dot{U}}_i \doteq \underline{\dot{U}}_i^n + \frac{\Delta t}{2}\underline{\ddot{U}}_i^n$
- Compute new configurations: $\underline{U}_i = \underline{U}_i^n + \Delta t\, {}^p\underline{\dot{U}}_i$
- Solve *free* problem for accelerations: $\underline{\ddot{U}}_{i,\text{free}} = \underline{M}_i^{-1}\underline{F}_i$
- Compute new free velocities: $\underline{\dot{U}}_{i,\text{free}} \doteq {}^p\underline{\dot{U}}_i + \frac{\Delta t}{2}\underline{\ddot{U}}_{i,\text{free}}$
- Compute: $\underline{H} \doteq \frac{\Delta t}{2}(\underline{C}_1\underline{M}_1^{-1}\underline{C}_1^T + \underline{C}_2\underline{M}_2^{-1}\underline{C}_2^T)$ and $\underline{d} \doteq -(\underline{C}_1\underline{\dot{U}}_{1,\text{free}} + \underline{C}_2\underline{\dot{U}}_{2,\text{free}})$

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Coupling at the Interfaces (10)

- Solve linear system for the Lagrange multipliers:

$$\underline{H}\,\underline{\Lambda} = \underline{d} \quad \rightarrow \quad \underline{\Lambda} = \underline{H}^{-1}\underline{d}$$

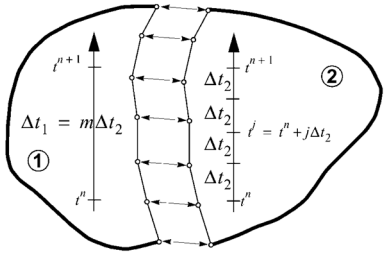
$\underline{H}$ is diagonal for conforming interface!

- Compute interaction forces: $\underline{R}_i = \underline{C}_i^T\,\underline{\Lambda}$
- Compute link accelerations: $\underline{\ddot{U}}_{i,\text{link}} \doteq \underline{M}_i^{-1}\underline{R}_i$ $\underline{M}$ is diagonal!
- Compute total accelerations: $\underline{\ddot{U}}_i = \underline{\ddot{U}}_{i,\text{free}} + \underline{\ddot{U}}_{i,\text{link}}$
- Compute new velocities: $\underline{\dot{U}}_i = \underline{\dot{U}}_{i,\text{free}} + \frac{\Delta t}{2}\underline{\ddot{U}}_{i,\text{link}}$

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Multiple scales in time

- Use <u>appropriate</u> time scale in each S/D
- Simplest case: <u>constant</u> steps, <u>hierarchic</u> case (exact multiples: $\Delta t_1 = m\Delta t_2$)
- Enforce continuity on <u>finest</u> time scale:



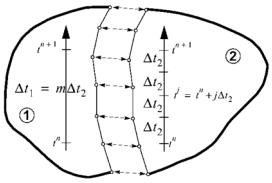
$$\boxed{\underline{C}_1\dot{\underline{U}}_1^j + \underline{C}_2\dot{\underline{U}}_2^j = 0}$$ at generic instant $t^j = t^n + j\Delta t_2$

- By decomposing the velocities this becomes:

$$\underline{C}_1\dot{\underline{U}}_{1,\text{link}}^j + \underline{C}_2\dot{\underline{U}}_{2,\text{link}}^j = -(\underline{C}_1\dot{\underline{U}}_{1,\text{free}}^j + \underline{C}_2\dot{\underline{U}}_{2,\text{free}}^j)$$

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Multiple scales in time (2)



- Solve *free* problem for both S/Ds:

$$\boxed{\underline{M}_1\ddot{\underline{U}}_{1,\text{free}} = \underline{F}_1}$$ for S/D 1 at time t^{n+1} $\qquad$ $$\boxed{\underline{M}_2\ddot{\underline{U}}_{2,\text{free}}^j = \underline{F}_2^j}$$ for S/D 2 at time t^j $\qquad$ $\Rightarrow \dot{\underline{U}}_{1,\text{free}}$ and $\dot{\underline{U}}_{2,\text{free}}^j$

- Estimate free velocity of S/D 1 at t^j by <u>linear interpolation</u>:

$$\boxed{\dot{\underline{U}}_{1,\text{free}}^j = (1-\alpha_j)\dot{\underline{U}}_{1,\text{free}}^n + \alpha_j\dot{\underline{U}}_{1,\text{free}}}$$ with $\alpha_j \doteq j/m$

- Same thing can be done for link velocity:

$$\boxed{\dot{\underline{U}}_{1,\text{link}}^j = (1-\alpha_j)\dot{\underline{U}}_{1,\text{link}}^n + \alpha_j\dot{\underline{U}}_{1,\text{link}}}$$

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Multiple scales in time (3)

- Express link velocities via link accelerations (multipliers).
  For S/D 2: $\boxed{\underline{\dot{U}}^{j}_{2,\text{link}} = \frac{\Delta t_2}{2} \underline{M}_2^{-1} \underline{C}_2^T \underline{\Lambda}^{j}}$

- For S/D 1: $\underline{\dot{U}}^{n}_{1,\text{link}} = \frac{\Delta t_1}{2} \underline{M}_1^{-1} \underline{C}_1^T \underline{\Lambda}^{n}$ at time t^n

  $\underline{\dot{U}}_{1,\text{link}} = \frac{\Delta t_1}{2} \underline{M}_1^{-1} \underline{C}_1^T \underline{\Lambda}$ at time t^{n+1}

- This, replaced into previous linear interpolation, yields:

$$\boxed{\underline{\dot{U}}^{j}_{1,\text{link}} = \frac{\Delta t_1}{2} \underline{M}_1^{-1} \underline{C}_1^T \underbrace{[(1-\alpha_j)\underline{\Lambda}^{n} + \alpha_j \underline{\Lambda}]}_{\underline{\Lambda}^{j}}}$$

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Multiple scales in time (4)

- This corresponds to assuming that the <u>interface stresses vary linearly</u> between any two "coarse" instants t^n and t^{n+1}.

- Finally we obtain the linear system:

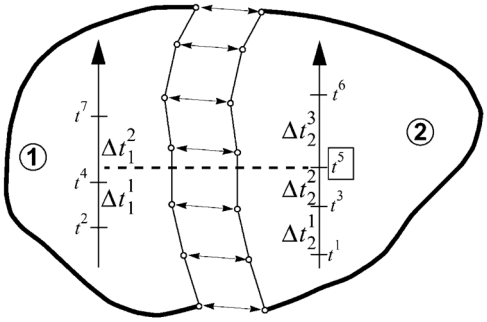
$$\boxed{\underline{H}\,\underline{\Lambda}^{j} = \underline{B}^{j}}$$

$$\boxed{\begin{aligned} \underline{H} &\doteq \frac{\Delta t_2}{2}(m\underline{C}_1\underline{M}_1^{-1}\underline{C}_1^T + \underline{C}_2\underline{M}_2^{-1}\underline{C}_2^T) \\ \underline{B}^{j} &\doteq -(\underline{C}_1\underline{\dot{U}}^{j}_{1,\text{free}} + \underline{C}_2\underline{\dot{U}}^{j}_{2,\text{free}}) \end{aligned}}$$

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Multiple scales in time (5)

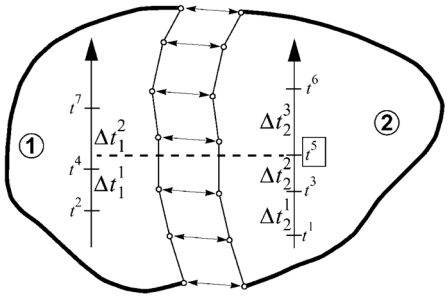
- The process can be generalized similarly to the case of fully variable and independent time scales:



- Enforce continuity on union of the two time scales. E.g:

$$\underline{C}_1\dot{\underline{U}}_1^5 + \underline{C}_2\dot{\underline{U}}_2^5 = 0$$ at generic instant t^5

Multiple scales in time (6)



- We obtain the linear system:

$$\underline{H}\,\underline{\Lambda}^5 = \underline{B}^5$$

$$\underline{H} \doteq \frac{\Delta t_1^2}{2}\underline{C}_1\underline{M}_1^{-1}\underline{C}_1^T + \frac{\Delta t_2^2}{2}\underline{C}_2\underline{M}_2^{-1}\underline{C}_2^T$$

$$\underline{B}^5 \doteq -(\underline{C}_1\dot{\underline{U}}_{1,\text{free}}^5 + \underline{C}_2\dot{\underline{U}}_{2,\text{free}}^5) - \underline{C}_1(1-\alpha_5)(\beta_5 - 1)\frac{\Delta t_1^2}{2}\ddot{\underline{U}}_{1,\text{link}}^4$$

$$\alpha_5 \doteq \frac{t_5 - t_4}{t_6 - t_4} \qquad \beta_5 \doteq \frac{\Delta t_1^1}{\Delta t_1^2}$$

Multiple scales in space

- Further gains can be obtained by allowing non-conforming meshes at the interfaces:

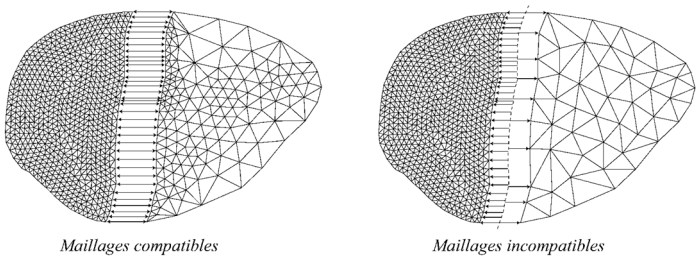


FIGURE [1.2.4.1] : *Maillages non-conformes - Découplage de la taille des éléments*

- Kinematic continuity has to be imposed on the interface I . At the continuous level in space (i.e. before discretization):

$$\boxed{\underline{\dot{U}}_1\big|_I = \underline{\dot{U}}_2\big|_I}$$

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Multiple scales in space (2)

- We impose continuity on the discrete mesh by means of Lagrange multipliers.
- Several alternatives are possible, depending on spatial location (support) of multipliers.
- LBB condition must be satisfied!
  - Space of multipliers should not be too rich
  - Number of conditions < than total number of concerned dofs
  - Too few conditions: loose coupling
  - Too many conditions: singular problem or spurious "locking" of the interface

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Multiple scales in space (3)

- "Optimal" method [Herry *et al.*, 2002]: support is union of interface nodes. Exact in 2D plane linear.
- Perfect coupling can be overconstraining (locking) if common nodes are scarce.
- Alternative: the "mortar" method [Bernardi *et al.*, 1990]: support is one of the two meshes, usually finest one.

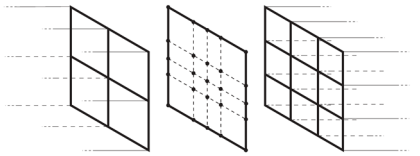


FIGURE [1.2.4.2] : *Méthode optimale - Support des multiplicateurs*

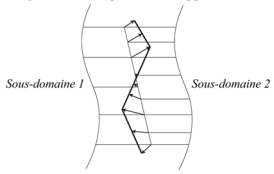


FIGURE [1.2.4.3] : *Méthode optimale 2D - Déformation possible de l'interface*

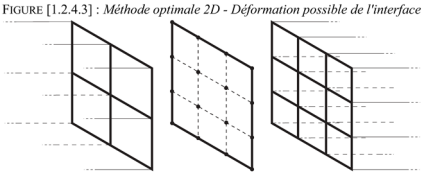


FIGURE [1.2.4.4] : *Méthode mortar - Support des multiplicateurs*

Solution of the interface problem

- In all cases we obtain a linear problem to be solved at the interfaces, of the form:

$$\underline{H}\,\underline{\Lambda} = \underline{B}$$

$\underline{H}$ ≐ interface operator
$\underline{\Lambda}$ ≐ Lagrange multipliers

- $\underline{H}$ is diagonal in the case of conforming interface, but not in the non-conforming case.
- In the presence of *cross points* $\underline{H}$ becomes singular! Suitable treatment is then needed for the solution of the system.

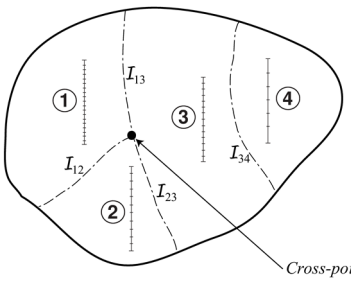


FIGURE [1.3.2.1] : *Interfaces et plusieurs échelles de temps*

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Multiple scales in frequency

- Some large (CPU!) problems contain multiple frequency scales.
- Impact raises high frequencies and non-linear effects *locally*.
- However, the bulk structure has low-frequency vibratory behaviour (linear).
- Fine FE discretization (to fit complex geometry) is too detailed to describe linear vibrations.

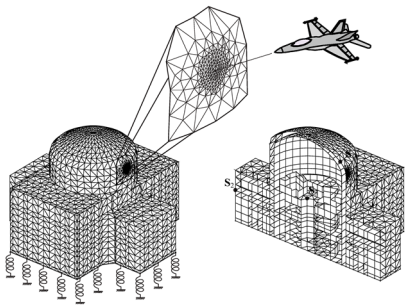


FIGURE [2.3.4.2] : *Ilot nucléaire - Maillage et conditions aux limites*

- Use modal projection: replace FE unknowns (dofs) by less numerous ones, specific to the chosen frequency spectrum.

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Multiple scales in frequency (2)

- Domain decomposition allows to separate the frequency scales.
- How can one suitably couple a linear, "modal" S/D with a non-linear, "direct" one? One arrives to a form (S/D 1 is modal):

$$\begin{bmatrix} \frac{\Delta t}{2}\hat{\underline{M}}_1 & 0 & -\frac{\Delta t}{2}\hat{\underline{C}}_1^T \\ 0 & \frac{\Delta t}{2}\underline{M}_2 & -\frac{\Delta t}{2}\underline{C}_2^T \\ -\frac{\Delta t}{2}\hat{\underline{C}}_1 & -\frac{\Delta t}{2}\underline{C}_2 & 0 \end{bmatrix} \begin{bmatrix} \ddot{\underline{\alpha}}_1 \\ \ddot{\underline{U}}_2 \\ \underline{\Lambda} \end{bmatrix} = \begin{bmatrix} \frac{\Delta t}{2}\hat{\underline{K}}_1\underline{\alpha}_1 \\ \frac{\Delta t}{2}\underline{F}_2 \\ \hat{\underline{C}}_1\,{}^p\dot{\underline{\alpha}}_1^n + \underline{C}_2\,{}^p\dot{\underline{U}}_2^n \end{bmatrix}$$

$\underline{\alpha}_1 \doteq$ generalized unknowns:

$$\begin{cases} \underline{U}_1 = \underline{\Phi}_1\underline{\alpha}_1 \\ \dot{\underline{U}}_1 = \underline{\Phi}_1\dot{\underline{\alpha}}_1 \\ \ddot{\underline{U}}_1 = \underline{\Phi}_1\ddot{\underline{\alpha}}_1 \end{cases}$$

linear behaviour:

$$\underline{F}_1 = \underline{K}_1\underline{U}_1 = \underline{K}_1\underline{\Phi}_1\underline{\alpha}_1$$

"projected" operators:

$$\begin{cases} \hat{\underline{M}}_1 \doteq \underline{\Phi}_1^T\underline{M}_1\underline{\Phi}_1 \\ \hat{\underline{K}}_1 \doteq \underline{\Phi}_1^T\underline{K}_1\underline{\Phi}_1 \\ \hat{\underline{C}}_1 \doteq \underline{C}_1\underline{\Phi}_1 \end{cases}$$

- This coupling is totally independent from the nature of the base used for modal reduction (free choice!).
- This is possible thanks to dual approach: interface dofs don't need to remain "visible" after reduction.

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Example: simplified engine

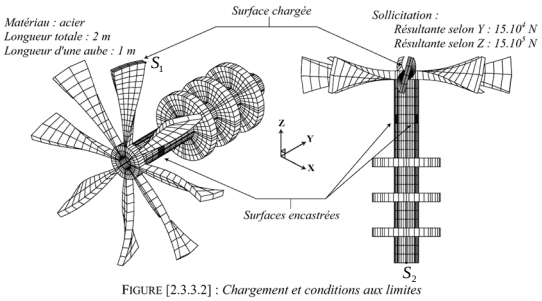


FIGURE [2.3.3.2] : *Chargement et conditions aux limites*

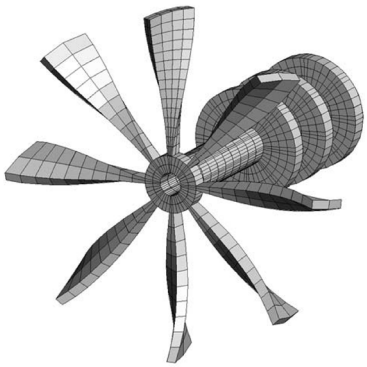


FIGURE [2.3.3.1] : *Structure 3D massive - Maillage*

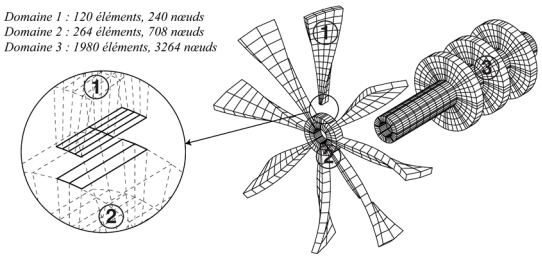


FIGURE [2.3.3.3] : *Décomposition en sous-domaines*

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Example: simplified engine (2)

	No S/Ds	3 S/Ds	3 S/Ds (#3 modal)
dofs S/D 1	720	720	720
dofs S/D 2	2124	2124	2124
dofs S/D 3	12636	12636	50 free modes
dofs total	12636	12636	2894
Δt^{crit} S/D 3 [µ s]	0.97	**0.97**	**80.**
CPU [s]	4630	3383	693
CPU %	**100**	**73**	**14**

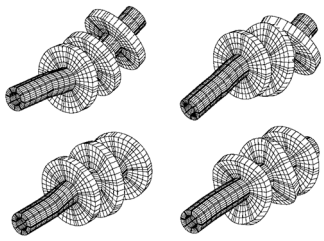


FIGURE [2.3.3.4] : *Modes propres libres sur le sous-domaine 3*

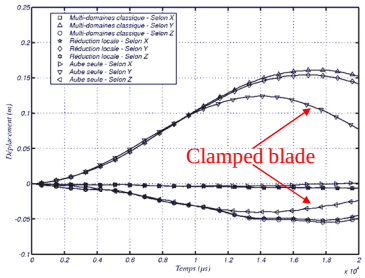


FIGURE [2.3.3.5] : *Déplacement au point* $\mathbf{S}_1$

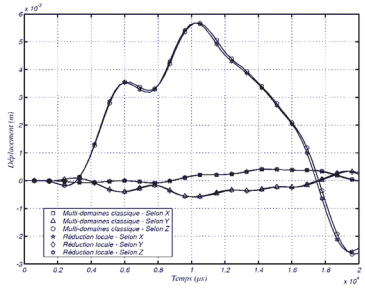


FIGURE [2.3.3.6] : *Déplacement au point* $\mathbf{S}_2$

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Example: power plant

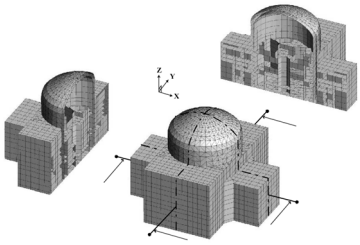


FIGURE [2.3.4.1] : *Structure 3D coque – Ilot nucléaire*

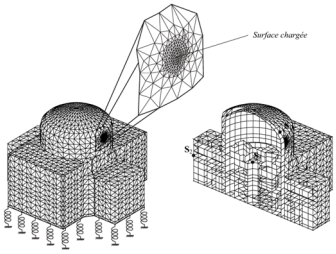


FIGURE [2.3.4.2] : *Ilot nucléaire - Maillage et conditions aux limites*

Domaine 1 : 6609 éléments à 3 nœuds et 5806 éléments à 4 noeuds
Domaine 2 : 158 éléments à 3 nœuds
Domaine 3 : 204 éléments à 3 nœuds

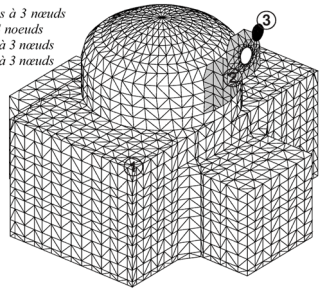


FIGURE [2.3.4.4] : *Décomposition en sous-domaines*

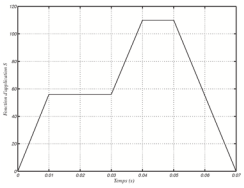


FIGURE [2.3.4.3] : *Fonction d'application temporelle du chargement*

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Example: power plant (2)

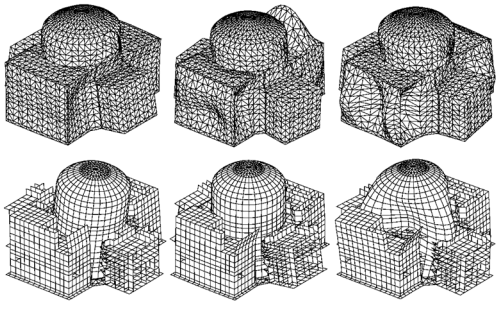


FIGURE [2.3.4.5] : *Modes de vibration encastrés (internes et externes)*

	No S/Ds	3 S/Ds	3 S/Ds (#1 modal)
dofs S/D 1	40338	40338	84 static + 150 clamped modes = 234
Δt^{crit} S/D 1 [μs]	26	**26**	**132**
CPU [s]	22722	3766	853
CPU %	**100**	**17**	**3.7**

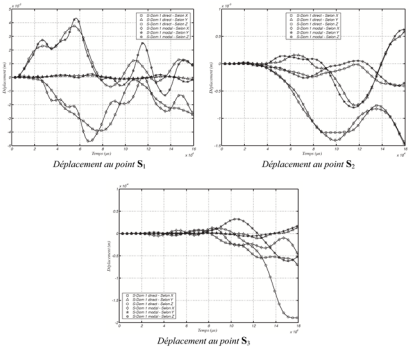


FIGURE [2.3.4.6] : *Déplacements aux points* S_1, S_2 *et* S_3

Bad results at S_3 due to wrong modeling of soil conditions (successively corrected)

174

Example: aircraft

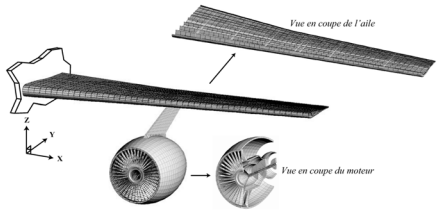
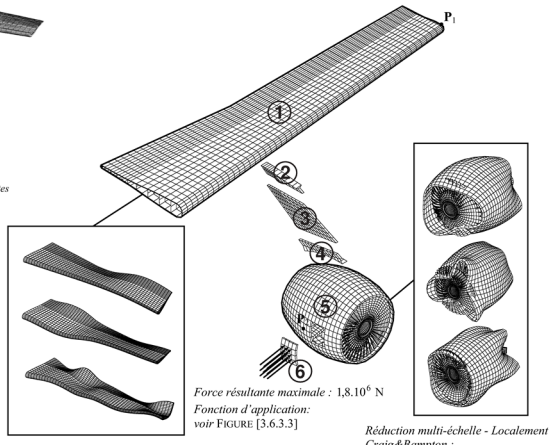


FIGURE [3.6.3.1] : *Impact sur un moteur d'avion - Maillage et conditions aux limites*

Material is linear elastic in S/Ds 1, 5 and 6, elasto-plastic in S/Ds 2, 3 and 4



Force résultante maximale : $1{,}8.10^6$ N
Fonction d'application: voir FIGURE [3.6.3.3]

Réduction linéaire Craig&Bampton :
78 modes statiques
100 modes propres à interface fixe

Réduction multi-échelle - Localement Craig&Bampton :
189 modes statiques
150 modes propres à interface fixe

FIGURE [3.6.3.2] : *Chargement, sous-domaines et modèles réduits*

175

Example: aircraft (2)

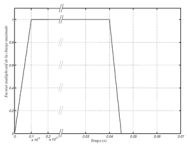
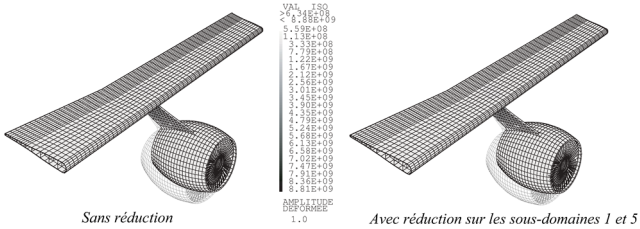


FIGURE [3.6.3.3] : *Fonction d'application temporelle du chargement*



Sans réduction — *Avec réduction sur les sous-domaines 1 et 5*

FIGURE [3.6.3.4] : *Comparaison des déformées et des contraintes de Von Mises au temps final*

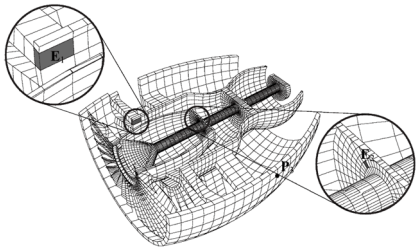


FIGURE [3.6.3.5] : *Coupe horizontale du moteur*

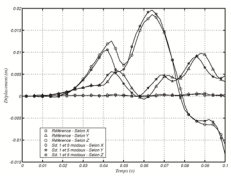


FIGURE [3.6.3.6] : *Déplacement au point* $\mathbf{P}_1$

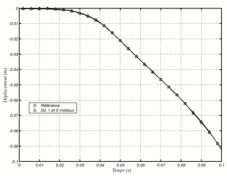
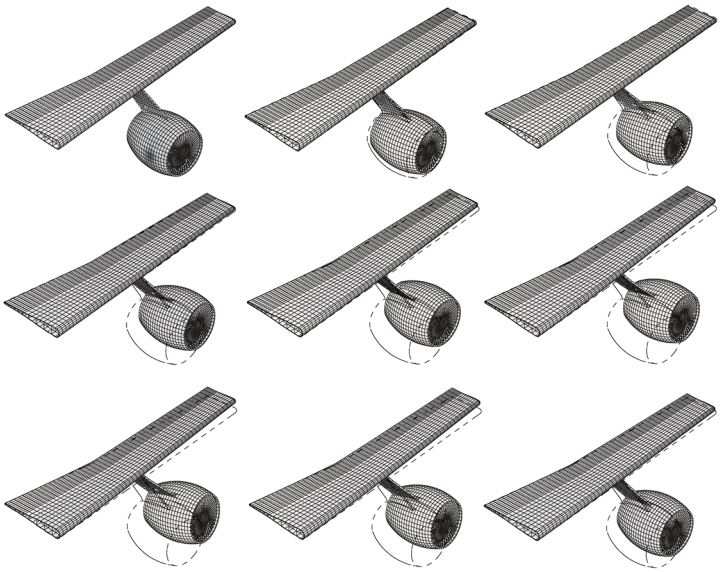


FIGURE [3.6.3.7] : *Déplacement relatif selon* x *entre les points* $\mathbf{P}_2$ et $\mathbf{P}_3$

176

Example: aircraft (3)



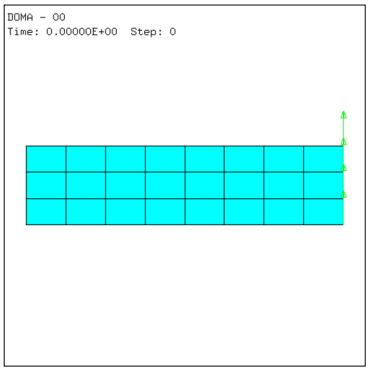
Thanks to CPU gain with modal S/Ds it was possible to pursue calculation for the whole first vibration mode of the wing

177

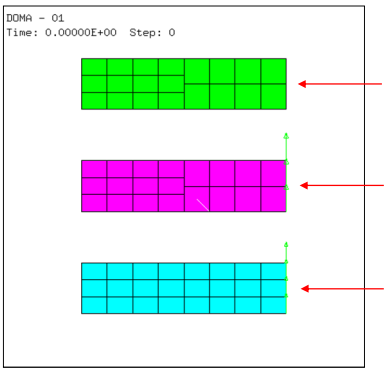
FIGURE [3.6.3.10] : *Simulation prolongée et premier mode d'ébranlement de l'aile*

Example 13 – Domains in 2D

- Thick plane strain beam under bending:



Reference Case (no decomposition)



Case with various decompositions

Two non-conforming subdomains (second one is modal)

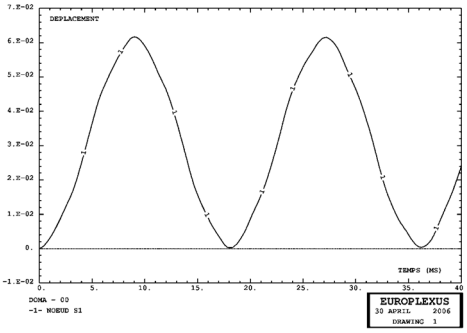
Two non-conforming subdomains

Two conforming subdomains

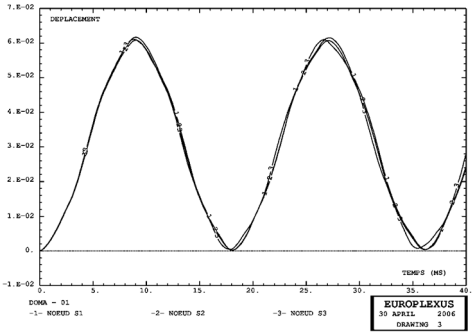
178

Example 13 – Domains in 2D (2)

- Tip displacement:



Reference Case (no decomposition)

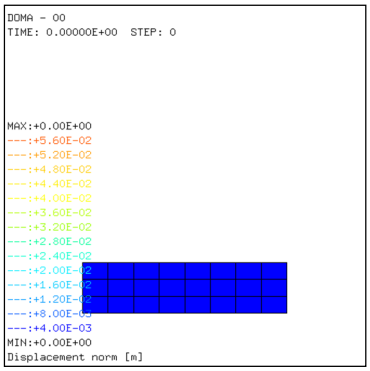


Case with various decompositions

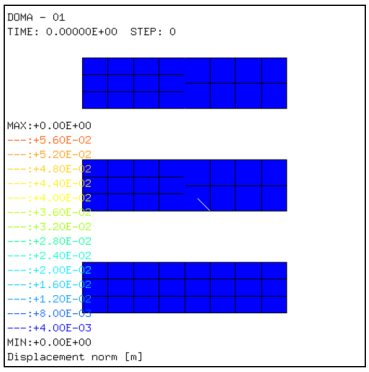
179

Example 13 – Domains in 2D (3)

- Displacement norm field:



Reference Case (no decomposition)



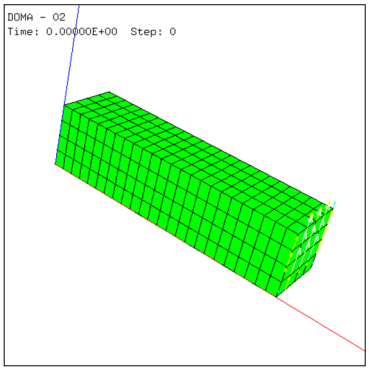
Case with various decompositions

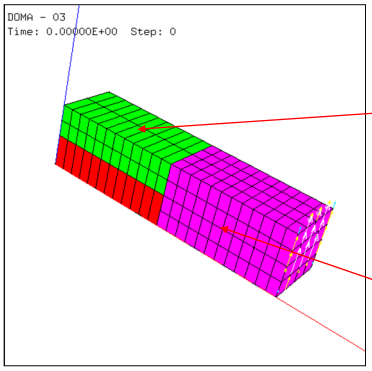
Compare

180

Example 14 – Domains in 3D

- Thick 3D beam under bending:





Subdomains 1 and 2 are conforming

Subdomains 1 (or 2) and 3 are non-conforming

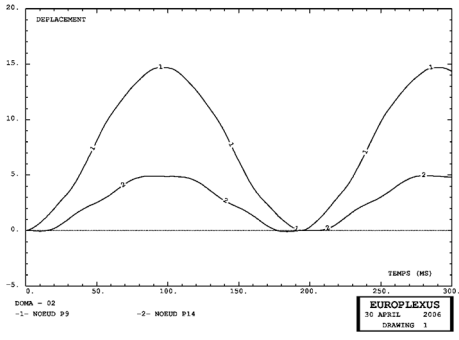
Reference Case (no decomposition)

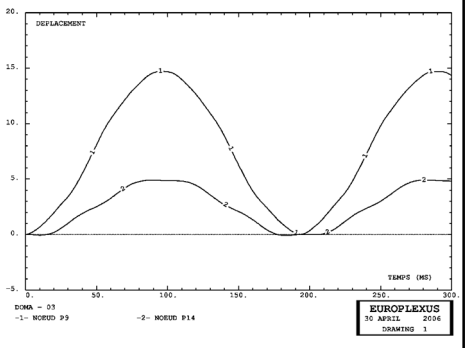
Case with domain decomposition

181

Example 14 – Domains in 3D (2)

- Tip displacement:





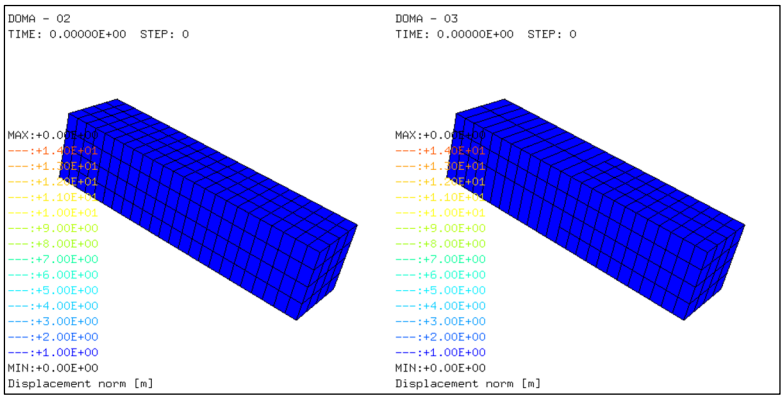
Reference Case (no decomposition)

Case with domain decomposition

182

Example 14 – Domains in 3D (3)

- Displacement norm field:



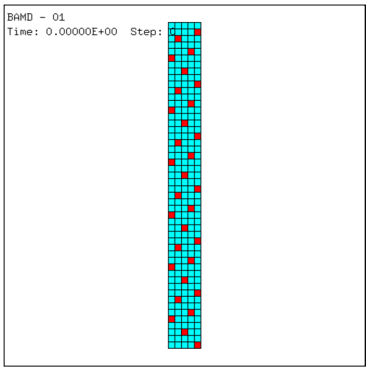
Reference Case (no decomposition)

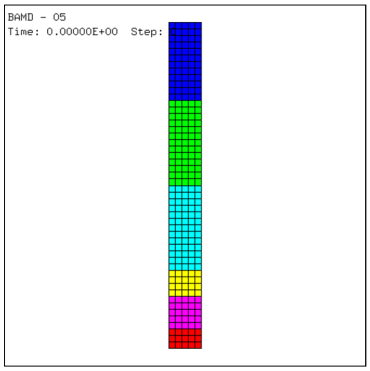
Case with domain decomposition

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Example 15 – Bar Impact Revisited

- Taylor bar impact test:





Reference Case (no decomposition)

Case with time step partitioning (OPTI PART)

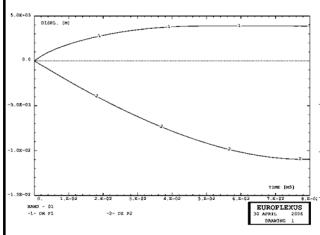
Case with domain decomposition (colors indicate sub-domains)

184

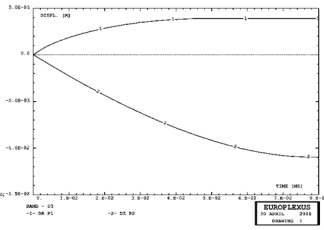
Example 15 – Bar Impact Revisited (2)

- Displace-ments:

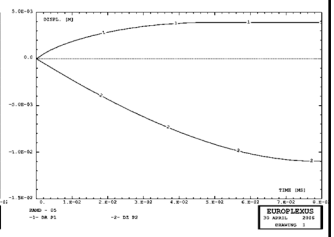
Case	Description	Time Steps	Time stations	CPU (s)
bamd01	Reference	59886	N/A	99.5
bamd03	OPTI PART	1165	N/A	13.3
bamd05	6 s/d, unequal size	1152	78948 [65246, 7545, 6218, 3265, 2303, 2303]	12.2



Reference Case (no decomposition)



Case with time step partitioning (OPTI PART)

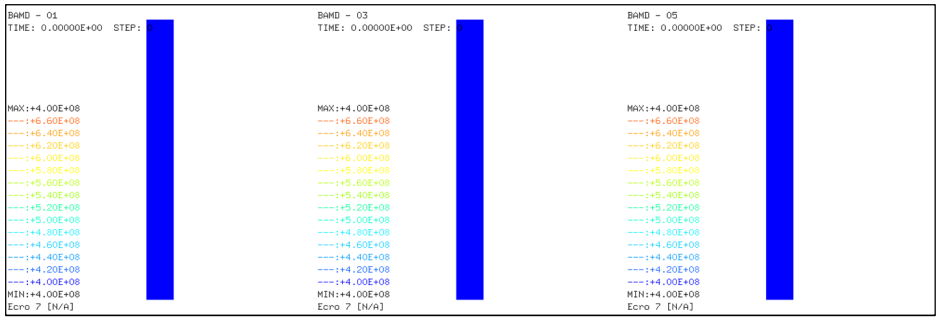


Case with domain decomposition

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Example 15 – Bar Impact Revisited (3)

- Current yield stress (plastic strain):



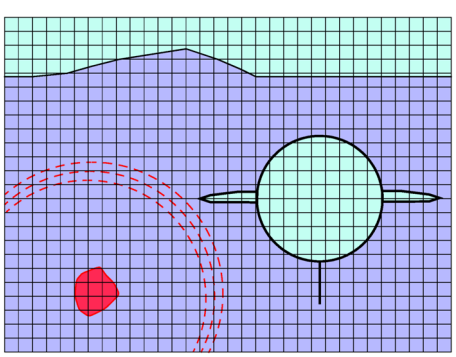
Reference Case (no decomposition)

Case with time step partitioning (OPTI PART)

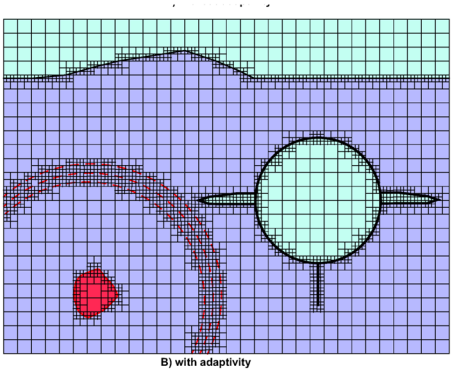
Case with domain decomposition

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Potential benefits of **Adaptivity**



A) without adaptivity



B) with adaptivity

Increase accuracy at :

- Wavefronts
- Material Interfaces (including FSI!!!)
- Free surfaces
- ...

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Adaptivity : Element Splitting

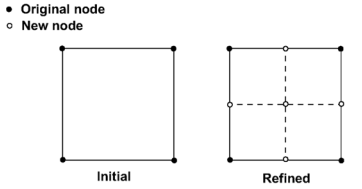


Figure 4 - Refinement of a quadrilateral in 2D

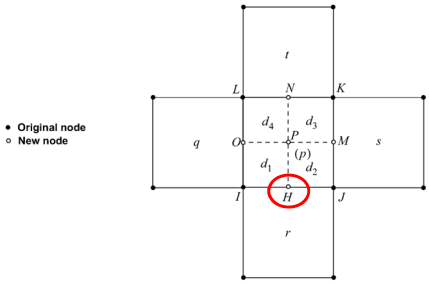


Figure 5 - Refinement of a quadrilateral in 2D with hanging nodes

- Chosen strategy for quadrilateral
- "Hanging" nodes

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Adaptivity : Element Splitting (2)

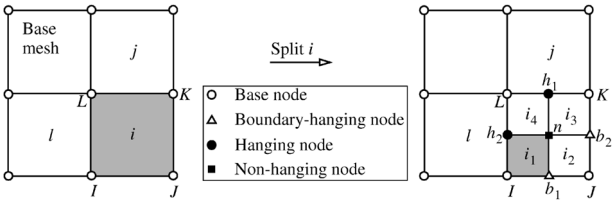


Fig. 1. Splitting a QUA4.

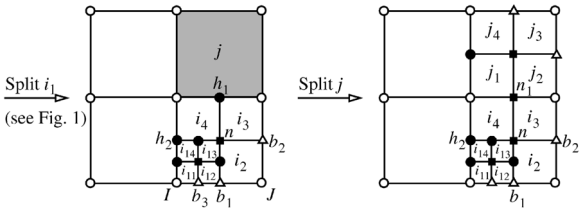


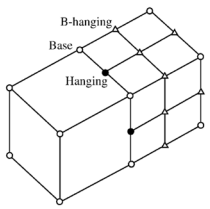
Fig. 2. Further splitting.

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Adaptivity : Nodes Classification

Table 1. A classification of nodes.

Node type	Location	Classification	Interface
Base	Internal	—	—
	Boundary	—	—
Descendent	Internal	Non-hanging	Conforming
		Hanging	Non-conforming
	Boundary	Hanging (3D only)	Non-conforming (internally)
		B-hanging	—



Example of hanging nodes on 3D boundary

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Adaptivity : Data Structure

Challenge : EUROPLEXUS is a “fixed-memory” code

Solution : over-allocation (base mesh + extension), needs user-given dimensioning of extension zones

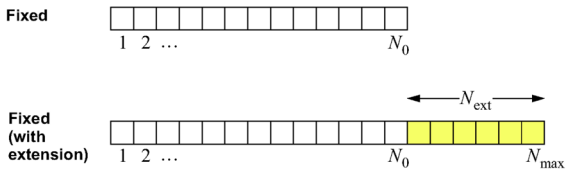
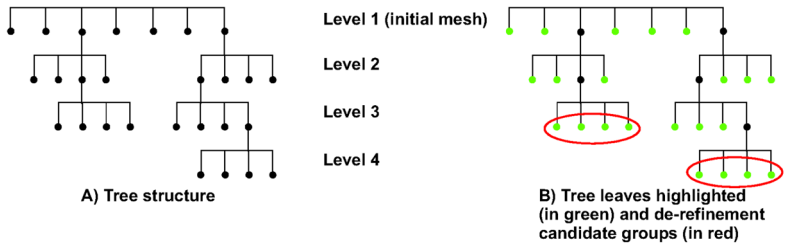


Figure 1 - Data structure without and with extension

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Adaptivity : Data Structure (2)

- Tree-like organization of elements



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Adaptivity : Data Structure (3)

- Tree-like organization of elements

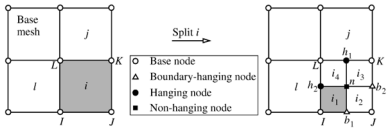


Fig. 1. Splitting a QUA4.

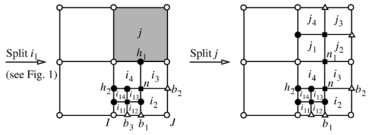


Fig. 2. Further splitting.

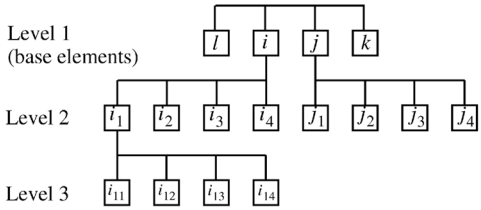
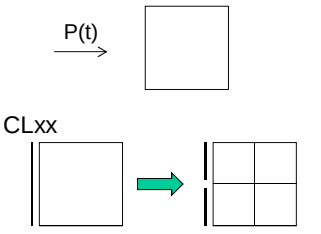


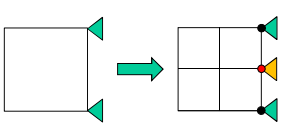
Fig. 3. Tree data structure for the elements.

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Adaptivity : Boundary Conditions

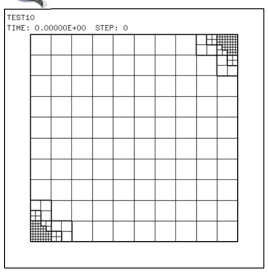
1. Applied pressures : **automatic** if represented by CLxx element (split/unsplit **together** with companion element)
2. Essential BCs (LINKs, by Lagrange Multipliers) : simple strategy is to inherit the BCs (e.g. blockages) from **parent nodes**

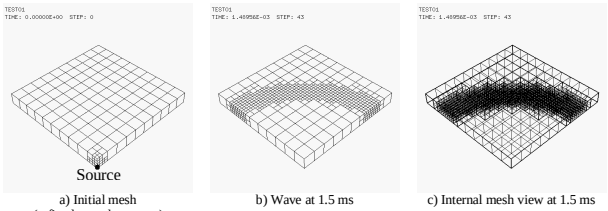




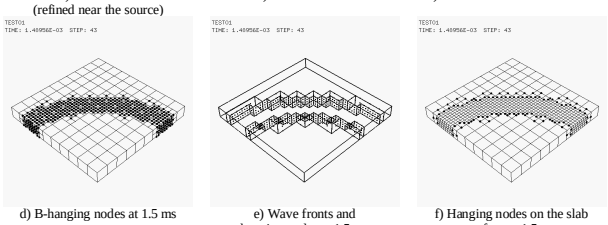
194

Example : wave in a slab





a) Initial mesh (refined near the source) | b) Wave at 1.5 ms | c) Internal mesh view at 1.5 ms



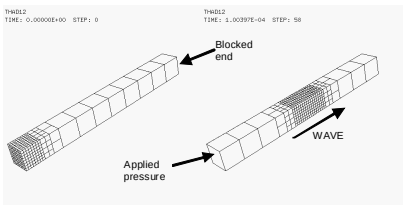
d) B-hanging nodes at 1.5 ms | e) Wave fronts and hanging nodes at 1.5 ms | f) Hanging nodes on the slab surface at 1.5 ms

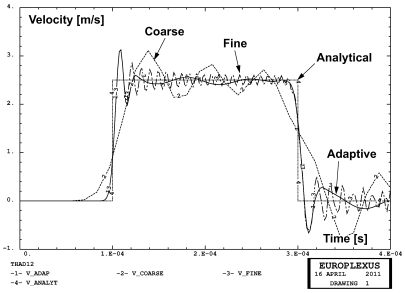
Figure 9. Spherical wave propagating in a 3D slab.

