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Strong and weak forms of a fully non-conforming FSI algorithm in fast transient dynamics for blast loading of structures

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Outline

- **Introduction**
- **Basic FSI algorithms of the strong type:**
  - Conforming FE
  - Non-conforming FE
  - NCFV
- **Basic FSI algorithms of the weak type:**
  - Conforming CCFV
  - Non-conforming CCFV
  - Structural failure
  - Comparison of strong and weak formulations
- **Embedded FSI algorithms**
  - Of the strong type
  - Application to NCFV
  - Of the weak type
- **Numerical examples**

Computational framework

- **Fast transient** dynamic applications with **FSI** (e.g. **blast loading** of structures, shocks, impacts ...)
- Discretization: FE (structure), FE/FV (fluid)
- **Explicit** time integration
- Lagrangian description of structure
- ALE or Eulerian description of fluid
- Need for **robust and efficient FSI algorithms**

3

A possible classification

- Each **FSI algorithm** consists of two parts:
  - A **detection** strategy
  - An **enforcement** strategy
- As concerns FSI detection, we distinguish:
  - **Basic** type (no structural failure, moderate rotations)
    - Conforming F-S meshes
    - Non-conforming F-S meshes
  - **Embedded** type (failure/fragmentation, large rotations)
- As concerns FSI enforcement, one can use:
  - **Strong** enforcement (via constraints on velocities)
  - **Weak** enforcement (via pressure forces / fluxes)

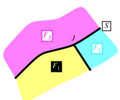
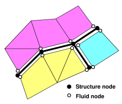
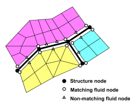
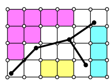
4

A possible classification

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

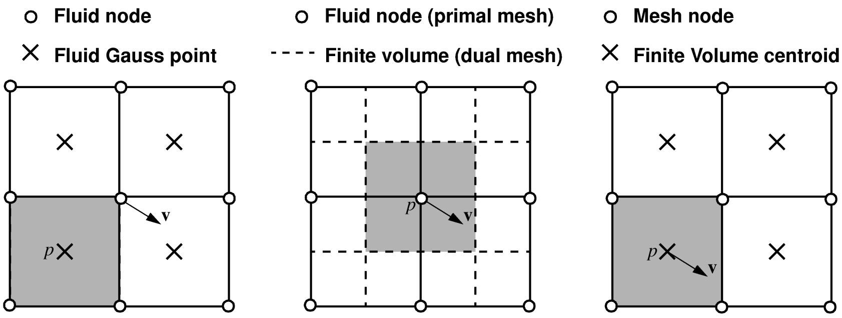
A Classification of FSI Algorithms

Available FSI Algorithms

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

A Summary of FSI Algorithms

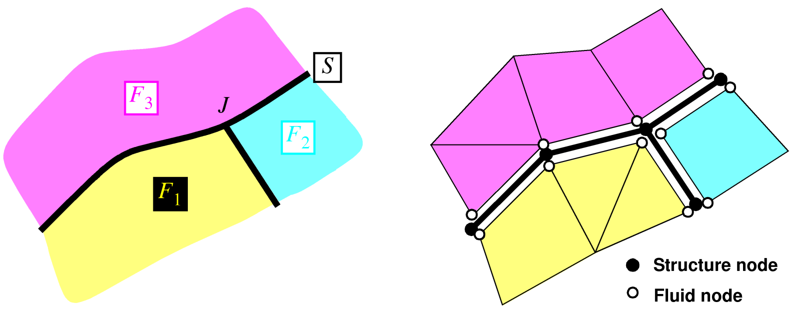
Spatial discretization for the fluid



a) FE mesh. b) NCFV mesh. c) CCFV mesh.

Both components of FSI algorithms must be adjusted to the chosen type of spatial discretization

Basic FSI algorithms

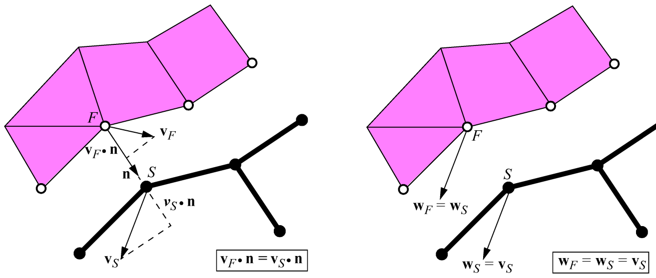


a) Continuous F-S domain. b) Nodally conforming discretization.

