Recent Developments on MPM and Its Application in Impact & Explosion Simulation

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Acknowledgement

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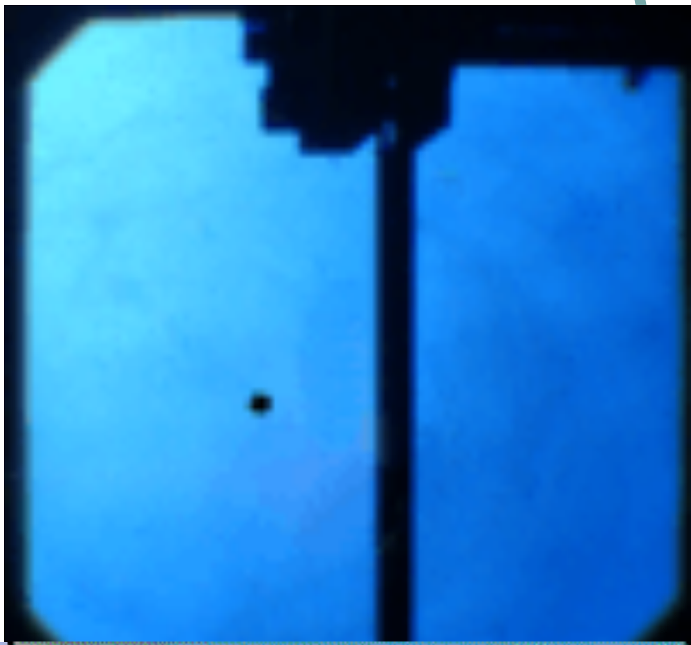
Outline

- **Introduction**
- Our improvements on MPM
  - Efficient implementation of MPM
  - Improved contact method
  - Adaptive Material Point Method
  - Parallelization based on OpenMP
  - Multi-Level Grid Material Point Method
  - Hybrid FE-MP method
  - Coupled FE-MP method
  - Adaptive FE-MP method
- MPM3D – A 3D explicit MPM code
- Applications
  - Impact
  - Explosion
  - Fluid-Structure Interaction
  - Nano- & Bio- Mechanics
- Concluding remarks

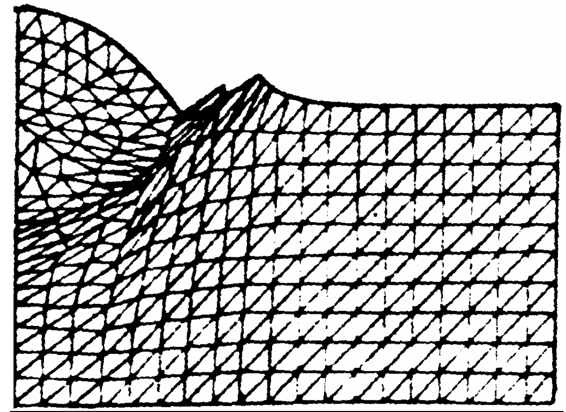
Introduction

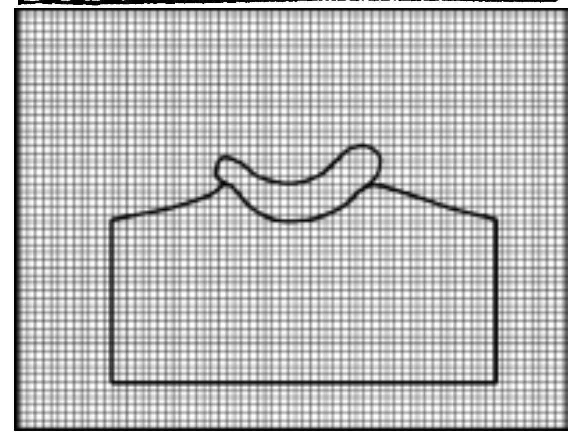
- Intense dynamic loading
  - Hyper velocity impact
  - Blast
- Highly nonlinear
  - Geometrical nonlinearity
  - Material nonlinearity
  - Boundary condition nonlinearity
- Deformation is highly localized

