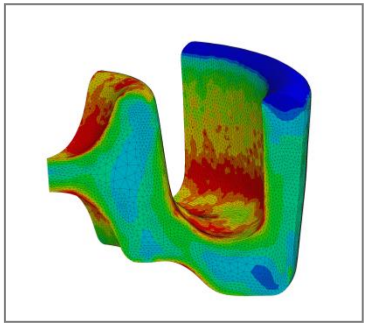

13. LS-DYNA® Forum
6 – 8 October 2014, Bamberg, Germany

Particle Methods in LS-DYNA®

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[3] Predictive Engineering, Portland (USA)

Introduction

- Overview on Meshfree Methods in LS-DYNA

Particle Methods

- Discrete
  - Explicit
    - DEM (Discrete Element Method)
    - CPM (Particle Gas)
- Continuum
  - Explicit Meshfree Collocation
    - SPH (Smoothed Particle Hydrodynamics)
  - Explicit Meshfree Galerkin
    - MLPG (Meshless Local Petrov Galerkin)
    - EFG (Element Free Galerkin)
    - MEFEM (Meshfree Enriched FEM)*
    - SPG (Smoothed Particle Galerkin)*
  - Implicit Meshfree Galerkin
    - EFG (Element Free Galerkin)
    - PFEM (Particle FEM >> ICFD)

*under heavy development

LS-DYNA Application Range for the Discrete Meshfree Methods

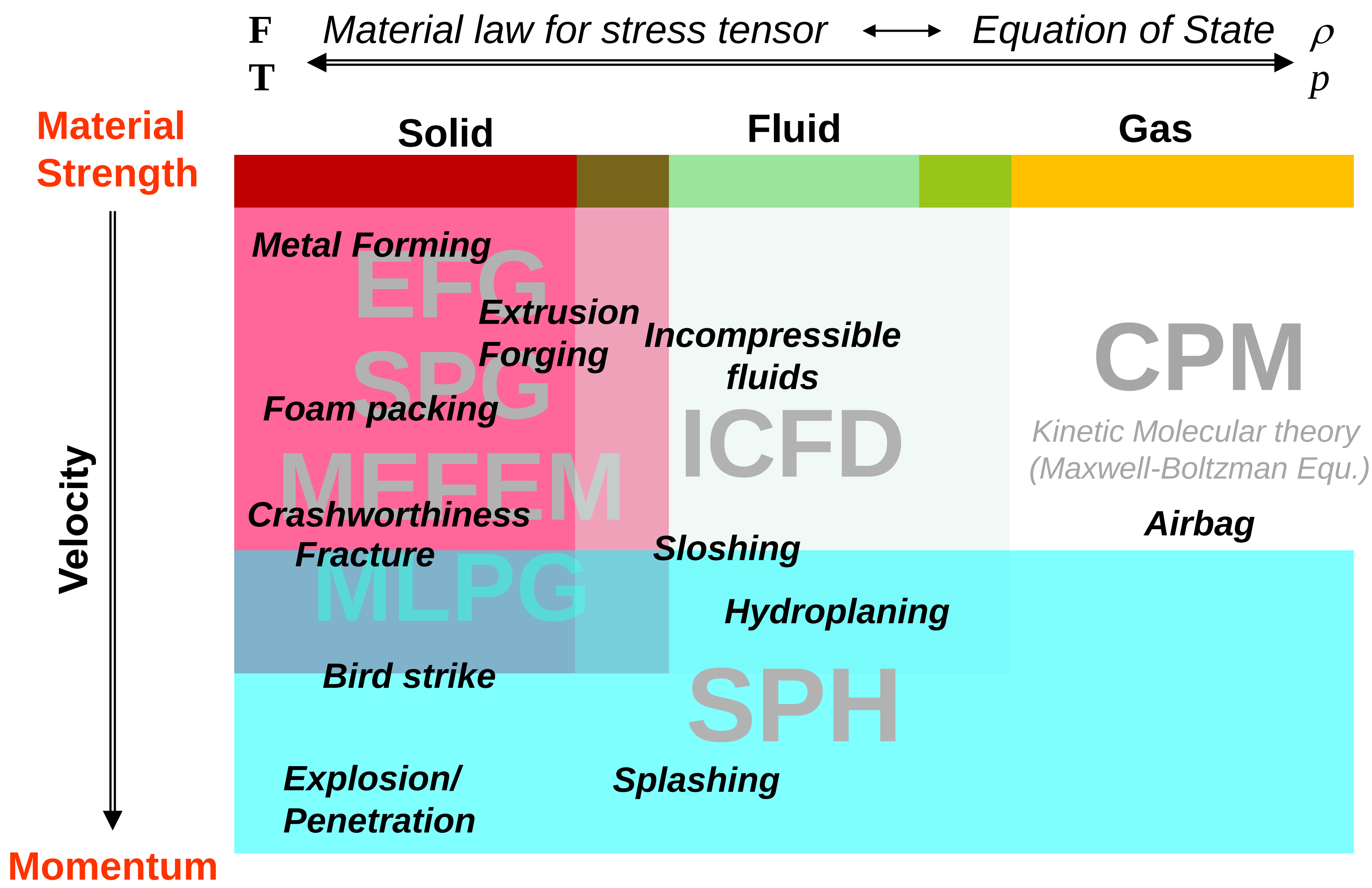
- Granular materials with internal friction
- Solid-like behavior when compacted
  - Static friction law not violated
  - Load carried by grain-to-grain contact
- Fluid-like behavior when in motion
  - Static friction law is violated
  - Motion induced by rolling/slipping

- Typical application for granular media
  - Storage
    - Silos, Piles
  - Transportation
    - Conveyor belts, screws, Pumps
  - Processing
    - Sorting, Mixing, Segregation
  - Filling
    - Hopper/ funnel flow
  - Mine Blast

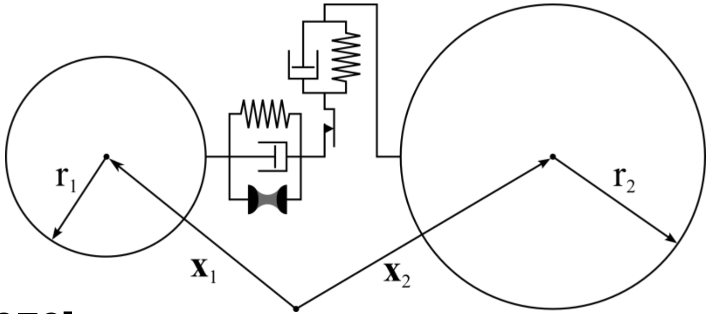
[The 2005 La Conchita Landslide]

[*Wiese Förderelemente GmbH*]

LS-DYNA Application Range for Continuum Meshfree Methods

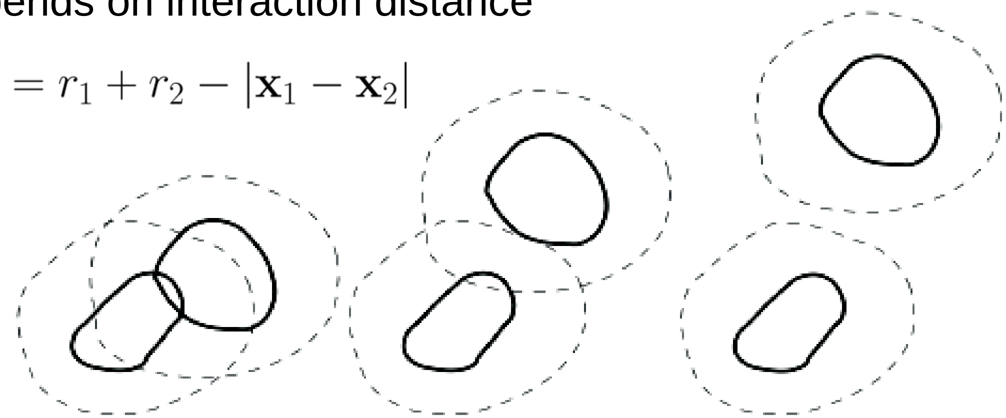


The Discrete-Element Method (DEM)

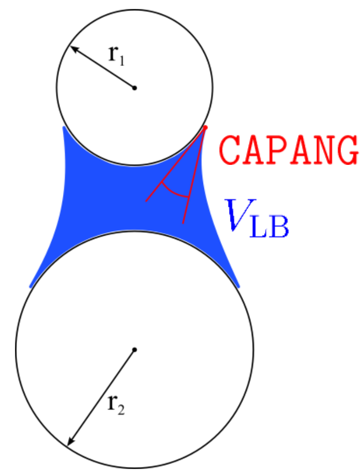


- Basic Ideas
  - Newtonian mechanics of a set of particles
- Definition of the Contact Between Particles
  - Mechanical penalty contact
    - Discrete-element formulation [*Cundall & Strack* 1979]
  - Extension to model cohesion using capillary forces
    - Idea of a liquid bridge with fixed volume [*Rabinovich* et al. 2005]
  - Possible collision states
    - Depends on interaction distance

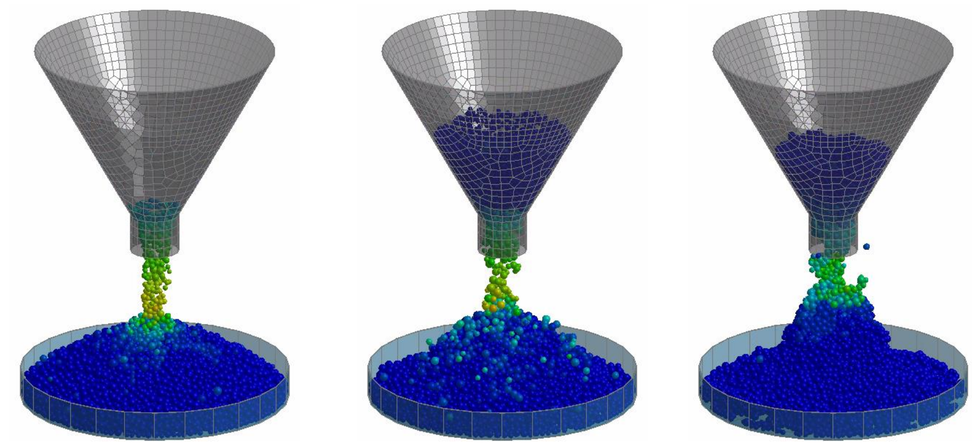
$$d_{\text{int}} = r_1 + r_2 - |\mathbf{x}_1 - \mathbf{x}_2|$$



$d_{\text{int}} \leq 0$ $\quad 0 < d_{\text{int}} \leq d_{\text{crit}}$ $\quad d_{\text{int}} > d_{\text{crit}}$

