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

Numerical Simulation of Fast Transient Phenomena in Fluid-Structure Systems

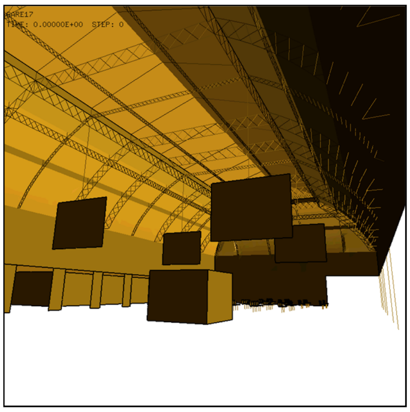
A Short Course by F. Casadei
Retired from European Commission, Joint Research Centre
Institute for the Protection and Security of the Citizen
T.P. 480, I-21027 Ispra (VA), Italy.
E-mail: casadeifolco@gmail.com

1

Contents

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

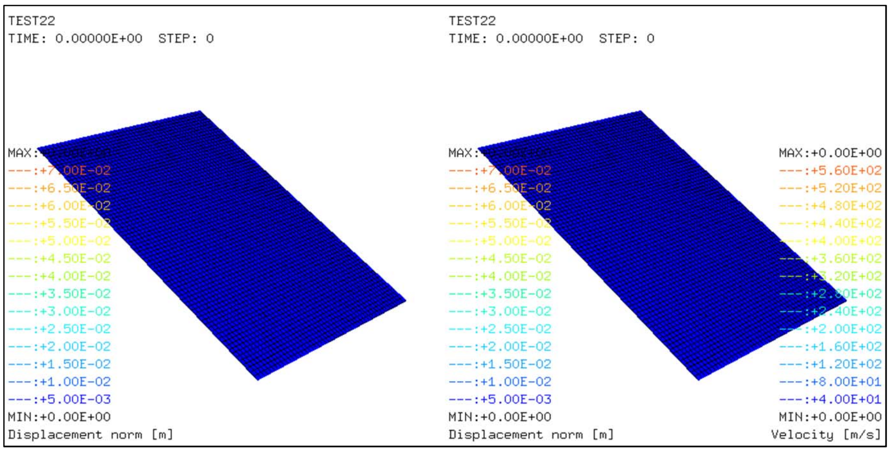
Detailed Contents (2/2)

- 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:

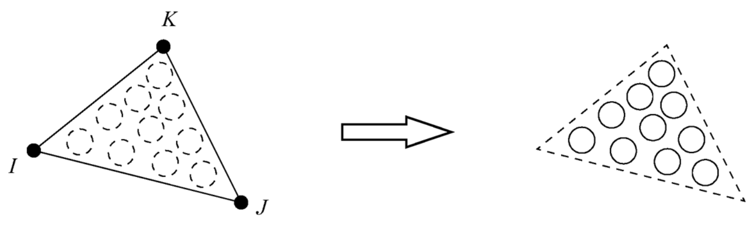
    `EROS e`
  - ➢ Choose a material possessing a failure criterion:

    `MATE VM23 … FAIL PEPR LIMI 0.1 …`
- The `EROS` global parameter `e` is : $0 \leq e \leq 1$. 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)



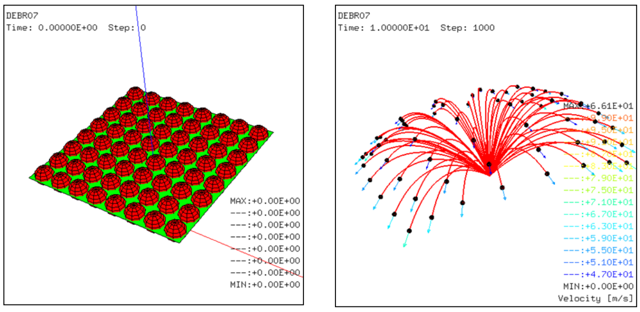
a) Before fragmentation b) After fragmentation

- 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 <u>mass</u> is conserved
- At failure, particles velocity is determined by velocity field in the eroded element (kinetic <u>energy</u> approximately conserved)



- Particles <u>trajectories</u> can be saved/visualized

9

Modeling of Flying Debris (3)

- Input directives:
  - ➢ Dimension (exactly) for total number of debris particles:

    DIME … DEBR 3500 …
  - ➢ Do <u>not</u> define debris elements in the geometry:

    GEOM …
  - ➢ Define elements that can generate debris in geometry complements:

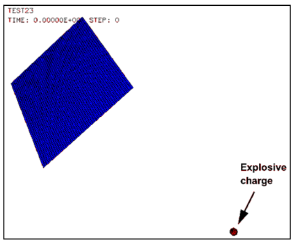
```
COMP … DEBR ROF 1.0 FILL PLEV 0
            RO 2500 DRAG 1.0 TRAJ
            OBJE /LECT/
```

- 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

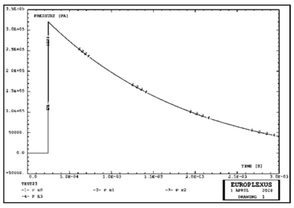
10

Modeling of Flying Debris (4)

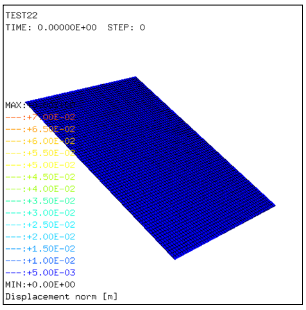
- Glass rupture revisited:



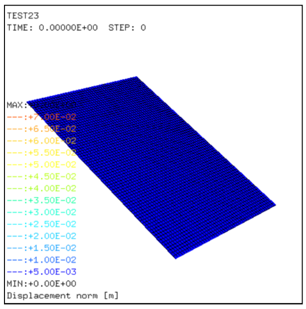
Geometry



Pressure (AIRB)



Erosion
(Macro fragments)

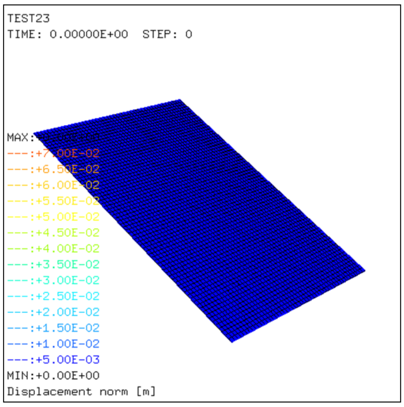


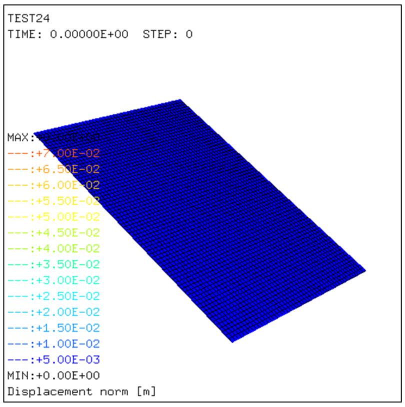
Erosion + Debris
(Macro and micro fragments)

11

Modeling of Flying Debris (5)

- These solutions are quite sensitive to failure parameters:

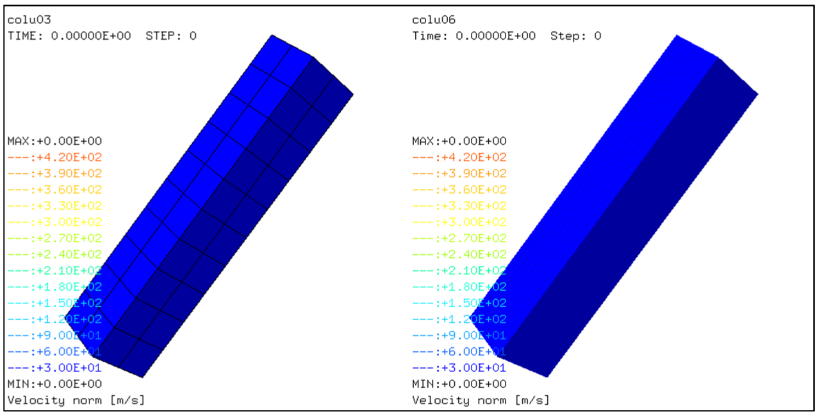




12

Modeling of Flying Debris (6)

- Fragmentation model can also be applied to <u>bulky</u> structures (e.g. a column made of unreinforced concrete)

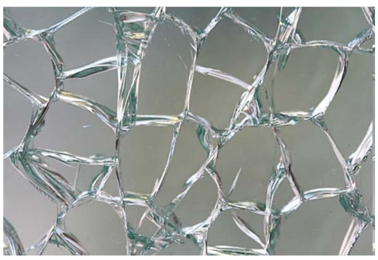


Coarse mesh, PLEV 1
320 particles

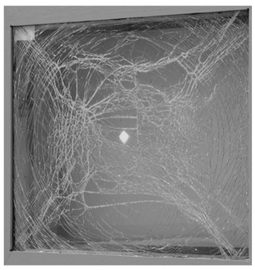
Fine mesh (4x), PLEV 2
163,840 particles

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**



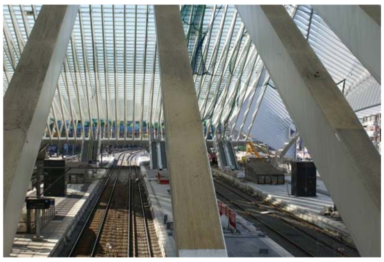
Source: www.zdnet.com



Source: www.glassfiles.com

Glazing of Stations and other Buildings

Broadgate Tower, London (under construction)



Railway station Liège

European Parliament, Strasbourg

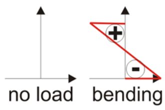
Railway station Berlin

15

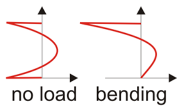
Source: wikipedia.org

Types of Glass

- **Annealed glass (brittle failure, small failure strength)**



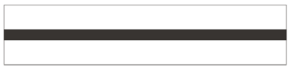
- **Tempered glass (prestressed, small splinters)**



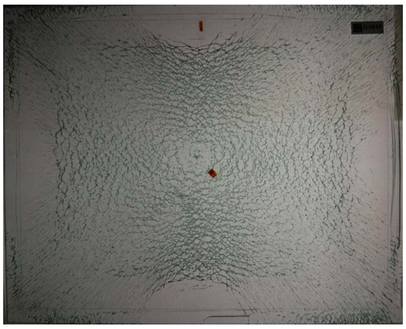
- **Laminated glass (splinters glued together)**
  Interlayer: Polyvinylbutyral (PVB)

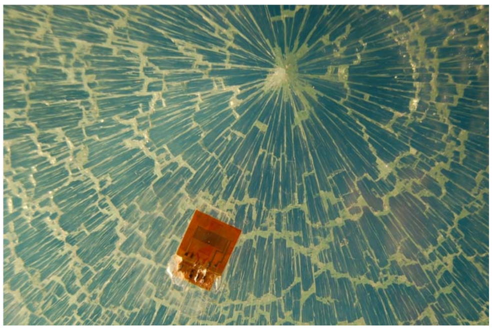
16

Complex Failure - Laminated Glass

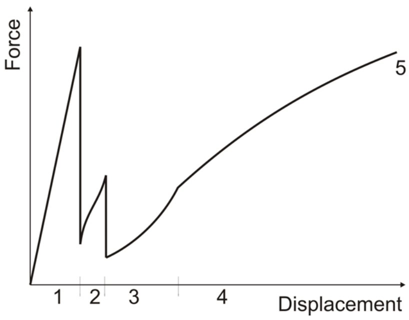


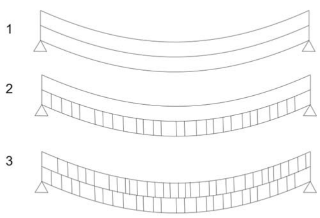
- Interlayer: Polyvinylbutyral (**PVB**)
- Interlayer keeps the glass plies **bonded** even when **cracked**
- Used very often for structures and vehicles
- Thickness: 6.4 – 100 mm, PVB: 0.4 mm and higher





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

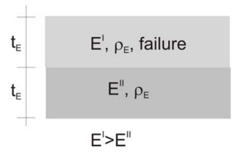
Failure of the interlayer is complex

18

Modelling of Laminated Glass

Smeared model

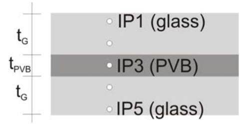
Two coincident shell elements
Stiffness before failure = Shell I+II
Stiffness after failure = Shell II



Phase 1 to 2
No shearing of the glass layers

Layered model

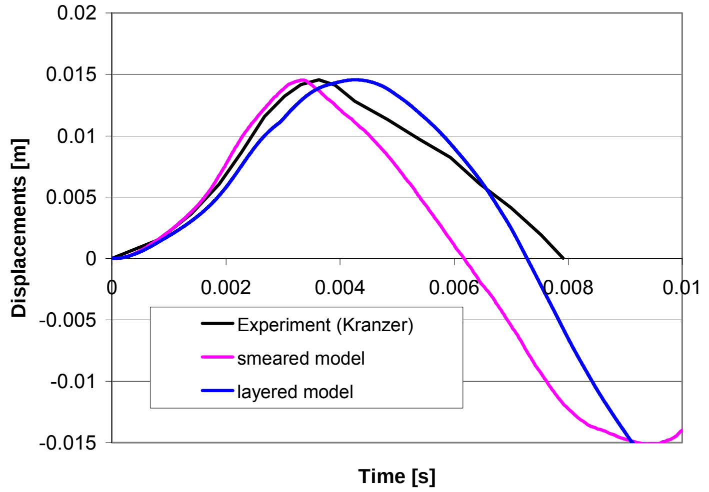
After failure of a layer, still
resists to compression



Phase 1 to 3 (5)
Better material law for PVB
Tearing of the PVB foil
No shearing of the glass layers

19

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%

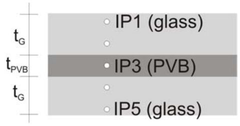
20

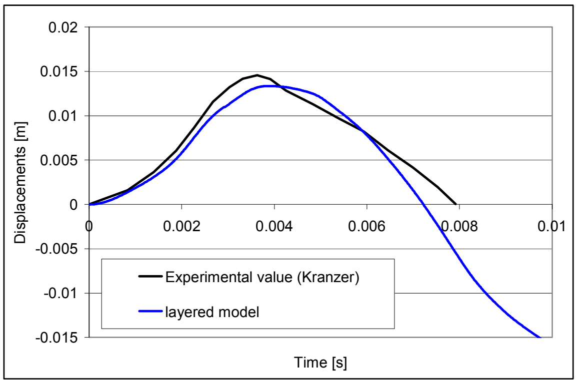
Experimental data: Kranzer 2005

Modelling of Laminated Glass

Layered glass model (LSGL material) :

Failure of a layer,
resistant against compression
Elastic-plastic material law for PVB





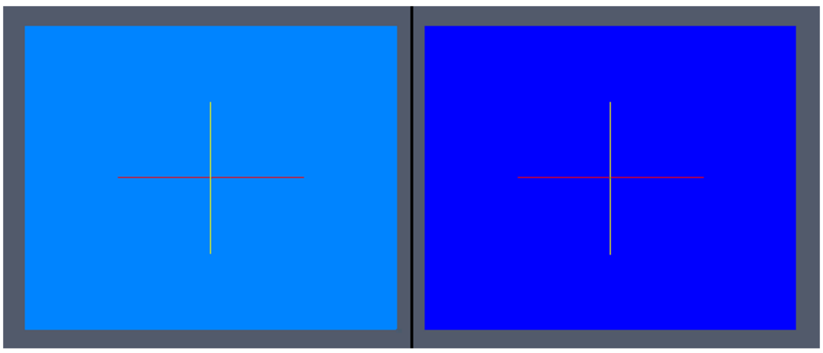
1.0 x 0.8 m, 7.5 mm thick LSG
125 g C4 @ 2 m

Experimental data: Kranzer et al. 2005

21

Glass Blast Simulation

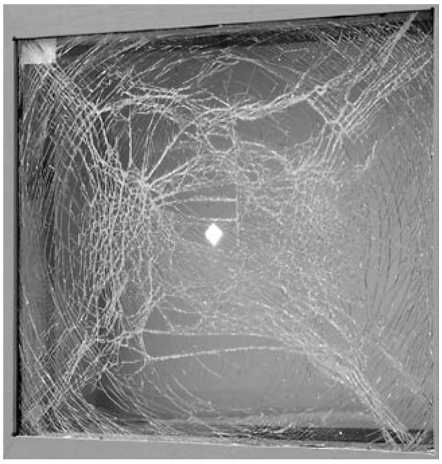
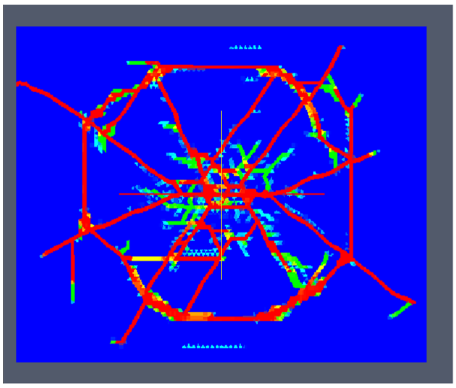
(glass failure only)



Displacements **Failure**

22

Comparison

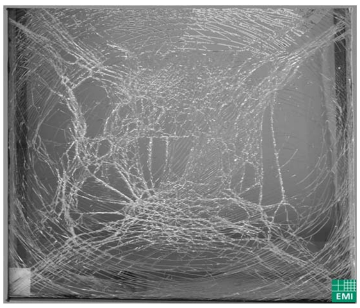



Kranzer et al. 2005

Experiment **Numerical failure**

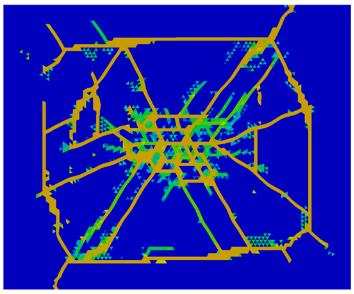
23

Crack Pattern (glass failure only)

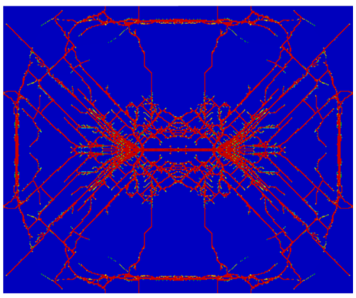


Kranzer et al. 2005

Experiment



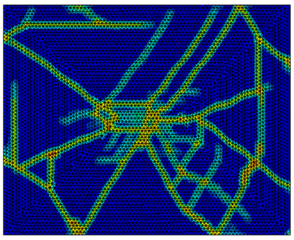
layered shell model
mesh 12.5 mm



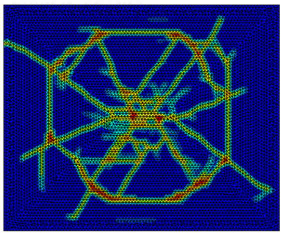
3D solid model
mesh 2.5 mm

24

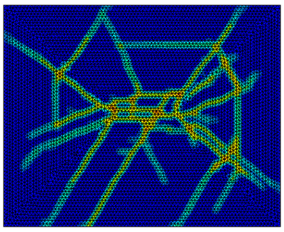
Influence of Boundary Conditions



sliding



elastic



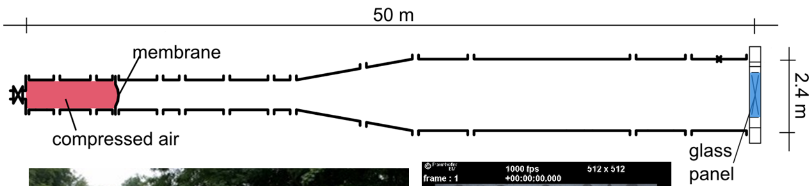
fixed

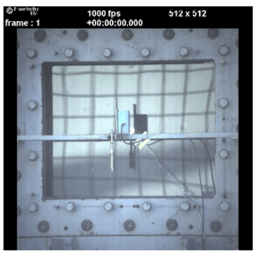
Kranzer, C. et al. 2005

25

Experiments (complete failure)

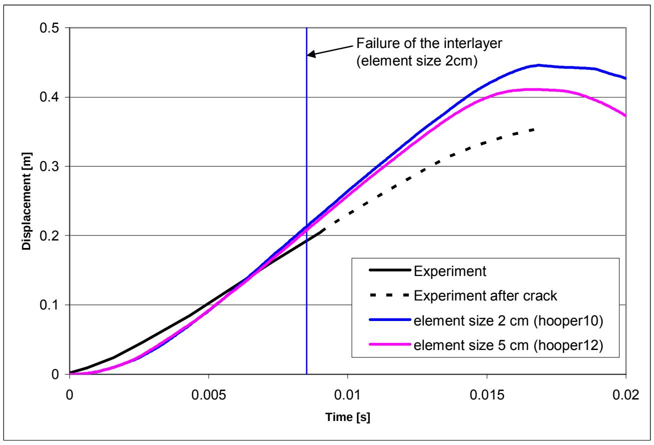
- Full scale test at Ernst-Mach-Institut, Fraunhofergesellschaft, Germany
- Shock tube using compressed air, laminated glass 14 mm thickness
- Overpressures: 82 – 150 kPa (430 – 2300 kg TNT; 40-55 m distance)
- Measurement of the overpressure, displacements, strains





26

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

27

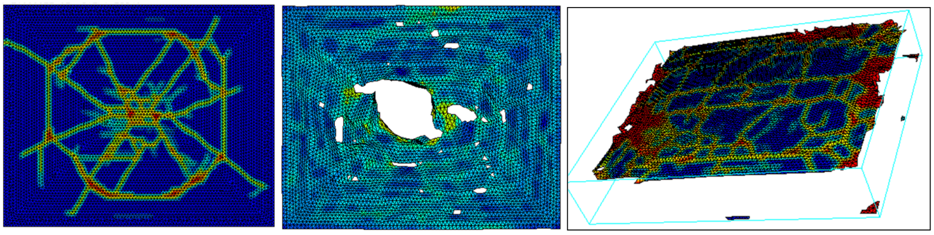
Simulation – Complete failure

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	1.5 x 1.2 m 17 kg TNT @ 13 m	1.0 x 0.8 m 5 kg TNT @ 1.8 m
No failure of the interlayer	Interlayer fails centrally (large displacements)	Interlayer fails early along the support

29

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

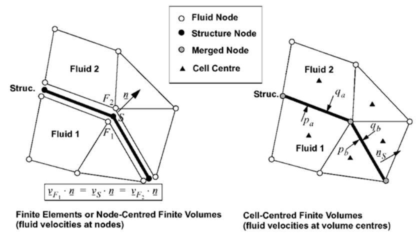
- GLAS material
- Failure stress of $159.6 \cdot 10^6$ N/mm^2
- Leads to complete failure of the glass
- Particles (debris) should be considered