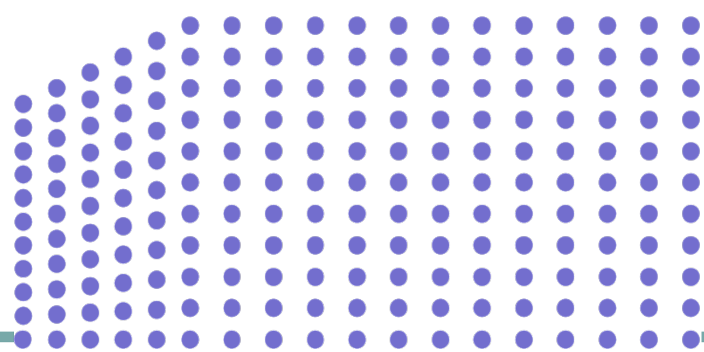


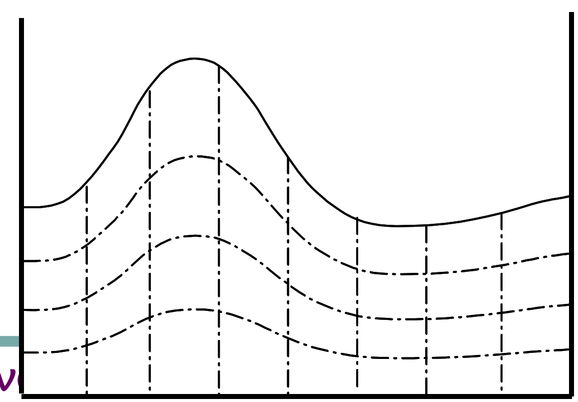
Introduction

- Numerical methods
  - Lagrangian method
  - Eulerian method
  - Hybrid Lagrangian-Eulerian methods
    - Arbitrary Lagrangian Eulerian (ALE)
    - **Particle In Cell (PIC)**
  - Meshfree methods
    - **SPH**
    - EFG
    - RKPM
    - MLPG
    - … …



