Coupling Possibilities in LS-DYNA: Development Status and Sample Applications

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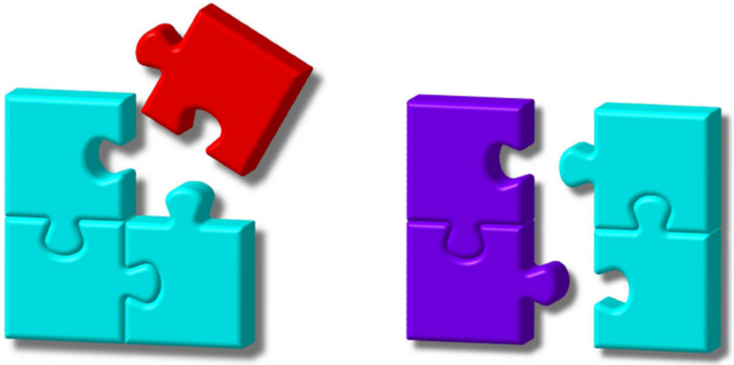
Outline

- Introduction
- Applications
- Conclusion

Introduction

Park & Felippa: Partitioned analysis of coupled systems. In Belytschko & Hughes (eds.): Computational Methods for Transient Analysis. Amsterdam 1983, pp. 157–219

- Coupled Problems
  - Dynamic Interaction of physically or computationally heterogeneous components
  - Interaction is multi-way



Partitioning or splitting of a coupled problem

- Coupled Multi-Field Problems
  - The individual field equations are also functions of the other field
    - Example: velocity and pressure fields for incompressible viscous flow
- Coupled Multi-Physics Problems
  - Multiple physical models or phenomena are handled simultaneously
  - Different discretization techniques are used for individual subproblems
    - Example: particle systems (DEM) interact with structures (FEM) on the same or multiple scales
  - Field variables represent different but interacting physical phenomena
    - Example: thermoelectricity combining heat conduction and electrodynamics

- Classification of the Coupling

- Volume Coupled
  - Discretized field variables (DOF) are coupled on the same domain
  - Weak coupling
    - Thermo-mechanical problem
      - ☐ displacement & thermal field
  - Strong coupling
    - Incompressible fluid flow
      - ☐ velocity & pressure field
    - Electro-magnetical problem
      - ☐ electric field & magnetic flux density
    - Porous-media problems
      - ☐ displacement & pressure field
      - ☐ displacement, pressure & concentration fields

- Surface Coupled
  - Discretized field variables (DOF) are coupled at an interface surface
  - Weak coupling
    - Mechanical contact
    - Heat transmission
    - Structural sound emission
    - Fluid-structure interaction (low-density fluids)
  - Strong coupling
    - Fluid structure interaction (high-density fluids)

- Solution of Coupled Problems
  - Spatial semi discretization
    - Finite-Element Method (FEM)
    - Finite-Difference Method (FDM)
    - Finite-Volume Method (FVM)
    - Arbitrary Lagrange Eulerian (ALE)
    - Boundary-Element Method (BEM)
    - Discrete-Element Method (DEM)
    - Smoothed Particle Hydrodynamics (SPH)
    - Element-Free Galerkin (EFG)
  - Time integration
    - Implicit and explicit time-stepping schemes
    - Monolithic or direct approach
      - the problem is treated monolithically
      - all components are integrated with the same scheme
    - Partitioned or iterative approach
      - system components are treated as isolated entities
      - separate time integration with arbitrary schemes
      - subcycling to account for different time scales
      - prediction, substitution, and synchronization techniques apply

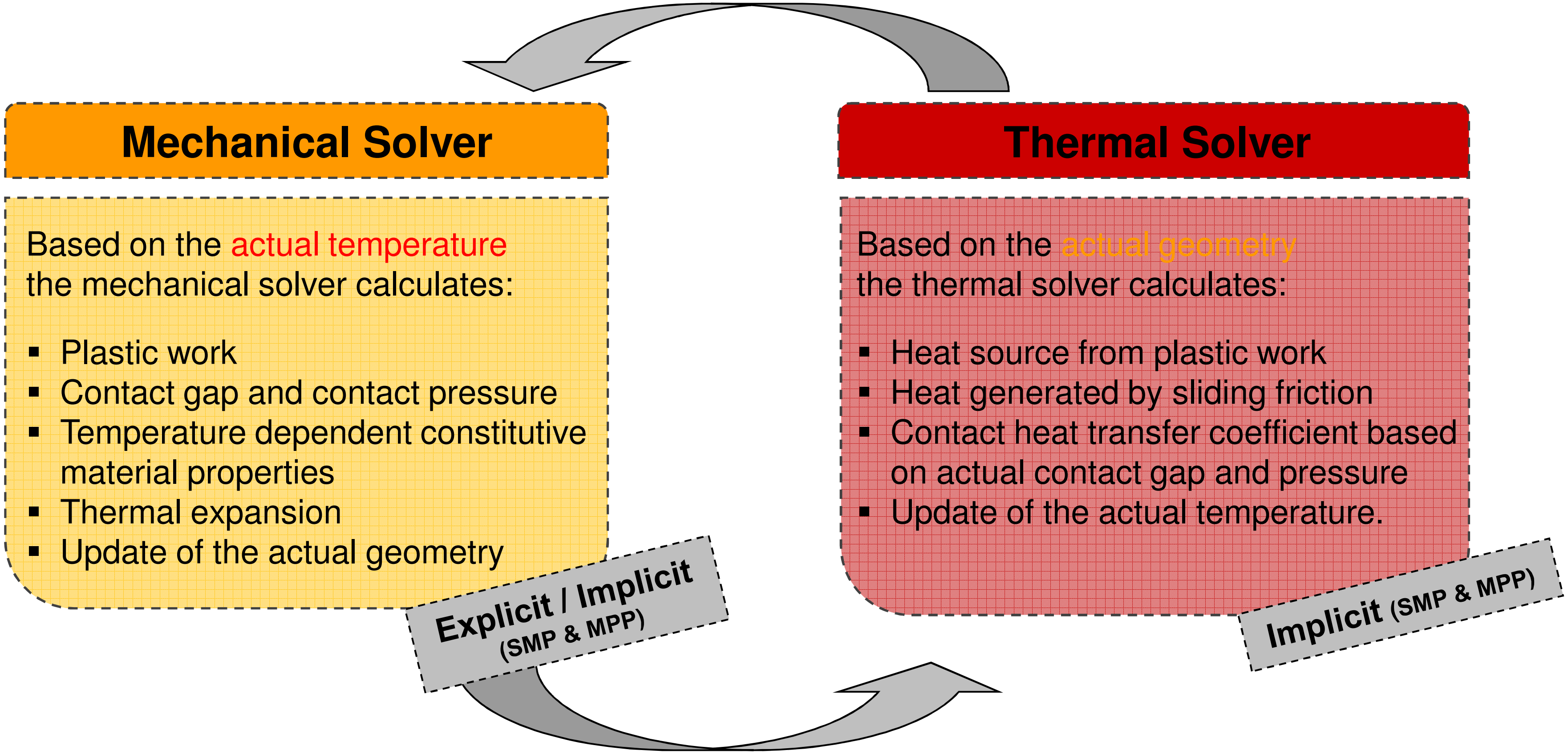
- One-Code Strategy for LS-DYNA

> “Combine the multi-physics capabilities into one scalable code for solving highly nonlinear transient problems to enable the solution of coupled multi-physics and multi-stage problems”
>
> -- John Hallquist (2012)

- Presented Simulations in the field of
  - Thermo-mechanical coupling
  - Electro-magnetical coupling
  - Fluid-structure interaction
  - Particle-structure interaction

Thermo-Mechanical Coupling

- Solvers are Connected in a Staggered Solution Scheme
  - Application: Hot stamping of high strength steel



Mechanical Solver

Based on the actual temperature
the mechanical solver calculates:

- Plastic work
- Contact gap and contact pressure
- Temperature dependent constitutive material properties
- Thermal expansion
- Update of the actual geometry

Explicit / Implicit
(SMP & MPP)

Thermal Solver

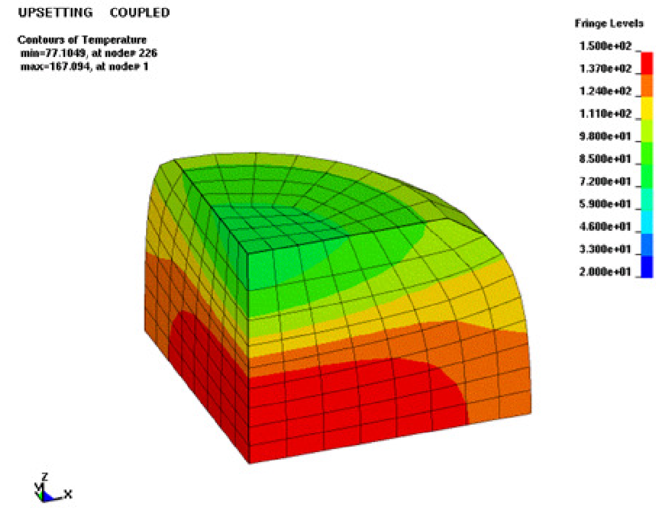
Based on the actual geometry
the thermal solver calculates:

- Heat source from plastic work
- Heat generated by sliding friction
- Contact heat transfer coefficient based on actual contact gap and pressure
- Update of the actual temperature.

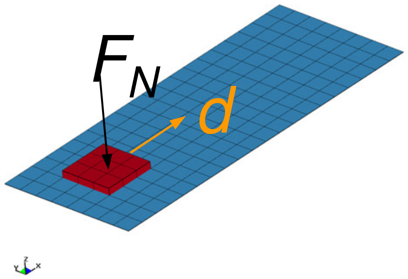
Implicit (SMP & MPP)

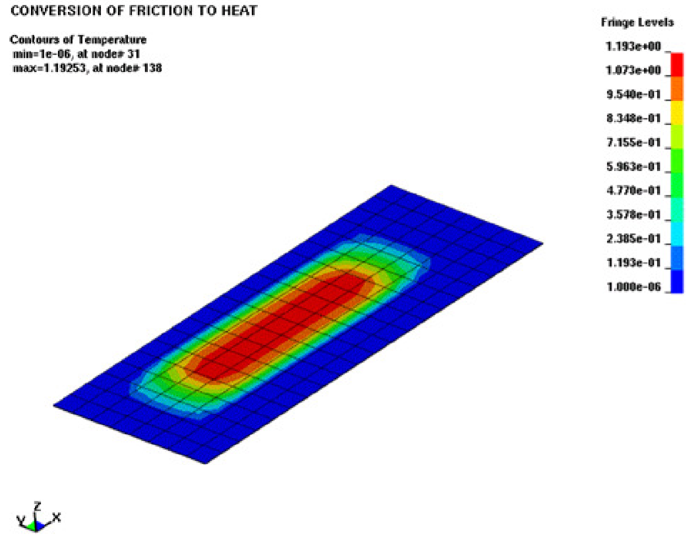
- Thermal Coupling Effects
  - Plastic work to heat conversion

$$w_{pl} = \rho\, c_p\, \Delta T = \eta \int_{\varepsilon_{pl}} \sigma^y d\varepsilon_{pl}$$



  - Friction-induced heat
    - Friction coefficient is very high (0.4 …0.6)





- Note: These are effects of second order in hot stamping

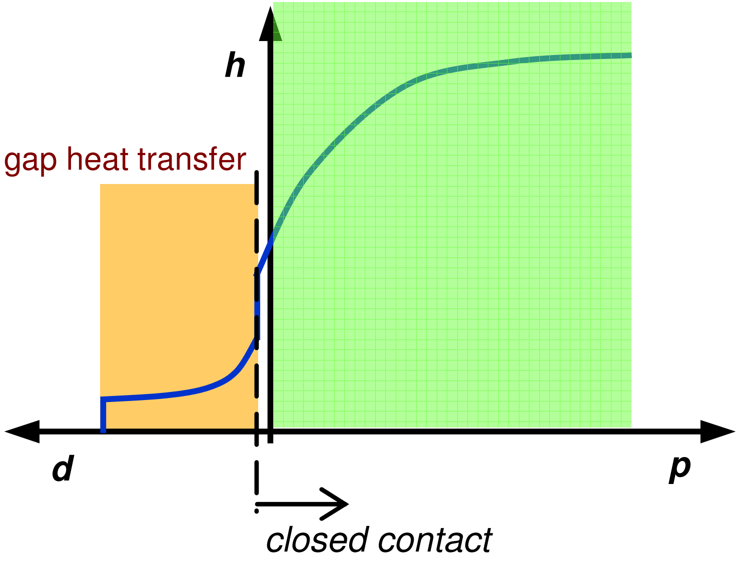
Thermal Contact – Heat Transfer Coefficient

- Gap heat transfer in LS-DYNA

$$h_{gap}=\frac{k}{L_{gap}}+f_{rad}\left(T+T_{\infty}\right)\left(T^{2}+T_{\infty}^{2}\right)$$

Sensitive to small gaps

Kelvin scale necessary



- Closed contact heat transfer in LS-DYNA

FORMULA	**pressure dependency** $h_{cont}(p)$
1	**curve h vs. p**
2	**3rd order polynom**
3	$h(p)=\frac{\pi k_{gas}}{4\lambda}\left[1.+85\left(\frac{p}{\sigma}\right)^{0.8}\right]=\frac{a}{b}\left[1.+85\left(\frac{p}{c}\right)^{0.8}\right]$
4	$h(p)=a\left[1-\exp\left(-b\frac{p}{c}\right)\right]^{d}$

parameters
a, b, c, d are
curves versus
temperature *f(T)*

- Subcycling of the Thermo-Mechanical Coupling
  - The “critical” implicit thermal timestep is usually some orders of magnitude greater than the critical explicit mechanical timestep

$$\Delta t_{therm} \leq \frac{1}{12} \cdot \frac{l^2}{a} \quad ; \quad a = \frac{\lambda}{\rho \cdot c}$$

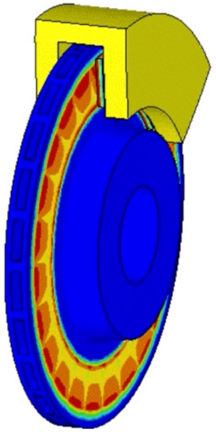
Model must be able to respond as fast as real life [*Owen* 1993]

$$\Delta t_{mech} \leq \frac{l}{c} \quad ; \quad c = \sqrt{\frac{E}{\rho\left(1-\nu^2\right)}}$$

CFL Condition

λ : thermal conductivity
c : heat capacity
ρ : density

E : Youngs modulus
ν : Poisson‘s ratio
ρ : density



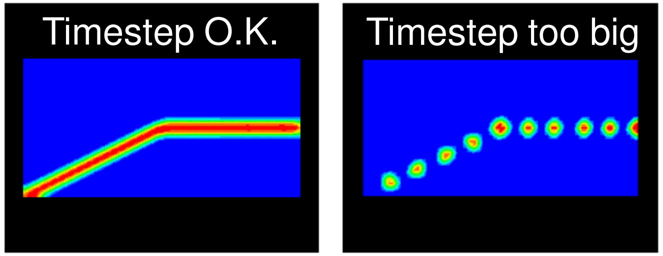
  - Example: Steel at room temperature with 1 mm edge length

Δt_{therm}=7.523·10^{-3} s

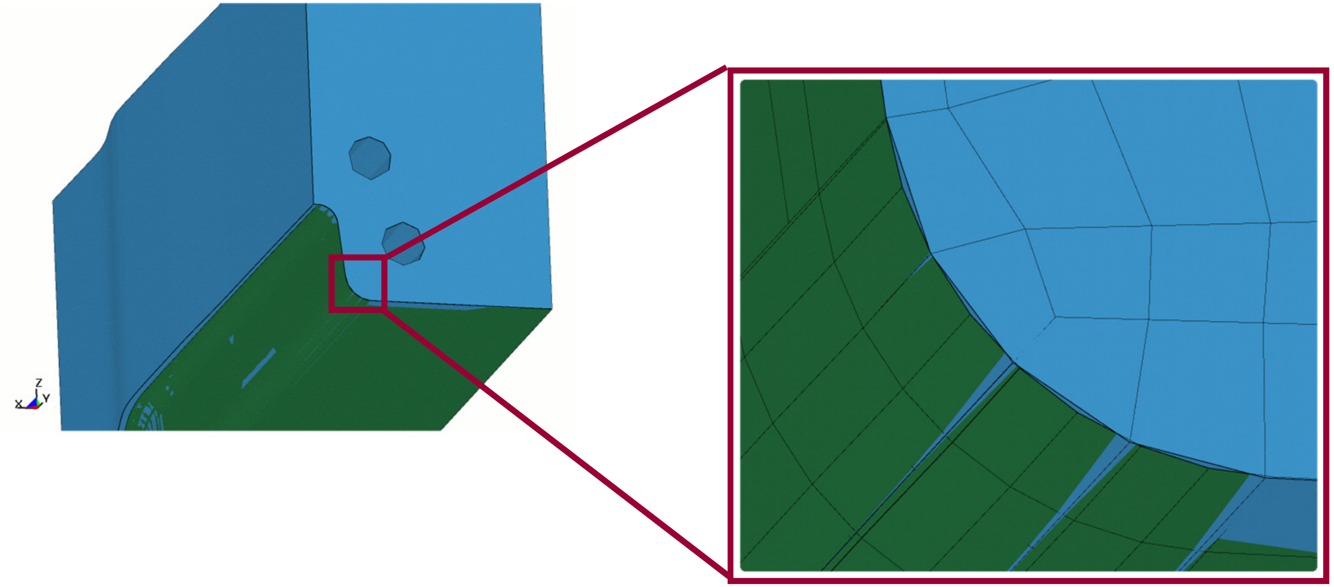
Δt_{mech}=1.844·10^{-7} s

  - Note: Make sure the thermal timestep is small enough to capture the mechanical motion

$$\Delta t_{\max} = \frac{d_{\max}}{v_{\max}} \quad ; \quad d_{\max} = 1 \ldots 5 \text{ mm} \quad ; \quad v_{\max} = 1 \ldots 5 \text{ m/s}$$