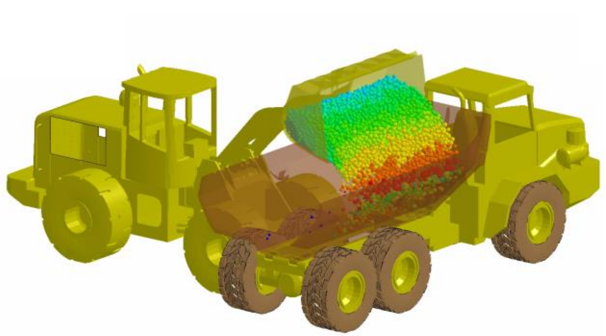


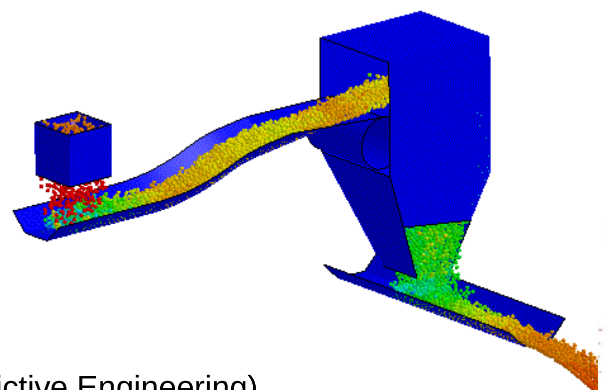
- Filling of dry / wet sand and mud
  - Robust interaction of particles with deformable / rigid structures

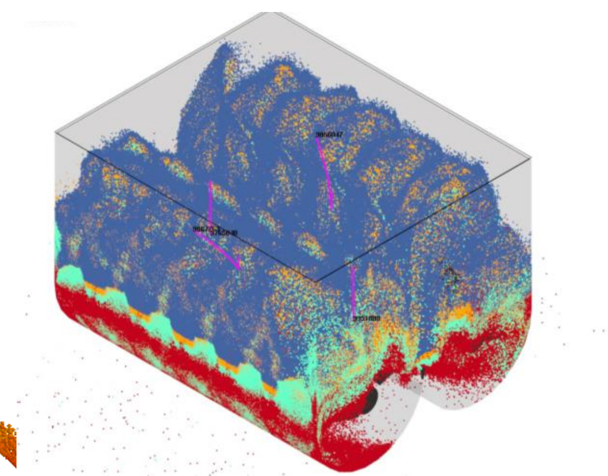


dry sand   wet sand   mud

- Good parallel scalability

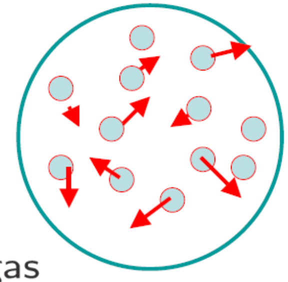






Courtesy Kirk Fraser (Predictive Engineering)

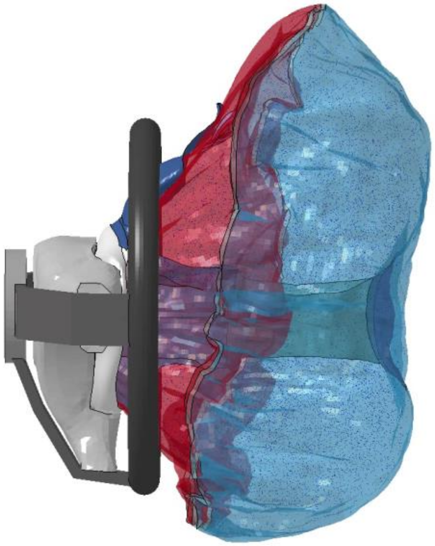
The Corpuscular Method (CPM)



- Basic Ideas
  - Based on the Kinetic Molecular Equations (Maxwell-Boltzman)
  - Reproduces the ideal gas law

$$V_{\mathrm{rms}} = \sqrt{\frac{1}{2} \sum v_i^2} \qquad V_{\mathrm{rms}}^2 = \frac{3\,R\,T}{M} \quad \text{where} \quad M: \text{Molar mass of the gas}$$

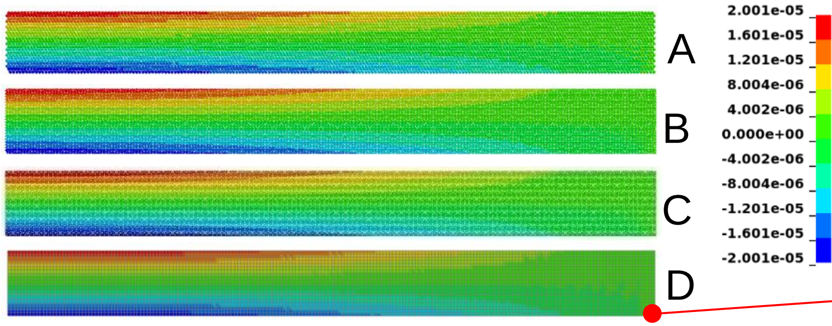
- Fluid-Structure Interaction for airbags

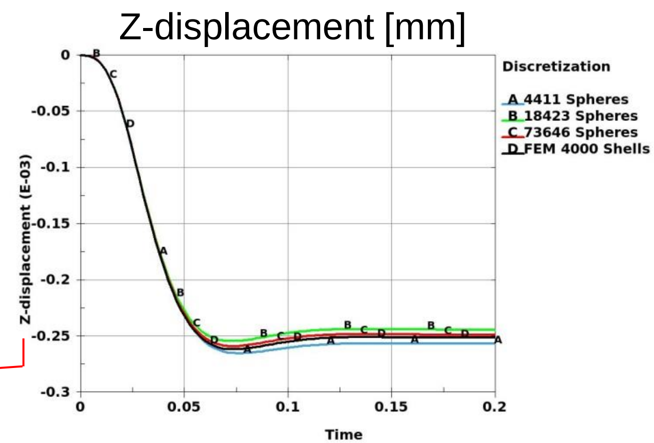


Courtesy of Daimler AG

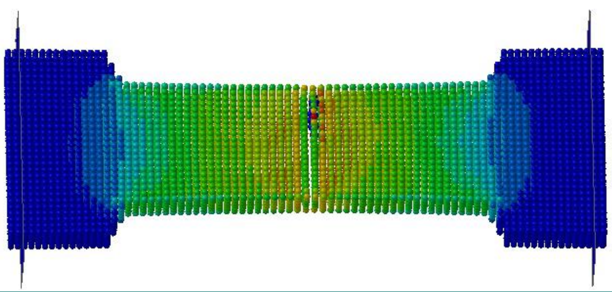
Meshless Local Petrov-Galerkin (MLPG)

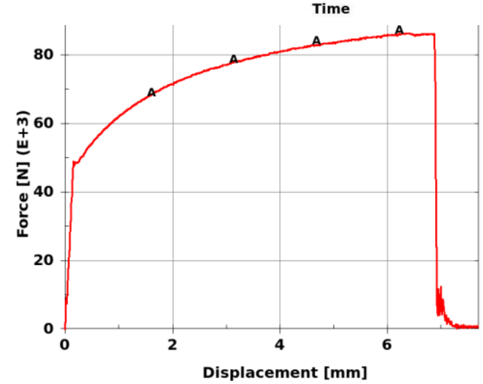
- Idea of Bonds Between Discrete Elements
  - Automatic definition of heterogeneous bonds: bondform=2
    - Based on continuum material models
  - Benchmark test: Beam under gravity loading
    - Goal: Reproduce linear-elastic material behavior



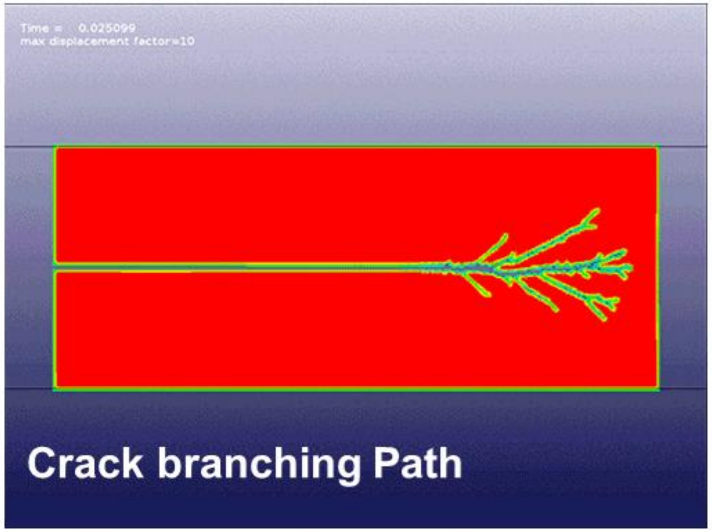


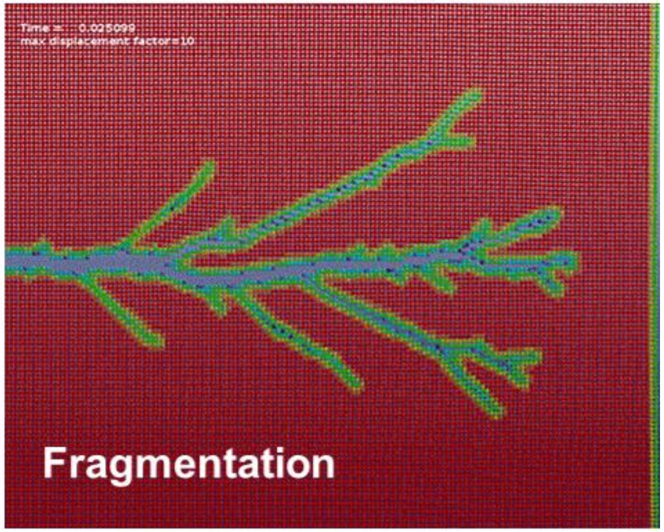
  - Benchmark test: Tension bar
    - Goal: Reproduce elasto-plastic material behavior

