Numerical simulation of blast-structure interaction

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Massachusetts Institute of Technology

Simulation of blast effects

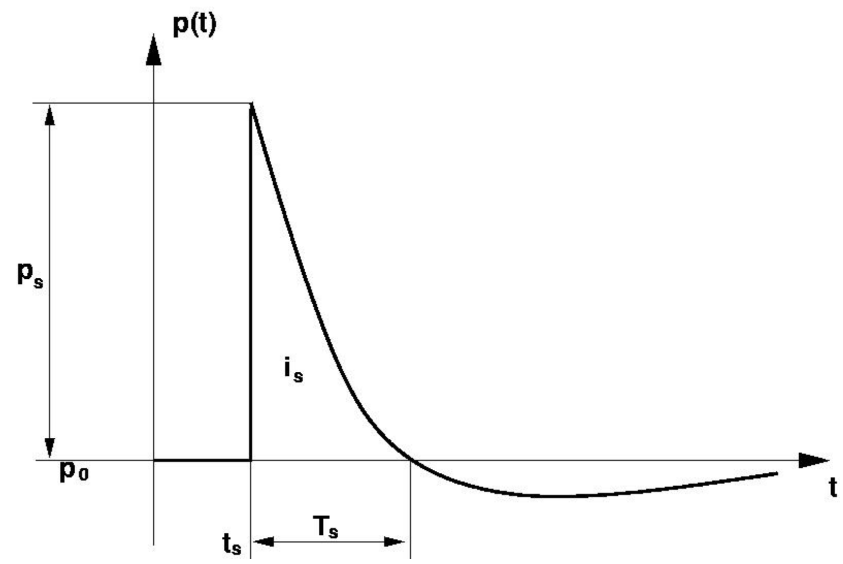
- Main objective: Given a weapon or threat at a given location, evaluate effectiveness of blast-protection system in mitigating blast damage
- Necessary steps:
  - Determine blast signatures:
    - Free field
    - Confined spaces
    - Account for coupling with body motion and structural deformations
  - Describe:
    - Wave propagation and interactions
    - Mechanical response
- Approach:
  - Coupled simulation of fluid-structure interaction

Outline

- Models of blast-wave propagation:
  - Description of blast wave
  - Numerical initialization of a blast wave
- Blast-structure interaction:
  - Numerical approach:
    - Solid mechanics
    - Fluid mechanics
    - Coupling
  - Validation:
    - Blast loaded stainless steel plates
    - Comparison between experiments and simulations
  - Practical applications:
    - Blast effects on human
    - Hardened unit load devices

Blast wave

- Chemical explosions:
  - Rapid oxidation of (H, C atoms), O atoms contained within explosive
  - Self-sustaining reaction (detonation)
    - Front speed up to 10 km/s, reaction finished in 10^{-6} sec.
    - Hot gas (3000 K)
    - High pressure (200 kbar)
- Blast wave:
  - Supersonic shock propagation
  - Rapid decay
  - Negative phase:
    - Pressure below atmospheric
    - Reversal of flow to the source



Blast wave

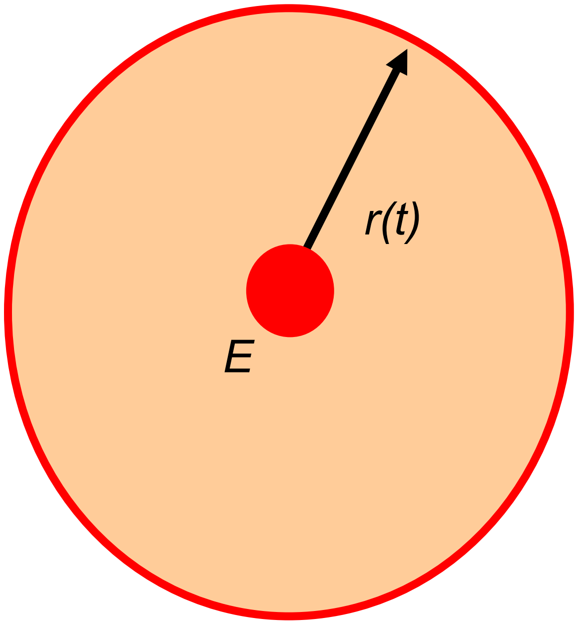
- G.I. Taylor (1941):
  - Wave-front radius

$$r = C(\gamma)\left(\frac{Et^2}{\rho_0}\right)^{\frac{1}{5}}$$

  - Pressure behind wave-front

$$p_s = C_p(\gamma)\left(\frac{E^2\rho_0^3}{t^6}\right)^{\frac{1}{5}}$$

$$p_s = C_r(\gamma)\frac{E}{r^3}$$



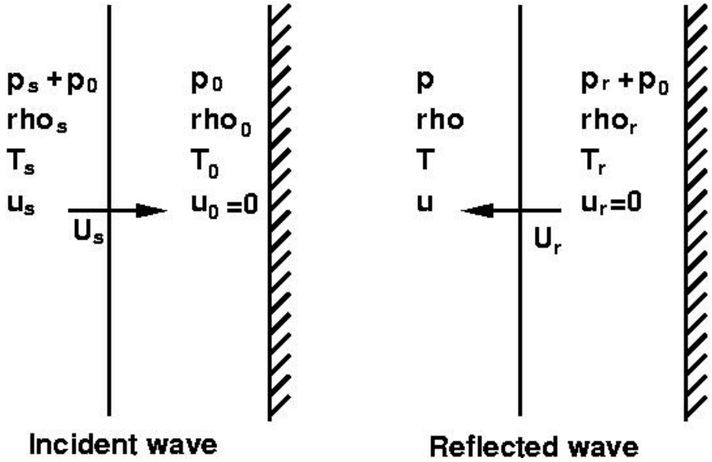
Blast wave

- Blast front parameters:
  - Wave front velocity: $$U_s^2 = a_0^2 \left[\frac{6}{7} \frac{p_s}{p_0} + 1 \right]$$
  - Velocity behind front: $$u_s = a_0 \frac{5}{7} \frac{p_s}{p_0} \frac{1}{\sqrt{6 \frac{p_s}{p_0} + 1}}$$
  - Density behind front: $$\rho_s = \frac{6p_s + 7p_0}{7p_0} \rho_0$$
  - Dynamic overpressure: $$q_s = \frac{1}{2} \rho_s u_s^2 = \frac{5p_s^2}{2(p_s + 7p_0)}$$
  - Specific impulse: $$i_s = \int_{t_s}^{t_s + T_s} p(t) dt$$

Compressibility effect

- Reflection with normal incidence on a rigid wall:
  - Reflected pressure:

$$p_r = 2p_s + (\gamma + 1)q_s = 2p_s\left(\frac{4p_s + 7p_0}{p_s + 7p_0}\right)$$