2D *3D*

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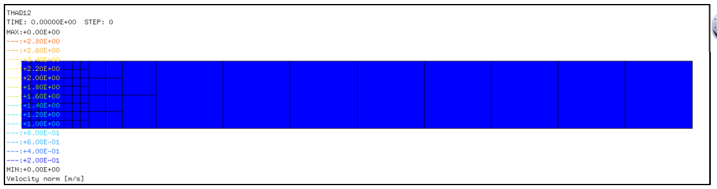
Wave in an elastic bar





a) Initial mesh and adapted mesh at 10 µs | b) Comparison of velocities at bar mid-point

Figure 10. Plane step wave in an elastic bar.



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Adaptivity in fluids : transport

- Introduce concept of **p-neighbor** at non-conforming element-to-element interface

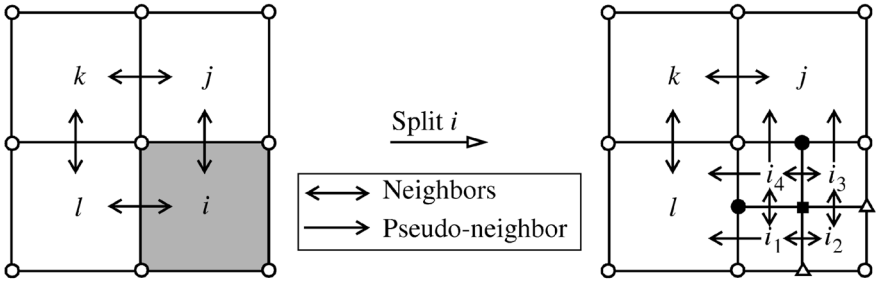
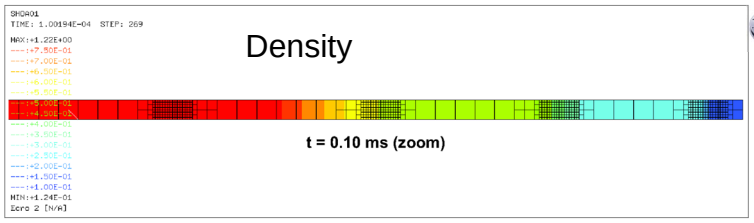
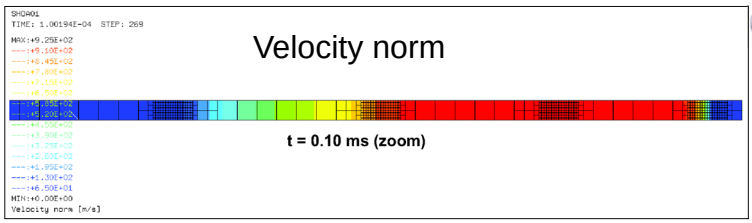


Fig. 4. Neighbors and pseudo-neighbors.

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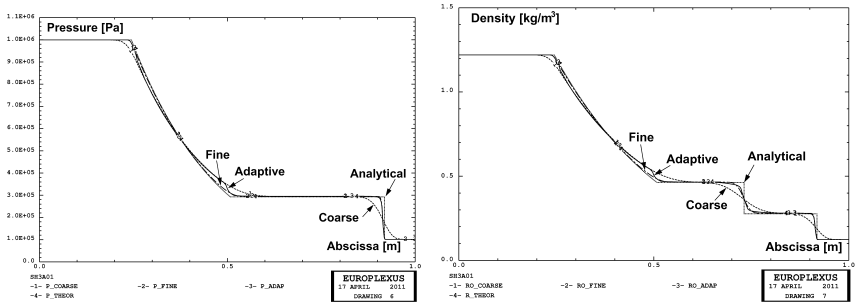
Shock tube : adaptive





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Shock tube



a) Pressure along the tube at 0.25 ms b) Density along the tube at 0.25 ms

Figure 11. Shock tube.

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Shock tube : CPU

Name	Base mesh	Extensions	Wave(s)	Steps	CPU [s]	Elements * steps
SHOR01	100 FL24	—	—	122	0.34	12,300
SHOR02	200 FL24	—	—	238	0.37	47,800
SHOR03	400 FL24	—	—	471	1.00	188,800
SHOR04	800 FL24	—	—	937	3.42	750,400
SHOA00	6,400 Q41L	—	—	937	23.81	6,003,200
SHOA04	6,400 Q41L	—	—	937	23.52	6,003,200
SHOA01	100 Q41L	NPOI 669 NDDL 1338 FL24 760	4 PLAN MAXL 4 H1 0.015 H2 0.05	899	4.06	556,026
SHOA03	100 Q41L	NPOI 669 NDDL 1338 FL24 760	4 PLAN MAXL 4 H1 0.015 H2 0.05	901	4.09	557,291

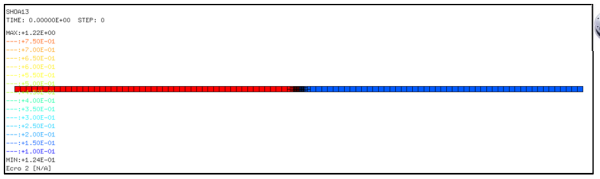
Table 1 - Numerical solutions of the shock tube problem

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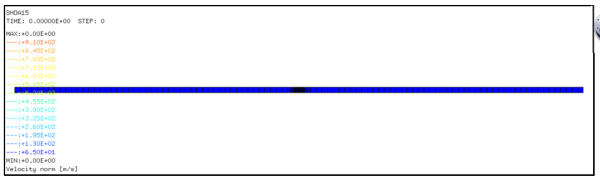
Towards “real” ADAP : Error Indicators

- Work is ongoing on **curvature-** or **gradient-based error indicators** with various types of (**node-** or **element-based**) quantities :

*Error indicator based on **velocity curvature** only captures shock*



*Error indicator based on **density gradient** captures both shock and contact discontinuity*

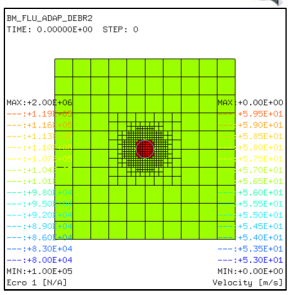


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Example of “smart” use of ADAP

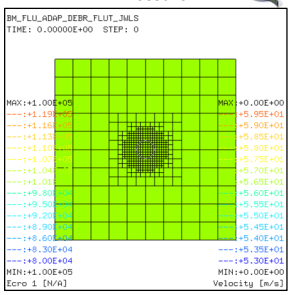
- Bomb explosion : ADAP is used to **initially refine** the bomb region. **After** bomb fragmentation and pressure wave expansion the fluid mesh is **unrefined** to increase computation efficiency!

Pressure

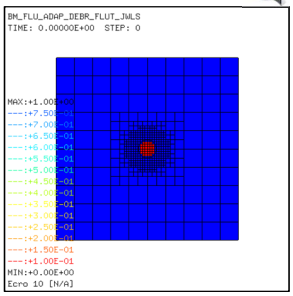


Compressed gas charge

Pressure



Solid fraction



Solid explosive charge (JWLS)

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Perspectives for Fluids

- Continue development of CCFV models:
  - Improve source term for explosions : **detonation** / **deflagration** …
  - Chemistry
  - Combustion
  - Improve **multi-phase** flow (VOFIRE ?)
- Full Navier-Stokes (incompressible or quasi-) with **deformable** structures
  - PFEM ?

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Perspectives for Solids / Structures)

- Improve damage and failure description:
  - Concrete (unreinforced / reinforced)
  - Glass
  - Composites
  - Soils and other geotechnical materials
  - Fracture mechanics (XFEM etc.)
  - Meshless methods (SPH etc.)
- Improve contact / impact and perforation:
  - DEM coupling with FE
  - “Generalized” pinball contact model

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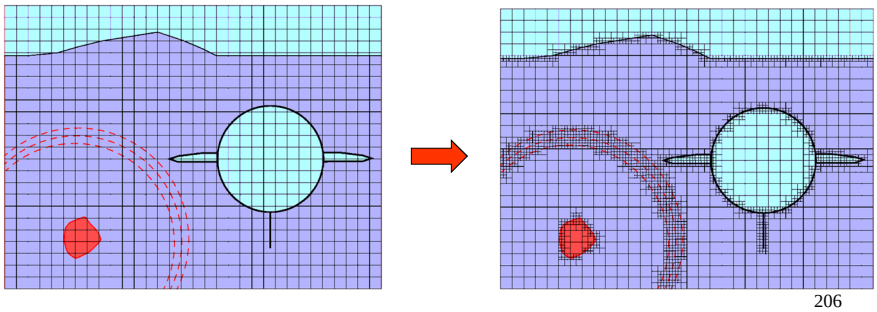
Perspectives for FSI

- Completion / improvement of FSI models battery (ongoing work):
  - Strong / Weak coupling
  - FE / FV (NC, CC) modeling of fluids
  - Conforming / non-conforming
  - "Embedded"-like techniques (FLSR, FLSW, …)
  - "Adaptivity" to increase accuracy of FLSR / FLSW
  - Combine ADAP with PART or/and S/D to increase calculation efficiency
- Towards fully automatic FSI (industrial production)
  - See example …

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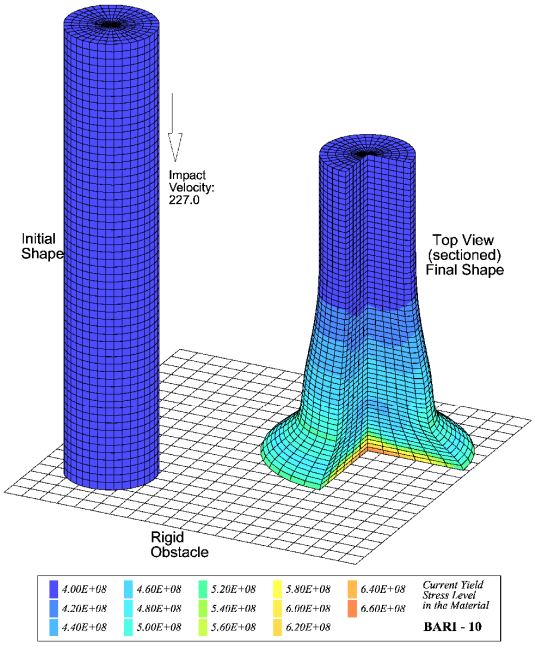
FLSW + Adaptivity + VOFIRE

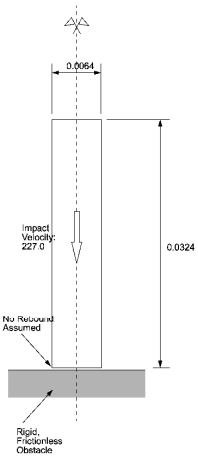
- Towards fully automatic FSI (industrial production):
  - **Only structure** is modelled "intelligently"
  - Eulerian "background" fluid mesh (automatic, highly optimized) with **FLSR / FLSW** (very fine mesh locally to enhance precision)
  - **Adaptivity** of fluid mesh on **shock fronts** + **FS interface** + **PART**
  - **Multi-phase / multi-component** techniques (+ VOFIRE)



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Example 1 – Taylor bar impact





Material Data	
Density	8930
Young's Modulus	1.17×10^{11}
Yield Stress	4.0×10^{8}
Plastic Modulus	1.0×10^{8}
Poisson's Ratio	0.35

7

Geometric data and materials:

See slide.

Numerical Solution

BARI10

The mesh generation file is:

```
*%siz 40

opti echo 1;
*
opti titr 'BARI - 10';
opti dime 2 elem qua4;
*
p0=0 0;
p1=3.2E-3 0;
p2=0 32.4E-3;
tol=0.01E-3;
*
base=p0 d 6 p1;
stru=base TRAN 60 p2;
elim tol (stru et p2);
*
symax=stru poin droi p0 p2 tol;
top=stru poin droi p2 (p1 PLUS p2) tol;
*
str1=chan 'POI1' stru;
bas1=chan 'POI1' base;
viti=diff str1 bas1;
lili=diff bas1 (p0 et p1);
slin=stru poin droi p1 (p1 plus p2) tol;
*
mesh=stru et symax et viti et lili et slin;
tass mesh;
*
opti sauv form 'bari10.msh';
sauv form mesh;
```

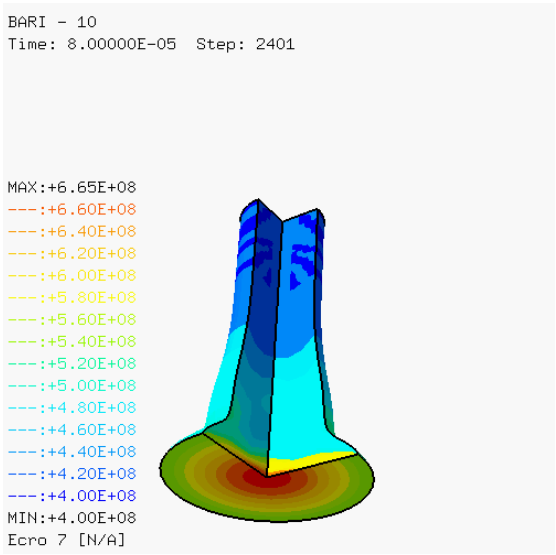
The input file is:

```
BARI - 10
*------------------------------------------------------------------------
ECHO
  CONV win
CAST MESH
*-------------------------------------------------------------Problem type
AXIS NONL ALE
*-------------------------------------------------------------Dimensioning
DIME
   PTZL 1000 Q41 360
   TABL 1 5
   ECRO 3960
   NALE 4 NBLE 354
   SLPC 1 SLPN 61
TERM
*------------------------------------------------------------------Geometry
GEOM Q41 STRU TERM
*-----------------------------------------------------Geometric Complements
COMP EPAI 1 TOUS
*-------------------------------------------------------------Grid motion
GRIL LAGR LECT P0 P1 TOP TERM
     ALE TOUS
     LIGN BASE LECT P0 P1 TERM LIST LECT LILI TERM
     SLIP EQUI LECT SLIN TERM
     AUTO AUTR
*-------------------------------------------------------------Material data
MATE VM23 RO 8930. YOUN 1.17D11 NU 0.35D0 ELAS 4.D8
          TRAC 2 4.D8 3.418803D-03 1.004D11 1000.003418803
          TOUS
*-----------------------------------------------------Boundary conditions
LINK COUP
     BLOQ 2 LECT BASE TERM
     CONT SPLA NX 1 NY 0 LECT SYMAX TERM
*-----------------------------------------------------Initial conditions
INIT VITE 2 -227. LECT VITI TERM
*------------------------------------------------------------------Outputs
ECRI DEPL VITE TFRE 10.E-6
          POIN LECT P1 TOP TERM
     FICH K200 TFRE 10.E-6 POIN TOUS
          VARI DEPL VITE ECRO ECRC LECT 2 7 TERM
     fich alic temp FREQ 1
                poin lect P1 P2 term
     fich alic tfre 1.e-6
*-------------------------------------------------------------------Options
OPTI NOTE
     CSTA 0.5
     LOG 1
*-----------------------------------------------------Transient calculation
```

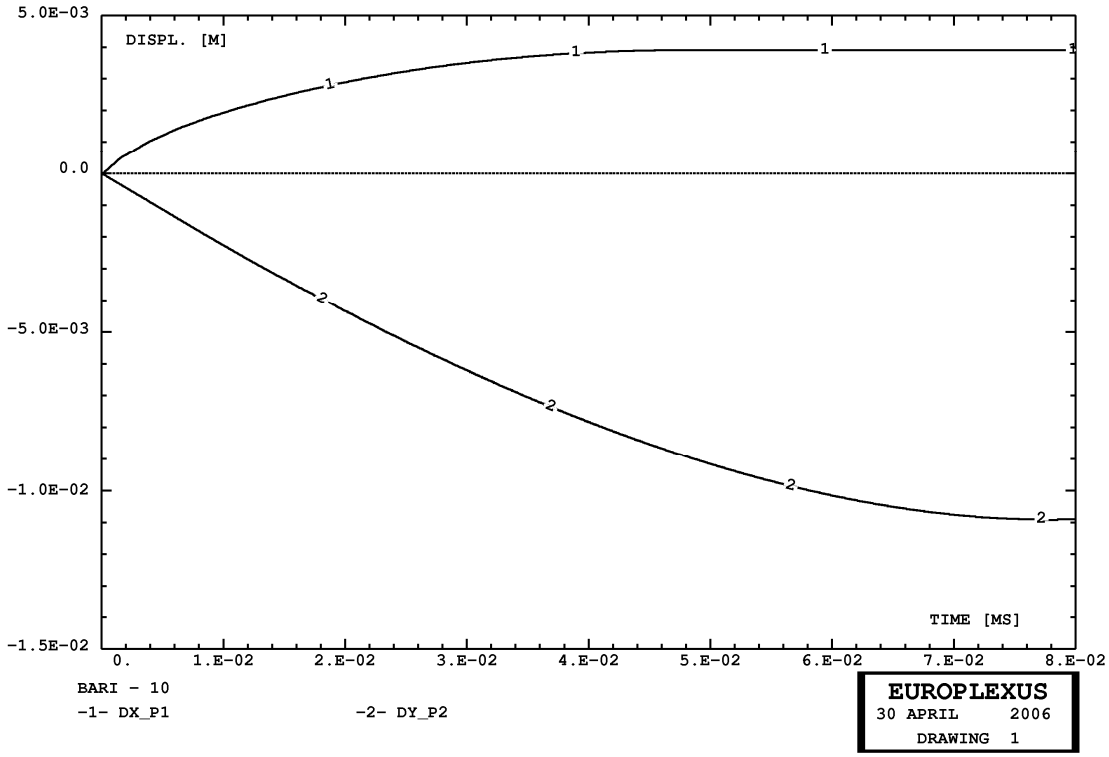
```
CALC TINI 0. TEND 80.D-6
*================================================================ANIMATION
PLAY
CAME   1 EYE    4.47289E-02 -3.66604E-02  6.13469E-02
!        Q      9.09576E-01  2.93578E-01  2.86788E-01 -6.50846E-02
         VIEW -4.83497E-01  5.71394E-01 -6.63129E-01
         RIGH  8.27033E-01  4.99905E-02 -5.59926E-01
         UP    2.86788E-01  8.19152E-01  4.96732E-01
         FOV   2.48819E+01
SCEN GEOM NAVI FREE
         LINE HEOU SSHA
     ISO  FILL FIEL ECRO 7 SCAL USER PROG 4.0D8 PAS 0.2D8 6.6D8 TERM
     TEXT ISCA
     colo pape
     LIMA ON
titl tit1 'EUROPLEXUS (C) Animation'
     tit2 'Taylor Bar Impact'
     tit3 'Author: F. Casadei'
sler cam1 1       nfra 20
trac offs fich avi                nocl nfto 101 fps 10 kfre 10 comp -1
                                                  AXIS 27 270 REND
sler cam1 1       nfra  1
TRAC OFFS FICH AVI CONT NOCL
                                                  AXIS 27 270 REND
```

```
FREQ 0 tfre 1.d-6
GOTR LOOP 79  OFFS FICH AVI CONT NOCL
                                                  AXIS 27 270 REND
GOTR          OFFS FICH AVI CONT
                                                  AXIS 27 270 REND
ENDPLAY
*=========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------------Curve definitions
COUR 1 'dx_P1'  DEPL COMP 1  LECT  P1 TERM
COUR 2 'dy_P2'  DEPL COMP 2  LECT  P2 TERM
*-------------------------------------------------------------------Plots
trac 1 2 axes 1.0 'DISPL. [M]' yzer
*-----------------------------------------------------Results qualification
QUAL DEPL COMP 1 lect  P1 term REFE  3.90999E-3 TOLE 5.E-3
     DEPL COMP 2 lect  P2 term REFE -1.09017E-2 TOLE 5.E-3
*=================================================================
FIN
```

The resulting final deformed mesh with superposed current yield stress (a measure of plastic deformation) is:

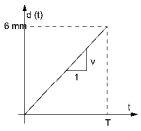


The displacements are:

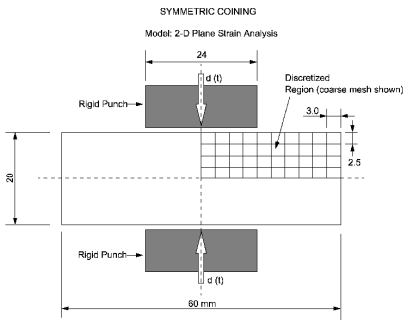


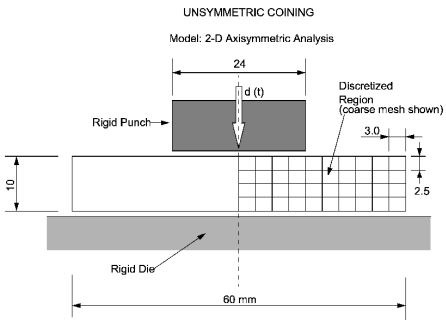
Example 3 – Coining

Material Data	
Density	8930
Young's Modulus	$2.\times10^{11}$
Yield Stress	2.5×10^{8}
Plastic Modulus	$1.\times10^{9}$
Poisson's Ratio	0.3



Punching Time T [ms]	Punching Velocity v [m/s]
40.00	0.15
2.00	3.00
0.10	60.00
0.02	300.00





Bilateral,
Plane strain

Unilateral,
Axisymmetric

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<u>Geometric data and materials:</u>
See slide.

<u>Numerical Solutions</u>

COIN05 (plane bilateral coining).

The mesh generation file is:

```
*%siz 100
opti echo 0;
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxpdroit.proc';
opti donn 'D:\Users\Folco\Plexis3c\Proc\ordpoin.proc';
opti echo 1;
*
opti titr 'COIN - 05';
opti dime 2 elem qua4;
*
p0=0 0;
p1=3.0E-2 0;
p2=3.0E-2 1.0E-2;
p3=0 1.0E-2;
*
tol=0.001E-02;
*
x y=coor p1;
dx=0 -(x / 20.0);
p4=p1 plus (dx 0);
p5=p2 plus (dx 0);
*
p6=1.2E-2 0;
p7=1.2E-2 1.0E-2;
*
c1=p0 d 20 p1;
c2=p1 d 8 p2;
c3=p2 d 20 p3;
c4=p3 d 8 p0;
```

```
stru=(daller c1 c2 c3 c4 'PLAN') coul rose;
*
elim tol (stru et p4 et p5 et p6 et p7);
*
lag=p0 et (stru poin droi p1 p2 tol);
lag=lag et (stru poin droi p4 p5 tol);
*
blocy=stru poin droi p0 p1 tol;
blocx=stru poin droi p0 p3 tol;
*
cha=pxpdroit stru p3 p7 tol;
*
sl=pxpdroit stru p5 p7 tol;
sli=folco sl p5;
*
eul=pxpdroit stru p3 p7 tol;
blocx=blocx et eul;
*
mesh=stru et lag et blocx et blocy et cha et sli et eul;
*
tass mesh;
*
opti sauv form 'coin05.msh';
sauv form mesh;
*
opti trac psc;
trac qual mesh;
fin;
```

The input file is:

```
COIN - 05
*------------------------------------------------------------------------
 ECHO
 CONV win
CAST MESH
*-------------------------------------------------------------Problem type
DPLA NONL ALE
*-------------------------------------------------------------Dimensioning
DIME
  PTGL 189 Q42G 160 NALE 1 NBLE 159
  BLOQ 110
  TABL 1 5
  DEPL 9
  SLPC 1 SLPN 20
  ECRO 7040
  mtpo 4 mtel 2
TERM
```

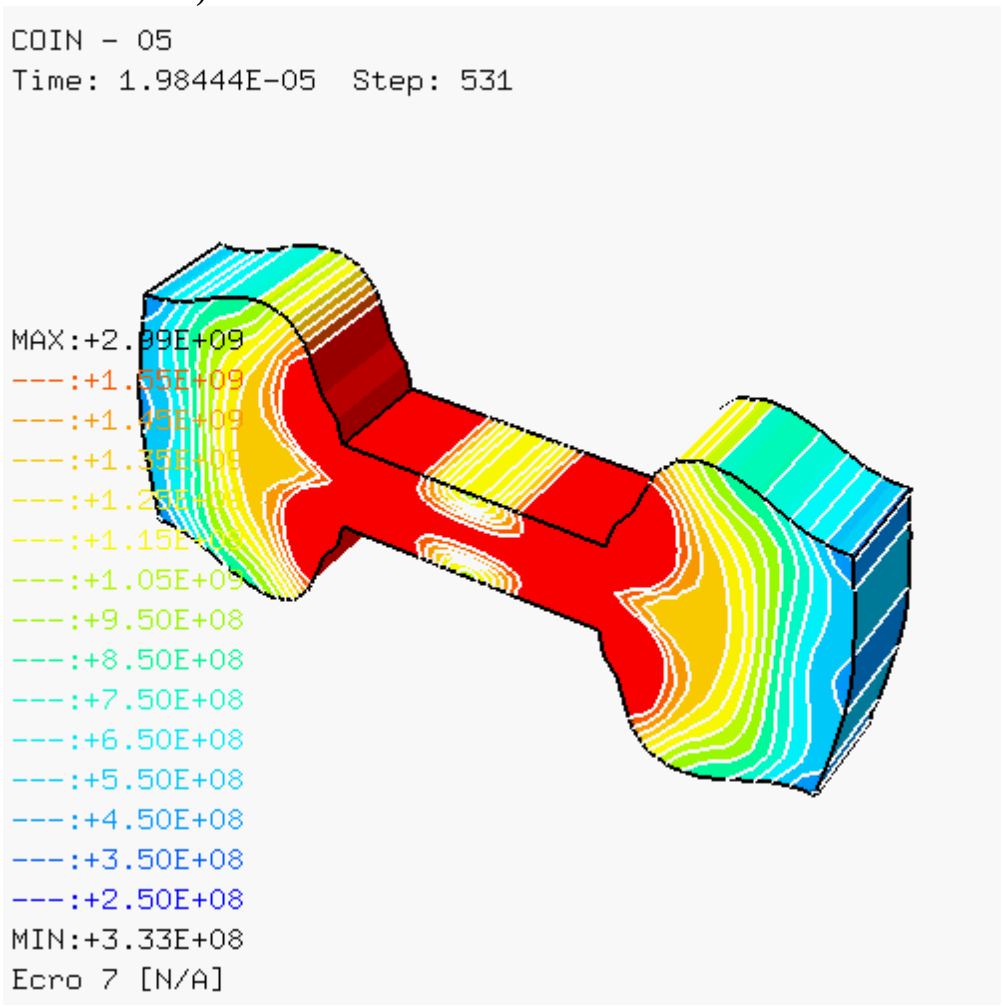
```
*-------------------------------------------------------------Geometry
GEOM Q42G STRU TERM
*-----------------------------------------------------Geometric Complements
COMP EPAI 1.0 TOUS
*-------------------------------------------------------------Grid motion
GRIL LAGR LECT LAG  TERM
     EULE LECT EUL  TERM
     ALE  LECT STRU TERM
     SLIP EQUI LECT SLI  TERM
     AUTO AUTR
*-------------------------------------------------------Material data
MATE VM23 RO 8930. YOUN 2.D11  NU 0.3D0 ELAS 2.5D8
          TRAC 2 2.5D8 1.25D-3 1.00025D12 1000.00125
          LECT STRU TERM
*-----------------------------------------------------Boundary conditions
LIAI RENU FREQ 1
     BLOQ 1 LECT BLOCX TERM
```

```
          2 LECT BLOCY TERM
*-------------------------------------------------------------Applied "loads"
CHAR 1 FACT 2 DEPL 2 -6.D-3 LECT CHA TERM
     TABL 3 0 0 20.D-6 1 1 1
*-------------------------------------------------------------------Outputs
ECRI COOR DEPL VITE CONT ECRO TFRE 20.D-6
     FICH K200 TFRE 4.D-6
               POIN TOUS CHAMELEM
     FICH TPLO FREQ 1 DESC 'COIN05'
               POIN LECT P1 P3 P7 P2 TERM
               ELEM LECT 1 141 TERM
     fich alic temp FREQ 1
                    poin lect P1 P2 term
                    elem lect 1 term
*-------------------------------------------------------------------Options
OPTI NOTE
     cstab 0.5
*-----------------------------------------------------Transient calculation
CALC TINI 0. TEND 20.D-6
*=================================================================ANIMATION
PLAY
CAME   1 EYE   7.32216E-02  1.05557E-01  1.32735E-01
!        Q     9.17872E-01 -2.89889E-01  2.51837E-01  1.00267E-01
         VIEW -4.04175E-01 -5.82665E-01 -7.05085E-01
         RIGH  8.53050E-01  3.80552E-02 -5.20440E-01
         UP   -3.30074E-01  8.11821E-01 -4.81661E-01
         FOV   2.48819E+01
SCEN GEOM NAVI FREE
          LINE HEOU SSHA
     ISO  FILI FIEL ECRO 7 SCAL USER PROG 2.5D8 PAS 1.0D8 1.55D9 TERM
     TEXT ISCA
     colo pape
     LIMA ON
titl titl 'EUROPLEXUS (C) Animation'
```

```
     tit2 'Symmetric Plane Coining'
     tit3 'Author: F. Casadei'
sler cam1 1        nfra 20
trac offs fich avi                  nocl nfto 75  fps 10 kfre 10 comp -1
                                         SYMX SYMY EXTZ 5 1.E-2 REND

sler cam1 1        nfra  1
TRAC OFFS FICH AVI CONT NOCL           SYMX SYMY EXTZ 5 1.E-2 REND
FREQ 10
GOTR LOOP 53  OFFS FICH AVI CONT NOCL SYMX SYMY EXTZ 5 1.E-2 REND
FREQ 9
GOTR          OFFS FICH AVI CONT      SYMX SYMY EXTZ 5 1.E-2 REND
ENDPLAY
*=========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------Curve definitions
COUR 1 'dx_P1'  DEPL COMP 1  LECT  P1 TERM
COUR 2 'dy_P1'  DEPL COMP 2  LECT  P1 TERM
COUR 3 'dx_P2'  DEPL COMP 1  LECT  P2 TERM
COUR 4 'dy_P2'  DEPL COMP 2  LECT  P2 TERM
*-------------------------------------------------------------------------Plots
trac 1 2 3 4 axes 1.0 'DISPL. [M]'
*-----------------------------------------Results qualification
QUAL DEPL COMP 1 lect  P1 term REFE  2.78556E-3 TOLE 5.E-3
     DEPL COMP 2 lect  P1 term REFE  0.00000E+0 TOLE 5.E-3
     DEPL COMP 1 lect  P2 term REFE  1.47361E-3 TOLE 5.E-3
     DEPL COMP 2 lect  P2 term REFE  1.34045E-3 TOLE 5.E-3
*=========================================================================
FIN
```

The resulting final deformed mesh with superposed current yield stress (a measure of plastic deformation) is:



COIN25 (axisymmetric unilateral coining).

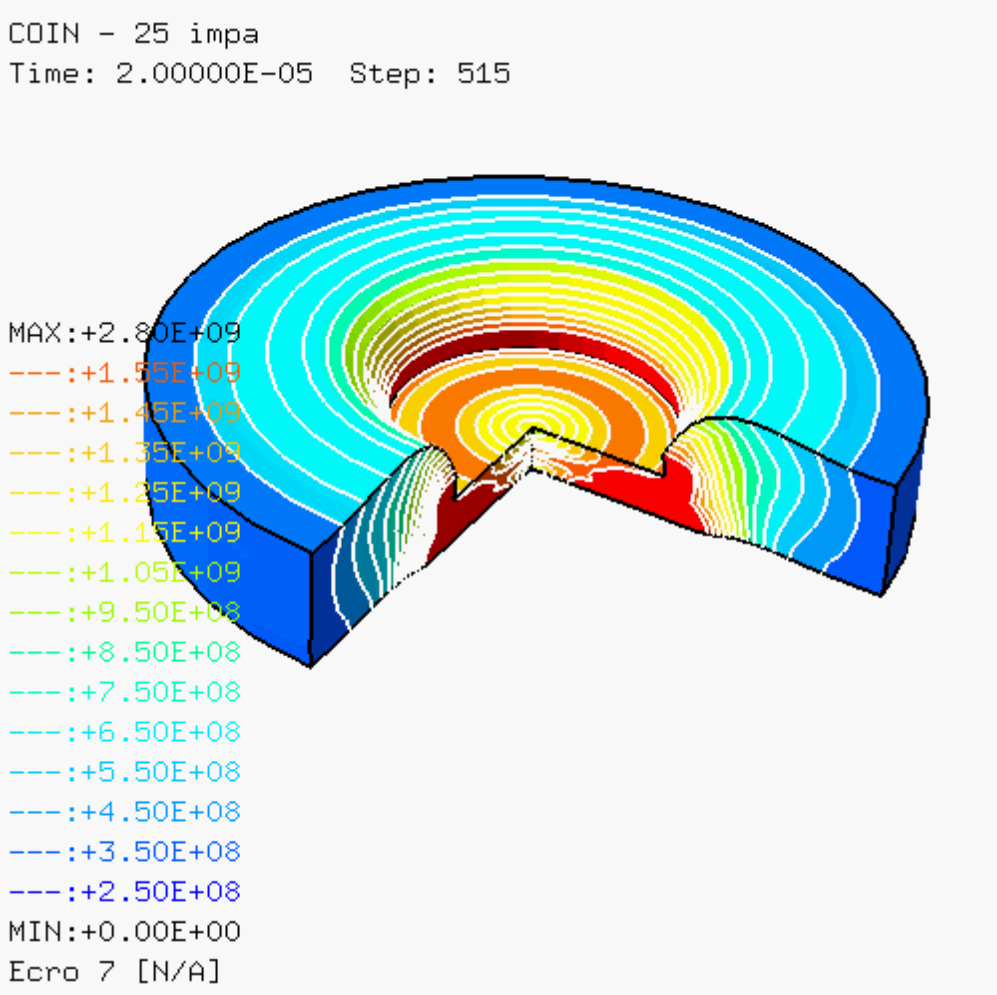
The mesh generation file is:

```
*%siz 100
*
opti echo 0;
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxpdroit.proc';
opti donn 'D:\Users\Folco\Plexis3c\Proc\ordpoin.proc';
opti echo 1;
*
opti titr 'COIN - 25';
opti dime 2 elem qua4;
*
p0=0 0;
p1=3.0E-2 0;
p2=3.0E-2 1.0E-2;
p3=0 1.0E-2;
*
tol=0.001E-02;
*
x y=coor p1;
dx=0 -(x / 20.0);
p4=p1 plus (dx 0);
p5=p2 plus (dx 0);
*
p6=1.2E-2 0;
p7=1.2E-2 1.0E-2;
*
c1=p0 d 20 p1;
c2=p1 d 8 p2;
c3=p2 d 20 p3;
c4=p3 d 8 p0;
stru=(daller c1 c2 c3 c4 'PLAN') coul rose;
*
elim tol (stru et p4 et p5 et p6 et p7);
p0m = 0 0;
pm = MANU 'POI1' p0m;
*
lag=p0 et p3 et (stru poin droi p1 p2 tol);
lag=lag et (stru poin droi p4 p5 tol);
*
blocy=pxpdroit stru p0 p6 tol;
blocx=pxpdroit stru p0 p6 tol;
blocx=blocx et (pxpdroit stru p0 p3 tol);
blocx=blocx et (pxpdroit stru p3 p7 tol);
*
uni1=pxpdroit stru p6 p1 tol;
pp6=uni1 elem 'CONTENENT' p6;
uni=diff uni1 pp6;
*
cha=pxpdroit stru p3 p7 tol;
*
sl1=pxpdroit stru p6 p4 tol;
slip1=folco sl1 p6;
*
sl2=pxpdroit stru p5 p7 tol;
slip2=folco sl2 p5;
*
au1=chan 'POI1' stru;
au2=diff au1 lag;
bad1=pxpdroit au2 p6 p1 tol;
au3=diff au2 bad1;
bad2=au3 poin droi p3 p2 tol;
au4=diff au3 bad2;
*
auto=au4 et (au1 elem 'CONTENENT' p6);
*
mesh=stru et pm et lag et blocx et blocy et uni
          et cha et slip1 et slip2 et auto;
*
tass mesh;
*
opti sauv form 'coin25.msh';
sauv form mesh;
*
opti trac psc ftra 'coin25_mesh.ps';
trac qual mesh;
fin;
```

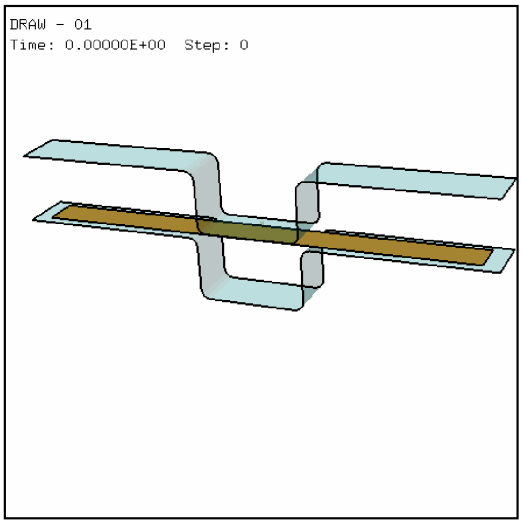
The input file is:

```
COIN - 25 impa
*------------------------------------------------------------------------
 ECHO
 CONV win
CAST MESH
*-------------------------------------------------------------Problem type
AXIS NONL ALE lagc
*-------------------------------------------------------------Dimensioning
DIME
  PT2L 190 Q42G 160 pmat 1 zone 2
  NALE 1 NBLE 142
  BLOQ 110
  TABL 1 5
  DEPL 9
  impa 1 psim 12
  SLPC 2 SLPN 20
  mtpo 2
TERM
*------------------------------------------------------------------Geometry
GEOM Q42G STRU pmat pm TERM
*-----------------------------------------------Geometric Complements
COMP EPAI 1.0 lect stru term
*-------------------------------------------------------------Grid motion
GRIL LAGR LECT LAG pm TERM
     ALE  LECT STRU TERM
     SLIP EQUI LECT SLIP1 TERM
          EQUI LECT SLIP2 TERM
     AUTO NOEU LECT AUTO TERM
*---------------------------------------------------------Material data
MATE VM23 RO 8930. YOUN 2.D11  NU 0.3D0 ELAS 2.5D8
          TRAC 2 2.5D8 1.25D-3 1.00025D12 1000.00125
          LECT STRU TERM
     mass 1.0 lect pm term
*-----------------------------------------------------Boundary conditions
LIAI RENU FREQ 1
     BLOQ 1 LECT BLOCX TERM
          2 LECT BLOCY TERM
          12 lect pm term
     impa ddl 2 cote 1
          proj lect pm term
          cibl lect UNI term
*-------------------------------------------------------Applied "loads"
CHAR 1 FACT 2 DEPL 2 -6.D-3 LECT CHA TERM
     TABL 3 0 0 20.D-6 1 1 1
*-------------------------------------------------------------------Outputs
ECRI COOR DEPL VITE CONT ECRO TFRE 20.D-6
     FICH K200 TFRE 4.D-6
               POIN TOUS CHAMELEM
     FICH TPLO FREQ 1 DESC 'COIN25'
               POIN LECT P1  P2 TERM
               ELEM LECT 1 TERM
     fich alic temp FREQ 1
                    poin lect P1  P2 term
                    elem lect 1 term
*-----------------------------------------------------------------Options
OPTI NOTE
     cstab 0.5
*-----------------------------------------------------Transient calculation
CALC TINI 0. TEND 20.D-6
*=============================================================ANIMATION
PLAY
CAME   1 EYE   7.32216E-02  1.05557E-01  1.32735E-01
!        Q     9.17872E-01 -2.89889E-01  2.51837E-01  1.00267E-01
         VIEW -4.04175E-01 -5.82665E-01 -7.05085E-01
         RIGH  8.53050E-01  3.80552E-02 -5.20440E-01
         UP   -3.30074E-01  8.11821E-01 -4.81661E-01
         POV   2.48819E+01
SCEN GEOM NAVI FREE
          LINE HEOU SSHA
     ISO  FILI FIEL ECRO 7 SCAL USER PROG 2.5D8 PAS 1.0D8 1.55D9 TERM
     TEXT ISCA
     colo pape
          LIMA ON
titl titl 'EUROPLEXUS (C) Animation'
     tit2 'Unilateral Axisymmetric Coining'
     tit3 'Author: F. Casadei'
sler cam1 1        nfra 20
trac offs fich avi               nocl nfto 73  fps 10 kfre 10 comp -1
                                      AXIS 27 270 REND
sler cam1 1        nfra  1
TRAC OFFS FICH AVI CONT NOCL          AXIS 27 270 REND
FREQ 10
GOTR LOOP 51  OFFS FICH AVI CONT NOCL AXIS 27 270 REND
FREQ 5
GOTR          OFFS FICH AVI CONT      AXIS 27 270 REND
ENDPLAY
*=========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-----------------------------------------------------------Curve definitions
COUR 1 'dx_P1'  DEPL COMP 1 NOEU LECT  P1 TERM
COUR 2 'dy_P1'  DEPL COMP 2 NOEU LECT  P1 TERM
COUR 3 'dx_P2'  DEPL COMP 1 NOEU LECT  P2 TERM
COUR 4 'dy_P2'  DEPL COMP 2 NOEU LECT  P2 TERM
*-------------------------------------------------------------------------Plots
trac 1 2 3 4 axes 1.0 'DISPL. [M]'
*-----------------------------------------------Results qualification
QUAL DEPL COMP 1 lect  P1 term REFE  1.03725E-3 TOLE 5.E-3
     DEPL COMP 2 lect  P1 term REFE  4.76203E-4 TOLE 5.E-3
     DEPL COMP 1 lect  P2 term REFE  7.19865E-4 TOLE 5.E-3
     DEPL COMP 2 lect  P2 term REFE  5.53042E-4 TOLE 5.E-3
*=========================================================================
FIN
```

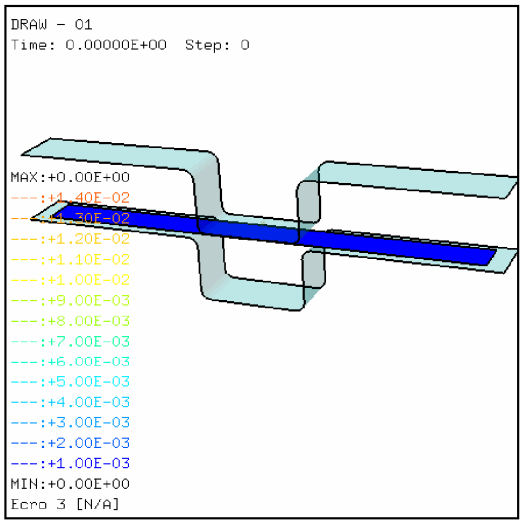
The resulting final deformed mesh with superposed current yield stress (a measure of plastic deformation) is:



Example 6a – Deep drawing A



Deformation



Plastic strain

30

Problem description:

This example is the deep drawing of a thin elasto-plastic metal strip which is pressed between a punch and a die.

The simulation assumes a rigid, fixed die and a rigid punch which is moving at constant velocity.

The model assumes perfect sliding between the contacting parts (no friction).

Numerical Solutions

DRAW01

This model uses 3904 elements of the Q4GS type to represent the piece, the punch and the die. Contact is prescribed by the GLIS directive between the piece and the punch and between the piece and the die.