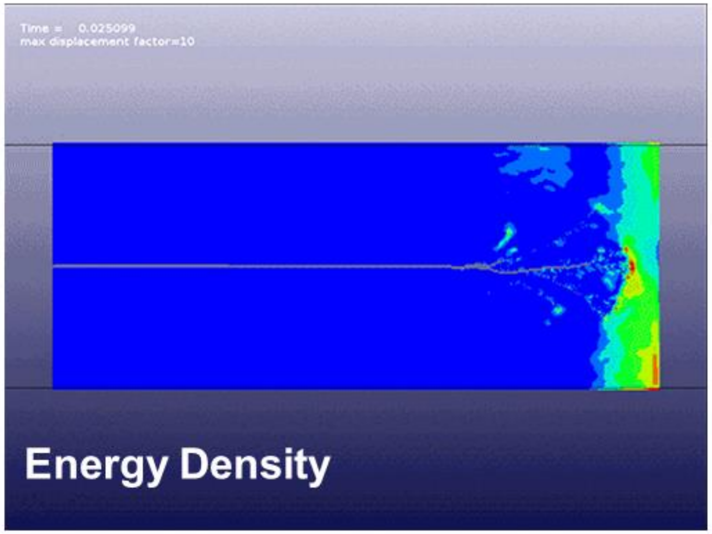


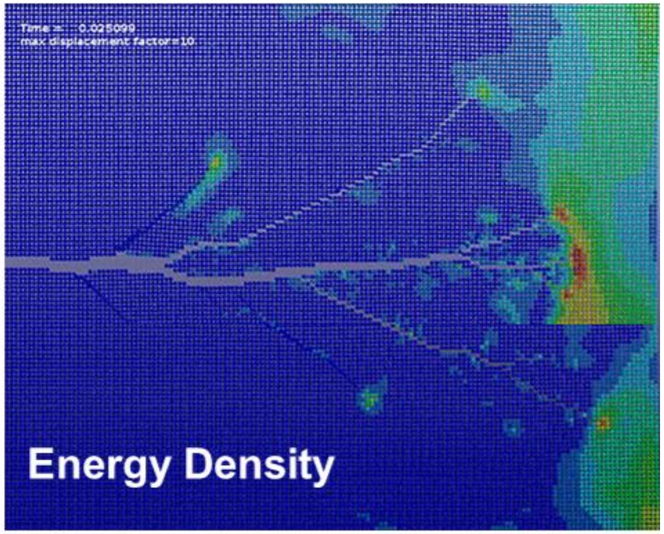


■ Fragmentation Analysis with MLPG (bonded particles)

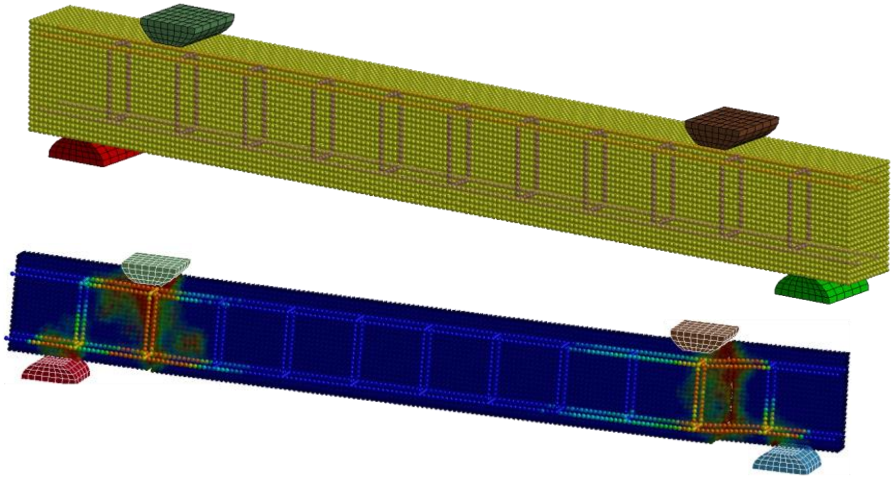


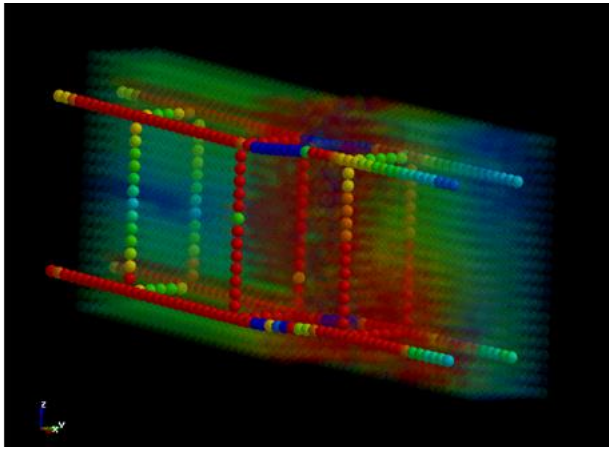


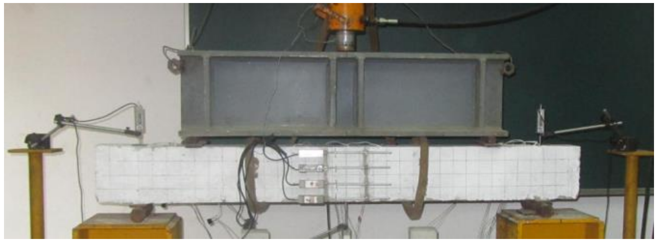


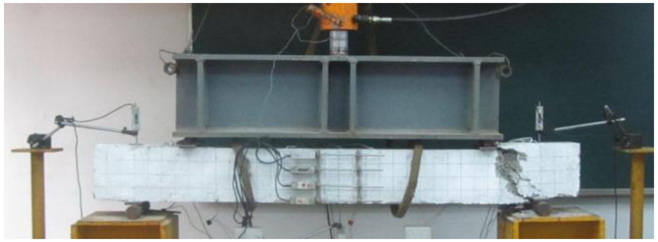


- Application for heterogeneous bond model
  - Failure of a reinforced concrete beam under 4-point bending
    - Possibility to distinguish between reinforcement bars and concrete

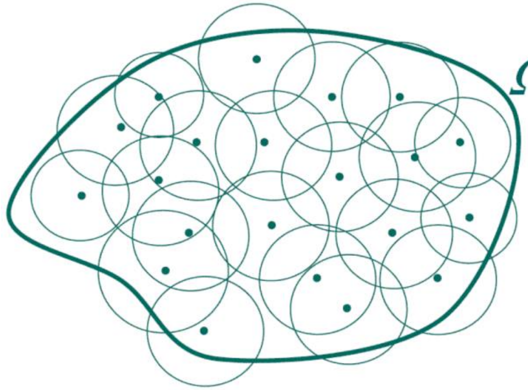








Smoothed-Particle Hydrodynamics (SPH)



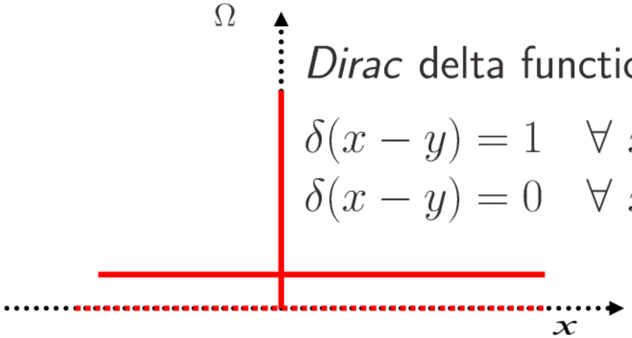
- Basic ideas
  - Replace the continuum by a set of particles
  - Construction of shape functions without a mesh [*Lucy* 1977, *Gingold & Monaghan* 1977, *Liu* 2003]
- Integral interpolant as approximation function
  - Exploitation of the identities

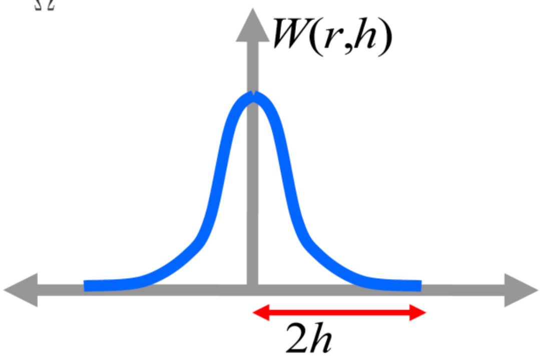
$$u(x) = \int_\Omega u(y)\, \delta(x-y)\, \mathrm{d}y \qquad < u(x) > = \int_\Omega u(r)\, W(r,\, h)\, \mathrm{d}r$$

with: $$\int_\Omega \delta(x-y)\, \mathrm{d}y = 1 \qquad$$ with: $$\int_\Omega W(r,h)\, \mathrm{d}r = 1$$

Dirac delta function δ

$$\delta(x-y) = 1 \quad \forall\ x = y$$
$$\delta(x-y) = 0 \quad \forall\ x \neq y$$

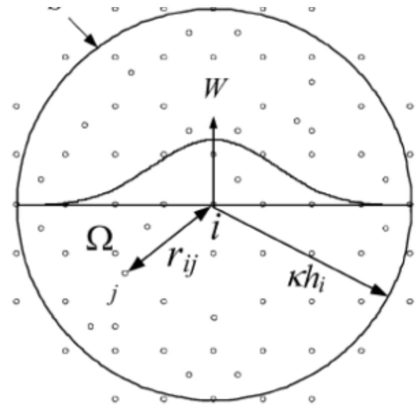




Approximation of the displacement/velocity

$$u_\alpha^h(\mathbf{x}_i) = \sum_j \frac{m_j}{\rho_j} u_\alpha(\mathbf{x}_j)\, W_{ij} \quad \text{with} \quad \mathbf{u}^h = u_\alpha^h\, \mathbf{e}_\alpha \quad \forall\, \alpha = 1,2,3$$

$$\text{with} \quad W_{ij} = W_i(r_{ij}, h_i) = \frac{1}{h_i^3}\,\Theta\left(\frac{r_{ij}}{h_i}\right) \quad \begin{cases} r_{ij} = |\mathbf{x}_i - \mathbf{x}_j| \\ 2h_i : \text{smoothing length} \\ m_i : \text{particle mass} \\ \rho_i : \text{density} \end{cases}$$

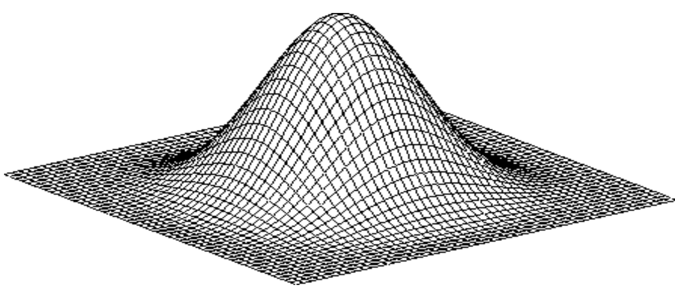


Approximation of the displacement/velocity gradient

$$\text{grad}\, \mathbf{u}^h(\mathbf{x}_i) = \frac{\mathrm{d}u_\alpha^h(\mathbf{x}_i)}{\mathrm{d}x_\beta} = \sum_j \frac{m_j}{\rho_j} \left[u_\alpha(\mathbf{x}_j)\, W_{ij,\beta} - u_\alpha(\mathbf{x}_i)\, W_{ji,\beta} \right]$$

$$\text{with} \quad W_{ij,\beta}(r_{ij}, h_i) = \frac{1}{h_i^4}\, \frac{\mathrm{d}}{\mathrm{d}x_\beta} \Theta\left(\frac{r_{ij}}{h_i}\right)$$