30

Structural failure with C-C Finite Volumes

(for a conforming FS mesh)

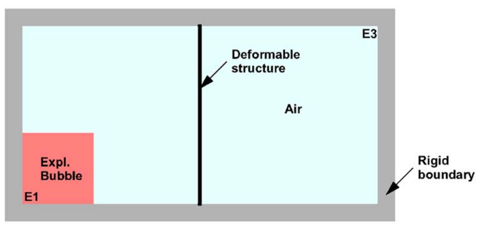
The **FLSR** model **cannot** be used with **CCFV** at the moment. However:



- To represent a <u>deformable structural boundary</u>, just <u>merge</u> 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 …)

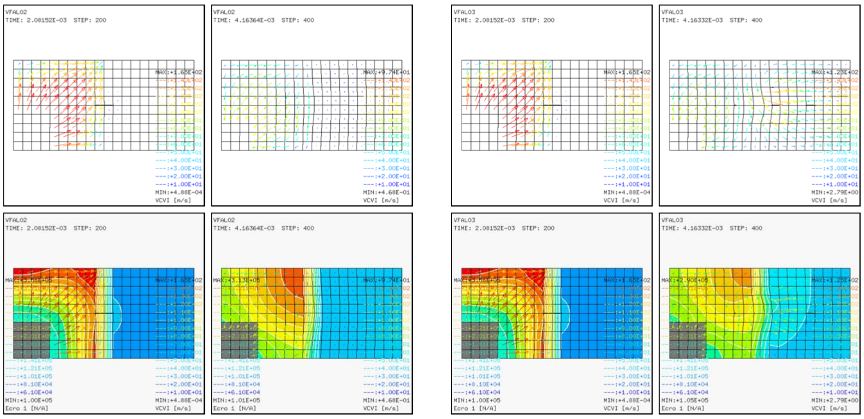
Exercise/Example 12c – Failure with CCFV

- Solve a FSI problem with failure and fragmentation by the CCFV fluid model (conforming meshes)



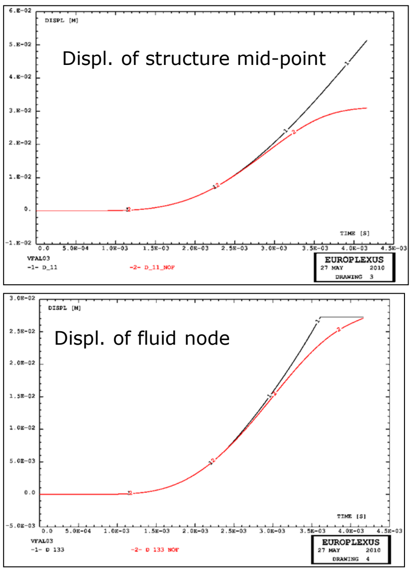
- Compare solutions without and with structural failure of the internal deformable wall

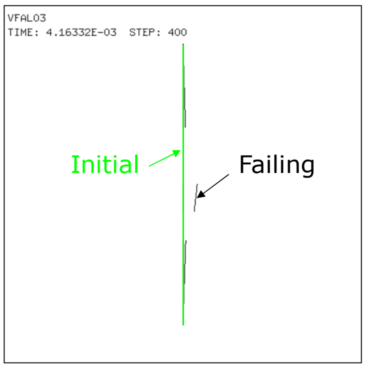
Exercise/Example 12c – Failure with CCFV (2)



No failure   Failure

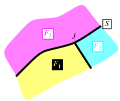
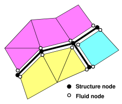
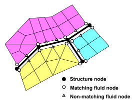
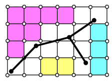
Exercise/Example 12c – Failure with CCFV (3)





Failure
No Failure

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

35

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]):

$$v_F \cdot n - v_S \cdot n = 0 \qquad \text{(n is the F-S normal)}$$

  - Solution e.g. by **Lagrange multipliers** (<u>implicit</u>)

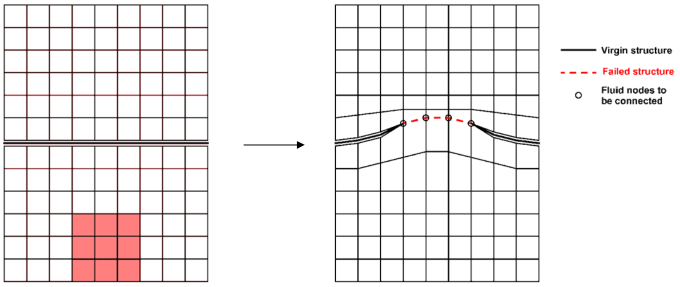
- Large motions and extreme strains (**structural failure**)
  - Failure in the structure is treated by suitable **failure criteria** and by **element erosion + flying debris model**
  - Special FSI technique required, based on **embedded** fluid and structure meshes (**FLSR / FLSW** models)

[2] Casadei F, Potapov S, <u>CMAME</u> **193** (2004) 4157-4194, *and references therein*.

36

Issues in FSI with failure/fragmentation

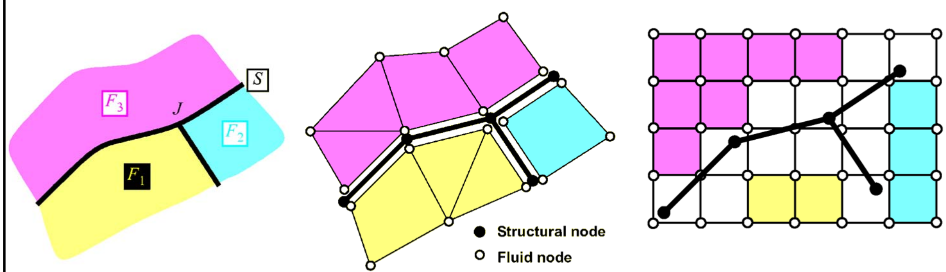
- When structure fails and is eroded, the FSI models seen so far are no longer applicable, because:
  - Difficult to "sew" the fluid meshes on either side of the failing structure
  - Automatic fluid mesh rezoning algorithms fail because the master domain (structure) "disappears"
  - Possible rotating macro fragments create rezoning problems
  - Etc. etc.



37

Issues in FSI with failure/fragmentation (2)

- Alternative approach : decouple structure from fluid at topological level (FLSR):



Continuous F/S Interface

Discretized F/S Interface (FSA, conforming)

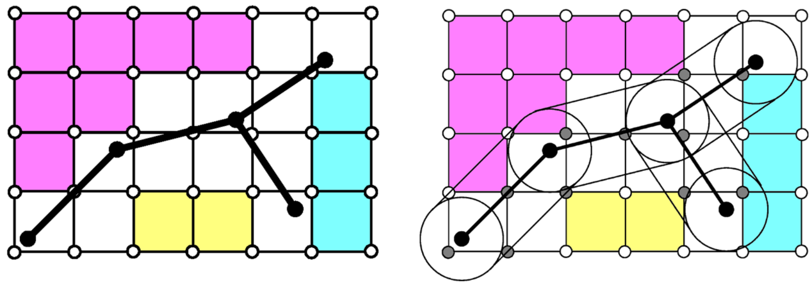
*Discretized F/S Interface (**FLSR**)*

38

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

39

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

40

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.) :

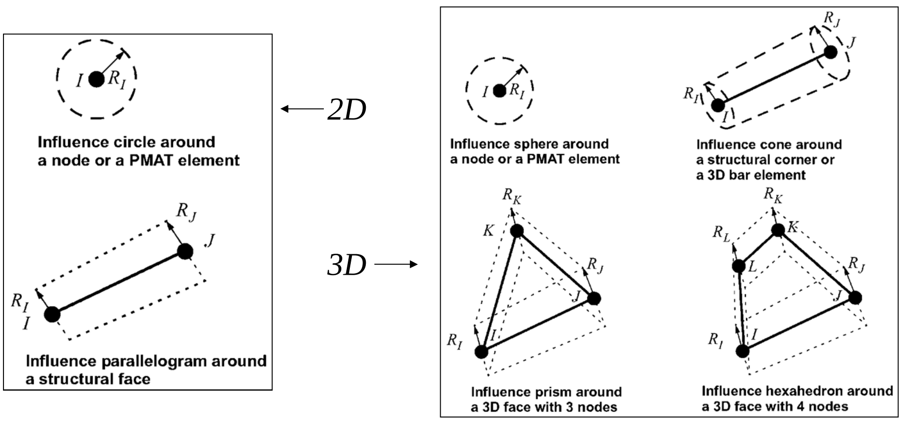
$$\underline{v}_F \cdot \underline{n} - \underline{v}_{S^*} \cdot \underline{n} = 0$$

- 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)

41

The FLSR Model (3)

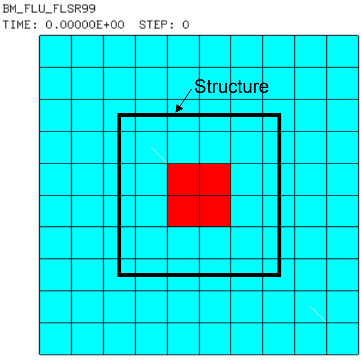
- The influence domain is the union of various entities:



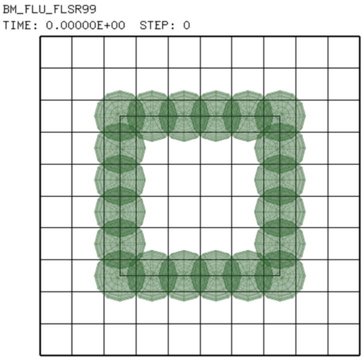
- Apply suitable precedence rules when a fluid node F belongs to more than one entity

42

FLSR Example

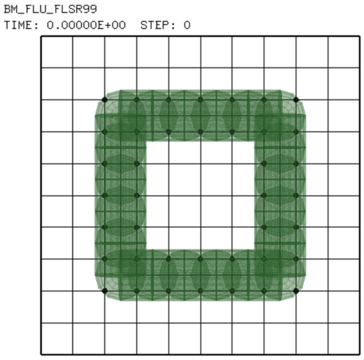


Initial mesh

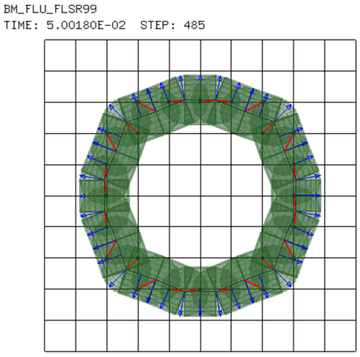


Initial FLSR nodal spheres

43



Initial FLSR domain and coupled fluid nodes

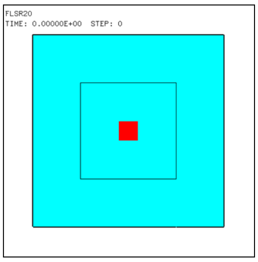


Final FLSR domain and coupled fluid nodes

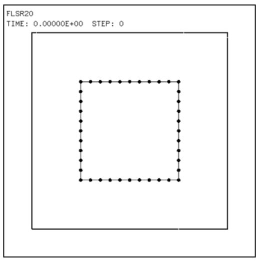
44

The FLSR Model (4)

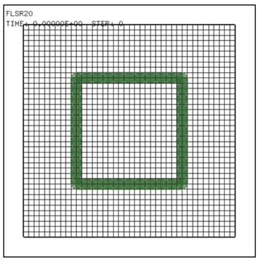
- Test FLSR model vs. FSA (without failure)



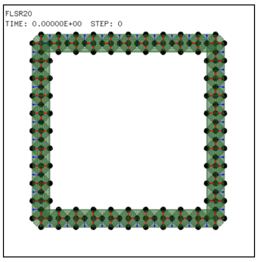
Outline



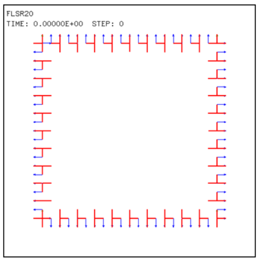
Structural nodes



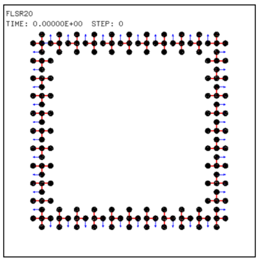
FLSR influence domain



FLSR fluid nodes

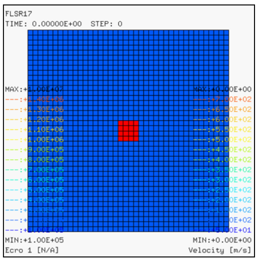


FLSR normals/links

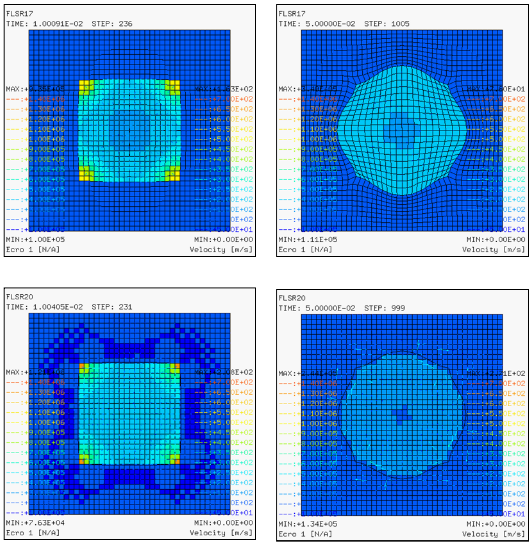


45

The FLSR Model (5)



t = 0



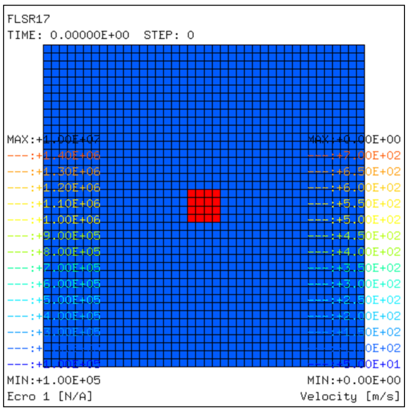
FSA

FLSR

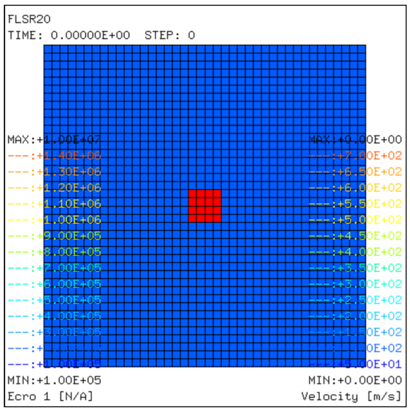
t = 10 ms *t = 50 ms*

46

The FLSR Model (5)



FSA



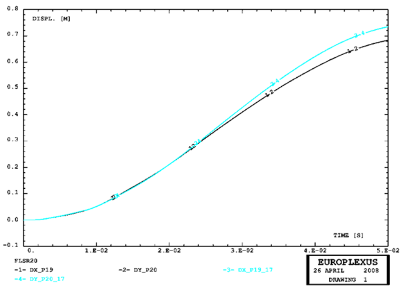
FLSR

Comparison

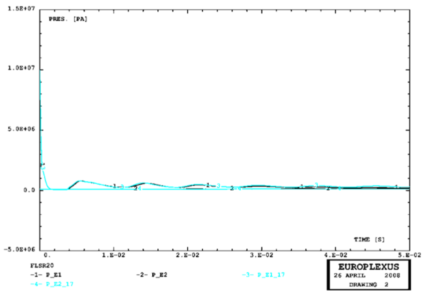
47

The FLSR Model (6)

- Compare FLSR model vs. FSA (without failure)



Structure displacements

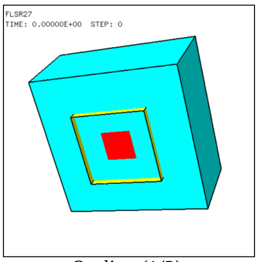


Fluid pressures

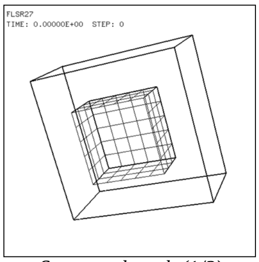
48

The FLSR Model (7)

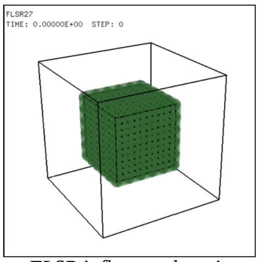
- Test FLSR model vs. FSA (without failure) in 3D



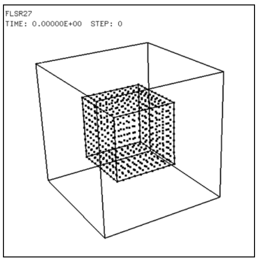
Outline (1/2)



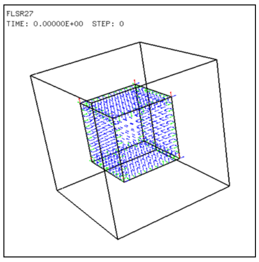
Structural mesh (1/2)



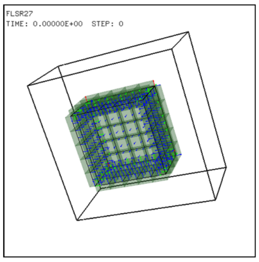
FLSR influence domain



FLSR fluid nodes



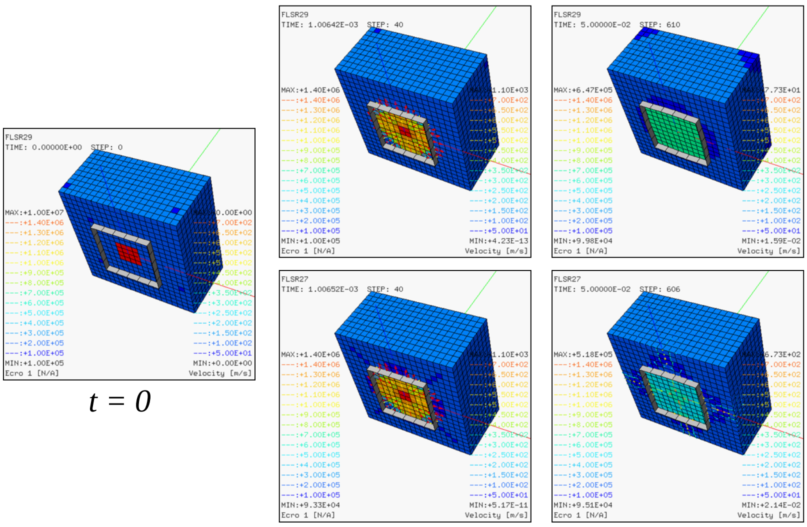
FLSR normals/links



FLSR influence hexahedra (1/2)

49

The FLSR Model (8)



FSA

FLSR

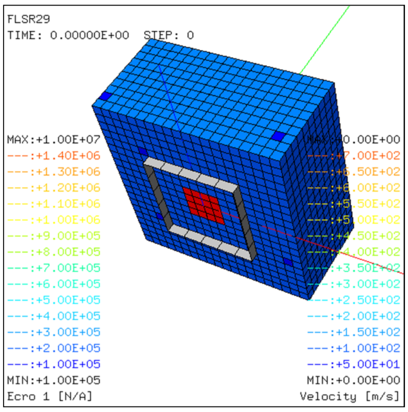
t = 0

t = 1 ms

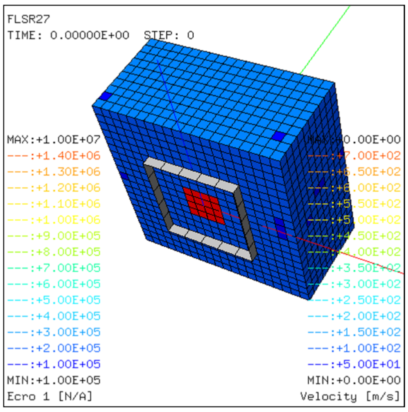
t = 50 ms

50

The FLSR Model (9)



FSA

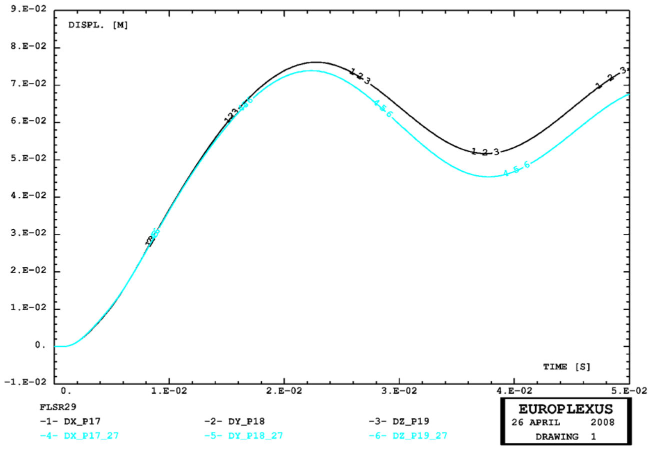


FLSR

Comparison

The FLSR Model (10)

- Compare FLSR model vs. FSA (without failure) in 3D



Structure displacements

The FLSR Model with NCFV

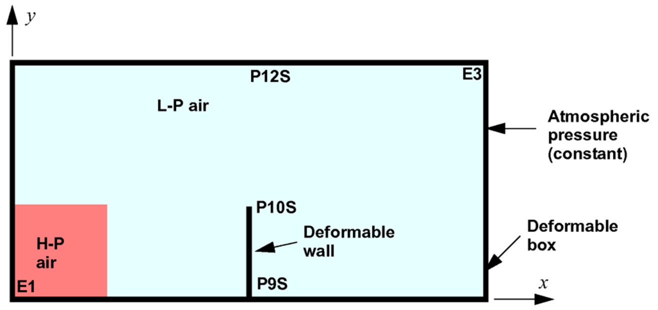
- The basic FLSR model described above does not work well with NCFV : large spurious passages of fluid (mass and energy fluxes) across the structure are observed
- Unlike in FE, blocking the momentum flux alone (through velocity constraints) does not ensure blocking of the other fluxes (mass, energy) 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