- Use of Thermal Contact to Enhance Modeling Skills
  - Die surface geometry accurately modeled with shell elements
  - Die volume geometry modeled with volume elements
  - Shell and volume mesh coupled with contact definition

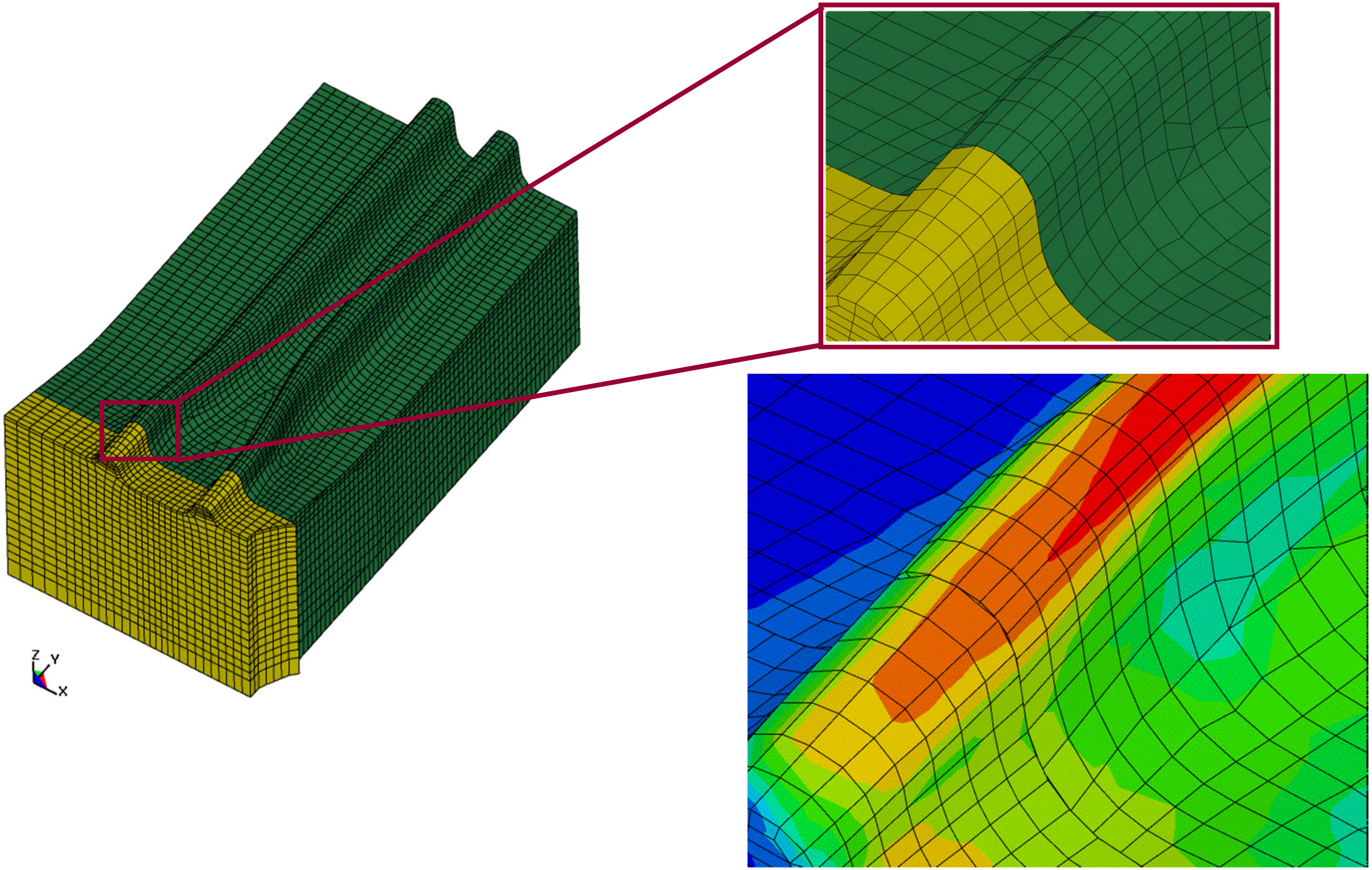


independent meshing of surface and volume

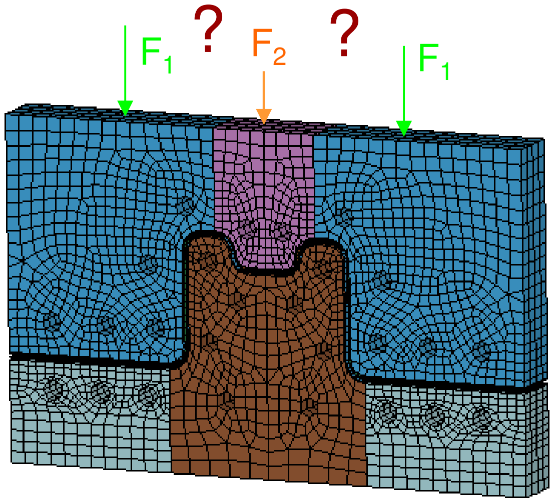
Penetrations between Volume Elements and Blank Shells are ignored in the mechanical contacts

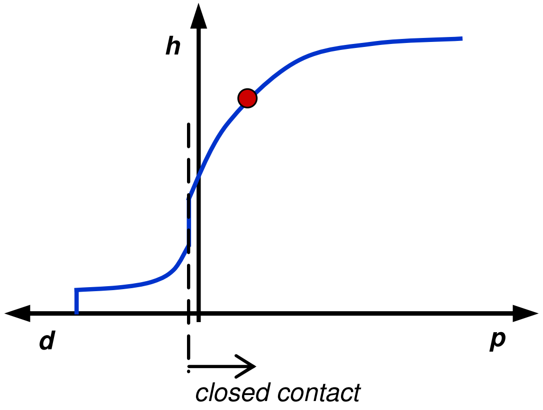
- Heat transfer from blank to die surface shell by thermal contact
- Heat dissipation into the dies by thermal contact between shell and volume mesh

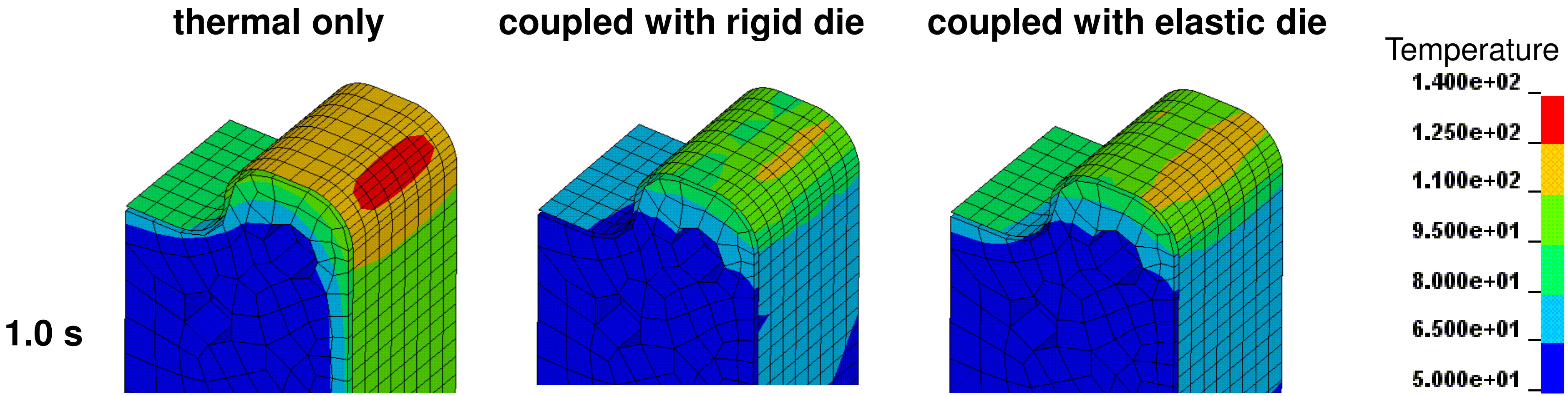
- Correct Temperature in Non-Matching Meshes



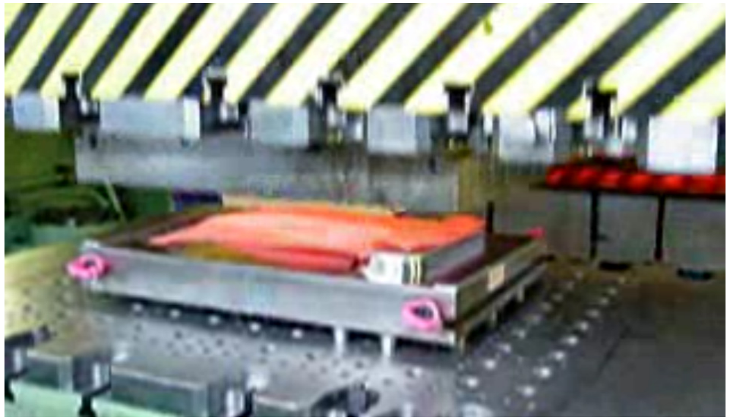
- Cooling Simulation – Is the Coupling Necessary?

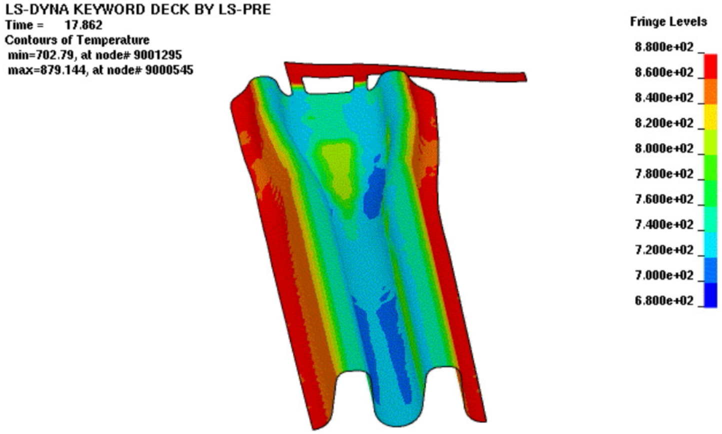


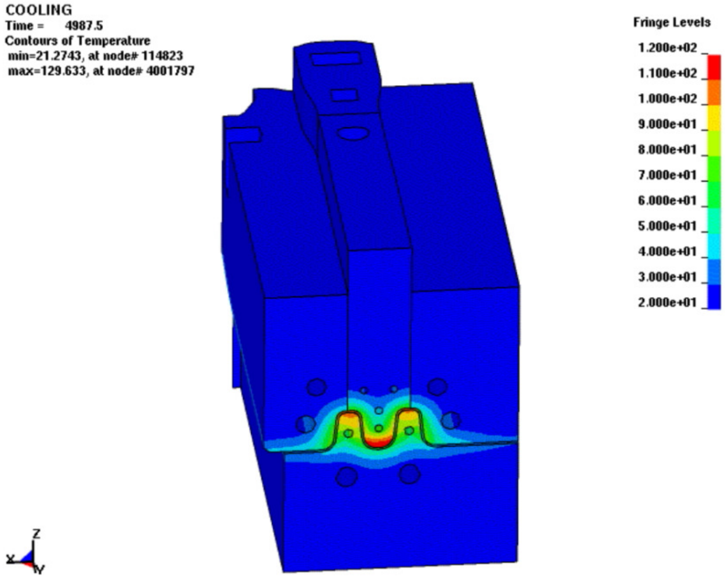


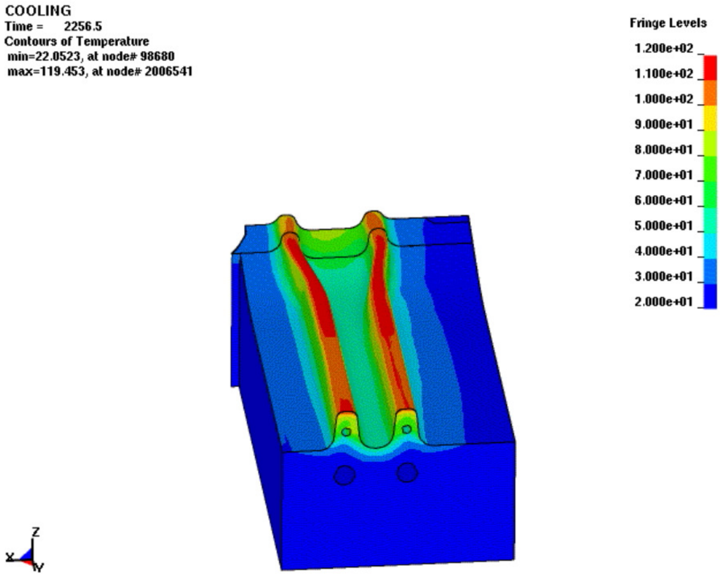


- Coupled Simulation of Forming and Cooling due to Contact with the Die









- Modeling Phase Transformations
  - **`*MAT_UHS_STEEL`** (**`*MAT_244`**)
    - Paul Akerstrom, “Modeling and Simulation of Hot Stamping”
      Ph.D. Thesis, Lulea University of Technology, 2006

Input includes:

1. 15 element constituents
2. Latent heat
3. Expansion coefficients
4. Phase hardening curves
5. Phase kinetic parameters
6. Cowper-Symonds parameters

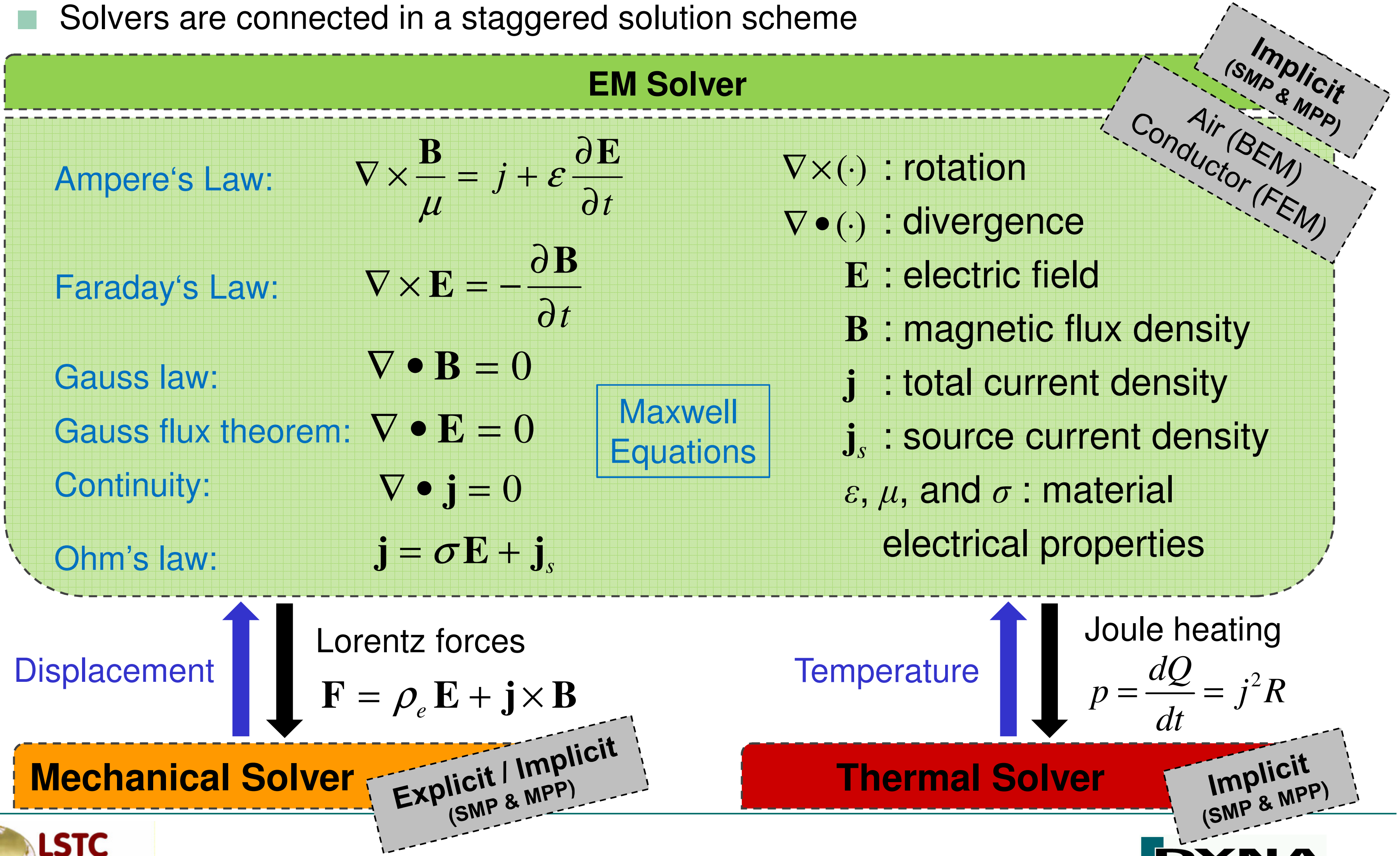
Output includes:

1. Austenite phase fraction
2. Ferrite phase fraction
3. Pearlite phase fraction
4. Bainite phase fraction
5. Martensite phase fraction
6. Vicker’s hardness distribution
7. Yield stress distribution

  - Phase Transformations due to Different Cooling Rates

Electro-Magnetical Coupling

- Electro-Magnetic Solver and Connection to Mechanical and Thermal Solvers
  - Solvers are connected in a staggered solution scheme



EM Solver

Implicit (SMP & MPP)

Air (BEM)
Conductor (FEM)

Ampere's Law: $\nabla \times \frac{\mathbf{B}}{\mu} = j + \varepsilon \frac{\partial \mathbf{E}}{\partial t}$

Faraday's Law: $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$

Gauss law: $\nabla \bullet \mathbf{B} = 0$

Gauss flux theorem: $\nabla \bullet \mathbf{E} = 0$

Continuity: $\nabla \bullet \mathbf{j} = 0$

Ohm's law: $\mathbf{j} = \sigma \mathbf{E} + \mathbf{j}_s$

Maxwell Equations

$\nabla \times (\cdot)$: rotation
$\nabla \bullet (\cdot)$: divergence
$\mathbf{E}$: electric field
$\mathbf{B}$: magnetic flux density
$\mathbf{j}$: total current density
$\mathbf{j}_s$: source current density
ε, μ, and σ : material electrical properties

Displacement

Lorentz forces

$\mathbf{F} = \rho_e \mathbf{E} + \mathbf{j} \times \mathbf{B}$

Temperature

Joule heating

$p = \frac{dQ}{dt} = j^2 R$

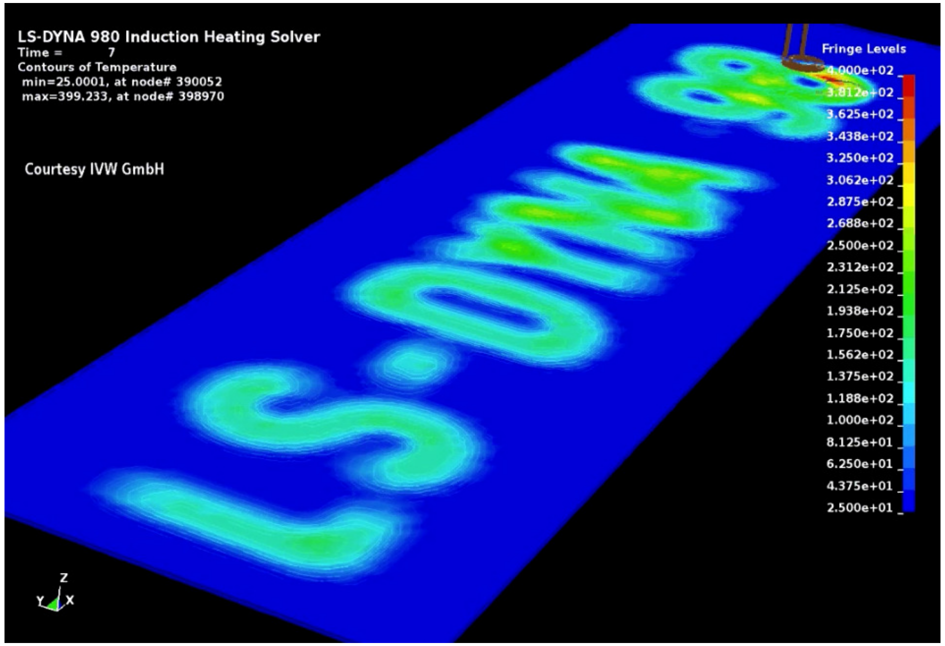
Mechanical Solver

Explicit / Implicit (SMP & MPP)

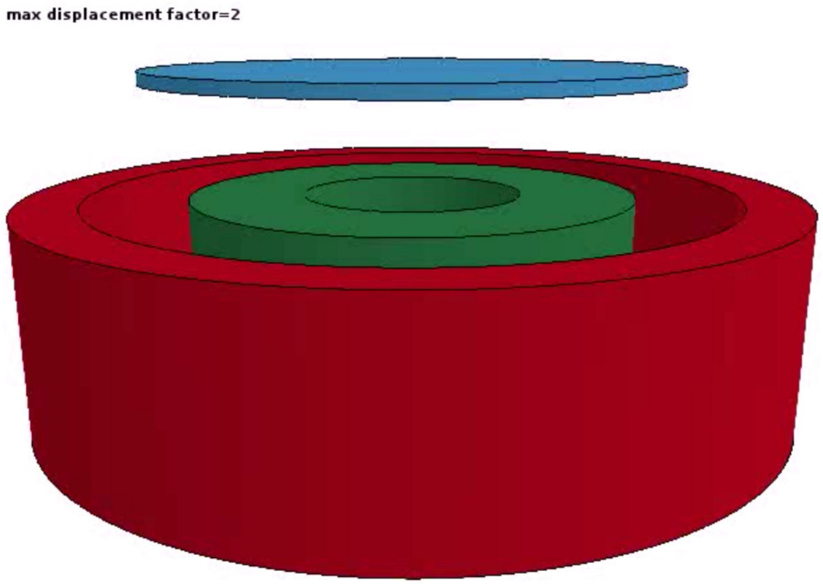
Thermal Solver

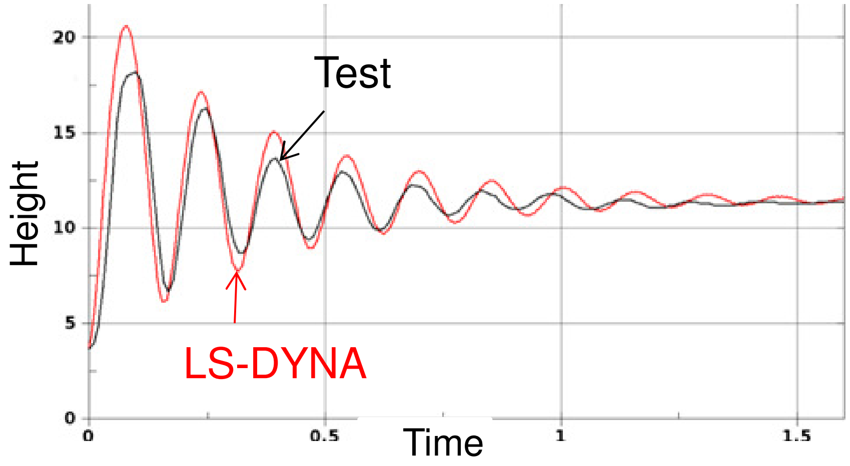
Implicit (SMP & MPP)

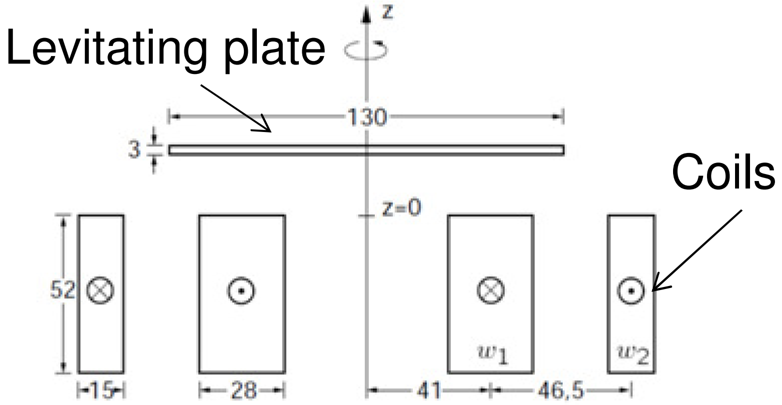
- Current EM Status
  - All EM solvers work on solid elements for conductors
    - Hexahedrons, tetrahedrons, wedges
  - Shells can be used for insulator materials
  - Available in both SMP and MPP
  - 2D axi-symmetric available
  - The EM fields as well as EM force and Joule heating can be visualized in LS-PREPOST :
    - Fringe components
    - Vector fields
    - Element histories
- Only Available in LS-DYNA 980



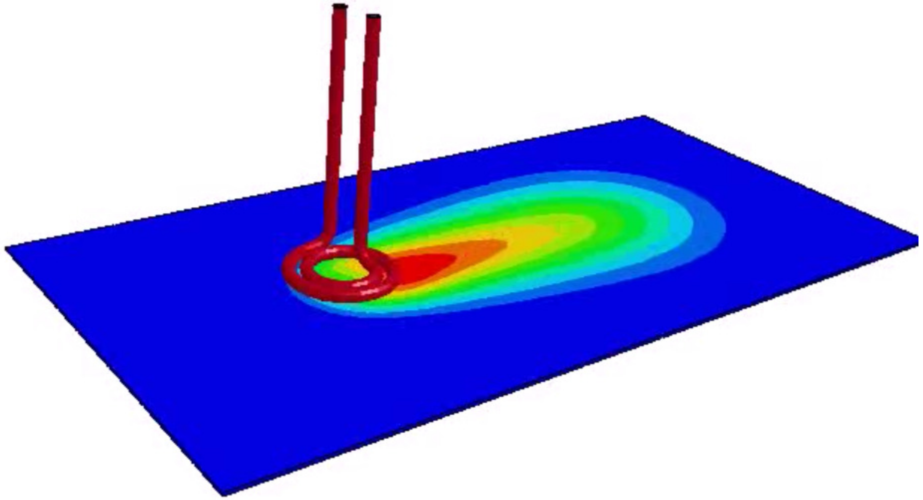
- EM Solver Validation
  - Some T.E.A.M. (Testing Electromagnetic Analysis Methods) test cases have been used to validate LS-DYNA's EM accuracy and to demonstrate its features
- T.E.A.M. 28 : An Electrodynamic Levitation Device
  - Conducting plate that levitates over two exciting coils
  - Plate oscillates and progressively reaches an equilibrium position

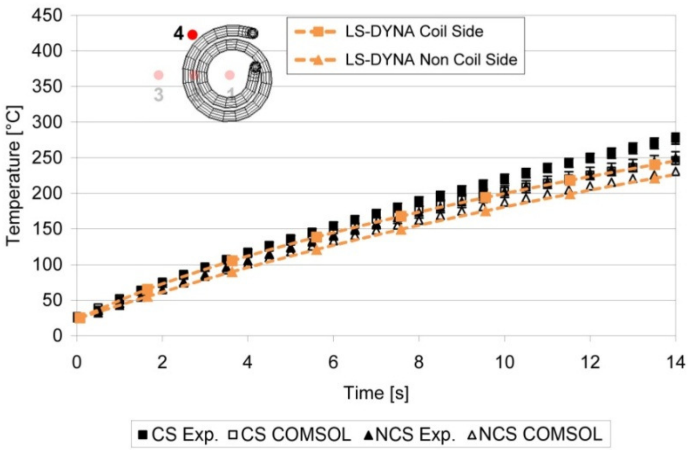


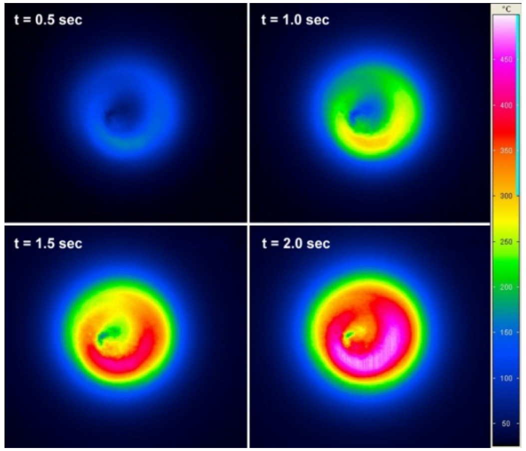




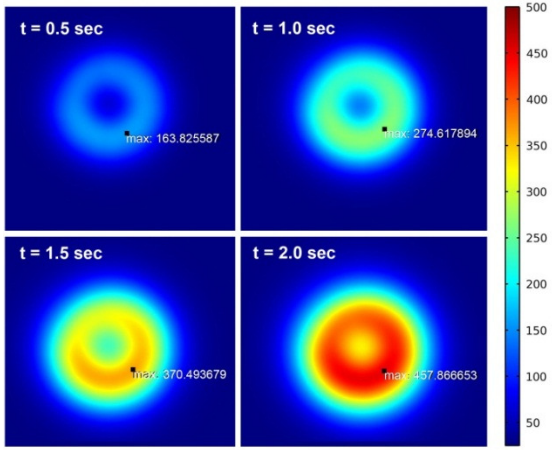
- EM Solver Validation (Cntd.)
  - Heating of a steel plate by induction
    - In collaboration with: M. Duhovic, Institut für Verbundwerkstoffe, Kaiserslautern, Germany





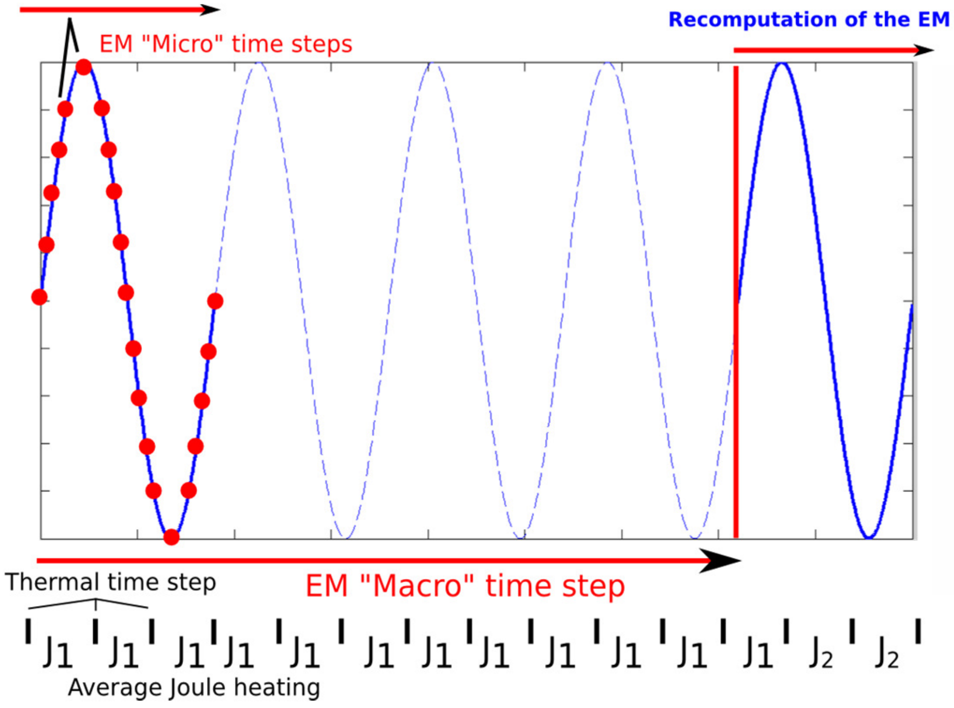


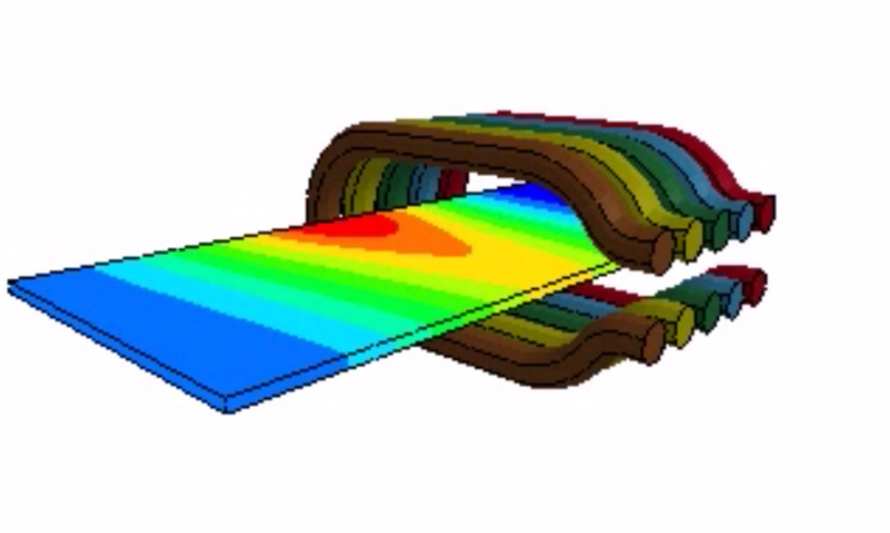
Thermal images from experiment



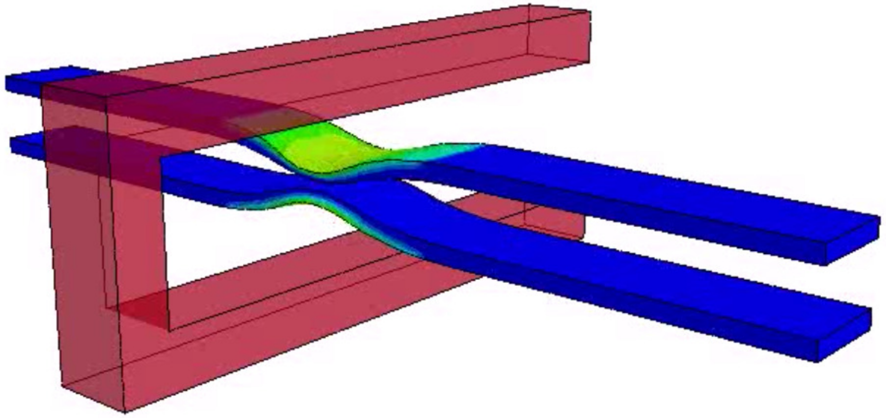
LS-DYNA temperature fringes

- Subcycling for the Induced Heating Problem
  - Problem: The coil’s current oscillation period is smaller than the total time of the problem
  - Consequence: Many small EM time steps needed
  - Solution: Induced heating solver with “micro” and “macro” time step
  - Application: Conducting plaque moving through coils that induce Joule heating