The input file is:

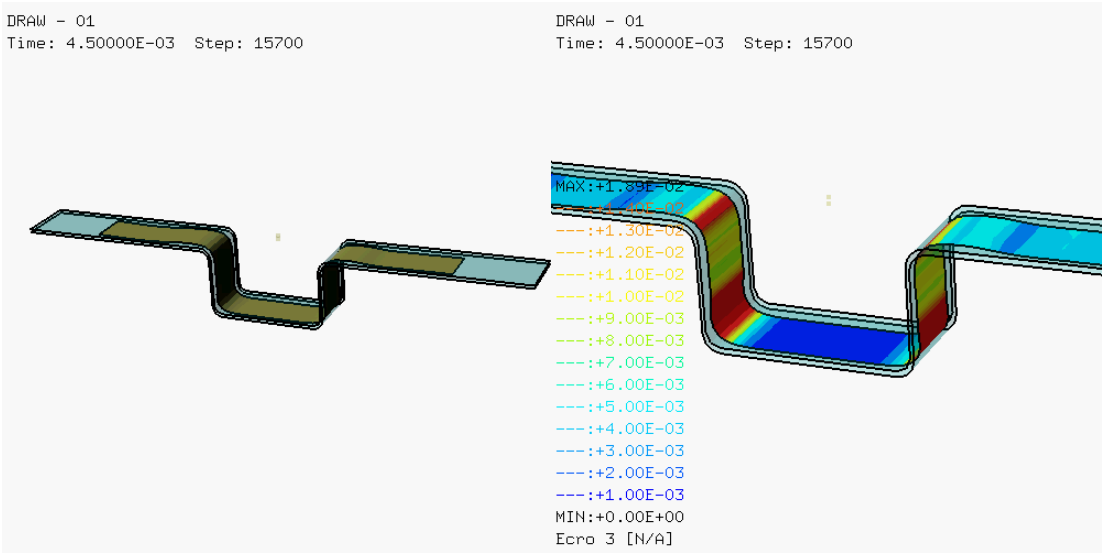
```
DRAW - 01
*
 ECHO
!CONV WIN
*-------------------------------------------------------Type of problem
 TRID NONL
 AMOR
*-------------------------------------------------------------------Sizing
DIME
 PT3L 2 PT6L 4297
 ZONE 2
 PMAT 2
 Q4GS 3904
 ECRO 858884
 BLOQ 25782
 GLIS 2 5000
 DDLI 5109 FCOE 5109
 DEPL 5109
 TABL 2 12 FNOM 2 FTAB 12
 MTPO 1 MTEL 1
```

```
TERM
*-------------------------------------------------------------Geometry (Mesh)
GEOM '(3E22.15)' '(7I10)' POIN 4299
 PMAT 2
 Q4GS 3904
TERM
*-------------------------------------------------------Nodal Coordinates
-1.000000000000000E-01 0.000000000000000E+00 5.000000000000000E-03
 . . . (omissis)
      3514      3515      4297      3512      3513      3514
*-----------------------------------------Additional geometrical data
COMP
 GROU 8 'masses' LECT    1           2 TERM
        'die'    LECT    3 PAS 1 1562 TERM
        'punch'  LECT 1563 PAS 1 3122 TERM
        'piece'  LECT 3123 PAS 1 3906 TERM
        'cmait'  LECT 3123 PAS 1 3906 TERM
        'cesc1'  LECT 1563 PAS 1 3122 TERM
        'cesc2'  LECT    3 PAS 1 1562 TERM
        'e_alit' LECT    1           TERM
```

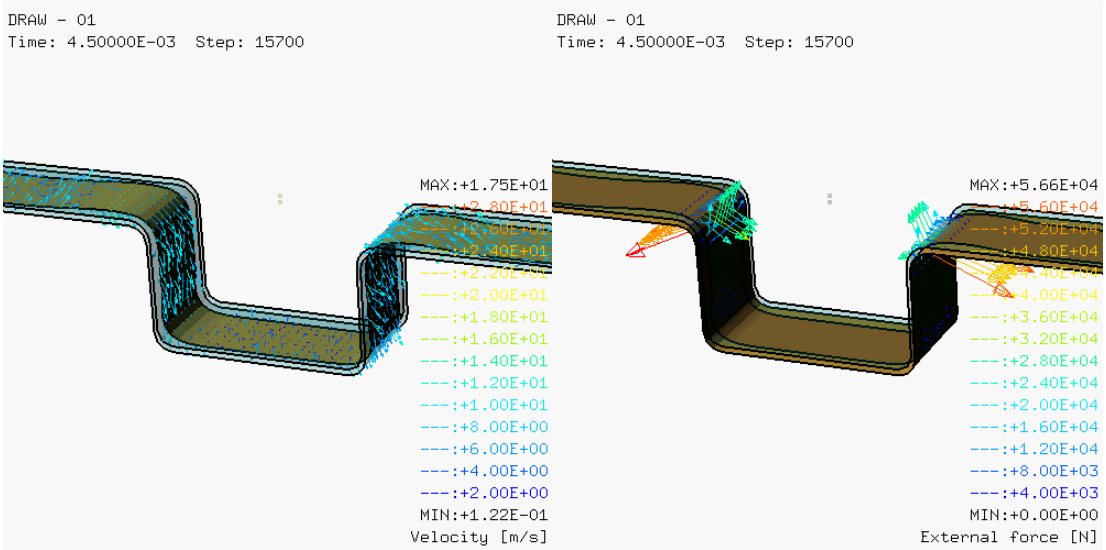
```
 COUL jaun LECT masses     TERM
      turq LECT punch die  TERM
      roug LECT piece      TERM
 NGRO 7 'n_masses' LECT masses TERM
        'n_die'    LECT die    TERM
        'n_punch'  LECT punch  TERM
        'n_piece'  LECT piece  TERM
        'n_ext1'   LECT 4298   TERM
        'n_ext2'   LECT 4299   TERM
        'n_alit'   LECT 1825   TERM
 EPAI 1.E-03 LECT punch die TERM
 EPAI 5.E-04 LECT piece     TERM
*------------------------------------------------------------Materials
MATE
 LINE RO  7.8E+03 YOUN  3.E+11
      NU  3.E-01
      LECT punch die TERM
 VMIS ISOT RO  2.767E+03 YOUN  7.E+10
      NU  3.E-01 ELAS  2.93E+08
      TRAC  12  2.93000E+08              4.18571E-03
                3.09400E+08              6.10600E-03
                3.16350E+08              7.12129E-03
                3.24380E+08              8.46700E-03
                3.33800E+08              1.02786E-02
                3.45120E+08              1.29853E-02
                3.59060E+08              1.70604E-02
                3.76870E+08              2.38049E-02
                4.00710E+08              3.62904E-02
                4.34740E+08              6.35266E-02
                4.87940E+08              1.40321E-01
                1.09500E+09              1.00016E+02
      LECT piece TERM
 MASS 0.1E-02 LECT masses TERM
*-------------------------------------------------------------Couplings
LIAIS
 BLOQ 123456 LECT die   TERM
       12456 LECT punch TERM
         246 LECT piece TERM
 DEPL 3 0.1E+01 FONC 1 LECT punch TERM
 GLIS 2
```

```
    CMAI LECT cmait TERM EXTE LECT n_ext1 TERM
    CESC LECT cesc1 TERM
    CMAI LECT cmait TERM EXTE LECT n_ext2 TERM
    CESC LECT cesc2 TERM
 FONC 1 TABL 2
        0.0E+00    0.0E+00
        0.501E-02 -0.405E-01
*-----------------------------------------------------Initial conditions
INIT VITE 3 -8.08383 LECT punch TERM
*-------------------------------------------------------------------Storage
ECRI
  DEPL VITE TFRE 4.5E-4 POIN LECT n_alit TERM
  FICH ALIC      TFRE 4.5E-05
  FICH ALIC TEMP TFRE 4.5E-06
                 POIN LECT n_alit TERM
                 ELEM LECT e_alit TERM
*-----------------------------------------------------------------Options
OPTI LOG 1
*-----------------------------------------------------------Time Steps
CALC TINI 0.E+00 TFIN 4.5E-03
*=====================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR  1 'dz'   DEPL COMP 3 NOEU LECT n_alit TERM
COUR  2 'vz'   VITE COMP 3 NOEU LECT n_alit TERM
*
trac 1 axes 1.0 'DISPL. [M]'
trac 2 axes 1.0 'VELOC. [M/S]'
*
QUAL DEPL COMP 3 LECT n_alit TERM REFE -3.63772E-2 TOLE 5.E-3
*=====================================================================
FIN
```

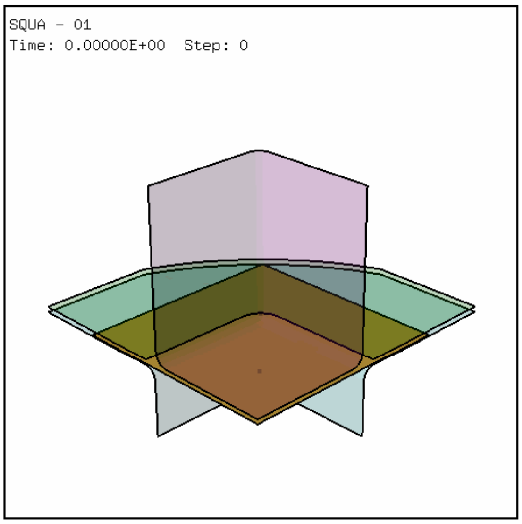
The final deformed mesh and plastic strains are:



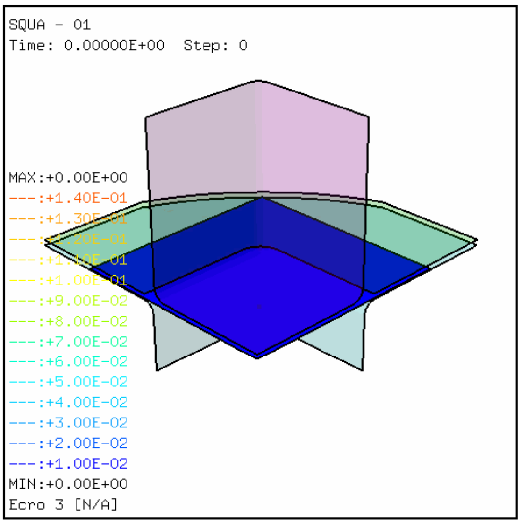
The final velocities and forces on the die:



Example 6b – Deep drawing B



Deformation



Plastic strain

32

Problem description:

This example is the deep drawing of a thin elasto-plastic square box starting from a thin square metal sheet which is pressed between a punch, a die and a holder.

The simulation assumes a rigid, fixed die and a rigid punch which is moving at constant velocity.

The model assumes friction between the contacting parts (but not between the piece and the holder).

Thanks to symmetries, only ¼ of the real geometry is modelled in the calculation.

Numerical Solutions

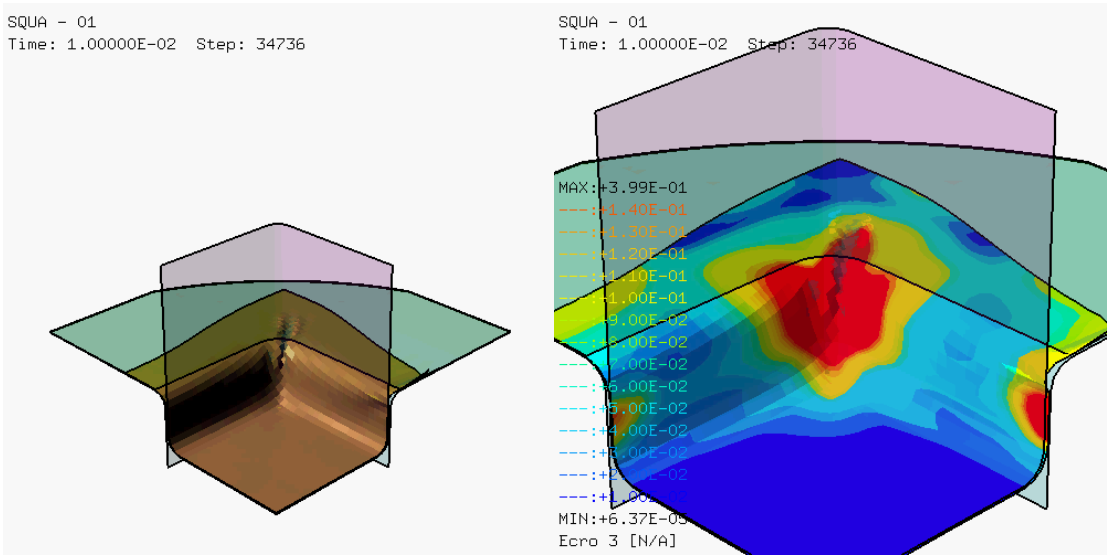
SQUA01

This model uses 6977 elements of the Q4GS type and 33 elements of the DST3 type to represent the piece, the punch, the die and the holder. Contact is prescribed by the GLIS directive between the piece and the punch (with friction), between the piece and the die (with friction) and between the piece and the holder (without friction).

The input file is:

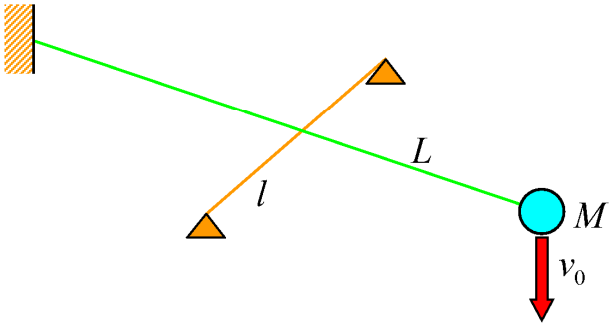
```
SQUA - 01
*
 ECHO
!CONV WIN
*-------------------------------------------------------------Type of problem
 TRID NONL
 AMOR
*-------------------------------------------------------------------Sizing
DIME
 PT3L 3 PT6L 7341
 ZONE 3
 PMAT 3
 DST3 33
 Q4GS 6977
 ECRO 1540391
 BLOQ 35382
 GLIS 3 10000
 DDLI 5280 FCOE 5280
 DEPL 5280 FORC 6
 TABL 3 12 FNOM 3 FTAB 12
 MTPO 2 MTEL 1
TERM
*-----------------------------------------------------------Geometry (Mesh)
GEOM '(3E22.15)' '(7I10)' POIN 7344
 PMAT 3
 DST3 33
 Q4GS 6977
TERM
*-------------------------------------------------------Nodal Coordinates
 0.000000000000000E+00 1.900000000000000E-01 1.000000000000000E-03
 . . . (omissis)
       5317      7341      7341      5317      5314      5346
*-----------------------------------------------Additional geometrical data
COMP
 GROU 6 'masses' LECT    1 PAS 1     3 TERM
        'piece'  LECT   37 PAS 1 1480 TERM
        'die'    LECT   23 PAS 1   36 4769 PAS 1 7013 TERM
        'punch'  LECT   22 3082 PAS 1 4768 TERM
        'holder' LECT    4 PAS 1   21 1481 PAS 1 3081 TERM
        'e_alit' LECT    1                 TERM
 COUL jaun LECT masses TERM
      roug LECT piece  TERM
      turq LECT die    TERM
      rose LECT punch  TERM
      vert LECT holder TERM
 NGRO 15 'n_masses' LECT masses TERM
         'n_piece'  LECT piece  TERM
         'n_die'    LECT die    TERM
         'n_punch'  LECT punch  TERM
         'n_holder' LECT holder TERM
         'n_ext1'   LECT 7342   TERM
         'n_ext2'   LECT 7343   TERM
         'n_ext3'   LECT 7344   TERM
         'n_pibloq' LECT 39     TERM
         'n_bl156'  LECT 1 PAS 1 38 TERM
         'n_bl246'  LECT 78 116 PAS 1 152 TERM
         'n_forcz'  LECT 2673 TERM
         'n_ali1'   LECT 1522 TERM
         'n_ali2'   LECT 3439 TERM
         'n_alit'   LECT n_ali1 n_ali2 TERM
 EPAI 0.8E-03 LECT piece TERM
 EPAI 1.0E-03 LECT die punch holder TERM
 FROT 1 MU0 0.25  MU1 0.25  GAMMA 1
 FROT 2 MU0 0.125 MU1 0.125 GAMMA 1
*-------------------------------------------------------------------Materials
MATE
 VMIS ISOT RO 2.767E+03 YOUN 7.0E+10 NU 3.E-01 ELAS 2.93E+08
      TRAC  12  2.93000E+08                4.18571E-03
                3.09400E+08                6.10600E-03
                3.16350E+08                7.12129E-03
                3.24380E+08                8.46700E-03
                3.33800E+08                1.03196E-02
                3.45120E+08                1.29853E-02
                3.59060E+08                1.70604E-02
                3.76870E+08                2.38049E-02
                4.00710E+08                3.62904E-02
                4.34740E+08                6.35266E-02
                4.87940E+08                1.40321E-01
                1.09500E+09                1.01564E+00
       LECT piece TERM
 LINE RO 7.8E+03 YOUN  2.E+11 NU 3.E-01
       LECT die punch holder TERM
 MASS 0.1E-02
       LECT masses TERM
*-----------------------------------------------------------------Couplings
LIAI
 BLOQ 123456 LECT die                      TERM
         156 LECT n_bl156                  TERM
       12456 LECT n_pibloq n_punch n_holder TERM
         246 LECT n_bl246                  TERM
 DEPL 3 0.1E+01 FONC 1 LECT punch TERM
 GLIS 3
   CMAI LECT piece  TERM EXTE LECT n_ext1 TERM
   CESC LECT punch  TERM
   CMAI LECT piece  TERM EXTE LECT n_ext2 TERM
   CESC LECT die    TERM
   CMAI LECT piece  TERM EXTE LECT n_ext3 TERM
   CESC LECT holder TERM
 FONC 1 TABL 2
        0.000E+00  0.000E+00
        0.101E-01 -0.500E-01
*-----------------------------------------------------Factorized loads
CHAR 1 FACT 2
 FORC 3 0.1E+01 LECT n_forcz TERM
        TABL 3
        0.000E+00  0.000E+00
        0.100E-02 -0.200E+05
        0.100E-00 -0.200E+05
*-----------------------------------------------------Initial conditions
INIT VITE 3 -4.95050 LECT punch TERM
*-------------------------------------------------------------------Storage
ECRI
  DEPL VITE TFRE 1.0E-3 POIN LECT n_alit TERM
  FICH ALIC     TFRE 1.0E-04
  FICH ALIC TEMP TFRE 1.0E-05
                POIN LECT n_alit TERM
                ELEM LECT e_alit TERM
*-----------------------------------------------------------------------Options
OPTI LOG 1
*-----------------------------------------------------------------Time Steps
CALC TINI 0.E+00 TFIN 10.E-03
*=======================================================================
SUIT
Post-treatment (time curves from alice temps file)
ECHO
*
RESU ALIC TEMP GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR  1 'dz_1' DEPL COMP 3 NOEU LECT n_ali1 TERM
COUR  2 'dz_2' DEPL COMP 3 NOEU LECT n_ali2 TERM
COUR  3 'vz_1' VITE COMP 3 NOEU LECT n_ali1 TERM
COUR  4 'vz_2' VITE COMP 3 NOEU LECT n_ali2 TERM
*
trac 1 2 axes 1.0 'DISPL. [M]'
trac 3 4 axes 1.0 'VELOC. [M/S]'
*
QUAL DEPL COMP 3 LECT n_ali2 TERM REFE -4.95050E-2 TOLE 5.E-3
*=======================================================================
FIN
```

The final deformed mesh and plastic strains are:



Example 7 – Cable impact

- A cable is fixed at one end and has a concentrated mass at the other end. The mass has an initial velocity. In its motion, the cable impacts on a second cable fixed at both extremities.
- Cables have no resistance to bending or compression (only to traction).



$L = 10$
$l = 2$
$M = 100$
$v_0 = -100$

45

Geometric data and materials:
See slide. The cable material is elastic (traction only) and has a density of 8000, a Young's modulus of 2×10^{11} and a Poisson's ratio of 0.3.

Numerical Solutions

WRAP06
The longer cable uses 20 elements of type FUN3, the shorter one 4 elements. Contact is treated by the pinball method, with hierarchic pinballs of level 2. The mesh generation file is:

```
OPTI ECHO 1;
OPTI DIME 3 ELEM SEG2;
p0 = 0 0 0;
p1 = 10 0 0;
n = 20;
tol = 0.001;
bar1 = (p0 d n p1) coul vert;
p2 = 5 -1 -1;
pc = 5  0 -1;
p3 = 5  1 -1;
n2 = n / 5;
bar2 = (p2 d n2 p3) coul jaun;
elim tol (bar2 et pc);
pm = (manu poi1 p1) coul turq;
pa = -0.5 0 -0.5;
pb = -0.5 0 0.5;
app1 = (manu tri3 p0 pb pa) coul rose;
pc = 4.5 -1 -1.5;
pd = 5.5 -1 -1.5;
app2 = (manu tri3 p2 pc pd) coul rose;
pe = 4.5  1 -1.5;
pf = 5.5  1 -1.5;
app3 = (manu tri3 p3 pe pf) coul rose;
mesh = bar1 et bar2 et pm et app1 et app2 et app3;
tass mesh;
opti sauv form 'wrap06.msh';
sauv form mesh;
opti trac psc ftra 'wrap06_mesh.ps';
trac qual mesh;
```

The input file is:

```
WRAP - 06
*------------------------------------------------------------------------
ECHO
 conv win
CAST mesh
*-------------------------------------------------------------Problem type
TRID NONL LAGR
*-------------------------------------------------------------Dimensioning
DIME
   PT3L 26 PT6L 9 FUN3 24 PMAT 1 COQI 3 ZONE 3
TERM
*------------------------------------------------------------------Geometry
GEOM FUN3 bar1 bar2 PMAT pm COQI app1 app2 app3 TERM
*-----------------------------------------------Geometric Complements
COMP EPAI 0.001 LECT bar1 bar2 TERM
     EPAI 0.5 LECT pm TERM ! only for graphical representation
     EPAI 1.0 LECT app1 app2 app3 TERM
*-------------------------------------------------------Material data
MATE FUNE RO 8000. YOUN 2.0E11 NU 0.3 ERUP 1.0
          ELAS 2.0E11
          TRAC 1 2.0E11 1.
          LECT bar1 bar2 TERM
     MASS 100 LECT pm TERM
     VM23 RO 8000 YOUN 2.E11 NU 0. ELAS 2.E11
          TRAC 1 2.E11 1.0
          LECT app1 app2 app3 TERM
*-----------------------------------------------------Boundary conditions
LINK COUP BLOQ 123 LECT p0 p2 p3 TERM
     PINB BODY MLEV 2 LECT bar1
          BODY MLEV 2 LECT bar2
*-----------------------------------------------------Initial conditions
INIT VITE 3 -100 LECT p1 TERM
*------------------------------------------------------------------Outputs
ECRI VITE TFRE 100.E-3
     FICH ALIC TEMP FREQ 5
               POIN LECT p1 pc TERM
*-------------------------------------------------------------------Options
OPTI NOTE CSTA 0.25E0
     nocr lect app1 app2 app3 term
     PINS CNOR
*-------------------------------------------------Transient calculation
CALC TINI 0 TFIN 0.900
*=============================================================ANIMATION
PLAY

CAME   1 EYE   5.00000E+00  0.00000E+00  2.51174E+01
!        Q     1.00000E+00  0.00000E+00  0.00000E+00  0.00000E+00
         VIEW  0.00000E+00  0.00000E+00 -1.00000E+00
         RIGH  1.00000E+00  0.00000E+00  0.00000E+00
         UP    0.00000E+00  1.00000E+00  0.00000E+00
         FOV   2.48819E+01
```

```
CAME   2 EYE   2.01169E+01 -1.88353E+01  8.04171E+00
!        Q     7.35450E-01  5.62509E-01  1.29873E-01  3.54725E-01
         VIEW -5.90102E-01  7.35256E-01 -3.33434E-01
         RIGH  7.14606E-01  6.67874E-01  2.08043E-01
         UP   -3.75657E-01  1.15508E-01  9.19533E-01
         FOV   2.48819E+01

scen
     geom
          !navi free
          line heou
          poin sphp
          pinb pare
      colo pape
      lima on

titl tit1 'EUROPLEXUS (C) Animation'
     tit2 'Cable Impact'
     tit3 'Author: F. Casadei'
sler cam1 1        nfra 30
trac offs fich avi      nocl nfto 1091 fps 25 kfre 10 comp -1 rend

titl tit2 'Geometry and Parent Pinballs'
sler cam1 1        nfra 30
trac offs fich avi cont nocl                                rend

sler cam1 1        nfra 1
trac offs fich avi cont nocl                                rend

!sler cam1 1 cam2 2 nfra 100 cent 5 0 0
sler cam1 1 cam2 2 nfra 100 cent 5 0 -0.5
trac offs fich avi cont nocl                                rend

titl tit2 'Transient with descendent pinballs'
sler cam1 1        nfra 30
trac offs fich avi cont nocl                                rend

scen geom navi free
          line heou
          poin sphp
          pinb cdes
```

```
     !VECT SCCO FIEL VITE SCAL USER PROG 5 PAS 5 70 TERM
     !                                                  SFAC 0.01
     !text vsca
     lima on

freq 0 tfre 1.E-3

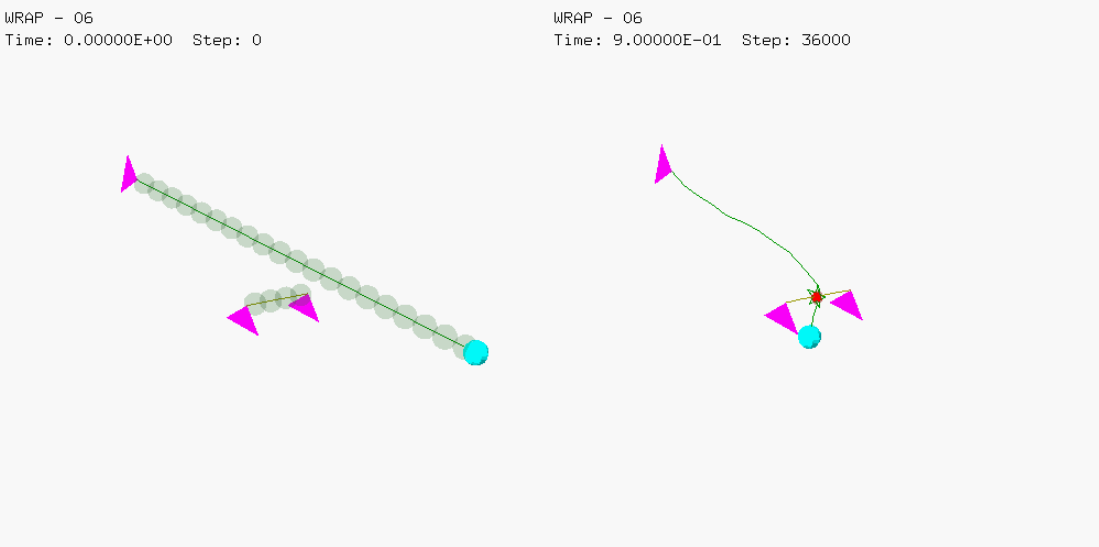
sler cam1 2        nfra 1

gotr loop 899 offs fich avi cont nocl                       rend

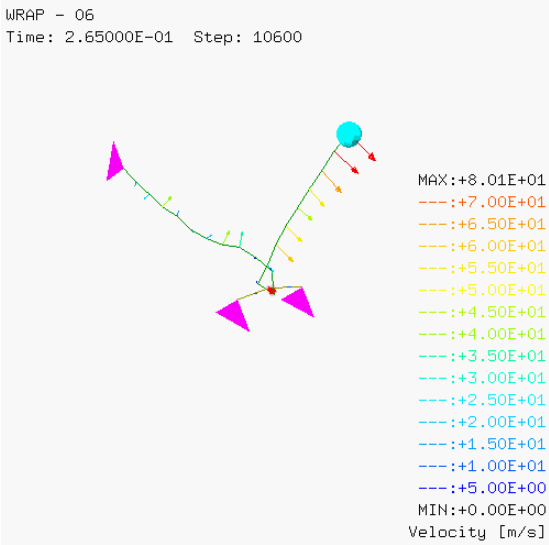
go
trac offs fich avi cont                                     rend

ENDPLAY
*=============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1000.0 'Time [ms]'
*-------------------------------------------------------------Curve definitions
COUR  1 'dx_p1'   DEPL COMP 1 NOEU LECT p1 TERM
COUR  2 'dy_p1'   DEPL COMP 2 NOEU LECT p1 TERM
COUR  3 'dz_p1'   DEPL COMP 3 NOEU LECT p1 TERM
COUR  4 'dx_pc'   DEPL COMP 1 NOEU LECT pc TERM
COUR  5 'dy_pc'   DEPL COMP 2 NOEU LECT pc TERM
COUR  6 'dz_pc'   DEPL COMP 3 NOEU LECT pc TERM
*--------------------------------------------------------------------Plots
trac 1 2 3 axes 1.0 'DISPL. [M]'
trac 4 5 6 axes 1.0 'DISPL. [M]'
*-----------------------------------------------Results qualification
QUAL DEPL COMP 1 LECT p1   TERM REFE -4.41946E+0 TOLE 5.E-3
     DEPL COMP 2 LECT p1   TERM REFE -2.42214E-2 TOLE 5.E-3
     DEPL COMP 3 LECT p1   TERM REFE -1.76791E+0 TOLE 5.E-3
     DEPL COMP 1 LECT pc   TERM REFE  0.00000E+0 TOLE 5.E-3
     DEPL COMP 2 LECT pc   TERM REFE  0.00000E+0 TOLE 5.E-3
     DEPL COMP 3 LECT pc   TERM REFE  0.00000E+0 TOLE 5.E-3
*=====================================================================
FIN
```

The initial configuration (with parent pinballs shown) and the final configuration are:

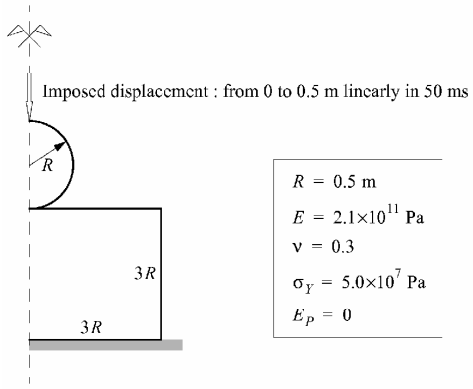


An example of intermediate velocities:



Example 7b – Indentation

- A rigid spherical indenter is pushed at constant speed of 10 m/s into a ductile block of material



- Compute the indentation force as a function of displacement
  - 2D axisymmetric solution
  - 3D solution(s)

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TITLE:
Indentation problem.
PROBLEM:
This problem was suggested by EDF as a check of the code capability to model a classical contact problem by the contact models available, in particular by the pinballs method. The ideal problem is a static one. A rigid spherical indenter is forced to penetrate into an elastic perfectly plastic half space. The computed result is the resultant of the contact forces in the indentation direction as a function of time.
An approximated analytical solution exists, due to Johnson.
MESH:
The 2D model is axisymmetric and uses 1694 elements Q42L for the piece (half space represented by a square region of side equal to 3 times the indenter radius), and one PMAT element for the indenter.
MATERIALS:
The VM23 material is assigned to the piece, with zero plastic hardening. The MASS element is assigned to the indenter.
BOUNDARY CONDITIONS:
All nodes on the axis of symmetry are blocked in the radial direction. The base of the piece is blocked in all directions. Contact is represented by the pinball model. A single pinball with radius equivalent to that of the indenter is associated with the PMAT element. The region of the piece likely to come in contact is filled by parent pinballs with a hierarchy level of 4 to get accurate contact resolution.
LOADING:
The indenter is pushed into the piece at constant imposed speed (linear displacement in time), until it reaches an indentation depth equal to the radius of the indenter.
INITIAL CONDITIONS
The indenter has an initial velocity equal to the imposed indentation velocity (to avoid an initial error in the energy balance).
CALCULATION:
The calculation is performed up to 50 ms. At the final time, the indenter has reached a depth equal to its radius.
RESULTS:
The computed resultant contact force is in good agreement with the approximate analytical solution up to an indentation depth equal to approximately 1/2 of the indenter radius. For larger indentations, the analytical (linear) solution is no longer valid.

POST-TREATMENT
Several animations of the computed results from this calculation are available on the EUROPLEXUS Consortium Web site.

REFERENCES:
The indentation problem is detailed in the following EDF document:
N. Tardieu, B. Serre: "Indentation elasto-plastique d'un bloc par un indenteur spherique elastique", Code_Aster, Manuel de Validation, Report V6.04.506, December 2002.
This calculation is detailed in:
F. Casadei: "Validation of the EUROPLEXUS Pinball Impact-Contact Model on an Indentation Problem", Technical Note in press, July 2007. (available on the EUROPLEXUS Consortium Web site).

Numerical Solutions

INDE10

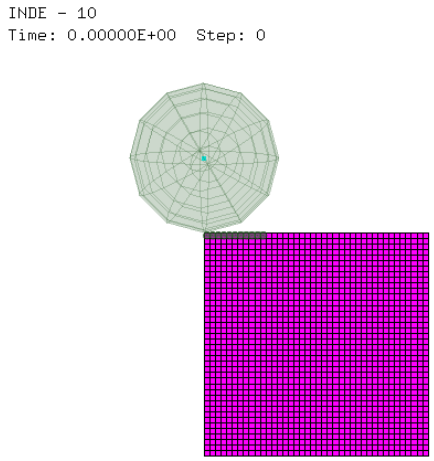
2D axisymmetric solution. The mesh generation file is:

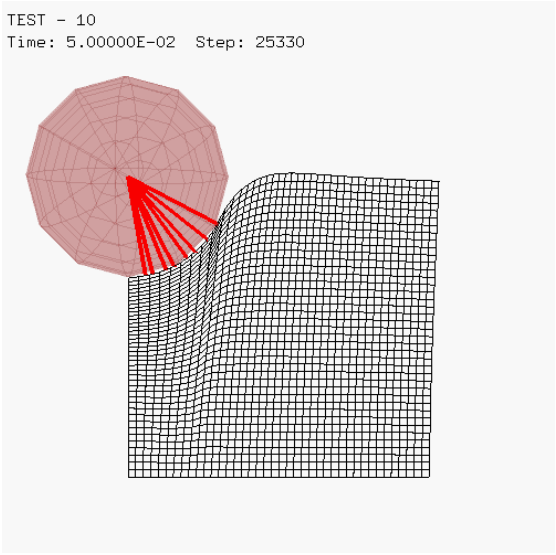
```
*%siz 50
opti echo 1;
opti dime 2 elem qua4;
p0 = 0 0;
p1 = 0 -1.5;
p2 = 1.5 -1.5;
p3 = 1.5 0;
pc = 0 0.5;
p13 = 0.375 0;
tol = 1.e-5;
piece = dall (p0 d 40 p1) (p1 d 40 p2) (p2 d 40 p3) (p3 d 40 p0) plan;
sphere = manu poi1 pc;
opti trac psc ftra 'vl_jrc_inde10_msh.ps';
trac qual (piece et sphere);
tout = piece et sphere;
axe = tout poin droi p1 pc tol;
base = piece poin droi p1 p2 tol;
cp = p0 d 10 p13;
elim tol (piece et cp);
c_p = piece elem appu larg cp;
mesh = tout et axe et base et c_p;
tass mesh;
opti sauv form 'vl_jrc_inde10.msh';
sauv form mesh;
list (nbno mesh);
list (nbel mesh);
fin;
```

The input file is:

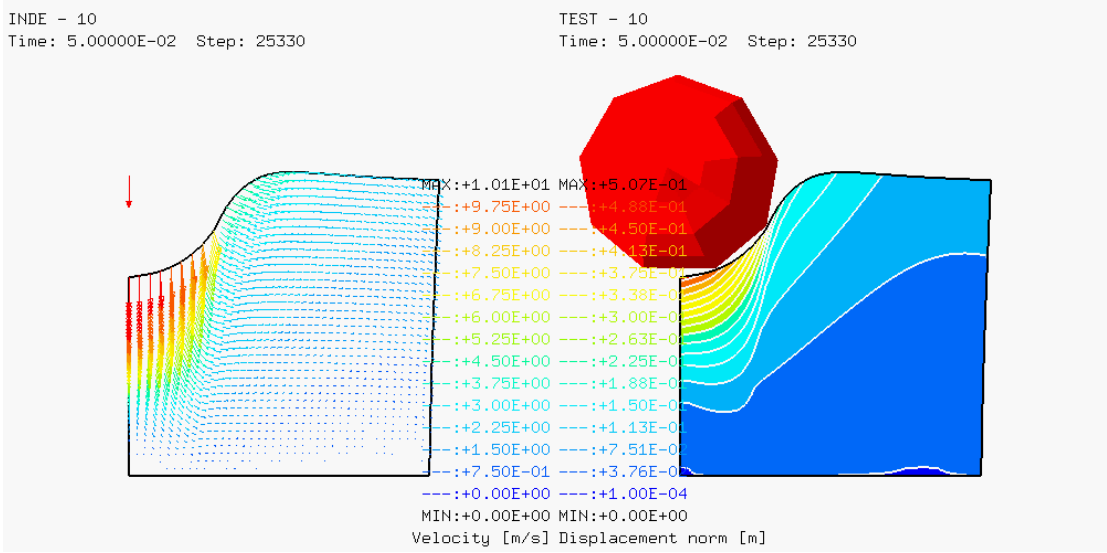
```
INDE - 10
ECHO
!CONV WIN
NONL AXIS
CAST mesh
DIME
  PT2L 1682
  Q42L 1694
  PMAT 1
  ZONE 2
TERM
GEOM
  Q42L piece PMAT sphere
TERM
COMP EPAI 1.0 LECT piece sphere TERM
     COUL rose LECT piece TERM
          turq LECT sphere TERM
MATE MASS 650.D0
          LECT sphere TERM
     VM23 RO 7800 YOUN 2.1E11 NU 0.3 ELAS 5.E7
          TRAC 2 5.E7 2.38095E-4 5.E7 1.0
          LECT piece TERM
OPTI PINS CNOR NCOL RCEL
LINK COUP
     BLOQ 1 LECT axe base TERM
          2 LECT base TERM
     DEPL 2 -1.D0 FONC 1 LECT sphere TERM
     PINB BODY DIAM 1.D0 LECT sphere TERM
          BODY MLEV 4    LECT c_p TERM
FONC 1 TABL 2 0. 0. 2. 20.
INIT VITE 2 -10. LECT sphere TERM
REGI 'r_piece' RESU LECT c_p  TERM
     'r_base'  RESU POIN LECT base TERM
ECRI DEPL VITE FEXT TFRE 0.005
     FICH ALIC TFRE 25.E-5
OPTI CSTA 0.5 LOG 1
CALCUL TINI 0. TFIN 50.E-3
FIN
```

The initial configuration (with parent pinballs shown) and the final configuration (with contacts shown) are:

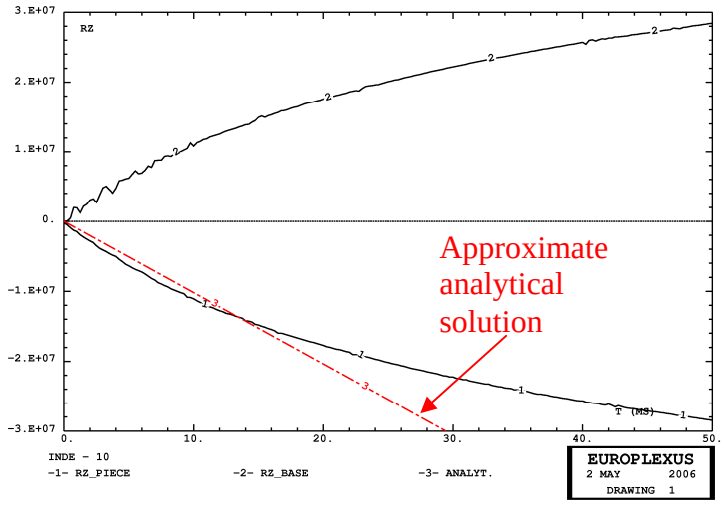




The final velocities and displacement norm:



The reaction force is:



INDE13

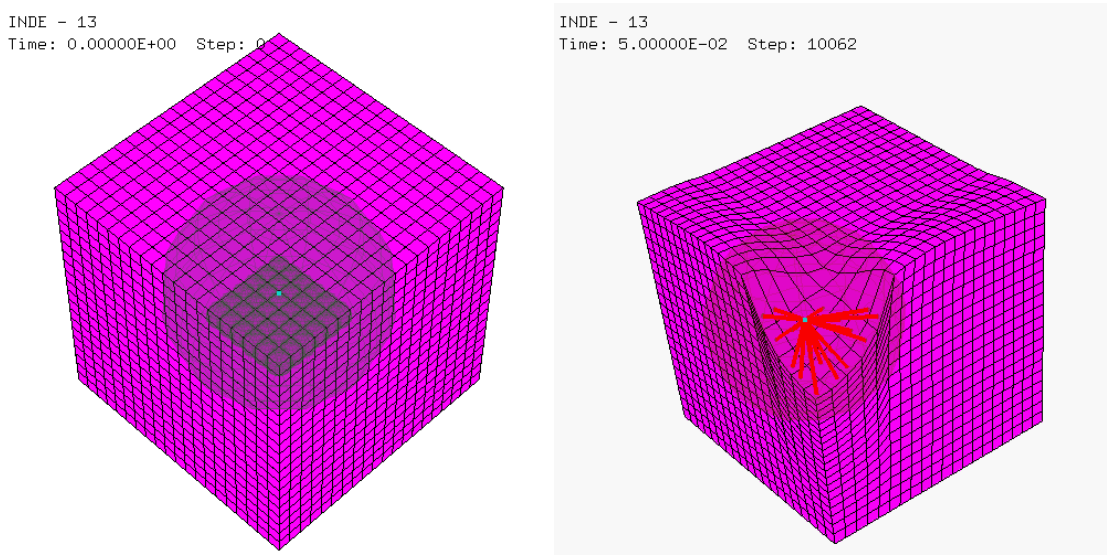
3D solution using only hexahedra. The model is not perfectly axisymmetric. The mesh generation file is:

```
*%siz 50
opti echo 1;
opti dime 3 elem cub8;
p0 = 0 0 0;
p1 = 0 0 -1.5;
p2 = 1.5 0 -1.5;
p3 = 1.5 0 0;
pc = 0 0 0.5;
p13 = 0.375 0 0;
vy = 0 1.5 0;
py = 0 0.375 0;
tol = 1.e-5;
piece2 = dall (p0 d 20 p1) (p1 d 20 p2) (p2 d 20 p3) (p3 d 20 p0) plan;
piece = piece2 volu tran 20 vy;
sphere = manu poi1 pc;
opti trac psc ftra 'vl_jrc_inde13_msh.ps';
trac cach qual (piece et sphere);
tout = piece et sphere;
blox = tout poin plan p1 p0 (p1 plus vy) tol;
bloy = tout poin plan p1 p0 p2 tol;
base = piece poin plan p1 p2 (p1 plus vy) tol;
p13y = p13 plus py;
cp = dall (p0 d 5 p13) (p13 d 5 p13y)
          (p13y d 5 py) (py d 5 p0) plan;
elim tol (piece et cp);
c_p = piece elem appu larg cp;
mesh = tout et blox et bloy et base et c_p;
tass mesh;
opti sauv form 'vl_jrc_inde13.msh';
sauv form mesh;
list (nbno mesh);
list (nbel mesh);
fin;
```

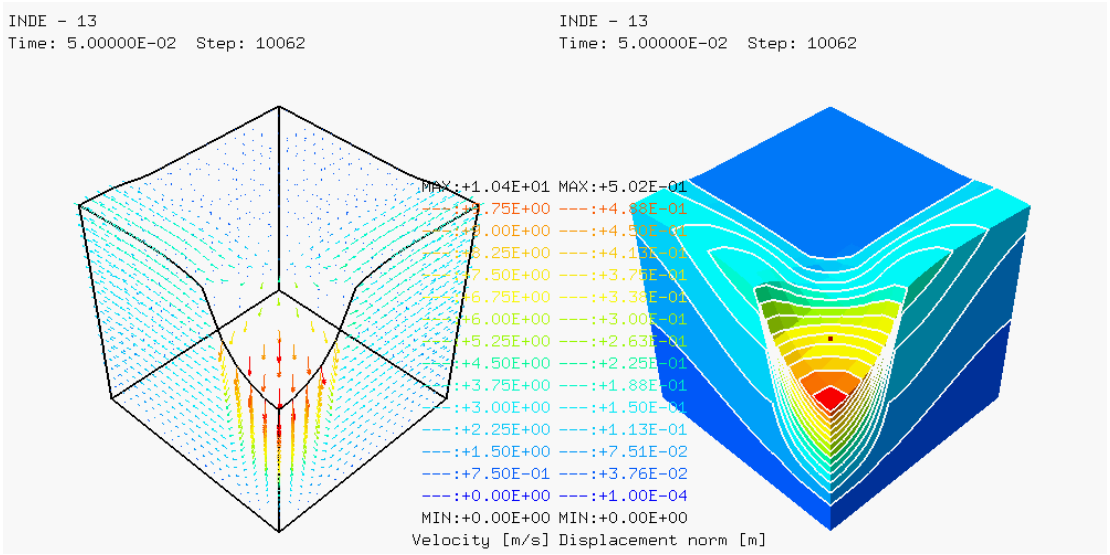
The input file is:

```
INDE - 13
ECHO
!CONV WIN
NONL TRID
CAST mesh
DIME
  PT3L 9262
  CUB8 9361
  PMAT 1
  ZONE 2
TERM
GEOM
   CUB8 piece PMAT sphere
TERM
COMP COUL rose LECT piece TERM
          turq LECT sphere TERM
MATE MASS 1021.02D0
          LECT sphere TERM
     VMIS PARF RO 7800 YOUN 2.1E11 NU 0.3 ELAS 5.E7
          LECT piece TERM
OPTI PINS CNOR NCOL RCEL
LINK COUP
     BLOQ 1 LECT blox base TERM
          2 LECT bloy base TERM
          3 LECT base TERM
     DEPL 3 -1.D0 FONC 1 LECT sphere TERM
     PINB BODY DIAM 1.D0 LECT sphere TERM
          BODY MLEV 4    LECT c_p TERM
FONC 1 TABL 2 0. 0. 2. 20.
INIT VITE 3 -10. LECT sphere TERM
REGI 'r_piece' RESU LECT c_p  TERM
     'r_base'  RESU POIN LECT base TERM
ECRI DEPL VITE FEXT TFRE 0.005
     FICH ALIC TFRE 25.E-5
OPTI CSTA 0.5 LOG 1
CALCUL TINI 0. TFIN 50.E-3
FIN
```

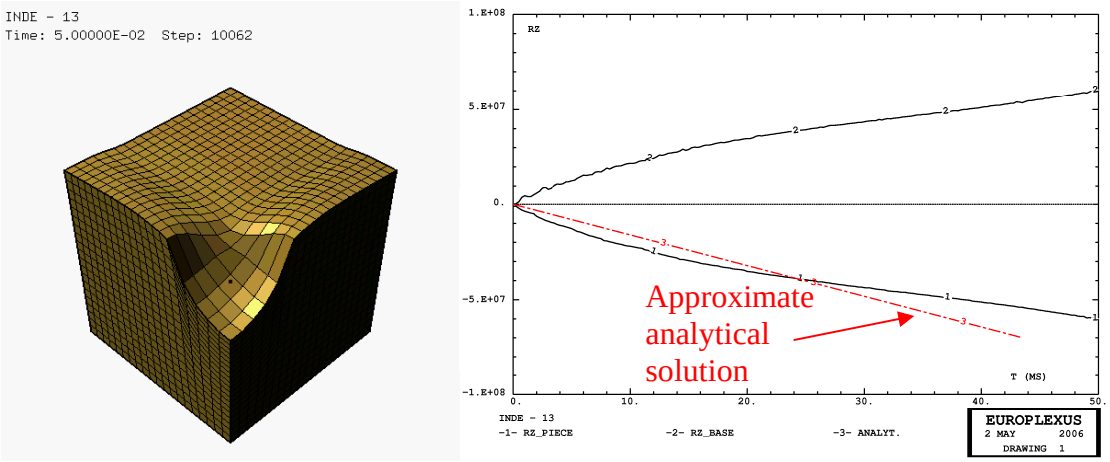
The initial configuration (with parent pinballs shown) and the final configuration) are:



The final velocities and displacement norm:



The final deformed shape and the reaction force are:



TEST14

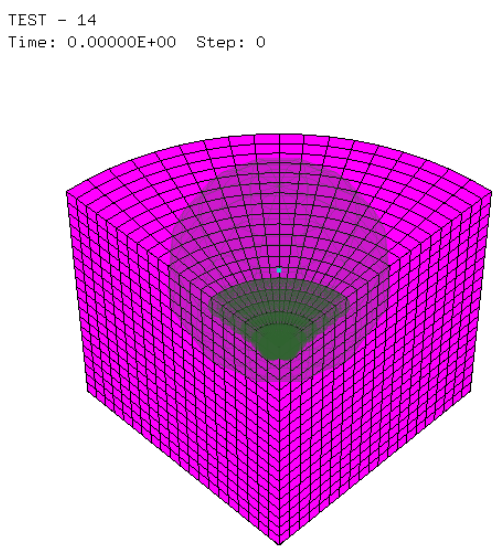
3D solution using an axisymmetric mes (hexahedra and prisms). The model is perfectly axisymmetric. The mesh generation file is:

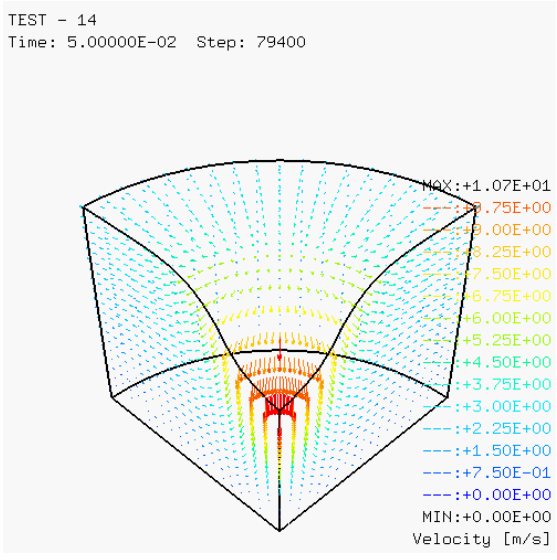
```
*%siz 50
opti echo 0;
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxordpoi.proc';
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxrota3d.proc';
opti echo 1;
opti dime 3 elem cub8;
p0 = 0 0 0;
p1 = 0 0 -1.5;
p2 = 1.5 0 -1.5;
p3 = 1.5 0 0;
pc = 0 0 0.5;
p13 = 0.375 0 0;
vy = 0 1.5 0;
py = 0 0.375 0;
tol = 1.e-5;
c1 = p1 d 20 p2;
ax = p1 d 20 p0;
base ier = pxrota3d c1 18 90.0 ax tol;
oubl ax;
piece = base volu tran 20 (0 0 1.5);
p_cube = piece elem cub8;
p_pris = piece elem pri6;
sphere = manu poi1 pc;
opti trac psc ftra 'test14_msh.ps';
trac cach qual (piece et sphere);
tout = piece et sphere;
blox = tout poin plan p1 p0 (p1 plus vy) tol;
bloy = tout poin plan p1 p0 p2 tol;
c2 = p0 d 5 p13;
ax2 = p0 d 1 pc;
cp ier = pxrota3d c2 18 90.0 ax2 tol;
oubl ax2;
elim tol (piece et cp);
c_p = piece elem appu larg cp;
mesh = tout et blox et bloy et base et c_p;
tass mesh;
opti sauv form 'test14.msh';
sauv form mesh;
list (nbno mesh);
list (nbel mesh);
list (nbel p_pris);
list (nbel p_cube);
fin;
```

The input file is:

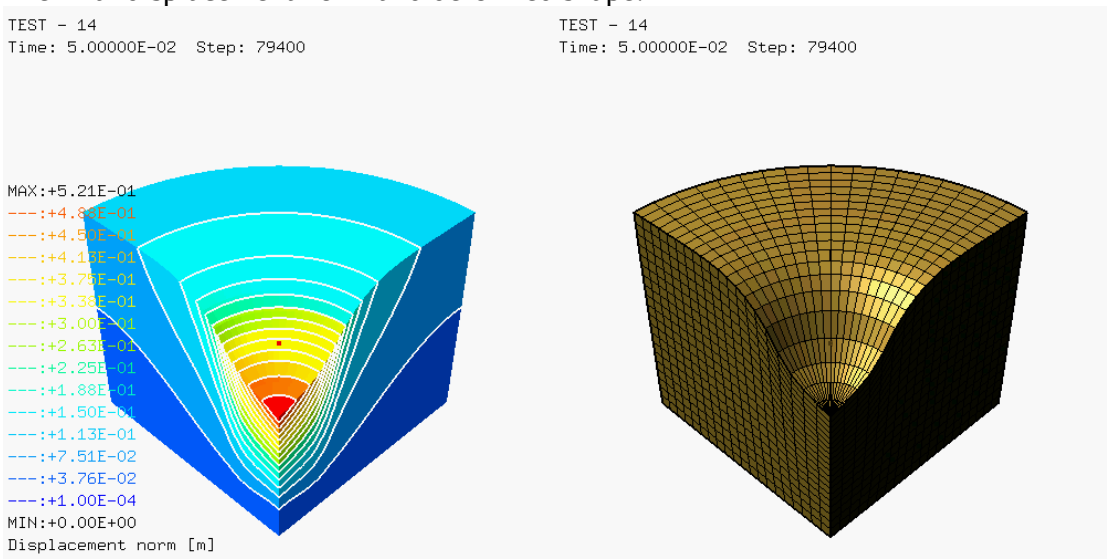
```
TEST - 14
ECHO
!CONV WIN
NONL TRID
CAST mesh
DIME
  PT3L 8002
  PR6  360
  CUB8 8192
  PMAT 1
  ZONE 3
TERM
GEOM
  PR6 p_pris CUB8 p_cube PMAT sphere
TERM
COMP COUL rose LECT piece TERM
          turq LECT sphere TERM
MATE MASS 1021.02D0
          LECT sphere TERM
     VMIS PARF RO 7800 YOUN 2.1E11 NU 0.3 ELAS 5.E7
          LECT piece TERM
OPTI PINS CNOR NCOL RCEL
LINK COUP
     BLOQ 1 LECT blox base TERM
          2 LECT bloy base TERM
          3 LECT base TERM
     DEPL 3 -1.D0 FONC 1 LECT sphere TERM
     PINB BODY DIAM 1.D0 LECT sphere TERM
          BODY MLEV 4    LECT c_p TERM
FONC 1 TABL 2 0. 0. 2. 20.
INIT VITE 3 -10. LECT sphere TERM
REGI 'r_piece' RESU LECT c_p  TERM
     'r_base'  RESU POIN LECT base TERM
ECRI DEPL VITE FEXT TFRE 0.005
     FICH ALIC TFRE 25.E-5
OPTI CSTA 0.5 LOG 1
CALCUL TINI 0. TFIN 50.E-3
FIN
```

The initial configuration (with parent pinballs shown) and the final velocities are:

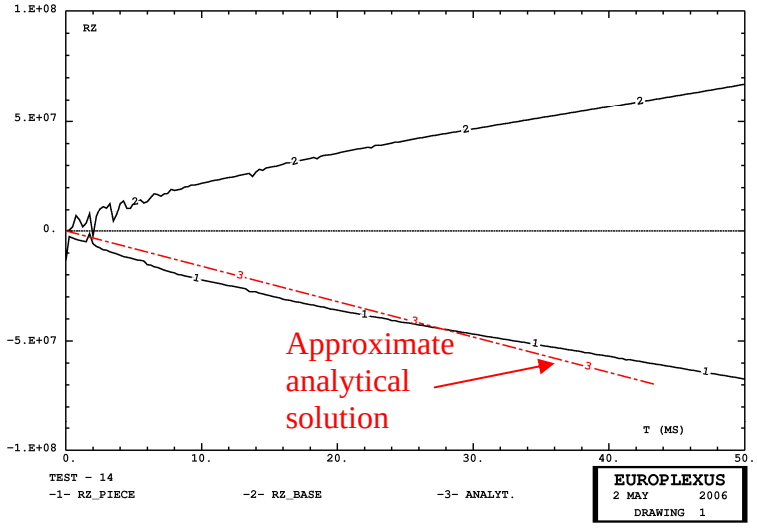




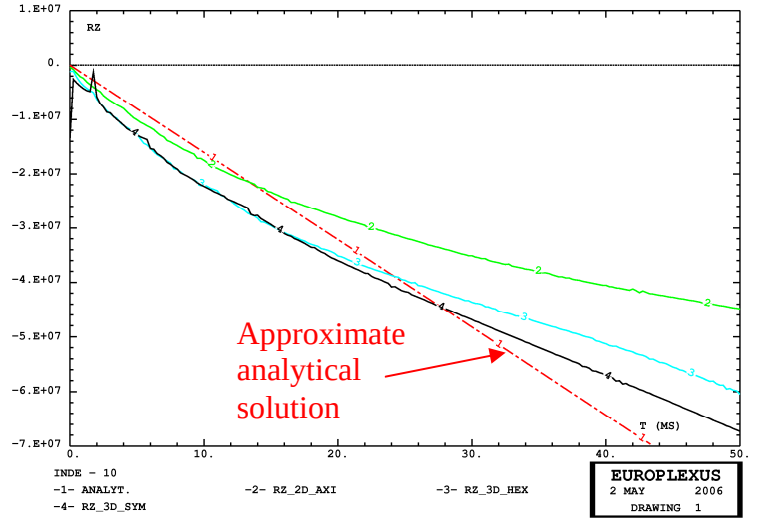
The final displacement norm and deformed shape:



The reaction force is:

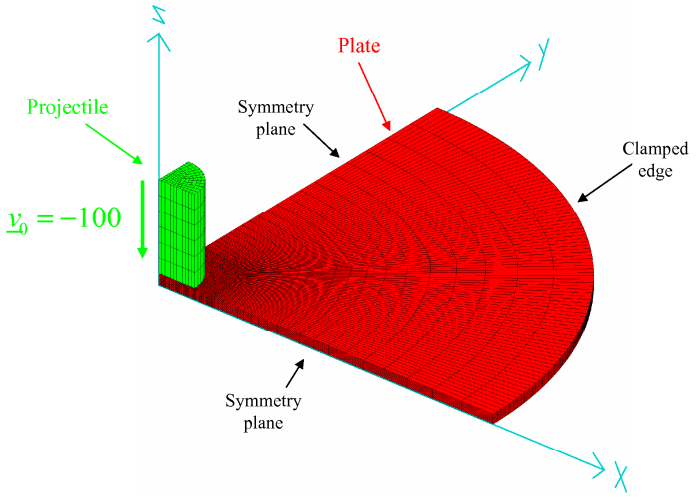


Comparison of all solutions:



Example 7c – Plate perforation (Courtesy of CEA)

- A tough cylindrical projectile impacts a ductile circular plate at the initial velocity of 100 m/s and completely perforates it



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TITLE:
Plate perforation problem.
PROBLEM:
This problem has been studied at CEA. An elastoplastic punch impacts a circular metallic plate at an initial velocity of 100 m/s and perforates it. The punch material is quite resistant and is only slight deformed, while the plate material is rather ductile and undergoes very large plastic strain, culminating into complete failure along the border of the zone in contact with the punch.
MESH:
Although the physical problem is 2D axisymmetric (both in the geometry and in the loading), a full 3D numerical model is assumed for the calculation, made of 55848 hexahedra (CUBE) elements and 62275 nodes. As many as twelve layers of elements are taken across the plate thickness, and the plate mesh is very refined in the region of contact between the plate and the punch, in order to represent plasticity and material failure in a rather accurate manner. Only ¼ of the geometry is modelled, by assuming two symmetry planes in *x*-*z* and *y*-*z*.
MATERIALS:
The VMIS ISOT (Von Mises law with isotropic hardening) material is assigned to the punch, while the plate has the LEM1material (Lemaitre elasto-plastic material with damage). In the latter material, there is coupling between damage and plasticity, represented vy 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: rupoture occures when the damage exceeds a critical value.
BOUNDARY CONDITIONS:
All nodes on the external circumference of the plate are blocked in all three space dimensions, so as to simulate plate clamping around the external perimeter. Two symmetry planes, along *x*-*z* and *y*-*z*, respectively, are specified as already mentioned above. Finally, the GLIS model is used to descrive the contact between the punch extremity and the central part of the plate.
LOADING:
No external loads are assumed.
INITIAL CONDITIONS
The punch has an initial velocity of 100 m/s in the vertical direction towards the plate.
CALCULATION:
The calculation is performed up to 1 ms. At the final time, the punch has completely perforated the plate.

POST-TREATMENT
A detailed animation of the computed results from this calculation is available on the EUROPLEXUS Consortium Web site.

Numerical Solutions

PERF01

3D solution (1/4 model). The mesh generation file is:

```
*%siz 300
*
opti echo 1;
OPTI DIME 3 ELEM CUB8 ;
OPTI SORT  'perf01.msh' ;
opti trac psc ftra 'perf01_mesh.ps';
*
*++++++  maillage de la plaque
*
REP1 = @REPERE (0. 0. 0.) (prog 0.3 0.3 0.15) turq ;
e_plaq   = 0.006 ;
r_plaq   = 0.225 ;
n_plaq   = 50 ;
n_couch1 = 12 ;
h_poin   = (e_plaq + 0.050) ;
r_poin   = 0.024 ;
n_poin   = 6 ;
n_couch2 = 6 ;
o_0  =                    0.                      0.  0. ;
p1_0e =                 r_plaq                    0.  0. ;
p2_0e =      (r_plaq*(cos 45))      (r_plaq*(sin 45))  0. ;
p3_0e =                   0.                  r_plaq  0. ;
p1_0i =             (r_plaq/6)                    0.  0. ;
p2_0i = ((1.2*r_plaq/6)*(cos 45))  ((1.2*r_plaq/6)*(sin 45))  0. ;
p3_0i =                   0.                (r_plaq/6)  0. ;
c12_0e = CERC n_plaq p1_0e o_0 p2_0e ;
c23_0e = CERC n_plaq p2_0e o_0 p3_0e ;
c13_0e = c12_0e ET c23_0e ;
d01_0i = o_0   DROI n_plaq p1_0i ;
d12_0i = p1_0i DROI n_plaq p2_0i ;
d23_0i = p2_0i DROI n_plaq p3_0i ;
d30_0i = p3_0i DROI n_plaq o_0 ;
*
* maillage du centre
*
s_centr = DALLER d01_0i d12_0i d23_0i d30_0i PLAN ;
v_plaq  = 0. 0. e_plaq ;
v_centr = (s_centr VOLU n_couch1 TRAN v_plaq) coul roug ;
* maillage de la partie extérieure
c13_0i  = d12_0i ET d23_0i ;
s_exter = c13_0i REGLE 'DINI' 0.002 'DFIN' 0.02 c13_0e ;
v_exter = (s_exter VOLU n_couch1 TRAN v_plaq) coul roug ;
plaq = v_centr et v_exter  ;
plaq = plaq coul roug ;
elim plaq 0.0001 ;
trac (plaq et rep1) face ;
*
*++++++  maillage du poinçon plat
*
o_3  =                    0.                      0.  (e_plaq + 0.001) ;

p1_3e =                 r_poin                    0.  (e_plaq + 0.001) ;
p2_3e =      (r_poin*(cos 45))      (r_poin*(sin 45))  (e_plaq + 0.001) ;
p3_3e =                   0.                  r_poin  (e_plaq + 0.001) ;

p1_3i =             (r_poin/2)                    0.  (e_plaq + 0.001) ;
p2_3i = ((r_poin/2)*(cos 45))  ((r_poin/2)*(sin 45))  (e_plaq + 0.001) ;
p3_3i =                   0.                (r_poin/2)  (e_plaq + 0.001) ;

c12_3e = CERC (n_poin) p1_3e o_3 p2_3e ;
c23_3e = CERC (n_poin) p2_3e o_3 p3_3e ;
c13_3e = c12_3e ET c23_3e ;

d01_3i = o_3   DROI (n_poin) p1_3i ;
d12_3i = p1_3i DROI (n_poin) p2_3i ;
d23_3i = p2_3i DROI (n_poin) p3_3i ;
d30_3i = p3_3i DROI (n_poin) o_3 ;

s0123_3i = DALLER d01_3i d12_3i d23_3i d30_3i PLAN ;

c13_3i = d12_3i ET d23_3i ;
s123_3 = c13_3i REGLE (n_poin) c13_3e ;

surf_3 = s0123_3i ET s123_3 ;

v_poin = 0. 0. h_poin ;
poinc  = surf_3 VOLU n_couch2 TRAN v_poin ;
poinc  = poinc COUL VERT ;
elim poinc 0.0001 ;

lig1    = (r_plaq 0. 0.) droi n_couch1 (r_plaq 0. e_plaq) ;
b_plaq  = rota lig1 n_plaq 90. (0. 0. 0.) (0. 0. 1.) ;

allmesh =  plaq et poinc et b_plaq ;
elim allmesh 0.0001 ;

TRAC (plaq et poinc et rep1) CACH face ;

pts_xoz = allmesh POIN PLAN (0. 0. 0.) (1. 0. 0.) (0. 0. 1.) 0.0005 ;
pts_zoy = allmesh POIN PLAN (0. 0. 0.) (0. 1. 0.) (0. 0. 1.) 0.0005 ;

sort allmesh ;

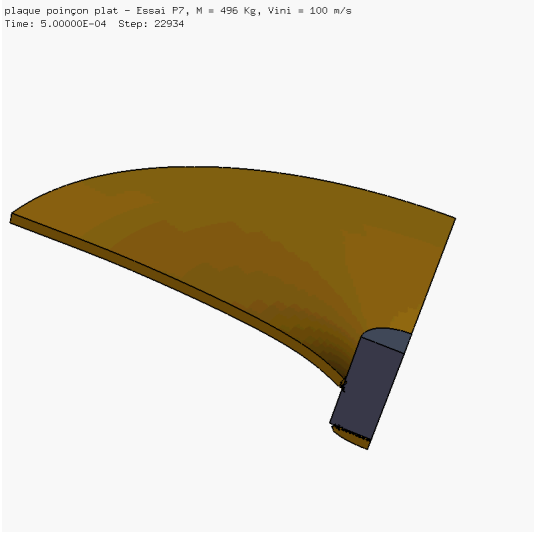
mess 'nb de noeuds =' (nbno allmesh) ;
mess 'nb d elements =' (nbel allmesh) ;
mess 'volume du poinçon =' (mesure poinc volu) 'm3';

fin;
```

The input file is:

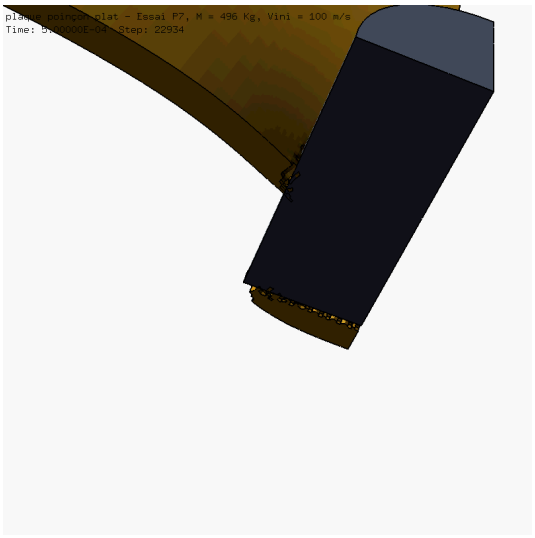
```
plaque poinçon plat - Essai P7, M = 496 Kg, Vini = 100 m/s
*
ECHO
 conv win
*
TRID NONL LAGC FAIL
*
GIBI allmesh
*
DIME
  PT3L 62275 CUBE 55848 ZONE 1
  BLOQ 1989
  LIAI 14661
  GLIS 1 200000
  ECRO 778632
  SYME 2
TERM
*
GEOM CUBE v_centr v_exter poinc TERM
*
MATE VMIS ISOT RO 4926245.4 YOUN 2.E13  NU 0.3  ELAS 300.E6
          TRAC 2
                    0.300E+09  1.5E-05
                    0.500E+09  45E-02
          LECT poinc TERM
     LEM1 RO 7850 YOUN 174410.E6 NU 0.3
          ELAS 166.5E6 EPSD 0. S0 16390295.E+12 DC 0.01 TRAC 96
             .1665E+09    .954704E-03
             .1764E+09    .1017E-02
             .2228E+09    .1374E-02
             .2597E+09    .1830E-02
             .2824E+09    .2404E-02
             .2952E+09    .3050E-02
             .3037E+09    .3763E-02
             .3090E+09    .4499E-02
             .3146E+09    .5263E-02
             .3183E+09    .6020E-02
             .3214E+09    .6766E-02
             .3254E+09    .7551E-02
             .3284E+09    .8324E-02
             .3309E+09    .9096E-02
             .3339E+09    .9870E-02
             .3365E+09    .1065E-01
             .3385E+09    .1142E-01
             .3406E+09    .1219E-01
             .3428E+09    .1297E-01
             .3451E+09    .1375E-01
             .3476E+09    .1453E-01
             .3486E+09    .1530E-01
             .3505E+09    .1578E-01
             .3545E+09    .1731E-01
             .3723E+09    .2502E-01
             .3873E+09    .3263E-01
             .4015E+09    .4008E-01
             .4161E+09    .4740E-01
             .4301E+09    .5461E-01
             .4441E+09    .6172E-01
             .4576E+09    .6875E-01
             .4700E+09    .7566E-01
             .4821E+09    .8246E-01
             .4954E+09    .8921E-01
             .5066E+09    .9584E-01
             .5189E+09    .1024E+00
             .5288E+09    .1089E+00
             .5407E+09    .1153E+00
             .5513E+09    .1216E+00
             .5620E+09    .1279E+00
             .5720E+09    .1341E+00
             .5816E+09    .1402E+00
             .5918E+09    .1462E+00
             .6004E+09    .1522E+00
             .6104E+09    .1582E+00
             .6246E+09    .1690E+00
             .6318E+09    .1752E+00
             .6411E+09    .1814E+00
             .6494E+09    .1875E+00
             .6581E+09    .1937E+00
             .6682E+09    .1998E+00
             .6767E+09    .2058E+00
             .6848E+09    .2118E+00
             .6932E+09    .2178E+00
             .7021E+09    .2237E+00
             .7096E+09    .2296E+00
             .7159E+09    .2355E+00
             .7256E+09    .2413E+00
             .7330E+09    .2471E+00
             .7421E+09    .2528E+00
             .7491E+09    .2586E+00
             .7564E+09    .2643E+00
             .7634E+09    .2700E+00
             .7721E+09    .2756E+00
             .7800E+09    .2812E+00
             .7865E+09    .2867E+00
             .7922E+09    .2923E+00
             .8006E+09    .2978E+00
             .8098E+09    .3033E+00
             .8159E+09    .3087E+00
             .8228E+09    .3142E+00
             .8287E+09    .3195E+00
             .8700E+09    .3500E+00
             .9338E+09    .4000E+00
             .1051E+10    .5000E+00
             .1188E+10    .6300E+00
             .1312E+10    .7600E+00
             .1427E+10    .8900E+00
             .1534E+10    .1020E+01
             .1634E+10    .1150E+01
             .1730E+10    .1280E+01
             .1821E+10    .1410E+01
             .1908E+10    .1540E+01
             .1992E+10    .1670E+01
             .2072E+10    .1800E+01
             .2150E+10    .1930E+01
             .2226E+10    .2060E+01
             .2299E+10    .2190E+01
             .2371E+10    .2320E+01
             .2440E+10    .2450E+01
             .2508E+10    .2580E+01
             .2574E+10    .2710E+01
             .2639E+10    .2840E+01
             .2702E+10    .2970E+01
             .2764E+10    .3100E+01
             .2825E+10    .3230E+01
          LECT v_centr v_exter TERM
*
LIAI BLOQ 123 LECT b_plaq TERM
     GLIS 1 MAIT LECT v_centr TERM
            ESCL LECT poinc TERM
     CONT SPLA NX  0 NY -1. NZ 0. LECT pts_xoz TERM
          SPLA NX -1 NY  0. NZ 0. LECT pts_zoy TERM
*
INIT VITE 3 -100 LECT poinc TERM
          3    0 LECT plaq  TERM
*
ECRI TFRE 1.E-6 NOPO NOEL
     FICH ALIC TFRE 1.E-5
     FICH K200 TFRE 10.E-5
          POIN TOUS CHAM
OPTI csta 0.5
     log 1
CALC TINI 0. TEND 100.E-5 NMAX 999999
FIN
```

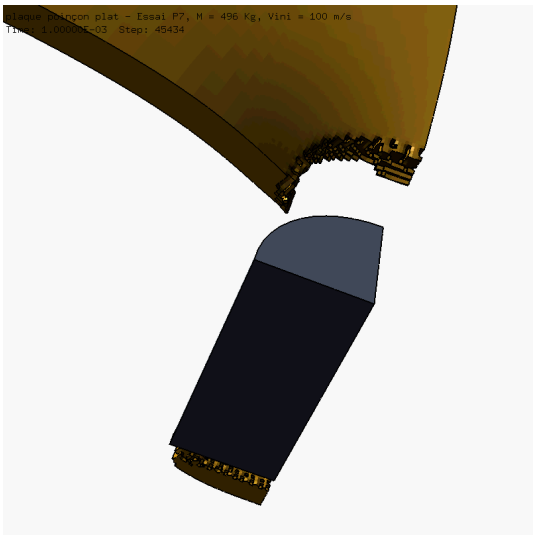
The configurations at 0.5 ms (half-time) and 1.0 ms (final time) are:



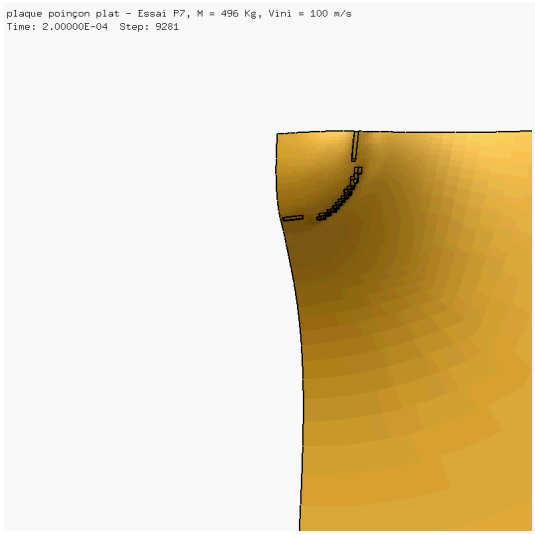


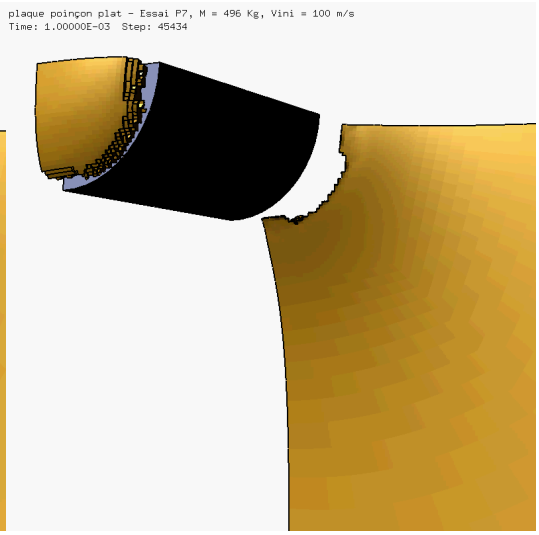
The same configurations, more detailed:



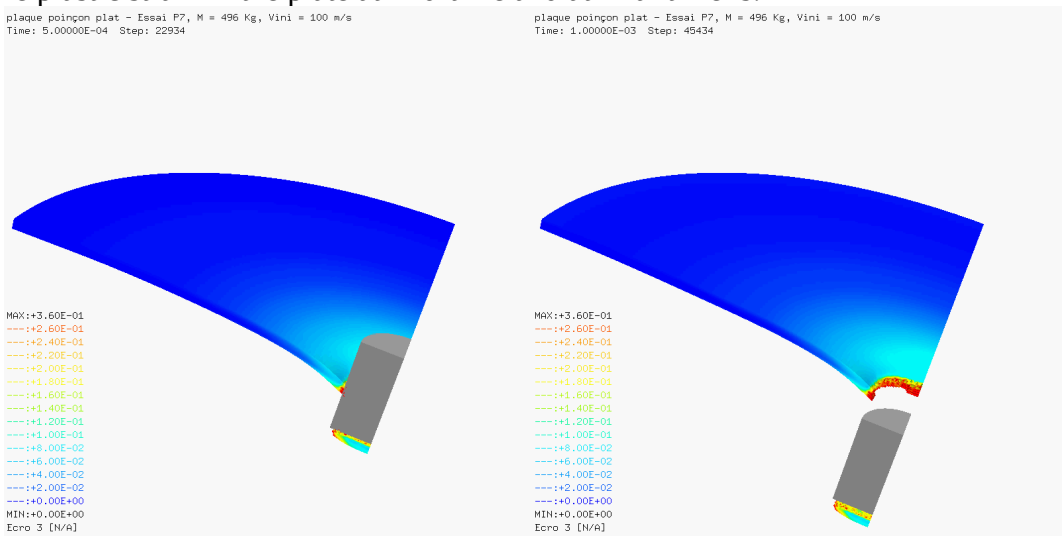


The first ruptured elements appear at time 0.2 ms (seen from below) and the final configuration:

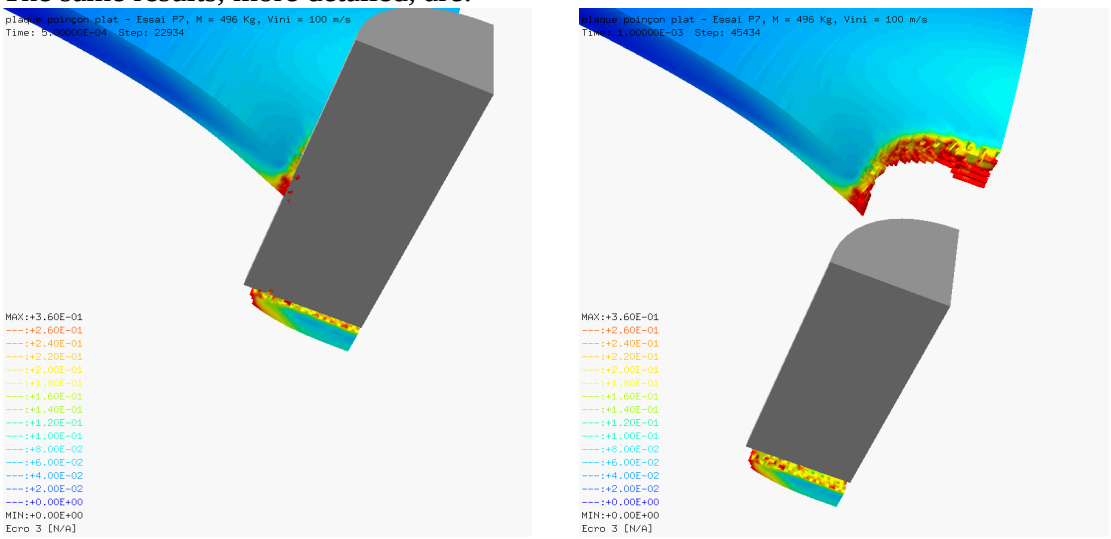




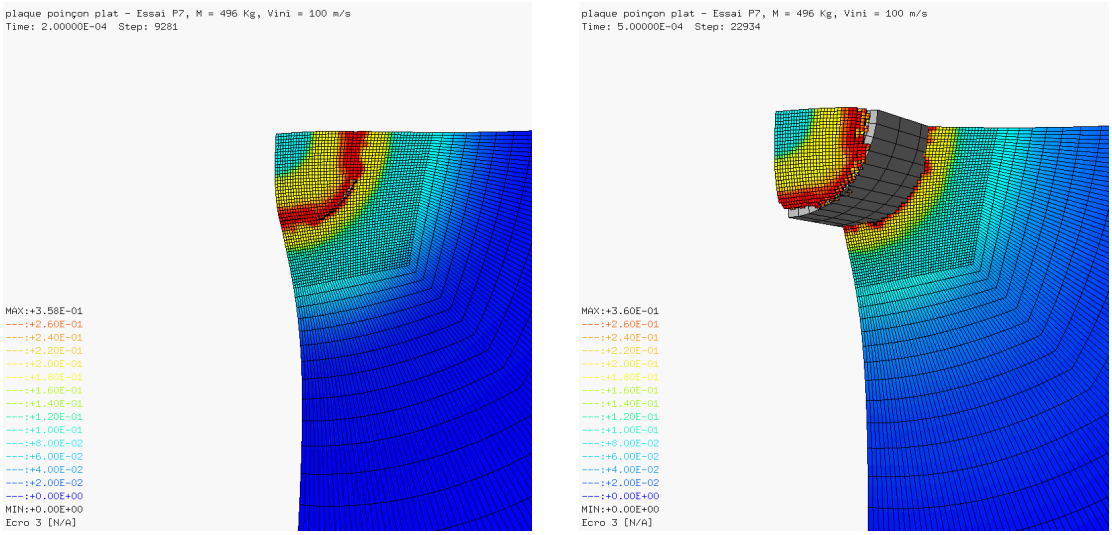
The plastic strain in the plate at mid-time and at final time is:



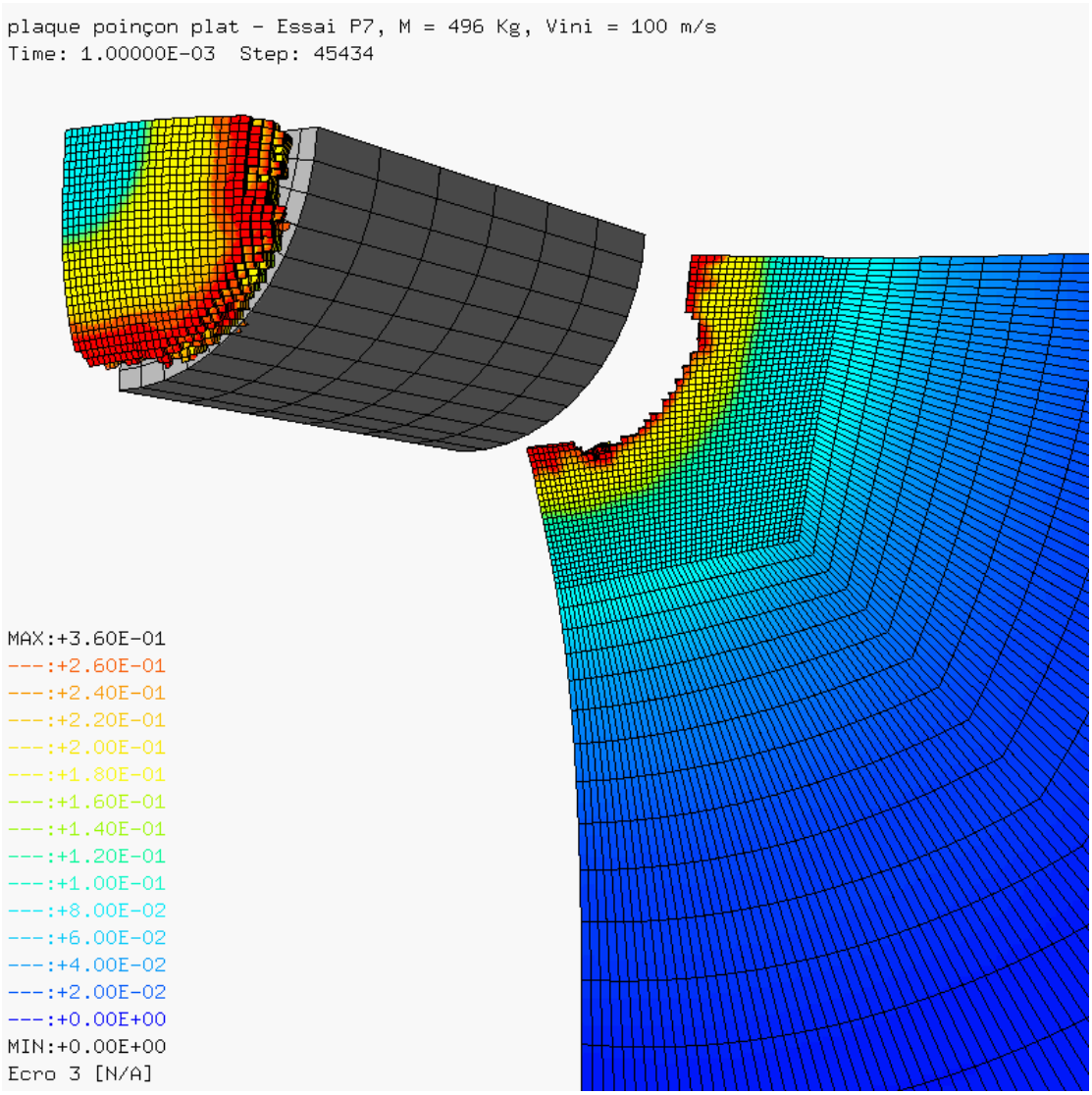
The same results, more detailed, are:



The plastic strains and the mesh, seen from below, are shown at time 0.2 ms when the first elements fail and the same at 0.5 ms:

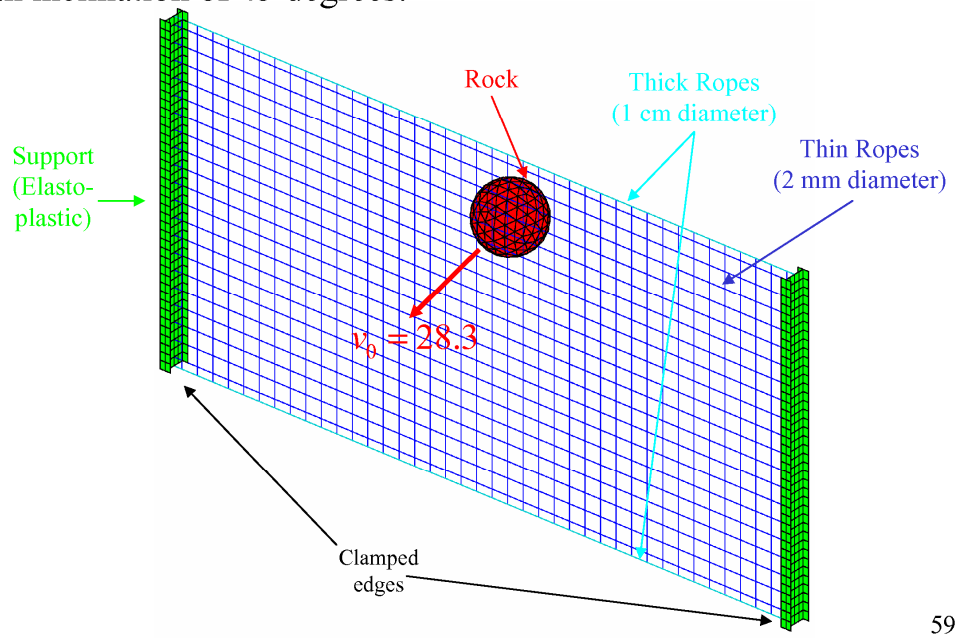


The final view is:



Example 7d – Falling Rock Catcher

- A falling rock catcher of 6 m by 3 m is hit by a spherical rock of 0.6 m diameter and a mass of 283 kg, at a speed of 100 km/h (28.3 m/s) and with an inclination of 45 degrees:



59

TITLE:
Falling rock catcher.

PROBLEM:
A rather rigid falling rock impacts a catcher made of an elasto-plastic net supported by two double-T shaped structures at the extremities. The net is 6 m and 3 m high. The rock has a diameter of 60 cm and a mass of 283 kg. Its initial velocity is 100 km/h (28.3 m/s) and it impacts the catcher at the position shown above (3/4 of height, centred horizontally) at an angle of 45 degrees. The net cables have a diameter of 2 mm, except the lower and higher horizontal cables which have a diameter of 1 cm. The thickness of the supports is 5 mm.

MESH:
Specialized 3D cable elements (FUN3) are used to discretize the net, 6720 elements altogether. The two supports are modelled by 640 shell elements (Q4GR). The falling mass is modelled by a material point.

MATERIALS:
The VM23 (Von Mises law with isotropic hardening) material is assigned to the supports, while the cables use the specialized FUNE material, characterized by no resistance in compression and an elasto-plastic behaviour in traction. Two solutions are presented, corresponding to rupture strains of 50% and 5%, respectively.

BOUNDARY CONDITIONS:

The two supports are clamped at the base. Contact between the falling mass and the net is modelled by pinballs, without taking into account any friction.

LOADING:
No external loads are assumed.

INITIAL CONDITIONS
The falling rock has an initial velocity of 100 km/h at an angle of 45 degrees towards the net.

CALCULATION:
The calculation is performed up to 100 ms. At the final time, the falling rock has completely perforated the net.

POST-TREATMENT
A detailed animation of the computed results from this calculation is available on the EUROPLEXUS Consortium Web site.

Numerical Solutions

NETCF6

Solution with a cables rupture strain of 50%. The mesh generation file is:

```
*%siz 300
*
opti echo 1;
opti dime 3 elem cub8;
opti sauv form 'netcf6.msh';
opti trac psc ftra 'netcf6_mesh.ps';
*
p0 = 0 0 0; tol = 0.001;
lx = 6.0; lz  = 3.0;
nx = 40; nz = 20;
fx = 4; fz = 4;
dx = lx / nx;
dz = lz / nz;
vx = dx 0 0; vz = 0 0 dz;
pa = (dx/2) 0 0;
pb = (dx/2) 0 lz;
cv = pa d (fz*nz) pb;
pc = 0 0 (dz/2);
pd = lx 0 (dz/2);
ch = pc d (fx*nx) pd;
clow = (ch plus (0 0 (0-dz/2))) coul turq;
chig = (clow plus (0 0 lz)) coul turq;
*
repe loopx nx;
  si (ega &loopx 1);
    netv = cv;
  sinon;
    cv = cv plus vx;
    netv = netv et cv;
  finsi;
fin loopx;
netv = netv coul bleu;
*
repe loopz nz;
  si (ega &loopz 1);
    neth = ch;
  sinon;
    ch = ch plus vz;
    neth = neth et ch;
  finsi;
fin loopz;
neth = neth coul bleu;
*
net = netv et neth et clow et chig;
elim tol net;
*
*trac qual net;
*net1 = chan 'POI1' net;
*trac qual net1;
list (nbel net);
list (nbno net);
*
tx = 0.1; ty = 0.2;
ta = (0-tx/2) (0-ty/2) 0;
tb = (  tx/2) (0-ty/2) 0;
tc = 0        (0-ty/2) 0;
td = (0-tx/2) (  ty/2) 0;
te = (  tx/2) (  ty/2) 0;
tf = 0        (  ty/2) 0;
ntx = 1; nty = 2;
t1 = ta d ntx tc d ntx tb;
t2 = td d ntx tf d ntx te;
t3 = tc d nty p0 d nty tf;
tt = t1 et t2 et t3;
elim tol tt;
supp1 = (tt tran (2*nz) (0 0 lz)) coul vert;
supp2 = (supp1 plus (lx 0 0)) coul vert;
supp = supp1 et supp2;
list (nbel supp);
list (nbno supp);
stru = supp et net;
elim tol stru;
*trac cach face stru;
list (nbel stru);
list (nbno stru);
*
bloq = supp poin plan p0 (1 0 0) (0 1 0) tol;
list (nbno bloq);
*trac bloq;
*
rfall = 0.3;
pfall = (lx/2) (rfall) (3*lz/4);
list pfall;
fall = (manu 'POI1' pfall) coul roug;
*trac cach face (stru et fall);
*
fac = 1.5;
*rfall2 = fac*rfall*rfall;
rfall2 = fac*rfall;
xf yf zf = coor pfall;
n = nbel net;
ni = 0;
repe loop3 n;
  ei = net elem &loop3;
  xb yb zb = coor (bary ei);
  dx = xb - xf;
* dz = zb - zf;
* d2 = (dx*dx) + (dz*dz);
  si (abs(dx) < rfall2);
* si (d2 < rfall2);
    ni = ni + 1;
    si (ega ni 1);
      neti = ei;
    sinon;
      neti = neti et ei;
    finsi;
  finsi;
fin loop3;
*neti = neti coul roug;
list ni;
*trac qual neti;
neto = diff net neti;
*trac qual neto;
trac face cach (neti et neto et supp et fall);
*
mesh = supp et neti et neto et fall et bloq;
tass mesh;
sauv form mesh;
*
fin;
```