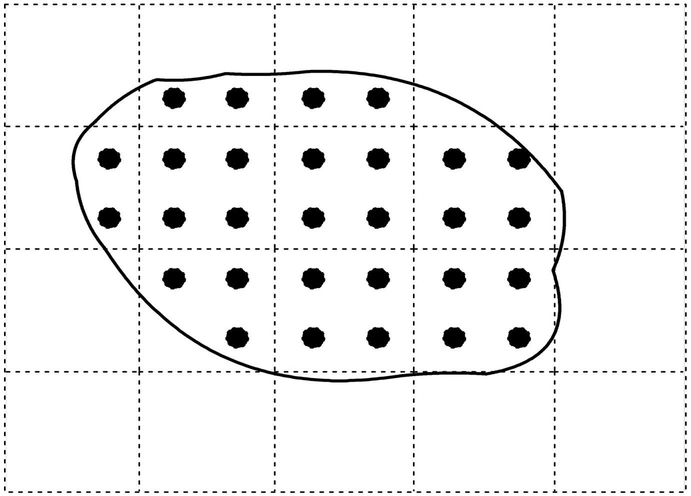






Introduction

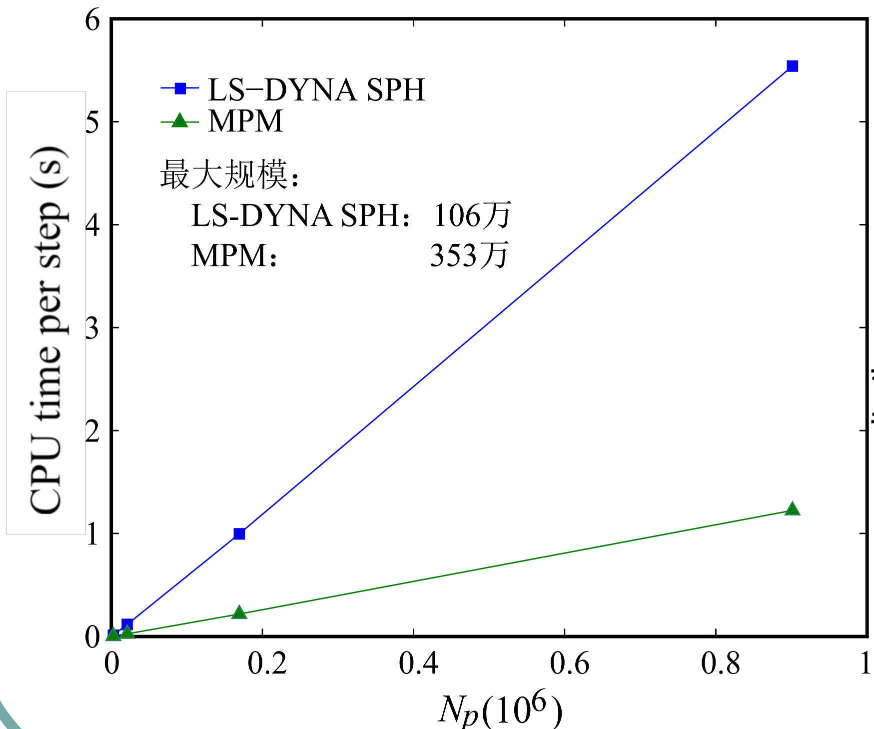
- Material Point Method (Sulsky, Chen et. al. 1994)
  - An extension of the FLIP PIC method to solid mechanics
  - Discretizes a material domain by particles moving through an Eulerian background mesh
  - Fully Lagrangian particle method
    - Particles carry all state variables
    - Grid carries no permanent information

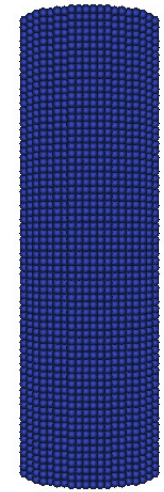


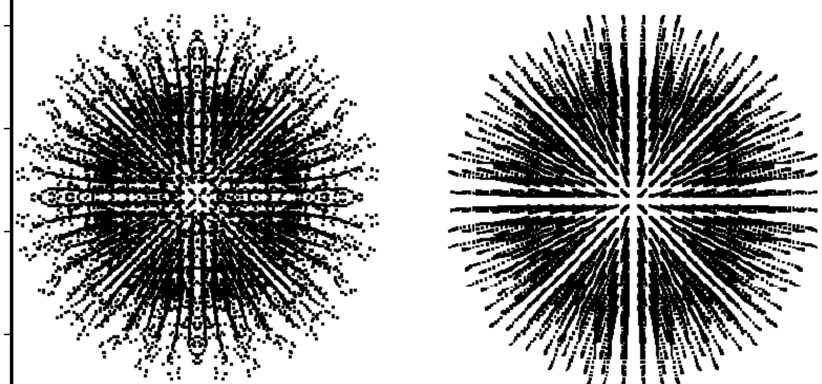
Introduction

- Much more efficient than SPH
  - The critical time step size depend on the cell size
  - No neighboring particles search

S Ma， X Zhang et al. Comparison study of MPM and SPH in modeling hypervelocity impact problems. ***IJIE*** 36: 272-282, 2009







SPH MPM

Final configuration of the bar (top view)

Introduction

- Combines the advantages of Lagrangian and Eulerian methods
  - History-dependent constitutive models
  - Free surfaces or multiple materials
  - No mesh distortion and element entanglement
  - Promising in modeling **extremely large deformation** and material discontinuities