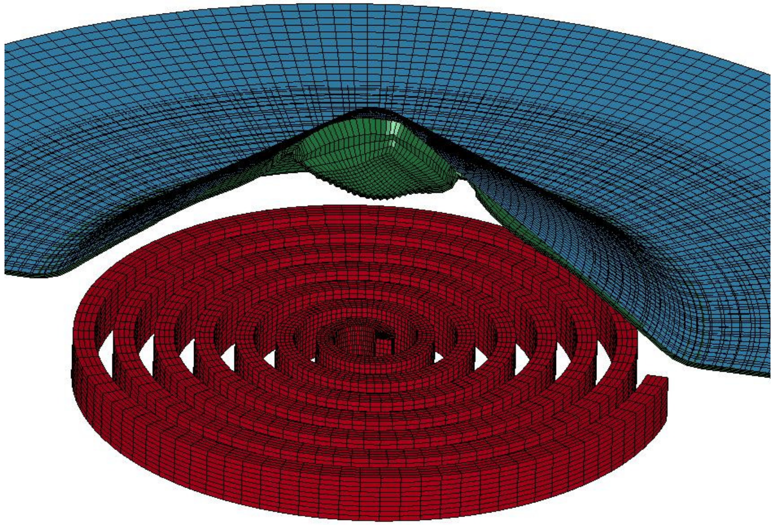


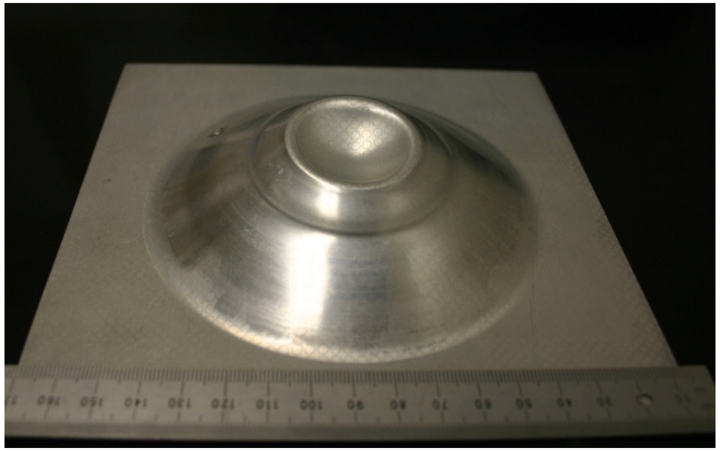


- EM Applications
  - Magnetic Metal Welding
    - Current density fringe



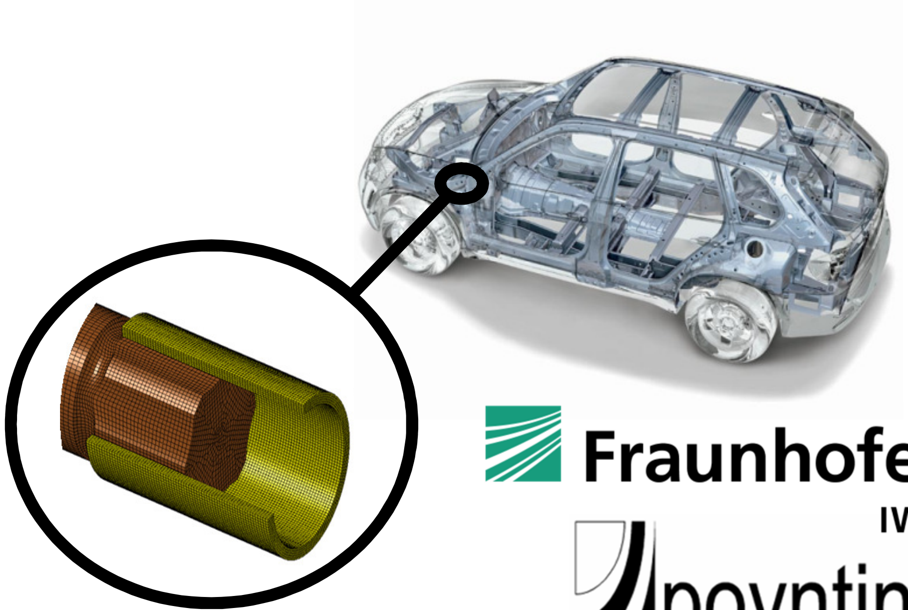
- Sheet forming on conical die

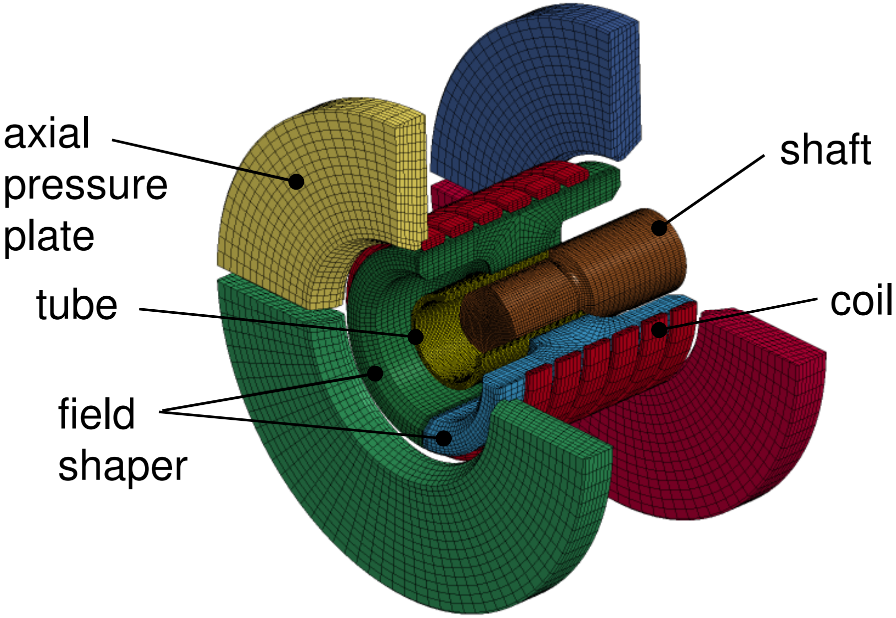




- In collaboration with:
  - M. Worswick & J. Imbert University of Waterloo, Canada

- EM Applications (Cntd.)
  - Forming of a tube-shaft joint

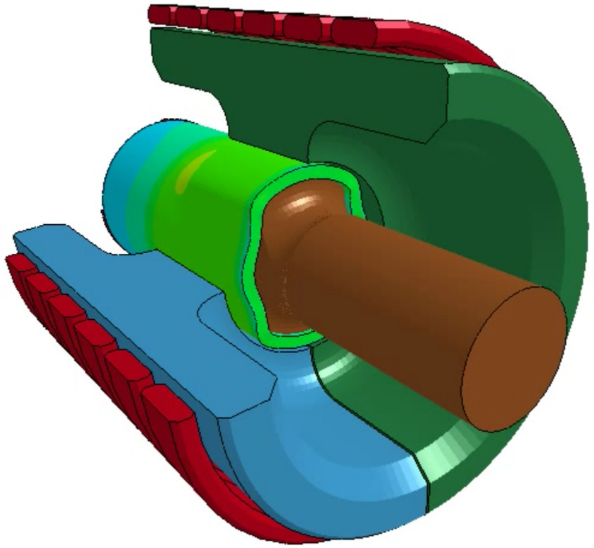




Fraunhofer IWU

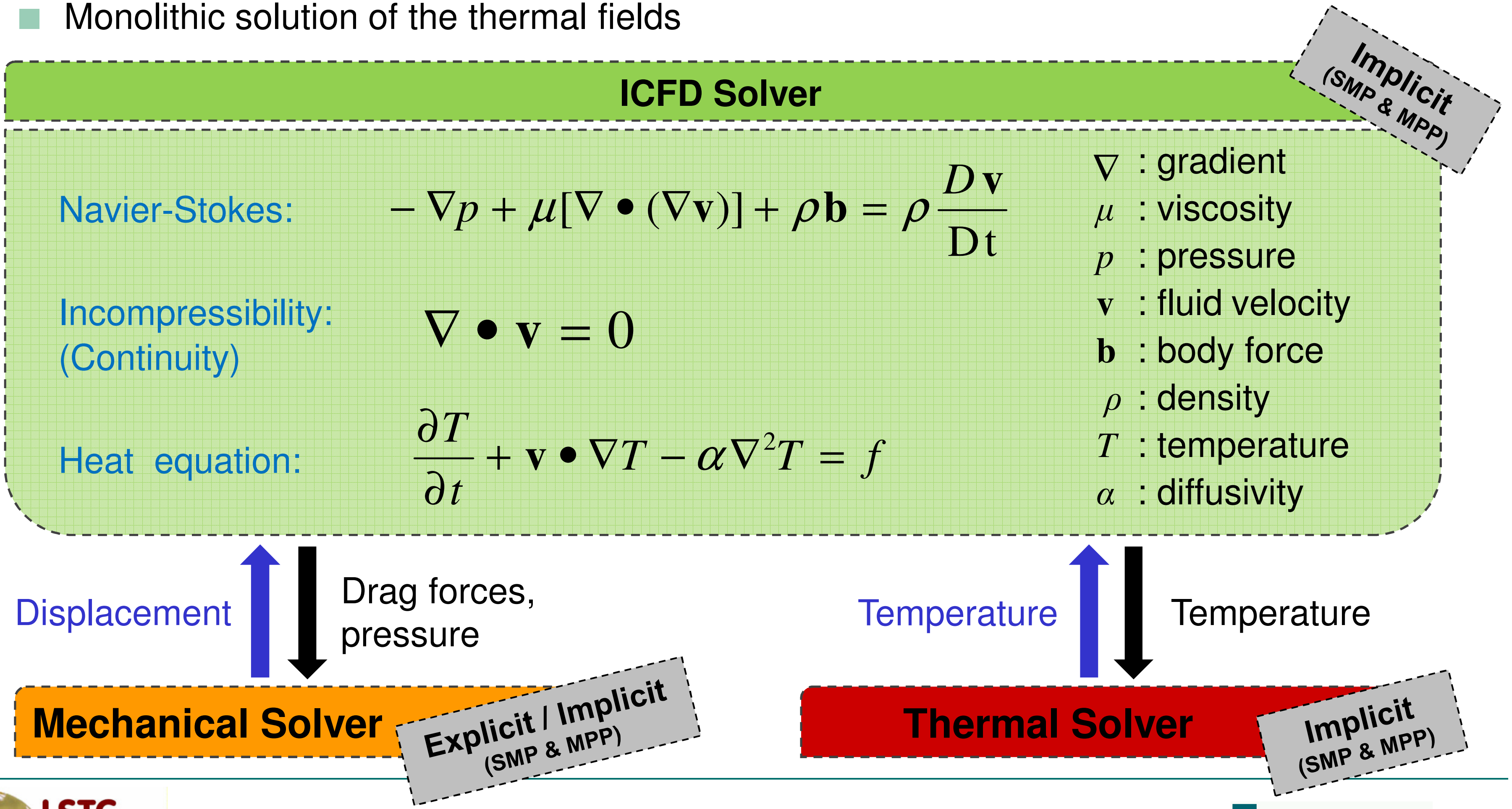
poynting

  - In collaboration with
    - Fraunhofer Institute for Machine Tools and Forming Technology IWU, Chemnitz Dipl.-Ing. Christian Scheffler
    - Poynting GmbH, Dortmund, Dr.-Ing. Charlotte Beerwald



Fluid-Structure Interaction

- Solver for Incompressible Fluid Dynamics (ICFD)
  - Weak and strong coupling to mechanical solver
  - Monolithic solution of the thermal fields



ICFD Solver

Implicit
(SMP & MPP)

Navier-Stokes: $$-\nabla p + \mu[\nabla \bullet (\nabla \mathbf{v})] + \rho \mathbf{b} = \rho \frac{D\mathbf{v}}{Dt}$$

Incompressibility:
(Continuity) $$\nabla \bullet \mathbf{v} = 0$$

Heat equation: $$\frac{\partial T}{\partial t} + \mathbf{v} \bullet \nabla T - \alpha \nabla^2 T = f$$

∇ : gradient
μ : viscosity
p : pressure
$\mathbf{v}$: fluid velocity
$\mathbf{b}$: body force
ρ : density
T : temperature
α : diffusivity

Displacement

Drag forces,
pressure

Temperature

Temperature

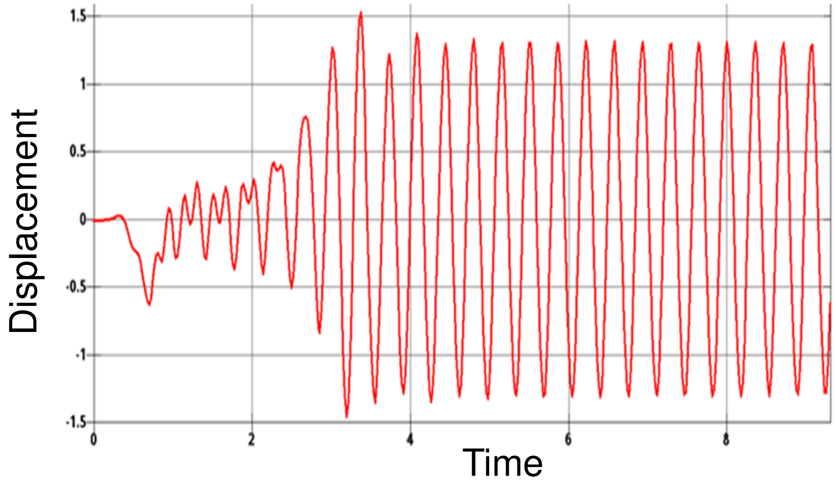
Mechanical Solver

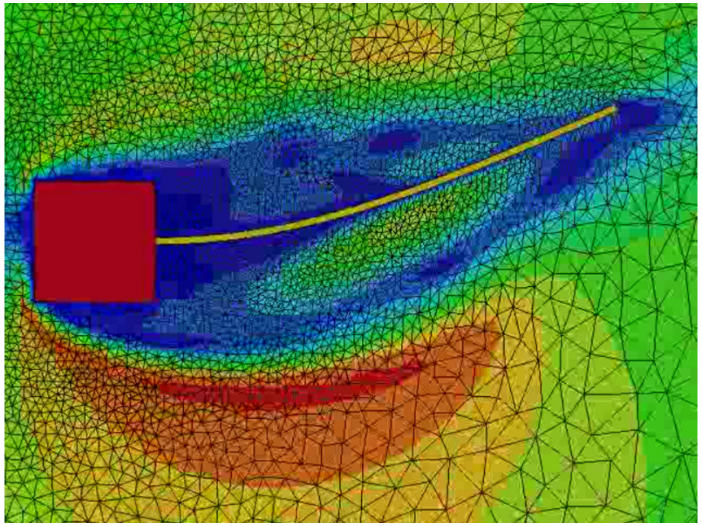
Explicit / Implicit
(SMP & MPP)

Thermal Solver

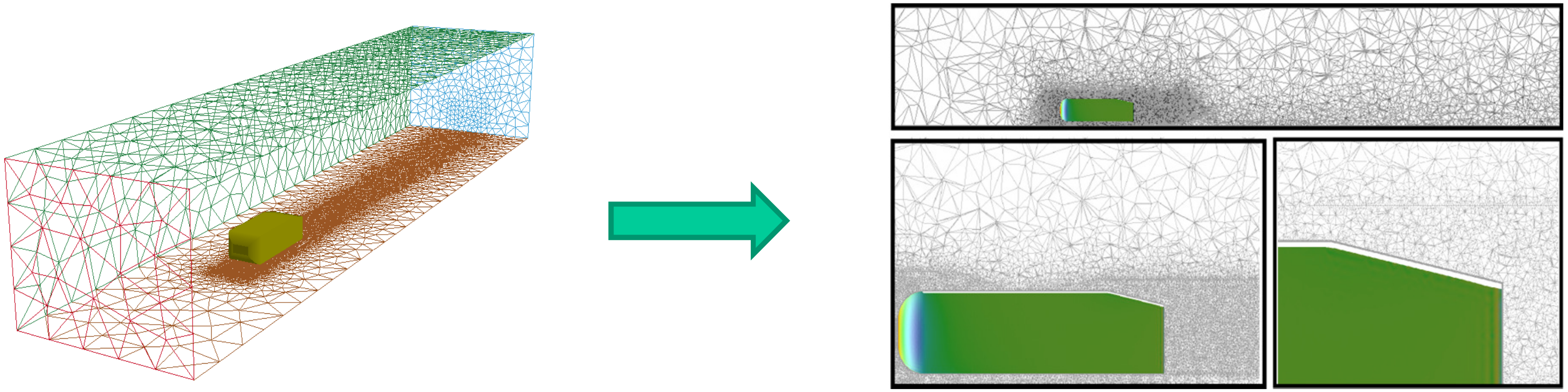
Implicit
(SMP & MPP)