Sample FSI problem and its **conforming** discretization

Strong approach

- Enforcement occurs via **constraints on velocities**
- These are imposed **strongly** via **Lagrange multipliers**
- **Implicit** treatment together with any other b.c.s

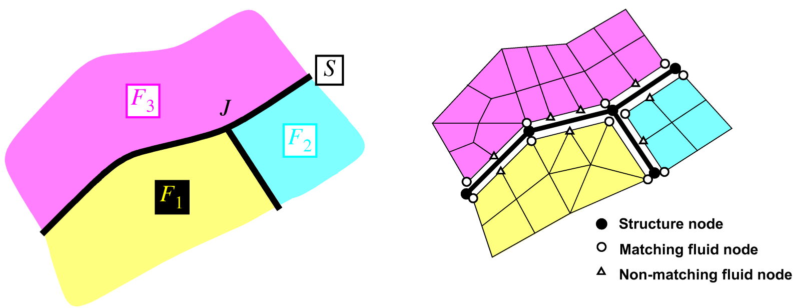


a) Constraints on particle velocities. b) Compatibility of mesh velocities.

The **FSA**[1] algorithm for a conforming mesh

[1] F. Casadei, J. P. Halleux, An algorithm for permanent fluid-structure interaction in explicit transient dynamics. *Computer Methods in Applied Mechanics and Engineering*, **128**/3-4, 231-289, 1995.

Basic FSI algorithms – Non-conforming

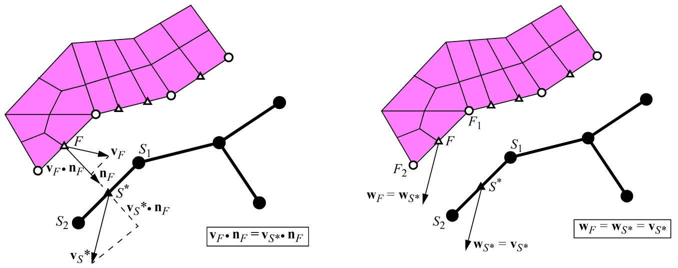


a) Continuous F-S domain. b) Non-conforming (hierarchic) discretization.

Sample FSI problem and its **non-conforming** discretization

Strong approach – Non-conforming

- Constraints are enforced both at **matching** and at **non-matching nodes**



a) Constraints on particle velocities. b) Compatibility of mesh velocities.

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

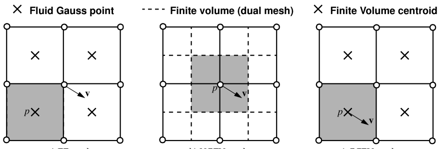
$$\mathbf{w}_F = \mathbf{w}_{S^*} = \mathbf{v}_{S^*} = (N_1 \mathbf{w}_{S_1} + N_2 \mathbf{w}_{S_2})$$

The **FSA**[2] algorithm for a non-conforming mesh

[2] F. Casadei, S. Potapov, Permanent fluid-structure interaction with non-conforming interfaces in fast transient dynamics. *Computer Methods in Applied Mechanics and Engineering*, **193**/39-41, 4157-4194, 2004.

Application to NCFV

- The same **FSA** algorithms (**strong** approach via Lagrange multipliers) can also be applied in a NCFV context, because velocities are discretized at nodes
- In this case the constraint is even "stronger", since the fluid velocity represents the (average) velocity over the entire FV, not a local value like in FE



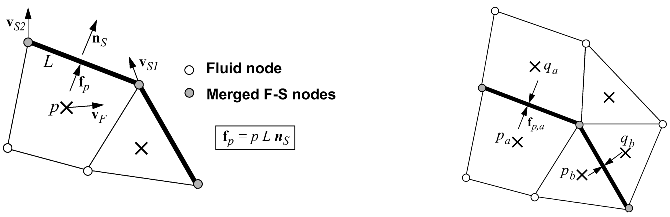
a) FE mesh. b) NCFV mesh. c) CCFV mesh.

The **FSA**[3] algorithm for a NCFV fluid discretization

[3] A. Soria, F. Casadei, Arbitrary Lagrangian-Eulerian multicomponent compressible flow with fluid-structure interaction. *International Journal for Numerical Methods in Fluids*, **25**, 1263-1284, 1997.