Kernel function θ



- Available formulations with/without normalization
  - Standard formulation
  - Symmetric formulation
  - Fluid formulation

Collocation method

- Kernel approximation of the strong form

Strong Form

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho \,\mathrm{div}\, \mathbf{v}$$

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \frac{1}{\rho} \,\mathrm{div}\, \mathbf{T}$$

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = \frac{1}{\rho} \mathbf{T} \cdot \mathrm{grad}\, \mathbf{v}$$

Kernel approximation →

"Weak Form"

$$\frac{\mathrm{d}\rho_i}{\mathrm{d}t} = -\rho_i \sum_j \frac{m_j}{\rho_j} \left[v_\alpha(\mathbf{x}_j) - v_\alpha(\mathbf{x}_i) \right] W_{ij,\beta}$$

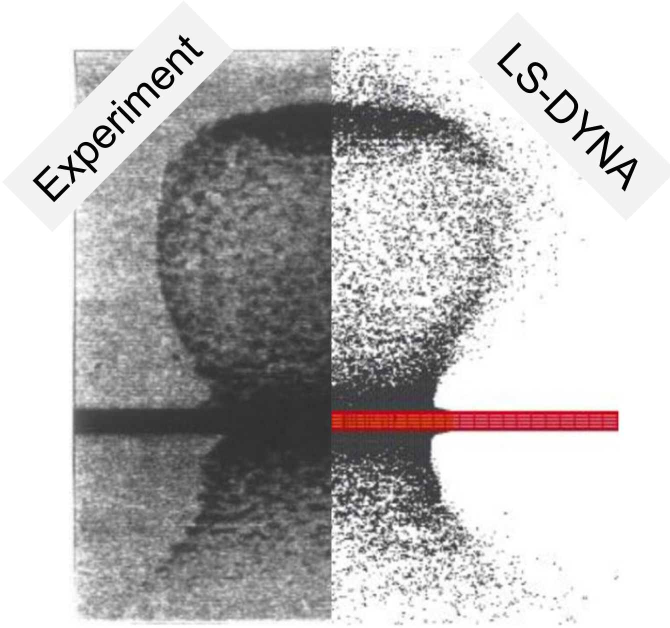
with
$$\begin{cases} \mathbf{v} = v_\alpha \,\mathbf{e}_\alpha \quad \forall\, \alpha = 1,2,3 \\ \rho_i = \rho(\mathbf{x}_i) = \sum_j m_j W_{ij} \end{cases}$$

$$\frac{\mathrm{d}v_\alpha(\mathbf{x}_i)}{\mathrm{d}t} = \sum_j m_j \left[\frac{t_{\alpha\beta}(\mathbf{x}_j)}{\rho_j^2} W_{ji,\beta} - \frac{t_{\alpha\beta}(\mathbf{x}_i)}{\rho_i^2} W_{ij,\beta} \right]$$

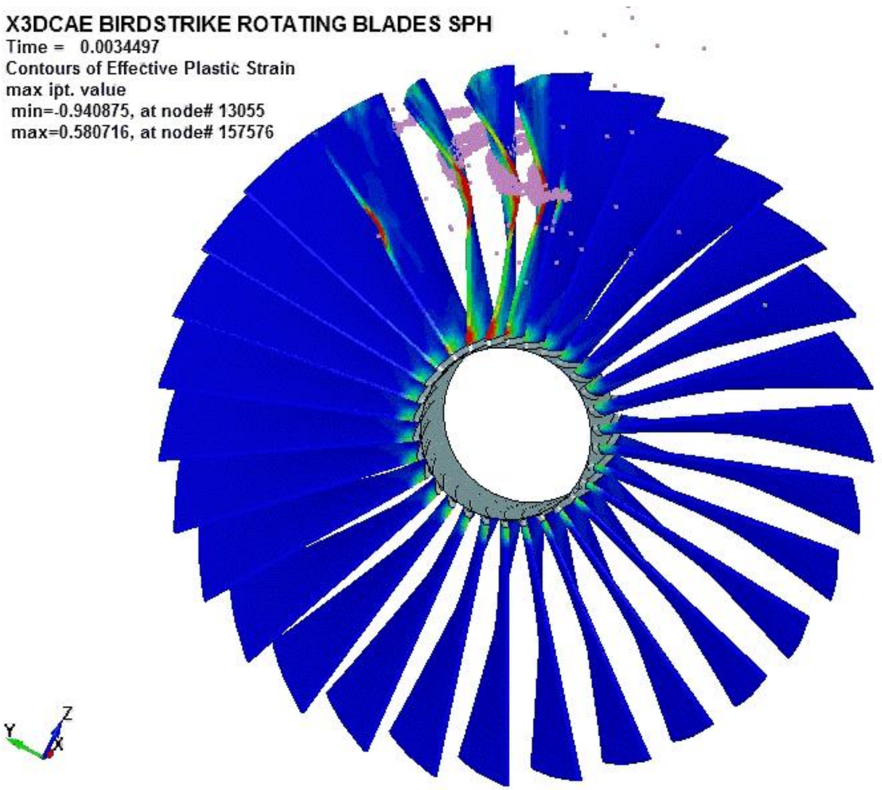
with $\mathbf{T} = t_{\alpha\beta}\, \mathbf{e}_\alpha \otimes \mathbf{e}_\beta \quad \forall\, \alpha, \beta = 1,2,3$

$$\frac{\mathrm{d}\varepsilon_i}{\mathrm{d}t} = \frac{t_{\alpha\beta}(\mathbf{x}_i)}{\rho_i^2} \sum_j m_j \left[(v_\alpha(\mathbf{x}_i) - v_\alpha(\mathbf{x}_j)\right] W_{ij,\beta}$$

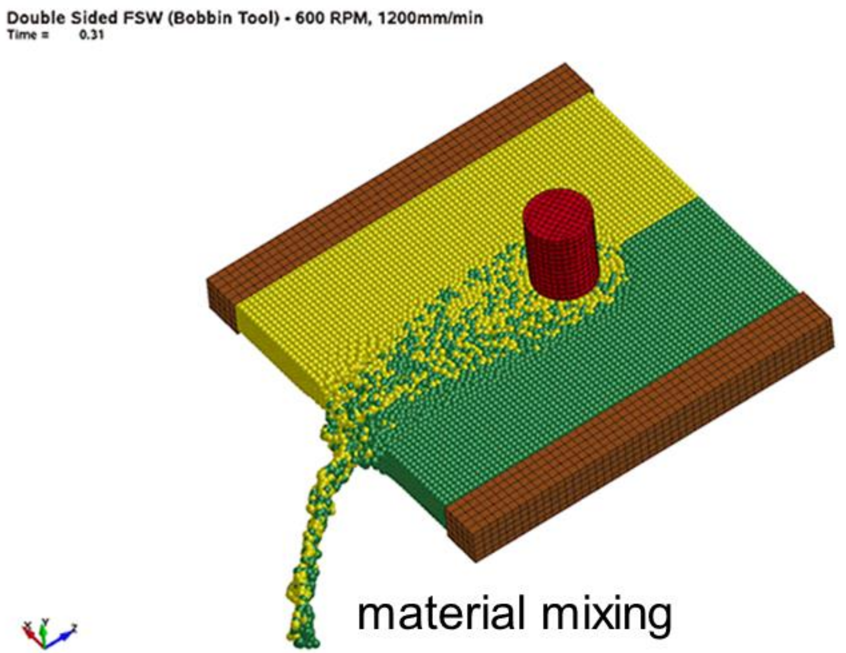
- Major applications for SPH
  - High velocity impacts
    - Projectile
      - Material: 304 L Steel
      - Velocity: 5530 m/s
      - Geometry: sphere, r = 5 mm
    - Target
      - Material: 6061-T651 Al
      - Thickness: 2.85 mm

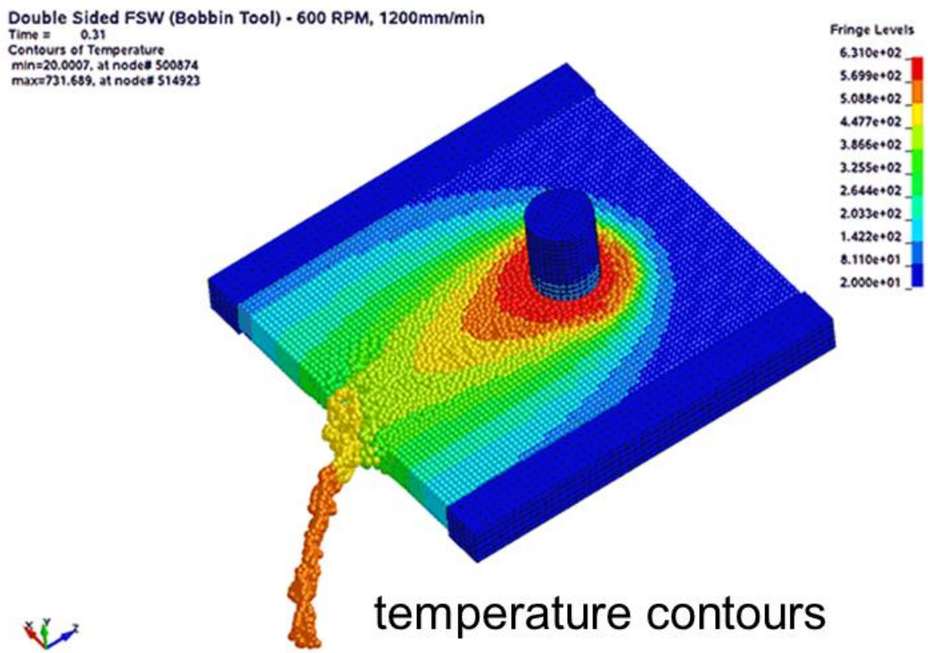


  - Bird strike



- Major applications for SPH (contd.)
  - Applications with material mixing
  - Here: Friction stir welding
    - Double sided FSW @ 600 RPM, 1200 mm/min
    - Plastic work and friction energy to heat