53

Exercise 12b – FLSR with NCFV

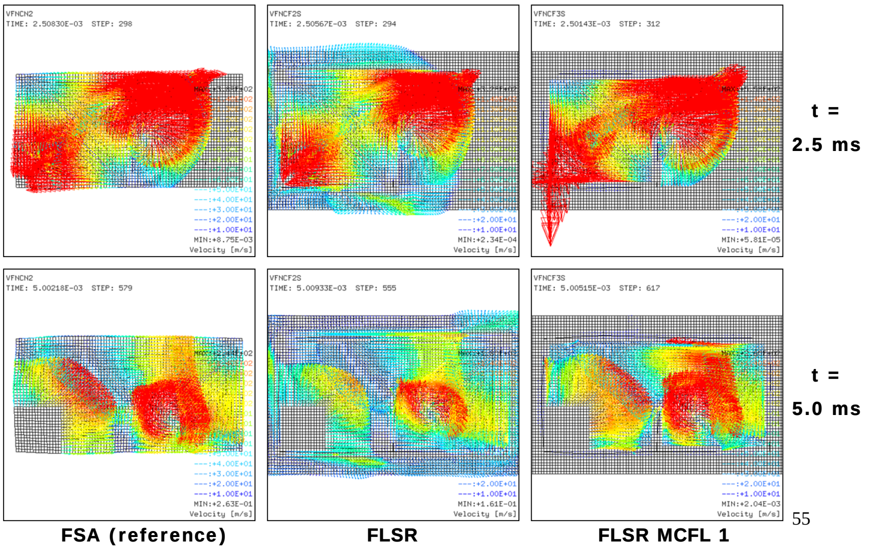


- The box problem of exercise 10b (Part 3) is solved with NCFV using the FLSR model for Fluid-Structure Interaction
  - Obtain solution with NCFV and FSA (reference solution) by using a fine fluid mesh and non-conforming FSA model (see Part 5)
  - Obtain solution with NCFV and basic FLSR : large spurious fluid leakage is observed
  - Add keyword **MCFL 1** : the spurious leakage disappears

54

Exercise 12b – FLSR with NCFV

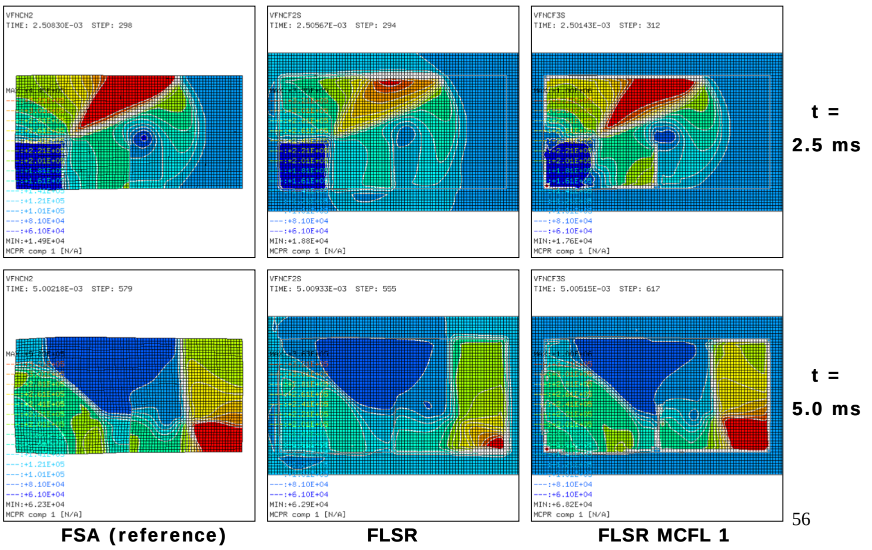
- Fluid velocities :



55

Exercise 12b – FLSR with NCFV

- Fluid pressures :

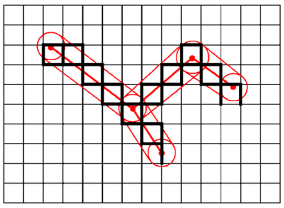


56

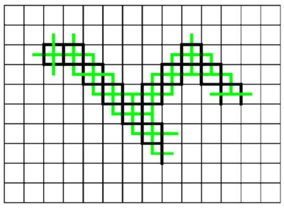
FLSW Model : a "weak" variant of FLSR

for use especially with CCFV

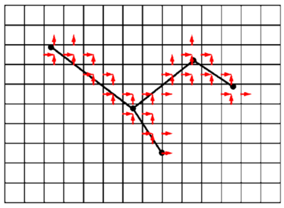
- Automatically build up an "**influence domain**" around the structure (exactly like for **FLSR**)
- Identify (fast search) **fluid volume centres** C **or fluid faces** F currently located within the influence domain
- Transmit **pressure drop forces** to the structure and block associated mass and energy **fluxes** (**weak** approach)



Influence domain of structure (in red) and associated FV faces (thick lines)



Blocked fluxes (in green)

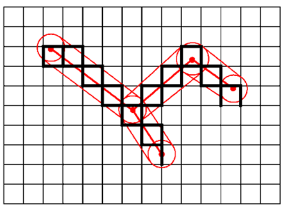


F) Forces to be applied to the structure (closest point)

Strategy 1 : detect directly fluid faces (CCFV only)

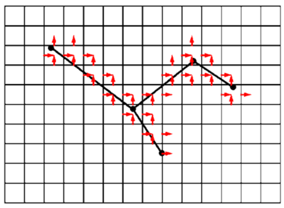
57

FLSW Model (2)



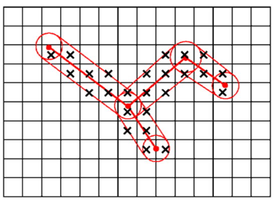
Influence domain of structure (in red) and associated FV faces (thick lines)

Blocked fluxes (in green)

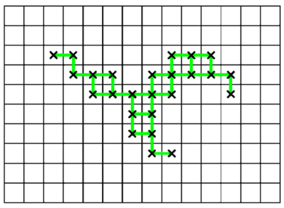


F) Forces to be applied to the structure (closest point)

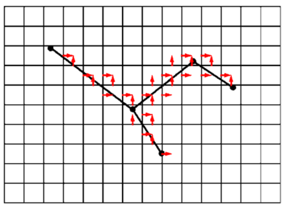
Strategy 1 : detect directly fluid faces (CCFV only)



Influence domain of structure (in red) and associated element centres (crosses)



Blocked fluxes (in green)

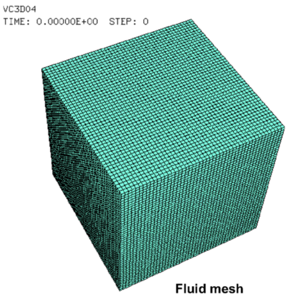


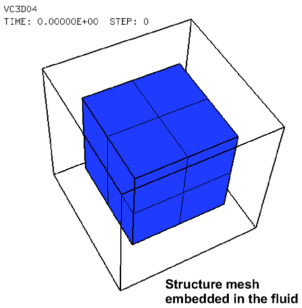
Forces to be applied to the structure (closest point

Strategy 2 : detect fluid elements, then faces

58

FLSW Model (3) : practical advantages





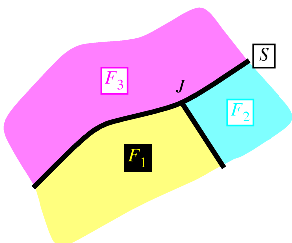
- **Fluid** mesh **much finer** than structure (in view of **adaptivity**)

- **Strong** approach (**FLSR**, implicit) slow due to large bandwidth of constraints matrix
- **Weak** approach (**FLSW**) much faster in this case

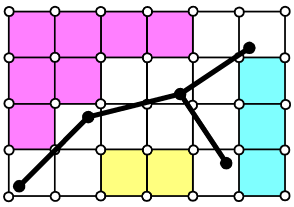
Case	Mesh	FSI model	Steps	CPU [s]	Elms * steps
VC3D04	110592 CUVF, 24 Q4GS (2nd order)	Fixed ext. boundary (no condition). FLSW R 0.0541875 HGRI 1.1 BFLU 2 FSCP 1	139	271	1.6×10^7
EF3D05	110592 FL38, 24 Q4GS	FSR on ext. boundary. FLSR R 0.0541875 HGRI 1.1 BFLU 2 FSCP 1 SOLV SPLI SPLT NONE	125	7,885	1.4×10^7

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

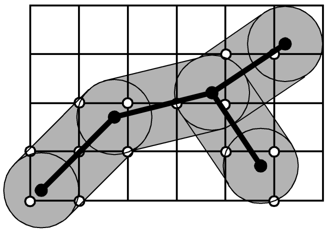
Strong embedded approach (FLSR)

- Detection via **influence domain** around structure
- **Fast** search of **coupled fluid nodes**
- Strong coupling with **closest** structure **point**

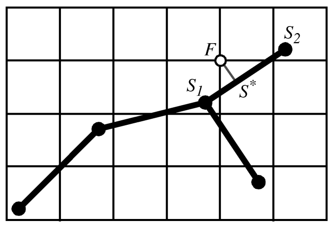
$$\mathbf{v}_F \cdot \mathbf{n}_S = \mathbf{v}_{S^*} \cdot \mathbf{n}_S = (N_1 \mathbf{v}_{S_1} + N_2 \mathbf{v}_{S_2}) \cdot \mathbf{n}_S$$

or more simply :

$$\mathbf{v}_F = \mathbf{v}_{S^*} = N_1 \mathbf{v}_{S_1} + N_2 \mathbf{v}_{S_2}$$



a) Influence domain (shaded) of the structure.



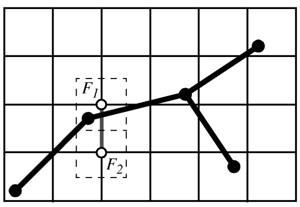
b) F-S coupling.

The **FLSR** embedded algorithm with a **strong** approach

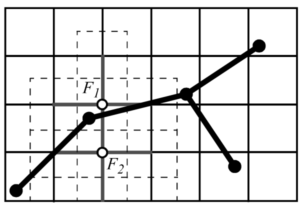
61

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).

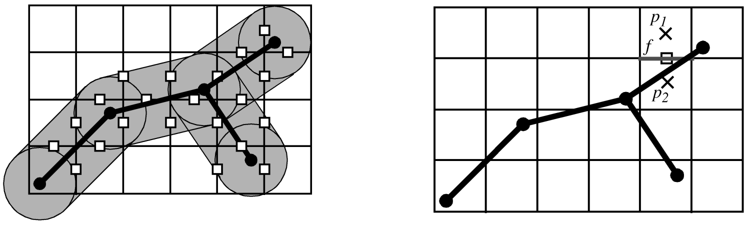


b) More restrictive flux blockage.

62

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.

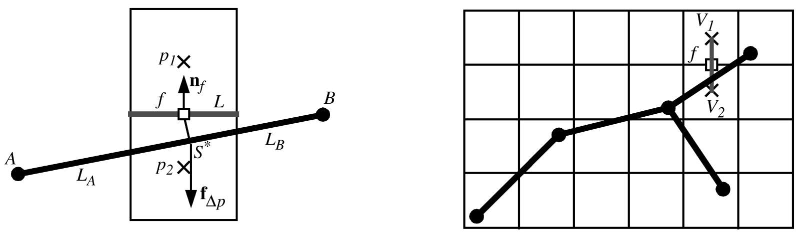
The **FLSW** embedded algorithm with a **weak** approach

63

Weak embedded approach (2)

$$\mathbf{f}_{\Delta p} = (p_1 - p_2) L \mathbf{n}_f$$

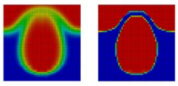
$$\mathbf{f}_{\Delta p,A} = (L_B / L_S)\mathbf{f}_{\Delta p} \quad ; \quad \mathbf{f}_{\Delta p,B} = (L_A / L_S)\mathbf{f}_{\Delta p}$$



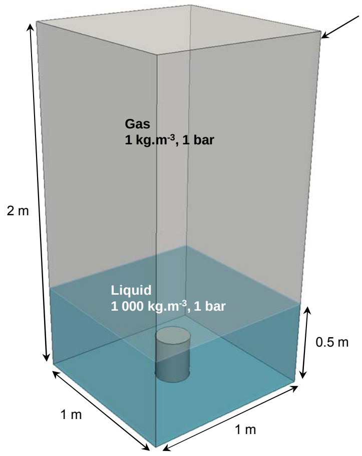
a) F-S coupling force.

b) CCFV flux blockage (thick shaded line).

64

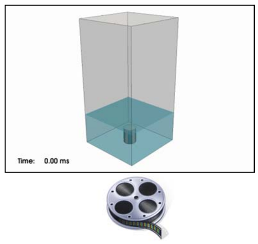


Under-water barrel explosion with anti-diffusion (Courtesy of CEA)



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

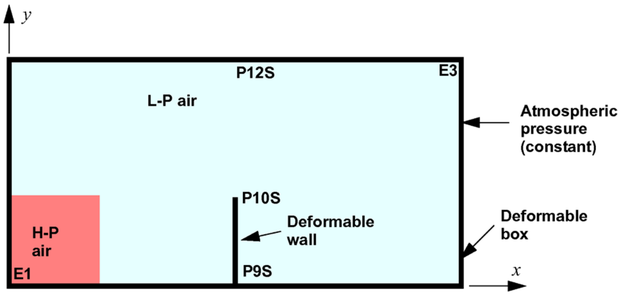
Residual limitations and prospects

- 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**

67

Exercise 6ter – Résumé of FSI models (2)

(All available non-conforming techniques)

- Resume of the 8 obtained solutions :

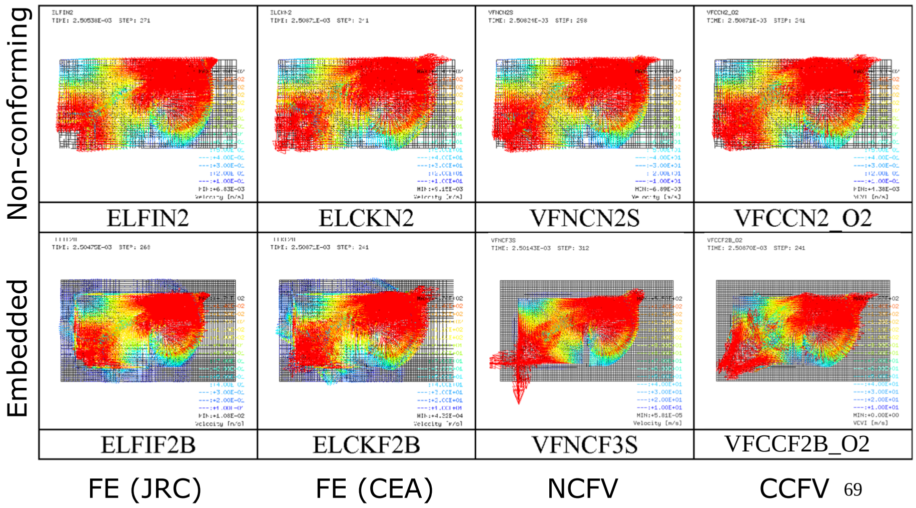
Fluid model / FSI model	FSA or weak (for CCFV)	Embedded: FLSR/FLSW
FE-JRC	ELFIN2	ELFIF2B
FE-CEA	ELCKN2	ELCKF2B
NCFV	VFNCN2S	VFNCF3S
CCFV	VFCCN2_O2	VFCCF2B_O2

68

Exercise 6ter – Résumé of FSI models (3)

(All available non-conforming techniques)

- Fluid velocities at 2.5 ms in the 7 solutions :

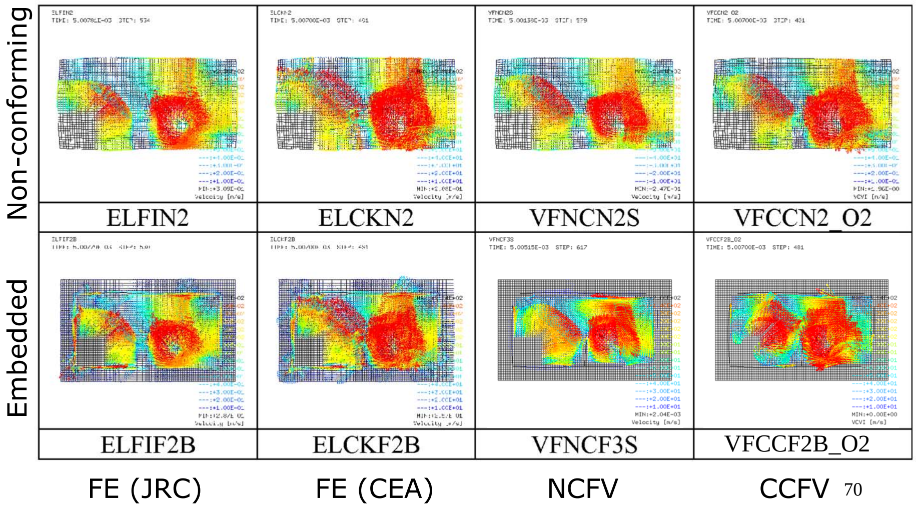


69

Exercise 6ter – Résumé of FSI models (4)

(All available non-conforming techniques)

- Fluid velocities at 5.0 ms in the 8 solutions :

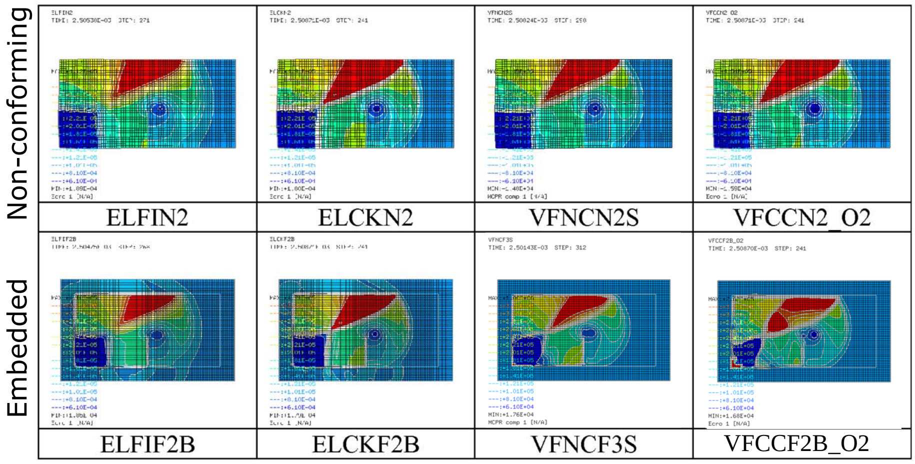


70

Exercise 6ter – Résumé of FSI models (5)

(All available non-conforming techniques)

- Fluid pressures at 2.5 ms in the 8 solutions :

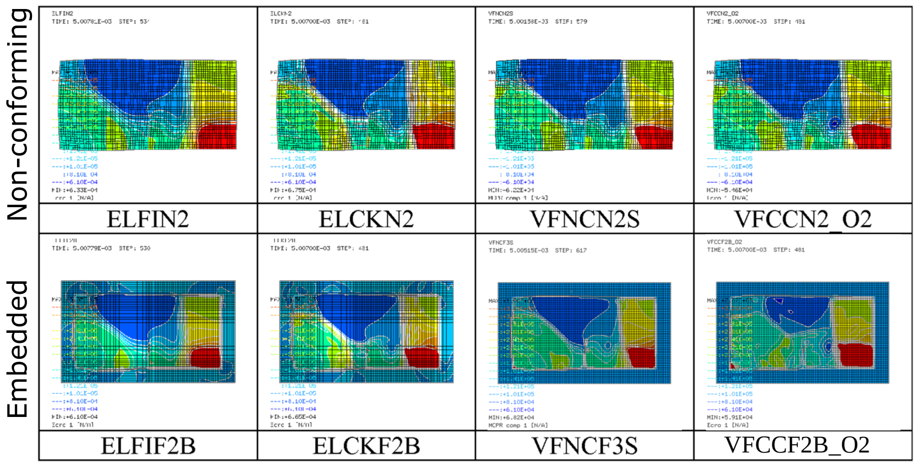


FE (JRC) FE (CEA) NCFV CCFV 71

Exercise 6ter – Résumé of FSI models (6)

(All available non-conforming techniques)

- Fluid pressures at 5.0 ms in the 8 solutions :

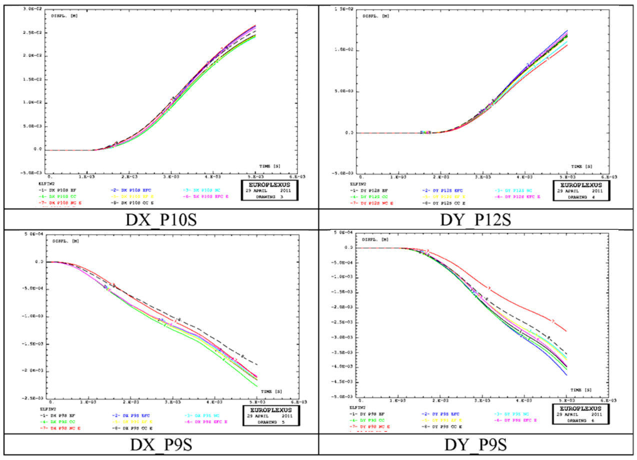


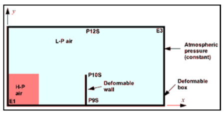
FE (JRC) FE (CEA) NCFV CCFV 72

Exercise 6ter – Résumé of FSI models (7)

(All available non-conforming techniques)

- Structural displacements in the 8 solutions :

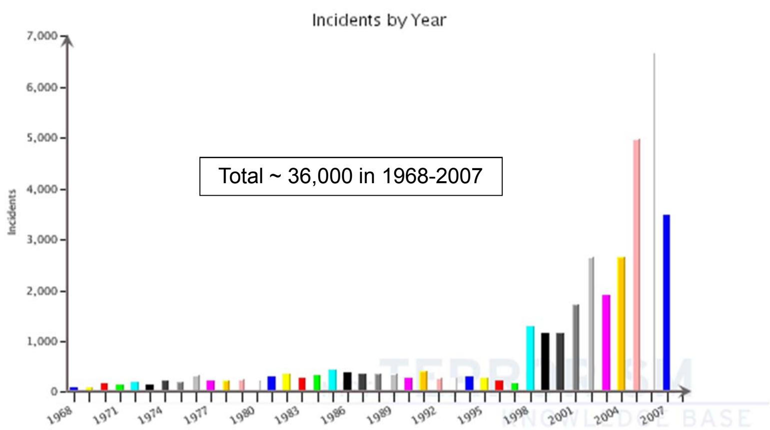




73

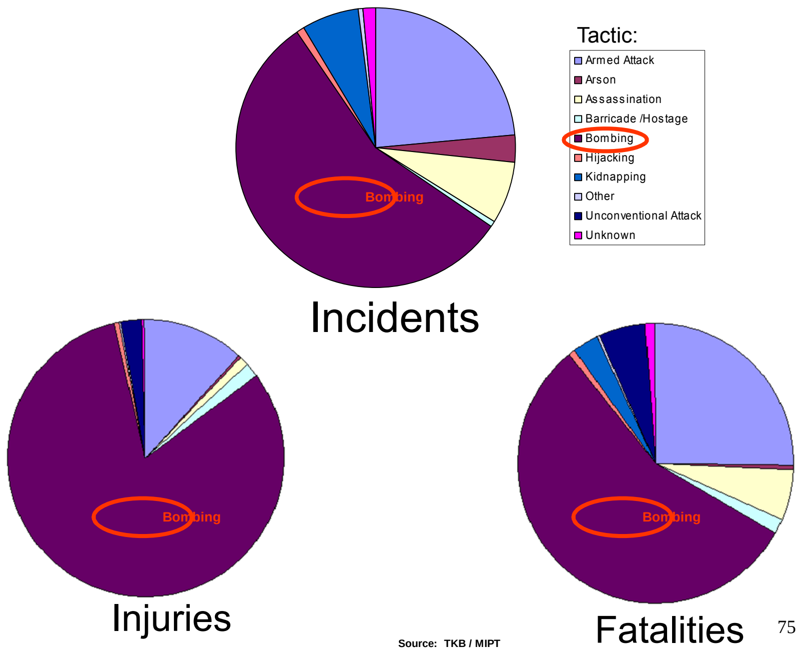
Land Transport Vulnerability: attack on train/metro stations / rolling stock – Background & motivation

Terrorist Incidents Pattern



Source: Terrorism Knowledge Base (TKB), Memorial Institute for the Prevention of Terrorism (MIPT), Last updated on Jan. 29, 2008

74



Source: TKB / MIPT

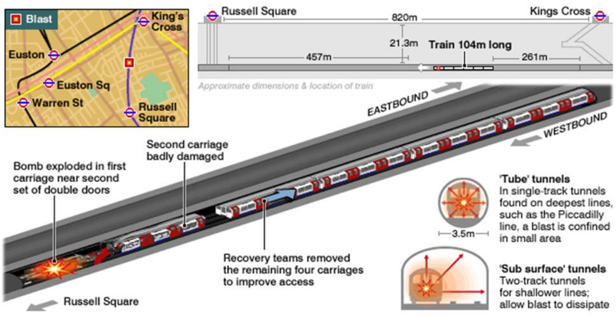
75

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.