The input file is:

```
NETCF6
*------------------------------------------------------------------------
ECHO
 conv win
CAST mesh
*-------------------------------------------------------------Problem type
TRID NONL LAGR FAIL
*-------------------------------------------------------------Dimensioning
DIME
   PT6L 738 PT3L 5859 FUN3 6720 PMAT 1 Q4GR 640 ZONE 3
TERM
*--------------------------------------------------------------------Geometry
GEOM FUN3 net PMAT fall Q4GR supp TERM
*-----------------------------------------------------Geometric Complements
COMP EPAI 3.14E-6 LECT netv neth TERM ! 2 mm diameter
     EPAI 7.85E-5 LECT clow chig TERM ! 1 cm diameter
     EPAI 0.6     LECT fall TERM ! only for graphical representation
     EPAI 0.005   LECT supp TERM      ! 5 mm thickness
*-------------------------------------------------------------Material data
MATE FUNE RO 8000. YOUN 2.0E11 NU 0.3 ERUP 0.5
          ELAS 0.440D9
          TRAC 5 0.440D9 2.200D-3 0.735D9 0.156D0
                 0.900D9 0.283D0 1.077D9 0.475D0 1.142D9 0.600D0
          LECT net TERM
```

```
     MASS 282.75 LECT fall TERM
     VM23 RO 8000. YOUN 1.95D11 NU 0.3 ELAS 1.95E+8
          TRAC 4 1.95E+8 .001 2.16E+8 .005 2.6E+8 .02 2.6E8 10.
          LECT supp TERM
*-------------------------------------------------------Boundary conditions
LINK COUP BLOQ 123456 LECT bloq TERM
     PINB BODY MLEV 0   LECT neti TERM
          BODY DIAM 0.6 LECT fall TERM
*-------------------------------------------------------Initial conditions
INIT VITE 2 -20 LECT fall TERM ! v_0 = about 100 km/h
     VITE 3 -20 LECT fall TERM
*-------------------------------------------------------------------Outputs
ECRI VITE TFRE 100.E-3
     FICH ALIC      TFRE 1.E-3
*-------------------------------------------------------------------Options
OPTI NOTE
     LOG 1
*-----------------------------------------------Transient calculation
CALC TINI 0 TFIN 0.100
*=================================================================ANIMATION
PLAY
CAME   1 EYE   8.41798E+00 -6.59217E+00  1.20611E+01
!        Q     8.68252E-01  3.25861E-01  9.16021E-02  3.62715E-01
         VIEW -3.95456E-01  4.99408E-01 -7.70848E-01
         RIGH  7.20094E-01  6.89555E-01  7.73214E-02
         UP   -5.70157E-01  5.24506E-01  6.32309E-01
         FOV   2.48819E+01
!CAME   2 EYE   4.76084E+00 -1.97370E+00  4.93234E+00
!!       Q     8.68252E-01  3.25861E-01  9.16021E-02  3.62715E-01
!        VIEW -3.95456E-01  4.99408E-01 -7.70848E-01
!        RIGH  7.20094E-01  6.89555E-01  7.73214E-02
!        UP   -5.70157E-01  5.24506E-01  6.32309E-01
!        FOV   2.48819E+01
CAME   2 EYE   8.34687E+00 -4.82530E+00  4.41693E+00
!        Q     7.83098E-01  4.84674E-01  2.27182E-01  3.16603E-01
         VIEW -6.62709E-01  6.15242E-01 -4.26958E-01
         RIGH  6.96303E-01  7.16080E-01 -4.89126E-02
         UP   -2.75643E-01  3.29707E-01  9.02948E-01
         FOV   2.48819E+01

!Sequence 01: Title (30 frames)
!------------------------------
scen geom navi free
     colo pape
titl tit1 'EUROPLEXUS (C) Animation'
     tit2 'Falling Rock Catcher'
     tit3 'Author: F. Casadei'
sler cam1 1        nfra 30
trac offs fich avi      nocl nfto 905 fps 10 kfre 10 comp -1 rend

!Sequence 02: Title (30 frames)
!------------------------------
titl tit2 'Geometry and Pinballs'
sler cam1 1        nfra 30
trac offs fich avi cont nocl                                    rend

!Sequence 03: Still from cam1 (15 frames)
!----------------------------------------
scen geom navi free
          line sfre !heou
          poin sphp
         !pinb pare cdes
     colo pape
     lima on
sler cam1 1        nfra 15
trac offs fich avi cont nocl                                    rend

!Sequence 04: Still from cam1 with pinballs (15 frames)
!-----------------------------------------------------
scen geom navi free
          line sfre !heou
         !poin sphp
          pinb pare cdes
     colo pape
     lima on
sler cam1 1        nfra 15
trac offs fich avi cont nocl                                    rend

!Sequence 05: Slerping from cam1 to cam2 (30 frames)
!---------------------------------------------------
scen geom navi free
          line sfre !heou
         !poin sphp
          pinb pare cdes
     colo pape
     lima on
sler cam1 1 cam2 2 nfra 30
trac offs fich avi cont nocl                                    rend

!Sequence 06: Transient (100 frames)
!-----------------------------------
sler cam1 2        nfra 1
freq 0 tfre 1.e-3
gotr loop 99 offs fich avi cont nocl obje nfai lect tous term rend
go
trac offs fich avi cont nocl obje nfai lect tous term              rend

ENDPLAY
*=========================================================POST-TREATMENT
SUIT
NETCF6 POST
*-------------------------------------------------------------------------
ECHO
 conv win
*
RESU ALIC GARD PSCR
*
OPTI PRIN
*
SORT VISU NSTO 1
*=================================================================ANIMATION
PLAY
CAME   1 EYE   8.41798E+00 -6.59217E+00  1.20611E+01
!        Q     8.68252E-01  3.25861E-01  9.16021E-02  3.62715E-01
         VIEW -3.95456E-01  4.99408E-01 -7.70848E-01
         RIGH  7.20094E-01  6.89555E-01  7.73214E-02
         UP   -5.70157E-01  5.24506E-01  6.32309E-01
         FOV   2.48819E+01
CAME   2 EYE   8.34687E+00 -4.82530E+00  4.41693E+00
!        Q     7.83098E-01  4.84674E-01  2.27182E-01  3.16603E-01
         VIEW -6.62709E-01  6.15242E-01 -4.26958E-01
         RIGH  6.96303E-01  7.16080E-01 -4.89126E-02
         UP   -2.75643E-01  3.29707E-01  9.02948E-01
         FOV   2.48819E+01
CAME   3 EYE   1.19987E+00 -1.01152E+00  8.34224E-01
!        Q     7.57665E-01  5.12725E-01  2.51753E-01  3.15716E-01
         VIEW -7.05240E-01  6.17983E-01 -3.47466E-01
         RIGH  6.73888E-01  7.36574E-01 -5.77375E-02
         UP   -2.20254E-01  2.74872E-01  9.35913E-01
         FOV   2.48819E+01

!Sequence 07: Title (30 frames)
!------------------------------
scen geom navi free
     colo pape
titl tit2 'Geometry only'
sler cam1 1        nfra 30
trac offs fich avi cont nocl                                    rend

!Sequence 08: Transient from cam1 (101 frames)
!--------------------------------------------
scen geom navi free
          line sfre heou
          face sbac
          poin sphp
         !pinb pare cdes
     colo pape
     lima on
sler cam1 1        nfra 1
trac offs fich avi cont nocl
     obje nfai lect tous term rend
gotr loop 99 offs fich avi cont nocl
     obje nfai lect tous term rend
go
trac offs fich avi cont nocl
     obje nfai lect tous term rend
ENDPLAY
*=================================================================
     VISU NSTO 1
*=================================================================
PLAY

!Sequence 09: Title (30 frames)
!------------------------------
scen geom navi free
     colo pape
titl tit2 'Velocities'
sler cam1 1        nfra 30
trac offs fich avi cont nocl rend

!Sequence 10: Transient from cam1 (101 frames)
!--------------------------------------------
scen geom navi free
          line sfre heou
          face sbac
          poin sphp
         !pinb pare cdes
     colo pape
     lima on
     VECT SCCO FIEL VITE SCAL USER PROG 2 PAS 2 28 TERM
     text vsca
sler cam1 1        nfra 1
trac offs fich avi cont nocl
     obje nfai lect tous term rend
gotr loop 99 offs fich avi cont nocl
     obje nfai lect tous term rend
go
trac offs fich avi cont nocl
     obje nfai lect tous term rend
ENDPLAY
*=================================================================
     VISU NSTO 1
*=================================================================
PLAY

!Sequence 11: Title (30 frames)
!------------------------------
scen geom navi free
     colo pape
titl tit2 'Strain in Cables'
sler cam1 1        nfra 30
trac offs fich avi cont nocl rend

!Sequence 12: Transient from cam1 (101 frames)
!--------------------------------------------
scen geom navi free
          line sfre heou
          face sbac
          poin sphp
         !pinb pare cdes
     colo pape
     lima on
     ISO  FILL FIEL ECRO 1 SCAL USER PROG 1.E-2 PAS 1.E-2 14.E-2 TERM
               SUPP LECT net TERM
     text isca
sler cam1 1        nfra 1
trac offs fich avi cont nocl
     obje nfai lect tous term rend
gotr loop 99 offs fich avi cont nocl
     obje nfai lect tous term rend
go
trac offs fich avi cont nocl
     obje nfai lect tous term rend
ENDPLAY
*=================================================================
     VISU NSTO 1
*=================================================================
PLAY

!Sequence 13: Title (30 frames)
!------------------------------
scen geom navi free
     colo pape
titl tit2 'Hardening in Supports'
sler cam1 1        nfra 30
trac offs fich avi cont nocl rend

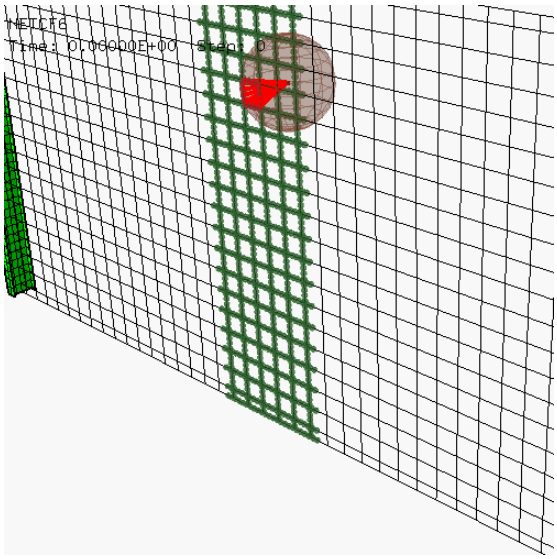
!Sequence 14: Transient from cam1 (101 frames)
!--------------------------------------------
scen geom navi free
          line sfre heou
          face sbac
          poin sphp
          !pinb pare cdes
     colo pape
     lima on
     ISO  FILL FIEL ECRO 7 SCAL USER PROG 1.95E8 PAS 0.05E8 2.6E8 TERM
               SUPP LECT supp TERM
     text isca
sler cam1 1        nfra 1
trac offs fich avi cont nocl
     obje nfai lect tous term rend
gotr loop 99 offs fich avi cont nocl
     obje nfai lect tous term rend
go
trac offs fich avi cont nocl
     obje nfai lect tous term rend
ENDPLAY
*=================================================================
     VISU NSTO 1
*=================================================================
PLAY

!Sequence 15: Title (30 frames)
!------------------------------
scen geom navi free
     colo pape
titl tit2 'Zoom on Support 1'
sler cam1 1        nfra 30
trac offs fich avi cont nocl rend

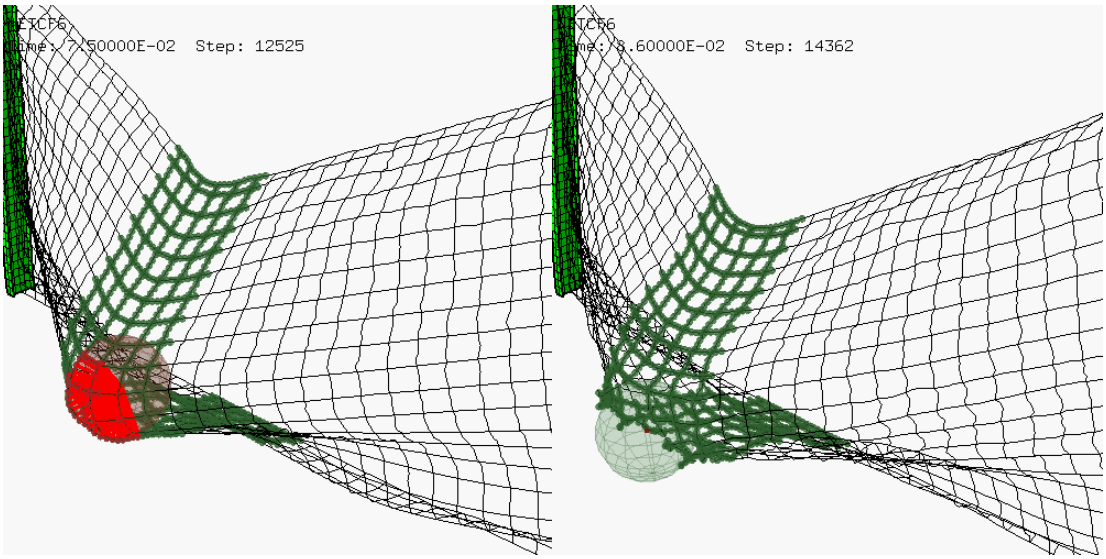
!Sequence 16: Slerp from cam1 to cam3 (30 frames)
!-----------------------------------------------
scen geom navi free
          line heou sfre
          face sbac
          poin sphp
         !pinb cdes
     colo pape
     lima on
sler cam1 1 cam2 3 nfra 30
trac offs fich avi cont nocl rend

!Sequence 17: Transient from cam3 (101 frames)
!--------------------------------------------
scen geom navi free
          line heou sfre
          face sbac
          poin sphp
         !pinb cdes
     colo pape
     lima on
     ISO  FILL FIEL ECRO 7 SCAL USER PROG 1.95E8 PAS 0.05E8 2.6E8 TERM
               SUPP LECT supp1 TERM
     text isca
sler cam1 3        nfra 1
trac offs fich avi cont nocl
     obje lect supp1 net term rend
gotr loop 99 offs fich avi cont nocl
     obje lect supp1 net term rend
go
trac offs fich avi cont
     obje lect supp1 net term rend
ENDPLAY
*=================================================================
FIN
```

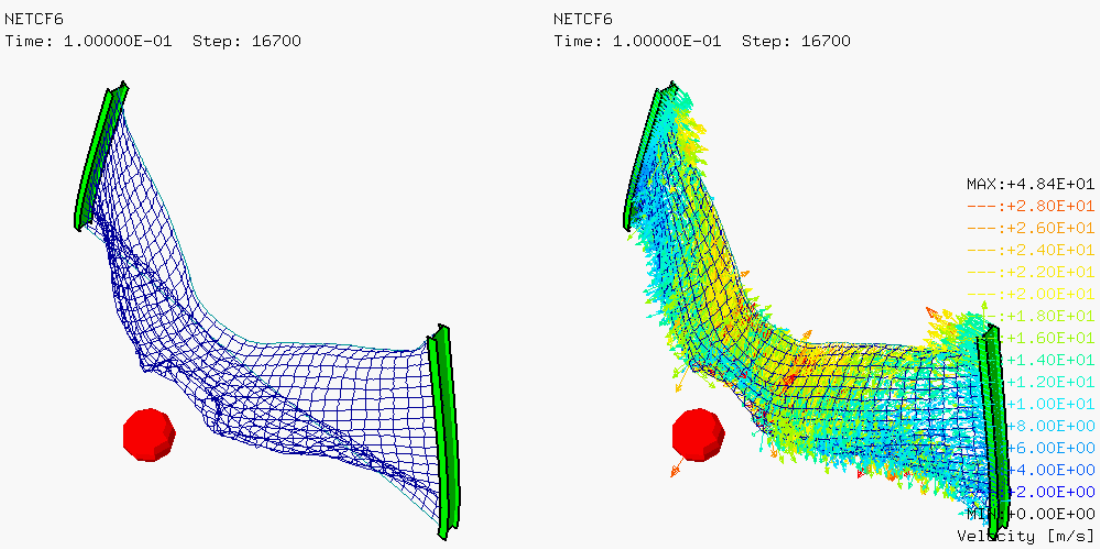
The initial configuration with pinballs shown is:



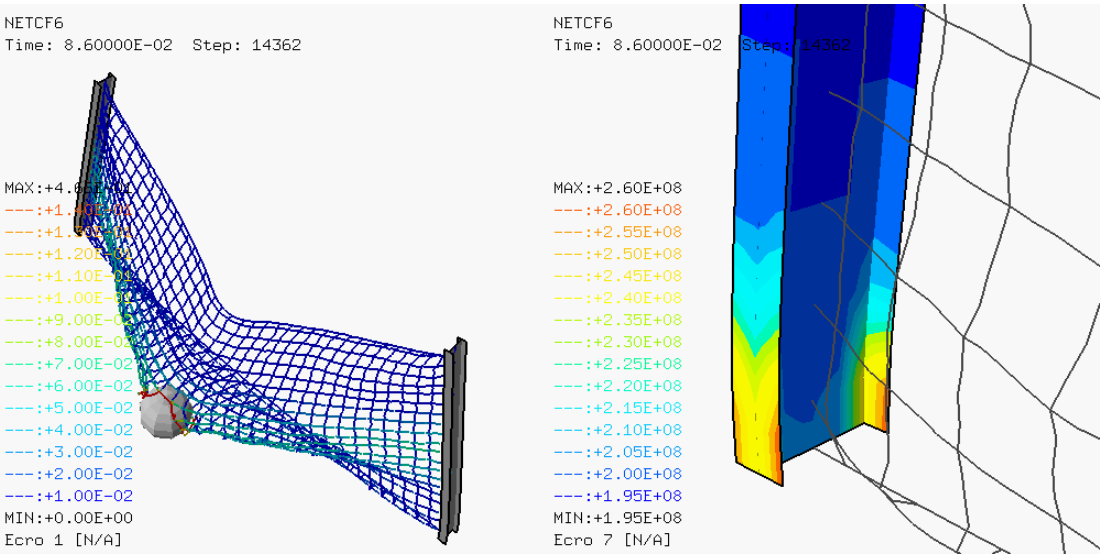
Rupture of the cables starts at around 75 ms and is completed at about 86 ms:



The final configuration (geometry only) and the final velocities are:

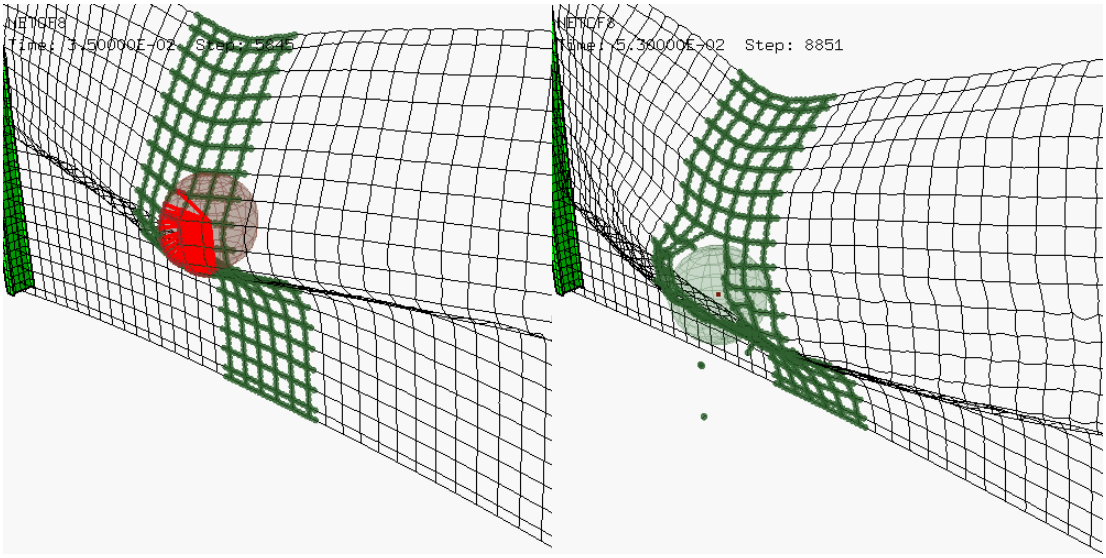


The strain in the cables at 86 ms and the hardening in the suuports is:

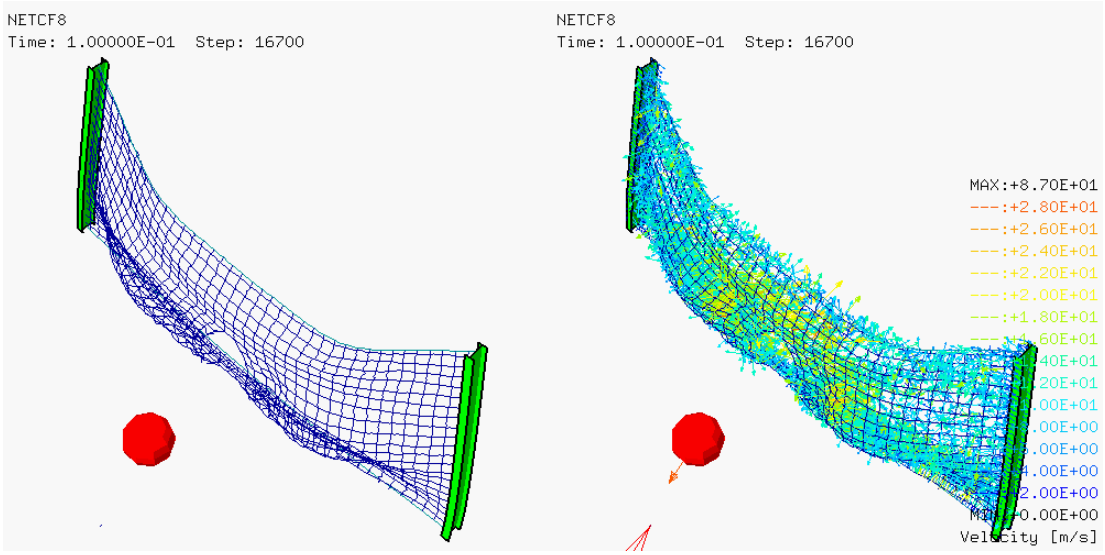


NETCF8

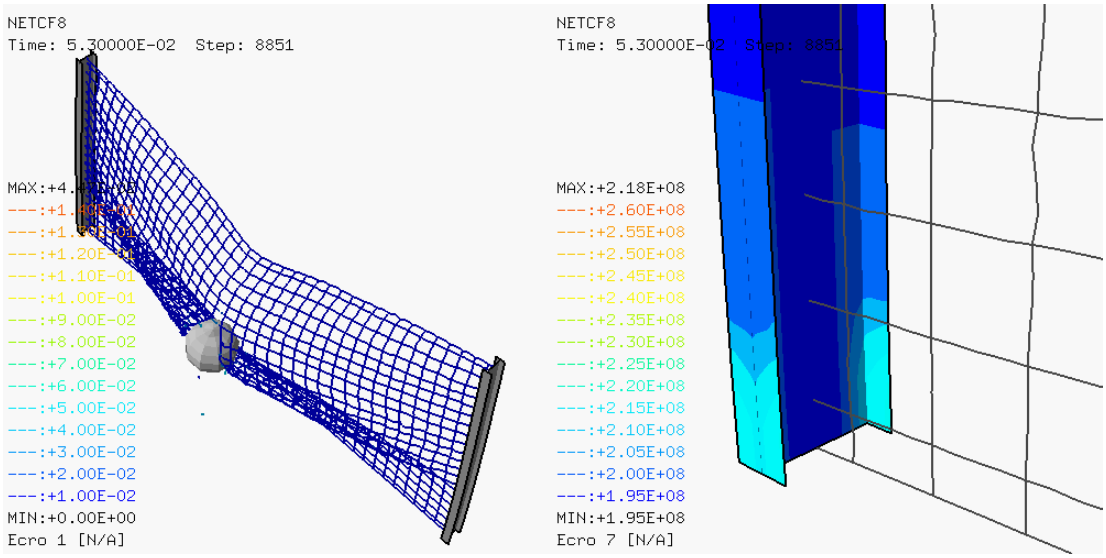
Solution with a cables rupture strain of 5%. Rupture of the cables starts at around 35 ms and is completed at about 53 ms:



The final configuration (geometry only) and the final velocities are:



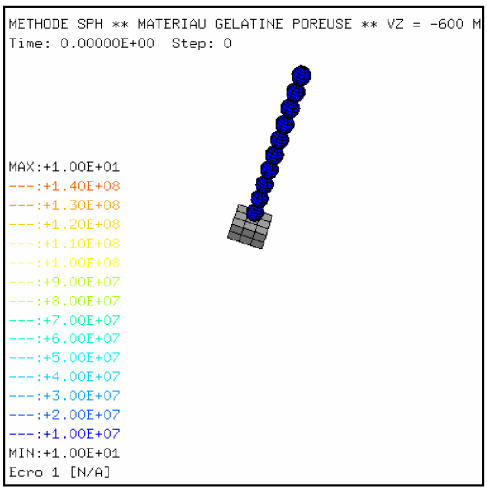
The strain in the cables at 53 ms and the hardening in the supports are:



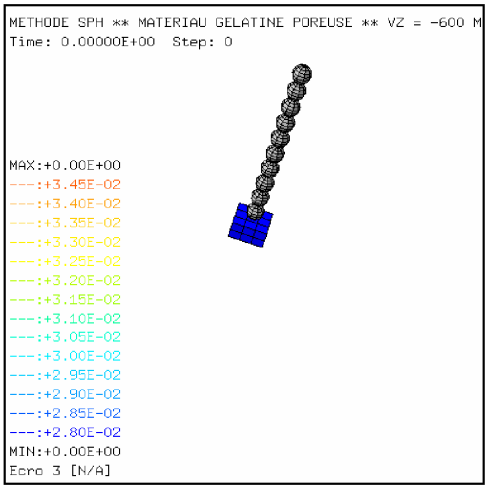
Example 8 – SPH impacts

(Courtesy of CEA and Samtech S.A.)

PRGL01:



Absolute pressure in projectile



Plastic strain in target

59

Numerical Solutions

PRGL01

Simplified impact (10 particles only). Porous jelly material.

The input file:

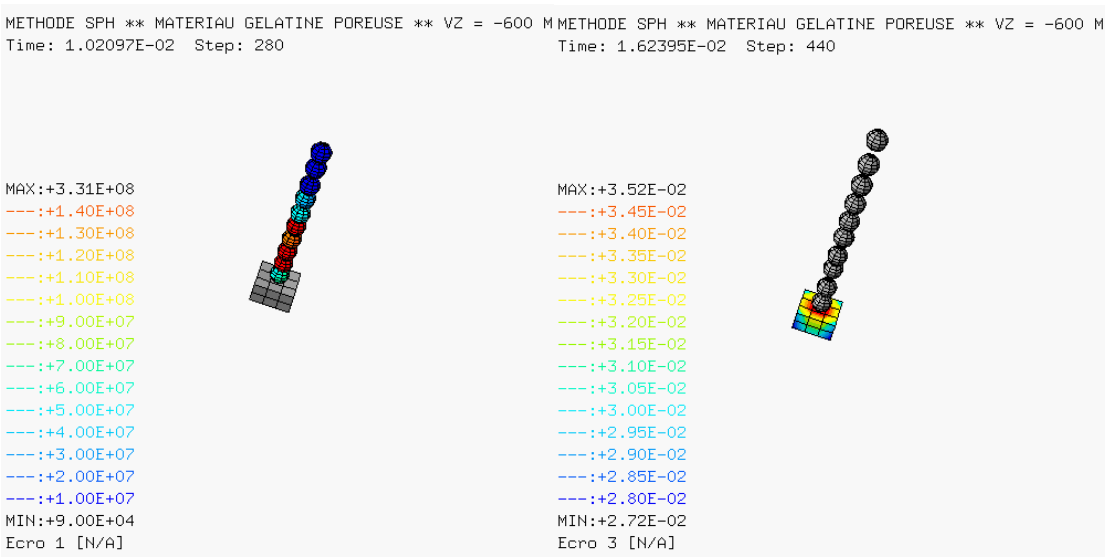
```
METHODE SPH ** MATERIAU GELATINE POREUSE ** VZ = -600 M/S UNITE M.K.S.
*-------------------------------------------------------------------------
ECHO
*conv win
*-----------------------------------------------------------------Problem type
TRID NONLIN
*-----------------------------------------------------------------Dimensioning
DIME
 PT3L 220       ZONE 2
 BLOQ 50
 BILL 10    CUBE 18
 NPEF 1 NPTS  100
 mtpo 10 mtel 5
TERM
*-----------------------------------------------------------------Geometry
GEOM LIBRE POIN 58 BILLE 10 CUBE 18 TERM
 1.00000E+00 1.00000E+00 9.50000E+00 1.00000E+00 1.00000E+00
 8.50000E+00 1.00000E+00 1.00000E+00 7.50000E+00
 1.00000E+00 1.00000E+00 6.50000E+00 1.00000E+00 1.00000E+00
 5.50000E+00 1.00000E+00 1.00000E+00 4.50000E+00
 1.00000E+00 1.00000E+00 3.50000E+00 1.00000E+00 1.00000E+00
 2.50000E+00 1.00000E+00 1.00000E+00 1.50000E+00
 1.00000E+00 1.00000E+00 5.00000E-01 2.00000E+00 2.00000E+00
-2.00000E-02 2.00000E+00 2.00000E+00-5.10000E-01
 2.00000E+00 2.00000E+00-1.00000E+00 1.33333E+00 2.00000E+00
-2.00000E-02 0.00000E+00 2.00000E+00-2.00000E-02
 6.66667E-01 2.00000E+00-2.00000E-02 1.33333E+00 2.00000E+00
-5.10000E-01 1.33333E+00 2.00000E+00-1.00000E+00
 0.00000E+00 2.00000E+00-5.10000E-01 6.66667E-01 2.00000E+00
-5.10000E-01 0.00000E+00 2.00000E+00-1.00000E+00
 6.66667E-01 2.00000E+00-1.00000E+00 2.00000E+00 1.33333E+00
-2.00000E-02 2.00000E+00 6.66667E-01-2.00000E-02
 2.00000E+00 0.00000E+00-2.00000E-02 2.00000E+00 1.33333E+00
-5.10000E-01 2.00000E+00 1.33333E+00-1.00000E+00
 2.00000E+00 6.66667E-01-5.10000E-01 2.00000E+00 0.00000E+00
-5.10000E-01 2.00000E+00 6.66667E-01-1.00000E+00
 2.00000E+00 0.00000E+00-1.00000E+00 1.33333E+00 1.33333E+00
-2.00000E-02 0.00000E+00 1.33333E+00-2.00000E-02
 6.66667E-01 1.33333E+00-2.00000E-02 1.33333E+00 1.33333E+00
-5.10000E-01 1.33333E+00 1.33333E+00-1.00000E+00
 0.00000E+00 1.33333E+00-5.10000E-01 6.66667E-01 1.33333E+00
-5.10000E-01 0.00000E+00 1.33333E+00-1.00000E+00
 6.66667E-01 1.33333E+00-1.00000E+00 1.33333E+00 6.66667E-01
-2.00000E-02 1.33333E+00 0.00000E+00-2.00000E-02
 0.00000E+00 6.66667E-01-2.00000E-02 6.66667E-01 6.66667E-01
-2.00000E-02 6.66667E-01 0.00000E+00-2.00000E-02
 0.00000E+00 0.00000E+00-2.00000E-02 1.33333E+00 6.66667E-01
-5.10000E-01 1.33333E+00 0.00000E+00-5.10000E-01
 1.33333E+00 6.66667E-01-1.00000E+00 1.33333E+00 0.00000E+00
-1.00000E+00 0.00000E+00 6.66667E-01-5.10000E-01
 6.66667E-01 6.66667E-01-5.10000E-01 0.00000E+00 0.00000E+00
-5.10000E-01 0.00000E+00 6.66667E-01-1.00000E+00
 6.66667E-01 6.66667E-01-1.00000E+00 6.66667E-01 0.00000E+00
-1.00000E+00 0.00000E+00 0.00000E+00-1.00000E+00
 6.66667E-01 0.00000E+00-5.10000E-01
   10    9    8    7    6    5    4    3    2    1
   57   56   55   54   53   58   52   51
   56   50   49   55   58   48   47   52
   50   31   30   49   48   29   28   47
   54   55   40   39   51   52   38   37
   55   49   36   40   52   47   35   38
   49   30   27   36   47   28   26   35
   39   40   22   21   37   38   20   19
   40   36   18   22   38   35   17   20
   36   27   13   18   35   26   12   17
   53   58   52   51   46   45   44   43
   58   48   47   52   45   42   41   44
   48   29   28   47   42   25   24   41
   51   52   38   37   43   44   34   33
   52   47   35   38   44   41   32   34
   47   28   26   35   41   24   23   32
   37   38   20   19   33   34   16   15
   38   35   17   20   34   32   14   16
   35   26   12   17   32   23   11   14
*-----------------------------------------------Geometric Complements
COMPLEMENT
CBILLE RAYON 0.5   LINE 0.2  QUAD 8.
SPHY 1 STRUCT LECT 11 PAS 1 28 TERM BILLE LECT 1 PAS 1 10 TERM
*-----------------------------------------------------------Material data
MATE VMIS ISOT RO 2800 YOUN 2.1E11 NU 0.3 ELAS 2.1E8
       TRAC 2   2.1E8  0.001     2.31E9 10
                                 LECT 11 PAS 1 28 TERM
     prgl ro1 1060 ro2 1.03 gamm 1.4 csn1 1482.9
       csn2 328 pini 1e5 pref 1e5 pmin 0. prop 0.9 cvt1 2.
       cvt2 1.03
                                 LECT 1 PAS 1 10 TERM
*-----------------------------------------------------Initial conditions
INIT VITESSE   3 -600. LECT 1 PAS 1 10 TERM
*-----------------------------------------------------Boundary conditions
LIAI BLOQ  1 LECT  1 PAS 1 10 TERM
           2 LECT  1 PAS 1 10 TERM
*-------------------------------------------------------------------Outputs
 ECRIT  depl VITE  ECROU FEXT FREQ  1000
 POIN LECT 1 PAS 1 10 TERM
 ELEM LECT 1 PAS 2 10 TERM
*-----------------------------------------------Transient calculation
 CALCUL   TINI 0    PAS1 2.5E-8    NMAX 3000    TFIN 4.695e-2
*=============================================================ANIMATION
PLAY
CAME   1 EYE   5.31177E-01 -4.80553E+01  3.57776E+01
!        Q     8.85803E-01  4.35282E-01 -7.43757E-02  1.42656E-01
         VIEW  7.57269E-03  7.92369E-01 -6.09995E-01
         RIGH  9.48235E-01  1.87982E-01  2.55956E-01
         UP   -3.17480E-01  5.80357E-01  7.49929E-01
         FOV   2.48819E+01
SCEN GEOM NAVI FREE
     POIN SPHP
          !LINE HEOU
     !VECT SCCO SCAL USER PROG 5.D0 PAS 10.D0 55.D0 TERM !LENG 2.0
     !TEXT VSCA
     !iso  fill fiel ecro 1 scal user prog 1.e7 pas 1.e7 1.4e8 term
     !                      SUPP LECT 1 PAS 1 10 TERM
     !text isca
     iso  fill fiel ecro 3 scal user prog 2.8e-2 pas .05e-2 3.45e-2 term
```

```
                    SUPP LECT 11 PAS 1 28 TERM
     text isca
     colo pape
     lima on

sler cam1 1        nfra 1
trac offs fich avi      nocl nfto 127 fps 10 kfre 10 comp -1
                                              rend

FREQ 10
GOTR LOOP 125 offs fich avi cont nocl
                                              rend
FREQ 5
GO
TRAC offs fich avi cont
                                              rend
ENDPLAY
*=========================================================POST-TREATMENT
QUAL ECRO comp 2 lect 5 term refer 883.94 toler 3E-3
*=========================================================================
FIN
```

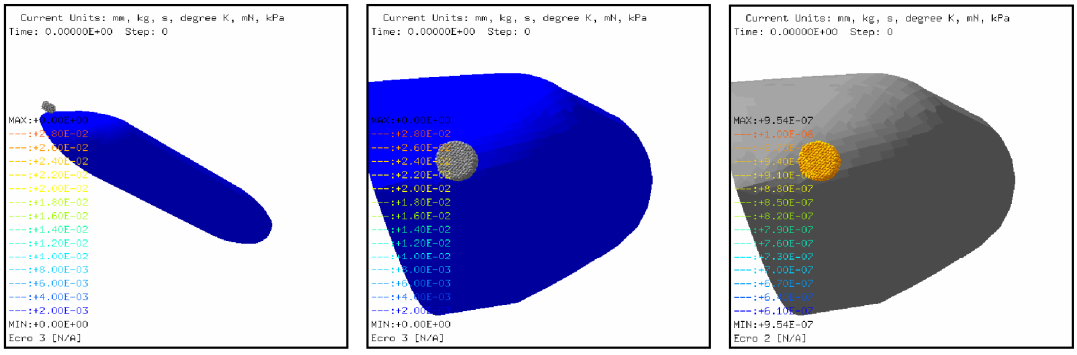
Some hardening quantity in the projectile and in the target:



Example 8 – SPH impacts

(Courtesy of CEA and Samtech S.A.)

ROMA01:



Plastic strain in structure

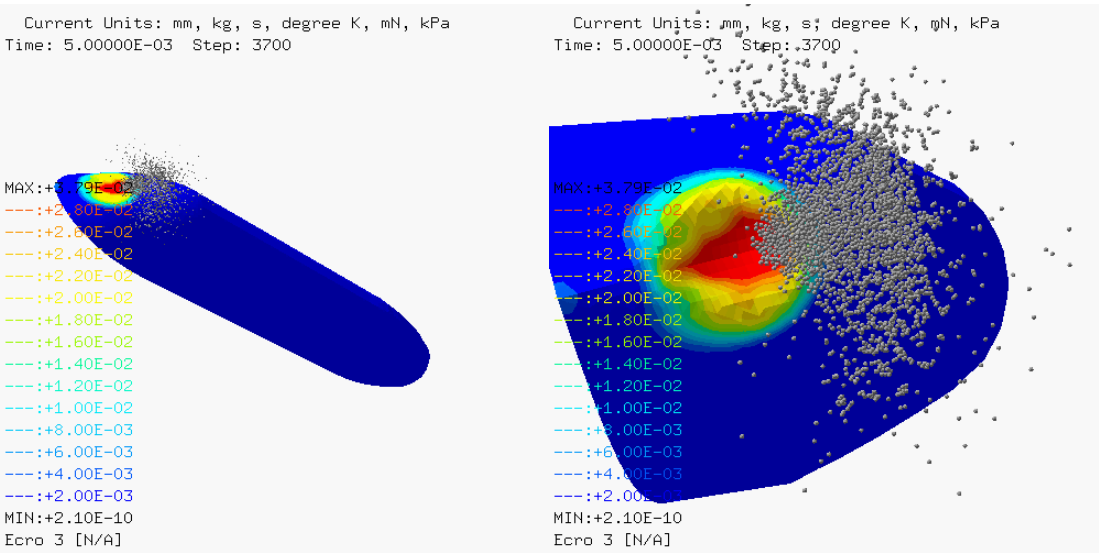
Plastic strain in structure (zoom)

Density in projectile

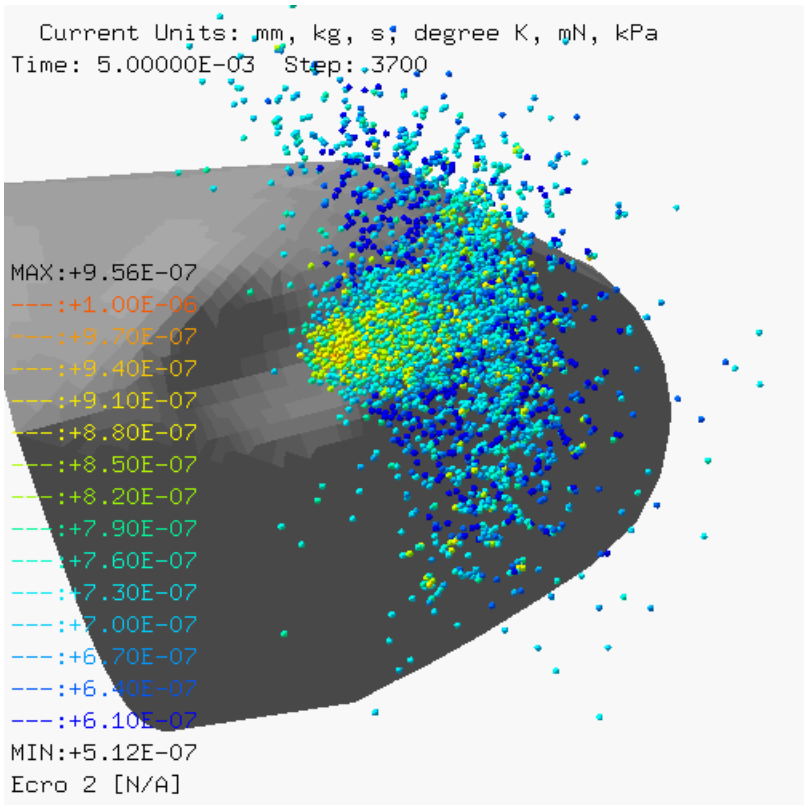
60

ROMA01

Final plastic streen in the target (full and zoom views):



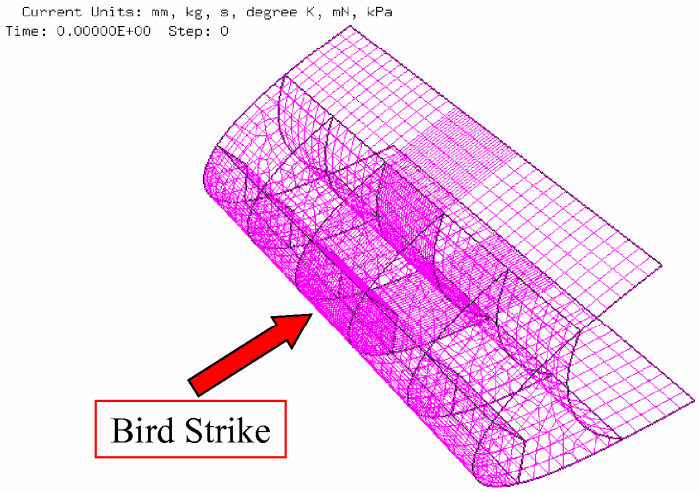
Final density in the projectile:



SONA01

Example 8 – SPH impacts (2)

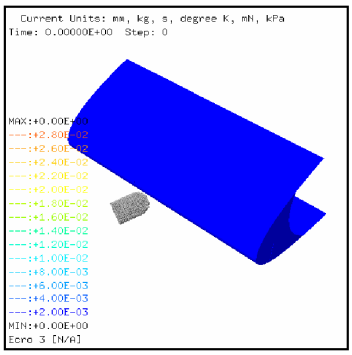
SONA01:



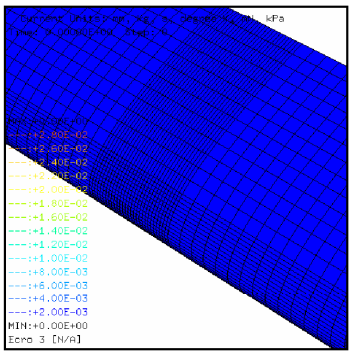
61

Example 8 – SPH impacts (3)

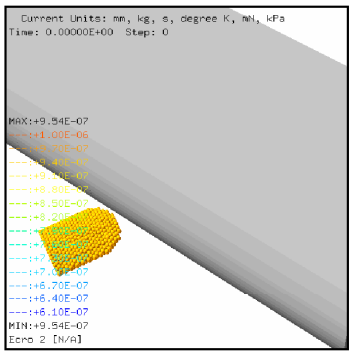
SONA01:



Plastic strain in structure



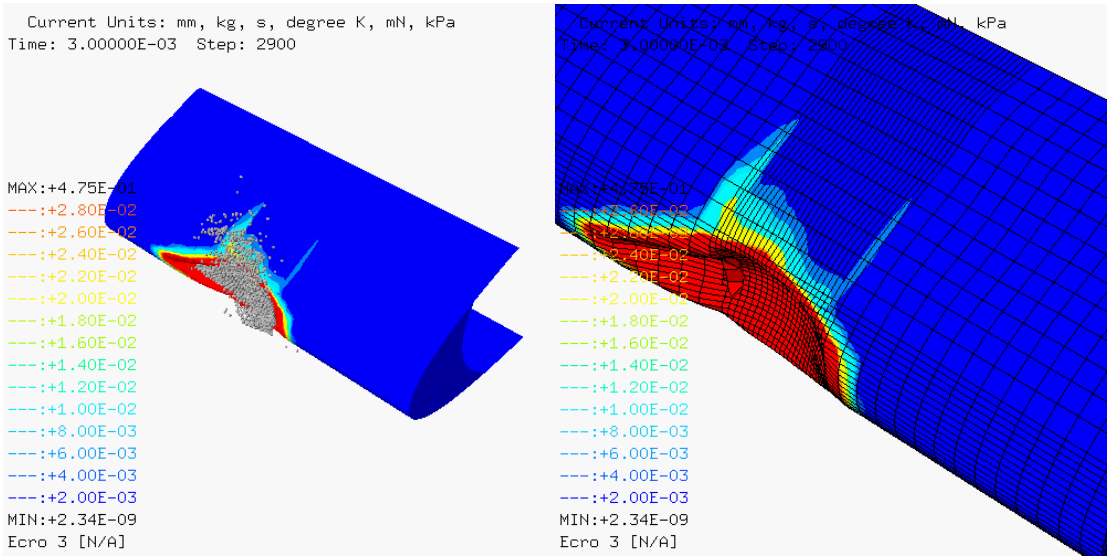
Plastic strain in structure (zoom)



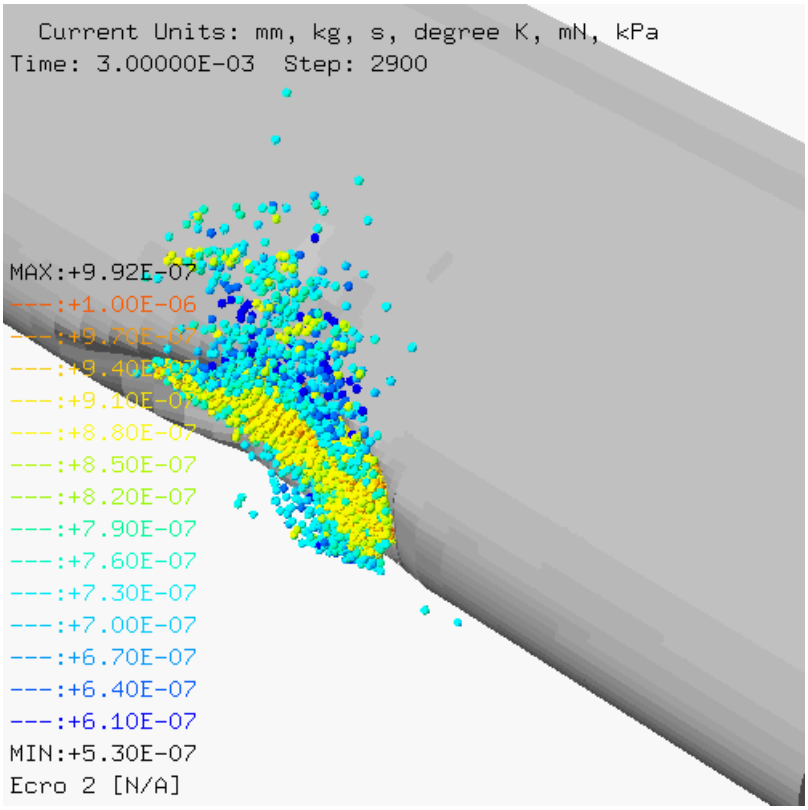
Density in the projectile

62

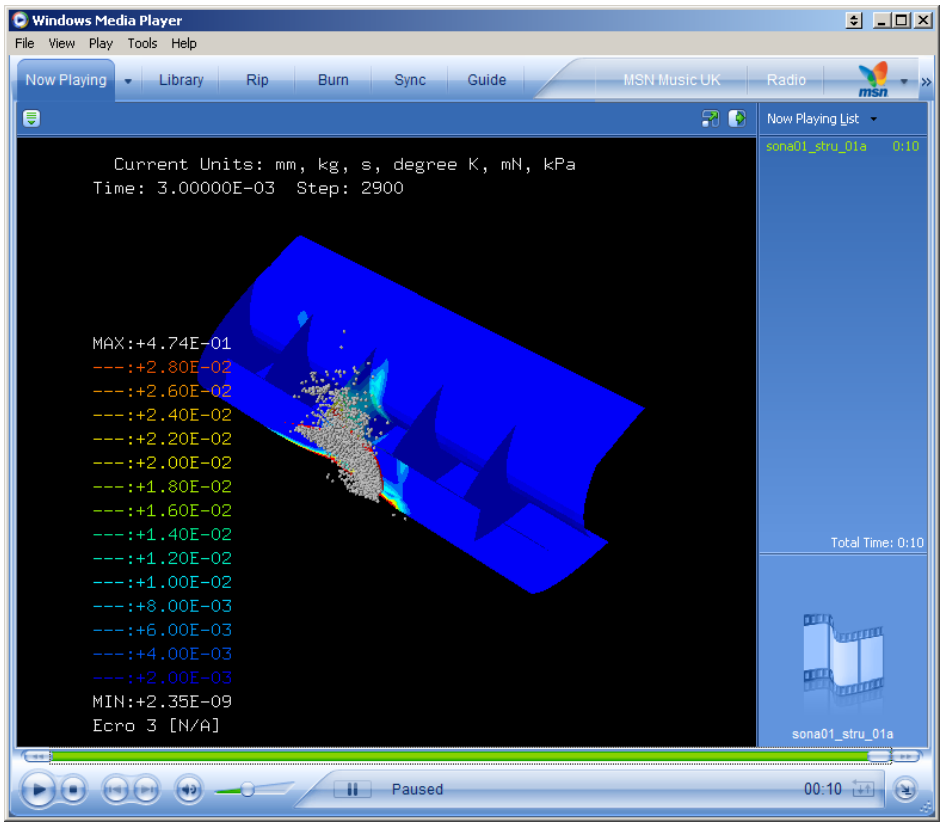
Final plastic strain in the target (full view and zoom):



Final density in the projectile:

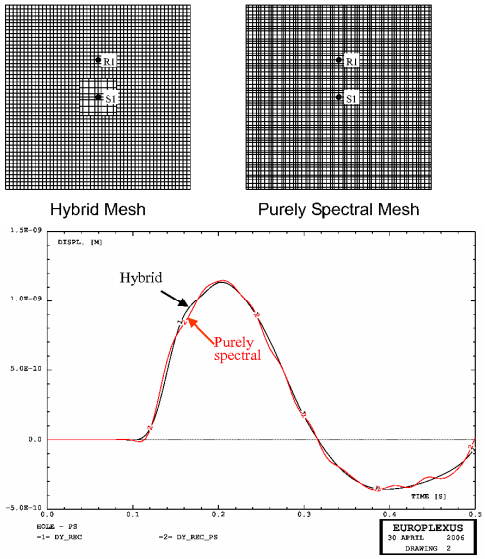


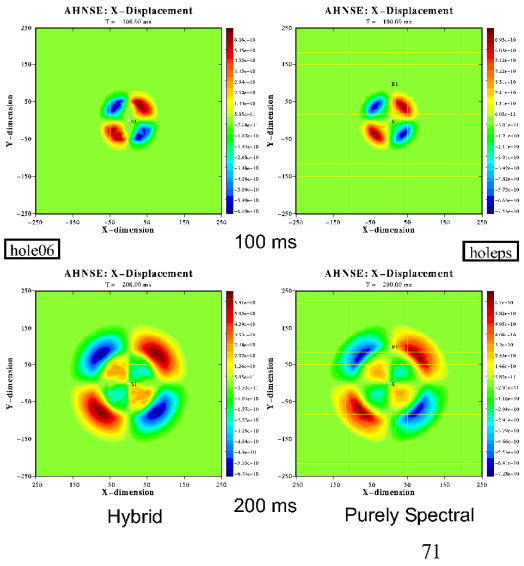
Final plastic strain in target internals (backfaces only):



Example 9 – Closed FE/SE interface

- Verification of coupling algorithm - closed interface test:





71

Problem description:

This example represents the propagation of a seismic wave in a square region. The wave is generated at the centre of the region, while a "receiver" (displacement transducer) is located at a certain height over the source.
The region immediately around the source is modelled by spectral elements, while the remaining parts of the domain may either be meshed by finite elements (hybrid solution), or by spectral elements (purely spectral solution).
By comparing the two solutions, an assessment of the quality of FE/SE coupling is obtained.