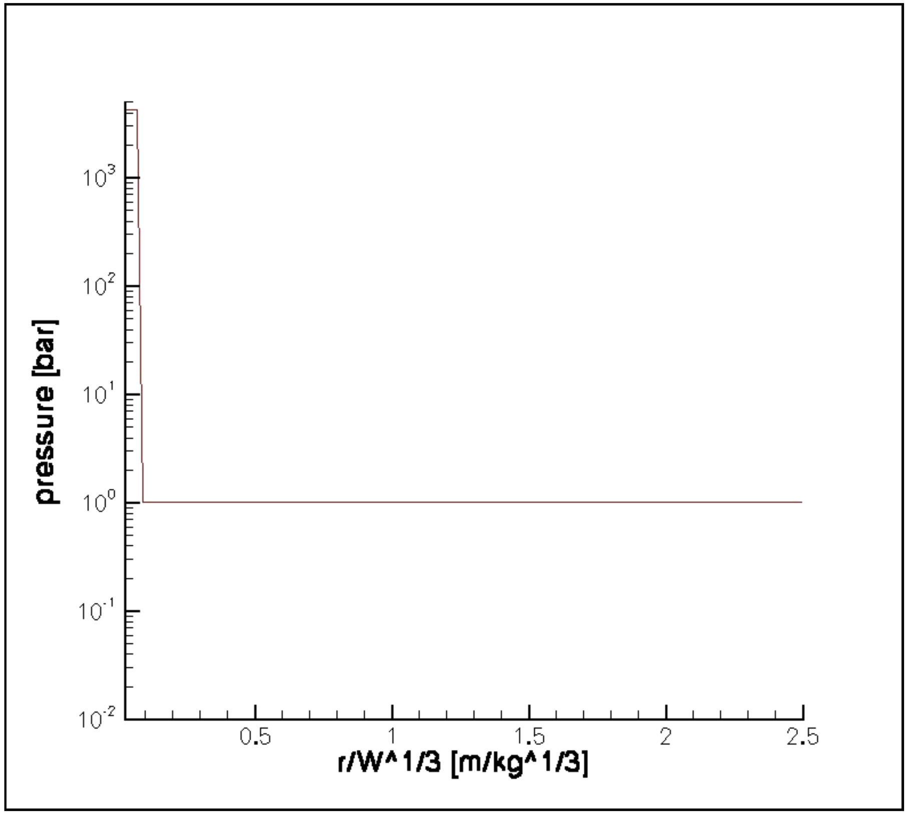
  - Reflection coefficient (up to 20 if dissociation effect):

$$C_R = \frac{p_r}{p_s}$$

$$2 \leq C_r \leq 8$$

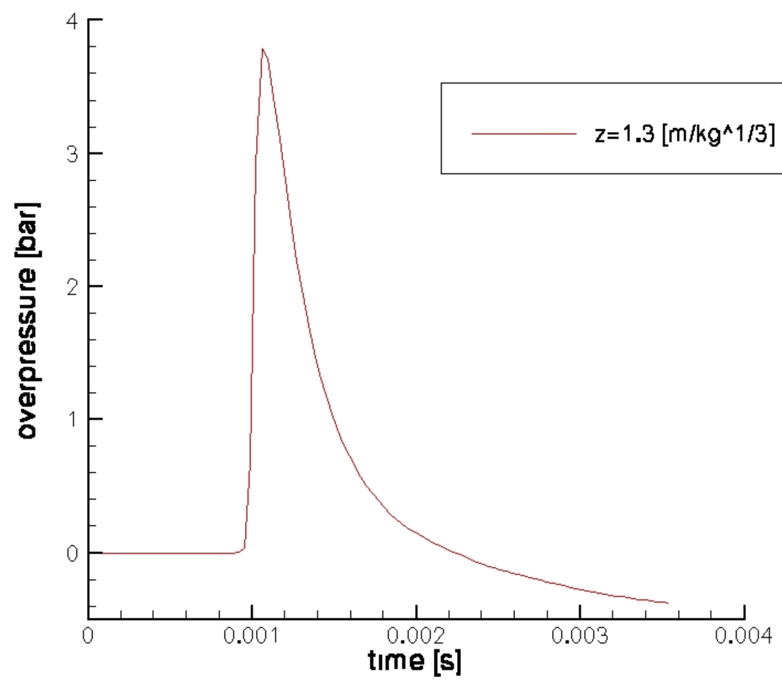
Numerical initialization of a blast wave

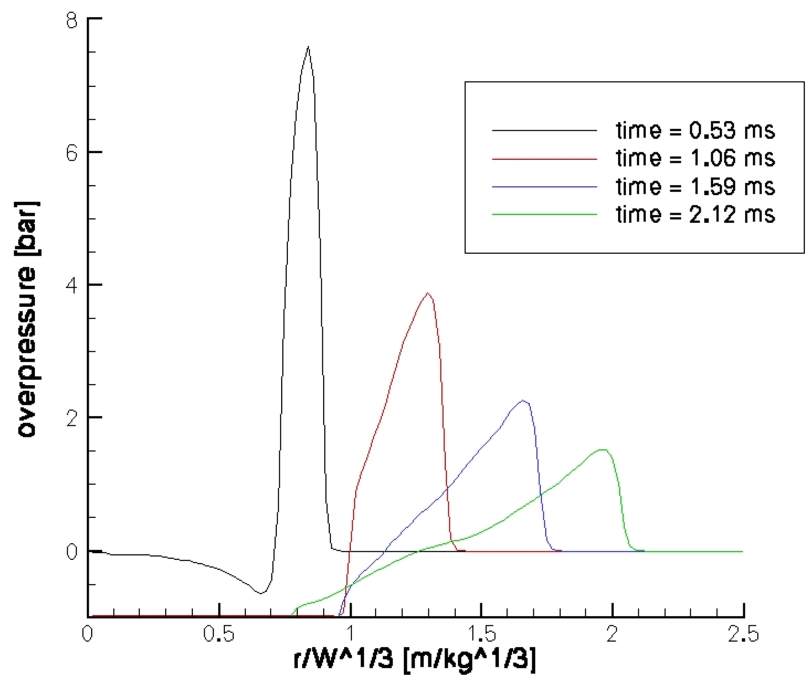
- Initial hot sphere of r_i =0.1m:
  - $p_i = \frac{3\gamma - 3}{4\pi} \frac{E_i}{r_i^3}$
  - $\rho_i = \frac{p_i}{RT_i}$
- Free parameter T_i:
  - Blast wave propagation independent of T_i for $r > 6\ r_i$
  - If $r < 6\ r_i$ the blast wave is not fully developed
  - Support von Neumann analytical solution, which predicts $T_i \rightarrow \infty$ at the source
- Good agreement with Brode's results (1955)