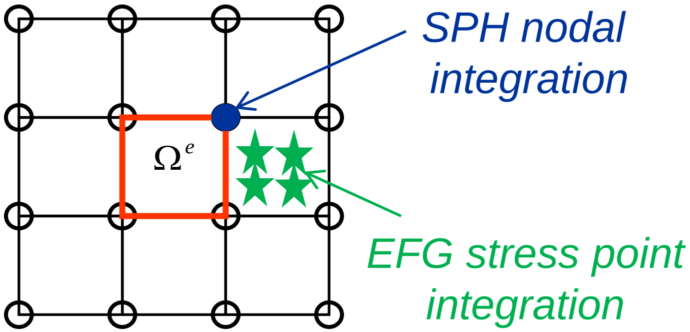


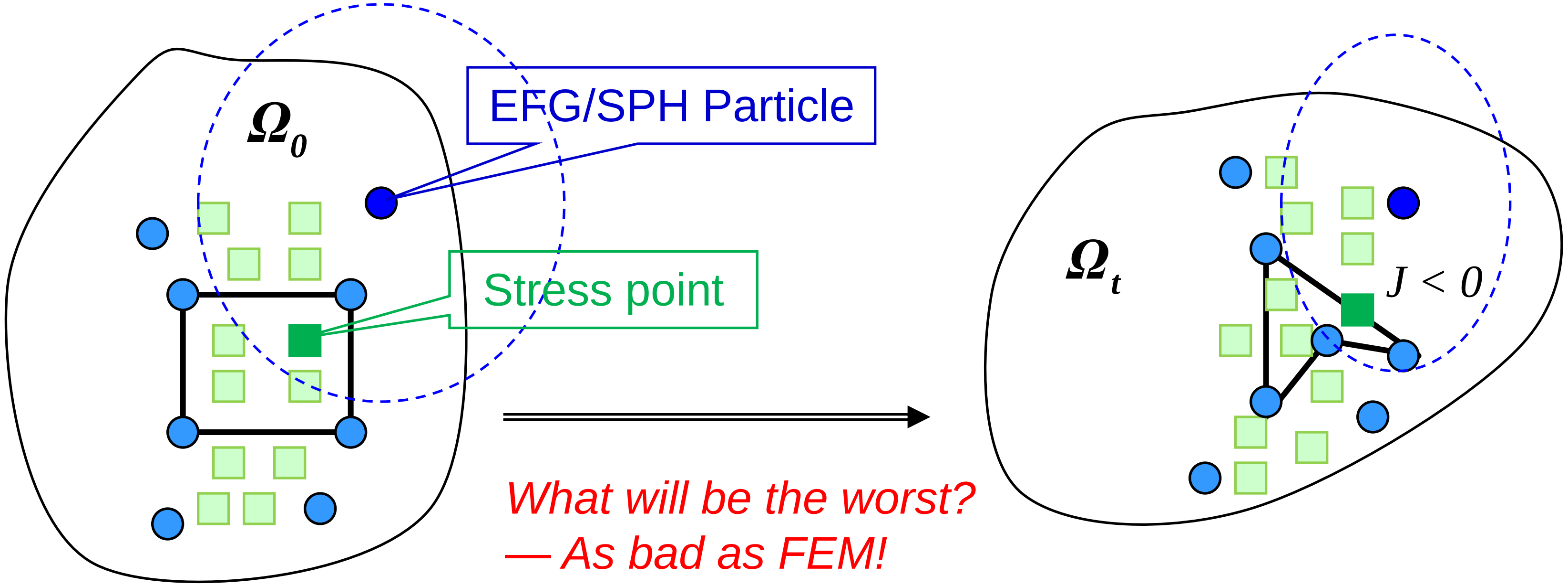


Courtesy Kirk Fraser (Predictive Engineering)

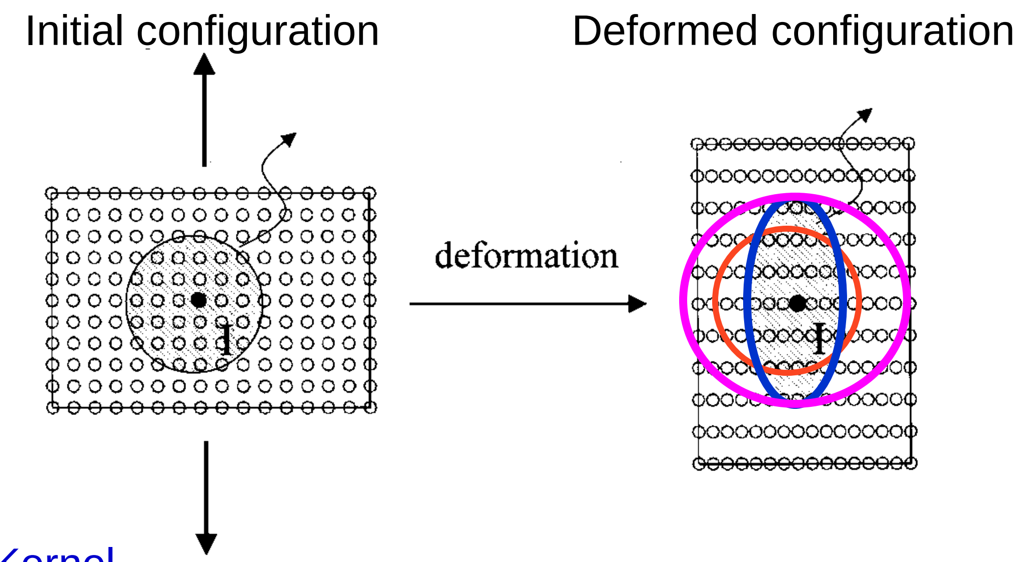
Element-Free Galerkin (EFG) in LS-DYNA

- Extension of SPH by integration cells
  - Real approximation of the Galerkin weak forms
  - Integration cells or background mesh needed to
    - Define the physical domain
    - Contact conditions
    - Impose boundary conditions
    - Perform volume integration via “stress points”



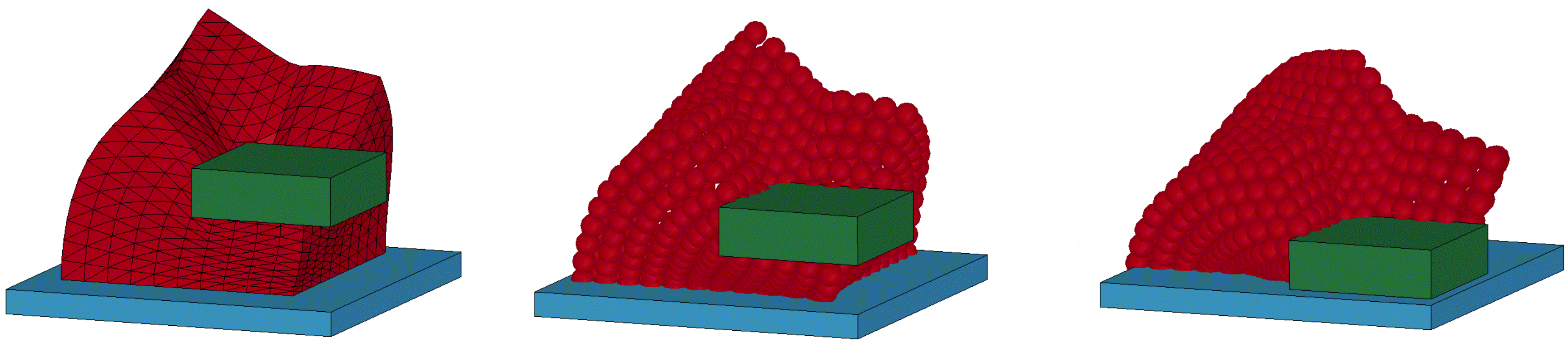


- Different descriptions of the EFG Kernel



- Lagrangean Kernel
  - Support is defined in the initial configuration
  - Support covers the same set of material points throughout time
- Eulerian Kernel
  - Support is defined in the current configuration
  - Support covers different material points throughout time
- Semi-Lagrangean Kernel
  - Support is defined in the current configuration
  - Support covers the same number of material points throughout time

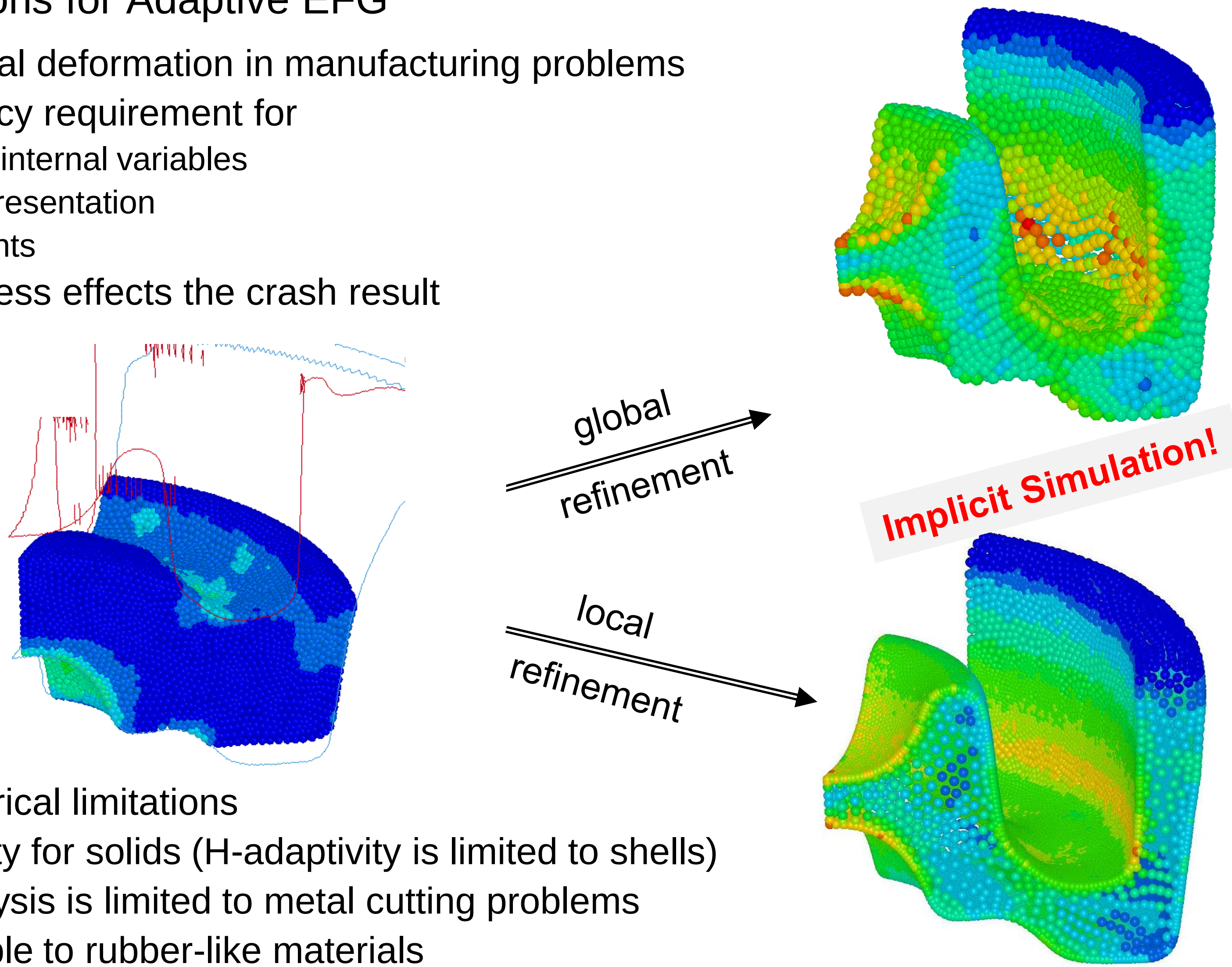
- Application to inhomogeneous foam compression