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  - **Improved contact method**
  - **Adaptive Material Point Method**
  - **Parallelization based on OpenMP**
  - **Multi-Level Grid Material Point Method**
  - **Hybrid FE-MP method**
  - **Coupled FE-MP method**
  - **Adaptive FE-MP method**
- MPM3D – A 3D explicit MPM code
- Applications
  - Impact
  - Explosion
  - Fluid-Structure Interaction
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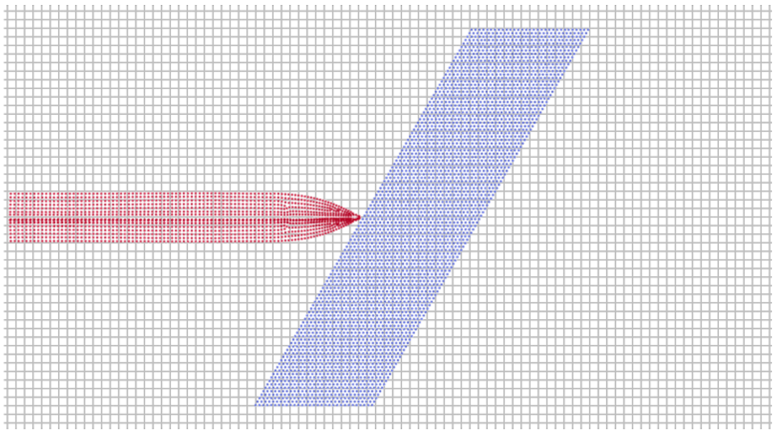
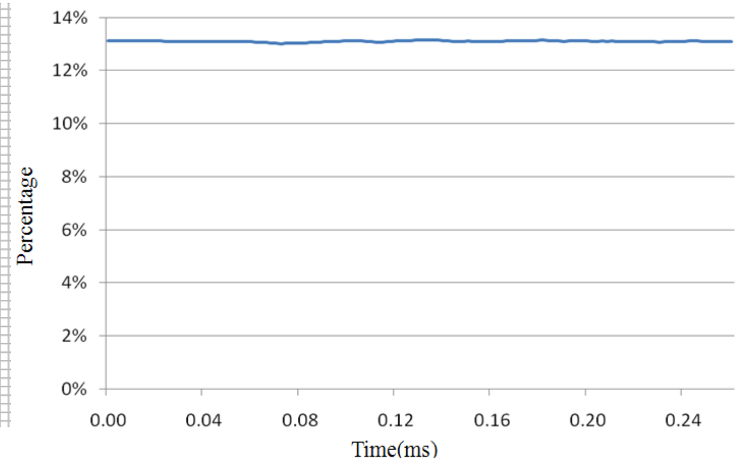
- Concluding remarks

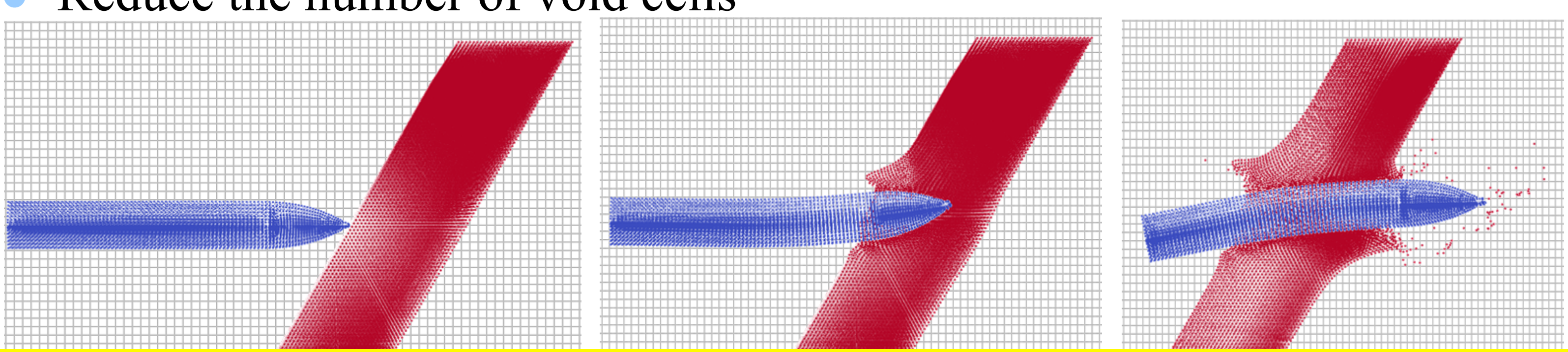
Efficient implementation of MPM

- Dynamic grid
  - Cells are dynamically created when occupied by at least one particle
  - Reduce CPU time and memory requirement significantly