Numerical initialization of a blast wave

- Approximation of Euler equations of compressible flow: gas dynamics





Computational strategy

- Lagrangian solid formulation ideal for:
  - Large deformations
  - Tracking of material interfaces
  - Materials with history
    - Unstructured mesh, finite element approach
- Eulerian fluid formulation:
  - Well-established shock capturing and advection schemes
    - Structured grid, finite volume approach
  - Automatic Mesh Refinement feature
    - Capture pressure/density gradient and boundary geometry
- FSI coupled approach: Virtual Test Facility (Deiterding Radovitzky et al, Eng. with Computers 2005):
  - Based on ghost-fluid method/level sets
  - Coupling enforced at every fluid time step

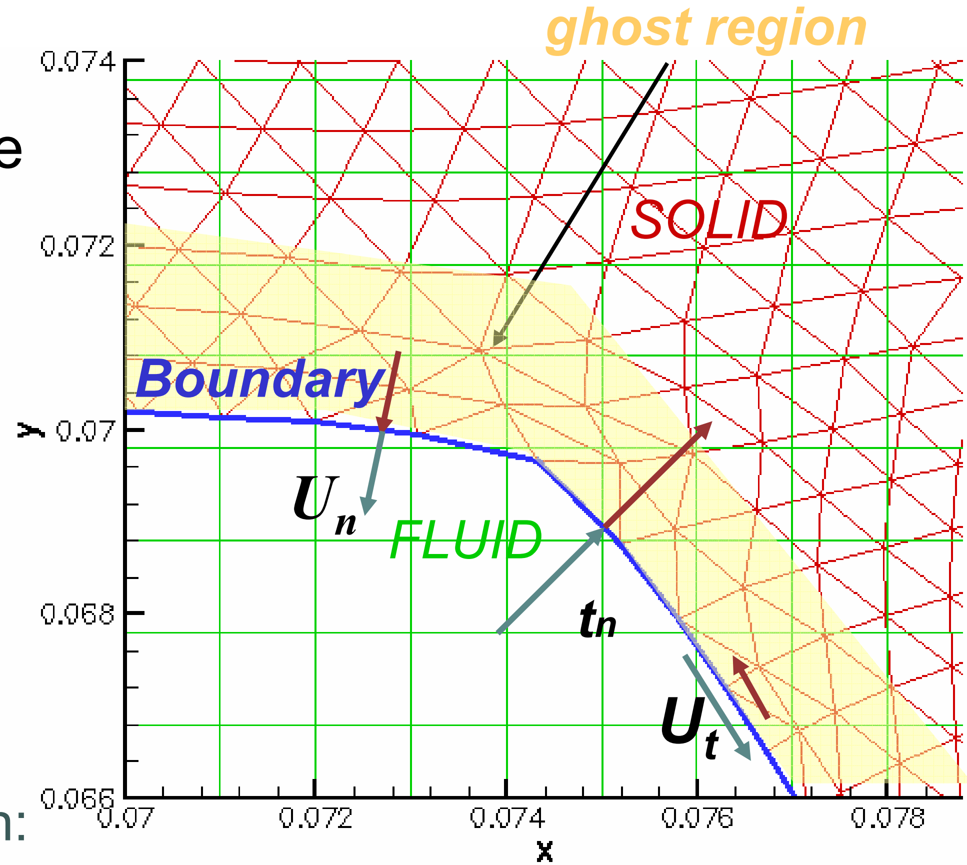
Computational strategy

- Coupling is achieved by enforcing at every fluid time step:
  - Continuity of normal velocity:

$$[\![\boldsymbol{v} \cdot \boldsymbol{n}]\!] = 0$$

  - Unconstrained tangential slip
  - Continuity of normal component of the traction:

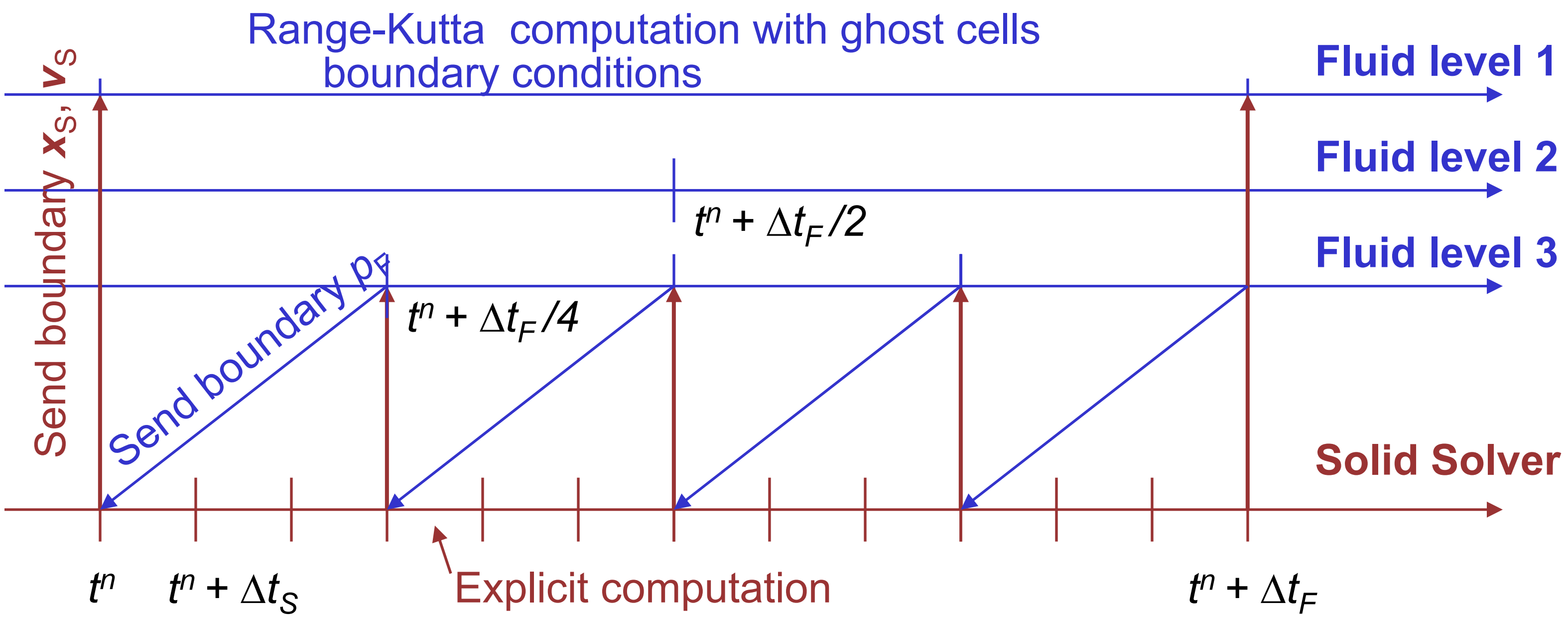
$$[\![\boldsymbol{t} \cdot \boldsymbol{n}]\!] = [\![\sigma_{ij} n_i n_j]\!] = [\![\sigma_n]\!] = 0$$