Weak approach

- Seems natural choice for **CCFV** (velocities at centres)
- Fluid **pressure force** is transmitted to the structure
- **Zero numerical fluxes** at the F-S interface
- Structure motion provides (weak) feedback on fluid

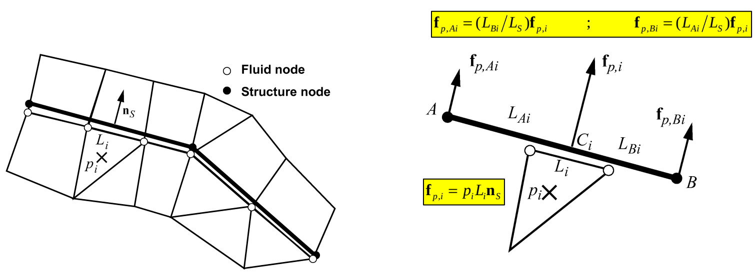


a) One fluid.   b) Two fluids.

Weak coupling for a **conforming** F-S mesh (**merged** nodes)

Weak approach – Non-conforming

- **Matching** nodes can be **merged or not** (irrelevant)
- **Non-matching** nodes are also present

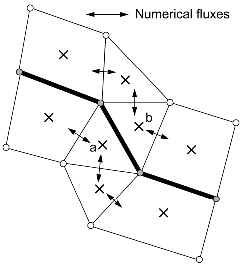


a) Hierarchic mesh, two fluids (continuous mesh).   b) Distribution of pressure force.

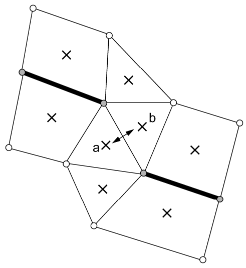
Weak coupling for a **non-conforming** F-S mesh

Structural failure and CCFV

- **CCFV** (velocities at centres) facilitates treatment of structural **failure**
- No fluxes across a solid structure
- Fluxes are activated when structure fails and is **eroded**
- Limitations : mesh entanglement with large rotations



Structure holds : no flux between a and b



Structure **fails** locally : flux is activated between a and b

Comparison strong / weak

Strong approach

- Most natural with **FE** (velocities at nodes).
- **Exact** enforcement of velocity constraints
- **No** master / slave

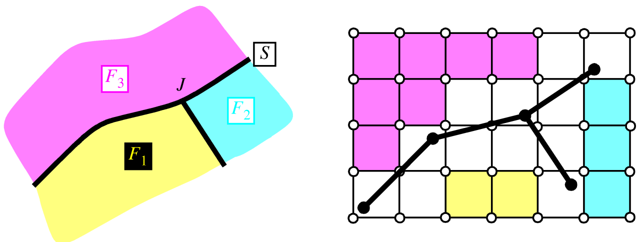
Weak approach

- Most natural with **CCFV** (velocities at centroids).
- Structure acts as **master**, fluid as **slave**
- Only **weak** feed-back

- **NCFV** (velocities at nodes, but average on volume) lie somewhat in between
- **Both** strong and weak approaches seem natural

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

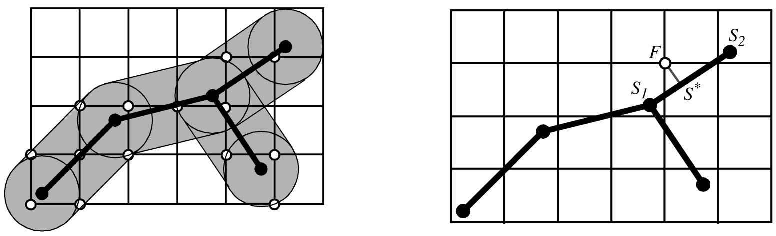
Strong embedded approach

- 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 :

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

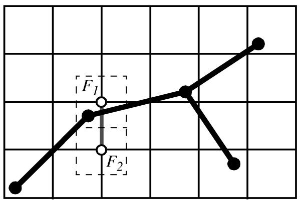


a) Influence domain (shaded) of the structure. b) F-S coupling.

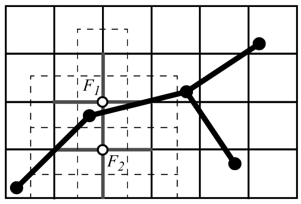
The **FLSR** embedded algorithm with a **strong** approach

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)



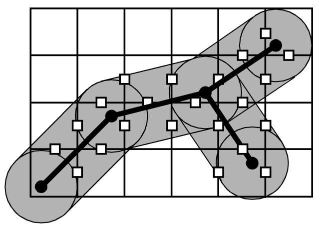
a) NCFV flux blockage (thick shaded line).

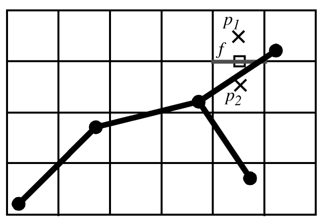


b) More restrictive flux blockage.