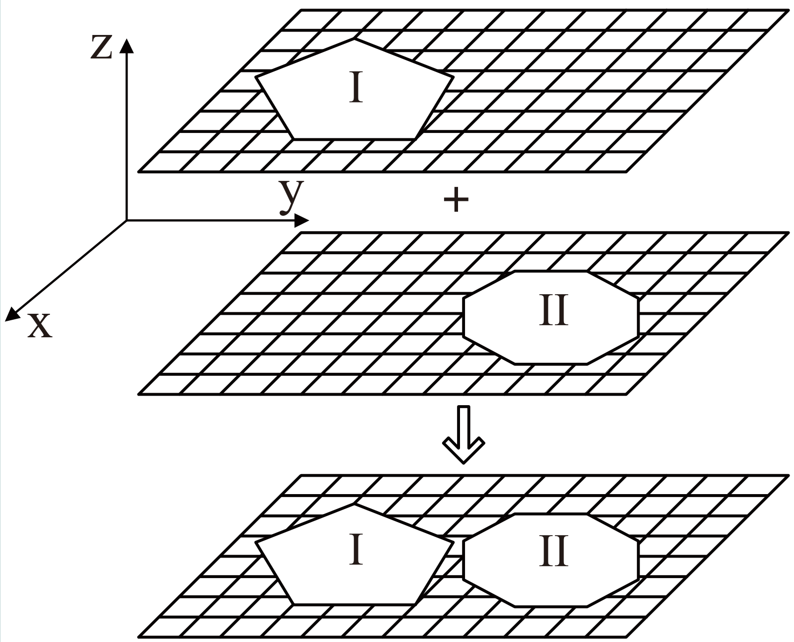
- Moving grid
  - Adjust grid according to the position of particles to just cove all bodies
  - Reduce the number of void cells

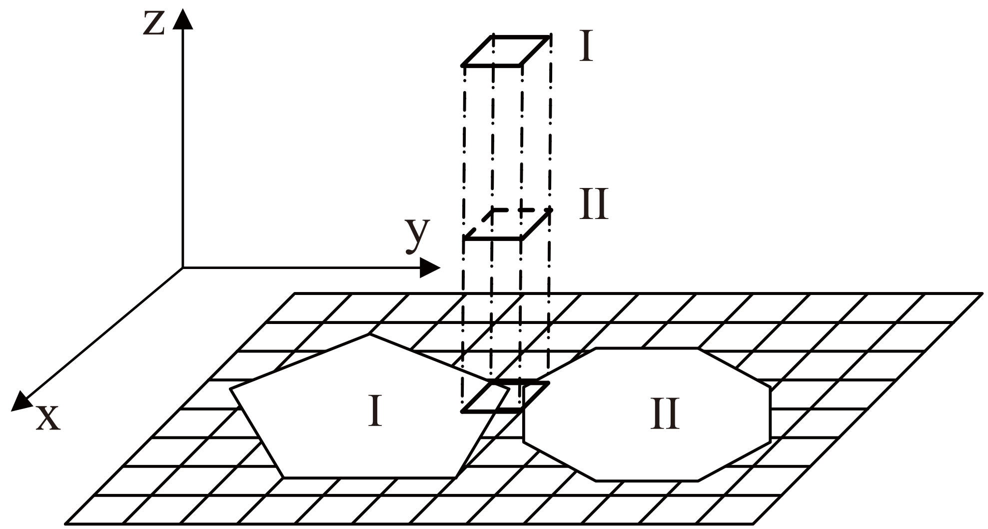


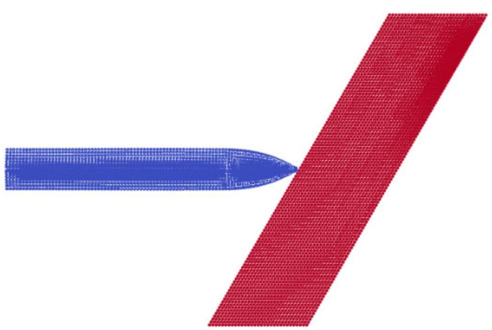
ZT Ma, X Zhang. An Object-Oriented MPM Framework for Simulation of Large Deformation and Contact of Numerous Grains. ***CMES*** 55(1): 61-88, 2010

Efficient implementation of MPM

- Local multi-mesh contact
  - Multi-meshes are only used at contacted grid nodes