Numerical Solutions

HOLE06

This calculation assumes a hybrid mesh composed of 4 macro spectral elements, 64 micro spectral elements and 2400 finite elements.

The coupling between FE and SE regions along the closed square interface is realized by means of the LINK COUP FESE directive.

The mesh generation file is:

```
*$siz 50
*
opti echo 1;
opti titr 'HOLE - 06';
*
opti echo 0;
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxleg2.proc';
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxspect2.proc';
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxpdroi1.proc';
opti echo 1;
*
```

```
opti dime 2 elem qua4;
p0 = 0 0;
p1 = -250.0 -250.0;
p2 = 250.0 -250.0;
p3 = -50.0 -50.0;
p4 =  50.0 -50.0;
p5 = -50.0 50.0;
p6 =  50.0 50.0;
p7 = -250 50.0;
p8 = 250.0 50.0;
p9 = -250 -50.0;
```

```
p10 = 250.0 -50.0;
*
p31 = p3 plus p0;
p41 = p4 plus p0;
p51 = p5 plus p0;
p61 = p6 plus p0;
n = 4;
tol=0.001;
*
c1 = p1 d 50 p2;
s1 = c1 tran 20 (0 200);
* trac s1;
c2 = p4 d 20 p10;
s2 = c2 tran 10 (0 100);
* trac s2;
c3 = p9 d 20 p3;
s3 = c3 tran 10 (0 100);
* trac s3;
c4 = p7 d 50 p8;
s4 = c4 tran 20 (0 200);
* trac s4;
* opti donn 5;
ss = s2 et s3;
elim tol (s1 et ss et p3 et p4 et p5 et p6);
* q1 = diff s1 ss;
fem = diff s1 ss;
elim tol (fem et s4 et p7 et p8 et p5 et p6);
fem = fem et s4;
```

```
trac fem;
c5 = p31 d 2 p41;
s5 = c5 tran 2 (0 100);
* trac (fem et s5);
sem = pxspect2 s5 n tol;
elim tol (s5 et p51 et p61);
trac (fem et sem);
mesh = fem et sem et s5;
nodf = pxpdroi1 fem p3 p4 tol;
nodf = nodf et (pxpdroi1 fem p4 p6 tol);
nodf = nodf et (pxpdroi1 fem p3 p5 tol);
nodf = nodf et (pxpdroi1 fem p5 p6 tol);
nods = pxpdroi1 sem p31 p41 tol;
nods = nods et (pxpdroi1 sem p41 p61 tol);
nods = nods et (pxpdroi1 sem p31 p51 tol);
nods = nods et (pxpdroi1 sem p51 p61 tol);
*
tpln=0.0 100.0;
elim tol (tpln et fem);
*
mesh= mesh et nodf et nods;
tass mesh;
*
opti sauv form 'hole06.msh';
sauv form mesh;
*
opti donn 5;
fin;
```

The input file is:

```
HOLE - 06
$
ECHO
$VERI
!CONV win
CAST MESH
DPLA NONL
$
DIME
  PT2L 2601 MS24 4 S24 64 CAR1 2400 ZONE 3
TERM
$
GEOM MS24 s5 S24 sem CAR1 fem TERM
$
MATE LINE RO 2500. YOUN 1.501196172E9 NU 0.200956938
          LECT s5 fem TERM
$
LINK COUP
     FESE FNOD LECT nodf TERM
          SNOD LECT nods TERM
CHAR SPEC POIN BET DELT
                SOUR BETA 50.0
                     AMP 10.0 X 0.0 Y 0.0
                     T0 0.01 ALFA 40.0
                     NX 0 NY 1
$
ECRI DEPL VITE ACCE FINT FEXT TFRE 0.25
     FICH ALIC FREQ 1
$
OPTI PAS UTIL NOTE
 LOG 1
$
CALC TINI 0. TEND 0.5d0 PASF 5.0D-3
*=====================================================================
SUIT
Post-treatment (bande alice)
ECHO
*
RESU alic GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 1 'dy_rec'  DEPL COMP 2 NOEU LECT tpln TERM
*
trac 1 AXES 1.0 'DISPL. [M]' yzer
list 1 AXES 1.0 'DISPL. [M]'
*
QUAL DEPL COMP 2 LECT tpln TERM REFE -5.50193E-11 TOLE 3.E-3
*=====================================================================
$
FIN
```

HOLEPS

This calculation assumes a purely spectral mesh composed of 225 macro spectral elements and 3600 micro spectral elements.

The mesh generation file is:

```
*%siz 50
*
opti echo 1;
opti titr 'HOLE - PS';
*
opti echo 0;
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxleg2.proc';
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxspect2.proc';
opti echo 1;
*
opti dime 2 elem qua4;
p0 = 0 0;
p1 = -250.0 -250.0;
p2 = 250.0 -250.0;
n = 4;
tol=0.001;
*
c1 = p1 d 15 p2;
```

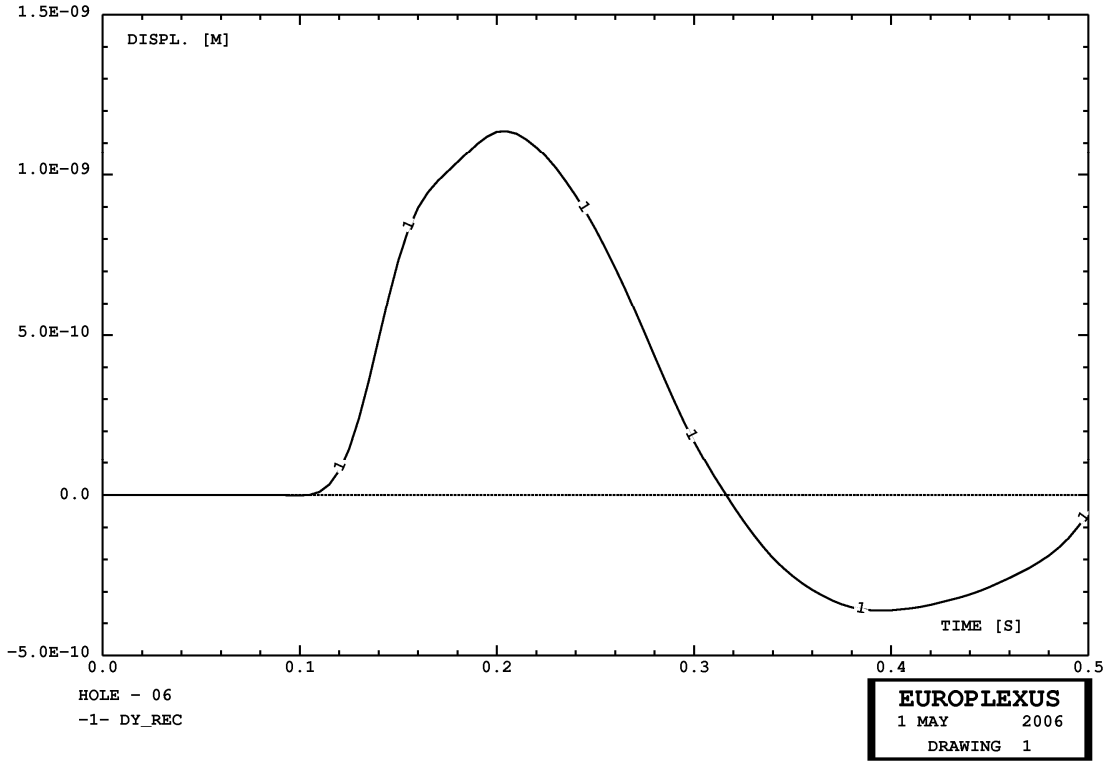
```
sm = c1 tran 15 (0 500);
trac sm;
elim tol (sm et p1 et p2);
sem = pxspect2 sm n tol;
trac (sm et sem);
*
tpln=0.0 100.0;
elim tol (tpln et sem);
*
mesh = sm et sem ;
*
tass mesh;
*
opti sauv form 'holePS.msh';
sauv form mesh;
*
opti donn 5;
fin;
```

The input file is:

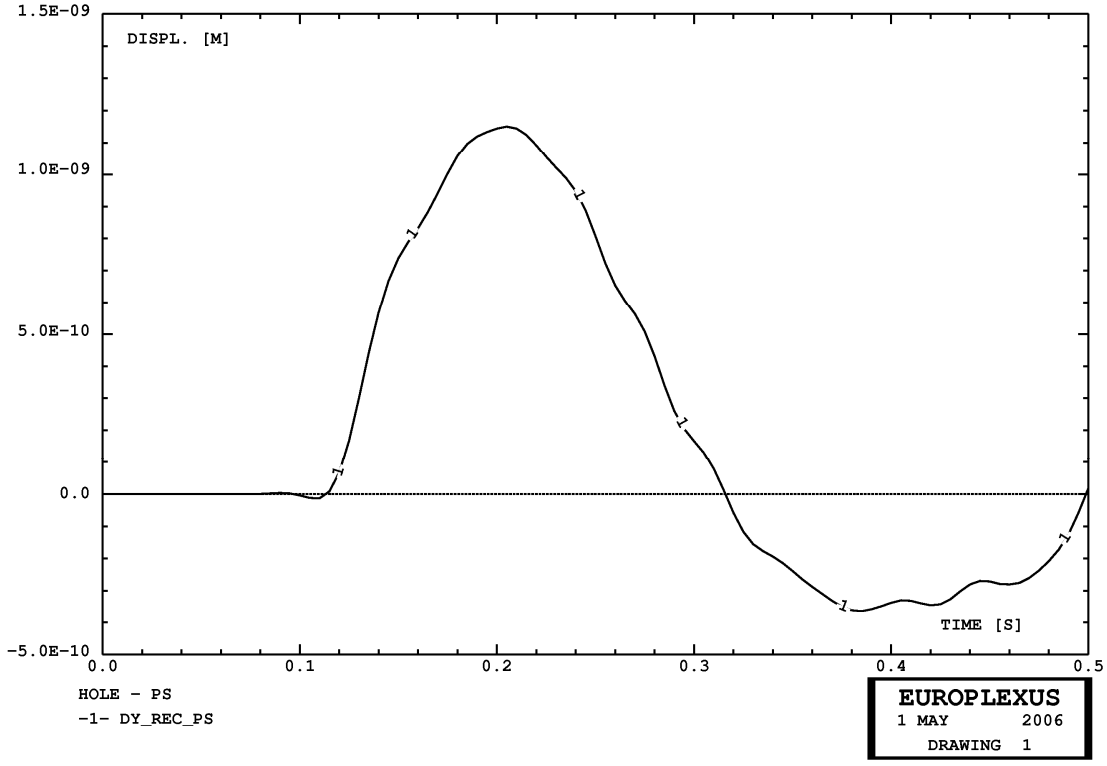
```
HOLE - PS
$
ECHO
$VERI
!CONV win
CAST MESH
DPLA NONL
$
DIME
  PT2L 3721 MS24 225 S24 3600 ZONE 2
TERM
$
GEOM MS24 sm S24 sem TERM
$
MATE LINE RO 2500. YOUN 1.501196172E9 NU 0.200956938
          LECT sm TERM
$
CHAR SPEC POIN BET DELT
                SOUR BETA 50.0
                     AMP 10.0 X 0.0 Y 0.0
                     T0 0.01 ALFA 40.0
                     NX 0 NY 1
$
ECRI DEPL VITE ACCE FINT FEXT TFRE 0.25
     FICH ALIC FREQ 2
$
```

```
OPTI PAS UTIL NOTE
 LOG 1
$
CALC TINI 0. TEND 0.5d0 PASF 2.5D-3
*=====================================================================
SUIT
Post-treatment (bande alice)
ECHO
*
RESU alic GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 1 'dy_rec_ps' DEPL COMP 2 NOEU LECT tpln TERM
RCOU 2 'dy_rec' FICH 'hole06.pun'
*
trac 1 AXES 1.0 'DISPL. [M]' yzer
trac 2 1 AXES 1.0 'DISPL. [M]' yzer
        COLO noir roug
*
QUAL DEPL COMP 2 LECT tpln TERM REFE  1.67558E-11 TOLE 3.E-3
*=====================================================================
FIN
```

The receiver signal in the coupled FE/SE case is:

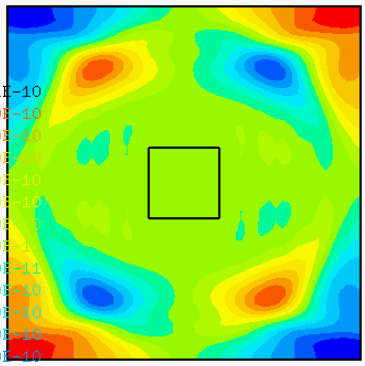


The receiver signal in the purely spectral case is:



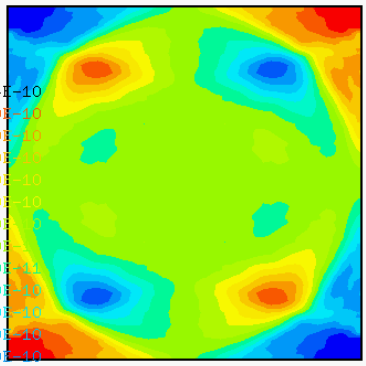
The final X-displacement in the hybrid and purely spectral solutions are:

HOLE - 06
Time: 5.00000E-01 Step: 100

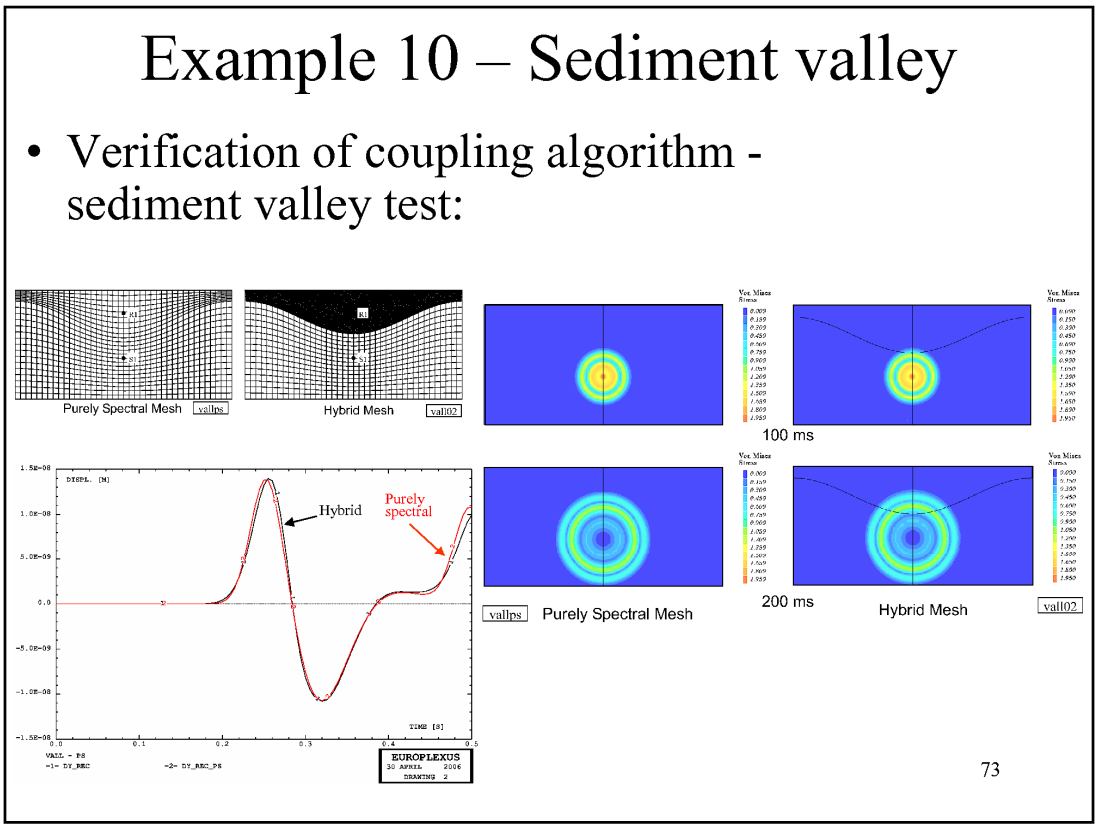


MAX:+9.01E-10
---:+6.50E-10
---:+5.50E-10
---:+4.50E-10
---:+3.50E-10
---:+2.50E-10
---:+1.50E-10
---:+5.00E-11
---:-5.00E-11
---:-1.50E-10
---:-2.50E-10
---:-3.50E-10
---:-4.50E-10
---:-5.50E-10
---:-6.50E-10
MIN:-9.01E-10
Displacement comp _X [m]

HOLE - PS
Time: 5.00000E-01 Step: 200



MAX:+8.84E-10
---:+6.50E-10
---:+5.50E-10
---:+4.50E-10
---:+3.50E-10
---:+2.50E-10
---:+1.50E-10
---:+5.00E-11
---:-5.00E-11
---:-1.50E-10
---:-2.50E-10
---:-3.50E-10
---:-4.50E-10
---:-5.50E-10
---:-6.50E-10
MIN:-8.84E-10
Displacement comp _X [m]



Problem description:

This example represents the propagation of a seismic wave in a sediment valley. The wave is generated at the centre of the region, while a “receiver” (displacement transducer) is located at a certain height over the source.
The bedrock, containing the source, is modelled by spectral elements, while the sediment valley may either be meshed by finite elements (hybrid solution), or by spectral elements (purely spectral solution).
By comparing the two solutions, an assessment of the quality of FE/SE coupling is obtained.

Numerical Solutions

VALL02

This calculation assumes a hybrid mesh composed of 320 macro spectral elements, 5120 micro spectral elements and 3035 finite elements. The coupling between FE and SE regions along the closed square interface is realized by means of the LINK COUP FESE directive.

The mesh generation file is:

```
*$siz 50
*
opti echo 0;
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxleg2.proc';
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxspect2.proc';
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxpdroi1.proc';
opti echo 1;
*
opti dime 2 elem qua4;
opti titr 'VALL - 02';
*
p0=0 0;
p1=500 0;
p2=0 300;
p3=500 450;
p4=0 500;
p5=500 500;
n=4;
tol=0.01;
tol2=0.1;
*
i=0; repe lab1 20;
  i=i + 1;
*
  xi = 25. * i;
  yy = cos( xi * 180. / 500.);
  yi = 375. - (75. * yy);
  pti = xi yi;
```

```
  si (ega i 1);
    c1 = d 1 p2 pti;
  sinon;
    c1 = c1 d 1 pti;
  finsi;
*
fin lab1;
elim tol (c1 et p3);
*
c2 = p3 d 16 p1;
c3 = p1 d 20 p0;
c4 = p0 d 16 p2;
*
sm = dall c1 c2 c3 c4 plan;
*
sem = pxspect2 sm n tol;
*
p2p=p2 plus p0;
p3p=p3 plus p0;
*
i=0; repe lab2 20;
  i=i + 1;
*
  xi = 25. * i;
  yy = cos( xi * 180. / 500.);
  yi = 375. - (75. * yy);
  pti = xi yi;
  si (ega i 1);
    c1p = d 4 p2p pti;
  sinon;
    c1p = c1p d 4 pti;
  finsi;
*
fin lab2;
elim tol (c1p et p3p);
*
c2p = p3p d 5 p5;
c3p = p5 d 80 p4;
c4p = p4 d 20 p2p;
opti elem tri3;
fem = surf (c1p et c2p et c3p et c4p) plan;
*
ptiold=p2;
i=0; repe lab3 20;
  i=i + 1;
*
  xi = 25. * i;
  yy = cos( xi * 180. / 500.);
  yi = 375. - (75. * yy);
  pti = xi yi;
  si (i ega 1);
    nods = pxpdroi1 sem ptiold pti tol2;
  sinon;
    nods = nods et (pxpdroi1 sem ptiold pti tol2);
  finsi;
  ptiold = pti;
*
fin lab3;
nodf=c1p;
*
tpln=0.0 400.0;
elim tol (tpln et fem);
*
blxs = pxpdroi1 sem p0 p2 tol2;
blxf = c4p;
*
trac (fem et sem);
*
mesh = fem et sem et sm et nodf et nods et tpln et blxs et blxf;
*
tass mesh;
*
opti sauv form 'vall02.msh';
sauv form mesh;
fin;
```

The input file is:

```
VALL - 02
$
ECHO
$VERI
!CONV win
CAST MESH
DPLA NONL
$
DIME
  PT2L 6876 MS24 320 S24 5120 TRIA 3035 ZONE 3
TERM
$
GEOM MS24 sm S24 sem TRIA fem TERM
$
MATE LINE RO 2500. YOUN 1.501196172E9 NU 0.200956938
         LECT sm fem TERM
$
LINK COUP
     CONT SPLA NX 1.0 NY 0.0 LECT blxf blxs TERM
     FESE FNOD LECT nodf TERM
          SNOD LECT nods TERM
CHAR SPEC POIN BET PRES
                SOUR BETA 200.0
                     AMP 10.0
                     T0 0.01
                     X 0.0 Y 200.0
                     ALFA 20.0
$
ECRI DEPL VITE ACCE FINT FEXT TFRE 0.5
     FICH ALIC FREQ 5
$
OPTI PAS UTIL NOTE
 LOG 1
$
CALC TINI 0. TEND 0.5d0 PASF 1.00D-3
*=================================================================
SUIT
Post-treatment (bande alice)
ECHO
*
RESU alic GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 1 'dy_rec'  DEPL COMP 2 NOEU LECT tpln TERM
*
trac 1 AXES 1.0 'DISPL. [M]' yzer
list 1 AXES 1.0 'DISPL. [M]'
*
QUAL DEPL COMP 2 LECT tpln TERM REPE  9.95286E-9 TOLE 3.E-3
*=================================================================
FIN
```

VALLPS

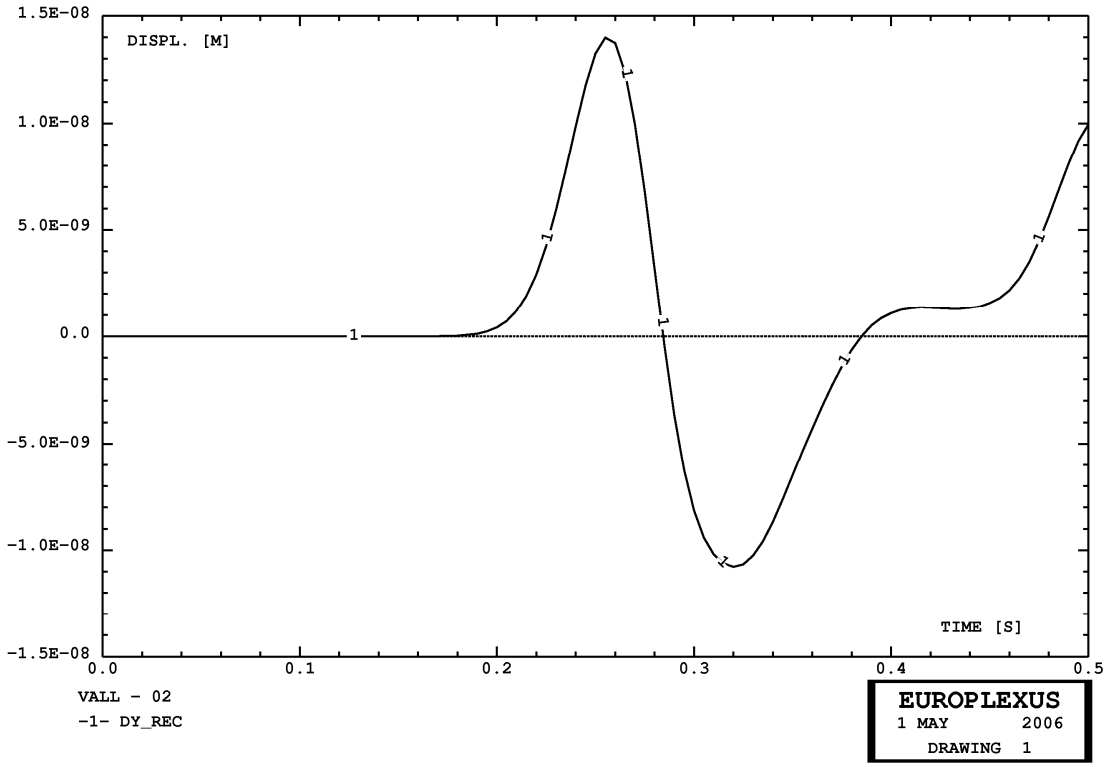
This calculation assumes a purely spectral mesh composed of 480 macro spectral elements and 7680 micro spectral elements. The mesh generation file is:

```
*%siz 50
*
opti echo 0;
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxleg2.proc';
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxspect2.proc';
opti donn 'D:\Users\Folco\Plexis3c\Proc\pxpdroi1.proc';
opti echo 1;
*
opti dime 2 elem qua4;
opti titr 'VALL - PS';
*
p0=0 0;
p1=500 0;
p2=0 300;
p3=500 450;
p4=0 500;
p5=500 500;
n=4;
tol=0.01;
tol2=0.1;
*
i=0; repe lab1 20;
  i=i + 1;
*
  xi = 25. * i;
  yy = cos( xi * 180. / 500.);
  yi = 375. - (75. * yy);
  pti = xi yi;
  si (ega i 1);
    c1 = d 1 p2 pti;
  sinon;
    c1 = c1 d 1 pti;
  finsi;
*
fin lab1;
elim tol (c1 et p3);
*
c2 = p3 d 16 p1;
c3 = p1 d 20 p0;
c4 = p0 d 16 p2;
*
sm1 = dall c1 c2 c3 c4 plan;
*
c5 = p3 d 8 p5;
c6 = p5 d 20 p4;
c7 = p4 d 8 p2;
*
sm2 = dall c1 c5 c6 c7 plan;
*
trac (sm1 et sm2);
*
sm = sm1 et sm2;
*
sem = pxspect2 sm n tol;
*
tpln=0.0 400.0;
elim tol (tpln et sem);
*
blxs = pxpdroi1 sem p0 p4 tol2;
*
mesh = sem et sm et tpln et blxs ;
*
tass mesh;
*
opti sauv form 'vallPS.msh';
sauv form mesh;
fin;
```

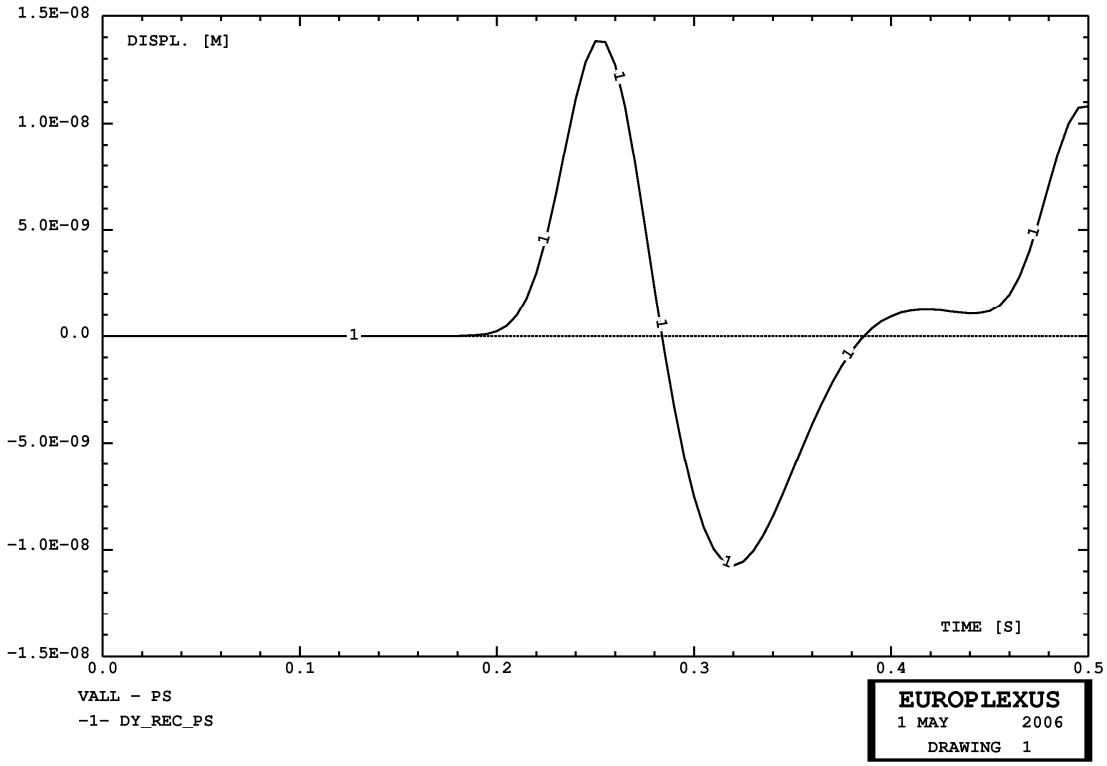
The input file is:

```
VALL - PS
$
ECHO
$VERI
!CONV win
CAST MESH
DPLA NONL
$
DIME
  PT2L 7857 MS24 480 S24 7680 ZONE 2
TERM
$
GEOM MS24 sm S24 sem TERM
$
MATE LINE RO 2500. YOUN 1.501196172E9 NU 0.200956938
         LECT sm TERM
$
LINK COUP
     CONT SPLA NX 1.0 NY 0.0 LECT blxs TERM
*
CHAR SPEC POIN BET PRES
                SOUR BETA 200.0
                     AMP 10.0
                     T0 0.01
                     X 0.0 Y 200.0
                     ALFA 20.0
$
ECRI DEPL VITE ACCE FINT FEXT TFRE 0.5
     FICH ALIC FREQ 10
$
OPTI PAS UTIL NOTE
$
CALC TINI 0. TEND 0.5d0 PASF 0.50D-3
*=================================================================
SUIT
Post-treatment (bande alice)
ECHO
*
RESU alic GARD PSCR
*
SORT GRAP
*
AXTE 1.0 'Time [s]'
*
COUR 1 'dy_rec_ps' DEPL COMP 2 NOEU LECT tpln TERM
RCOU 2 'dy_rec' FICH 'vall02.pun'
*
trac 1 AXES 1.0 'DISPL. [M]' yzer
trac 2 1 AXES 1.0 'DISPL. [M]' yzer
        COLO noir roug
*
QUAL DEPL COMP 2 LECT tpln TERM REPE  1.07909E-8 TOLE 3.E-3
*=================================================================
FIN
```

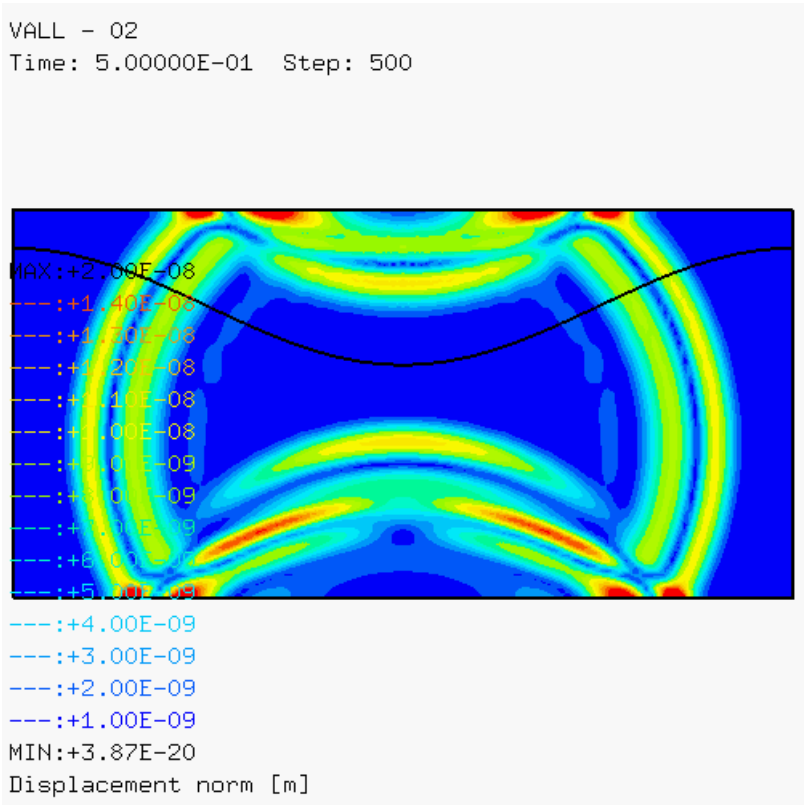
The receiver signal in the coupled FE/SE case is:



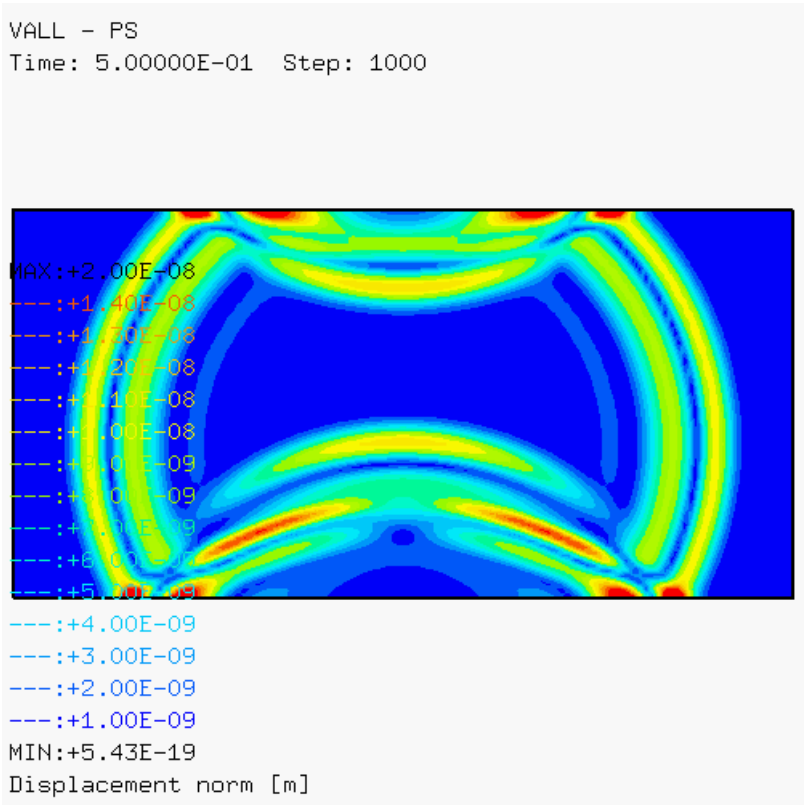
The receiver signal in the purely spectral case is:



The final displacement norm in the hybrid solution is:

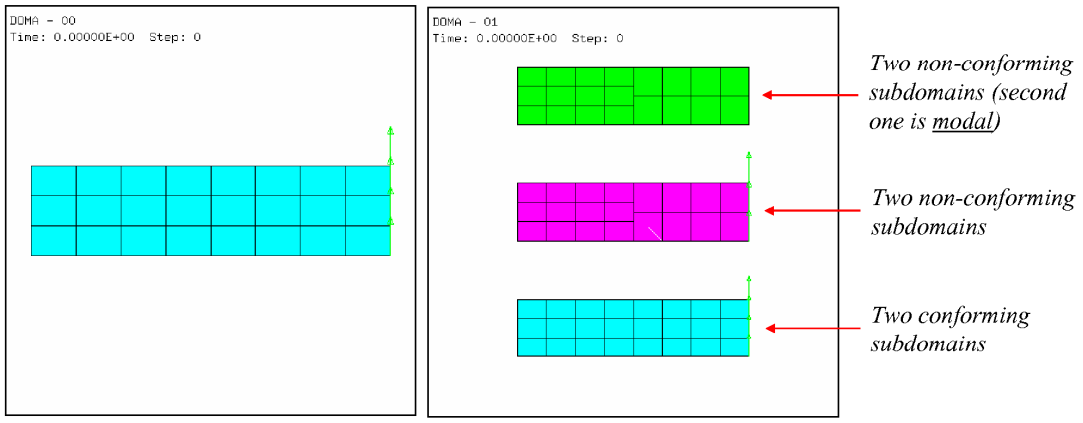


The final displacement norm in the purely spectral solution is:



Example 13 – Domains in 2D

- Thick plane strain beam under bending:



Reference Case (no decomposition)

Case with various decompositions

104

Problem description:

This example represents the bending of a thick beam in 2D plane strain conditions. The beam is clamped at the left end and loaded by concentrated forces at the right end. The material is linear elastic.

Two solutions are obtained. The first one without domain decomposition is used as a reference, while the second uses various alternative domain decompositions, one of which is modal.

Numerical Solutions

DOMA00

This calculation uses no domain decomposition and is used to obtain a reference solution. It uses a regular mesh of 24 elements of type CAR4.

The mesh generation file is:

```
*$siz 50
*
OPTI ECHO 1 DIME 2 ELEM QUA4;
opti titr 'DOMA - 00';
opti trac psc ftra 'doma00_mesh.ps';
*
P11=0. 0.;
P12=0. 1.;
P13=2. 0.;
P14=2. 1.;
*
VEC1=2. 0.;
*
P1=P11;
R1=P13;
S1=P13 PLUS VEC1;
*
N2=3;
N3=4;
*
P11_P12=P11 D N2 P12;
P11_P12P=P11_P12 PLUS VEC1;
P13_P14=P13 D N2 P14;
P13_P14P=P13_P14 PLUS VEC1;
*
DOM11=P11_P12 REGL N3 P11_P12P;
DOM12=P13_P14 REGL N3 P13_P14P;
*
TRAC (DOM11 ET DOM12);
*
ELIM 0.001 (DOM11 ET DOM12 ET P1 ET R1 ET S1);
*
TOUT=DOM11 ET DOM12;
*
OPTI SAUV FORMAT 'doma00.msh';
SAUV FORMAT TOUT;
*
FIN;
```

The input file is:

```
DOMA - 00
*------------------------------------------------------------------------
ECHO
!conv win
CAST tout
*-------------------------------------------------------------Problem type
DPLA NONL
*-------------------------------------------------------------Dimensioning
DIME
  PTZL 36 CAR4 24
  TABL 1 4 ECRO 522
  FORC 10  MTPO 9
TERM
*------------------------------------------------------------------Geometry
GEOM CAR4 tout
     TERM
*-----------------------------------------------Geometric Complements
COMP GROU 1
     'prob1'  LECT dom11 dom12 TERM
     NGRO 3
     'tpln'   LECT p1 r1 s1 TERM
     'char2'  LECT p13_p14p TERM
     'bloqa'  LECT p11_p12  TERM
     COUL turq LECT prob1 TERM
*-------------------------------------------------------------Material data
MATE
   LINE RO 7800. YOUN 210.E9 NU 0.3
        LECT tout TERM
*-----------------------------------------------------------Applied "loads"
CHAR 1 FACT 2
   FORC 2 0.75E7 LECT char2 TERM
   TABL 2 0.0 1.0 1.0 1.0
*-----------------------------------------------------------Boundary conditions
LINK COUP BLOQ 12 LECT bloqa TERM
```

```
*------------------------------------------------------------------Outputs
ECRI DEPL TFRE 4D-3 NOEL
          POIN LECT tpln TERM
     FICH ALIC TEMP TFREQ 0.2D-3
          POIN LECT tpln TERM
          ELEM LECT 1 TERM
     FICH ALIC TFRE 40.E-5
*------------------------------------------------------------------Options
OPTI CSTA 0.5
  LOG 1
*-----------------------------------------------------Transient calculation
CALC TINI 0. TFIN 40.E-3
*=========================================================POST-TREATMENT
SUIT
Post-treatment
```

```
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1E3 'Temps (ms)'
*-----------------------------------------------------Curve definitions
COUR  1 'noeud P1' DEPL COMP 2 NOEU LECT p1 TERM
COUR  2 'noeud R1' DEPL COMP 2 NOEU LECT r1 TERM
COUR  3 'noeud S1' DEPL COMP 2 NOEU LECT s1 TERM
*------------------------------------------------------------------Plots
trac  3 AXES 1 'Deplacement' yzer
trac  1 2 3 AXES 1 'Deplacement' yzer
*-----------------------------------------------------Results qualification
QUAL DEPL COMP 2 REFE 2.38669E-02 TOLE 1.E-2 LECT s1 TERM
*=====================================================================
FIN
```

DOMA01

This calculation uses three alternative domain decompositions (in just one run of the code):

- Two conforming domains (lower mesh) with the same grid as in the reference solution;
- Two non-conforming domains (middle mesh) of which the left one has the same element size as the reference, while the right one is coarser. The interface between these two domains is therefore non-conforming.
- Same as the previous case (upper mesh) but the right, coarse sub-domain is represented by a modal reduction.
-

The mesh generation file, including also the Cast3m command to compute the modes in the modal sub-domain, is:

```
*%siz 50
*
OPTI ECHO 1 DIME 2 ELEM QUA4;
opti titr 'DOMA - 01';
opti trac psc ftra 'doma01_mesh.ps';
*
P11=0. 0.;
P12=0. 1.;
P13=2. 0.;
P14=2. 1.;
*
P21=0. 2.;
P22=0. 3.;
P23=2. 2.;
P24=2. 3.;
*
P31=0. 4.;
P32=0. 5.;
P33=2. 4.;
P34=2. 5.;
*
VEC1=2. 0.;
*
P1=P11;
R1=P13;
S1=P13 PLUS VEC1;
*
P2=P21;
R2=P23;
S2=P23 PLUS VEC1;
*
P3=P31;
R3=P33;
S3=P33 PLUS VEC1;
*
N1=2;
N2=3;
N3=4;
*
P11_P12=P11 D N2 P12;
P11_P12P=P11_P12 PLUS VEC1;
P13_P14=P13 D N2 P14;
P13_P14P=P13_P14 PLUS VEC1;
*
DOM11=P11_P12 REGL N3 P11_P12P;
DOM12=P13_P14 REGL N3 P13_P14P;
*
P21_P22=P21 D N2 P22;
P21_P22P=P21_P22 PLUS VEC1;
P23_P24=P23 D N1 P24;
P23_P24P=P23_P24 PLUS VEC1;
*
DOM21=P21_P22 REGL N3 P21_P22P;
DOM22=P23_P24 REGL N3 P23_P24P;
*
P31_P32=P31 D N2 P32;
P31_P32P=P31_P32 PLUS VEC1;
P33_P34=P33 D N1 P34;
P33_P34P=P33_P34 PLUS VEC1;
*
DOM31=P31_P32 REGL N3 P31_P32P;
DOM32=P33_P34 REGL N3 P33_P34P;
*
TRAC (DOM11 ET DOM12 ET DOM21 ET DOM22 ET DOM31 ET DOM32);
*
ELIM 0.001 DOM11 (P1 ET R1);
ELIM 0.001 DOM12 (R1 ET S1);
ELIM 0.001 DOM21 (P2 ET R2);
ELIM 0.001 DOM22 (R2 ET S2);
ELIM 0.001 DOM31 (P3 ET R3);
ELIM 0.001 DOM32 (R3 ET S3);
*
TOUT=DOM11 ET DOM12 ET DOM21 ET DOM22 ET DOM31 ET DOM32;
*
OPTI SAUV FORMAT 'doma01.msh';
SAUV FORMAT TOUT;
*
*=====================================================================
* Reduction Craig-Bampton sur le domaine 2 du cas 3
*
NMOD1=10;
*
MOD1=MODELE DOM32 MECANIQUE ELASTIQUE ISOTROPE;
MAT1=MATERIAU MOD1 YOUN 210.E9 NU 0.3 RHO 7800.;
*
CL1=BLOQ DEPL P33_P34;
*
MAS1=MASSE MOD1 MAT1;
RIG1=(RIGIDITE MOD1 MAT1) ET CL1;
*
```