Deiterding Radovitzky et al, Eng. with Computers 2005

Computational strategy

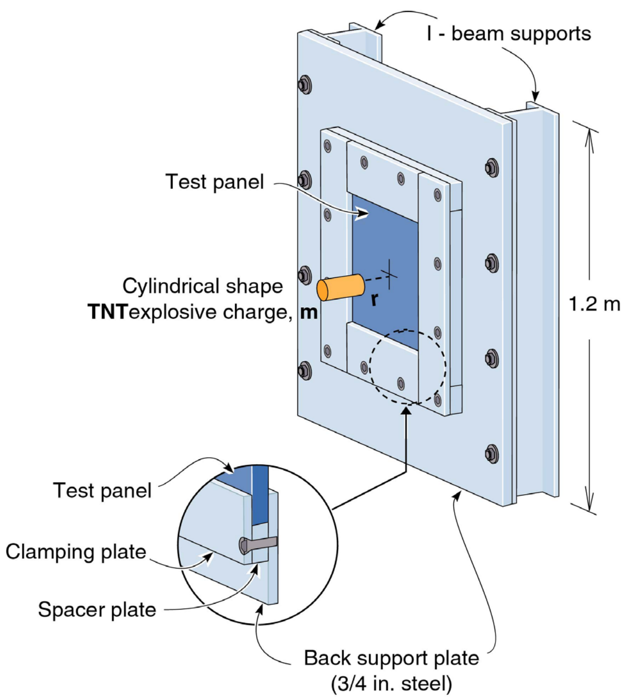
- Coupling of the solid solver with the fluid solver:
  - Mesh refinement of the fluid method
  - Coupling occurs at the highest fluid level to have a better description of the solid boundary



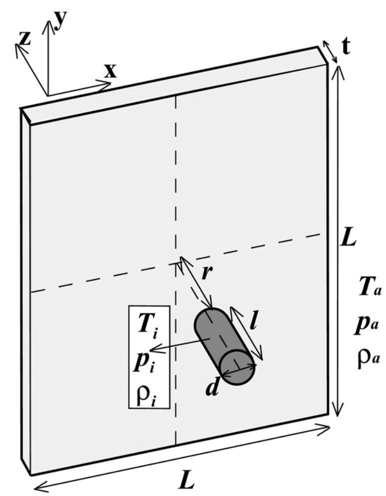
Validation: Explosively loaded steel plates

- Different TNT charges at constant stand-off distances *r*:

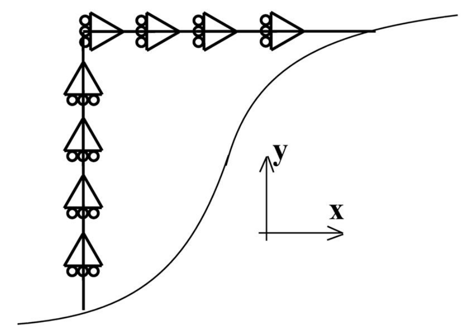
Experimental tests (K. Darhmasena, H. Wadley, University of Virginia)



Numerical simulations (L. Noels, R. Radovitzky, MIT)



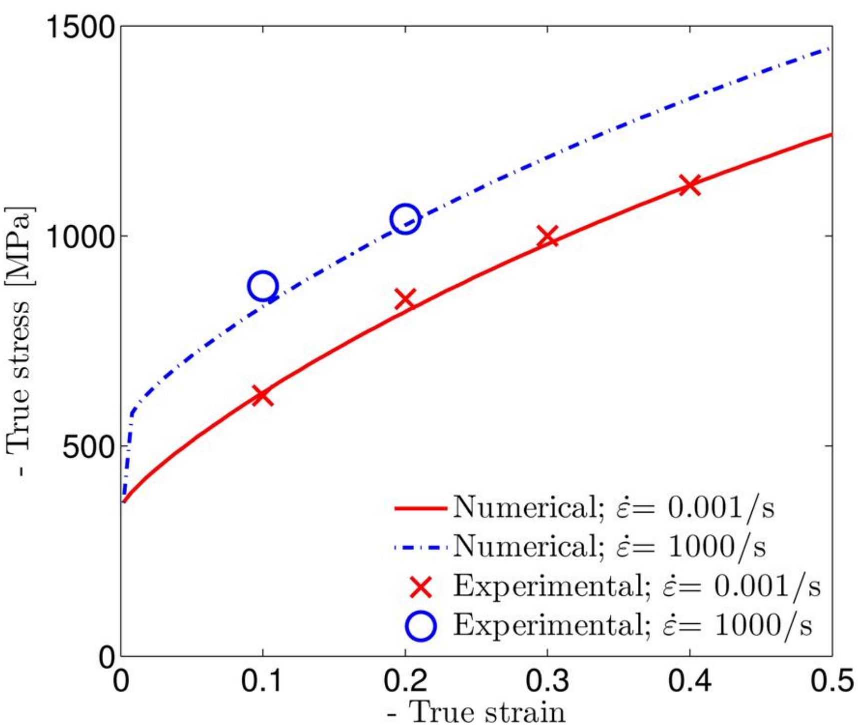
Not perfectly clamped boundary conditions



TNT [kg]	*L* [m]	*t* [mm]	r [m]	*l* [m]	*d* [m]	T_i [K]	p_i [GPa]	ρ_i [kg/m^3]
2	0.6	12.7	0.1	0.15	0.13	2930	1.87	2236
3	0.6	12.7	0.1	0.18	0.15	2930	1.67	1996
2	0.6	12.7	0.1	0.15	0.13	1465	1.87	4472
3	0.6	12.7	0.1	0.18	0.15	1465	1.67	3993

Validation: Explosively loaded steel plates

- Material model:
  - J2-plasticity; power law hardening and rate dependency



$$\sigma^y = \sigma_0^y \left[1 + \left(\frac{\varepsilon^{\mathrm{pl}}}{\varepsilon_0} \right)^{\frac{1}{\eta_\varepsilon}} + \left(\frac{\dot{\varepsilon}^{\mathrm{pl}}}{\dot{\varepsilon}_0} \right)^{\frac{1}{\eta_{\dot{\varepsilon}}}} \right]$$