- Current ICFD Status
  - Based on a stabilized finite-element formulation
  - Stand alone implicit CFD solver with coupling to the
    - Mechanical solver (FSI problems)
    - Thermal solver (Conjugate heat transfer problems)
  - ALE approach for mesh movement
  - Boundaries of FSI are Lagrangean and deform with the structure
    - Strong coupling available for implicit mechanics (more robust but more costly)
    - Loose coupling for explicit mechanics (less robust and less costly)
- Only Available in LS-DYNA 980

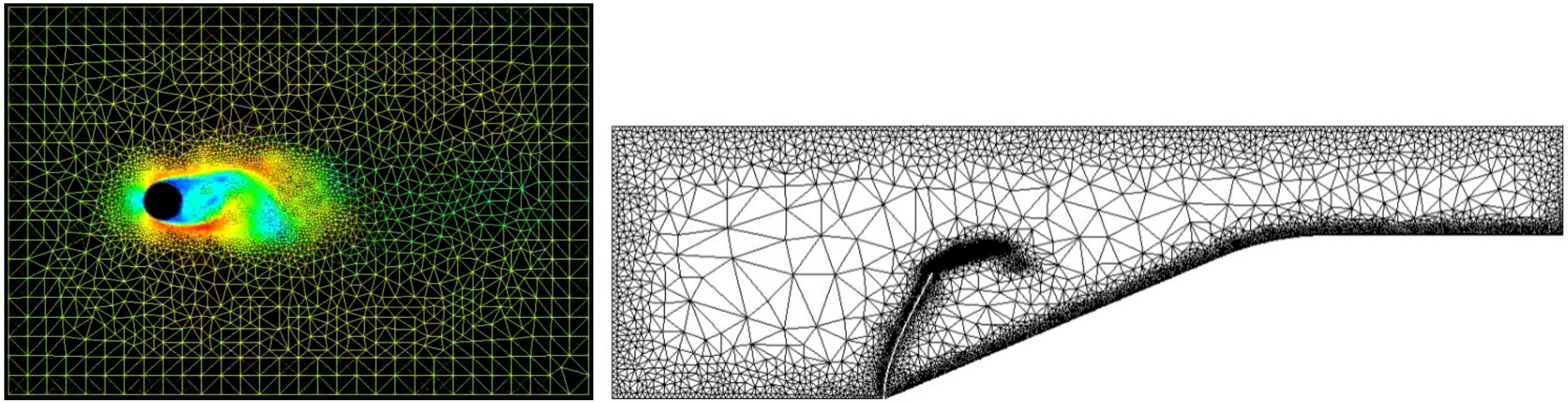




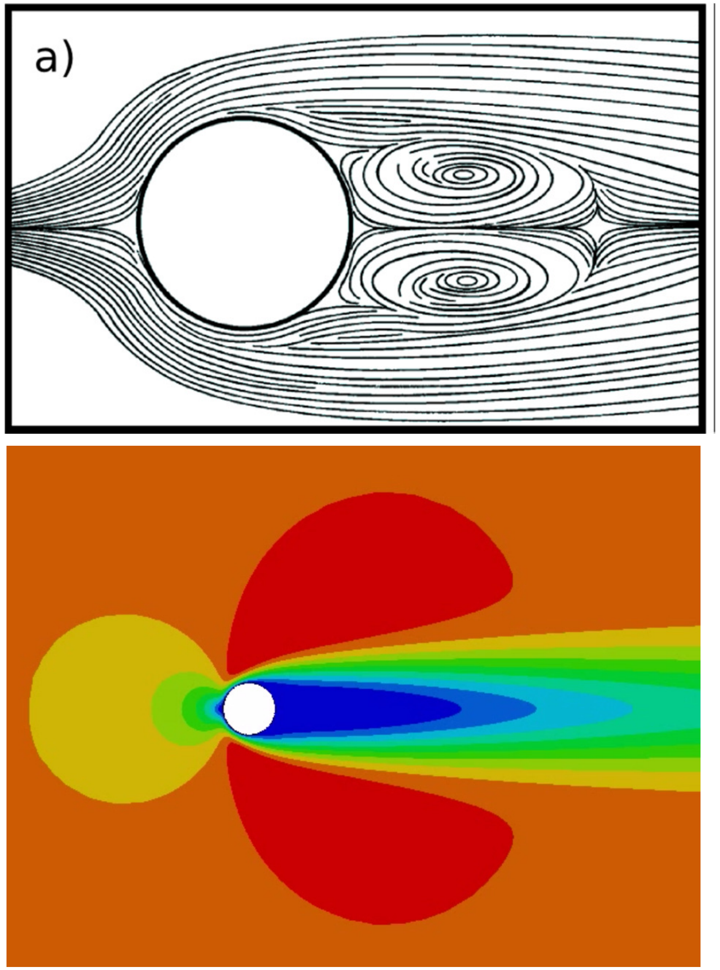
- Automatic Mesh Generation and Refinement
  - Automatic generation of the volume mesh and the boundary layer mesh
  - Possibility to specify local mesh size for better resolution



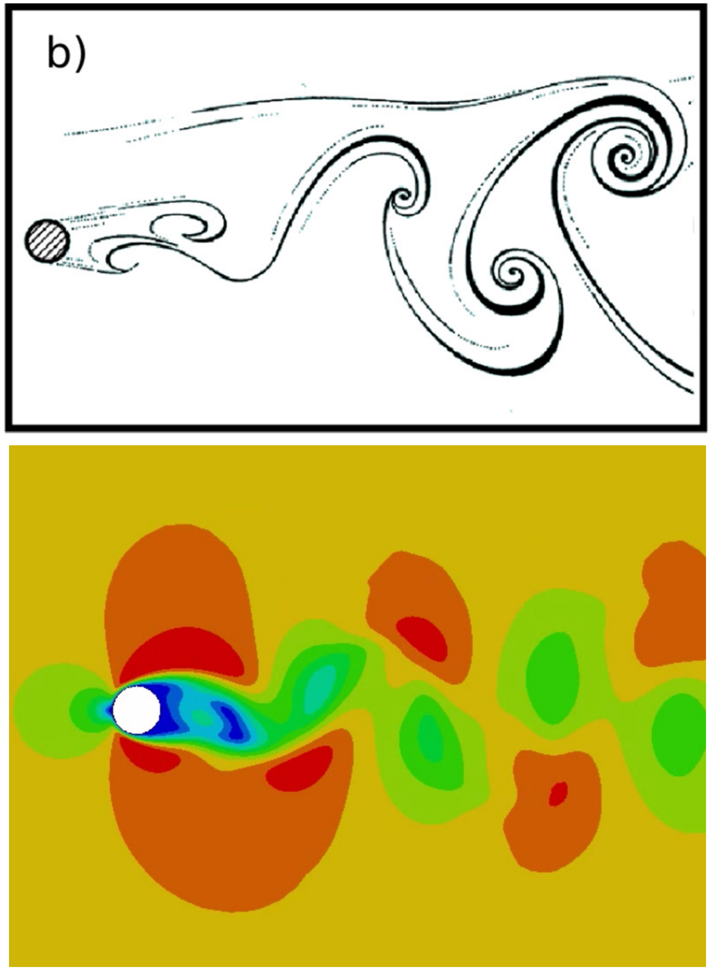
  - Error estimators may be used to trigger adaptive re-meshing



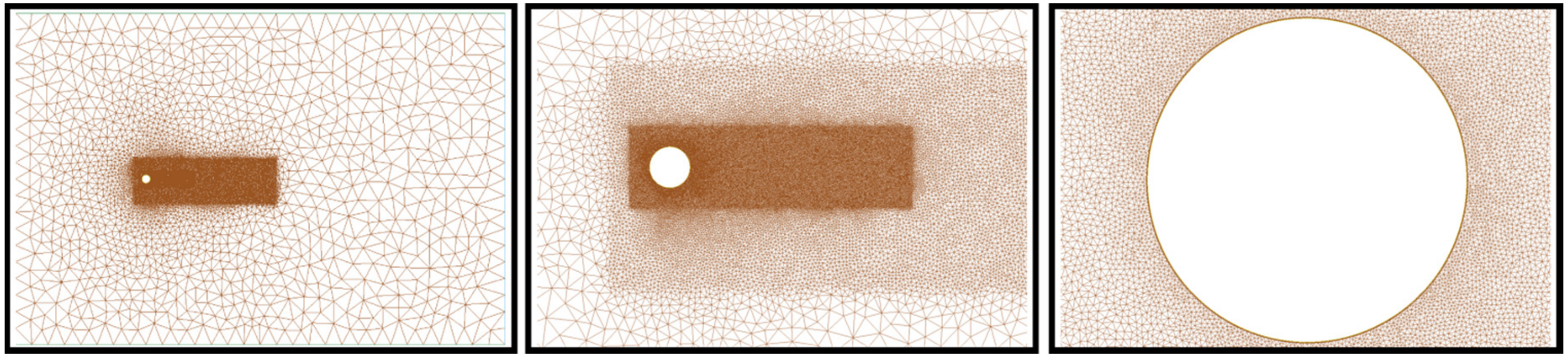
- ICFD Solver Validation
  - Flow around a cylinder
    - Re=40: Symmetric flow separation



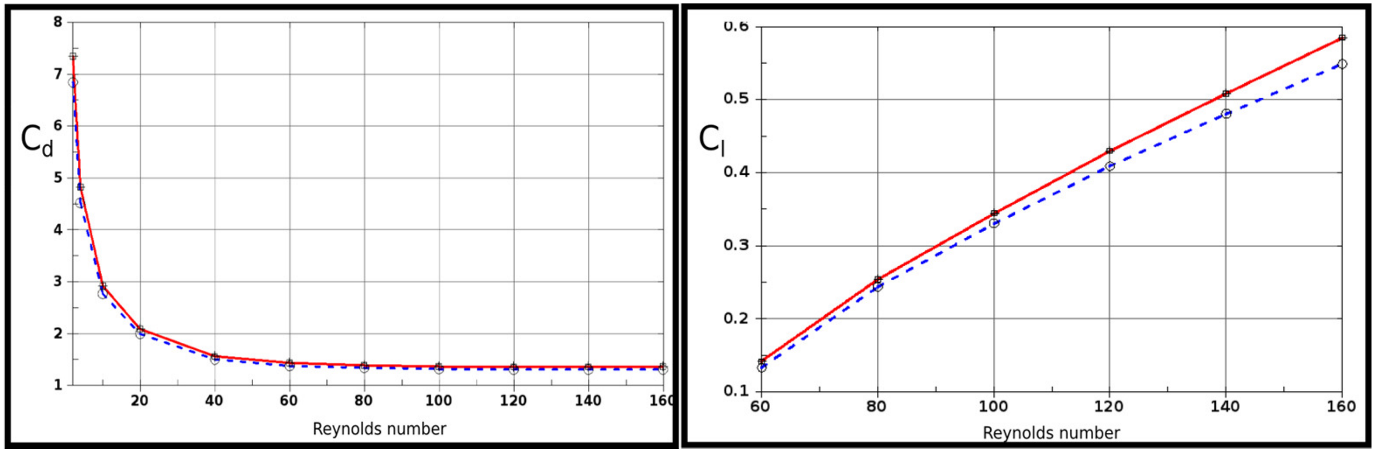
    - Re=100: Von Karman Vortex Street



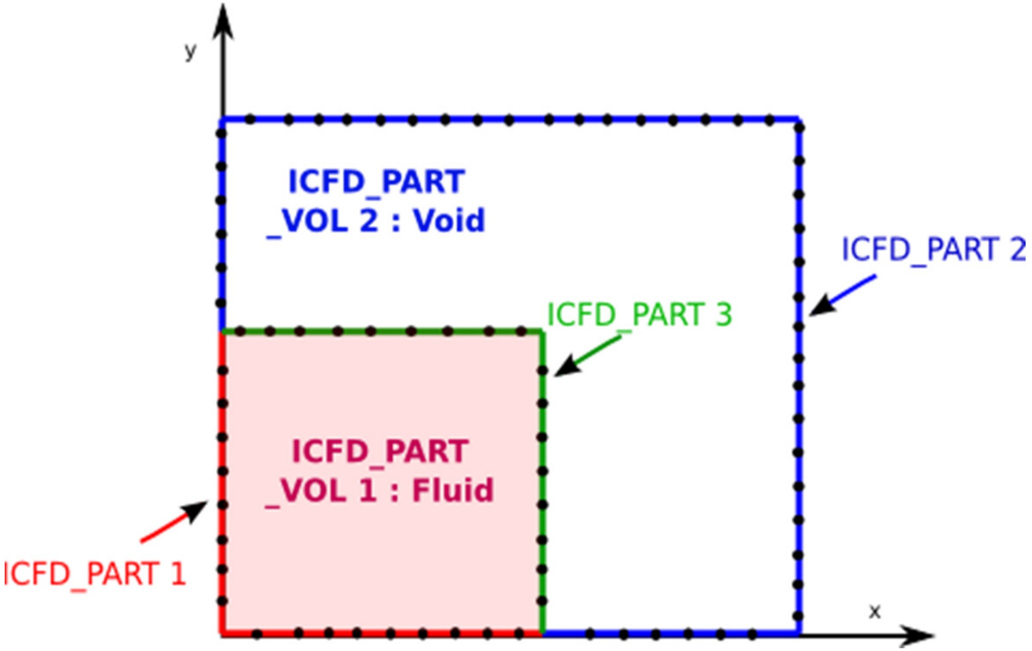
- Mesh used for the simulation
  - Cylinder element size based on a unity Diameter value : 0.01
  - 3 elements added to the Boundary layer
  - 90 0000 elements in total

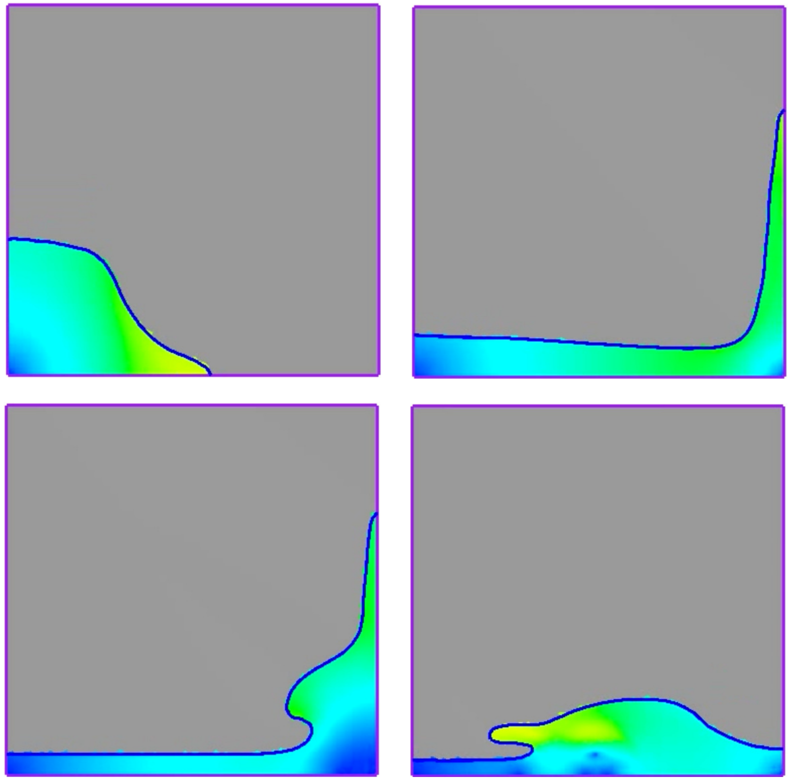


- Comparison of the simulation (red) with experiments (blue)

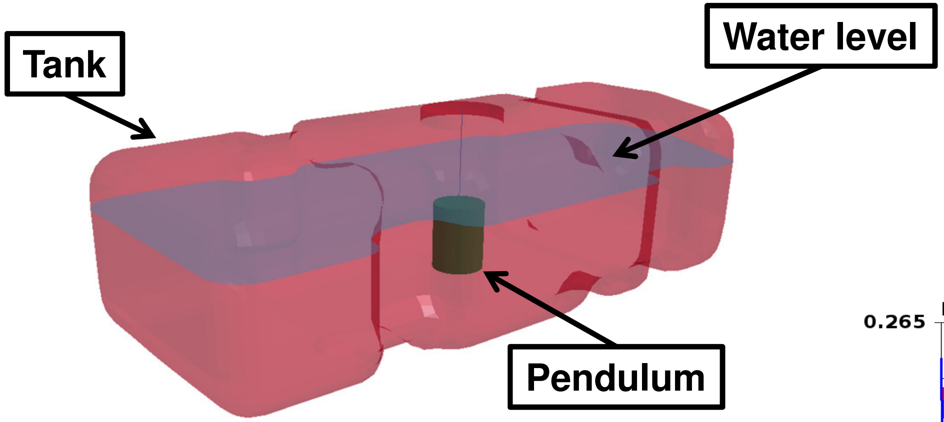


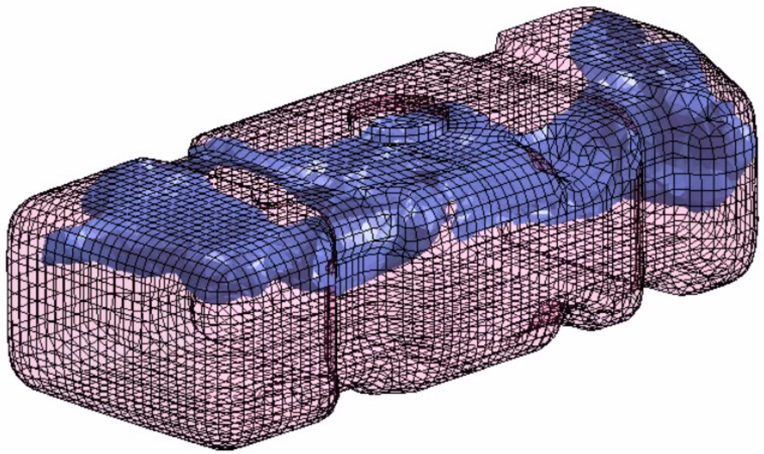
- Level Set Function for Free Surface Problems
  - Interface is defined by a implicit distance function, i.e., the level set function φ
    - Evolution of φ is computed with a convection equation
    - At the interface: $\varphi = 0$
    - Air or Liquid: $\varphi \neq 0$