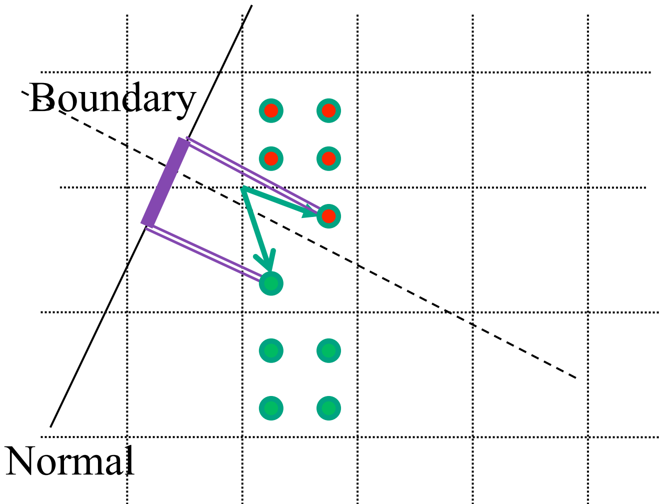


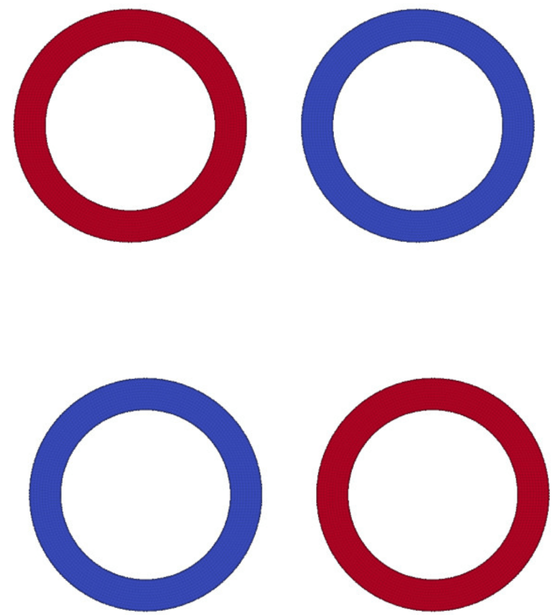


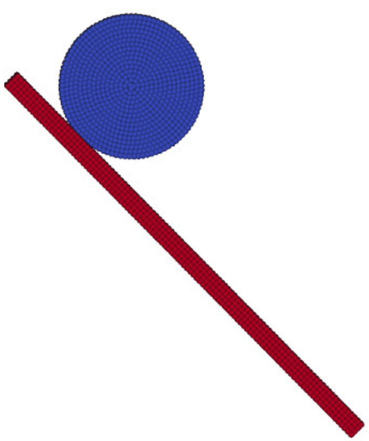
N_p / N_g	CPU time Reduced	Memory Reduced
200,864/ 170,688	88.8%	49.7%

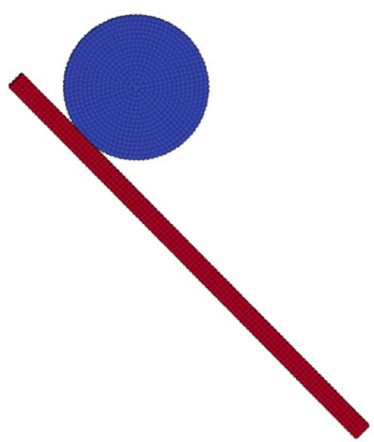
Improved contact algorithm

- Satisfy the collinearity condition which insures the momentum conservation
- Improved contact detection scheme