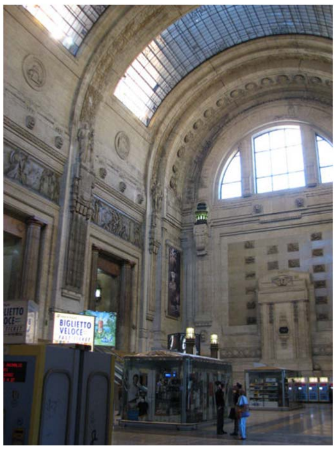
The starting point:

- **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

Land Transport Vulnerability: attack on train/metro stations and rolling stock

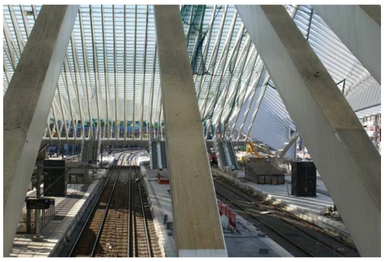
Old stations …

Milan Central station



Glazing of Stations and other Buildings

Broadgate Tower, London (under construction)



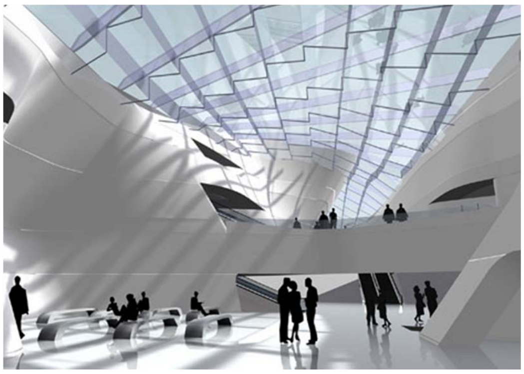
Railway station Liège

European Parliam Strasbourg

Railway station Berlin

80

Source: wikipedia.org



Naples, Afragola

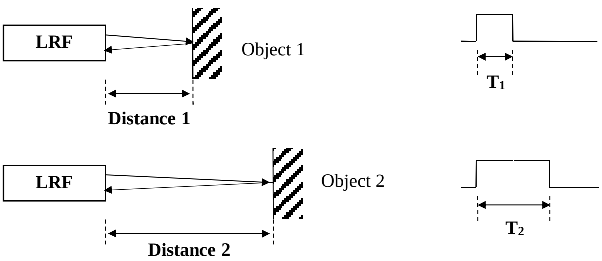
Future stations …

Florence, Belfiore

Are explosion effects considered ?

Getting the Real Geometry (JRC 3D Reconstructor)

- Laser scanner and digital camera



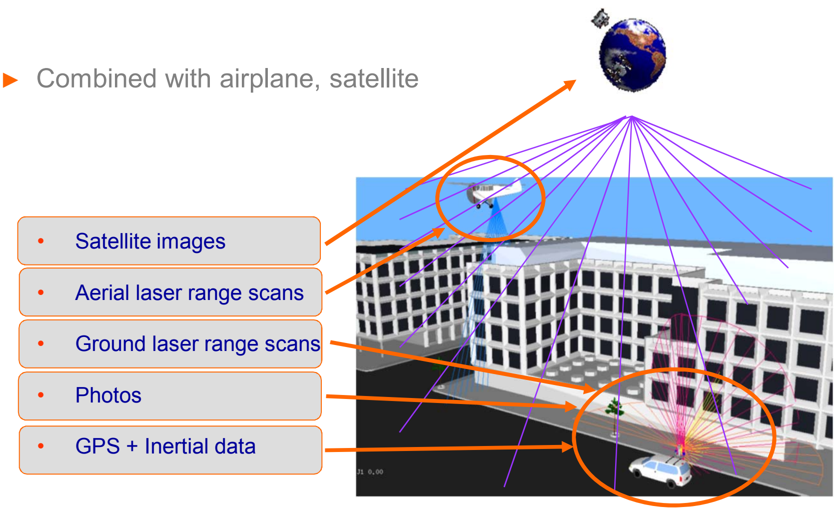
Getting the Geometry (2)

- Tripod and/or vehicle

83

Getting the Geometry (3)

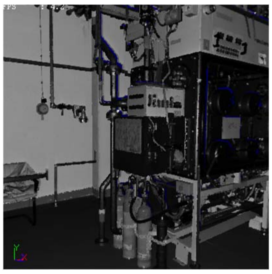
- Combined with airplane, satellite



Computer simulation of the data acquisition system

Example : detecting changes

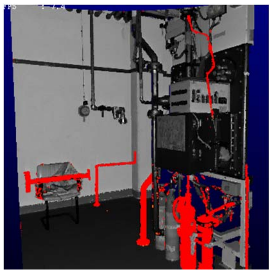
Reference



Verification

Differences

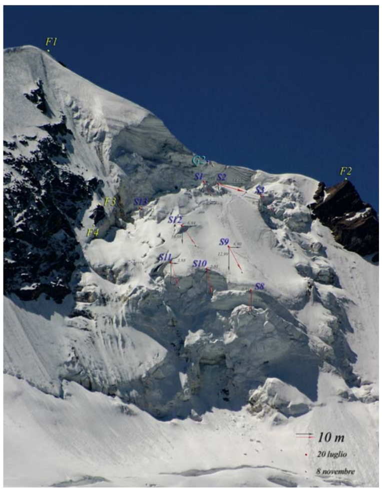
highlighted by JRC 3D Reconstructor software

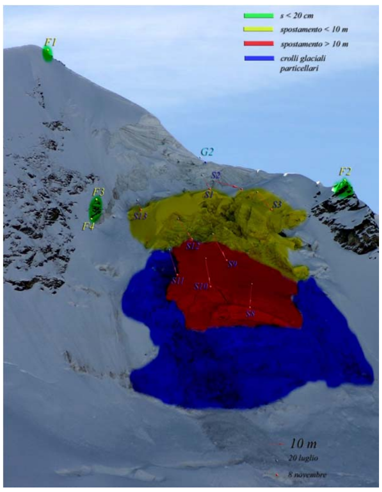


85

Example : detecting changes (2)

- Evaluate possible damage in case of the ice fall collapse



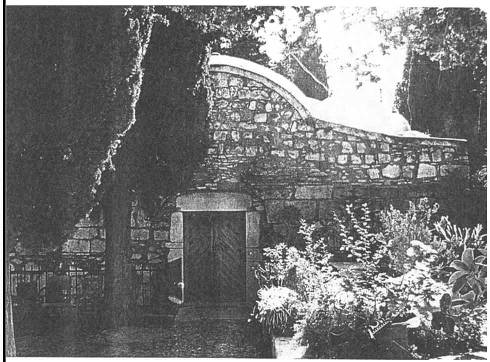


Source: InnTec, University of Brescia, Servizio Glaciologico Lombardo Arpa

86

Exercise/Example 13 – Building Vulnerability

• Internal blast in a (deformable) building (but no failure yet!):

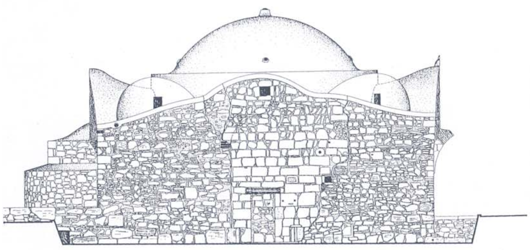


Front View

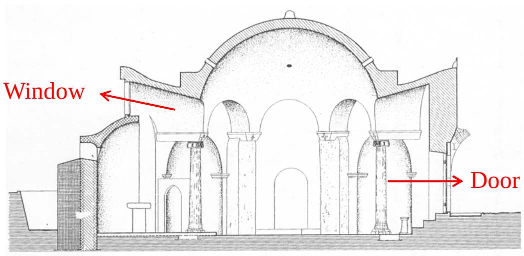
Back View

87

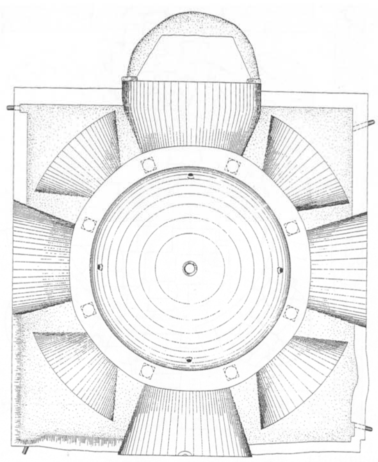
Exercise/Example 13 – Building Vulnerability (2)



Side View



Sectioned View

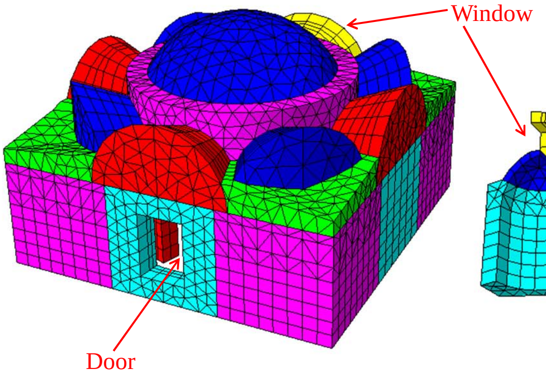


Top View

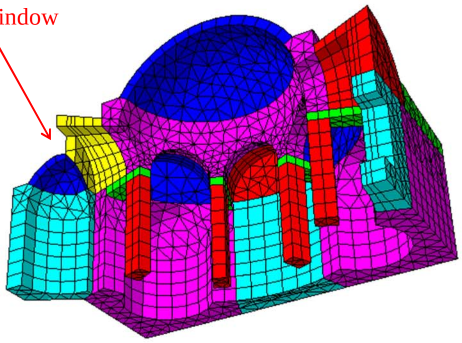
88

Exercise/Example 13 – Building Vulnerability (3)

- Structural mesh:



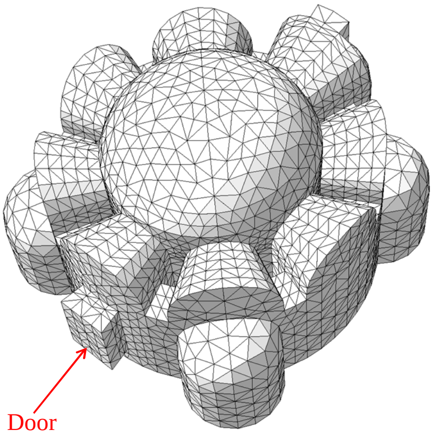
Complete View



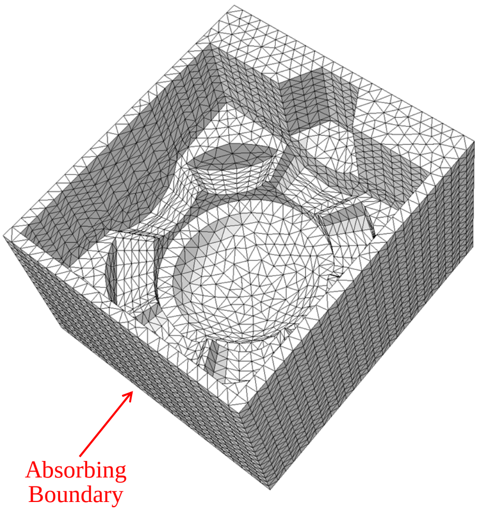
Sectioned View Along Symmetry Plane

Exercise/Example 13 – Building Vulnerability (4)

- Fluid mesh:



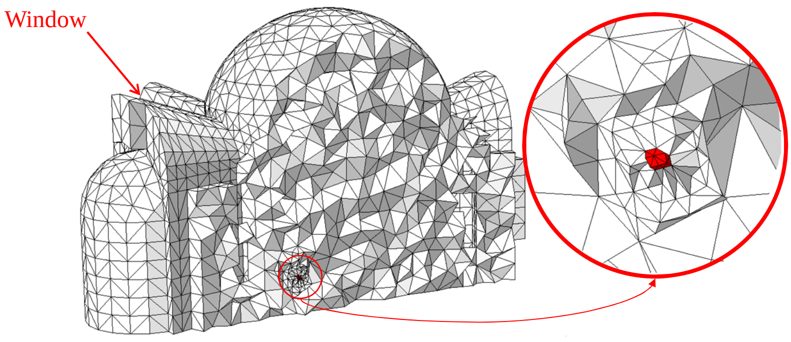
Internal Fluid (from top)



External Fluid (from bottom)

Exercise/Example 13 – Building Vulnerability (5)

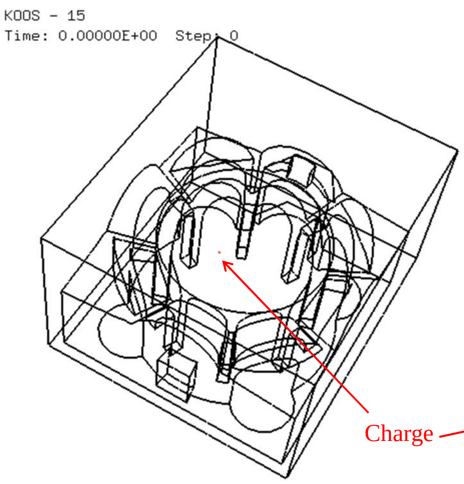
- Explosive charge (solid TNT):

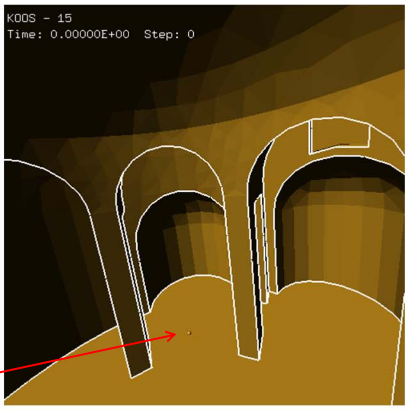


91

Exercise/Example 13 – Building Vulnerability (6)

- Explosive charge (solid TNT):

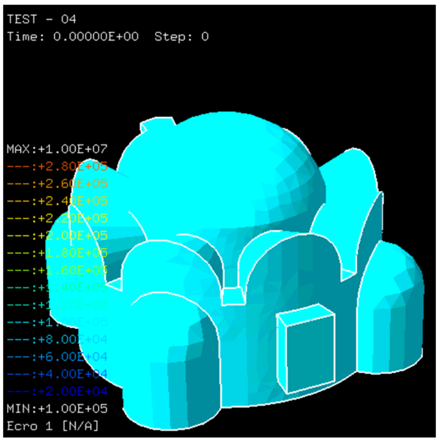


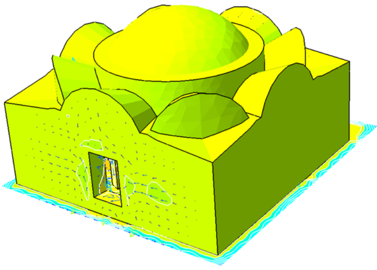


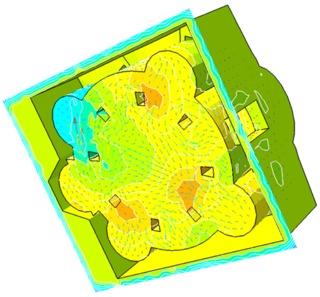
92

Exercise/Example 13 – Building Vulnerability (7)

- Pressures/velocities in fluid:



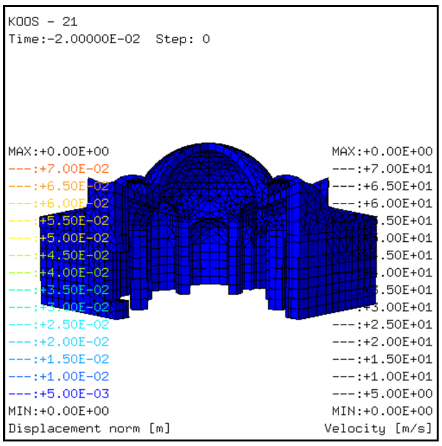


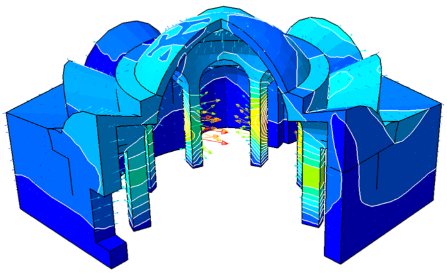


93

Exercise/Example 13 – Building Vulnerability (8)

- Structural deformations and velocities:





94

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

Exercise/Example 13 – Building Vulnerability (10)

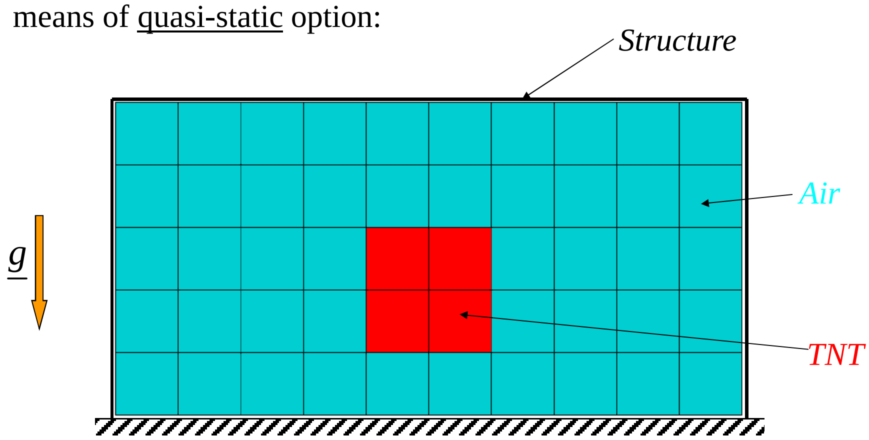
EUROPLEXUS (C) Animation

Explosion in Kos Baptistery – Model

Authors: F. Casadei & A. Anthoine

Exercise 14 – Improving Initial Conditions

• Take into account static loading (gravity, fluid pressure) by means of quasi-static option:



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>
```

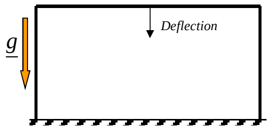
• Add a viscous force proportional to momentum for each dof:

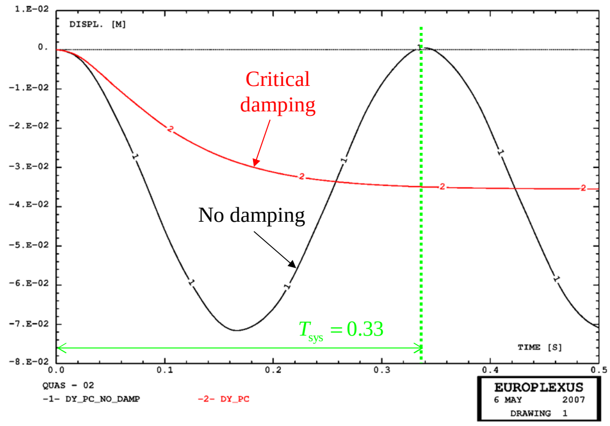
$$F_{iQS} = -4\pi\beta f_{sys} M_i v_i$$

• $\beta = 1$ corresponds to critical damping for the frequency f_{sys}.

Exercise 14 – Improving Initial Conditions (3)

- Compute system frequency under gravity load:





$T_{sys} = 0.33$

⇓

$f_{sys} = 1/T_{sys} = 3$

⇓

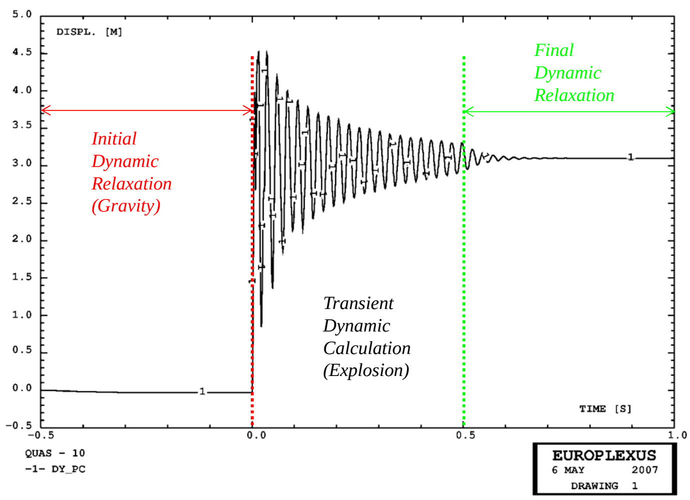
OPTI QUAS STAT 3.0 1.0

99

Exercise 14 – Improving Initial Conditions (4)

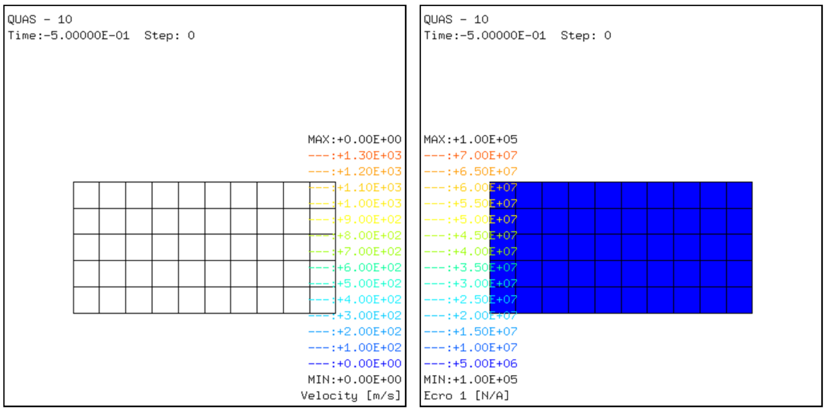
- Transient calculation with <u>initial</u> and <u>final</u> quasistatic option:

OPTI QUAS STAT 3. 1. UPTO 0. FROM .5



100

Exercise 14 – Improving Initial Conditions (5)



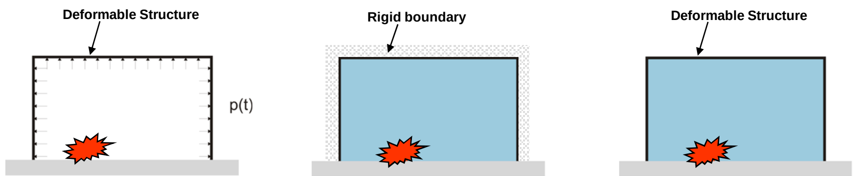
Velocities *Pressures*

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

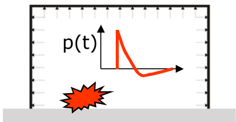


Pressure-time curve (AIRB) | Fluid + Rigid boundary (FSR) | Fluid / Structure (FLSR)

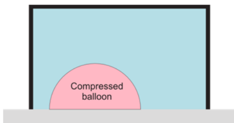
102

Three ways to model the explosive charge :

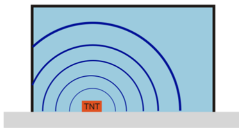
- **Pressure-time empirical function (AIRB)**
- **Compressed Bubble (BUBB) :** calibration needed
- **Solid TNT (JWLS) :** requires fine mesh (CPU-expensive)



Pressure-time curve
(AIRB)



Compressed bubble
(BUBB)



Solid TNT
(JWLS)

Realism / Difficulty / Cost

103

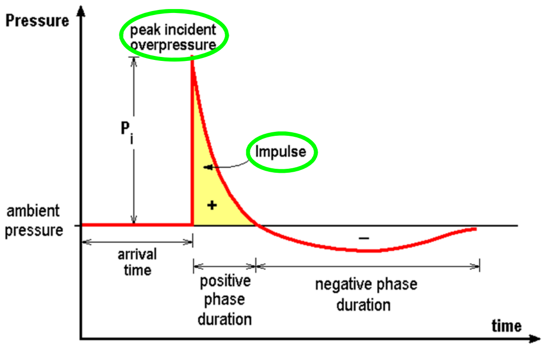
Air Blast Simulation

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)

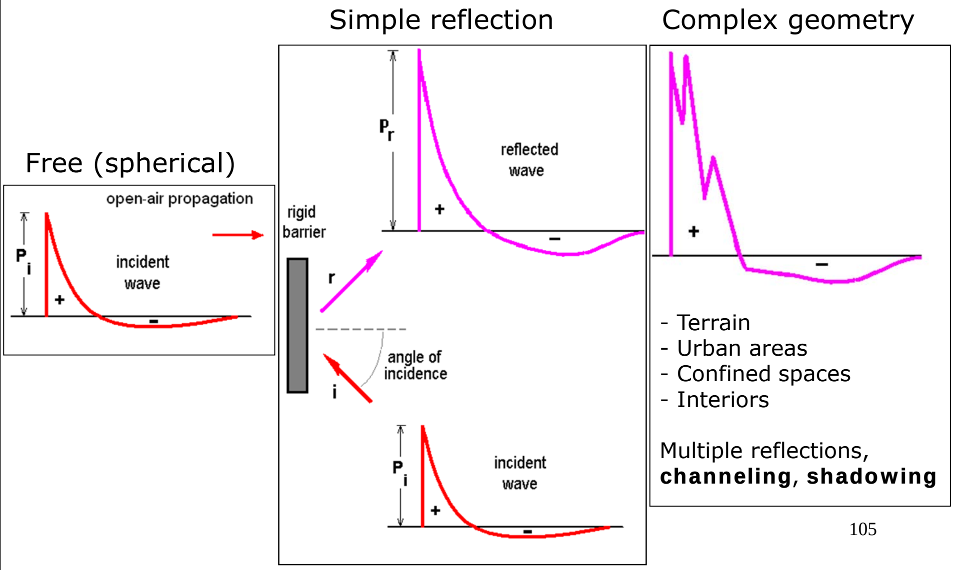
  p = p (m, d, t)

- Parameter tables in the literature (Baker, Kinney, Kingery, …)



104

Pressure Wave Propagation

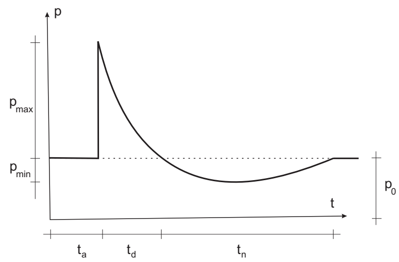


105

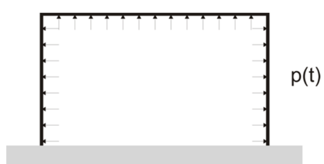
Simple "AIRB" model

- Modified Friedlander equation:

$$p = p(m, d, t)$$



- This pressure can be <u>directly</u> 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 <u>simple</u> geometrical situations)



106

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/**

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/**

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**

109

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

110

Mechanisms of Blast Injury

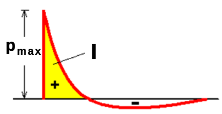
Primary blast injury
(due to **overpressure** :
eardrum rupture, lung injury …)

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

Risk evaluation (see Ferradás *et al.* [1])



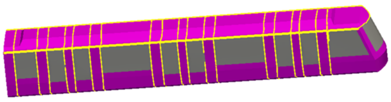
- Risk depends on **peak overpressure p_{max}** (in Pa) and on the **positive impulse I** (in Pa·s) in the **fluid**
- Use is made of following **probit functions**

  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**

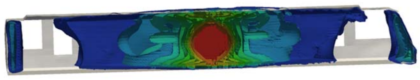
  Non-lethal blast injuries :
  - $Y_5 = - 12.6 + 1.524 \ln (p_{max})$: **Eardrum rupture**
- Probability of occurrence (or % of affected population) is :
  - $P_i = - 3.25 Y_i^3 + 48.76 Y_i^2 - 206.60 Y_i + 270.35$, $i = 1, \ldots, 5$
- Death risk is maximum of the above lethal risks :
  - $P_{death} = \max (P_1, P_2, P_3, P_4)$

[1] Ferradás EG *et al.*, Process Safety and Environmental Protection **86** (2008) 121-129.

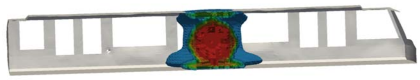
Risk maps are directly obtained in the **fluid** sub-domain :



Metro carriage



Eardrum rupture risk



Death risk

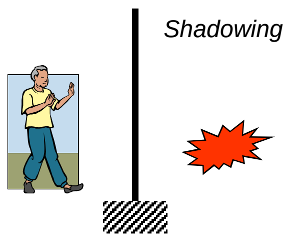
Risk evaluation <u>requires</u> **modeling of the fluid**

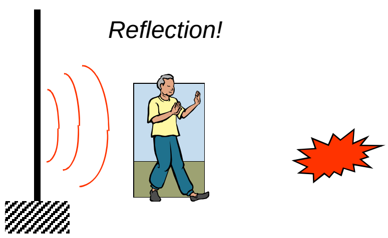
113

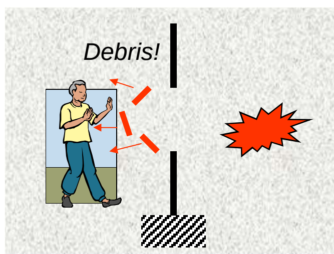
Explosion effects (qualitative)

One should consider the following **trade-offs**:

- Presence or not of a structure:
  - Shadowing
  - Reflections / channeling
  - Secondary debris
- Relative positioning

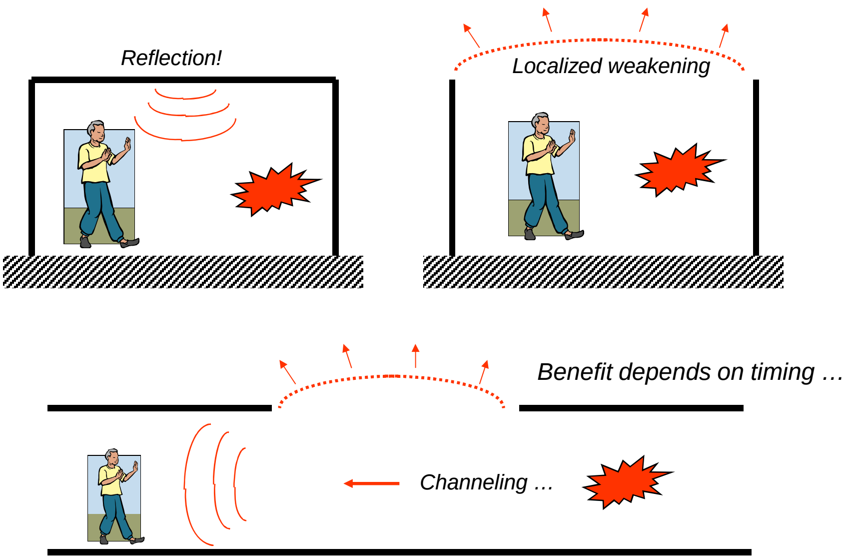






114

Explosion effects (qualitative)



115

Case Study 1 - Historic Railway Station

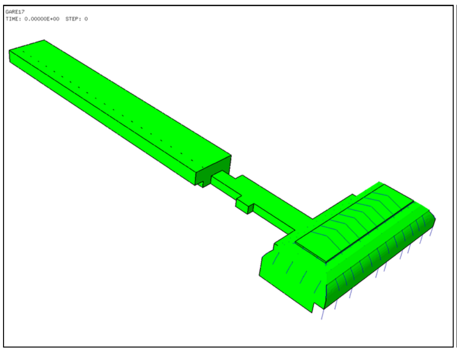
116

Historic Railway Station (2)

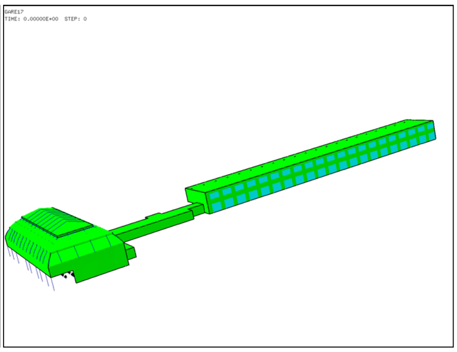
In-Situ Laser Scan + "JRC 3D-Reconstructor"

Historic Railway Station (3)

Structural model :



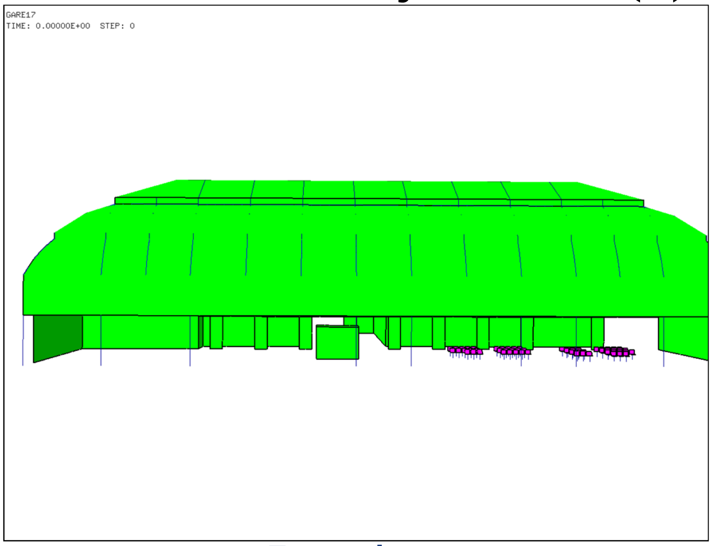
Left outside view



Right outside view

118

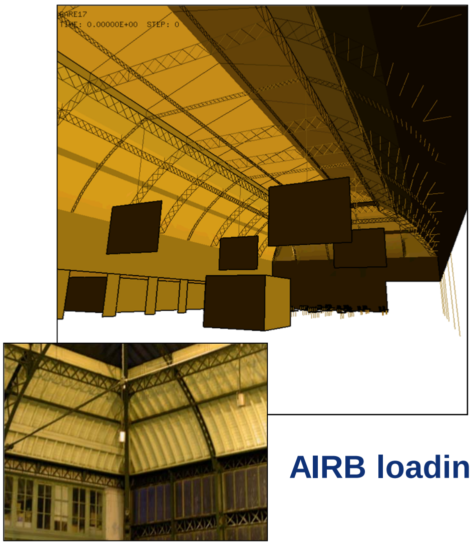
Historic Railway Station (4)

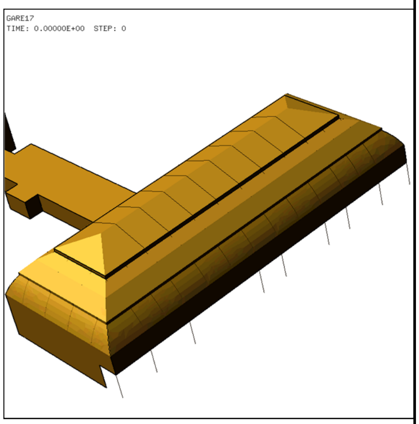


Front view

119

Historic Railway Station (5)



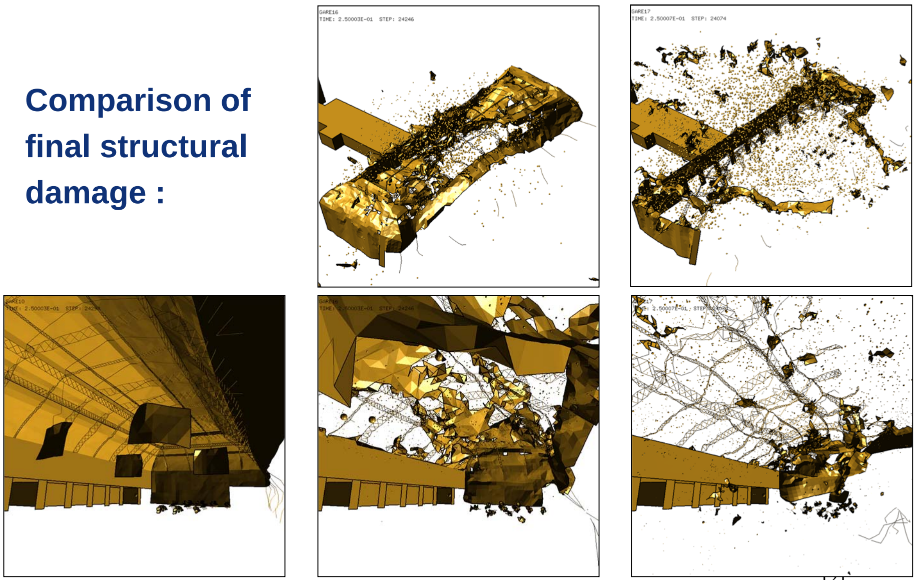


AIRB loading, large TNT mass

120

Historic Railway Station (6)

Comparison of final structural damage :



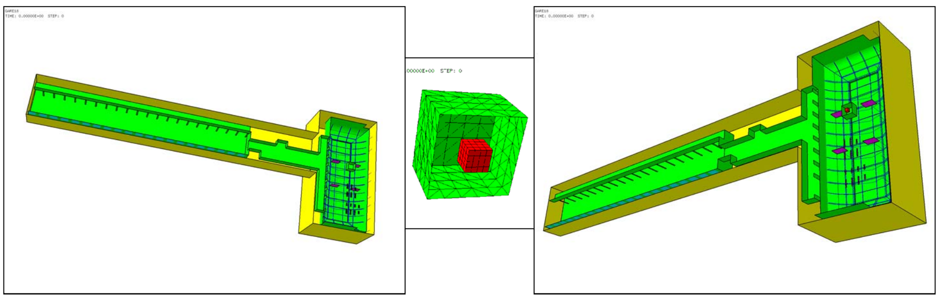
Small charge **Medium charge** **Large charge**

121

Historic Railway Station (7)