- Parameters for AL6XN stainless steel

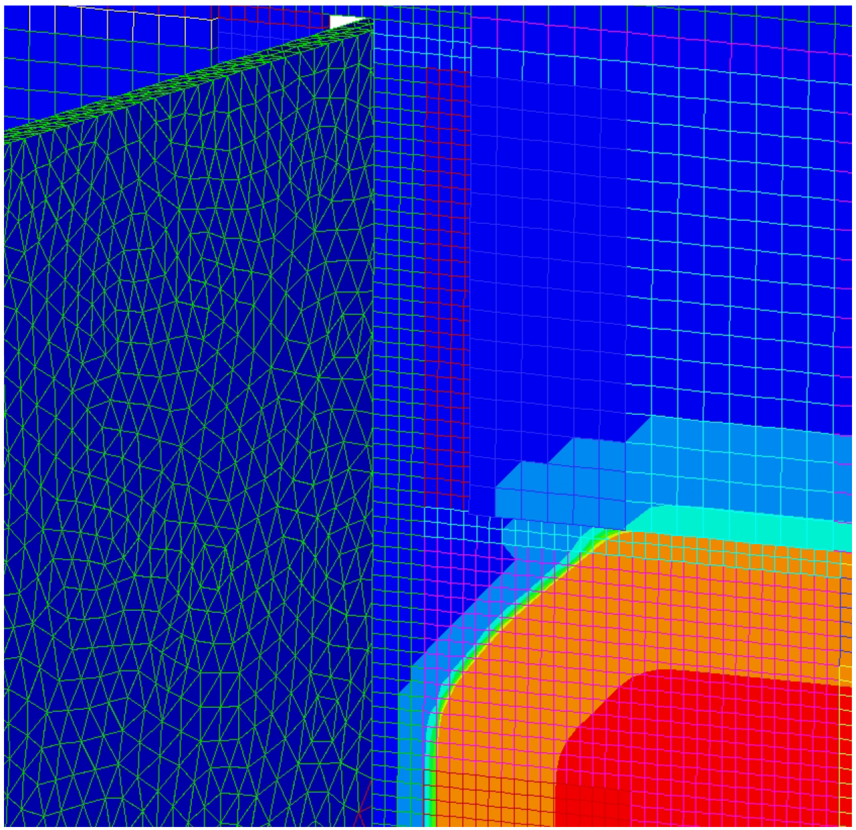
σ_0^y	ε_0	η_ε	$\dot{\varepsilon}_0$	$\eta_{\dot{\varepsilon}}$
365 Mpa	0.136	1.19	14518	4.82

- Calibration with experimental tests (Nemat-Nasser, JMPS 2001)

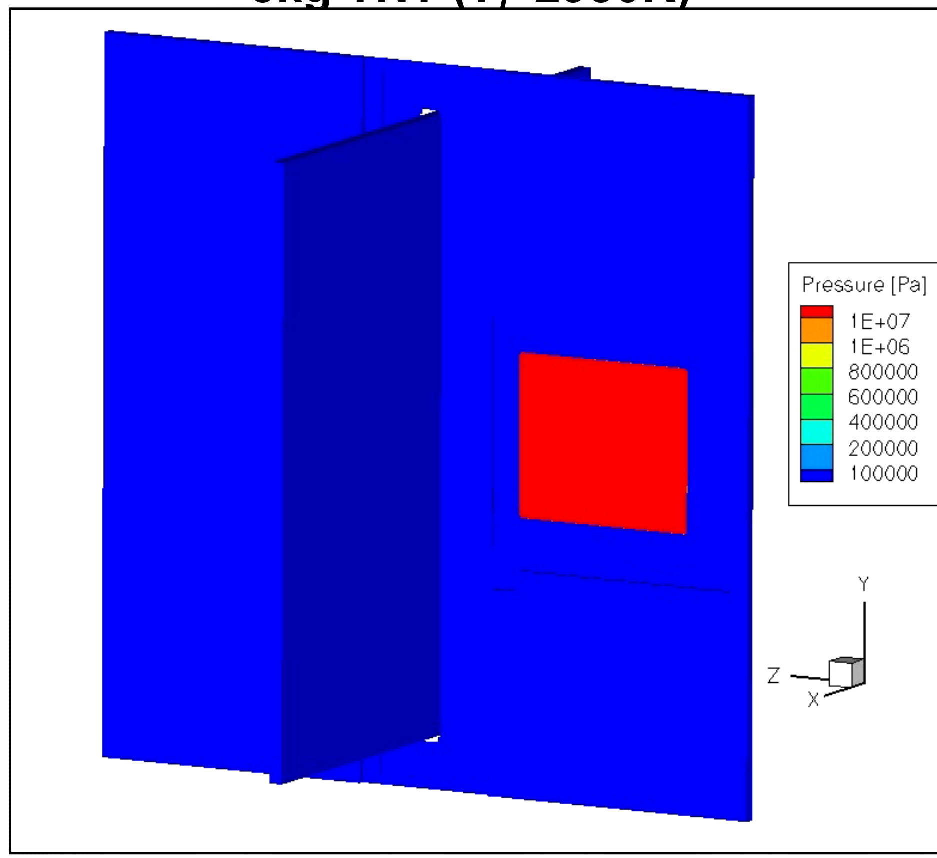
Validation: Explosively loaded steel plates

- Numerical simulations (10 Dual 1.8 GH/nodes; 36h):