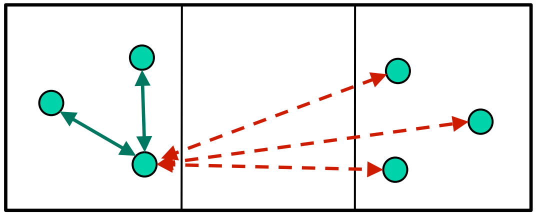


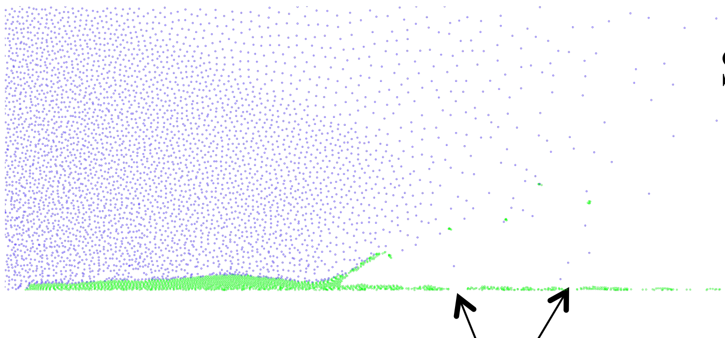


P Huang, X Zhang et al. Contact Algorithms for the Material Point Method in Impact and Penetration Simulation. ***IJNME*** 85(4): 498-517, 2011

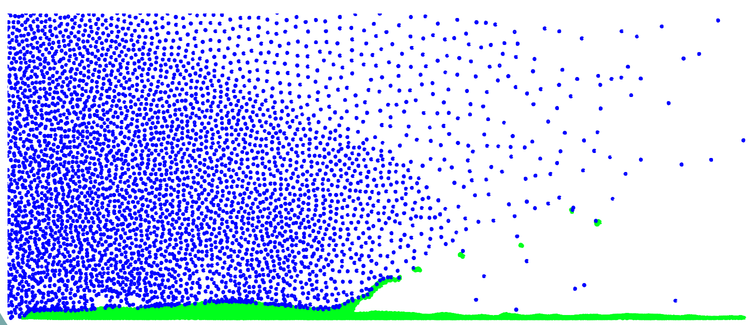
Adaptive Material Point Method

Numerical fracture





Numerical fracture



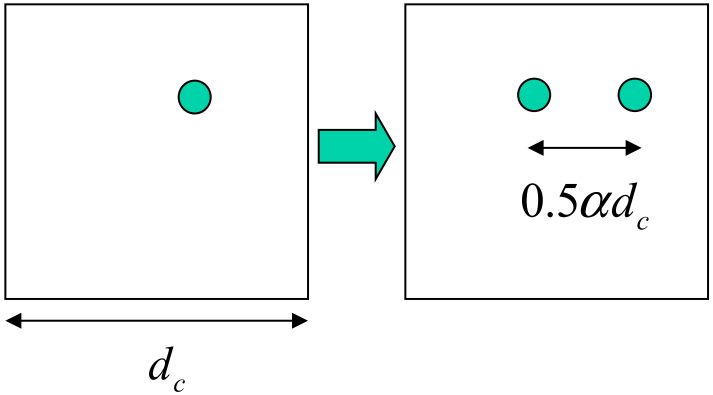
- Adaptive particle split scheme

Accumulated strain: $\varepsilon_{xx} = \sum_k \Delta\varepsilon_{xx}^k = \sum_k D_{xx}^k \Delta t$