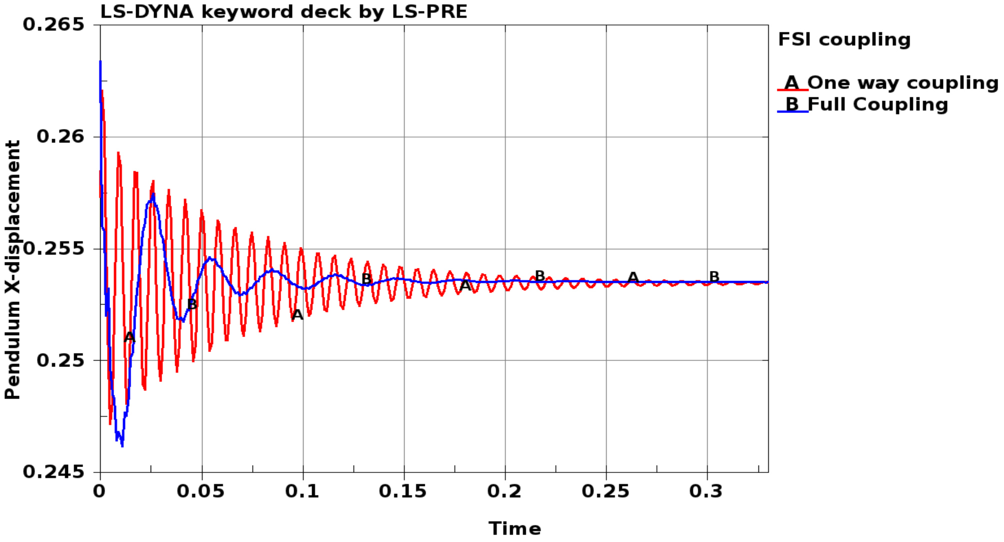




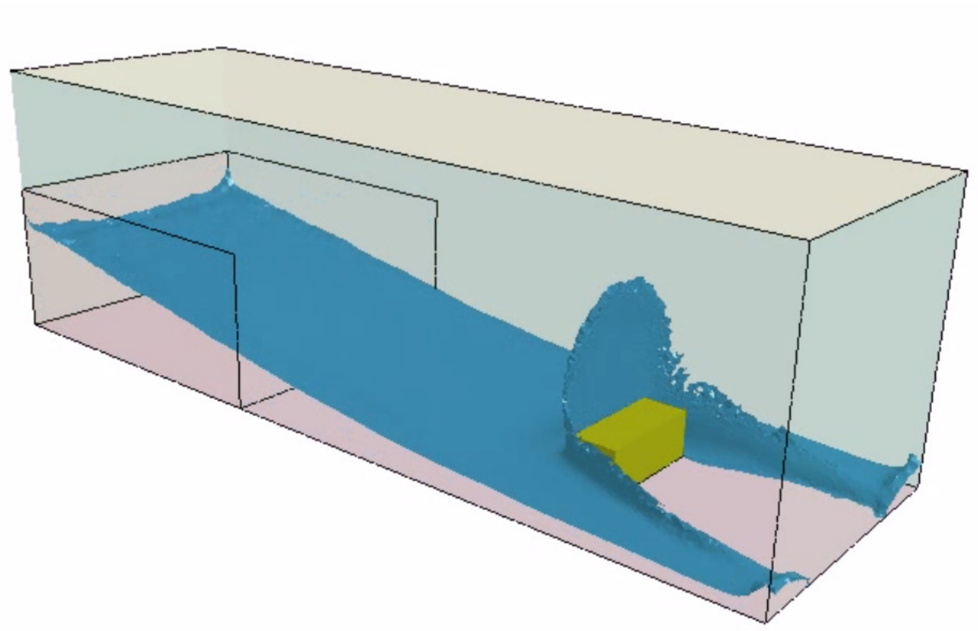
- Sloshing in a Water Tank
  - Moving Water Tank coming to a brutal halt
  - Sloshing occurs
  - Study of pendulum oscillations

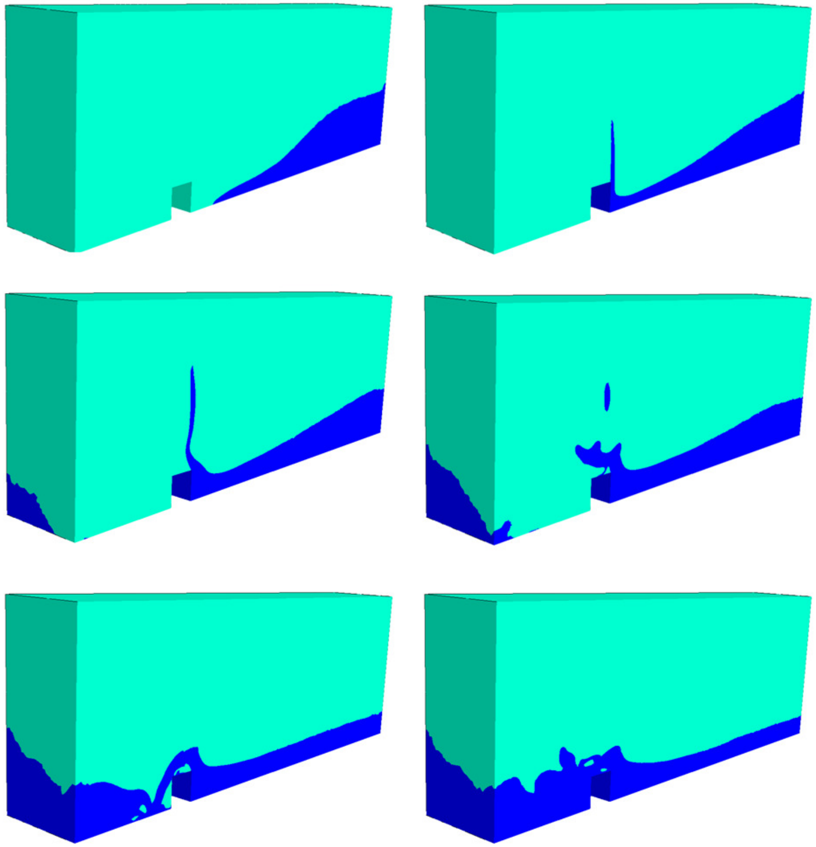




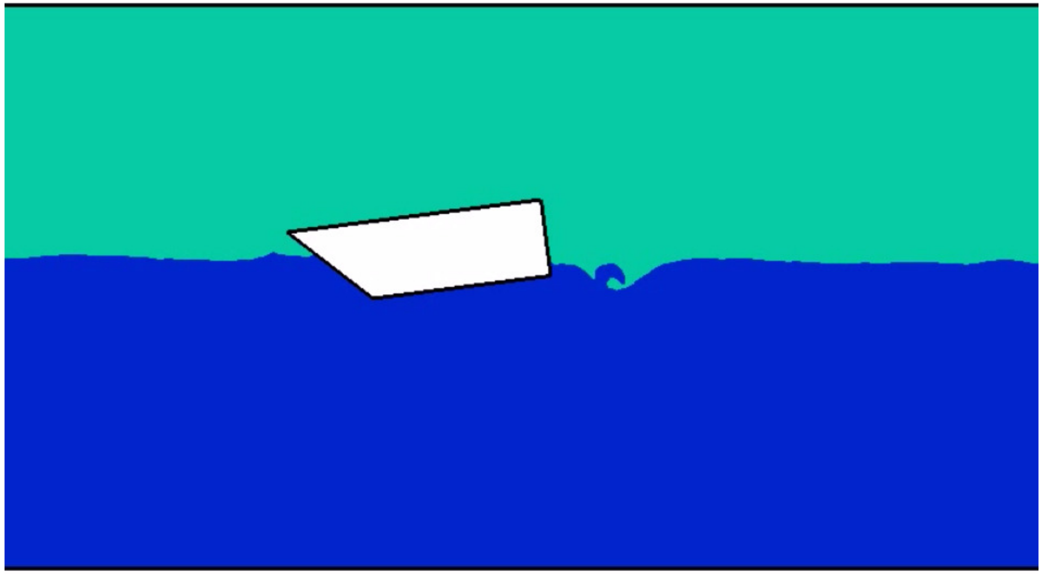


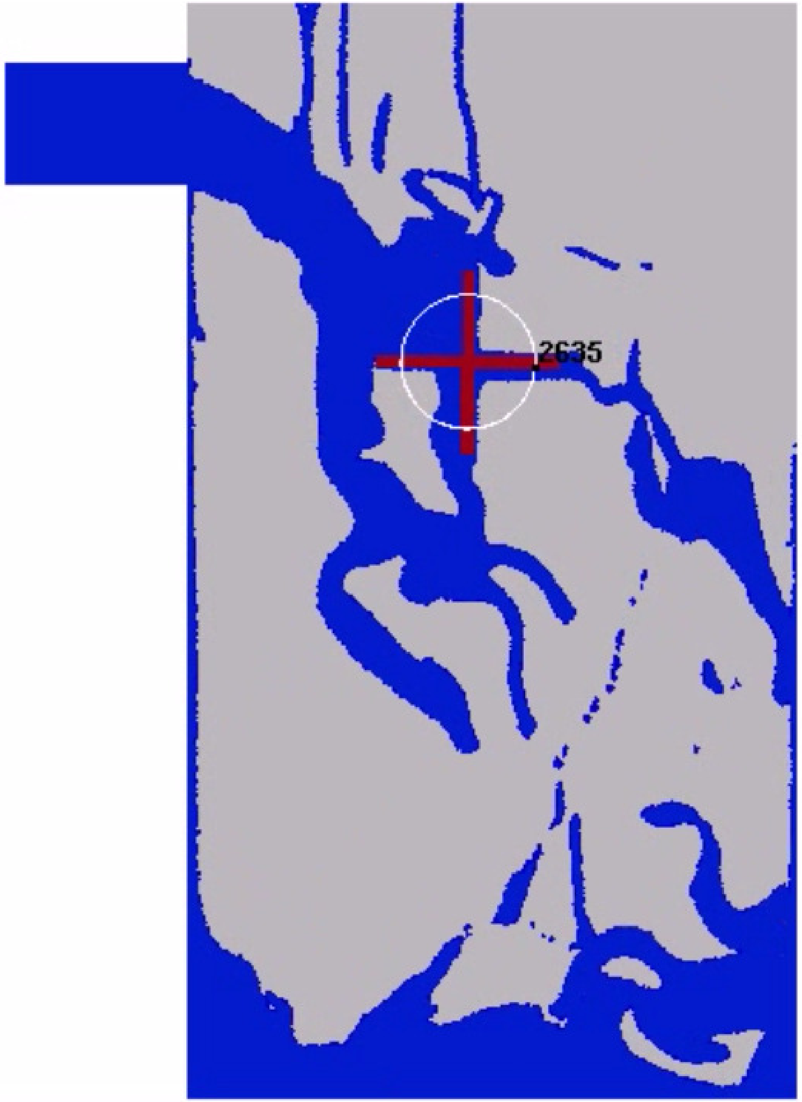
- Wave Impact on a Rectangular-Shaped Box:
  - Used to predict the force of impact on structure
  - The propagation of the wave shape can also be studied
  - Will be used and presented as a validation test case in the short term future





- Source and Sink Problems
  - Complex free-surface problems with
    - Source and sink terms
    - Strong FSI coupling
    - Dynamic remeshing
    - Boundary layer mesh



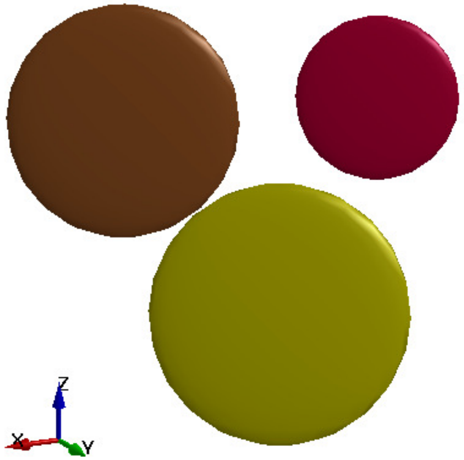


Particle-Structure Interaction

- Definition of the Discrete Elements
  - Particles are approximated with spheres via
    - **`*PART, *SECTION_SOLID`**
    - Coordinate using **`*NODE`** and with a `NID`
    - Radius, Mass, Moment of Inertia

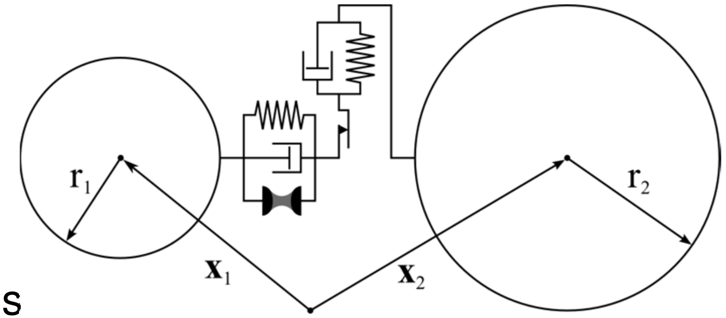
$$M = V\rho = \frac{4}{3}\pi r^3 \rho \qquad I = \frac{2}{5} M r^2 = \frac{8}{15}\pi r^5 \rho$$

  - Density is taken from **`*MAT_ELASTIC`**



```
*ELEMENT_DISCRETE_SPHERE_VOLUME
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$#     NID       PID      MASS   INERTIA     RADII
     30001         4  570.2710  6036.748      5.14
     30002         5  399.0092  3328.938      4.57
     30003         6  139.1240   575.004      3.21
*NODE
$--+---1-------+-------2-------+-------3-------+-------4---+---5---+---6
$#   NID               X               Y               Z      TC      RC
   30001          -29.00           -26.8             8.7       0       0
   30002          -21.00           -24.8            18.2       0       0
   30003          -27.00           -14.7            21.2       0       0
```

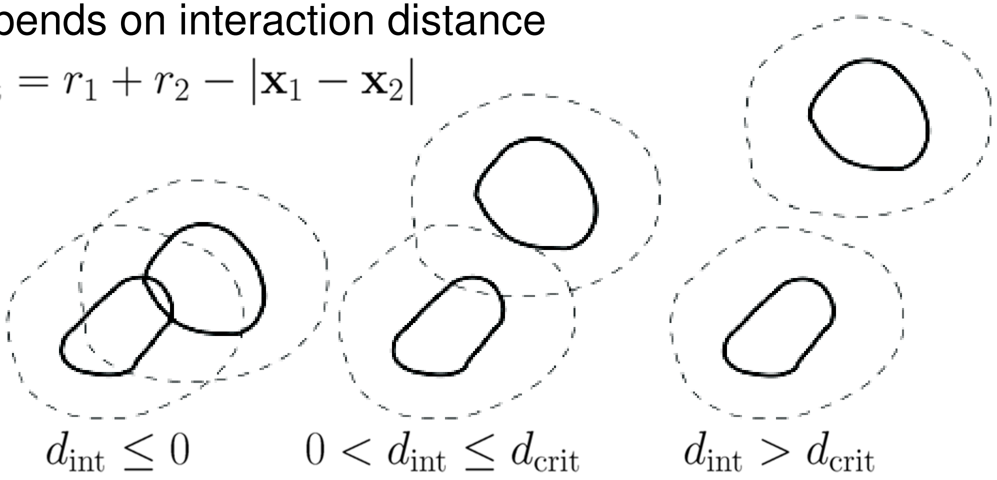
- Definition of the Contact between Particles
  - Mechanical contact
    - Discrete-element formulation according to [*Cundall & Strack* 1979]
  - Extension to model cohesion using capillary forces

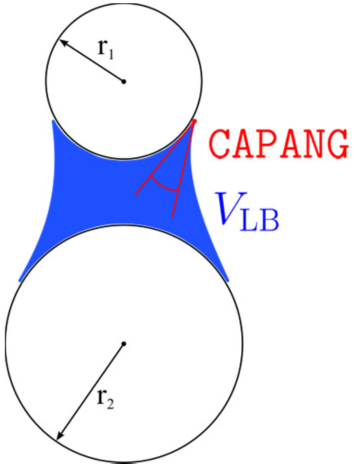


```
*CONTROL_DISCRETE_ELEMENT
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$#    NDAMP     TDAMP      Fric     FricR     NormK    ShearK       CAP     MXNSC
      0.700     0.400      0.41     0.001      0.01    0.0029         0         0
$#    Gamma    CAPVOL    CAPANG
       26.4      0.66       10.0
```