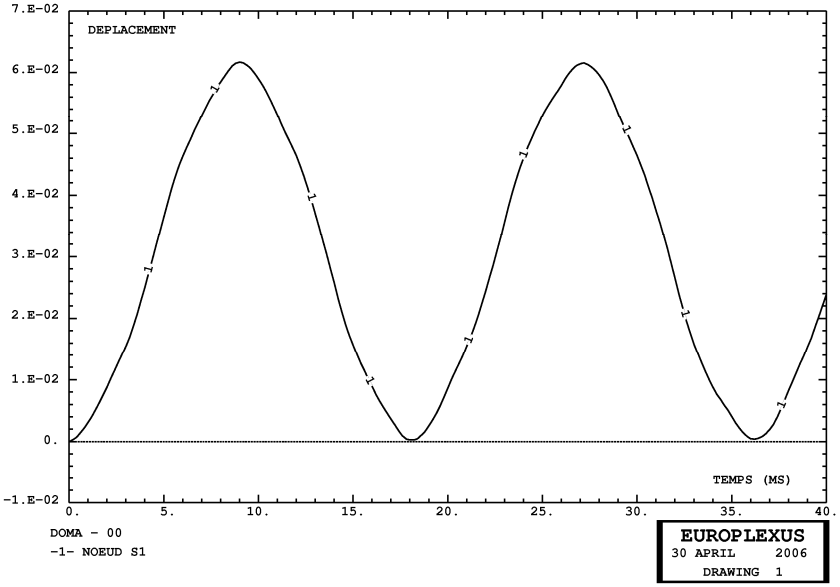
```
* Calcul des modes statiques
*
TDEPI1=TABLE;
TLREE1=TABLE;
NBN1=NBNO(P33_P34);
NSTA1=0;
*
REPETER BCL1 (NBN1);
   SI (&BCL1 EGA 1);
      LREEL1=PROG 1 * 1. (NBN1-1) * 0.;
      LREEL2=PROG NBN1 * 0.;
   SINON;
      SI (&BCL1 EGA NBN1);
         LREEL1=PROG (NBN1-1) * 0. 1 * 1.;
         LREEL2=PROG NBN1 * 0.;
      SINON;
         LREEL1=PROG (&BCL1-1) * 0. 1. (NBN1-&BCL1) * 0.;
         LREEL2=PROG NBN1 * 0.;
      FINSI;
   FINSI;
   REPETER BCL2 (2);
      REPETER BCL3 (2);
         TLREE1 . &BCL3=LREEL2;
      FIN BCL3;
      TLREE1 . &BCL2=LREEL1;
      CHIMP1=MANU CHPO P33_P34 2 UX TLREE1 . 1 UY TLREE1 . 2;
      CHIMP11=REDU DOM32 CHIMP1;
      NSTA1=NSTA1+1;
      TDEPI1 . NSTA1=CHIMP11;
   FIN BCL2;
FIN BCL1;
*
TSTAT1=TABLE;
*
REPETER BCL4 (2*NBN1);
   CHFOR1=DEPI CL1 TDEPI1 . &BCL4;
   CHSTA1=RESOUD RIG1 CHFOR1;
   TSTAT1 . &BCL4=CHSTA1;
   LIST &BCL4;
FIN BCL4;
*
* Modes propres encastres
*
TMOD1=VIBR 'SIMULTANE' 10. NMOD1 MAS1 RIG1 IMPR TBAS;
*
TDYN1=TABLE;
*
REPETER BCL5 (NMOD1);
   CHMOD1=TMOD1 . MODES . &BCL5 . DEFORMEE_MODALE;
   TDYN1 . &BCL5=CHMOD1;
FIN BCL5;
*
* Normalisation des modes dynamiques
*
REPETER BCL6 (NMOD1);
   CHPO1=TDYN1 . &BCL6;
   SCAL1=XTMX CHPO1 MAS1;
   SCAL1=SCAL1 ** 0.5;
   CHPO1=CHPO1 / SCAL1;
   CHPO1=ENLEVER CHPO1 LX;
   TDYN1 . &BCL6=CHPO1;
FIN BCL6;
*
* On retire aux modes statiques leur contribution sur les modes dynamiques
*
REPETER BCL7 (NSTA1);
   CHPO1=TSTAT1 . &BCL7;
   CHPO2=TSTAT1 . &BCL7;
   REPETER BCL8 (NMOD1);
      CHPO3=TDYN1 . &BCL8;
      SCAL1=YTMX MAS1 CHPO1 CHPO3;
      CHPO3=SCAL1 * CHPO3;
      CHPO2=CHPO2 - CHPO3;
   FIN BCL8;
   CHPO2=ENLEVER CHPO2 LX;
   TSTAT1 . &BCL7=CHPO2;
   LIST &BCL7;
FIN BCL7;
*
* Orthogonalisation de la famille des modes statiques modifies
*
TSTAT2=TABLE;
REPETER BCL9 (NSTA1);
   CHPO1=TSTAT1 . &BCL9;
   CHPO2=TSTAT1 . &BCL9;
   BOOL1=&BCL9 > 1;
   SI BOOL1;
      REPETER BCL10 (&BCL9-1);
         CHPO3=TSTAT2 . &BCL10;
         SCAL1=YTMX MAS1 CHPO1 CHPO3;
```

```
        CHPO3=SCAL1 * CHPO3;
        CHPO2=CHPO2 - CHPO3;
      FIN BCL10;
   FINSI;
   CHPO2=ENLEVER CHPO2 LX;
   SCAL1=XTMX CHPO2 MAS1;
   SCAL1=SCAL1 ** 0.5;
   CHPO2=CHPO2 / SCAL1;
   TSTAT2 . &BCL9=CHPO2;
   LIST &BCL9;
FIN BCL9;
*
* Base modale finale
*
TBAS1=TABLE 'BASE_MODALE';
TVEC1=TABLE 'MODES';
TVEC1 . MAILLAGE=TMOD1 . MODES . MAILLAGE;
REPETER BCL11 (NSTA1);
   TVEC1 . &BCL11=TABLE 'MODE';
   TVEC1 . &BCL11 . DEFORMEE_MODALE=TSTAT2 . &BCL11;
   TVEC1 . &BCL11 . POINT_REPERE=(0. 0.);
   TVEC1 . &BCL11 . FREQUENCE=0.;
   TVEC1 . &BCL11 . MASSE_GENERALISEE=1.;
FIN BCL11;
REPETER BCL12 (NMOD1);
   TVEC1 . (NSTA1 + &BCL12)=TABLE 'MODE';
   TVEC1 . (NSTA1 + &BCL12) . DEFORMEE_MODALE=TDYN1 . &BCL12;
   TVEC1 . (NSTA1 + &BCL12) . POINT_REPERE=(0. 0.);
   TVEC1 . (NSTA1 + &BCL12) . FREQUENCE=0.;
   TVEC1 . (NSTA1 + &BCL12) . MASSE_GENERALISEE=1.;
FIN BCL12;
TBAS1 . MODES=TVEC1;
*
* Projection des matrices de masse et de rigidite
*
MASP1=PJBA MAS1 TBAS1;
RIGP1=PJBA RIG1 TBAS1;
*
* Frequence max du systeme reduit
*
TSTAB1=VIBR 'INTERVALLE' 0. 50000. HAUTE 1 MASP1 RIGP1 'IMPR' 'TBAS';
*
* Sauvegarde des donnees pour PLEXUS
*
NTOT1=NSTA1 + NMOD1;
TSORT1=TABLE;
REPETER BCL13 (NTOT1);
   TSORT1 . &BCL13=TBAS1 . MODES . &BCL13 . DEFORMEE_MODALE;
FIN BCL13;
*
OPTI SAUV FORMAT 'doma01.modes';
SAUV FORMAT TOUT TSORT1;
*
TDON1=TABLE;
TDON1 . 1=NSTA1;
TDON1 . 2=NMOD1;
TDON1 . 3=TSTAB1 . MODES . 1 . FREQUENCE;
*
OPTI SAUV FORMAT 'doma01.matr';
SAUV FORMAT TDON1 MASP1 RIGP1;
*
FIN;
```

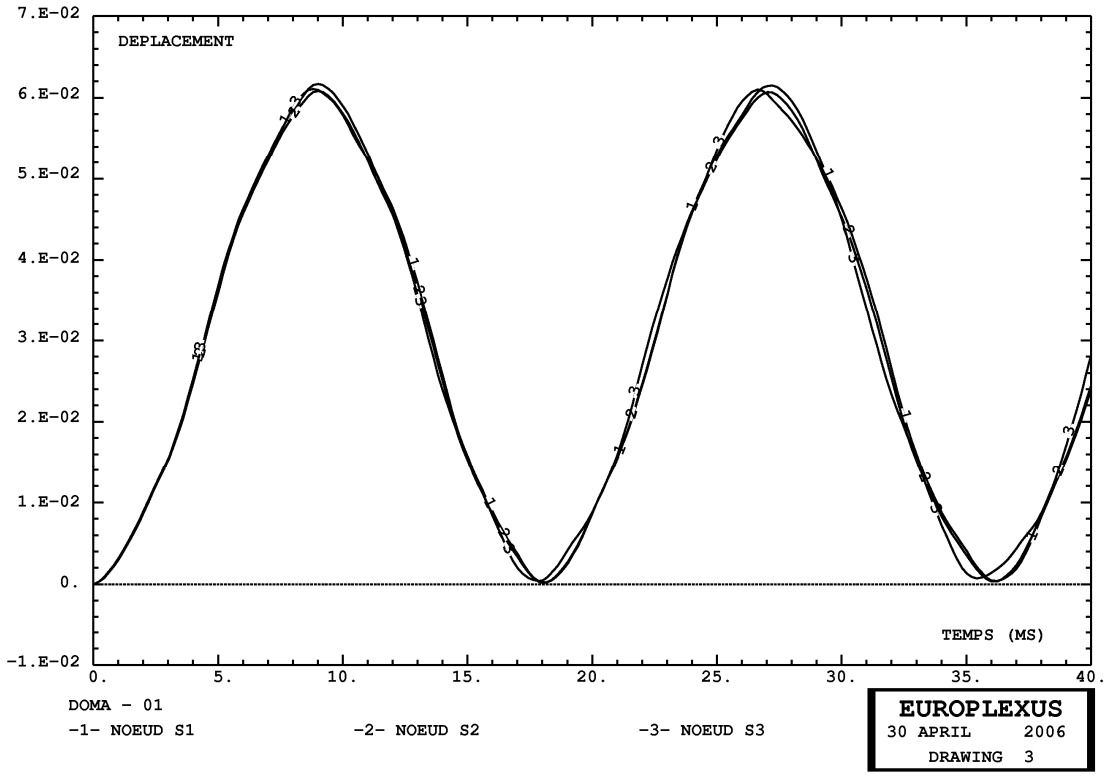
The input file is:

```
DOMA - 01
*------------------------------------------------------------------------
ECHO
!conv win
CAST tout
*-------------------------------------------------------------Problem type
DPLA NONL
*-------------------------------------------------------------Dimensioning
DIME
  PT2L 110 CAR4 64 CL2D 10 ZONE 2
  TABL 1 4 ECRO 522
  FORC 10  MTPO 9
TERM
*------------------------------------------------------------------Geometry
GEOM CAR4 tout
     CL2D p21_p22p p23_p24 p31_p32p p33_p34
     TERM
*-----------------------------------------------Geometric Complements
COMP GROU 4
     'interf' LECT p21_p22p p23_p24 p31_p32p p33_p34 TERM
     'prob1'  LECT dom11 dom12 TERM
     'prob2'  LECT dom21 dom22 p21_p22p p23_p24 TERM
     'prob3'  LECT dom31 dom32 p31_p32p p33_p34 TERM
     NGRO 4
     'tpln'   LECT p1 r1 s1 p2 r2 s2 p3 r3 s3 TERM
     'char1'  LECT p23_p24p p33_p34p TERM
     'char2'  LECT p13_p14p TERM
     'bloqa'  LECT p11_p12 p21_p22 p31_p32 TERM
     COUL turq LECT prob1 TERM
          rose LECT prob2 TERM
          vert LECT prob3 TERM
*-----------------------------------------------------------Material data
MATE
   LINE RO 7800. YOUN 210.E9 NU 0.3
        LECT tout TERM
   FANT 0.
        LECT interf TERM
*-----------------------------------------------------------Applied "loads"
CHAR 1 FACT 2
   FORC 2 1.E7   LECT char1 TERM
   FORC 2 0.75E7 LECT char2 TERM
   TABL 2 0.0 1.0 1.0 1.0
*-----------------------------------------------------Boundary conditions
LINK COUP BLOQ 12 LECT bloqa TERM
*-------------------------------------------------------------------Outputs
ECRI DEPL TFRE 4D-3 NOEL
          POIN LECT tpln TERM
     FICH ALIC TEMP TFREQ 0.2D-3
          POIN LECT tpln TERM
          ELEM LECT 1 TERM
     FICH ALIC FREQ 8
*------------------------------------------------------------------Options
OPTI CSTA 0.5
  LOG 1
*-----------------------------------------------Domain decomposition
STRU 6
   DOMA LECT dom11          TERM IDEN 91
   DOMA LECT dom12          TERM IDEN 92
   DOMA LECT dom21 p21_p22p TERM IDEN 93
   DOMA LECT dom22 p23_p24  TERM IDEN 94
   DOMA LECT dom31 p31_p32p TERM IDEN 95
   MODA LECT dom32 p33_p34  TERM IDEN 96
   FICH FORM 9 POST TOUS
$
$--- Attention : pour les BENCHs, le fichier des modes est concatené au
$               fichier maillage. D'ou la valeur 9, qui est la valeur par
$               defaut du fichier maillage, affectée au fichier  des modes.
$               Ce fait vient du fait que l'atelier logiciel ne peut gérer
$               pour l'instant que 2 fichiers input
$
$    POUR LES CALCULS STANDARDS : ces deux fichiers DOIVENT ETRE SEPARES !!!
$    Il faut donner un numero logique différent de 9 (unité logique par défaut
$    du fichier maillage)
$    Si ce numero n'est pas donné, Europlexus l'affectera le numero 50
$    et l'extension par defaut du fichier est '.mod'
$
INTE 3
   COMP TOLE 0.001
      DOMA 91 LECT p11_p12p TERM
      DOMA 92 LECT p13_p14  TERM
   OPTI
      DOMA 93 LECT p21_p22p TERM
      DOMA 94 LECT p23_p24  TERM
   MORT
      DOMA 96 LECT p33_p34  TERM
      DOMA 95 LECT p31_p32p TERM
*-----------------------------------------------------Transient calculation
CALC TINI 0. TFIN 40.E-3
*============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1E3 'Temps (ms)'
*-----------------------------------------------------Curve definitions
COUR  1 'noeud P1' DEPL COMP 2 NOEU LECT p1 TERM
COUR  2 'noeud R1' DEPL COMP 2 NOEU LECT r1 TERM
COUR  3 'noeud S1' DEPL COMP 2 NOEU LECT s1 TERM
COUR 11 'noeud P2' DEPL COMP 2 NOEU LECT p2 TERM
COUR 12 'noeud R2' DEPL COMP 2 NOEU LECT r2 TERM
COUR 13 'noeud S2' DEPL COMP 2 NOEU LECT s2 TERM
COUR 21 'noeud P3' DEPL COMP 2 NOEU LECT p3 TERM
COUR 22 'noeud R3' DEPL COMP 2 NOEU LECT r3 TERM
COUR 23 'noeud S3' DEPL COMP 2 NOEU LECT s3 TERM
*-------------------------------------------------------------------Plots
trac  1 11 21 AXES 1 'Deplacement' yzer
trac  2 12 22 AXES 1 'Deplacement' yzer
trac  3 13 23 AXES 1 'Deplacement' yzer
*-----------------------------------------------Results qualification
QUAL DEPL COMP 2 REFE 2.38669E-02 TOLE 1.E-2 LECT s1 TERM
     DEPL COMP 2 REFE 2.44172E-02 TOLE 1.E-2 LECT s2 TERM
     DEPL COMP 2 REFE 2.81579E-02 TOLE 1.E-2 LECT s3 TERM
*=====================================================================
FIN
```

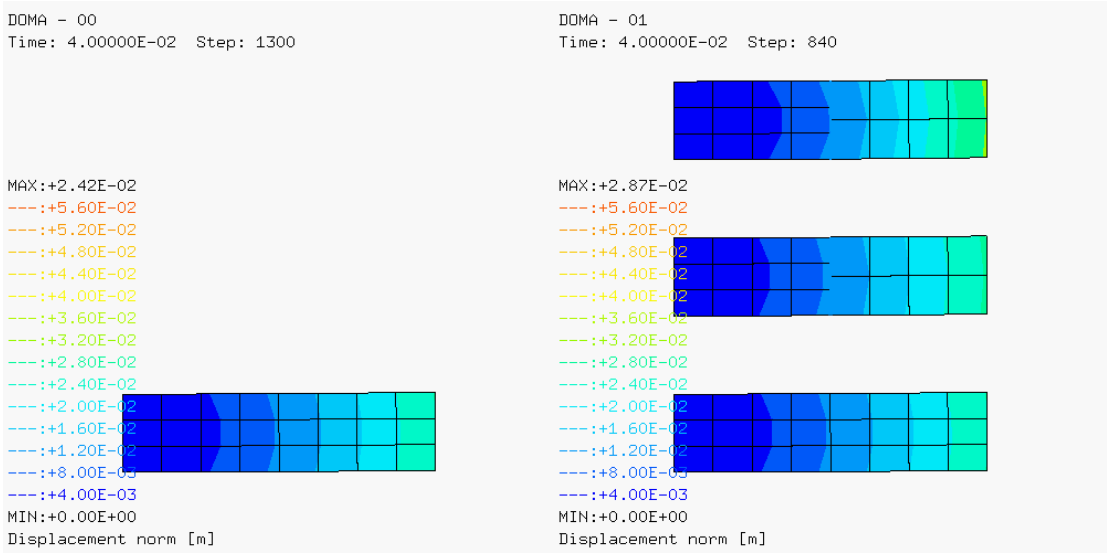
The tip displacement in the reference case is:



The tip displacement in the three cases with domain decomposition are:

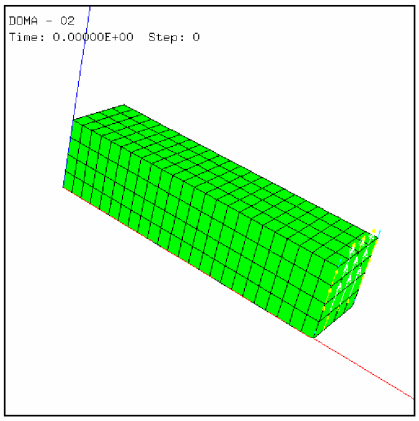


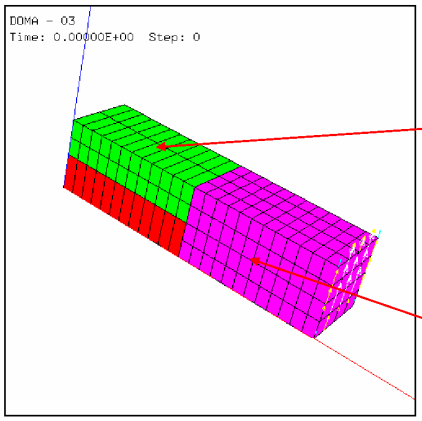
The final displacement field in the reference case and in the three cases with domain decomposition are:



Example 14 – Domains in 3D

- Thick 3D beam under bending:





Subdomains 1 and 2 are conforming

Subdomains 1 (or 2) and 3 are non-conforming

Reference Case (no decomposition)

Case with domain decomposition

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Problem description:

This example represents the bending of a thick beam in 3D conditions. The beam is clamped at the left end and loaded by concentrated forces at the right end. The material is linear elastic.

Two solutions are obtained. The first one without domain decomposition is used as a reference, while the second uses decomposition in three sub-domains, one of which is non-conforming with the other two.

Numerical Solutions

DOMA02

This calculation uses no domain decomposition and is used to obtain a reference solution. It uses a regular mesh of 384 elements of type CUB8.

The mesh generation file is:

```
*%siz 50
*
OPTI ECHO 1 ELEM CUB8 DIME 3;
opti titr 'DOMA - 02';
opti trac psc ftra 'doma02_mesh.ps';
*
P1=0. 0. 0.;
P2=0. 10. 0.;
P3=0. 10. 10.;
P4=0. 0. 10.;
*
P9=40. 5. 5.;
P14=20. 5. 5.;
*
BASE = DALL (P1 D 4 P2) (P2 D 4 P3) (P3 D 4 P4) (P4 D 4 P1) PLAN;
VECT=40. 0. 0.;
*
P1P = P1 PLUS VECT;
P2P = P2 PLUS VECT;
P3P = P3 PLUS VECT;
P4P = P4 PLUS VECT;
*
BODY = VOLU BASE TRAN 24 VECT;
ELIM 0.001 BODY (P9 ET P14 ET P1P ET P2P ET P3P et P4P);
CLIM1 = P1P ET P2P ET P3P ET P4P;
CLIM2 = BODY POIN DROI P1P P2P 0.001;
CLIM2 = CLIM2 ET (BODY POIN DROI P2P P3P 0.001);
CLIM2 = CLIM2 ET (BODY POIN DROI P3P P4P 0.001);
CLIM2 = CLIM2 ET (BODY POIN DROI P4P P1P 0.001);
SURF3 = BODY POIN PLAN P1P P2P P3P 0.001;
TOUT = BODY ET CLIM1 ET CLIM2 ET SURF3;
TASS TOUT;
*
OPTI SAUV FORMAT 'doma02.msh';
SAUV FORMAT TOUT;
*
OEIL1=-10000. -10000. 10000.;
OEIL2=10000. -10000. 10000.;
*
TRAC OEIL2 BODY;
TRAC CACH OEIL2 BODY;
*
fin;
```

The input file is:

```
DOMA - 02
*------------------------------------------------------------------------
ECHO
!conv win
CAST tout
*-------------------------------------------------------------Problem type
TRID NONL
*-------------------------------------------------------------Dimensioning
DIME
  PT3L 625 CUB8 384
  MTPO 2
  TABL 1 4 FORC 200
TERM
*-----------------------------------------------------------------Geometry
GEOM CUB8 body
     TERM
*-----------------------------------------------Geometric Complements
COMP COUL vert LECT body TERM
*-----------------------------------------------------------Material data
MATE
   LINE RO 7800. YOUN 210E9 NU 0.
        LECT body TERM
*-----------------------------------------------------------Applied "loads"
CHAR 1 FACT 2
   FORC 3 -1.E9 LECT clim1 TERM
   FORC 3 -2.E9 LECT clim2 TERM
   FORC 3  4.E9 LECT surf3 TERM
   TABL 2 0.0 1.0 1.0 1.0
*-----------------------------------------------Boundary conditions
LINK COUP BLOQ 123 LECT base TERM
*-------------------------------------------------------------------Outputs
ECRI DEPL TFRE 2.5E-2
         POIN LECT p9 p14 TERM
         NOEL
     FICH ALIC TEMP FREQ 1
         POIN LECT p9 p14 TERM
         ELEM LECT 1 TERM
     FICH ALIC TFRE 3.E-3
*------------------------------------------------------------------Options
OPTI CSTA 0.5
     LOG 1 DPSD
*-----------------------------------------------------Transient calculation
CALC TINI 0.0 TFIN 300.E-3
*=========================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1E3 'Temps (ms)'
*-------------------------------------------------------Curve definitions
COUR 1 'noeud P9'  DEPL COMP 3 NOEU LECT p9  TERM
COUR 2 'noeud P14' DEPL COMP 3 NOEU LECT p14 TERM
*-------------------------------------------------------------------Plots
TRAC 1 2 AXES 1 'Deplacement' yzer
*-----------------------------------------------Results qualification
QUAL DEPL COMP 3 LECT p9  TERM REFE 1.43266E+01 TOLE 1E-2
     DEPL COMP 3 LECT p14 TERM REFE 4.82882E+00 TOLE 1E-2
*========================================================================
FIN
```

DOMA03

This calculation uses decomposition into three sub-domains:

- Domain 1 corresponds to ¼ of the beam and is coarser than the reference;
- Domain 2 corresponds to ¼ of the beam, is also coarser than the reference and is conforming with domain 1.
- Domain 3 corresponds to the remaining ½ of the structure. It has the same mesh as the reference and is therefore non-conforming with respect to both domain 1 and domain 2.

Altogether, the mesh contains 264 elements of type CUB8 and 22 elements of type CL3D to define the interfaces between non-conforming sub-domains.

The mesh generation file is:

```
*$siz 50
*
OPTI ECHO 1 ELEM CUB8 DIME 3;
opti titr 'DOMA - 03';
opti trac psc ftra 'doma03_mesh.ps';
*
P1=0. 0. 0.;
P2=0. 10. 0.;
P3=0. 10. 10.;
P4=0. 0. 10.;
*
P5=20. 0. 0.;
P6=20. 10. 0.;
P7=20. 10. 10.;
P8=20. 0. 10.;
*
P10=0. 0. 5.;
P11=0. 10. 5 .;
P12=20. 0. 5.;
P13=20. 10. 5 .;
*
P9=40. 5. 5.;
P14=20. 5. 5.;
*
NY1=2; NZ1=1;
NY2=2; NZ2=2;
NY3=4; NZ3=2;
NY32=4; NZ32=2*NZ3;
NX1=12; NX2=12;
*
VECT=20. 0. 0.;
*
CLIM1=(P5 ET P6 ET P7 ET P8);
CLIM1=CLIM1 PLUS VECT;
CLIM2=(P5 D NY3 P6 D NZ32 P7 D NY3 P8 D NZ32 P5);
CLIM2=CLIM2 PLUS VECT;
*
P1_P2=P1 D NY1 P2;
P2_P11=P2 D NZ1 P11;
P11_P10=P11 D NY1 P10;
P10_P1=P10 D NZ1 P1;
*
SURF01=DALLER P1_P2 P2_P11 P11_P10 P10_P1;
*
P10_P11=P10 D NY2 P11;
P11_P3=P11 D NZ2 P3;
P3_P4=P3 D NY2 P4;
P4_P10=P4 D NZ2 P10;
*
SURF02=DALLER P10_P11 P11_P3 P3_P4 P4_P10;
*
SURF0=SURF01 ET SURF02;
*
P6_P13=P6 D NZ3 P13;
P13_P12=P13 D NY32 P12;
P12_P13=P12 D NY32 P13;
P12_P5=P12 D NZ3 P5;
P13_P7=P13 D NZ3 P7;
P8_P12=P8 D NZ3 P12;
*
P5_P6=P5 D NY32 P6;
P6_P7=P6 D NZ32 P7;
P7_P8=P7 D NY32 P8;
P8_P5=P8 D NZ32 P5;
*
SURF2=DALLER P5_P6 P6_P7 P7_P8 P8_P5;
SURF21=DALLER P5_P6 P6_P13 P13_P12 P12_P5;
SURF22=DALLER P12_P13 P13_P7 P7_P8 P8_P12;
*
SURF11=SURF01 PLUS VECT;
SURF12=SURF02 PLUS VECT;
SURF3=SURF2 PLUS VECT;
*
P10_P11P=P10_P11 PLUS VECT;
SURFC1=P10_P11 REGL NX1 P10_P11P;
SURFC2=SURFC1 PLUS (0. 0. 0.);
SURFC1=SURFC1 COUL ROUGE;
SURFC2=SURFC2 COUL BLEU;
*
ELIM 0.001 SURF3 (CLIM1 ET CLIM2 ET P9);
*
ZONE1=SURF01 VOLU NX1 SURF11;
ZONE2=SURF02 VOLU NX1 SURF12;
ZONE3=SURF2 VOLU NX2 SURF3;
*
ELIM 0.001 ZONE1 (SURFC1 ET SURF0 ET SURF11);
ELIM 0.001 ZONE1;
ELIM 0.001 ZONE2 (SURFC2 ET SURF0 ET SURF12);
ELIM 0.001 ZONE2;
ELIM 0.001 ZONE3;
ELIM 0.001 ZONE3 (SURF3 ET SURF21 ET SURF22 ET P14);
*
TOUT=ZONE1 ET ZONE2 ET ZONE3;
*
OPTI SAUV FORMAT 'doma03.msh';
SAUV FORMAT TOUT;
*
OEIL1=-10000. -10000. 10000.;
OEIL2=10000. -10000. 10000.;
*
TRAC CLIM2;
TRAC (CLIM1 ET CLIM2);
TRAC (SURF3 ET CLIM1 ET CLIM2);
TRAC SURF0;
TRAC (SURF11 ET SURF12 );
TRAC SURF21;
TRAC SURF22;
TRAC (SURF21 ET SURF22 );
TRAC (SURF11 ET SURF12 ET SURF21 ET SURF22 ET SURFC1 ET SURFC2);
TRAC CACH OEIL2 ZONE1;
TRAC CACH OEIL2 ZONE2;
TRAC CACH OEIL1 ZONE3;
TRAC OEIL2 TOUT;
TRAC CACH OEIL2 TOUT;
*
OPTI DONN 5;
fin;
```

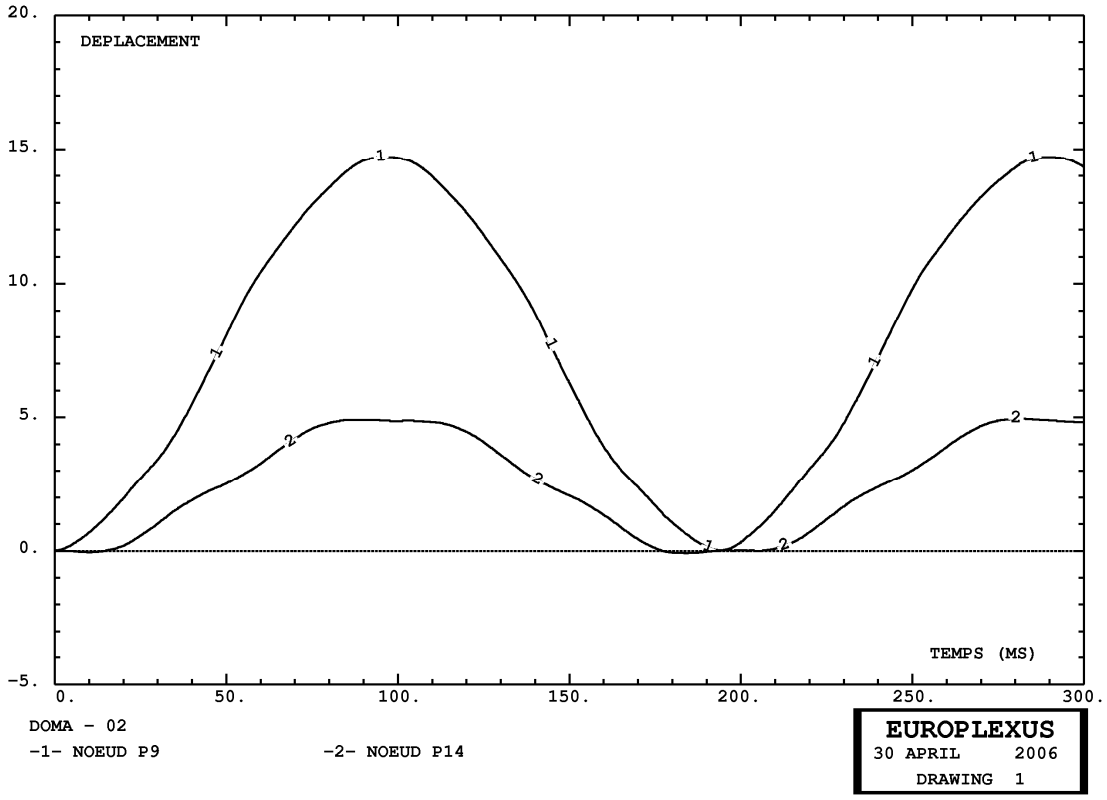
The input file is:

```
DOMA - 03
*------------------------------------------------------------------------
ECHO
!conv win
CAST tout
*-------------------------------------------------------------Problem type
```

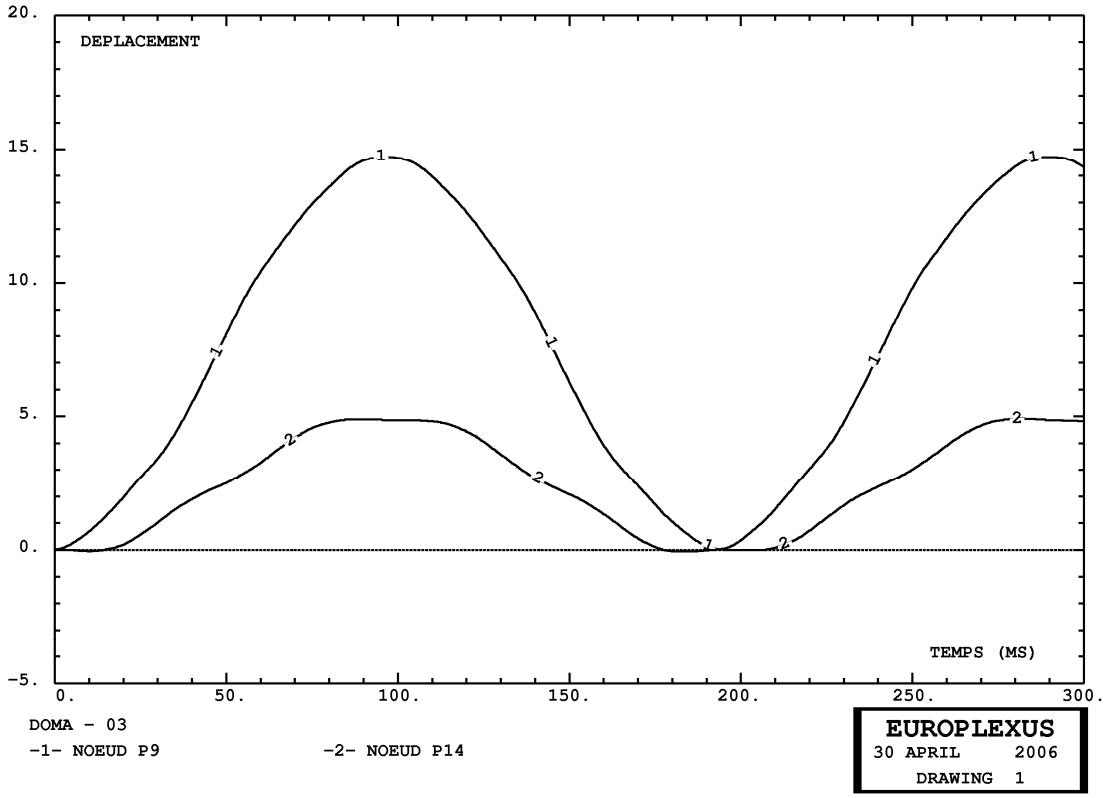
```
TRID NONL
*-------------------------------------------------------------Dimensioning
DIME
  PT3L 1000 CUB8 1000 CL3D 1000 ZONE 2
  MTPO 2
  TABL 1 4 FORC 200
TERM
*-----------------------------------------------------------------Geometry
GEOM CUB8 tout
     CL3D surf11 surf12 surf21 surf22
     TERM
*-----------------------------------------------Geometric Complements
COMP COUL roug LECT zone1 surf11 TERM
          vert LECT zone2 surf12 TERM
          rose LECT zone3 surf21 surf22 TERM
*-------------------------------------------------------------Material data
MATE
   LINE RO 7800. YOUN 210E9 NU 0.
        LECT zone1 zone2 zone3 TERM
   FANT 0.
        LECT surf11 surf12 surf21 surf22 TERM
*-----------------------------------------------------------Applied "loads"
CHAR 1 FACT 2
   FORC 3 -1.E9 LECT clim1 TERM
   FORC 3 -2.E9 LECT clim2 TERM
   FORC 3  4.E9 LECT surf3 TERM
   TABL 2 0.0 1.0 1.0 1.0
*-----------------------------------------------------Boundary conditions
LINK COUP BLOQ 123 LECT surf0 TERM
*-------------------------------------------------------------------Outputs
ECRI DEPL TFRE 2.5E-2
          POIN LECT p9 p14 TERM
          NOEL
     FICH ALIC TEMP FREQ 1
          POIN LECT p9 p14 TERM
          ELEM LECT 1 TERM
     FICH ALIC TFRE 3.E-3
```

```
*-----------------------------------------------------------------Options
OPTI CSTA 0.5
     LOG 1 DPSD
*-----------------------------------------------Domain decomposition
STRU 3
   DOMA LECT zone1 surf11        TERM
   DOMA LECT zone2 surf12        TERM
   DOMA LECT zone3 surf21 surf22 TERM
INTE 3
   COMP
      DOMA 1 LECT surfc1 TERM
      DOMA 2 LECT surfc2 TERM
   MORT
      DOMA 1 LECT surf11 TERM
      DOMA 3 LECT surf21 TERM
   MORT
      DOMA 2 LECT surf12 TERM
      DOMA 3 LECT surf22 TERM
*-----------------------------------------------Transient calculation
CALC TINI 0.0 TFIN 300.E-3
*=============================================================POST-TREATMENT
SUIT
Post-treatment
ECHO
RESU ALIC TEMP GARD PSCR
SORT GRAP
AXTE 1E3 'Temps (ms)'
*-----------------------------------------------Curve definitions
COUR 1 'noeud P9'  DEPL COMP 3 NOEU LECT p9  TERM
COUR 2 'noeud P14' DEPL COMP 3 NOEU LECT p14 TERM
*-----------------------------------------------------------------------Plots
TRAC 1 2 AXES 1 'Deplacement' yzer
*-----------------------------------------------Results qualification
QUAL DEPL COMP 3 LECT p9  TERM REFE 1.43266E+01 TOLE 1E-2
     DEPL COMP 3 LECT p14 TERM REFE 4.82882E+00 TOLE 1E-2
*=====================================================================
FIN
```

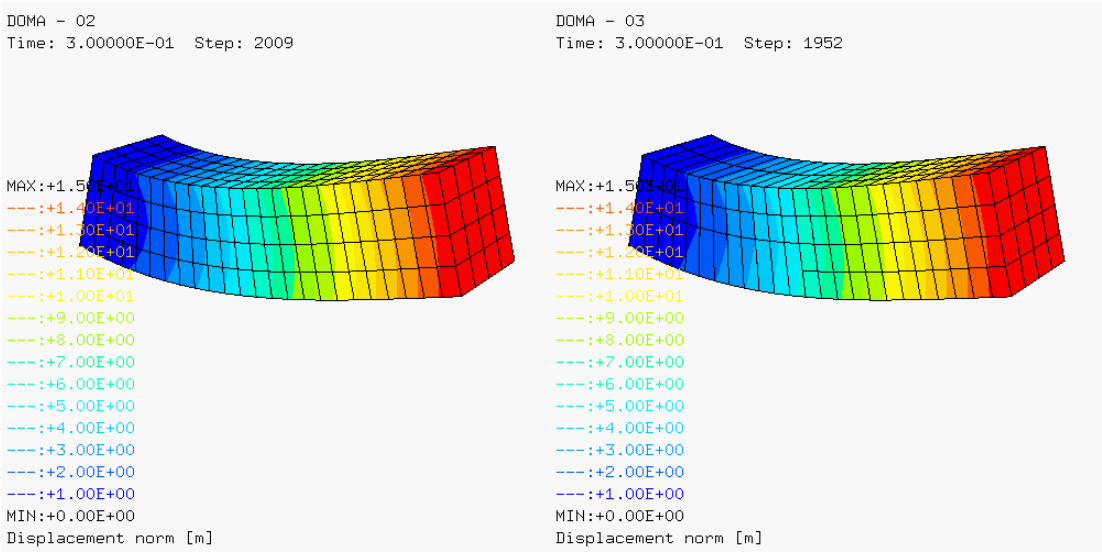
The tip displacement in the reference case is:



The tip displacement in the case with domain decomposition is:

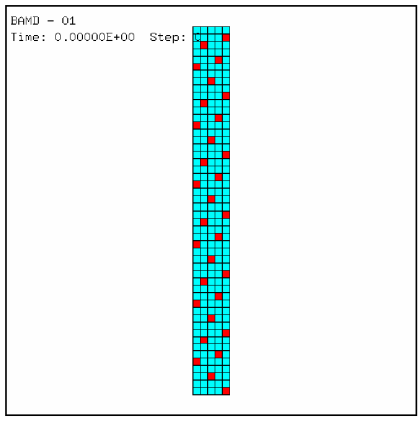


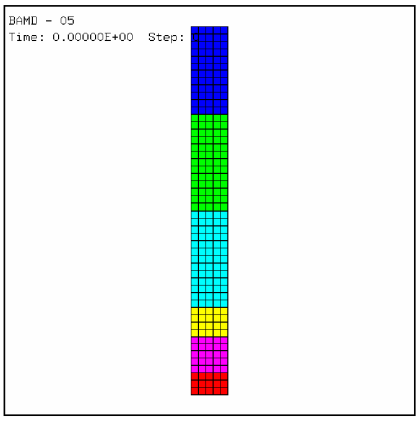
The final displacement field in the reference case and in the case with domain decomposition are:



Example 15 – Bar Impact Revisited

- Taylor bar impact test:





Reference Case (no decomposition)

Case with time step partitioning (OPTI PART)

Case with domain decomposition (colors indicate sub-domains)

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Problem description:

This example represents the bending of a thick beam in 3D conditions. The beam is clamped at the left end and loaded by concentrated forces at the right end. The material is linear elastic.

Two solutions are obtained. The first one without domain decomposition is used as a reference, while the second uses decomposition in three sub-domains, one of which is non-conforming with the other two.

Numerical Solutions

BAMD01

This calculation uses no domain decomposition and is used to obtain a reference solution. It uses a regular mesh of 306 elements of type Q41L and 219 elements of type Q42L.

The mesh generation file is:

```
*%siz 40
*
opti echo 1;
*
opti titr 'BAMD - 01';
opti dime 2 elem qua4;
*
p0=0 0;
p1=3.2E-3 0;
p2=0 32.4E-3;
tol=0.01E-3;
*
base=p0 d 5 p1;
stru=base TRAN 50 p2;
elim tol (stru et p2);
*
symax=stru poin droi p0 p2 tol;
top=stru poin droi p2 (p1 PLUS p2) tol;
*
str1=chan 'POI1' stru;
bas1=chan 'POI1' base;
viti=diff str1 bas1;
*
nstr=nbel stru;
nten=(nstr + 1) / 8;
nten=enti nten;
j=0;
*
i=0 - 3;repe loop nten;i=i+8;
  si (<eg i nstr);
    eli=stru elem i;
    si (ega j 0);
      sq42=eli;
    sinon;
      sq42=sq42 et eli;
    fins1;
    j=j+1;
  fins1;
fin loop;
*
```

```
sq41=diff stru sq42;
*
mesh=stru et symax et viti;
tass mesh;
*
opti sauv form 'bamd01.msh';
sauv form mesh;
```

```
*
opti trac psc ftra 'bamd01_mesh.ps';
sq41=sq41 coul 'TURQ';
sq42=sq42 coul 'ROUG';
trac face (sq41 et sq42);
trac qual mesh;
fin;
```

The input file is:

```
BAMD - 01
$
ECHO
$VERI
$CONV win
CAST MESH
AXIS NONL
$
DIME
  PT2L 306 Q41L 219 Q42L 31 ZONE 2
  TABL 1 5
  mtpo 7
  depl 200
  tabl 1 2
TERM
$
GEOM Q41L SQ41 Q42L SQ42 TERM
$
COMP EPAI 1 TOUS
$
MATE VM23 RO 8930. YOUN 1.17D11 NU 0.35D0 ELAS 4.D8
          TRAC 2 4.D8 3.418803D-03 1.004D11 1000.003418803
          TOUS
$
CHAR 1 FACT 2
     DEPL 2 0.0 LECT BASE  TERM
     DEPL 1 0.0 LECT SYMAX TERM
     TABL 2 0.0 1.0 1.0 1.0
$
INIT VITE 2 -227. LECT VITI TERM
$
ECRI DEPL VITE TFRE 10.E-6
```

```
          POIN LECT P1 TOP TERM
     fich alic tfre 80.e-8
$
OPTI NOTE
  csta 0.5
  log 1
$
CALC TINI 0. TEND 80.D-6
*=====================================================================
SUIT
Post-treatment of bar impact problem
ECHO
*
RESU alic GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR 1 'dr_p1'  DEPL COMP 1 NOEU LECT p1  TERM
COUR 2 'dz_p2'  DEPL COMP 2 NOEU LECT p2  TERM
COUR 3 'vr_p1'  VITE COMP 1 NOEU LECT p1  TERM
COUR 4 'vz_p2'  VITE COMP 2 NOEU LECT p2  TERM
*
TRAC 1 2 AXES 1.0 'DISPL. [M]' yzer
TRAC 3 4 AXES 1.0 'VELOC. [M/S]' yzer
*
QUAL DEPL COMP 1 LECT p1  TERM REFE  3.88425E-3 TOLE 1.E-3
     DEPL COMP 2 LECT p2  TERM REFE -1.09666E-2 TOLE 1.E-3
*=====================================================================
FIN
```

BAMD03

This calculation uses the seame mesh as the previous one (no domain decomposition). The time step partitioning technique is activated by specifying OPTI PART.

The mesh generation file is:

```
*%siz 40
*
opti echo 1;
*
opti titr 'BAMD - 03';
opti dime 2 elem qua4;
*
p0=0 0;
p1=3.2E-3 0;
p2=0 32.4E-3;
tol=0.01E-3;
*
base=p0 d 5 p1;
stru=base TRAN 50 p2;
elim tol (stru et p2);
*
symax=stru poin droi p0 p2 tol;
top=stru poin droi p2 (p1 PLUS p2) tol;
*
str1=chan 'POI1' stru;
bas1=chan 'POI1' base;
viti=diff str1 bas1;
*
nstr=nbel stru;
nten=(nstr + 1) / 8;
nten=enti nten;
j=0;
```

```
*
i=0 - 3;repe loop nten;i=i+8;
  si (<eg i nstr);
    eli=stru elem i;
    si (ega j 0);
      sq42=eli;
    sinon;
      sq42=sq42 et eli;
    finsi;
    j=j+1;
  finsi;
fin loop;
*
sq41=diff stru sq42;
*
mesh=stru et symax et viti;
tass mesh;
*
opti sauv form 'bamd03.msh';
sauv form mesh;
*
opti trac psc ftra 'bamd03_mesh.ps';
sq41=sq41 coul 'TURQ';
sq42=sq42 coul 'ROUG';
trac face (sq41 et sq42);
trac qual mesh;
fin;
```

The input file is:

```
BAMD - 03
$
ECHO
$VERI
$CONV win
CAST MESH
AXIS NONL
$
DIME
  PT2L 306 Q41L 219 Q42L 31 ZONE 2
  TABL 1 5
  mtpo 7
  depl 200
  tabl 1 2
TERM
$
GEOM Q41L SQ41 Q42L SQ42 TERM
$
COMP EPAI 1 TOUS
$
MATE VM23 RO 8930. YOUN 1.17D11 NU 0.35D0 ELAS 4.D8
          TRAC 2 4.D8 3.418803D-03 1.004D11 1000.003418803
          TOUS
$
CHAR 1 FACT 2
     DEPL 2 0.0 LECT BASE  TERM
     DEPL 1 0.0 LECT SYMAX TERM
     TABL 2 0.0 1.0 1.0 1.0
$
INIT VITE 2 -227. LECT VITI TERM
$
ECRI DEPL VITE TFRE 10.E-6
```

```
          POIN LECT P1 TOP TERM
     fich alic tfre 80.e-8
$
OPTI PART NOTE step io
  csta 0.5
  log 1
$
CALC TINI 0. TEND 80.D-6
*=====================================================================
SUIT
Post-treatment of bar impact problem
ECHO
*
RESU alic GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR 1 'dr_p1'  DEPL COMP 1 NOEU LECT p1  TERM
COUR 2 'dz_p2'  DEPL COMP 2 NOEU LECT p2  TERM
COUR 3 'vr_p1'  VITE COMP 1 NOEU LECT p1  TERM
COUR 4 'vz_p2'  VITE COMP 2 NOEU LECT p2  TERM
*
TRAC 1 2 AXES 1.0 'DISPL. [M]' yzer
TRAC 3 4 AXES 1.0 'VELOC. [M/S]' yzer
*
QUAL DEPL COMP 1 LECT p1  TERM REFE  3.88425E-3 TOLE 1.E-3
     DEPL COMP 2 LECT p2  TERM REFE -1.09666E-2 TOLE 1.E-3
*=====================================================================
FIN
```

BAMD05

This calculation uses the same mesh as the previous ones, but with decomposition into six sub-domains of various sizes. These are all conforming with respect to one another.