FEM | EFG + Lagrangean Kernel | EFG + Semi-Lagrangean Kernel

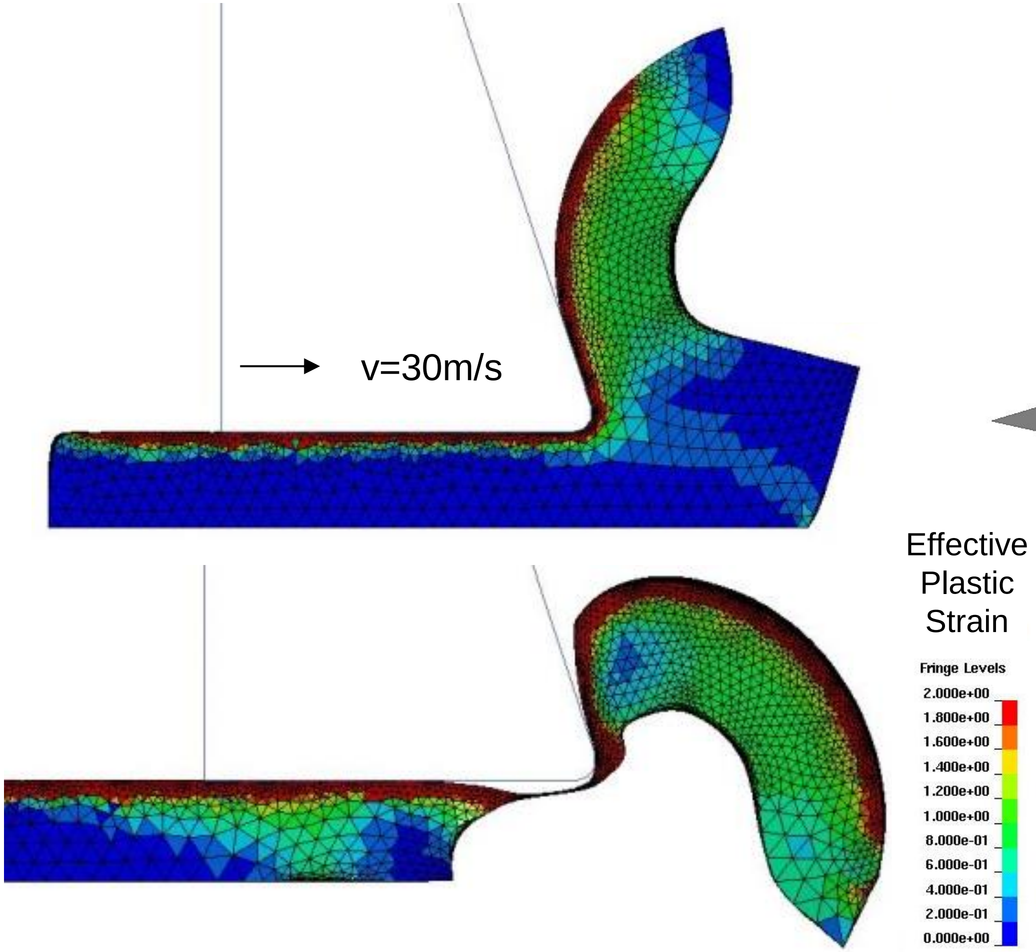
- Overview on available implementations in LS-DYNA
  - Stabilized formulation (explicit)
    - Lagrangean kernel: Rubber materials, etc.
    - Semi-Lagrangean kernel: Foam materials, etc.
  - Adaptive formulation (explicit & implicit)
    - Large strains in metal materials for manufacturing analysis
  - Strong-discontinuity formulation (explicit)
    - Quasi-brittle material fracture

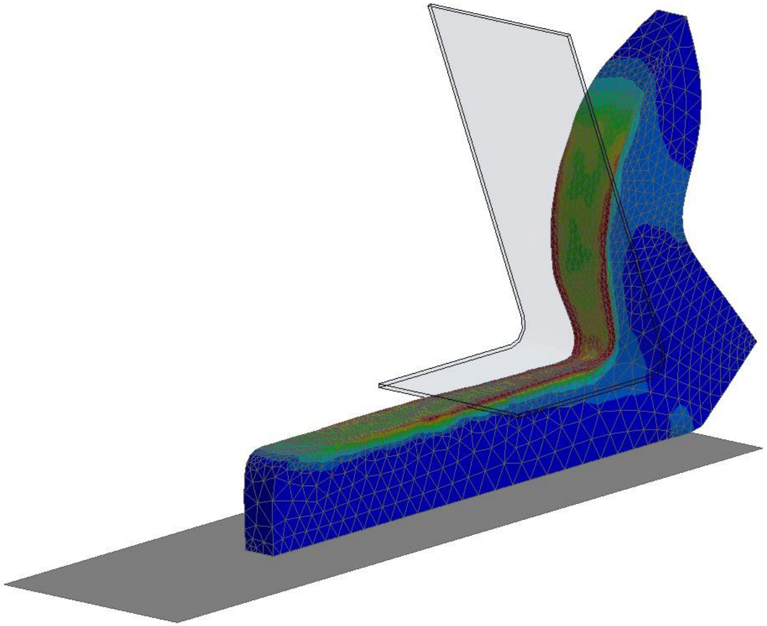
- Major applications for Adaptive EFG
  - Severe material deformation in manufacturing problems
    - High accuracy requirement for
      - mapping of internal variables
      - surface representation
      - high gradients
    - Residual stress effects the crash result

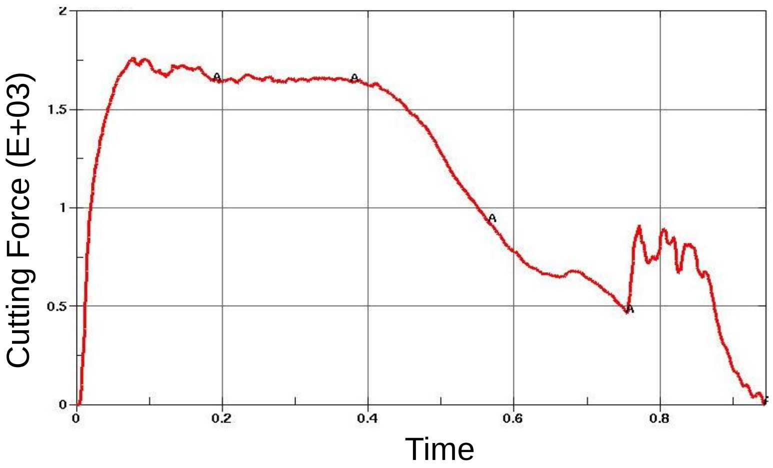


- Current numerical limitations
  - RH-adaptivity for solids (H-adaptivity is limited to shells)
  - Failure analysis is limited to metal cutting problems
  - Not applicable to rubber-like materials

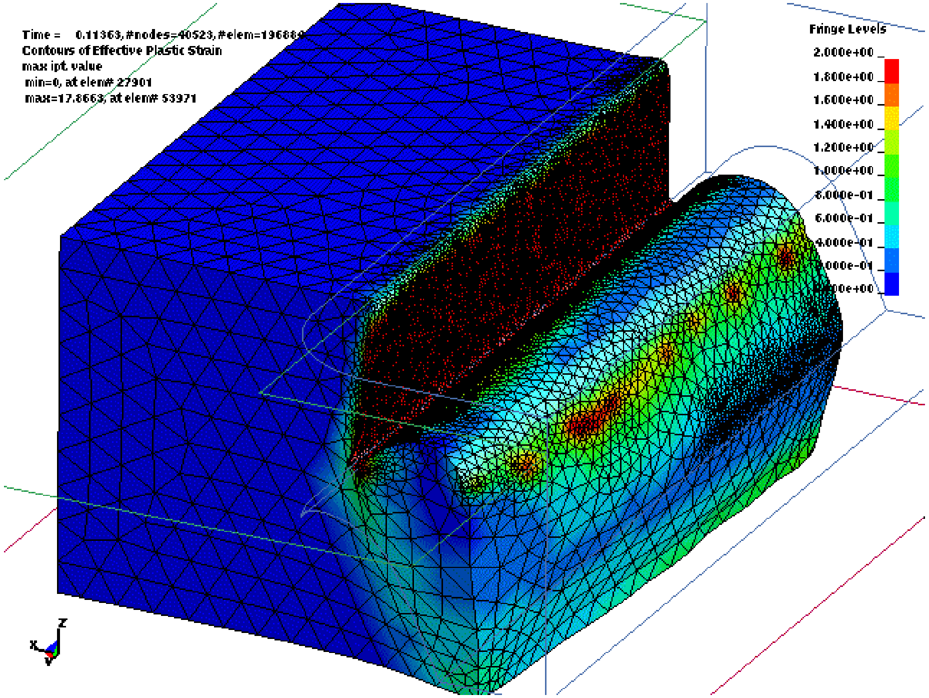
- Major applications for adaptive EFG
  - Metal cutting analysis (implicit analysis)
  - Local adaptivity to capture sharp corners