- Possible collision states
  - Depends on interaction distance

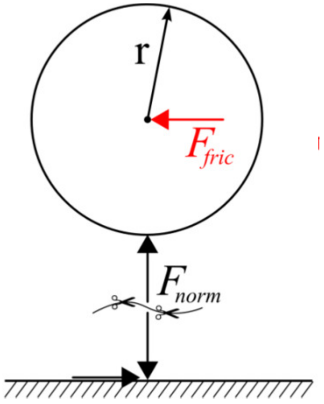
$$d_{\text{int}} = r_1 + r_2 - |\mathbf{x}_1 - \mathbf{x}_2|$$



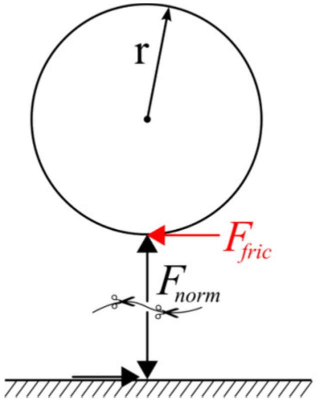


Definition of the Particle-Structure Interaction

- Classical contact: **`*CONTACT_AUTOMATIC_NODES_TO_SURFACE_ID`**
  - Well-proven and tested contact definition
  - Benefits of the contact definition
    - static and dynamic friction coefficients
    - works great with MPP
  - Drawbacks of the contact definition
    - not possible to apply rolling friction
    - friction force is applied to particle center

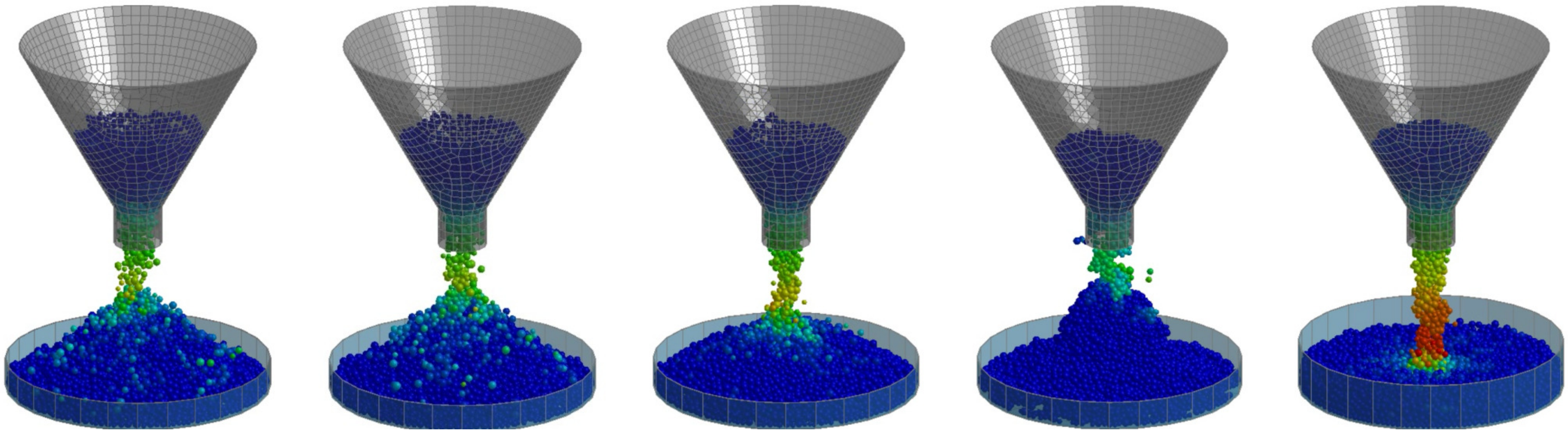


- New contact: **`*DEFINE_DE_TO_SURFACE_COUPLING`**
  - Damping determines if the collision is elastic or “plastic”
  - Benefits of the contact definition
    - static and rolling friction coefficients
    - friction force is applied at the perimeter
    - possibility to define transportation belt velocity
  - Drawbacks of the contact definition
    - sometimes problems with MPP



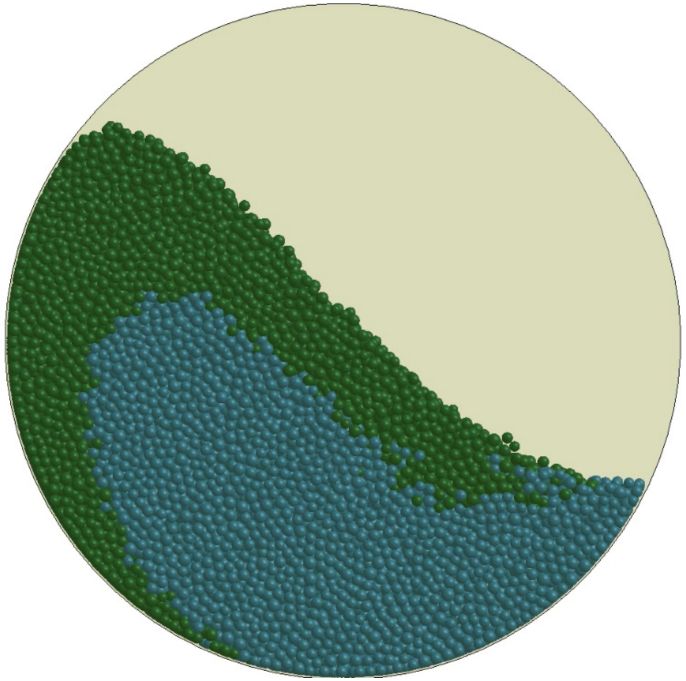
- Funnel Flow
  - Variation of the parameters in
    - **`*CONTROL_DISCRETE_ELEMENT`**
    - **`*DEFINE_DE_TO_SURFACE_COUPLING`**

```
$-------+-------1--------+--------2---------+--------3---------+--------4---------+--------5
RHO        0.80E-6          2.63E-6           2.63E-6           2.63E-6            1.0E-6
P-P Fric      0.57             0.57              0.57              0.10              0.00
P-P FricR     0.10             0.10              0.01              0.01              0.00
P-W FricS     0.27             0.30              0.30              0.10              0.01
P-W FricD     0.01             0.01              0.01              0.01              0.00
CAP              0                0                 1                 1                 1
Gamma         0.00             0.00           7.20E-8           2.00E-6            7.2E-8
$-------+-------1--------+--------2---------+--------3---------+--------4---------+--------5
```

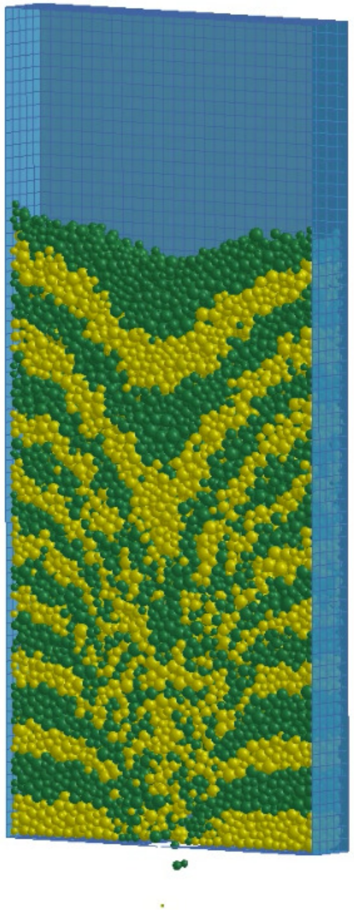


foamed clay dry sand wet sand fresh concrete “water”

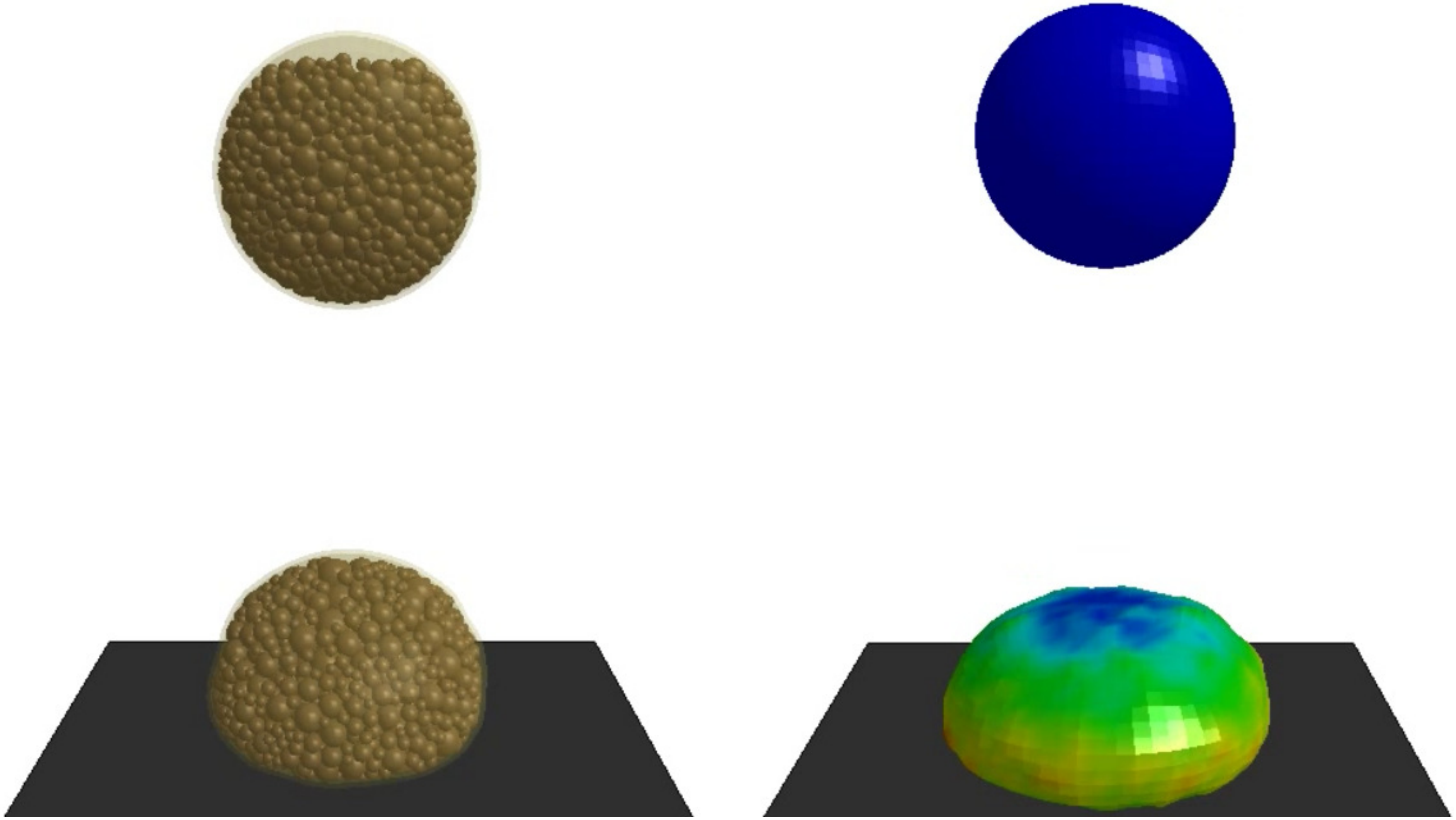
- Drum Mixer
  - 12371 particles with two densities
    - Green: foamed clay
    - Blue: sand



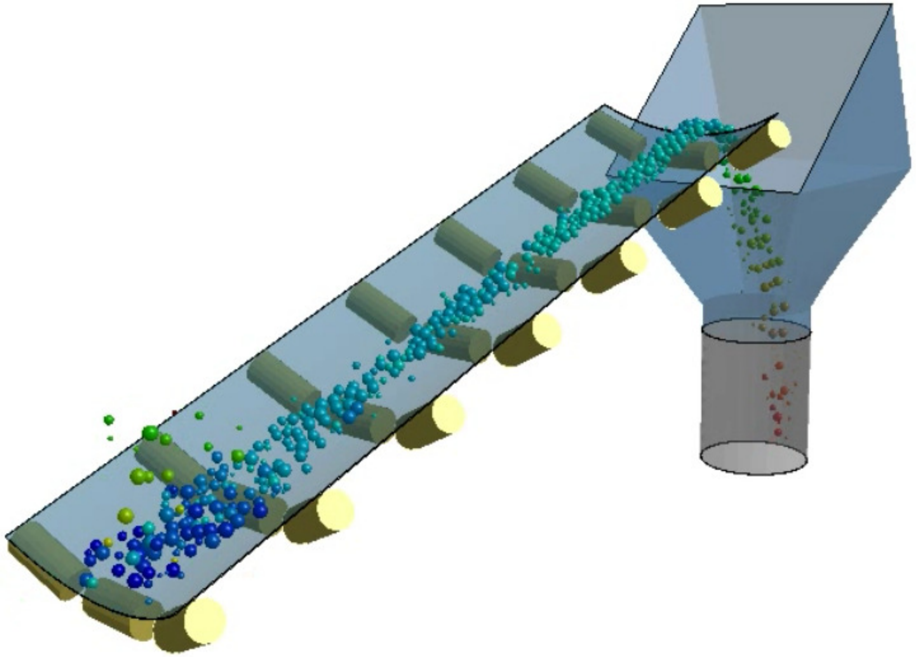
- Hopper Flow
  - 17000 particles of the same kind
    - Radii from 1.5 – 3 mm
    - Static & rolling friction of 0.5



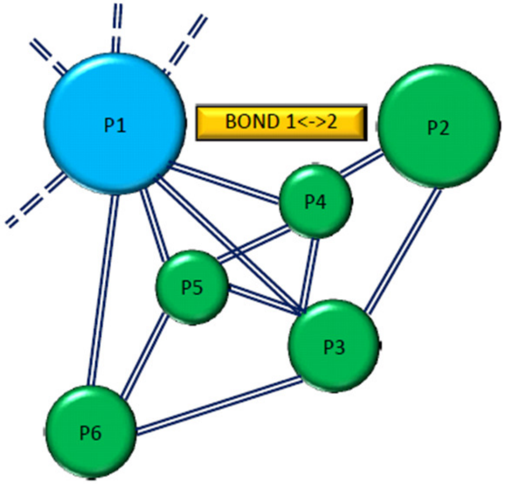
- Large Deformations Demand for a Coupled Solution
  - Drop of a particle-filled ball from 1m above the rigid ground
    - Inside: 1941 particles (dry sand)
    - Outside: 1.8 mm thick visco-elastic latex membrane

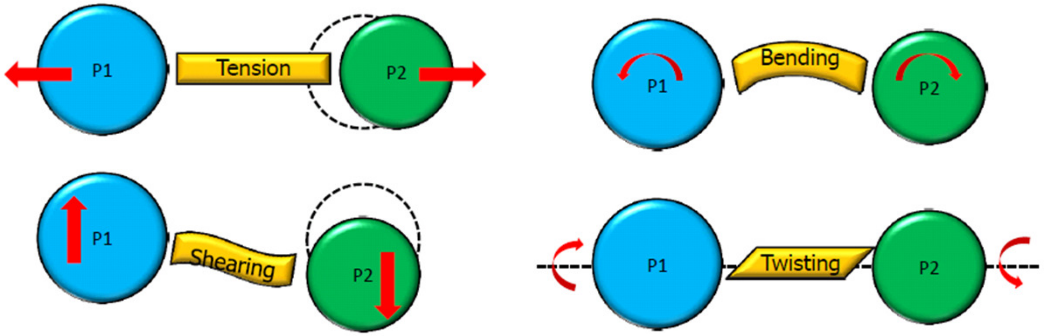


- Bulk Flow Analysis
  - Introduction of a particle source and “sink”
    - **`*DEFINE_DE_INJECTION`**
      - ☐ possibility to prescribe
        - location and rectangular size of the source
        - mass flow rate, initial velocity
        - min. and max. radius
    - **`*DEFINE_DE_ACTIVE_REGION`**
      - ☐ definition via bounding box
- Problem Description
  - Belt conveyor
    - Deformable belt
    - Transport velocity
    - Contact with rigid supports
  - Generated particles
    - Plastic grains



- Introduction of `*DEFINE_DE_BOND`
  - All particles are linked to their neighboring particles through Bonds
  - Bonds represent the complete mechanical behavior of Solid Mechanics
  - Bonds are calculated from the Bulk and Shear Modulus of materials
  - Bonds are independent of the DEM
  - Every bond is subjected to
    - Stretching, bending
    - Shearing, twisting

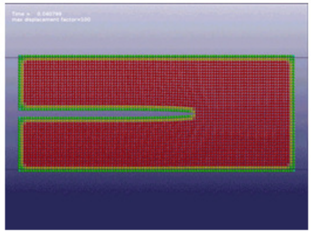




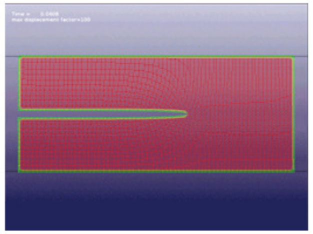
  - The breakage of a bond results in Micro-Damage
    which is controlled by a prescribed critical fracture energy release rate

First Benchmark Test with Different Sphere Diameters

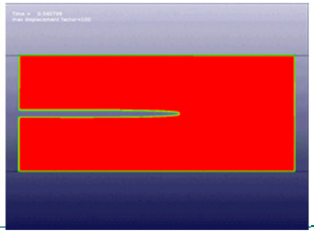
- Pre-notched plate under tension
  - Quasi-static loading
  - Material: Duran 50 glass
  - Density: 2235kg/m^3
  - Young’s modulus: 65GPa
  - Poisson ratio: 0.2
  - Fracture energy release rate: 204 J/m^2
- Case I
  - 4000 spheres r = 0.5 mm
  - Crack growth speed: 2012 m/s
  - Fracture energy: 10.2 mJ