The scope is to activate a sort of sub-cycling in the sub-domains that undergo larger deformations than the others (i.e. the two sub-domains close to the projectile tip).

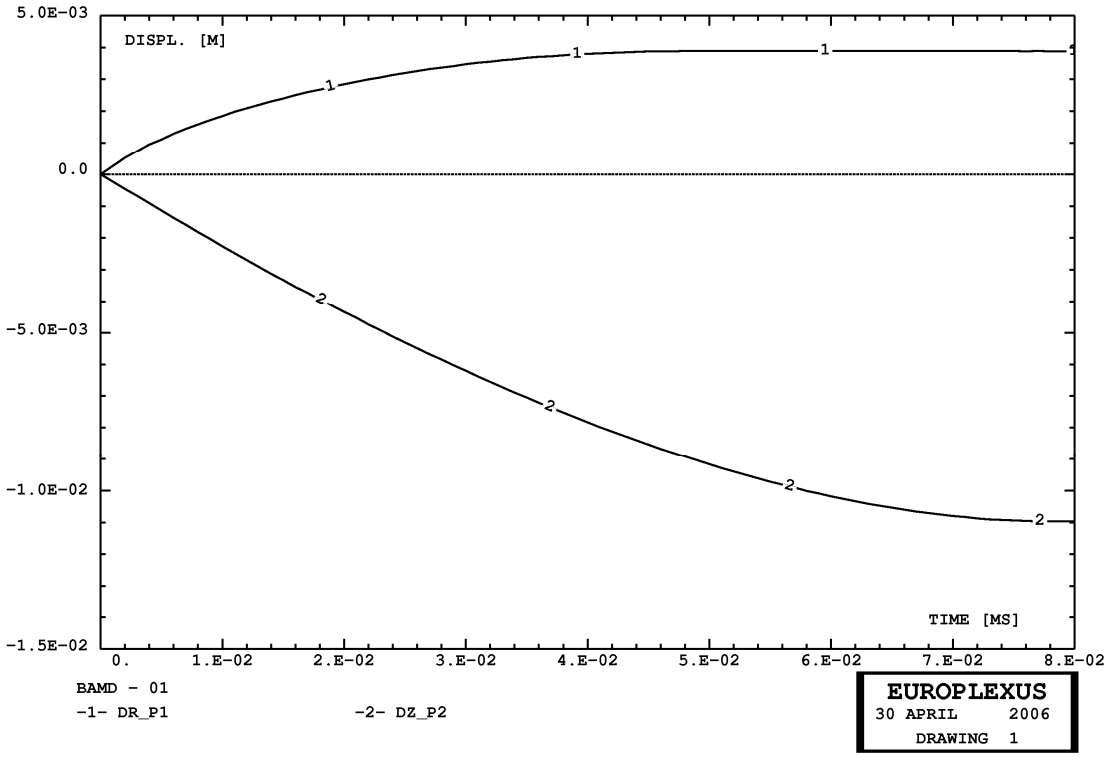
The mesh generation file is:

```
*%siz 40
*
opti echo 1;
*
opti titr 'BAMD - 05';
opti dime 2 elem qua4;
*
p0=0 0;
p1=3.2E-3 0;
p2=0 32.4E-3;
tol=0.01E-3;
*
base=p0 d 5 p1;
stru=base TRAN 50 p2;
elim tol (stru et p2);
*
symax=stru poin droi p0 p2 tol;
top=stru poin droi p2 (p1 PLUS p2) tol;
*
str1=chan 'POI1' stru;
bas1=chan 'POI1' base;
viti=diff str1 bas1;
*
nstr=nbel stru;
nten=(nstr + 1) / 8;
nten=enti nten;
j=0;
*
i=0 - 3;repe loop nten;i=i+8;
  si (<eg i nstr);
    eli=stru elem i;
    si (ega j 0);
      sq42=eli;
    sinon;
      sq42=sq42 et eli;
    finsi;
    j=j+1;
  finsi;
fin loop;
*
sq41=diff stru sq42;
*
h1=2.1e-3;
h2=5.1e-3;
h3=8.1e-3;
h4=16.2e-3;
h5=24.3e-3;
*
n1=0;n2=0;n3=0;n4=0;n5=0;n6=0;
i=0;repe loop2 (nbel stru);i=i+1;
  ei = stru elem i;
  bi = bary ei;
  xb yb = coor bi;
  si (<eg yb h1);
    si (ega n1 0);
      s1=ei;
    sinon;
      s1=s1 et ei;
    finsi;
    n1=n1+1;
  sinon;
    si (<eg yb h2);
      si (ega n2 0);
        s2=ei;
      sinon;
        s2=s2 et ei;
      finsi;
      n2=n2+1;
    sinon;
      si (<eg yb h3);
        si (ega n3 0);
          s3=ei;
        sinon;
          s3=s3 et ei;
        finsi;
        n3=n3+1;
      sinon;
        si (<eg yb h4);
          si (ega n4 0);
            s4=ei;
          sinon;
            s4=s4 et ei;
          finsi;
          n4=n4+1;
        sinon;
          si (<eg yb h5);
            si (ega n5 0);
              s5=ei;
            sinon;
              s5=s5 et ei;
            finsi;
            n5=n5+1;
          sinon;
            si (ega n6 0);
              s6=ei;
            sinon;
              s6=s6 et ei;
            finsi;
            n6=n6+1;
          finsi;
        finsi;
      finsi;
    finsi;
  finsi;
fin loop2;
*
list (nbel s1);
list (nbel s2);
list (nbel s3);
list (nbel s4);
list (nbel s5);
list (nbel s6);
list (nbel stru);
*
mesh=stru et symax et viti;
tass mesh;
*
opti sauv form 'bamd05.msh';
sauv form mesh;
*
opti trac psc ftra 'bamd05_mesh.ps';
sq41=sq41 coul 'TURQ';
sq42=sq42 coul 'ROUG';
trac face (sq41 et sq42);
trac qual mesh;
fin;
```

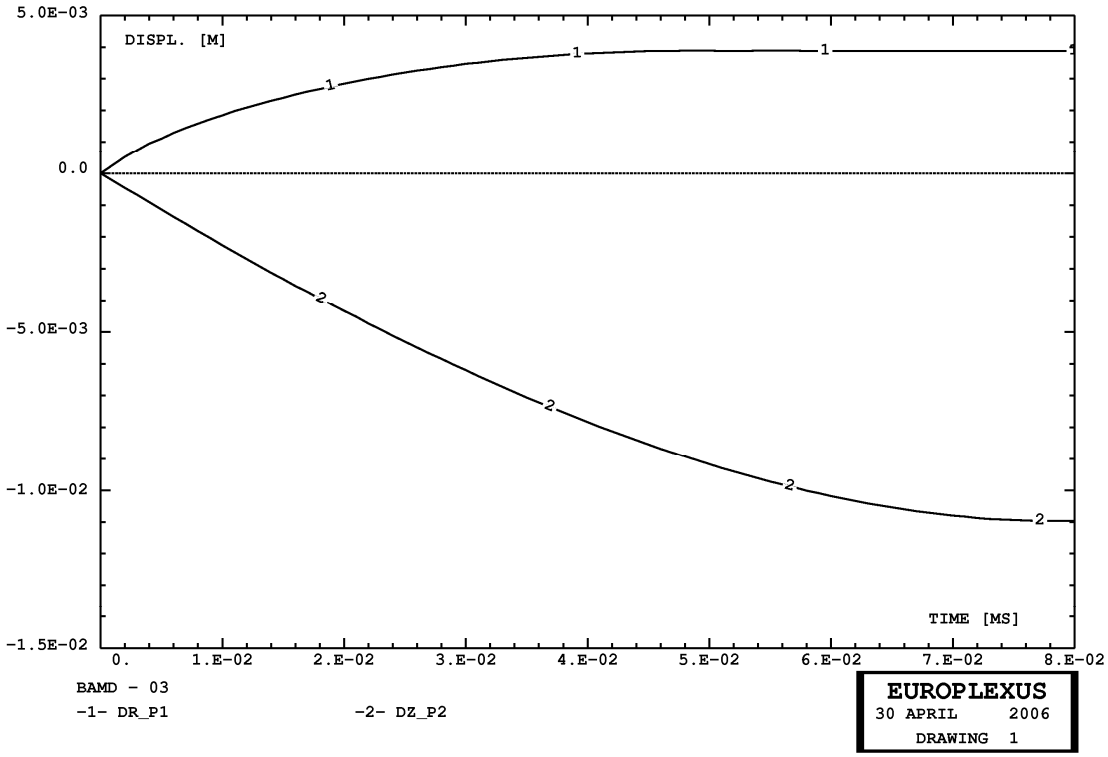
The input file is:

```
BAMD - 05
$
ECHO
$VERI
*CONV win
CAST MESH
AXIS NONL
$
DIME
  PT2L 306 Q41L 219 Q42L 31 ZONE 2
  mtpo 7
TERM
$
GEOM Q41L SQ41 Q42L SQ42 TERM
$
COMP EPAI 1 TOUS
$
MATE VM23 RO 8930. YOUN 1.17D11 NU 0.35D0 ELAS 4.D8
          TRAC 2 4.D8 3.418803D-03 1.004D11 1000.003418803
          TOUS
$
LINK COUP
     BLOQ 2 LECT BASE TERM
     BLOQ 1 LECT SYMAX TERM
$
INIT VITE 2 -227. LECT VITI TERM
$
ECRI DEPL VITE TFRE 10.E-6
          POIN LECT P1 TOP TERM
     fich alic tfre 80.e-8
$
OPTI NOTE
  csta 0.5
  log 1
*
STRU 6
     DOMA LECT s1 TERM
     DOMA LECT s2 TERM
     DOMA LECT s3 TERM
     DOMA LECT s4 TERM
     DOMA LECT s5 TERM
     DOMA LECT s6 TERM
$
CALC TINI 0. TEND 80.D-6
*=====================================================================
SUIT
Post-treatment of bar impact problem
ECHO
*
RESU alic GARD PSCR
*
SORT GRAP
*
AXTE 1000.0 'Time [ms]'
*
COUR 1 'dr_p1'  DEPL COMP 1 NOEU LECT p1  TERM
COUR 2 'dz_p2'  DEPL COMP 2 NOEU LECT p2  TERM
COUR 3 'vr_p1'  VITE COMP 1 NOEU LECT p1  TERM
COUR 4 'vz_p2'  VITE COMP 2 NOEU LECT p2  TERM
*
TRAC 1 2 AXES 1.0 'DISPL. [M]' yzer
TRAC 3 4 AXES 1.0 'VELOC. [M/S]' yzer
*
QUAL DEPL COMP 1 LECT p1  TERM REFE  3.88425E-3 TOLE 1.E-2
     DEPL COMP 2 LECT p2  TERM REFE -1.09666E-2 TOLE 1.E-2
*=====================================================================
FIN
```

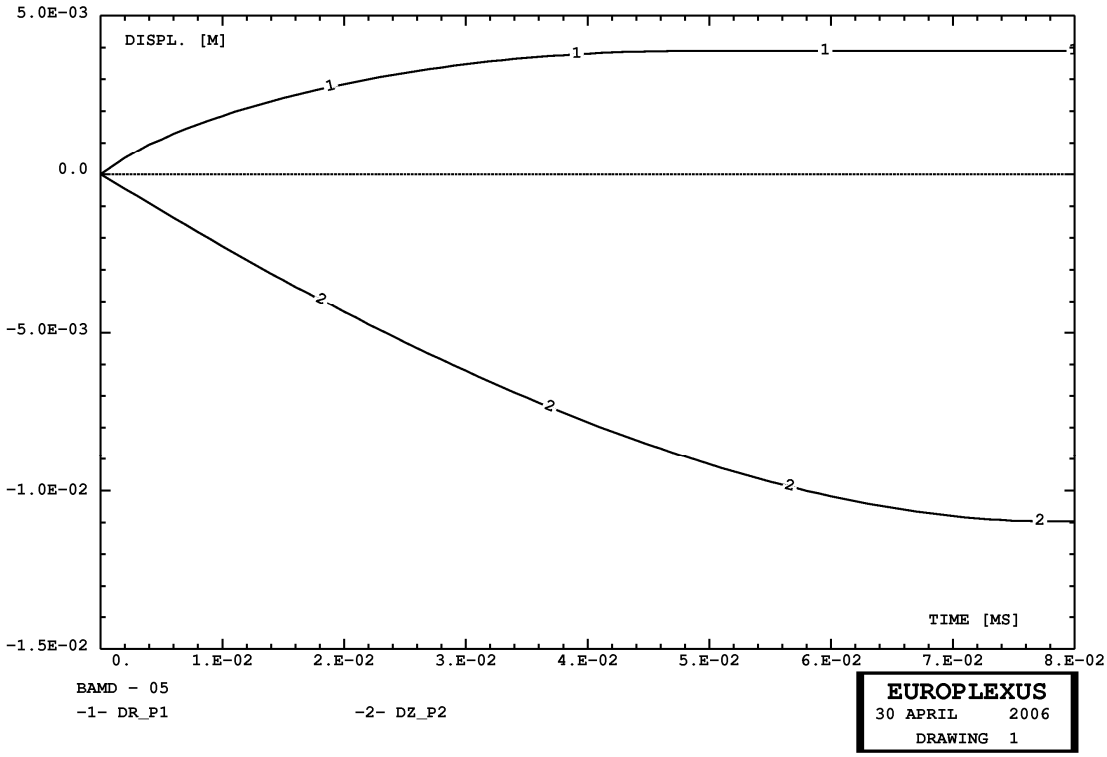
The characteristic displacements in the reference case are:



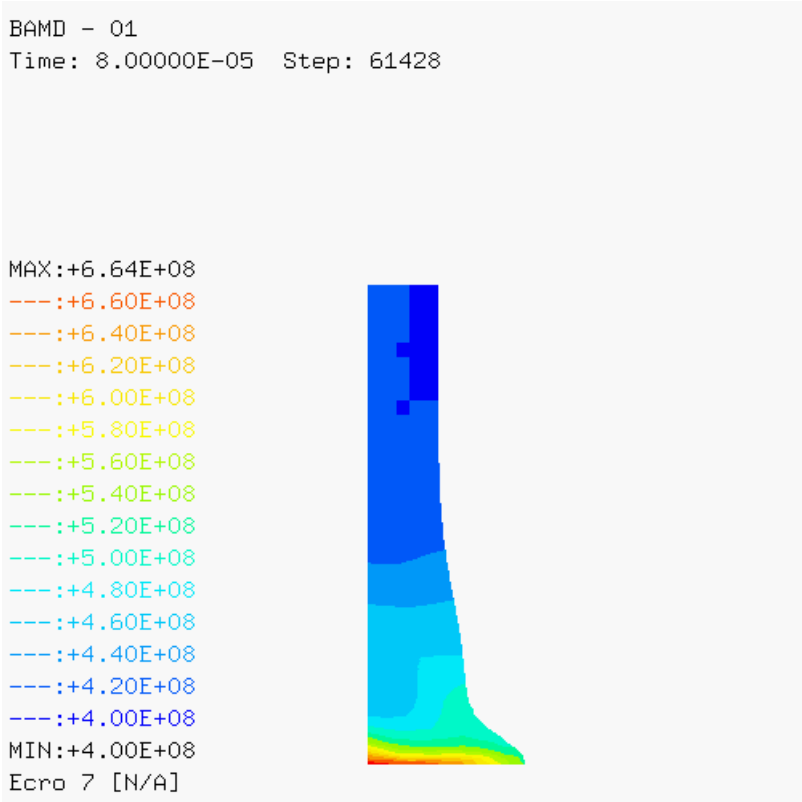
The displacements in the case with OPTI PART are:



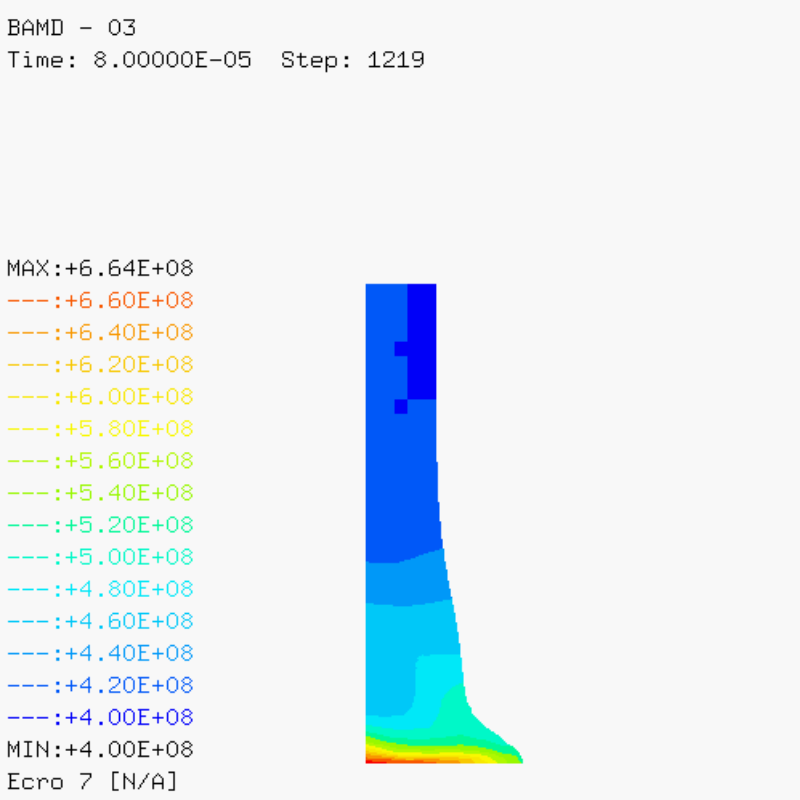
The displacements in the case with domain decomposition are:



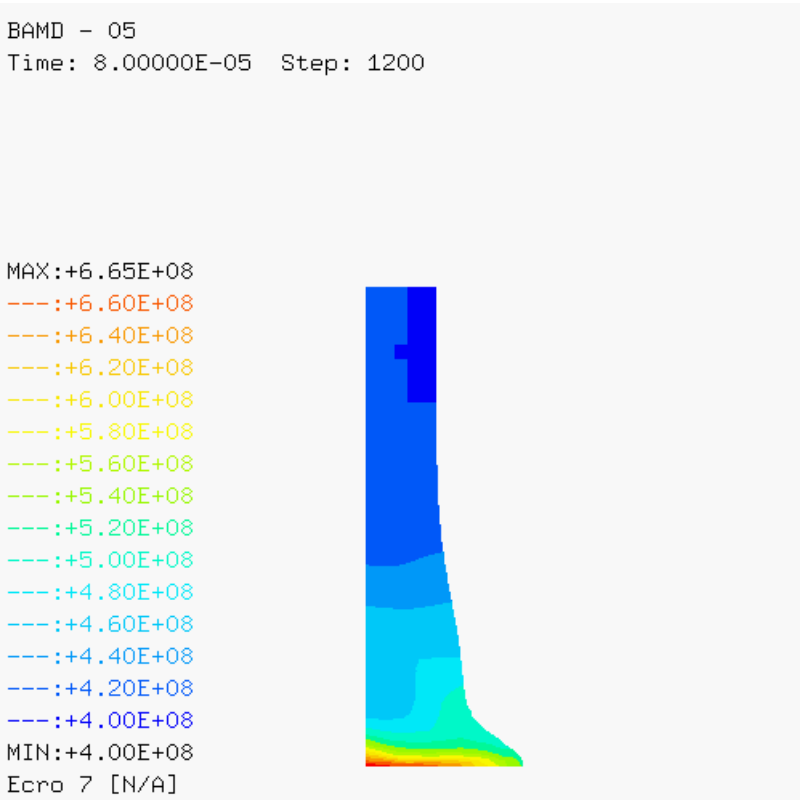
The final yield stress field in the reference case is:



The final yield stress field in the case with OPTI PART is:



The final yield stress field in the case with domain decomposition is:



Name: ……..… Date: …….. Signature ……

Universitat Politècnica de Catalunya, Barcelona, April 15–19, 2013

Numerical Simulation of Fast Transient Dynamic Phenomena in Fluid-Structure Systems

Questions/Exercises on Part I

Note: some questions may admit more than one answer. You may mark all answers you think are appropriate, and eventually add some comments of your own.

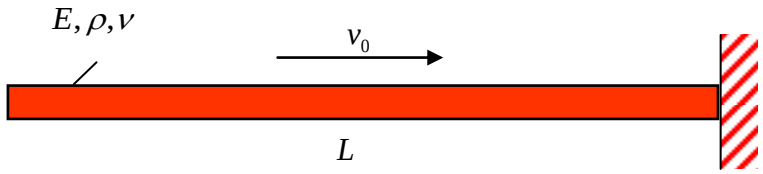
1. In explicit transient dynamics the fundamental governing equation for a Lagrangian formulation is:
    a. The principle of virtual work
    b. The conservation of momentum
    c. The conservation of mass
    d. The conservation of energy
2. In the approach chosen here, equilibrium is expressed:
    a. In the initial configuration
    b. In the previous configuration
    c. In the current configuration
3. In explicit time integration by the Central Difference scheme, the fundamental quantity is:
    a. The (full-step) velocity
    b. The mid-step velocity
    c. The acceleration
    d. The displacement
4. The Central Difference integration scheme is:
    a. First-order accurate and introduces some numerical damping
    b. First-order accurate and without numerical damping
    c. Second-order accurate and introduces some numerical damping
    d. Second-order accurate and without numerical damping
5. The Central Difference integration scheme is:
    a. Unconditionally stable
    b. Conditionally stable
    c. Unconditionally unstable
6. In the chosen implementation of the Central Difference integration scheme, during a generic time step (not the first one!) one obtains:
    a. First the (new) displacements, then the accelerations and finally the velocities
    b. First the velocities, then the accelerations and finally the displacements
    c. First the accelerations, then the velocities and finally the displacements
    d. First the displacements, then the velocities and finally the accelerations

7. Which of the following combinations is preferable in transient numerical analyses?
    a. Explicit time integrator and consistent mass matrix
    b. Implicit time integrator and lumped mass matrix
    c. Explicit time integrator and lumped mass matrix
    d. Implicit time integrator and consistent mass matrix
8. In the chosen explicit strategy, stress update is conveniently expressed in:
    a. Total form, based upon the total strains
    b. Rate form, based upon the strain increments
    c. Rate form, based upon the total strains
9. The radial return algorithm for plasticity:
    a. Always requires iterations to find the new stress state
    b. Requires iterations only if the trial stress state lies outside the yield surface
    c. Never requires iterations, but possibly just a projection of the trial stress state
10. A so-called co-rotational formulation may simplify the treatment of geometric nonlinearities:
    a. In continuum-like elements
    b. In structural elements such as bars and beams
    c. In plate and shell elements
11. Which of the following strain measures is more appropriate?
    a. Engineering strain in small-strain analyses
    b. Natural strain in small-strain analyses
    c. Engineering strain in large-strain analyses
    d. Natural strain in large-strain analyses
12. During the transient solution, checking the energy balance is:
    a. Redundant, because the chosen method ensures it *a priori*
    b. Necessary, because it is used in the algorithm to advance in time the solution
    c. Useful, because it gives a hint on the quality of the numerical solution obtained
13. The method of Lagrange multipliers used to impose the essential boundary conditions:
    a. Is always completely explicit, like the rest of the chosen solution strategy
    b. Leads in general to an implicit treatment of the constrained degrees of freedom
    c. Requires an implicit treatment of all degrees of freedom in the model
14. The basic "ingredients" used by the Lagrange multipliers method are:
    a. The constraint equation and the chosen time integration scheme
    b. The constraint equation and the constitutive law in the material(s)
    c. Only the constraint equation
    d. Only the time integration scheme
15. The Lagrange multipliers method:
    a. Yields the reaction forces, which are then treated as externally applied loads
    b. Does not provide the reactions, but ensures that the constraints are satisfied
    c. Yields the reaction forces, which then need a special treatment

Name: ……..… Date: …….. Signature ……

Exercise 1

An elastic bar of length $L = 1$ m, constant cross-section and homogeneous material impacts a rigid wall at an initial velocity v_0. We want to compute the transient behavior of the bar from time $t_0 = 0$ up to time $t_f = 2.0 \times 10^{-3}$ s.



The relevant material properties are: Young's modulus $E = 1.0 \times 10^9$ Pa, density $\rho = 1.0 \times 10^3$ Kg/m^3 and Poisson's coefficient $\nu = 0$. Assume a linear analysis since $v_0 \ll c$, where c is the sound speed in the material.

The bar is uniformly discretized in space by a certain number N of 2-node bar elements.

A. Estimate the sound speed in the bar:

$$c \approx ...$$

B. Estimate the stability step Δt^{crit} as a function of the number N of elements:

N	Δt^{crit}
10	
100	
1000	

C. Estimate the total number of steps n needed in the transient calculation, by assuming a stability safety factor $\varphi = 0.5$ (i.e. by using a time increment $\Delta t = \varphi \cdot \Delta t^{\text{crit}}$):

N	n
10	
100	
1000	

D. Estimate the total cost of the calculation in terms of memory size and of CPU time, by arbitrarily letting 1.0 be the cost of the solution with the coarsest mesh ($N = 10$):

N	Memory	CPU time
10	1.0	1.0
100		
1000		

Name: ……..… Date: …….. Signature ……

Facultative additional questions:

Imagine now that the bar material is elasto-plastic and that the initial velocity is sufficiently high to produce quite some plastification (a longitudinal strain, say, of the order of 10%) in the bar. Which of the following statements is correct, and why?

E. The stability step:

   a. Is not affected at all
   b. Varies because the sound speed in the material changes
   c. Varies because the length of the elements changes
   d. Varies because both the sound speed and the elements length change

[Hint: consider the onset of plastic waves in addition to elastic waves]

Comments/discussion:

……
……
……
…….

F. Assuming the radial return algorithm to treat plasticity, the CPU cost of the calculation with respect to a purely elastic solution:

   a. Is not affected at all
   b. Increases only slightly and in a fairly predictable way
   c. May no longer be estimated

Comments/discussion:

……
……
……
…….

G. With respect to an elastic solution, the elasto-plastic solution is expected:

   a. To be smoother, because the time integration scheme dissipates some energy
   b. To be smoother, because the material law dissipates some energy
   c. To present roughly the same numerical oscillations as in the elastic case

Comments/discussion:

……
……
……
…….

H. In the elasto-plastic solution:

   a. The total energy should not be conserved
   b. The total energy should be conserved

Comments/discussion:

……
……
……
……...

Name: ……..… Date: …….. Signature ……

Universitat Politècnica de Catalunya, Barcelona, April 15–19, 2013

Numerical Simulation of Fast Transient Dynamic Phenomena in Fluid-Structure Systems

Questions/Exercises on Part II

Note: some questions may admit more than one answer. You may mark all answers you think are appropriate, and eventually add some comments of your own.

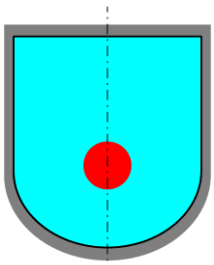
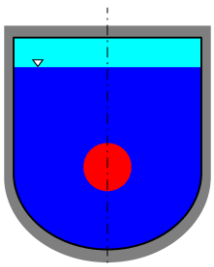
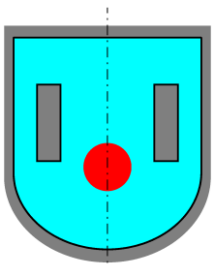
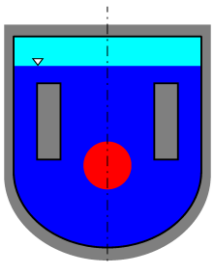
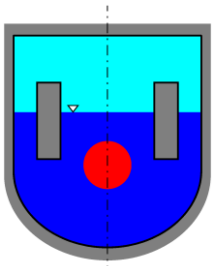
1. In dealing with explicit transient dynamics for fluids (explosions, shocks, impacts), Euler equations (and not full Navier-Stokes equations) are considered because:
    a. Compressibility is often important while viscosity is not
    b. Viscous forces may not be neglected
    c. Pressure forces are prevailing but viscosity may never be neglected
2. In a purely fluid problem (possibly with some rigid boundaries) the most natural description is typically:
    a. The Lagrangian description
    b. The ALE description
    c. The Eulerian description
3. In an ALE description the so-called "referential domain" (mesh):
    a. Follows the motion of material particles
    b. Is fixed
    c. Moves arbitrarily
4. The most important difference between an ALE and a Lagrangian formulation is:
    a. The presence of convective terms
    b. The presence of pressure terms
    c. The presence of body forces
5. In the FE approach to fluids presented, time integration of the governing equations:
    a. Is fully explicit like for structures (Lagrangian)
    b. Is implicit
    c. Requires a fractional step method that leads to an implicit solution
    d. Requires a fractional step method but in practice remains explicit
6. The accuracy of the proposed FE time integration scheme for fluids is:
    a. Second order like for structures (Lagrangian)
    b. First order
    c. Somewhat between first and second order

7. In a numerical model based upon the ALE formulation, the local description of motion (Lagrangian, Eulerian, ALE):
    a. Must be chosen element by element
    b. Must be chosen node by node
    c. Must be the same for the whole domain
    d. Must be uniform over each sub-domain (structure, fluid)
8. Pseudo-viscosity (in the form of a pseudo-viscous pressure term) in the fluid is:
    a. Useful to smooth out numerical solutions
    b. Essential in Lagrangian solutions to stabilize shock fronts
    c. Useful in Eulerian/ALE solutions to avoid excessive oscillations at shock fronts
    d. Not applicable in Lagrangian solutions
9. The pseudo-viscous term acts:
    a. Over the entire fluid sub-domain
    b. Only in fluid regions subjected to rapid compression
    c. Only in fluid regions subjected to rapid rarefaction
    d. Only in fluid regions where the fluid pressure is varying rapidly
10. Upwinding is used to treat:
    a. The pressure terms in Euler equations
    b. The transport terms
    c. The body force terms
11. Full-donor upwinding ($\alpha = 1$) is:
    a. More diffusive than a centred approximation ($\alpha = 0$)
    b. Less diffusive than a centred approximation
    c. Approximately as diffusive as a centred approximation
12. Lagrangian solutions for fluid problems are:
    a. Impossible to obtain
    b. Difficult to obtain but always quite accurate
    c. Easy to obtain but quite inaccurate
    d. Difficult to obtain and accurate only as long as the mesh does not deform too much
13. The so-called “mesh rezoning” techniques discussed in the course:
    a. Operate at constant mesh topology (just move the mesh)
    b. Just add or remove nodes where required
    c. Move the mesh and add or remove nodes where required
    d. Compute a new mesh but by keeping the same number of nodes and of elements
14. The most important task of mesh rezoning in an ALE description is:
    a. To keep the fluid mesh as uniform as possible
    b. To prevent excessive distortions in the fluid mesh
    c. To keep the fluid mesh attached to the structural mesh
15. In the chosen ALE formulation, the motion of free surfaces may be modeled:
    a. By just setting them as Lagrangian
    b. By just setting them as Eulerian
    c. By just setting them as ALE
    d. Up to a certain point (moderate distortion) by setting them as Lagrangian only in the normal direction

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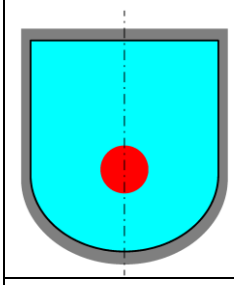
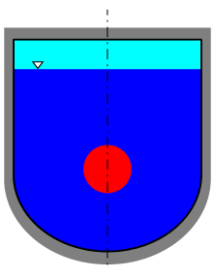
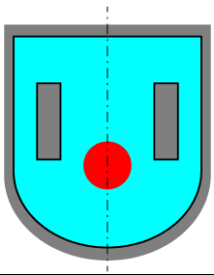
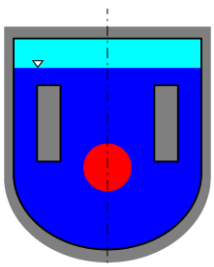
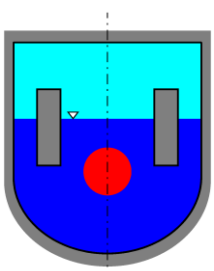
Exercise 1

A rigid container is subjected to an internal explosion, represented by a bubble of high-pressure gas (red zone). The rest of the container is filled by the same gas at atmospheric pressure (cyan zone). In addition, one may optionally consider a pool of liquid (blue zone) and the presence of some internal rigid structures (grey blocks). For each case, indicate whether each solution type is (likely) easy, possible, difficult or impossible to obtain, and why. For ALE solutions, specify which mesh parts should be modeled as Lagrangian, Eulerian or ALE. Assume first to use the basic, single-component fluid material model.

Problem	Solution(s) with single-phase single-component material model
	☐ Lagrangian ☐ Eulerian ☐ ALE
	☐ Lagrangian ☐ Eulerian ☐ ALE
	☐ Lagrangian ☐ Eulerian ☐ ALE
	☐ Lagrangian ☐ Eulerian ☐ ALE
	☐ Lagrangian ☐ Eulerian ☐ ALE

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Now assume having at disposal a multi-component fluid material model, which allows mixing up various materials in the same finite element. In which cases would you use it to obtain a (better) solution? And how? Put your comments and observations.

Problem	Solution(s) with multi-phase multi-component material model
	
	
	
	
	

Additional comments/observations:

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Numerical Simulation of Fast Transient Dynamic Phenomena in Fluid-Structure Systems

Questions/Exercises on Part III

Note: some questions may admit more than one answer. You may mark all answers you think are appropriate, and eventually add some comments of your own.

1. In fast transient dynamics (explosions, shocks, impacts) FSI usually plays an important role in the presence of:
    a. Incompressible or nearly incompressible fluids
    b. Highly compressible fluids and very stiff structures
    c. Highly compressible fluids and very deformable structures
2. The presence of a fluid free surface or of a Lagrangian interface between two fluids usually:
    a. Leads to non-permanent FSI
    b. Leads to permanent FSI
    c. Has no effect on the type of FSI
3. In the chosen FSI formulation, the contact pressure acts along:
    a. The tangent to the FSI interface
    b. The direction of the relative velocity
    c. The normal to the FSI interface
4. The governing equation of the chosen FSI model is the so-called (material) velocity compatibility condition, which involves:
    a. The particles velocity
    b. The mesh velocity
    c. The relative velocity
5. In the ALE formulation for FSI, the mesh velocitiy of fluid nodes on the F-S interface:
    a. Is arbitrary, as always in ALE methods
    b. Must be equal in all components to the mesh velocity of the structure
    c. Must be equal to the mesh velocity of the structure only along the normal to the interface
    d. Is set to zero
6. The most delicate ingredient of the proposed FSI model is:
    a. Finding the "true" normal(s) to the continuous F-S interface
    b. Writing down the velocity compatibility condition
    c. Finding the normal(s) to the discrete F-S interface

7. In the chosen approach, the resulting FSI coupling conditions are typically:
    a. Solved together with any other boundary conditions via Lagrange multipliers
    b. Treated separately from other boundary conditions because of their special nature
    c. Solved explicitly because they always lead to an uncoupled set of equations
8. Geometric FSI methods such as the FSA/FSR algorithm are based upon:
    a. The conservation of fluid, i.e. zero net flux across the F-S interface at fluid nodes
    b. The balance between forces in the fluid and forces in the structure
    c. The geometric shape of the structure interface near the node considered
    d. The geometric shape of the fluid interface near the node considered
9. Which of the following statements about the FSA/FSR algorithm are correct?
    a. It yields one discrete normal per node
    b. It may lead to spurious velocities in 3D when the FSI interface is warped
    c. It works well at submerged structural edges (shells, plates without a topological thickness)
10. Which of the following statements about the equilibrium-based UP algorithm are correct?
    a. It yields (at most) one discrete normal per node
    b. It may lead to spurious velocities in 3D when the FSI interface is warped
    c. It works well at submerged structural edges (shells, plates without a topological thickness)
11. In the code input, the various FSI coupling conditions must be applied to:
    a. Fluid nodes along the F-S interface
    b. Fluid elements along the F-S interface
    c. Structure nodes along the F-S interface
    d. Both fluid an structure nodes along the F-S interface
12. In a FSI problem involving only rigid (fixed) structures one would normally:
    a. Discretize only the fluid domain and use the FSR algorithm to impose conditions along the F-S interface
    b. Discretize only the fluid domain and simply block all nodes along the F-S interface
    c. Discretize both the fluid and the structure, block the structure nodes and use the FSR algorithm on fluid nodes along the F-S interface
13. In the code, fluid nodes subjected to FSI for which the number of distinct normals found is equal to the space dimension (2 in 2-D, 3 in 3-D) are:
    a. Automatically blocked in all directions
    b. Automatically coupled with the structure along all directions
    c. Automatically declared as Lagrangian and coupled with the structure along all directions
14. The FSI models presented so far (FSA, FSR, UP) are in principle applicable only to:
    a. Permanent FSI
    b. Non-permanent FSI
    c. Both permanent and non-permanent FSI
15. The FSI models presented so far (FSA, FSR, UP) assume:
    a. Distinct but coincident (superposed) structure and fluid nodes along the F-S interface (conforming interface)
    b. Distinct and arbitrarily located structure and fluid nodes along the F-S interface (non-conforming interface)
    c. The same node (but with distinct degrees of freedom) to represent both the structure and the fluid

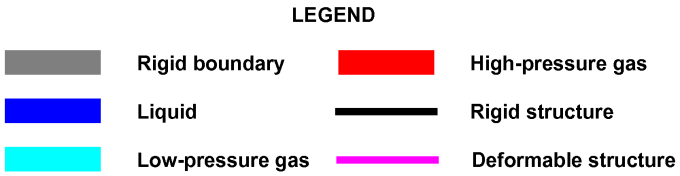
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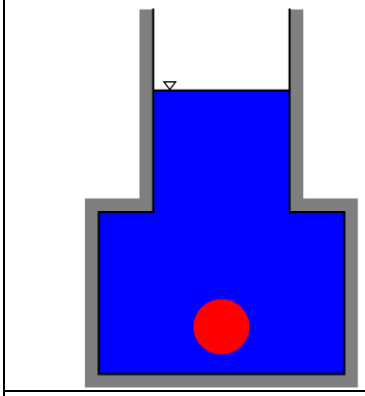
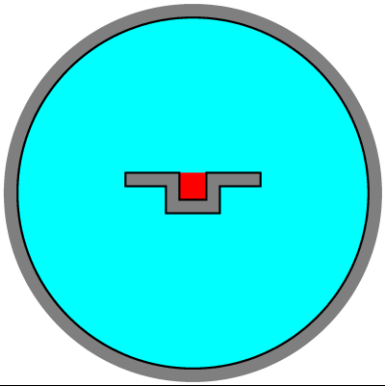
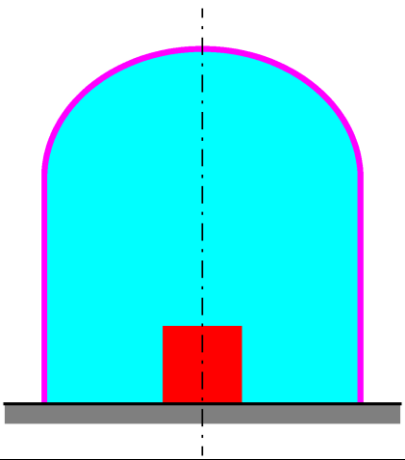
Exercise 1

For each of the following applications, indicate the most appropriate FSI model(s) among those presented in the Course:

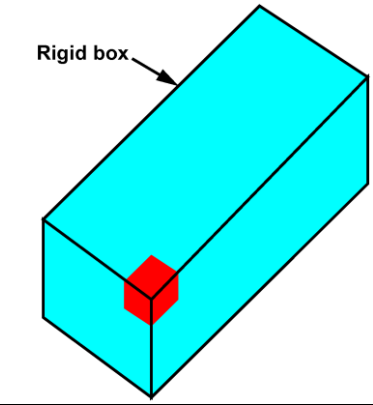
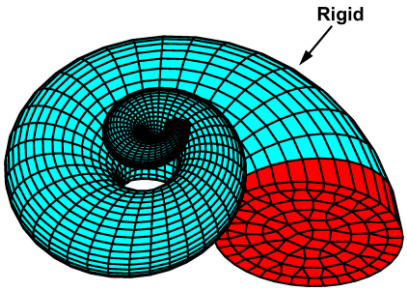
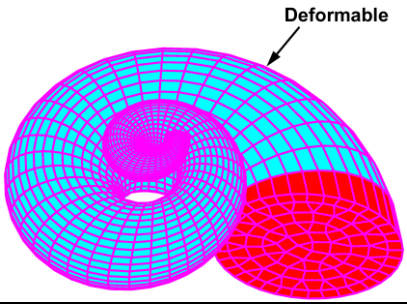
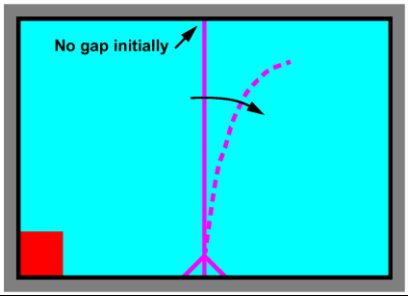
Blockage of global fluid dofs, **FSA,** **FSR,**
FSCR, **FLSR.**

Motivate your choices. In some cases more than one model is applicable, or different models are appropriate for different regions of the mesh.



Problem	FSI modeling
	
	
	

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Additional comments/observations:

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Exercise 2 (optional)

Sketch a fluid-structure interaction problem of your choice. Qualitatively discuss (at least) the following aspects:

- Type of global formulation adopted (Lagrangian, Eulerian, ALE)
- (In case of ALE formulation) The type of grid motion adopted for the various zones of the mesh
- The FSI model(s) adopted and the corresponding mesh zone(s)

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Numerical Simulation of Fast Transient Dynamic Phenomena in Fluid-Structure Systems

Questions/Exercises on Part IV

Note: some questions may admit more than one answer. You may mark all answers you think are appropriate, and eventually add some comments of your own.

1. In an ALE description for structures (solids) the major difficulty with respect to fluids is:
    a. The mesh rezoning algorithm
    b. The stress transport algorithm
    c. The presence of materials with memory
2. In the proposed ALE description for structures time integration is:
    a. Implicit
    b. Explicit
    c. Explicit but requires a fractional step approach like in fluids
3. The main advantage of using ALE for structures is that:
    a. It increases the precision of numerical solutions
    b. It allows to treat problems with larger deformations thanks to rezoning
    c. It always reduces the CPU time
    d. It reduces the CPU time in problems with very large deformations
4. In the proposed strategy for non-conforming FSI, velocity compatibility constraints are based upon:
    a. Every fluid node along the F-S interface
    b. Every structural node along the F-S interface
    c. Every fluid and every structural node along the F-S interface
5. The best configuration in non-conforming FSI is usually:
    a. Hierarchic (fluid finer than structure)
    b. Hierarchic (fluid coarser than structure)
    c. There is no clear advantage of hierarchic or of non-hierarchic
6. The proposed non-conforming FSI technique:
    a. Typically allows direct solution of constraints at non-matching nodes
    b. Leads to a coupled set of equations similar to the conforming case
    c. Leads to a coupled set of equations with larger bandwidth, thus requiring increased memory storage and CPU time

7. Conventional contact-impact methods based upon slide lines or slide surfaces:
    a. Always detect penetration
    b. May fail to detect penetration in complex or ambiguous cases
    c. May lead to redundant contact detections
8. Pinball-based contact-impact methods:
    a. Always detect penetration
    b. May fail to detect penetration in complex or ambiguous cases
    c. May lead to redundant contact detections
9. In the contact-impact methods illustrated in the Course, solution by Lagrange multipliers:
    a. Must be used in the pinball-based method
    b. May not be used in the slide line or slide surface method
    c. May be used in either method
    d. Must be used in the slide line or slide surface method
10. So-called Spectral Element methods are useful/convenient for:
    a. Problems with sharp discontinuities
    b. Problems with smooth solutions
    c. Linear problems
    d. Highly non-linear problems
11. In spectral elements the nodes are:
    a. Uniformly spaced in each element
    b. Randomly spaced in each element
    c. Non-uniformly spaced in each element, at special positions
12. Coupling of spectral elements and finite elements:
    a. Is only possible when the two meshes are conforming
    b. Is preferably done by local (node-by-node) conditions, like in FSI
    c. Is preferably done by integral conditions such as the mortar method
13. The proposed spatial partitioning technique is based upon:
    a. A binary (2-based) partition of the time step over the spatial mesh
    b. An arbitrary partition of the time step over the spatial mesh
    c. A graded mesh with a binary (2-based) size ratio between neighboring elements
14. In principle, the proposed domain decomposition technique allows:
    a. Using different time steps in each sub-domain
    b. Using sub-domains with non-conforming interfaces
    c. Using different time integration schemes in each sub-domain
    d. Mixing up modal analysis and direct time integration
15. From the user's viewpoint, spatial partitioning is:
    a. Much simpler to use than domain decomposition, but less general
    b. More difficult to use than domain decomposition, but more general
    c. About equivalent to domain decomposition in both respects

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Overall Course evaluation

The Course has presented a set of techniques and of models for the numerical simulation of fast transient problems in fluid-structure systems, with special emphasis on FSI issues. In your opinion:

- What are the strong points (if any) of the proposed methods and models?

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- What are the weak points (if any) of the proposed methods and models?

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- What remains to be developed and which are the priorities?

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Numerical Simulation of Fast Transient Dynamic Phenomena in Fluid-Structure Systems

Students' Feedback

Please evaluate on a scale from 1 (very bad) to 10 (very good) the various aspects of the Course:

Subject	**Notation**	**Comments (if any)**
Interest of proposed subjects		
Completeness of subjects		
Teaching skills		
Theoretical material		
Application examples		
Practical exercises		
Day 1		
Day 2		
Day 3		
Day 4		
Day 5		
Did the Course fill your expectations?		

Please express any additional comments and suggestions:

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European Commission
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Title: Numerical Simulation of Fast Transient Phenomena in Fluid-Structure Systems

Author(s): Folco Casadei, George Solomos, Georgios Valsamos

Luxembourg: Publications Office of the European Union

2013 – 692 pp. – 21.0 x 29.7 cm

Abstract

The present document contains the presentation slides and the traces of proposed exercises/examples related to the Course: Numerical Simulation of Fast Transient Dynamic Phenomena in Fluid-Structure Systems, given by F. Casadei at the Universitat Politècnica de Catalunya, Barcelona, April 15–19, 2013.

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