Weak embedded approach

- 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.



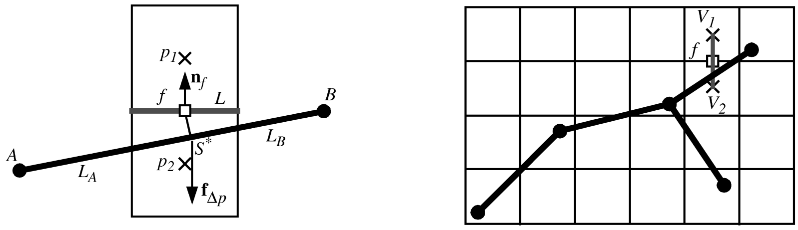
b) Pressure drop force calculation.

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

Weak embedded approach (2)

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

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

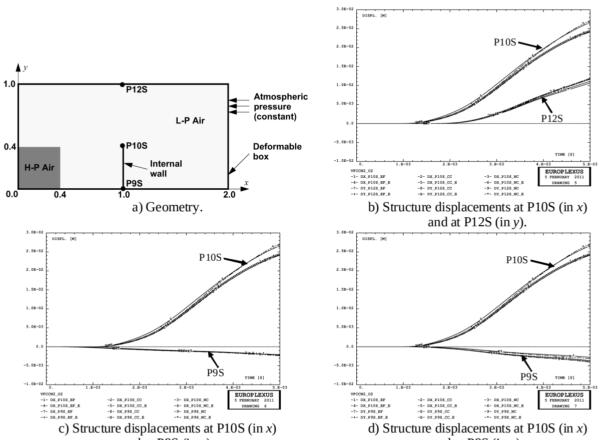


a) F-S coupling force.

b) CCFV flux blockage (thick shaded line).

Explosion in a metallic box

- Fluid mesh 4 times finer than structure
- **FE**, **NCFV**, **CCFV**.
- **Basic** (non-conforming) or **embedded**
- 3 x 2 = 6 solutions
- Structure motion is ~ 1 fluid element



a) Geometry.

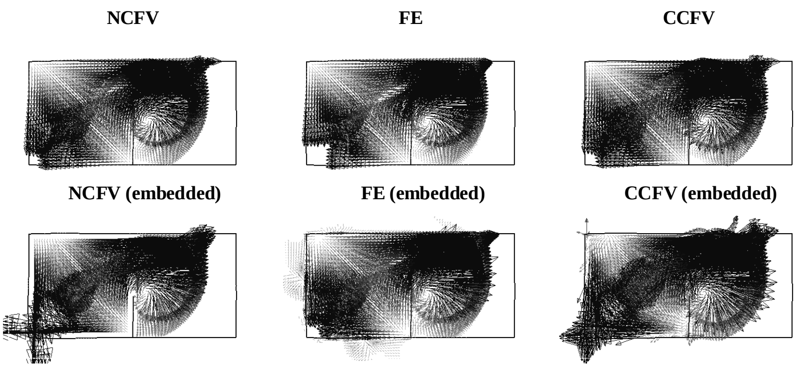
b) Structure displacements at P10S (in *x*) and at P12S (in *y*).

c) Structure displacements at P10S (in *x*) and at P9S (in *x*).

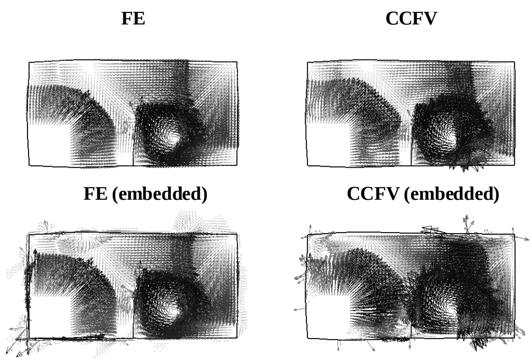
d) Structure displacements at P10S (in *x*) and at P9S (in *y*).