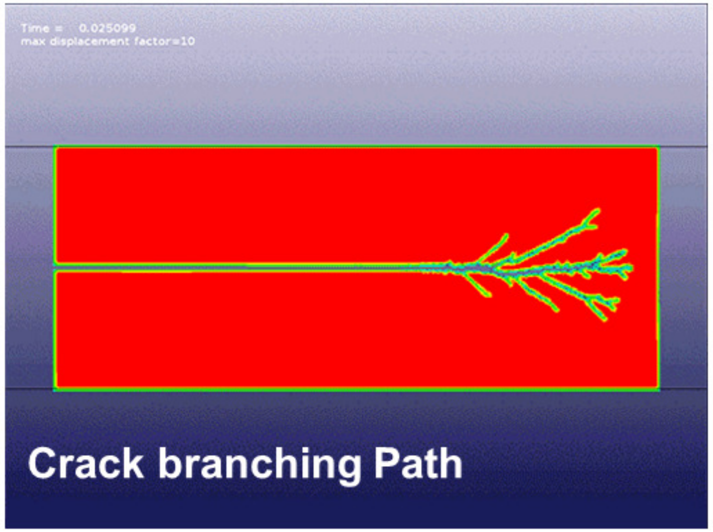
- Case II
  - 16000 spheres r = 0.25 mm
  - Crack growth speed: 2058 m/s
  - Fracture energy: 10.7 mJ

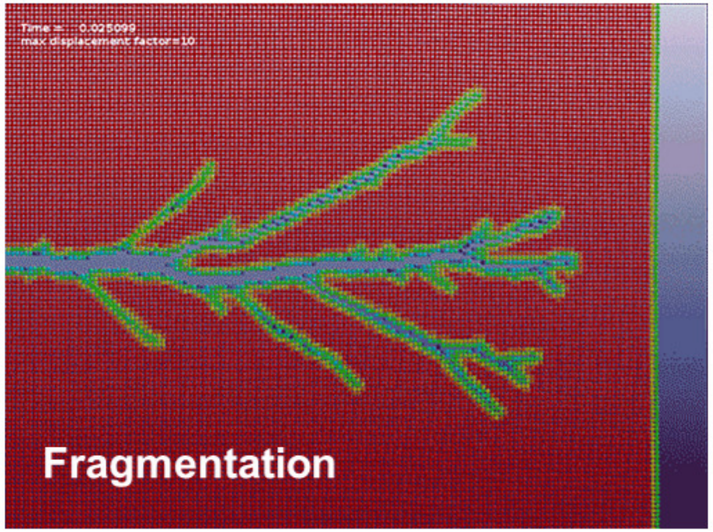


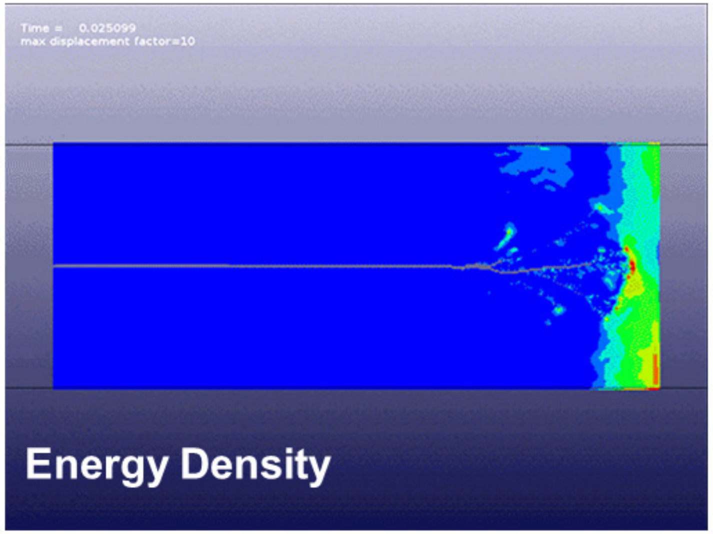
- Case III
  - 64000 spheres r = 0.125 mm
  - Crack growth speed: 2028 m/s
  - Fracture energy: 11.1 mJ

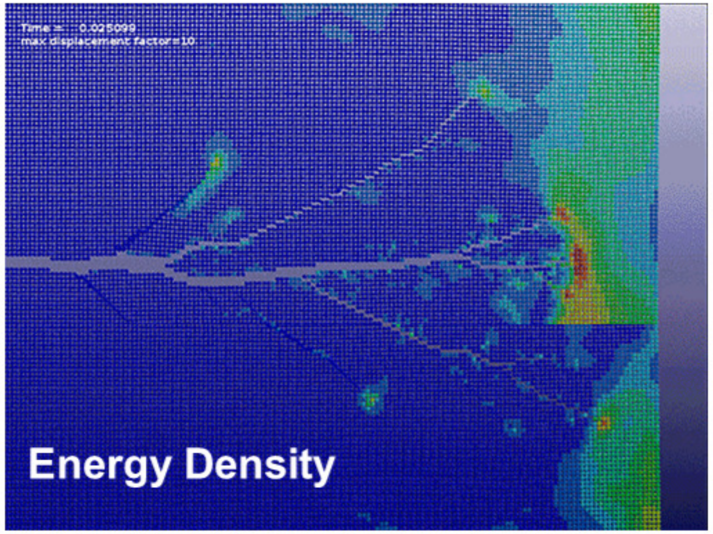


- Fragmentation Analysis with Bonded Particles

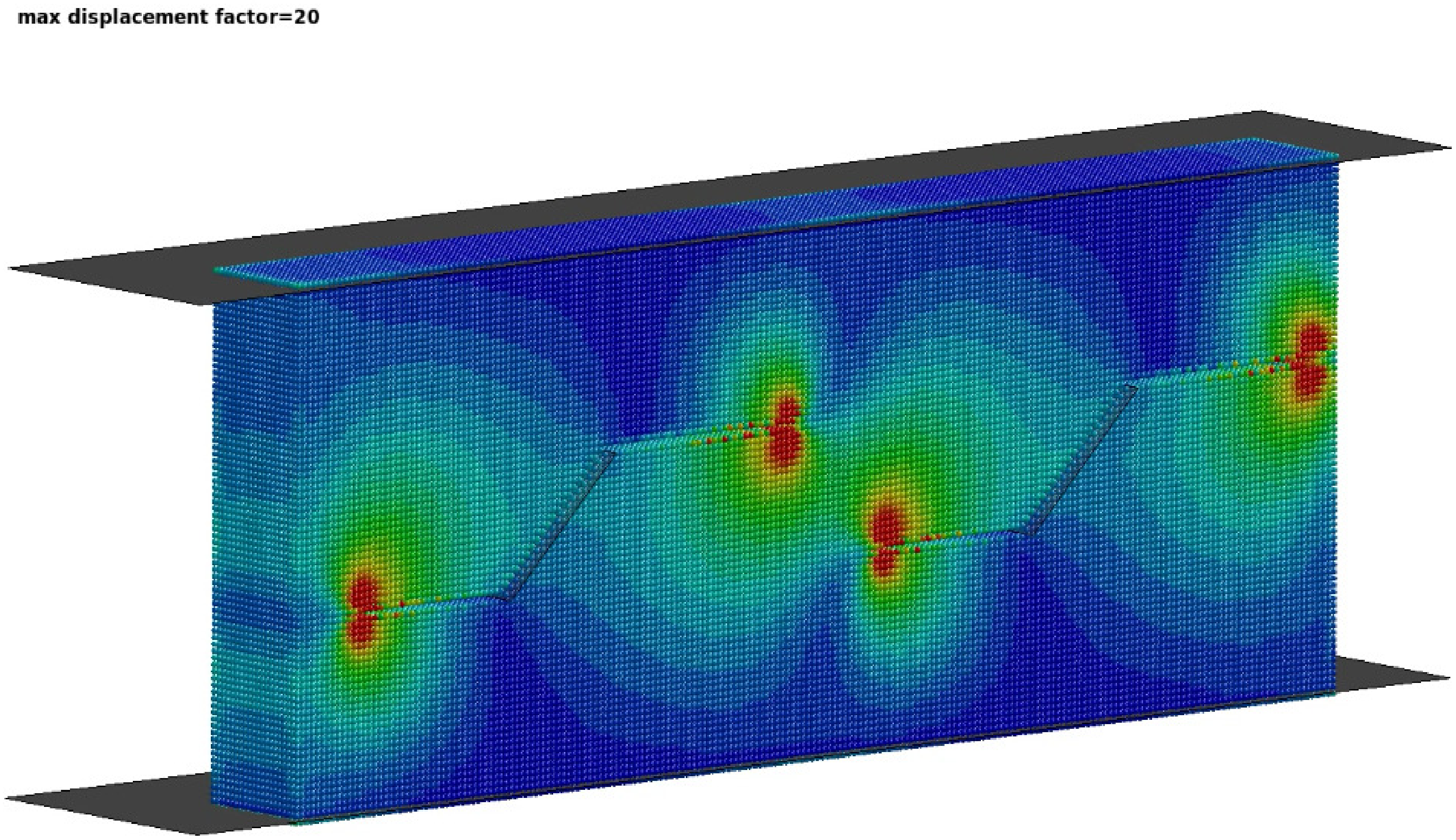






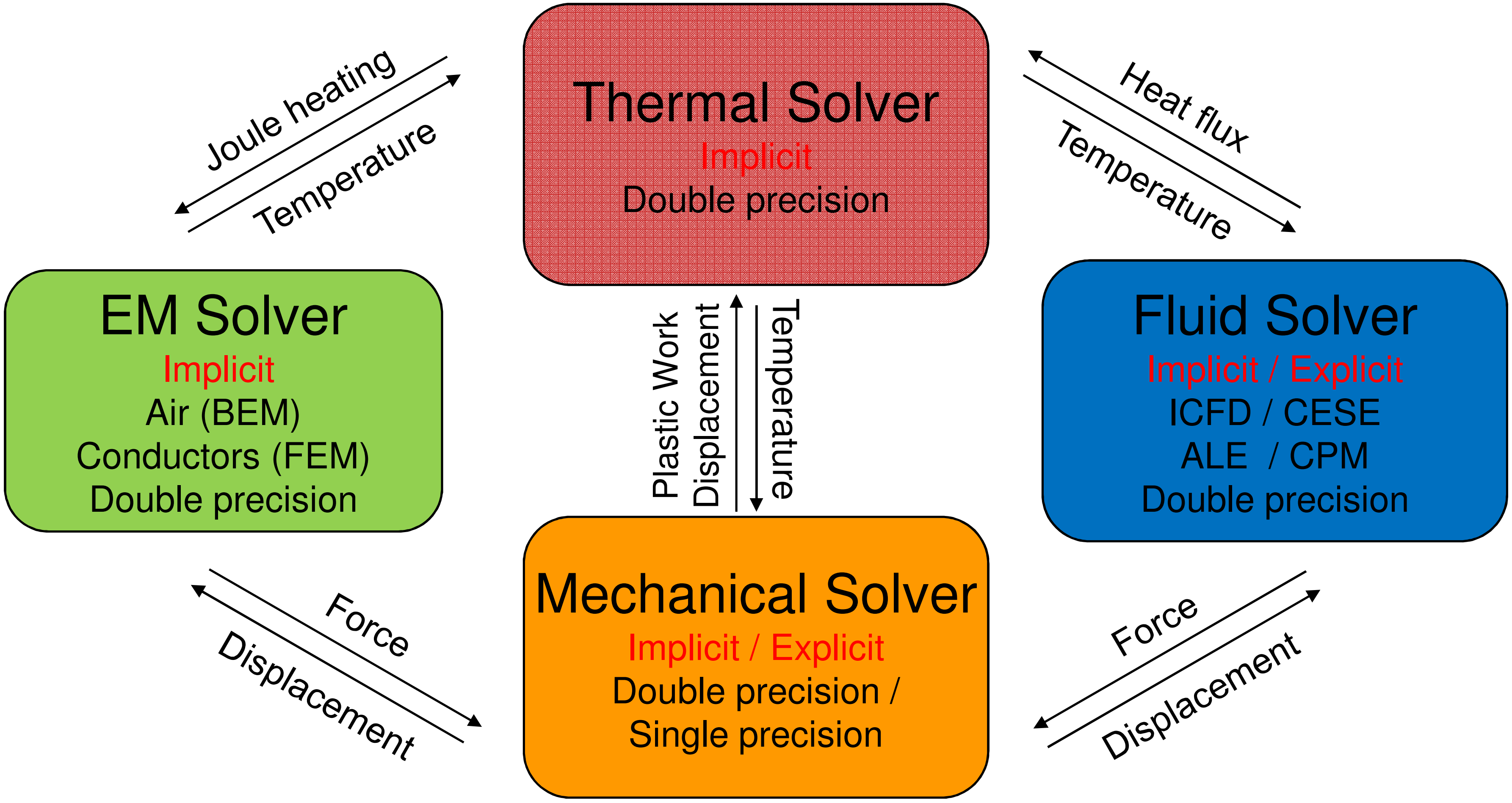


- Pre-Cracked specimen
  - Loading plates via **`*CONTACT_CONSTRAINT_NODES_TO_SURFACE`**
  - Pre-Cracks defined by shell sets



Conclusion

- One Code for Multi-Physics Solutions



Thermal Solver
Implicit
Double precision

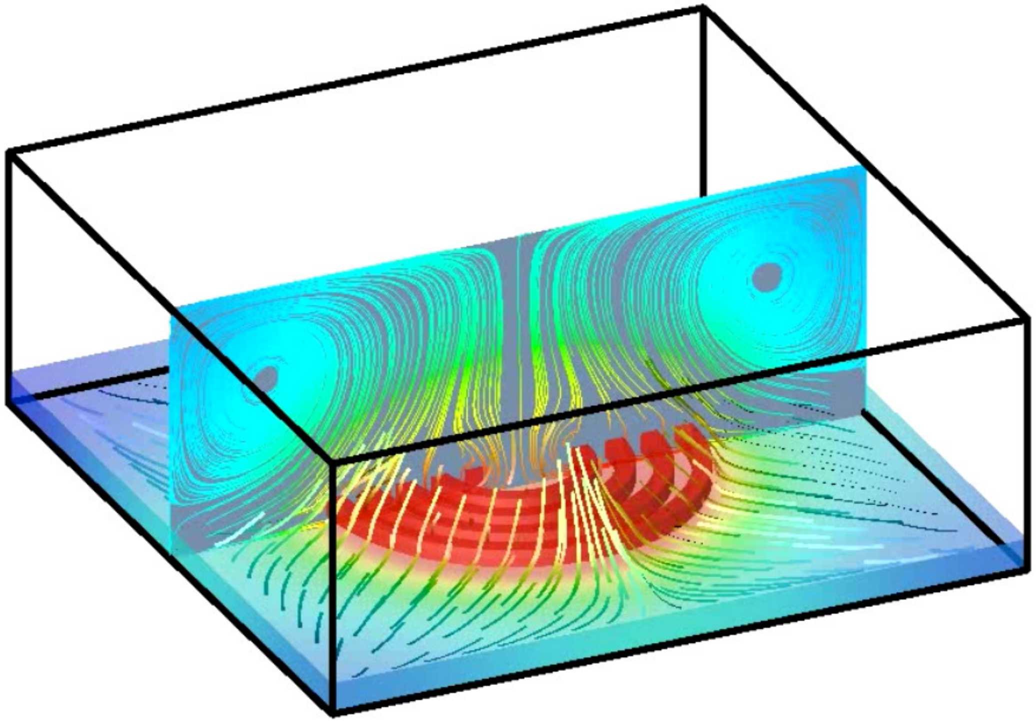
EM Solver
Implicit
Air (BEM)
Conductors (FEM)
Double precision

Fluid Solver
Implicit / Explicit
ICFD / CESE
ALE / CPM
Double precision

Mechanical Solver
Implicit / Explicit
Double precision /
Single precision

Conclusion

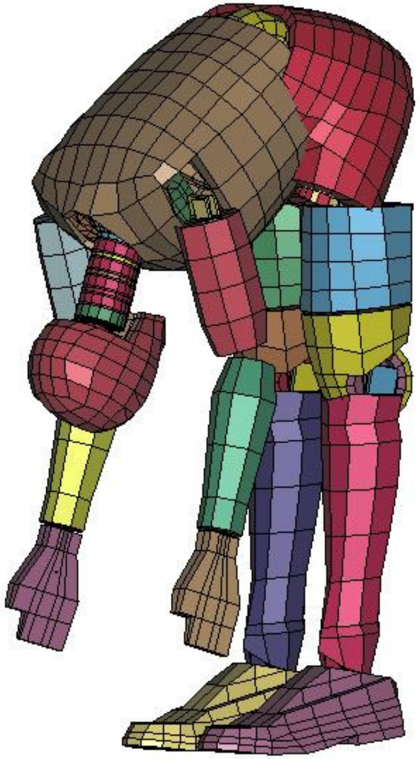
- Finally, LS-DYNA can boil water!



- “Test Drivers” Welcome!
  - Information on EM solver: www.lstc.com/applications/em
  - Information on ICFD solver: www.lstc.com/applications/icfd

Thank you for your attention!

Your LS-DYNA distributor and more



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