Full FSI modeling : both Fluid and Structure are modeled

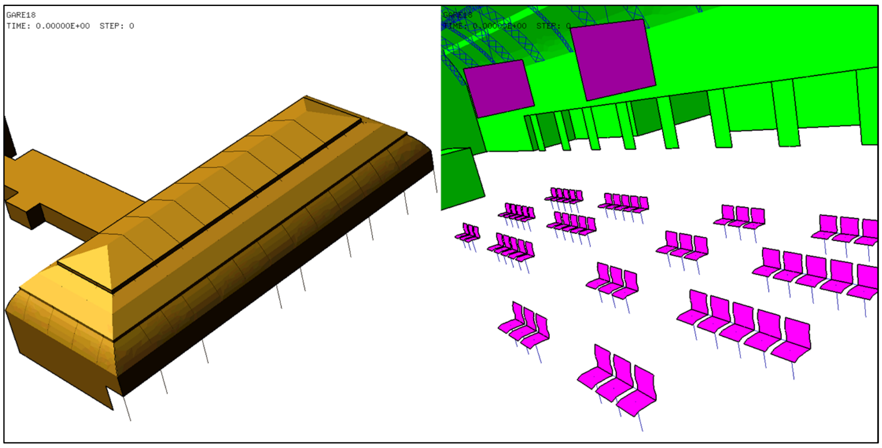
- Compressed bubble model (BUBB)
- Non-conforming Fluid-Structure Interaction (FLSR)
- Absorbing conditions around fluid domain



4.3 million elements (mostly fluid hexa.), 14.6 days CPU

122

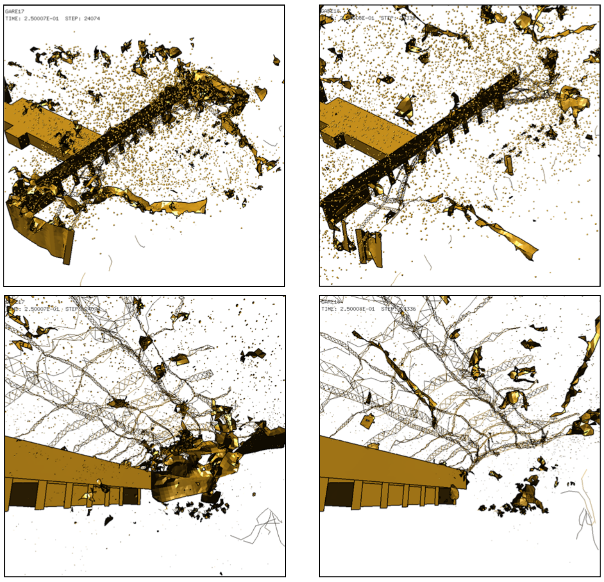
Historic Railway Station (8)



Large charge

123

Historic Railway Station (9)



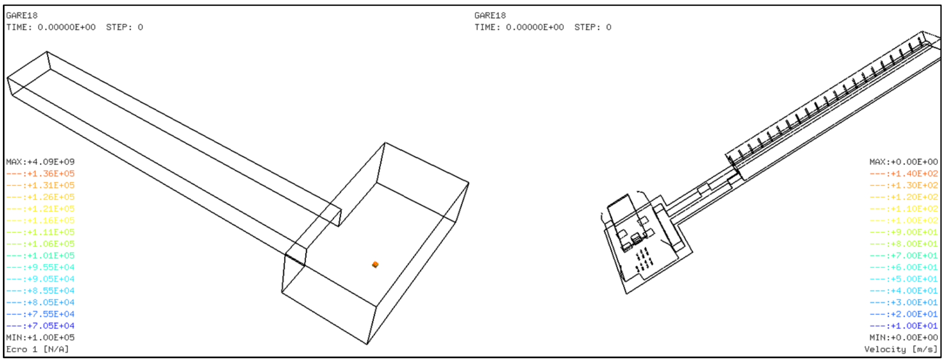
AIRB **FLSR**

Comparison of final structural damage for large charge

124

Historic Railway Station (10)

Fluid Pressure | **Fluid Velocity**

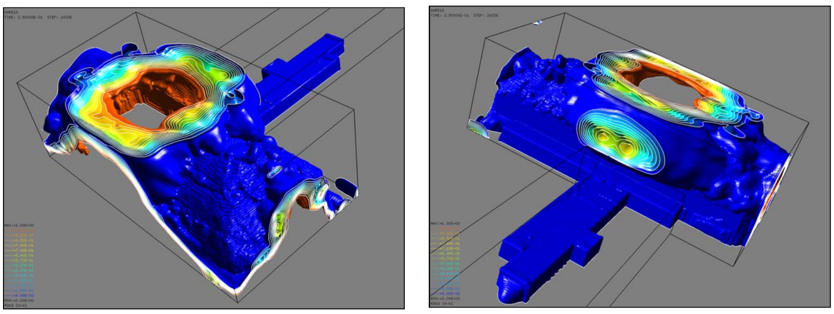


Large charge

125

Historic Railway Station (11)

Final Death Risk

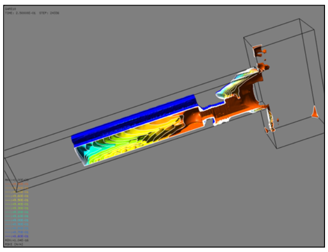


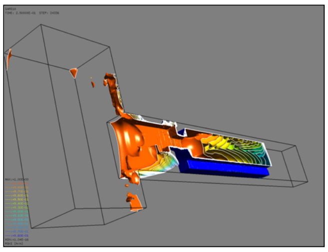
Large charge

126

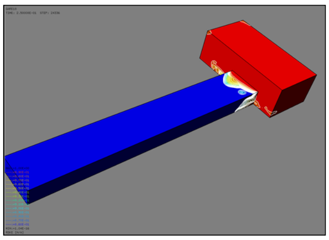
Historic Railway Station (12)

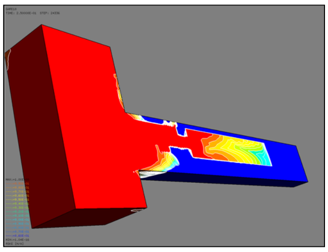
Final Eardrum Rupture Risk





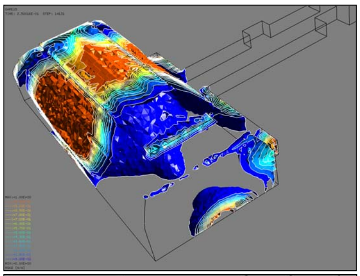
Large charge



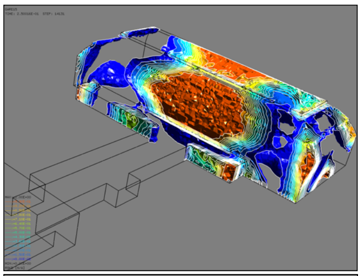


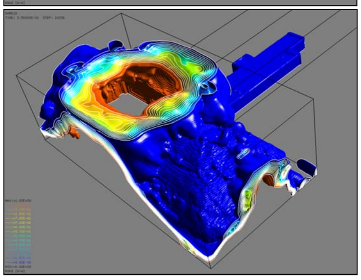
Historic Railway Station (13)

Comparison of Risk : Death Risk

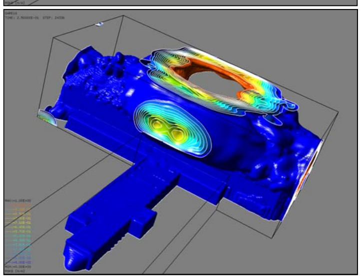


FSR, Small charge (rigid structure)





FLSR, Large charge (deformable Structure)



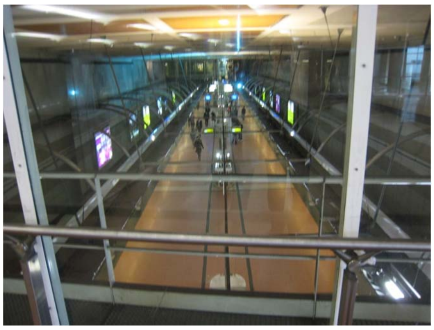
Summary of Approaches

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

129

Case Study 2 - Recent Metro Station

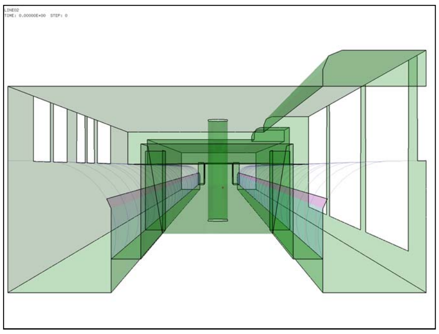


Corridor with sliding doors

130

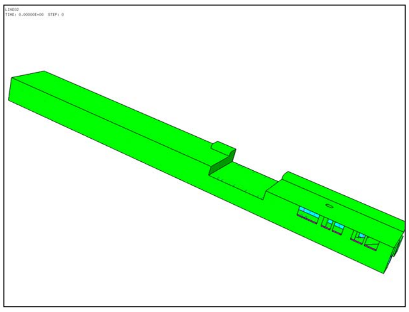
Metro Line Station (2)

Laser Scan

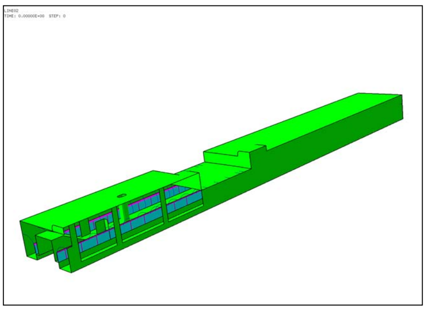


Numerical model

Metro Line Station (3)



Left outside view

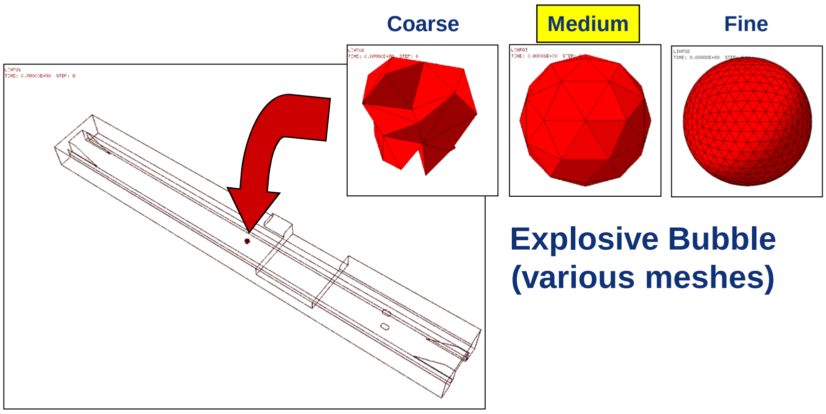


Right outside view

Metro Line Station (4)

Second approach : only the Fluid is modeled

- Compressed bubble model (BUBB)
- Rigid inviscid boundary (FSR)

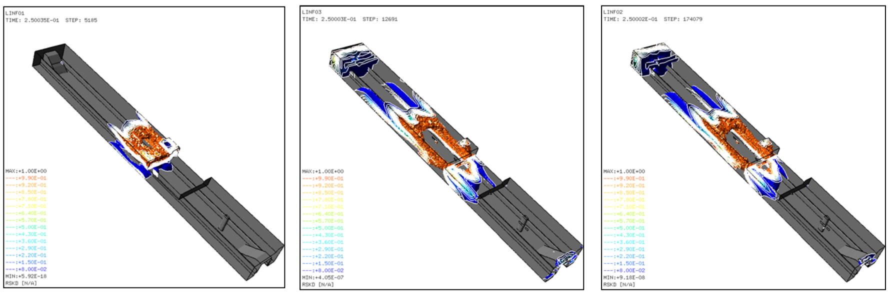


Explosive Bubble
(various meshes)

Metro Line Station (5)

Influence of bubble discretization :

Final Death Risk for Large Charge



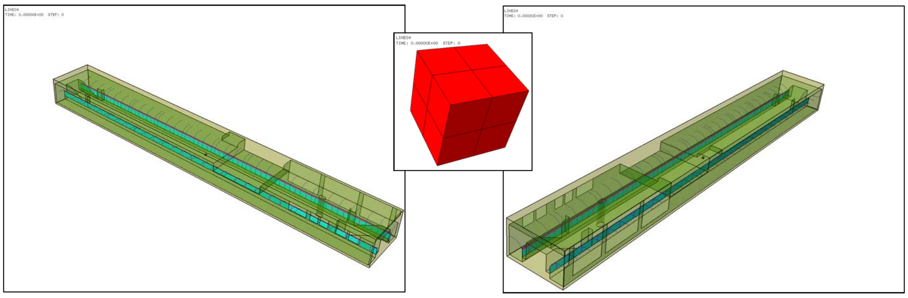
Coarse (43 tetr.) 0.5 days CPU	Medium (190 tetr.) 1.3 days CPU	Fine (9564 tetr.) 18.3 days CPU

Total # of elements roughly identical : 1.1 million tetr.

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

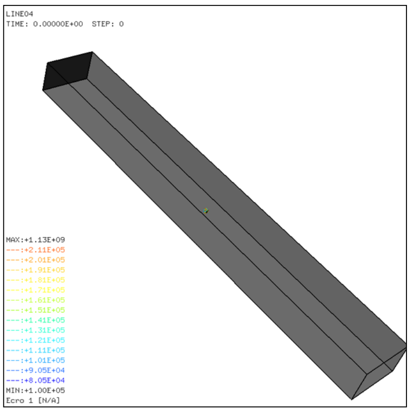


2.0 million elements (mostly fluid hexa.), 8.5 days CPU

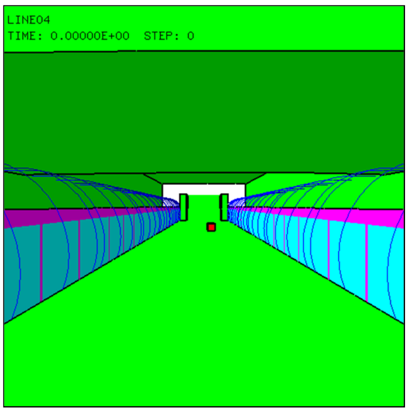
135

Metro Line Station (7)

Large charge



Fluid Pressure

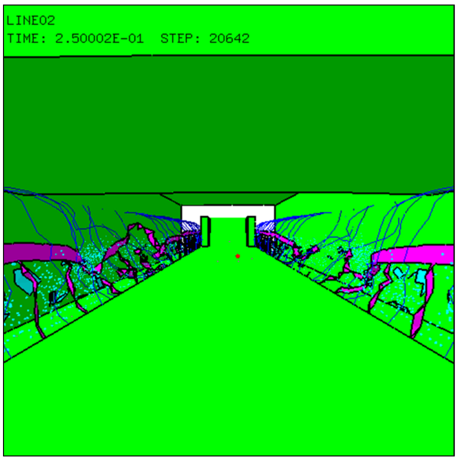


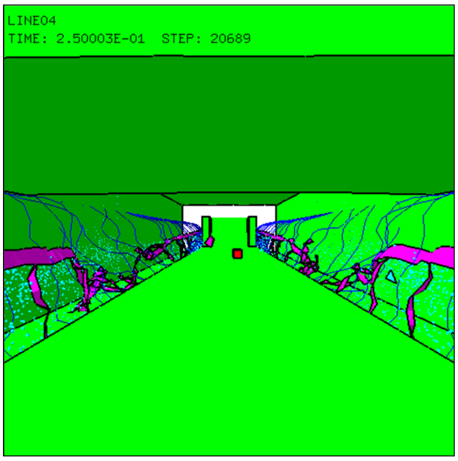
Structural Failure

136

Metro Line Station (8)

Large Charge





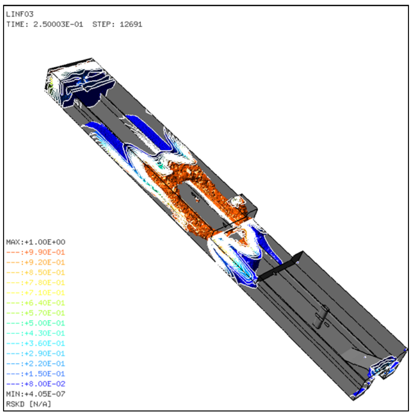
AIRB
156,000 elems, 0.9 days

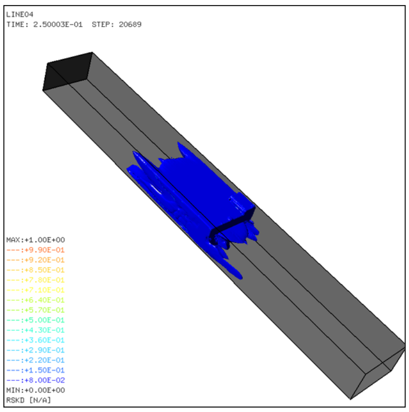
FLSR
2,022,000 elements, 8.5 days

137

Metro Line Station (9)

Comparison of Final Death Risk





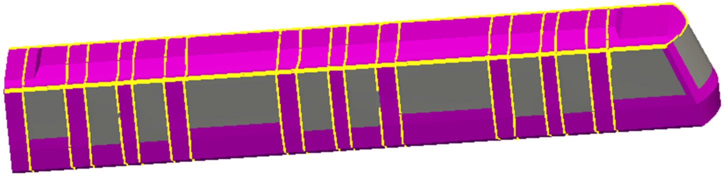
FSR
1.1 million elements
1.3 days CPU

Large Charge

FLSR
2.0 million elements
8.5 days CPU

138

Case Study 3 – Metro Line Carriage



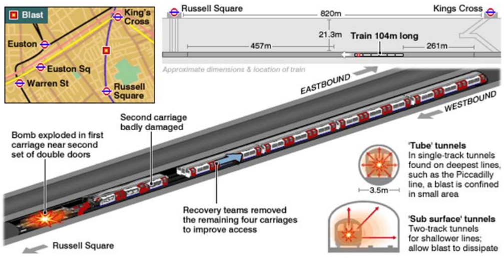
Geometry : JRC 3D Reconstructor

139

Motivation

Madrid, 11 March 2004 :
Fatalities 191
Injured 1200

London, 7 July 2005:
Fatalities 50
Injured 700



140

Source: www.bbc.co.uk

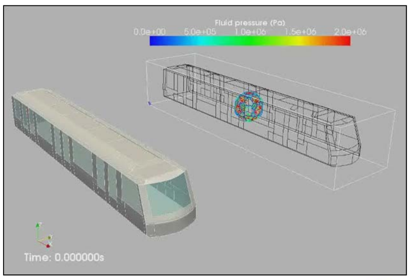
Blast-related phenomena

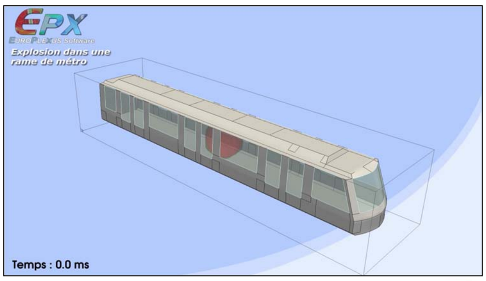
Source: www.spiegel.de

Bag bomb : main effects

Simulation vs. reality

Example of metro carriage

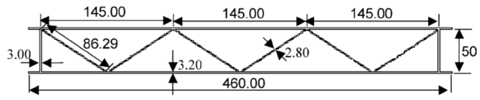




Carriage Structure

Honeycomb structure

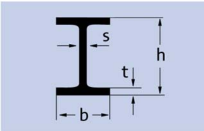
- Detailed model too expensive
- Sandwich element with
  same thickness, mass and stiffness



Zheng 2005

OR : Frame structure

- IPE80
- 3 mm aluminum sheet
  welded on frame structure

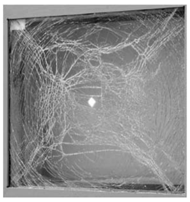


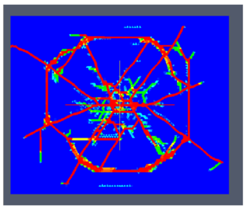
A [m²]	7.60E-04
max I [m⁴]	8.01E-07
h [m]	0.08
c [m/s]	5092

- Floor fixed
- Explosive in the centre of the carriage

Windows: Laminated glass

- LSGL material

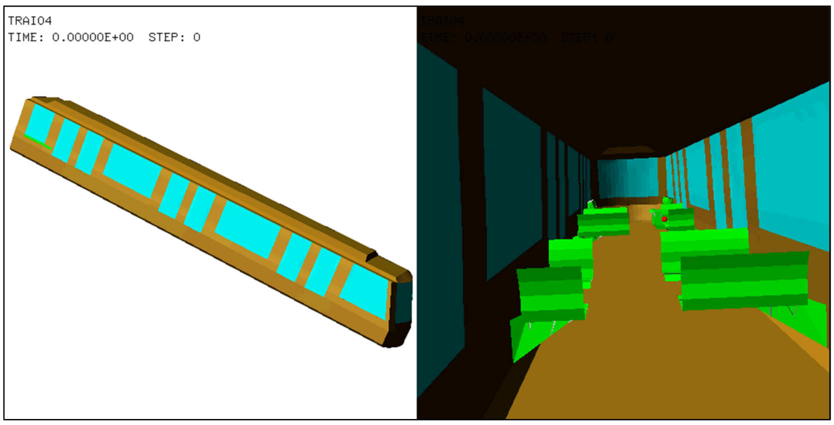




143

Train (AIRB)

Trai04ba_01 Trai04fa_01

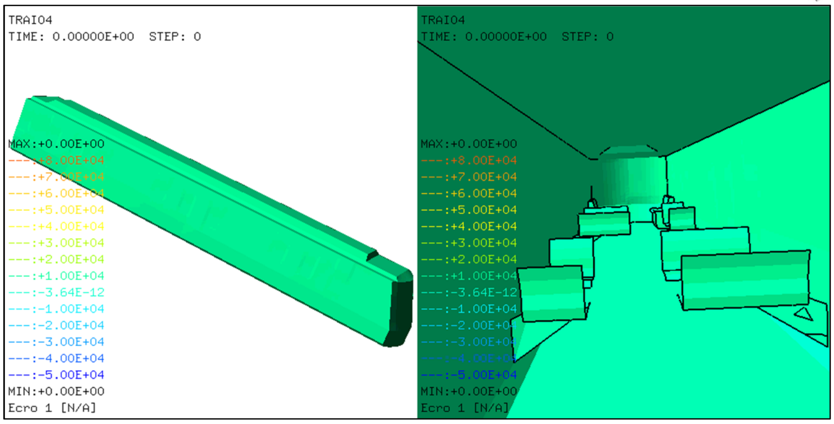


Structural deformation and failure

144

Train (AIRB) (2)

Trai04da_01 Trai04ha_01

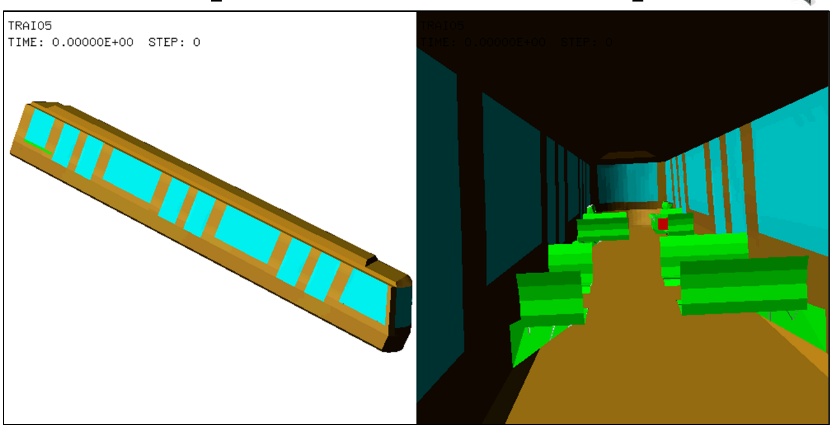


AIRB pressure

145

Train (Fluid/FLSR) (3)

Trai05ba_01 Trai05fa_01

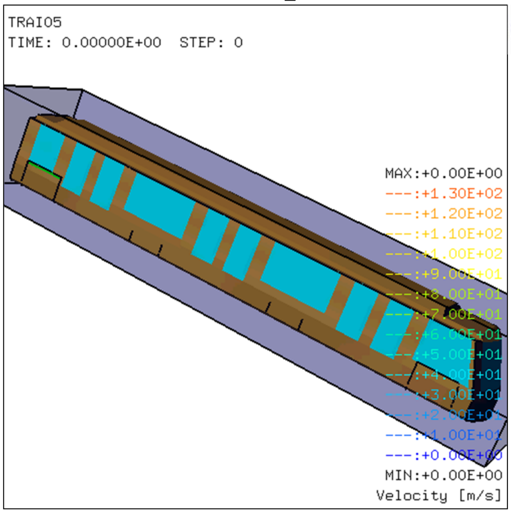


Structural deformation and failure

146

Train (Fluid/FLSR) (4)

Trai05ha_01

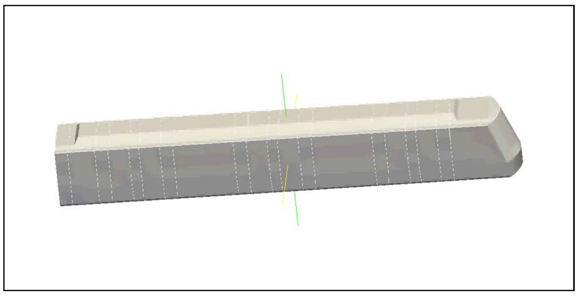


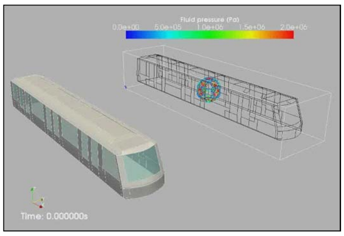
Fluid velocities

147

Blast Simulation

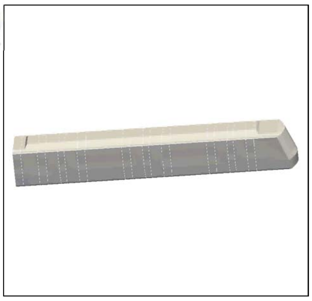