AMR feature

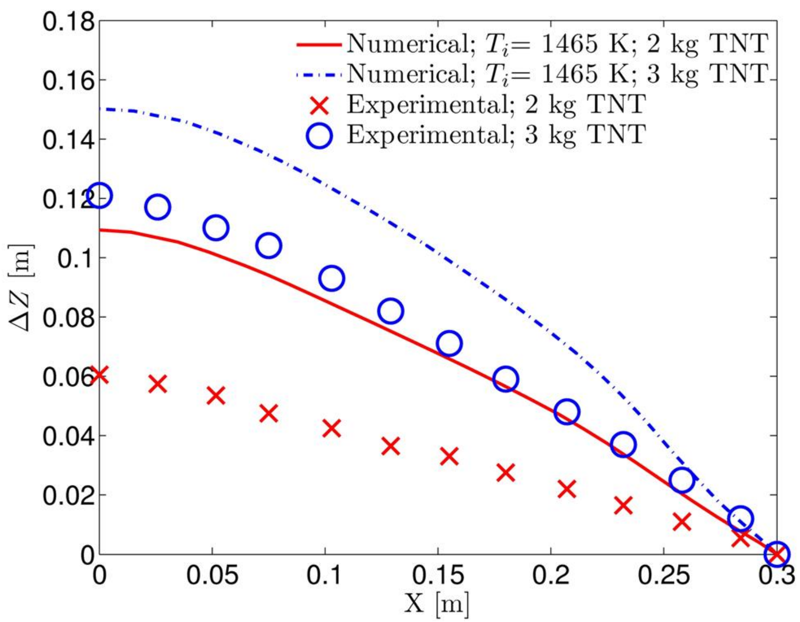


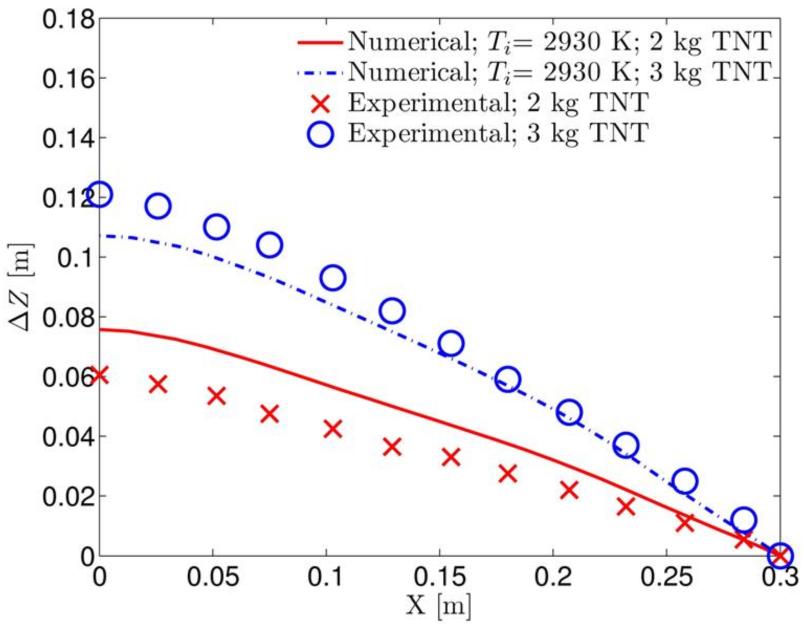
3kg TNT (T_i=2930K)



Validation: Explosively loaded steel plates

- Final deformations of the plate:
  - Blast wave propagation depends on the initial temperature T_{i} of the hot sphere, for short distance (Brode 1955)
  - T_i=2930K gives good agreement with experiments when comparing the final plate profile (deflection)





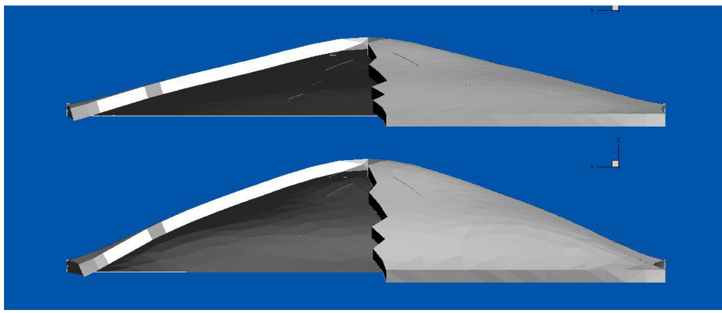
Validation: Explosively loaded steel plates

- Validation of the method:

Numerical simulations (T_i=2930K) | **Experimental tests**

2kg TNT

3kg TNT

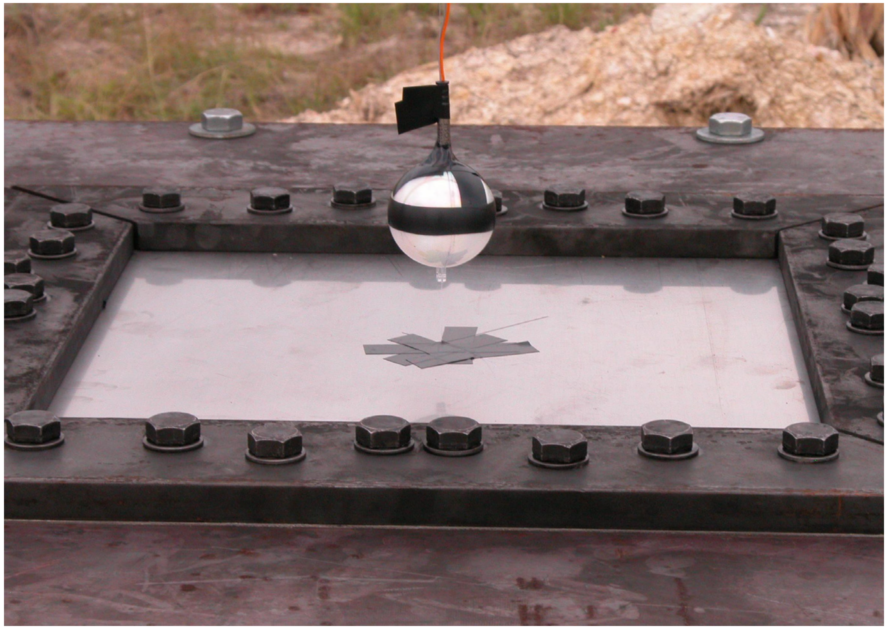


  - Sources of discrepancy:
    - Experimental boundary conditions affected by frame compliance
    - Elastic spring-back
  - Other observations:
    - Sensitive to charge geometry
    - Other than T_i, parameter-free model

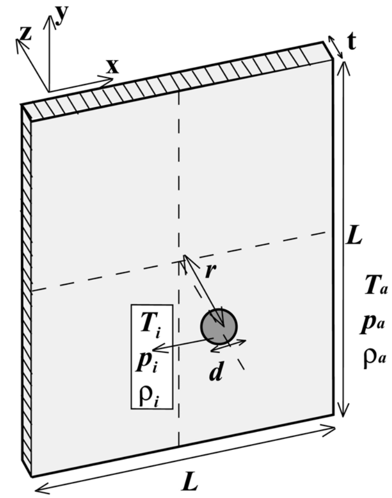
Validation: Explosively loaded steel plates

- Perfect clamping of the plate, constant C4 charge (150 g) at different stand-off distances *r*:

Experimental tests
(K. Darhmasena, H. Wadley, University of Virginia)



Numerical simulations
(L. Noels, R. Radovitzky, MIT)