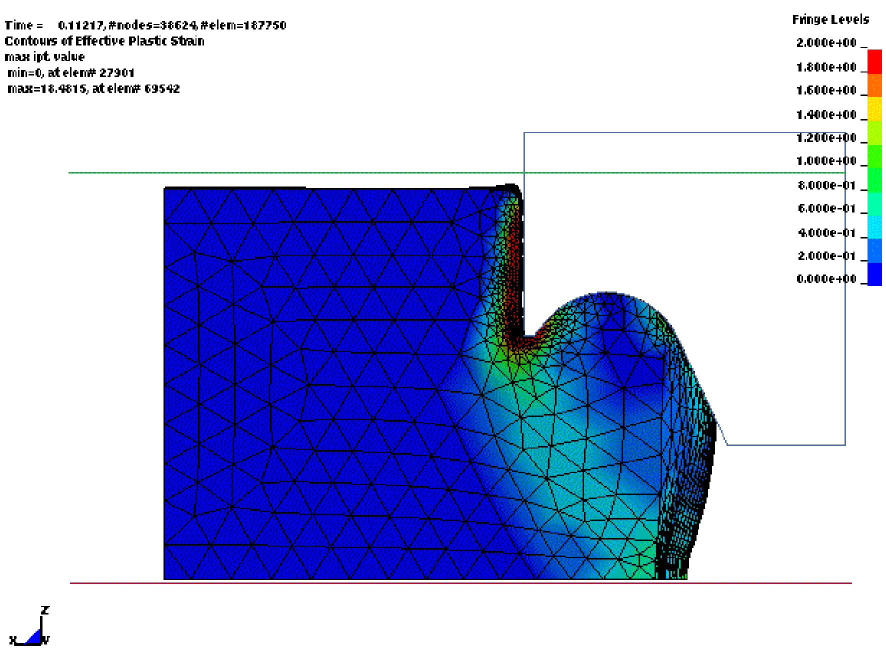




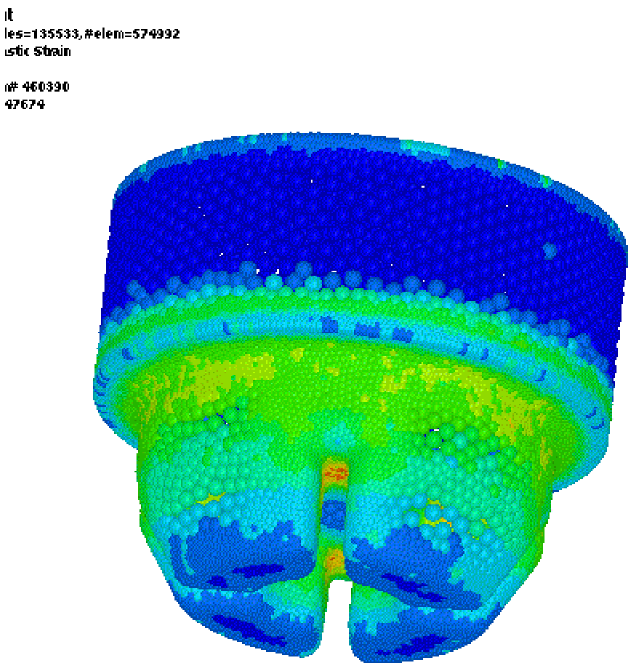


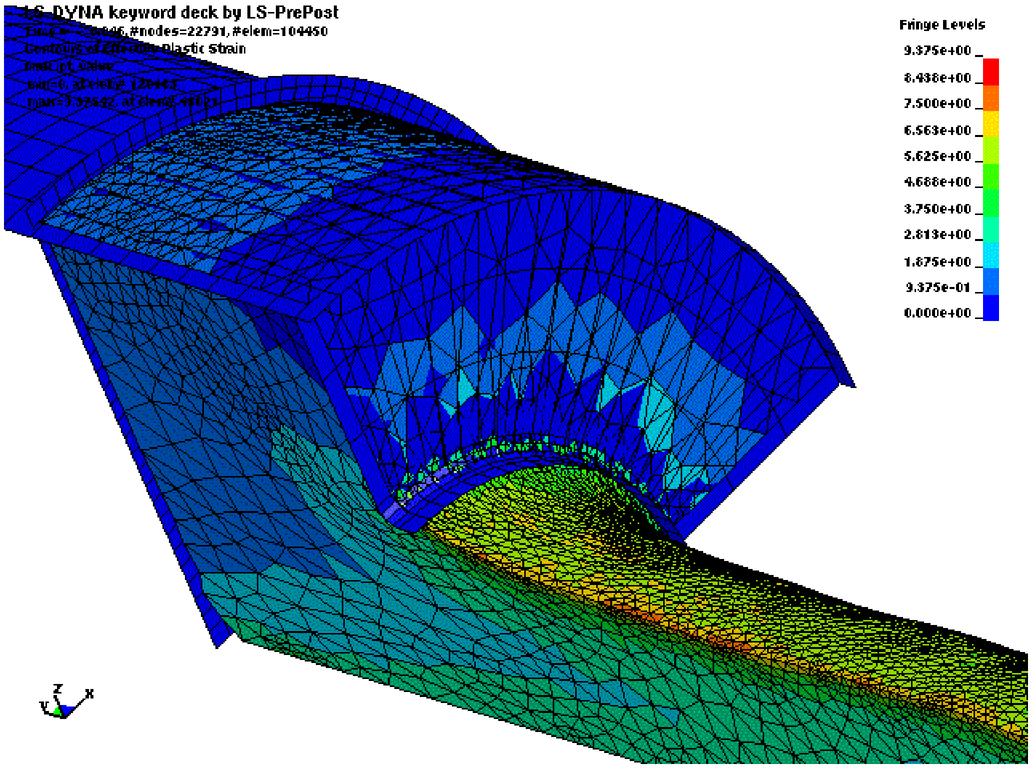
- Major applications for adaptive EFG
  - Metal cutting and forging (implicit analysis)
  - Local adaptivity to capture sharp corners



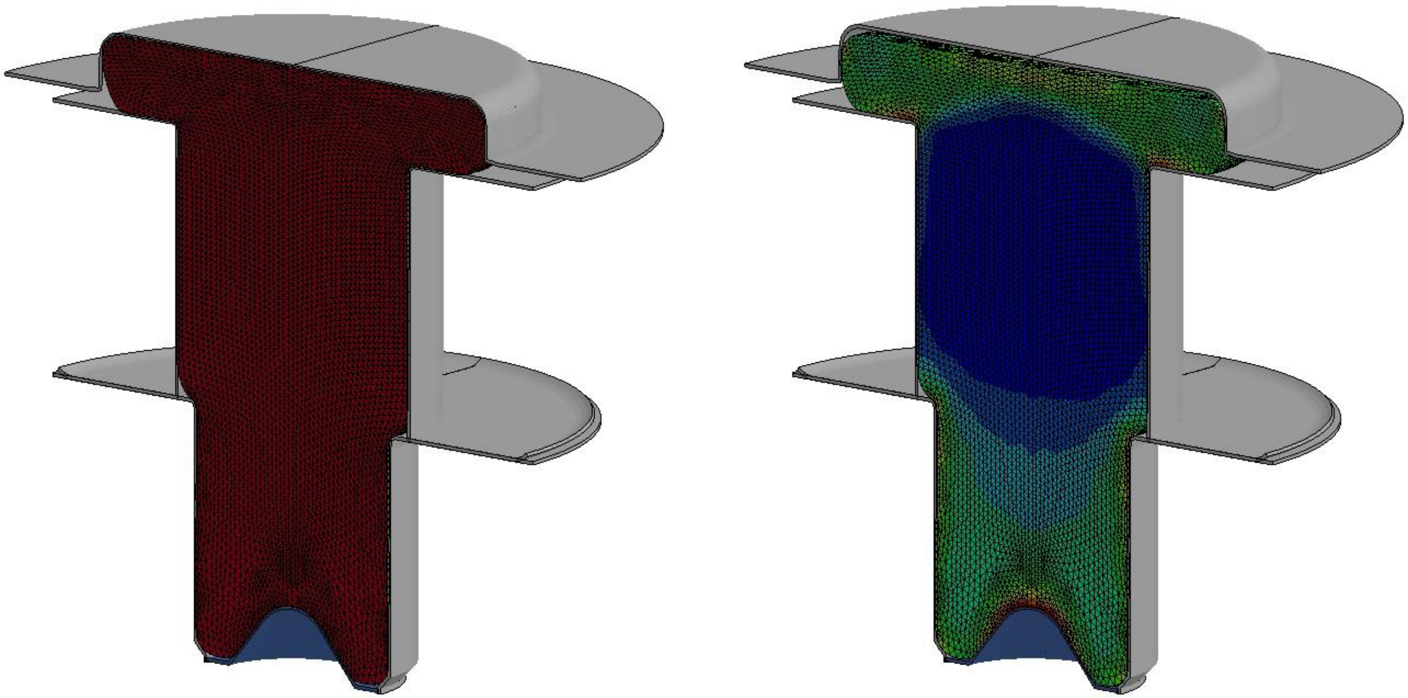


- Major applications for adaptive EFG
  - Extrusion processes (implicit analysis)
  - Local adaptivity to capture sharp corners