Bag bomb,
frame structure,
laminated glass

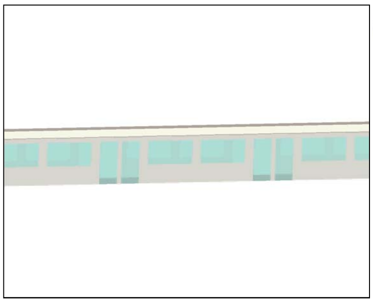


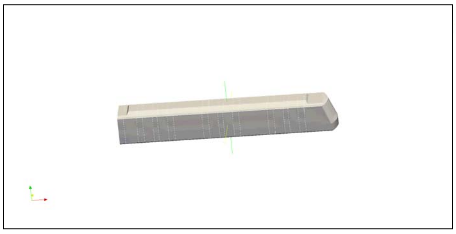


148

Example of metro carriage





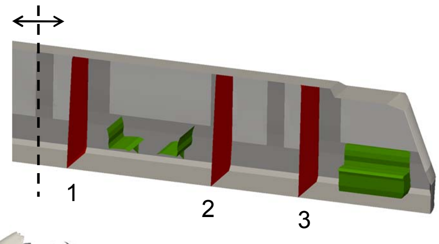


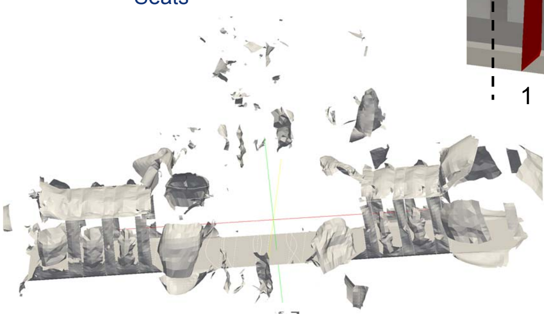
149

Effect of internal Structures

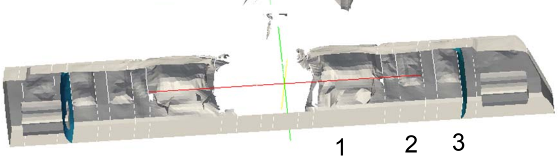
FSI, Laminated glass, frame structure, 10kg TNT:

- Internal walls
  - Seats





No internal walls

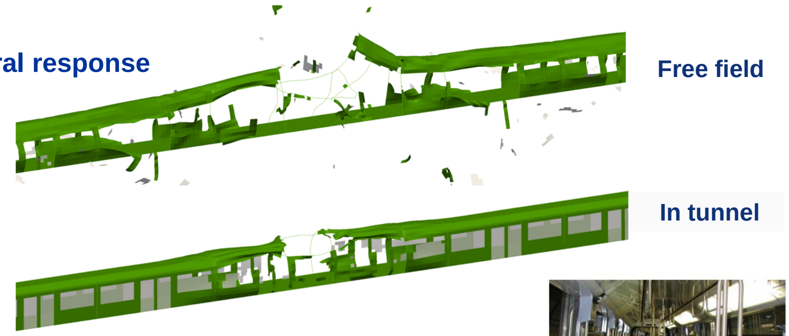


Internal walls : failure is **more localized**

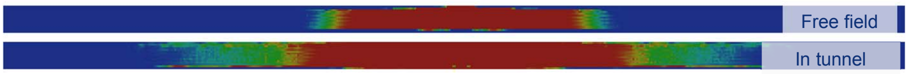
150

Influence of a tunnel

Structural response



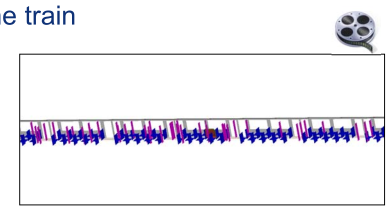
Human injuries

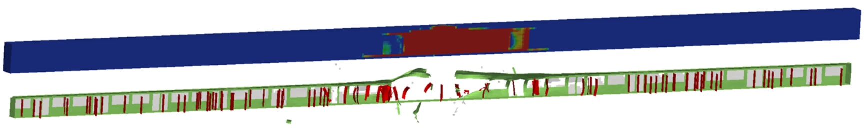


Probability of death

Influence of Passengers / Seats

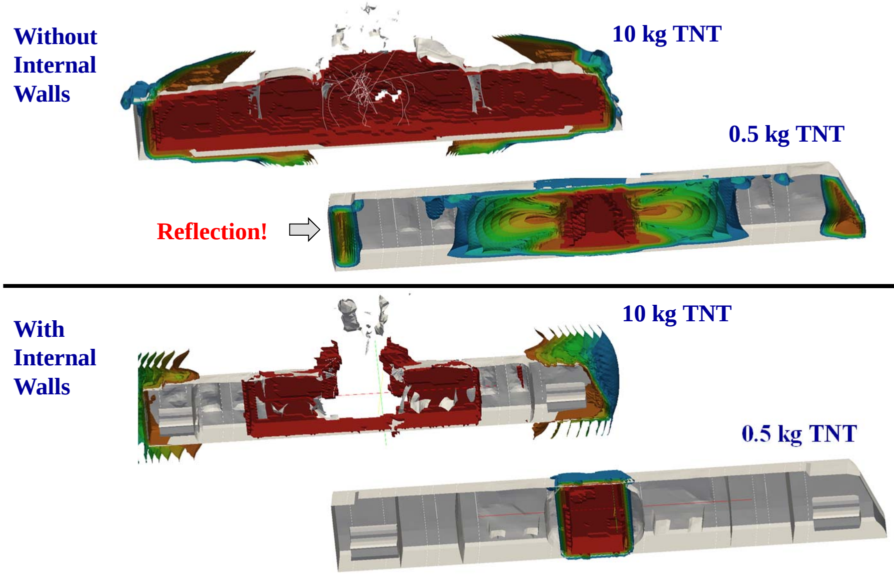
- Simple model with shell elements, thickness 10 cm
- Standard weight (~70 kg)
- 100/500 passengers randomly in the train
- No connection to floor
- Aluminium seats, thickness 3 mm



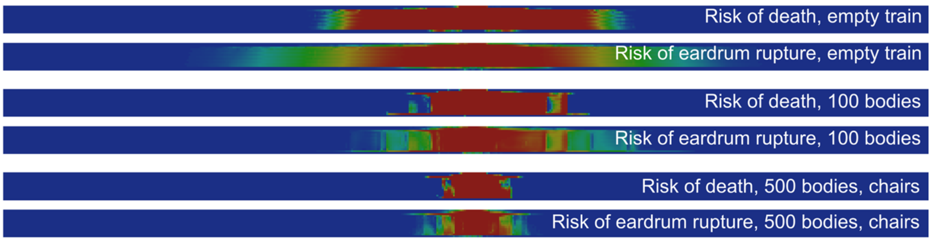


152

Death Risk Maps

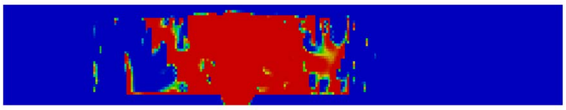


10 kg TNT, including passengers & seats

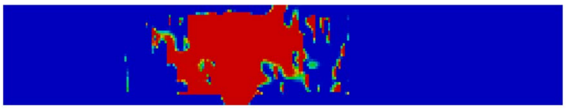


Seats	Number of passengers	Length of high-death-risk zone [m]	Number of affected passengers
No seats	—	27.4	—
No seats	100	13.2	12.7
No seats	500	7.9	41.1
Seats	—	17.6	—
Seats	100	10.0	9.6
Seats	500	7.6	36.5

Effect of Open Doors



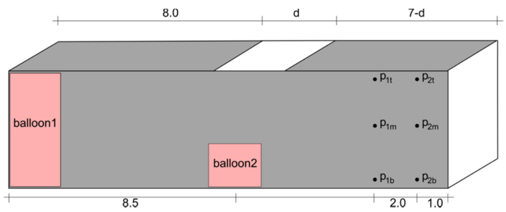
Closed doors



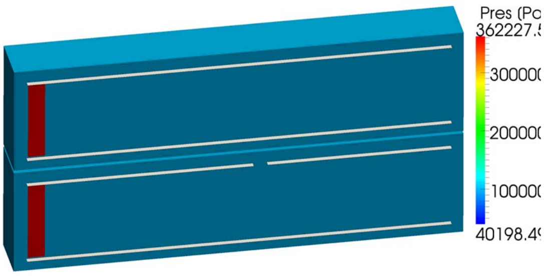
Open doors

Effect of Venting Areas

Calculations with d = 0.5, 1.0, 2.0 m and 2 x 1.0 m



d = 0.5



However : **roof hatches** are very useful in case of crash (**rescue**)

Nosaby, Sweden (2004)

157

Complete Station Simulation

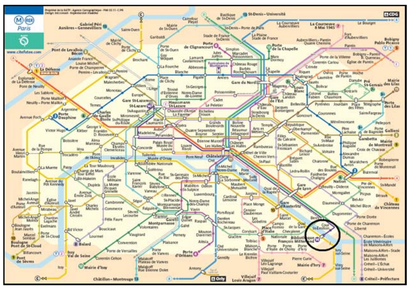
The starting point:

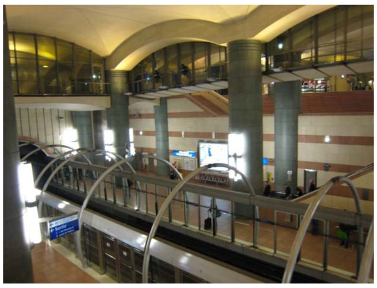
- **SECUR-ED** project (2012-ongoing)
  - Coordinated by THALES
  - Enhance **urban transport** security
  - SP3/WP32 involves JRC, TNO, RATP and others
- Main contributors at JRC:
  - G. Solomos, G. Valsamos, F. Casadei

158

Complete Station Simulation (2)

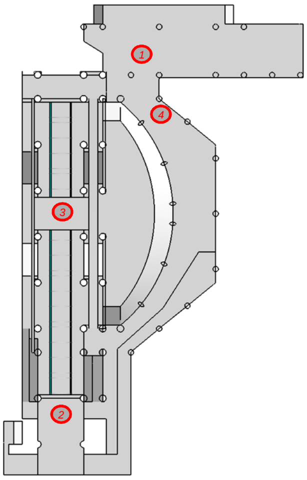
- “Bibliothèque François Mitterrand” Station
  - Transfer point between Metro “Line 14” and Railway “RER C”
  - No major openings to the atmosphere
  - Numerous fragile glass panels





Complete Station Simulation (3)

- Blast Scenarios (courtesy RATP)
  - Avenue de France (1)
  - Rue de Chevaleret (2)
  - Footbridge (3)
  - Hemicycle (4)



Complete Station Simulation (4)

Numerical Simulation Approach

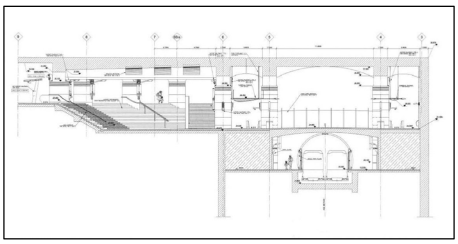
- Set up **geometric model**
  - Structural mesh from blueprints and photos (by Cast3m)
  - Regular fluid mesh ("embedded" FSI technique: essential!!!)
- Main modeling **assumptions**
  - Rigid structural walls (thick reinforced concrete)
  - Deformable glass panels and metallic components
- Main calculation **parameters**
  - Material properties
  - Boundary conditions
  - Element types (for the fluid: either FE or CCFV)
  - Solution methodology

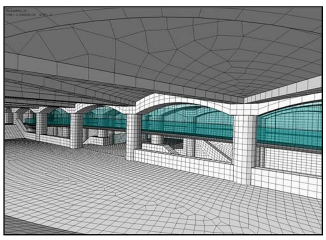
161

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 …

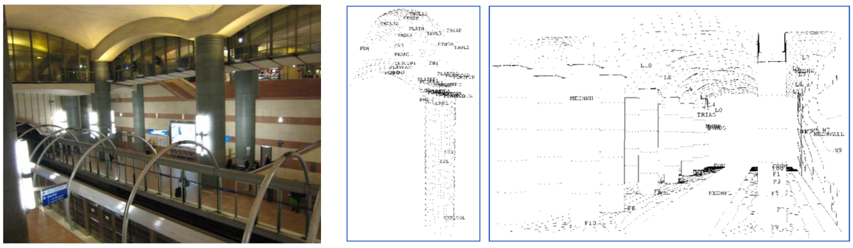


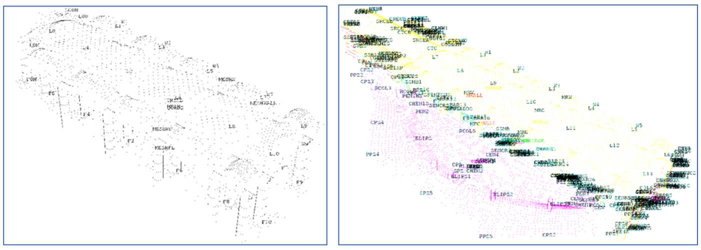


162

Complete Station Simulation (6)

Cast3m model for the structure :



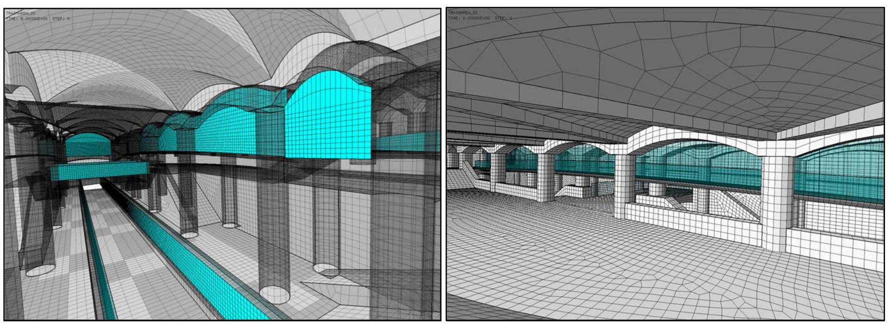


163

Complete Station Simulation (7)

FE structural **model (Cast3m)**:

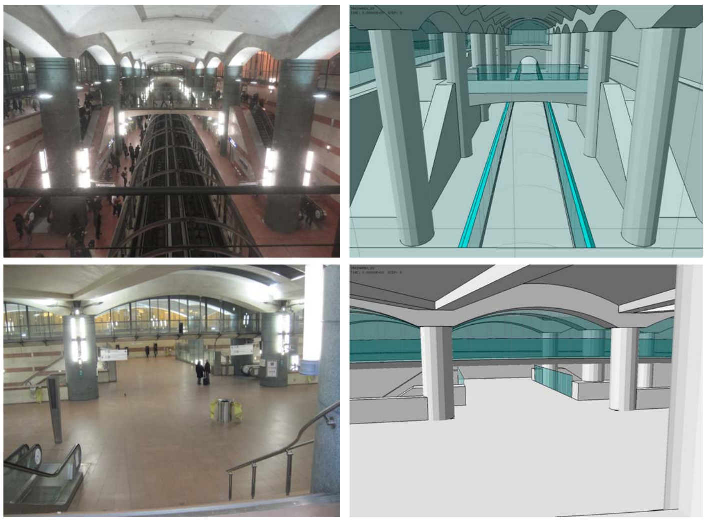
- Average element size for rigid parts : 0.50 m
- Min element size for deformable parts : 0.25 m



164

Complete Station Simulation (8)

Model fidelity:



165

Complete Station Simulation (9)

Virtual Tour of the Station:

EUROPLEXUS Animation

Gare "Bibliothèque François Mitterrand"

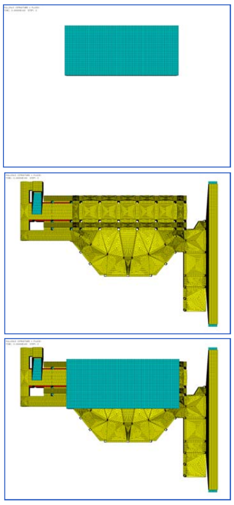
Authors: G. Valsamos, F. Casadei, G. Solomos

166

Complete Station Simulation (10)

Fluid mesh (FE or CCFV) :

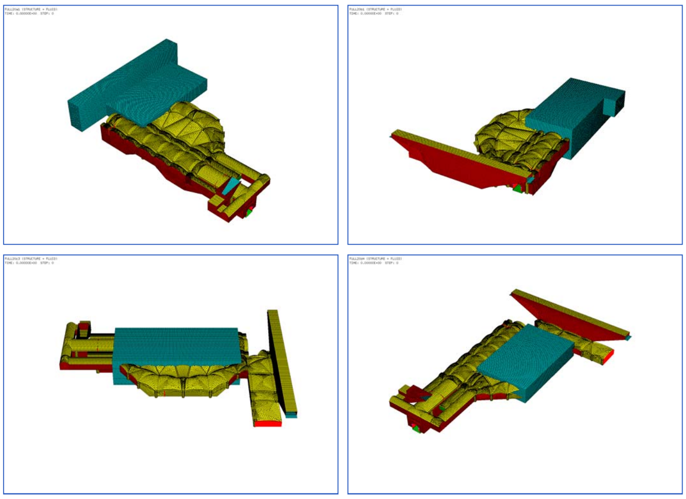
- **Regular** parallelepiped grid(s)
- **Non-conforming** with structure
- The meshes are simply **superposed**
- **Absorbing** fluid envelope



167

Complete Station Simulation (11)

Examples of assembled F/S meshes :



168

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)

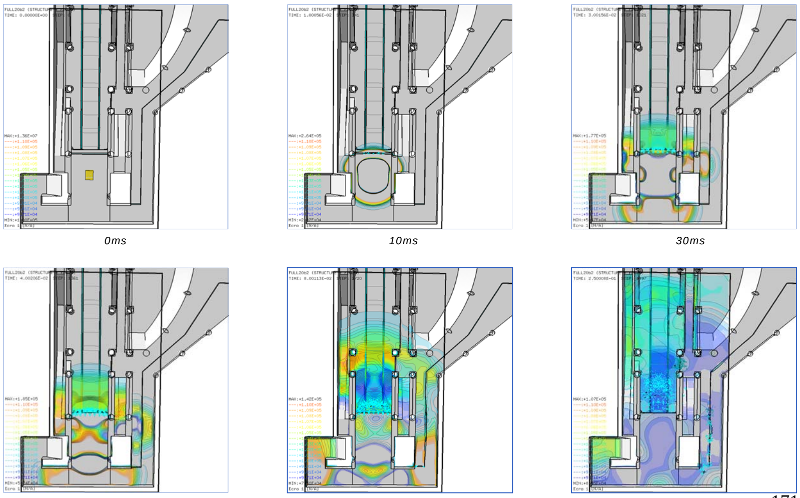
Complete Station Simulation (13)

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)

Complete Station Simulation (14)

Typical numerical results (pressures, debris …) :



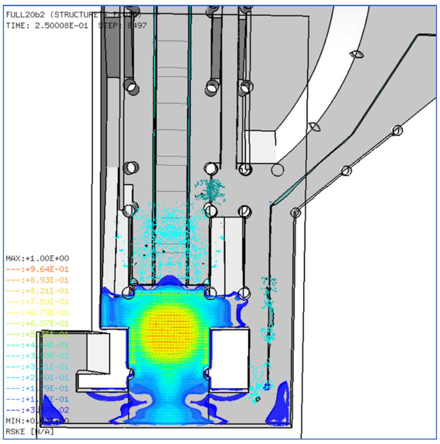
0ms 10ms 30ms

40ms 80ms 250ms

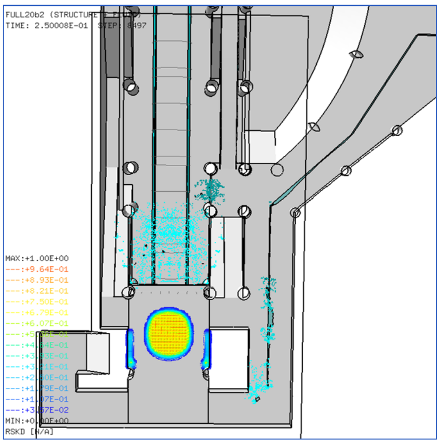
171

Complete Station Simulation (15)

Typical numerical results (risk) :



Eardrum rupture RISK