Goal : compare **all** algorithms in case with large strains but **moderate rotation** and **no** structural **failure**

Fluid velocity at 2.5 ms

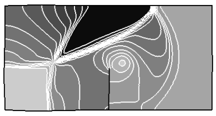


Fluid velocity at 5.0 ms

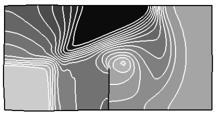


Fluid pressure at 2.5 ms

NCFV

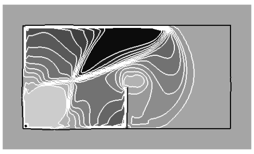


FE

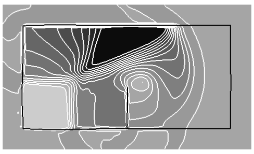


CCFV

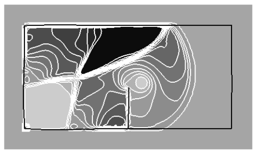
NCFV (embedded)



FE (embedded)

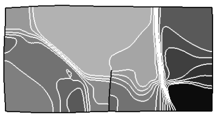


CCFV (embedded)

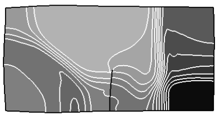


Fluid pressure at 5.0 ms

NCFV

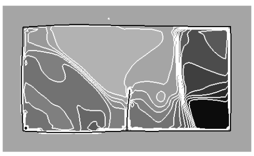


FE

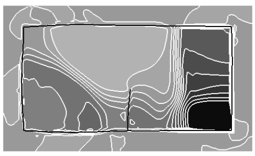


CCFV

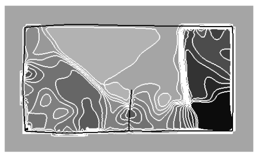
NCFV (embedded)



FE (embedded)

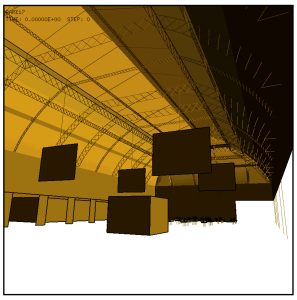


CCFV (embedded)



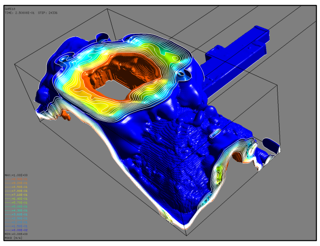
Blast effects in a railway station

Historical building

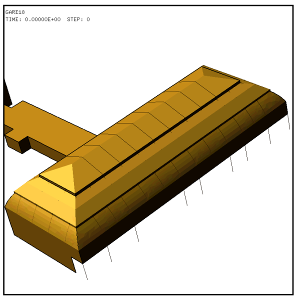


Model, internal

4.5 M FE (98% fluid) with **FLSR**



Risk map

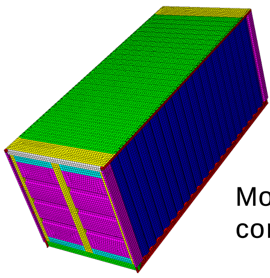


Model, external

27

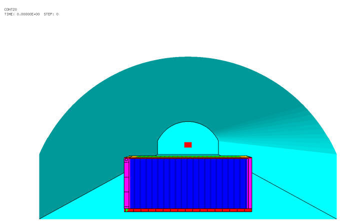
Blast on ISO container (Courtesy NTNU)

Blast test in tunnel



Model of container

Simulation (applied pressure)



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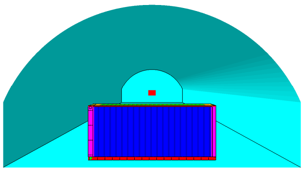
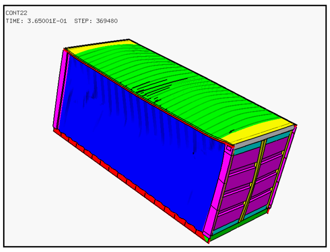
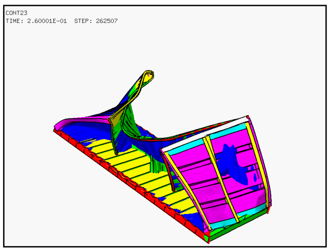
Predictive simulations require FSI



Model of container in tunnel



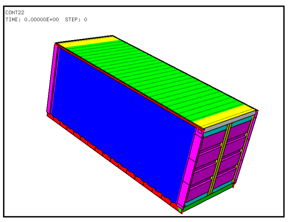
Load case 1: FE + FLSR

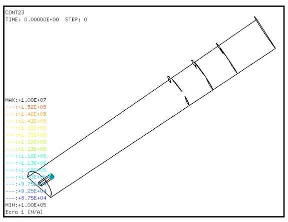


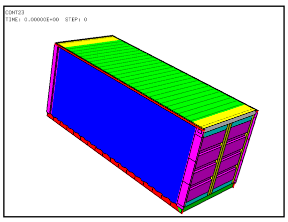
Load case 2: CCFV + FLSW

29

Container simulations with FSI







Load case 1: FE + FLSR

Load case 2: CCFV + FLSW

30