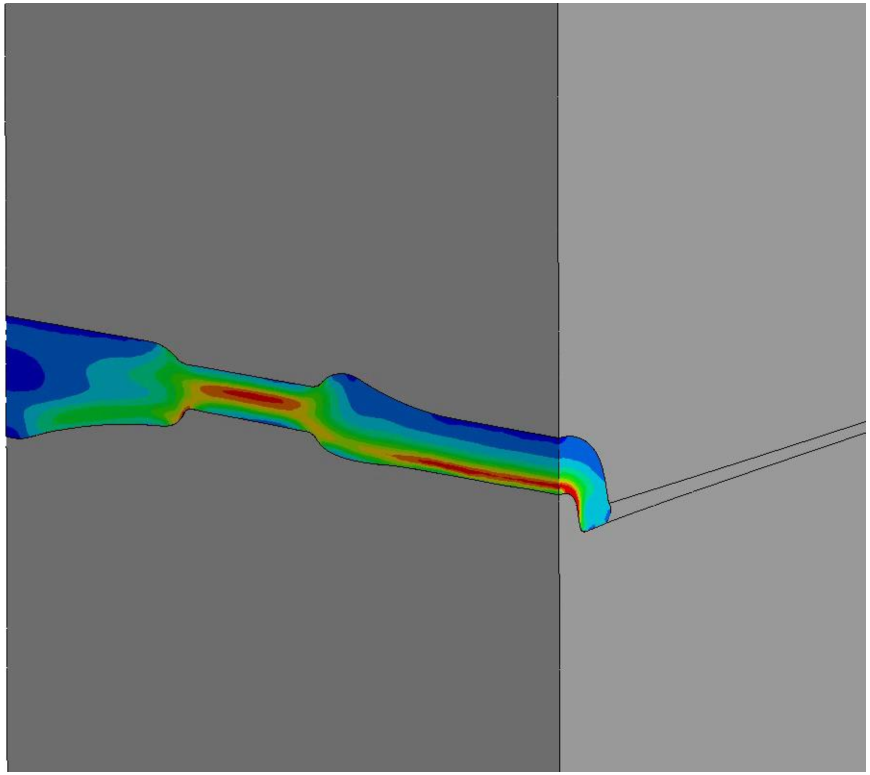




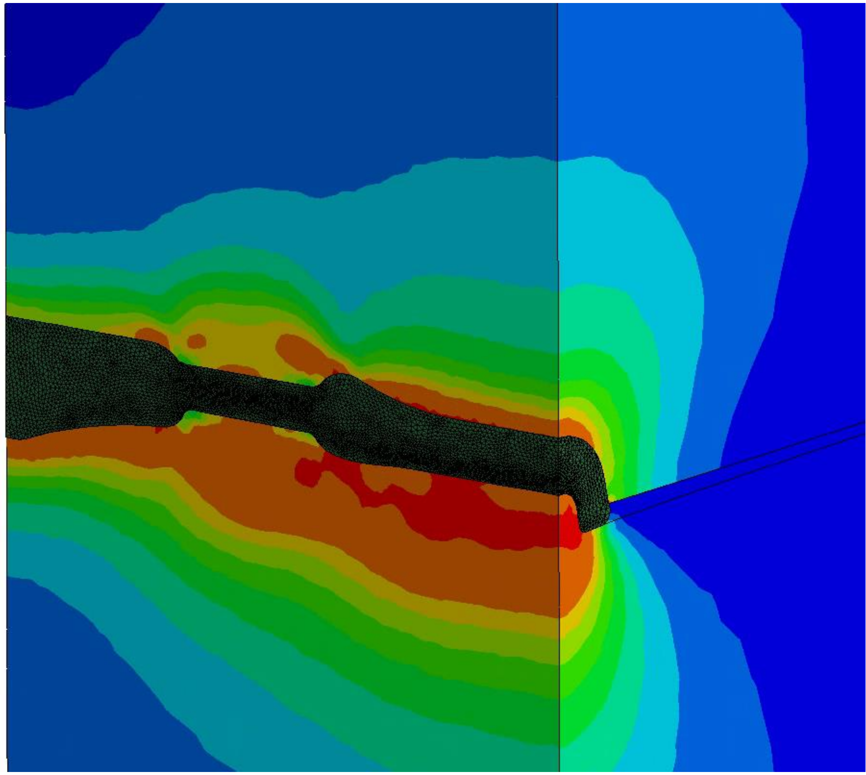
- User testimonials for adaptive EFG
  - Cold forming of a pre-stressed rivet head
  - Computation times
    - LS-DYNA (explicit): 1 day on 6 CPU
    - LS-DYNA (implicit): 20 min on 6 CPU



- User testimonials for adaptive EFG
  - Cold forming of an automotive part
  - Here: deformable tools!

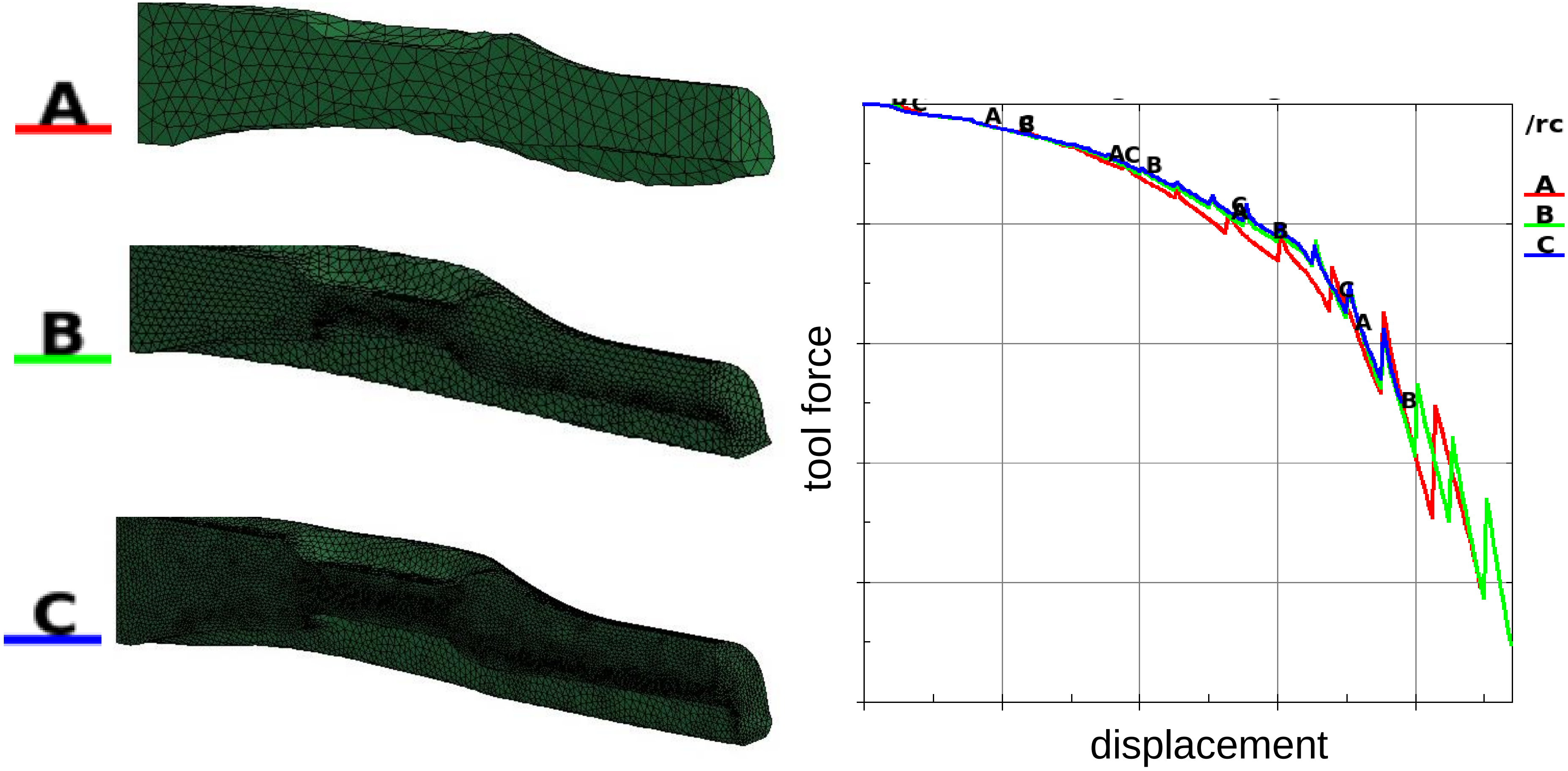


equivalent plastic strain



von Mises stress

- User testimonials for adaptive EFG
  - Cold forming of an automotive part
  - Comparison of the background mesh size



Things to Keep in Mind for Adaptive EFG

- After ever remeshing step
  - Geometry is slightly changed
  - Contact force might be reduced
  - Part of the solution is lost due to variable transfer
- Trigger as few remeshing steps as possible!
- Coarser mesh needs less remeshing!

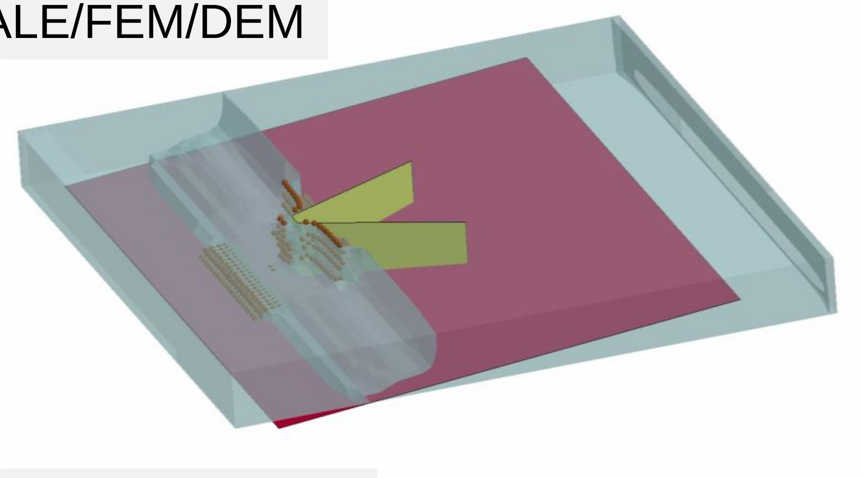
	Implicit	Explicit
Time step size	independent of deformation	dependent on deformation
Deformation until	background mesh degenerates	time step size drops
Remeshing needed due	to severe deformation	to practical time step size
# of remeshing steps	usually less	usually a lot more
Contact problems cause	convergence problems	shooting nodes

- Mesh size after remeshing
  - As large as the geometry approximation is still acceptable
  - As small as the smallest corner where the material “flows” by

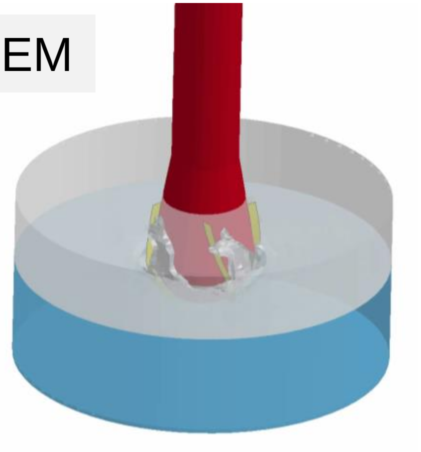
Advanced Multiphysics Coupling

- Couple Meshfree Methods with other Features of LS-DYNA

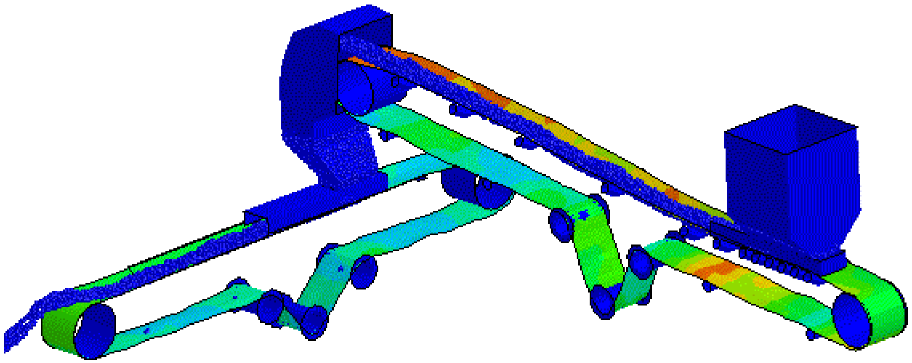
ALE/FEM/DEM

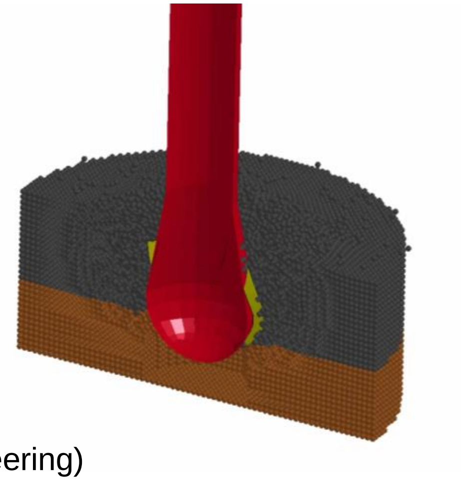


ALE/FEM/DEM



FEM/SPH or DEM





Courtesy Kirk Fraser (Predictive Engineering)

Thank you for your attention!

DYNA MORE

Your LS-DYNA distributor and more