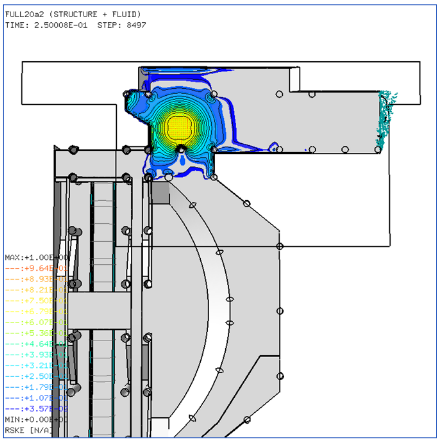


Death RISK

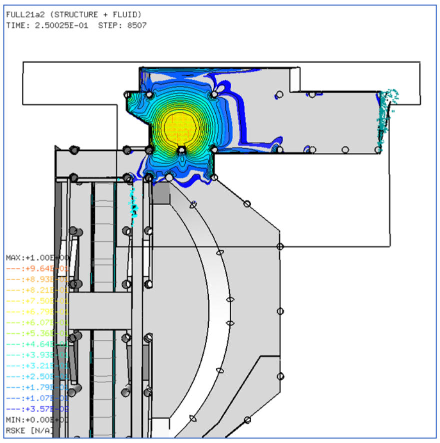
172

Complete Station Simulation (16)

Accuracy assessment (coarse and fine solutions) :



Coarse model

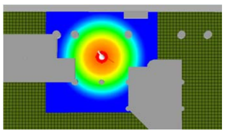


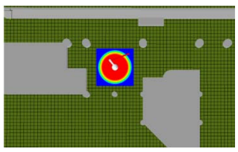
Fine model

173

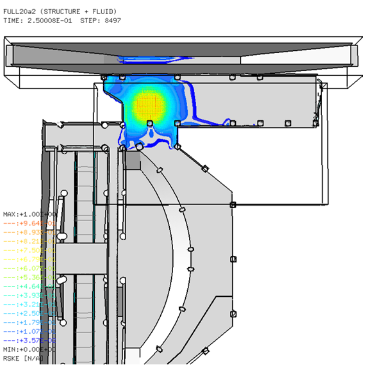
Complete Station Simulation (17)

Comparison with another risk assessment methodology:

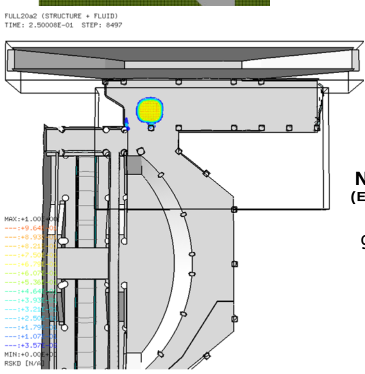




Analytical (empirical)
No reflections!



Eardrum rupture RISK



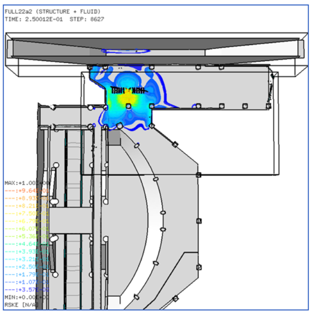
Death RISK

Numerical (EUROPLEXUS)
Full geometric effects

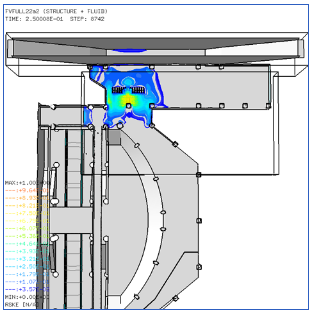
174

Complete Station Simulation (18)

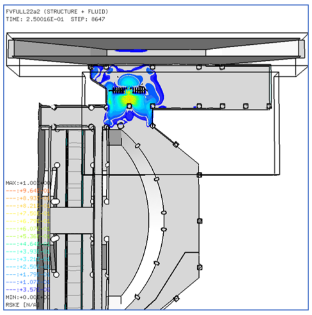
Comparison of different fluid formulations :



FE



VFCC 1st order



VFCC 2nd order

175

Complete Station Simulation (19)

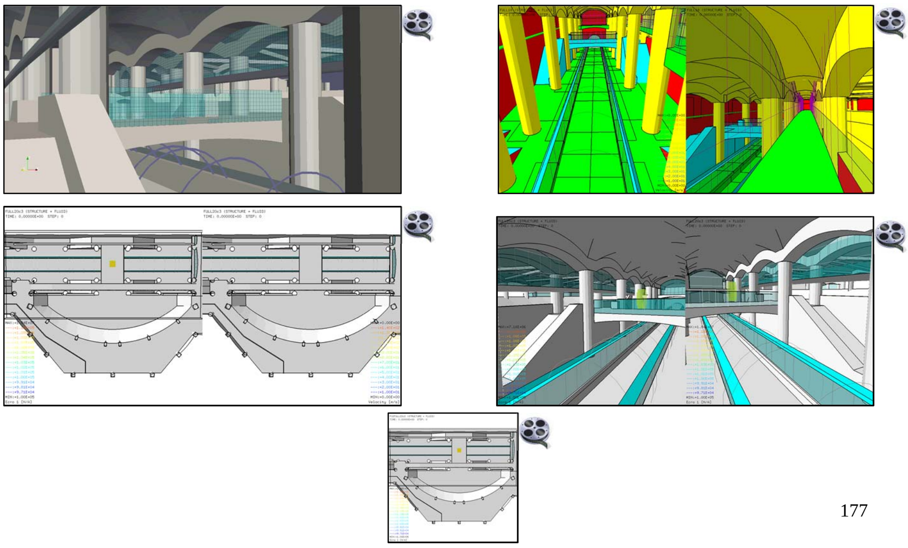
Solution data - Comparison FE / VFCC :

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)

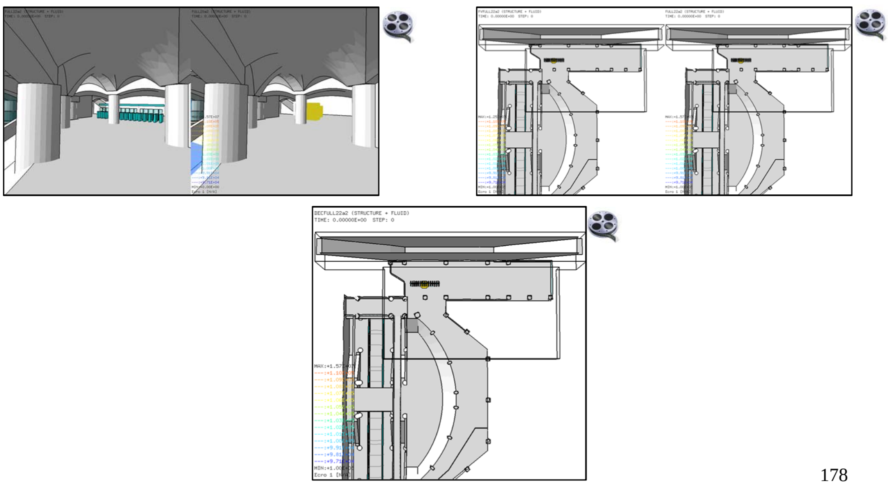
Footbridge:



177

Complete Station Simulation (21)

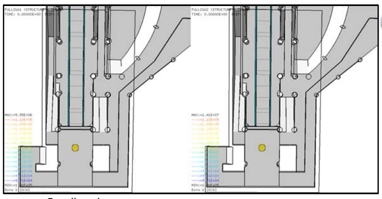
Avenue de France:



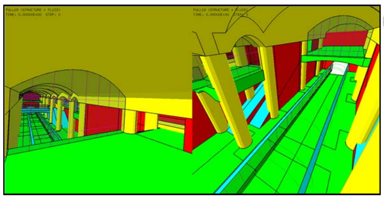
178

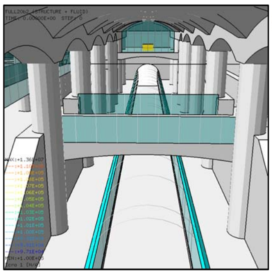
Complete Station Simulation (22)

Rue de Chevaleret:



Smaller charge *Larger charge*

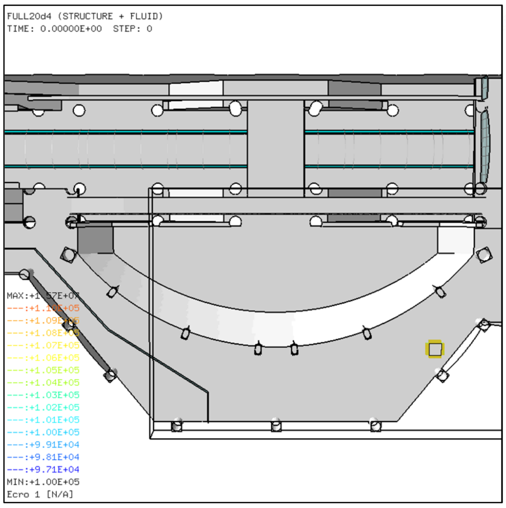




179

Complete Station Simulation (23)

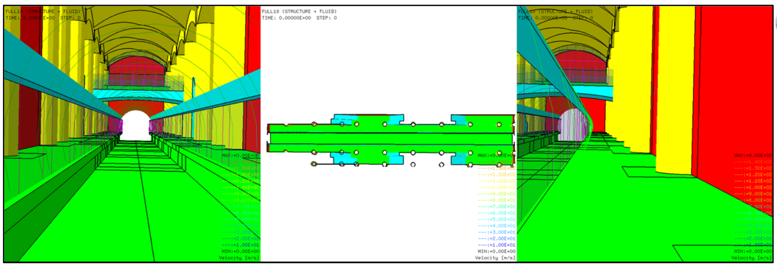
Hemicycle :



180

Complete Station Simulation (24)

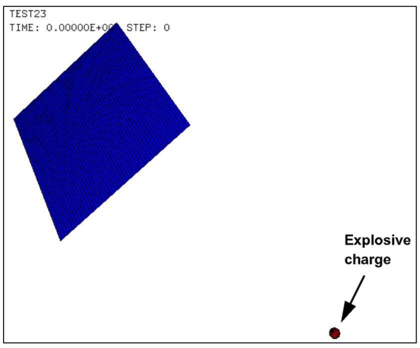
Metro Platform :



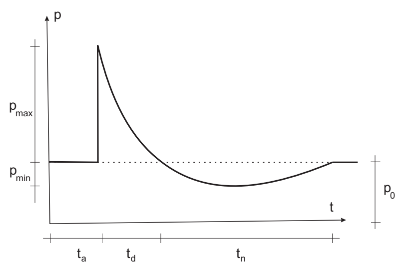
181

Exercise 15 – Blast on a glass sheet

Simulate the fragmentation of a glass sheet subjected to a blast wave using the AIRB model



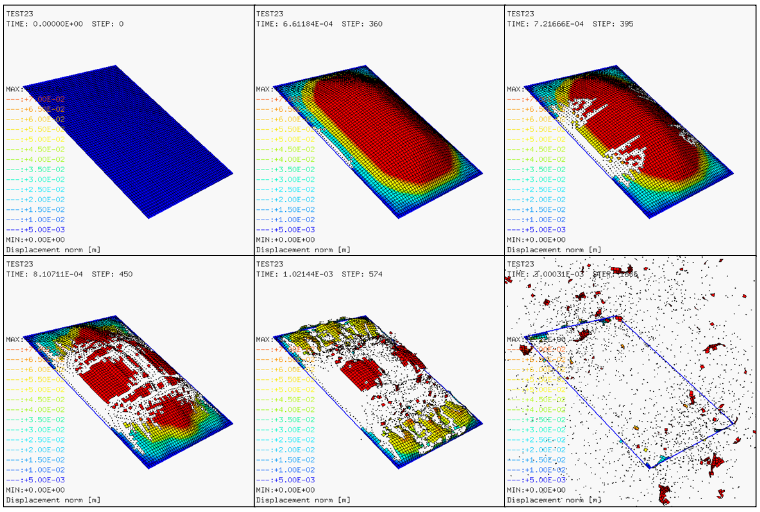
Geometry



Pressure (AIRB)

182

Exercise 15 – Blast on a glass sheet (2)

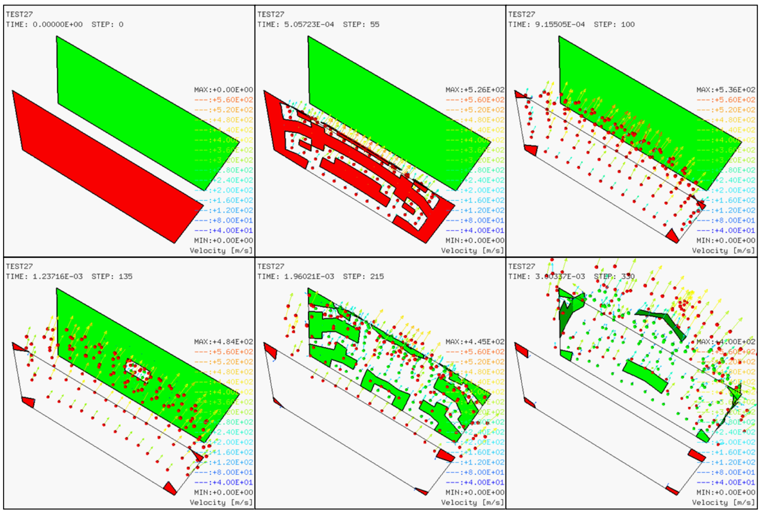


Fragmentation

183

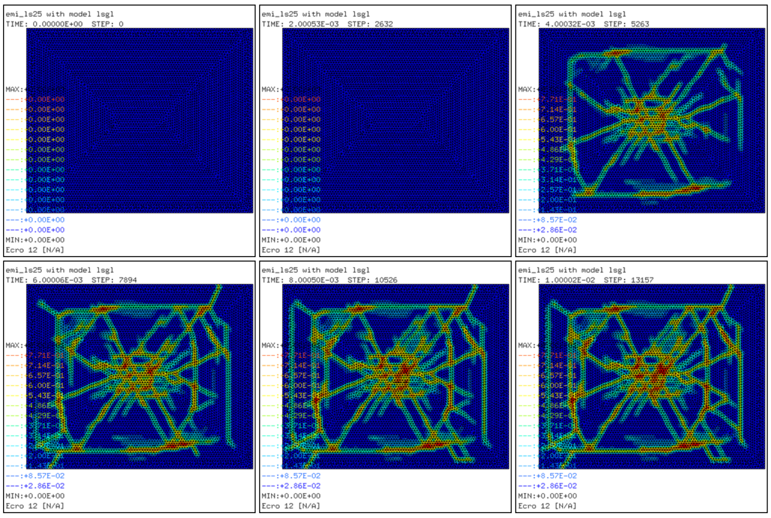
Exercise 15b – Secondary debris

Simulate the formation of secondary debris due to impact of primary debris on a glass sheet :



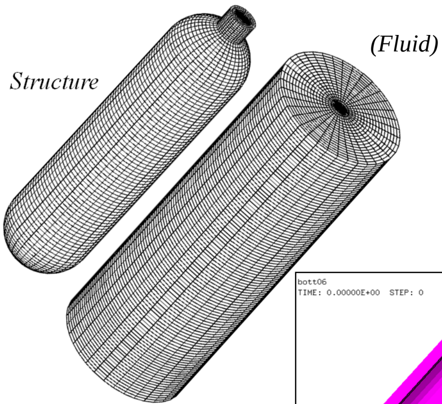
184

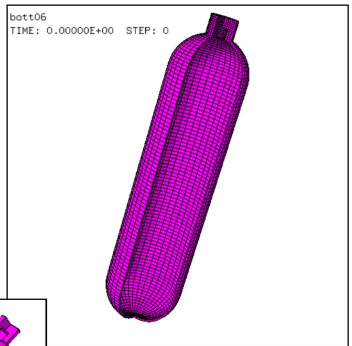
Exercise 15c – Crack formation
in Laminated Glass

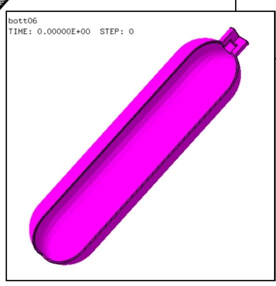


185

Exercise 16 – Explosion of an air bottle







- Structure-only calculation
- Fluid-structure calculation

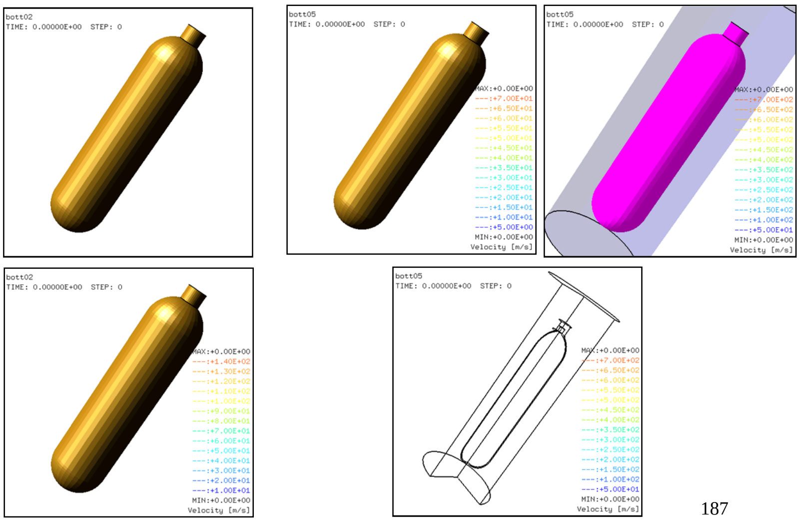
186

Exercise 16 – Explosion of an air bottle (2)

Structure-only solution — Fluid-structure solution

Fragmentation

Velocities



Blast on ISO container (Courtesy NTNU)

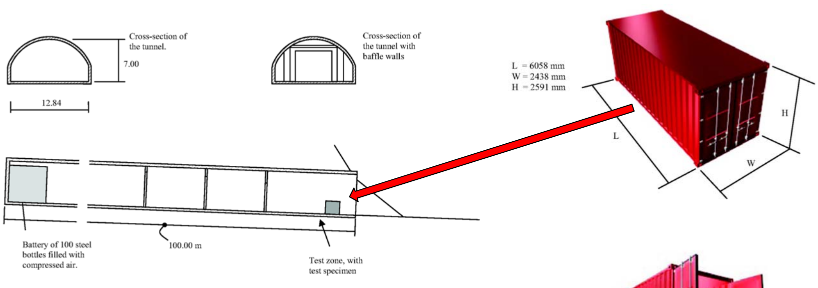
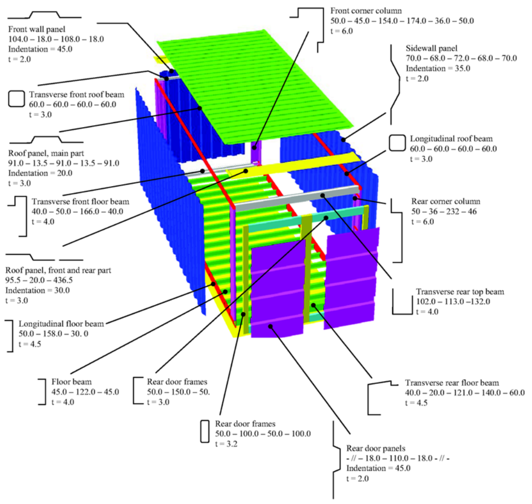
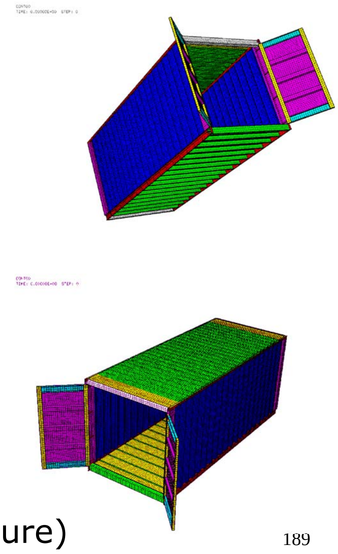


Figure 1 A schematic view of the Large Blast Simulator (LBS) at Bundeswehr Technical Center for Protective and Special Technologies (WTD 52) in Oberjettenberg, Germany /2/. Courtesy WTD 52 .

Standard 20 ft ISO container /1/

FE model

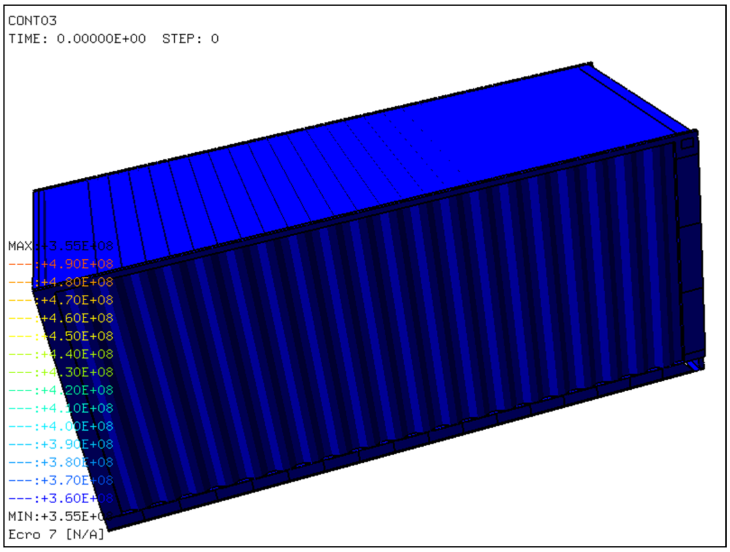




- ~ 43,000 elements (structure)

189

Preliminary simulation with AIRB



Current
Yield stress
(plasticity)

190

Simulation (applied test pressure) vs experiment

Blast test in tunnel

Simulation

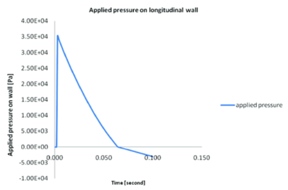


Figure 8 Pressure versus time function applied on the container.

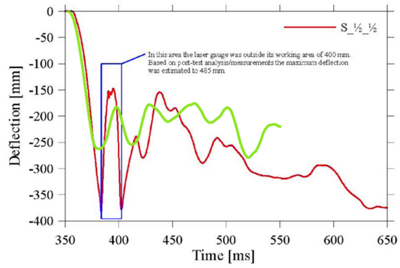
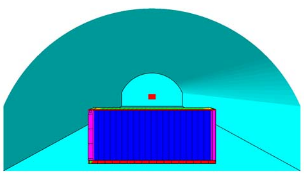


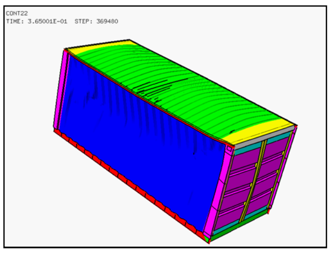
Figure 20 Displacement of the mid-point of the longitudinal wall of the container. Experimental results (red curve) compared with numerical results for the cont1000 model (green curve).

191

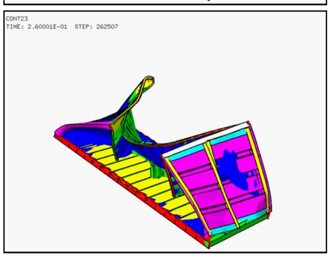
Predictive simulations require FSI



Model of container in tunnel



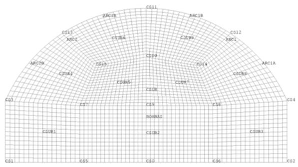
Load case 1: FE + FLSR



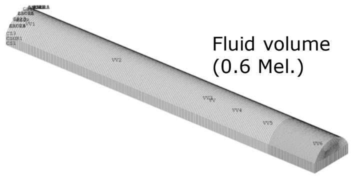
Load case 2: CCFV + FLSW

192

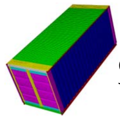
Full (Blind) Simulation with FSI



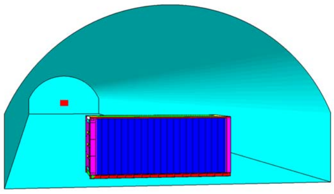
Fluid cross-section



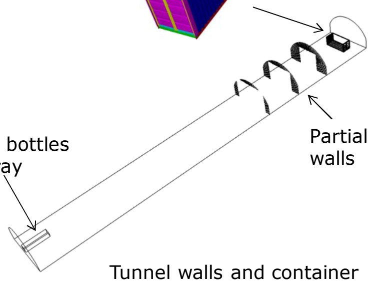
Fluid volume
(0.6 Mel.)



Container (43 kel.)

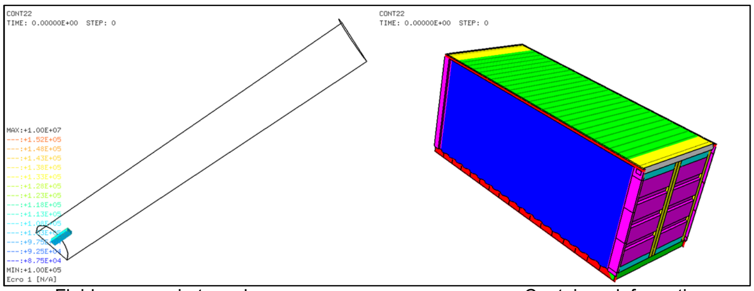


Container within tunnel

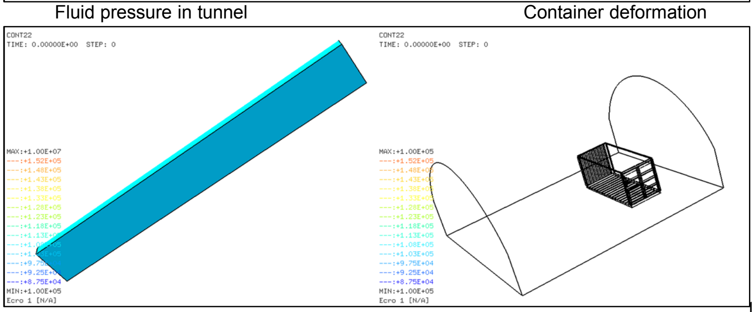


Tunnel walls and container

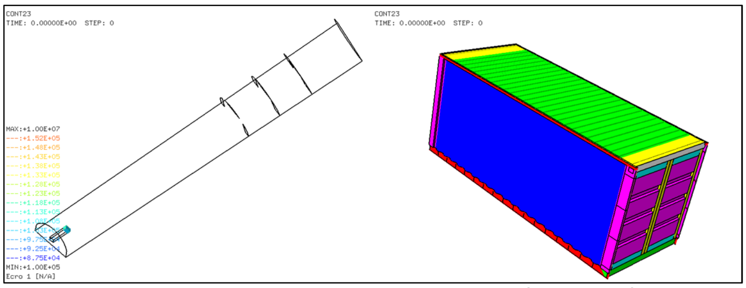
FE fluid with FLSR



Fluid pressure in tunnel Container deformation

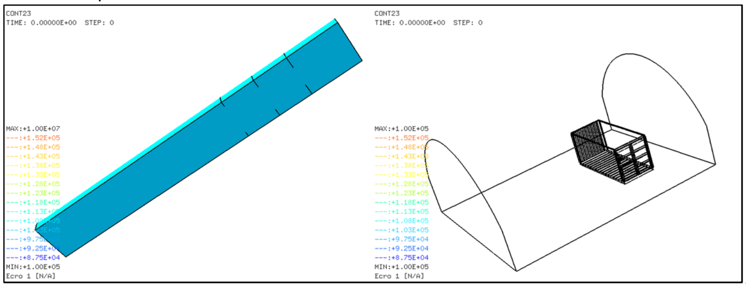


CCFV fluid with FLSW (preliminary)



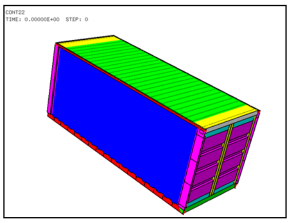
Fluid pressure in tunnel

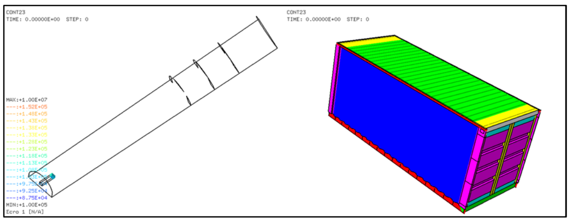
Container deformation



195

Container simulations with FSI





Load case 1:
FE + FLSR

Load case 2:
CCFV + FLSW

196