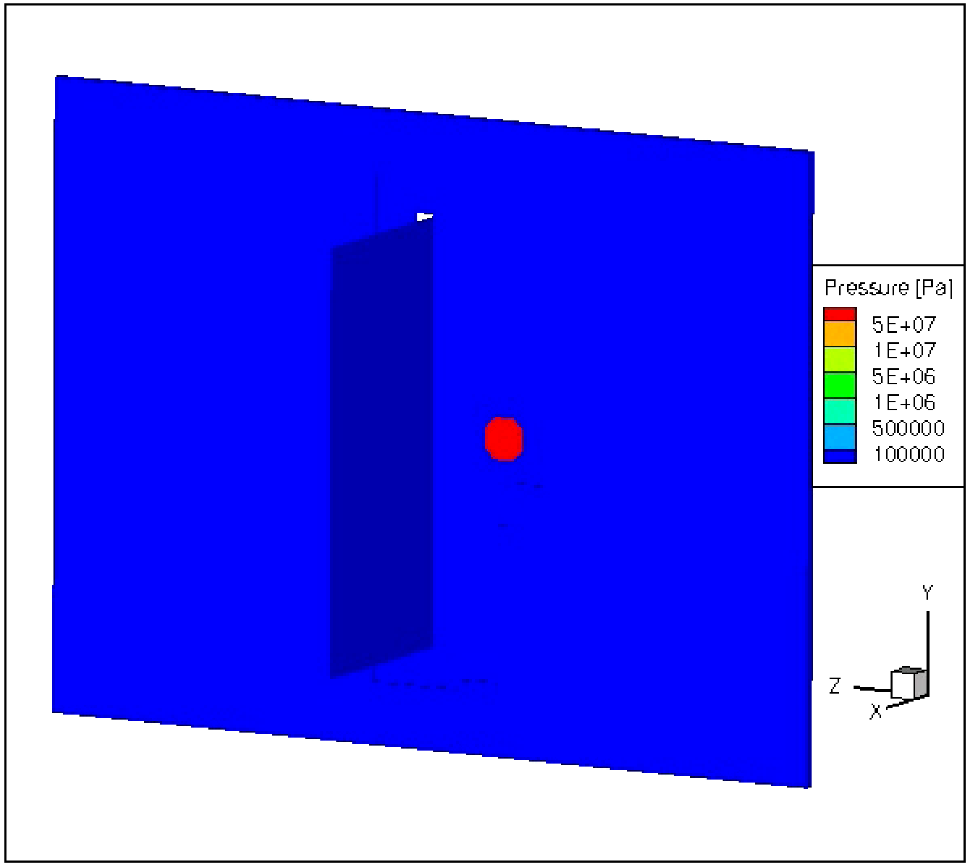


TNT [kg]	*L* [mm]	*t* [mm]	*r* [m]	*d* [m]	T_i [K]	p_i [GPa]	ρ_i [kg/m^3]
0.192	406.4	1.9	0.15	0.04	5860	10.4	6220
0.192	406.4	1.9	0.075	0.03	5860	24.7	14750

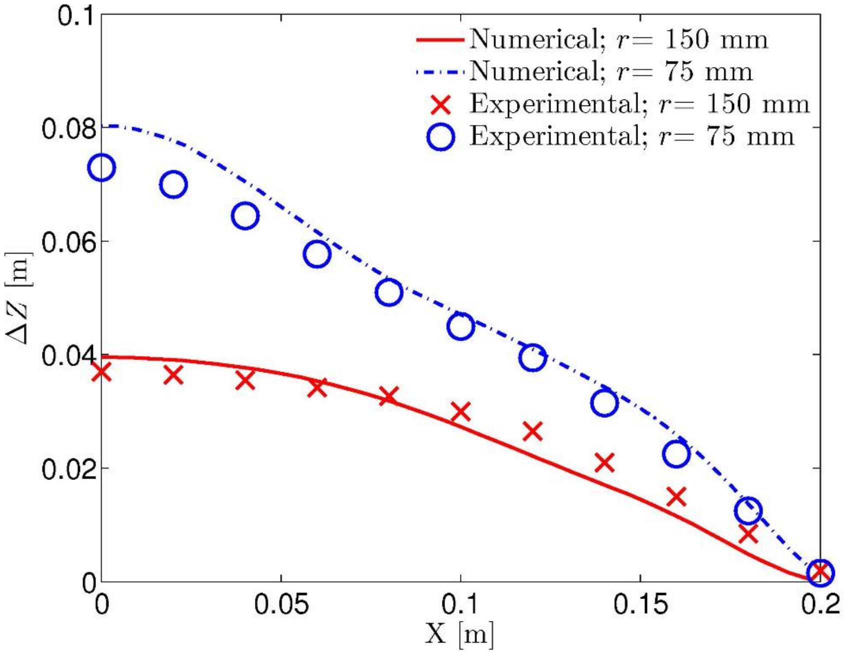
Validation: Explosively loaded steel plates

- Numerical simulations (5 dual nodes /dual core; 2.2Ghz; 24 h):

Time evolution

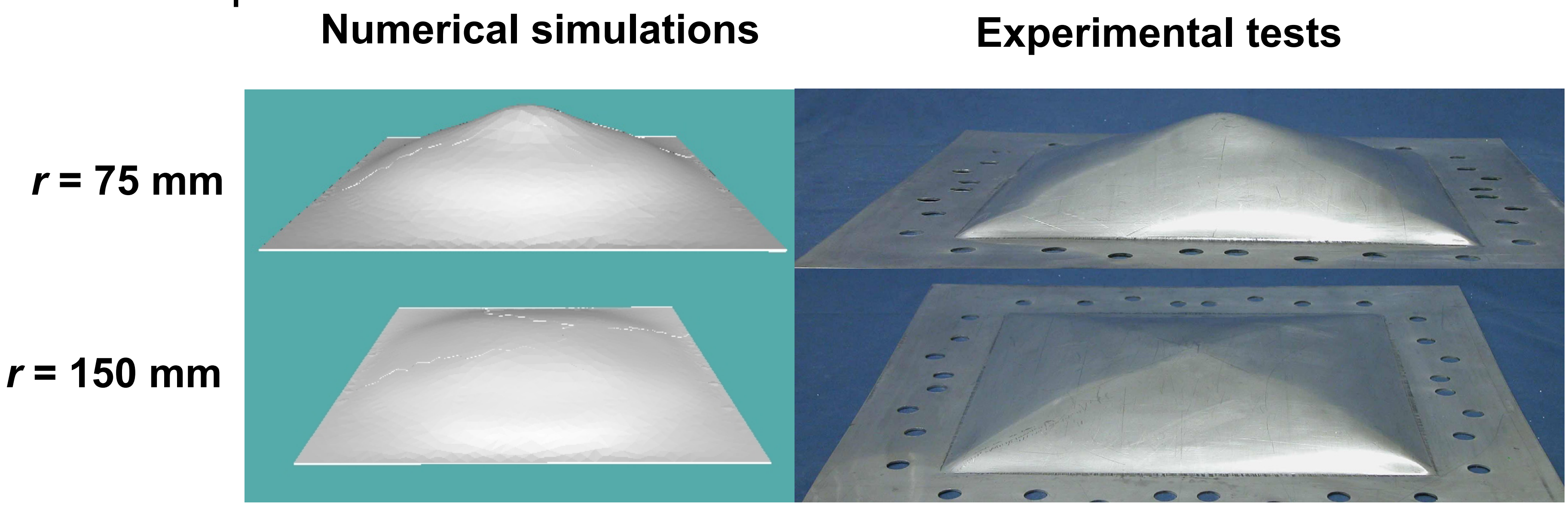


Deformed profiles



Validation: Explosively loaded steel plates

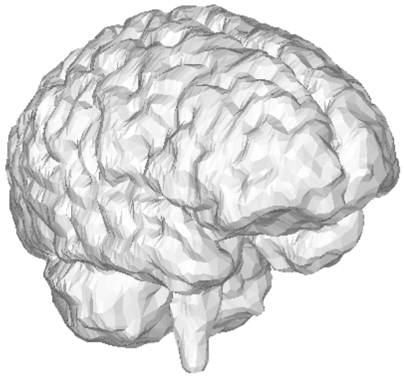
- Comparisons:

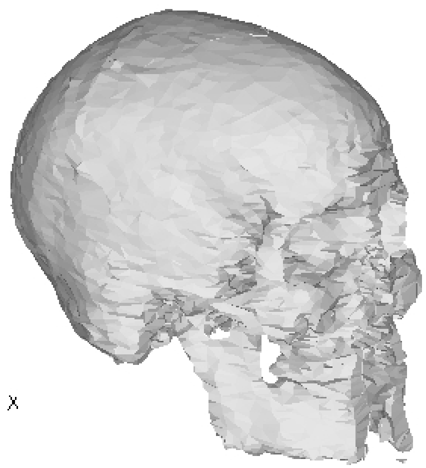


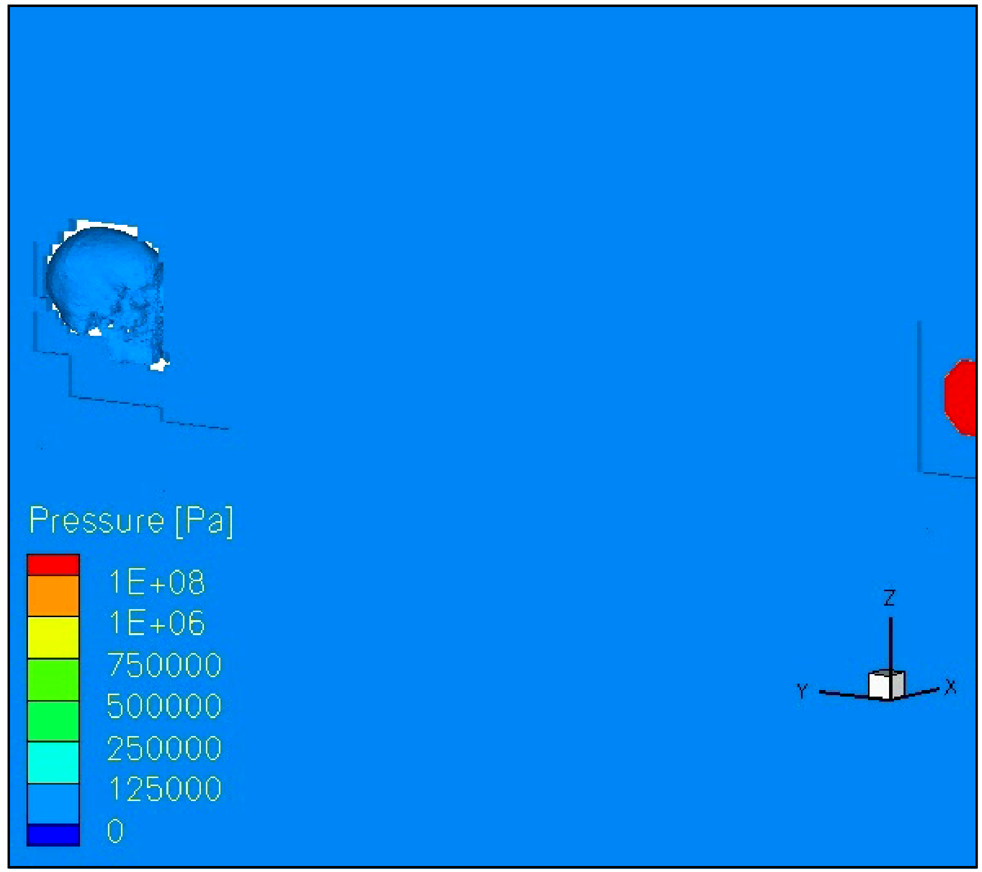
  – Accuracy of results due to the:
    - Good representation of the boundary conditions
    - Good description of the charge geometry
    - Accurate material model
    - Use of high initial temperature

Practical application: Blast injuries

- Meshes from neuroimagery (Harvard Medical School):

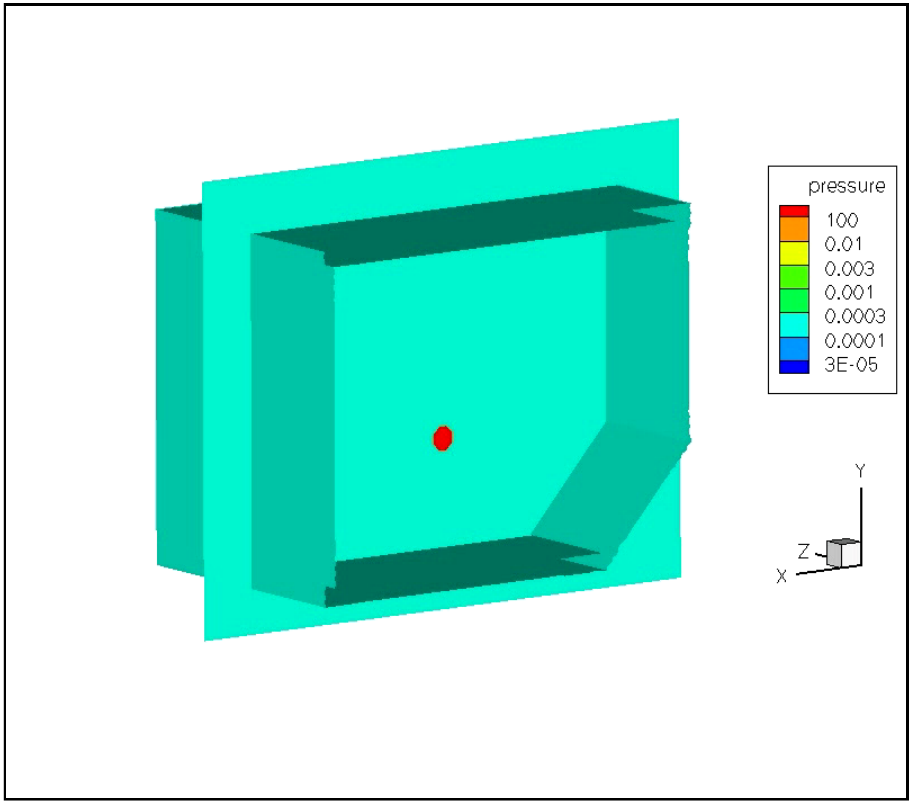






Practical application: Blast-structures

- Blast-resistant luggage containers:



Summary

- Blast effects on structures:
  - Accurate representation of the fluid
  - Accurate representation of the solid
  - State of the art fluid fluid-structure interaction method
- Methodology validated against blast-plate interactions:
  - Excellent agreements if use of:
    - Accurate material models
    - Accurate boundary conditions
    - Initial pressurized bubble at high temperature