Characteristic particle length: $L_{px} = (1+\varepsilon_{xx})\sqrt[3]{V_0}$

Splitting criterion: $L_{px} > \alpha d_c$

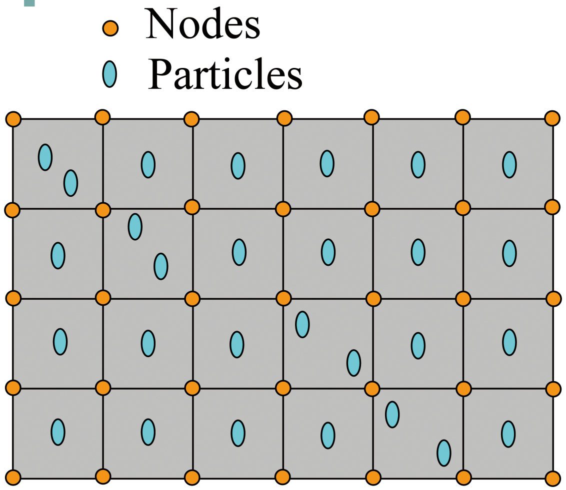
Split: mass, volume, internal energy



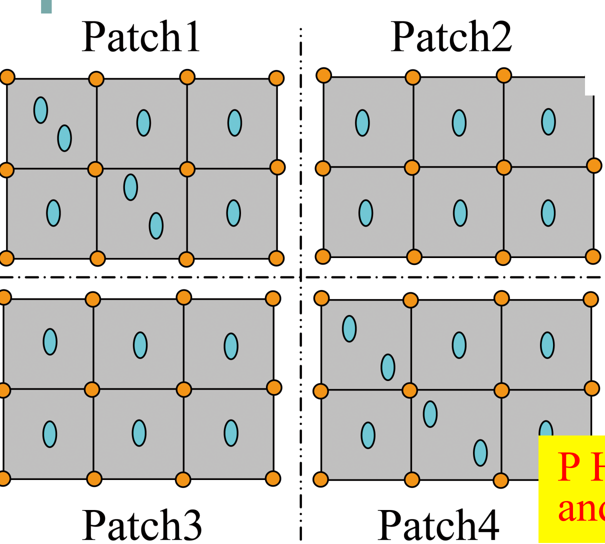
S Ma, X Zhang et al. Simulation of high explosive explosion using adaptive material point method. *CMES* 39(2):101-123, 2009

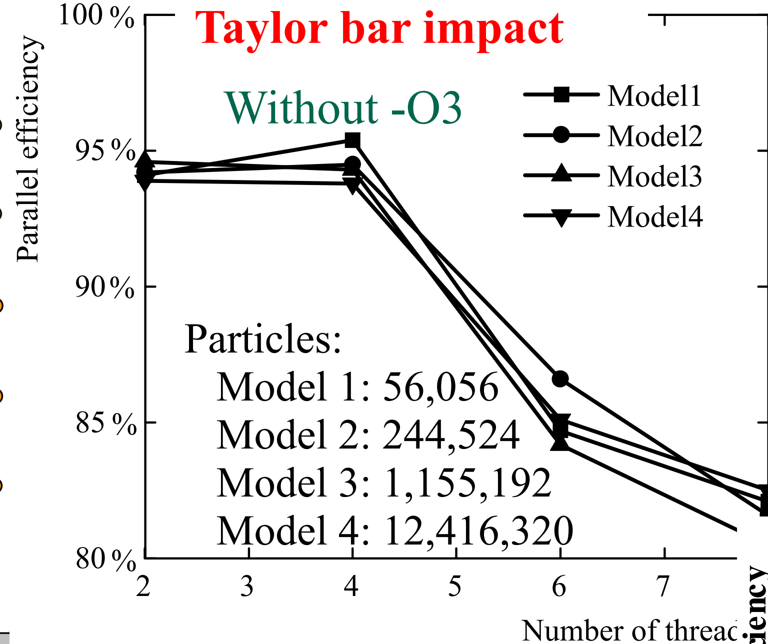
Parallelization based on OpenMP

- Symmetric multiprocessing (SMP)
- Background grid decomposition



Computational Domain

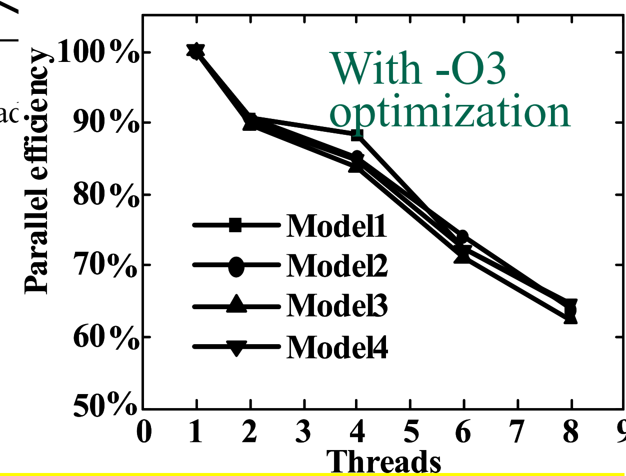




HP DL140G3 server

- 2 Quad-Core Intel Xeon 2.66GHz processors
- 8 GB memory

Requires significant modification to original code



P Huang, X Zhang. Shared Memory OpenMP Parallelization of Explicit MPM and Its Application to Hypervelocity Impact. *CMES* 38(2):119-148, 2008

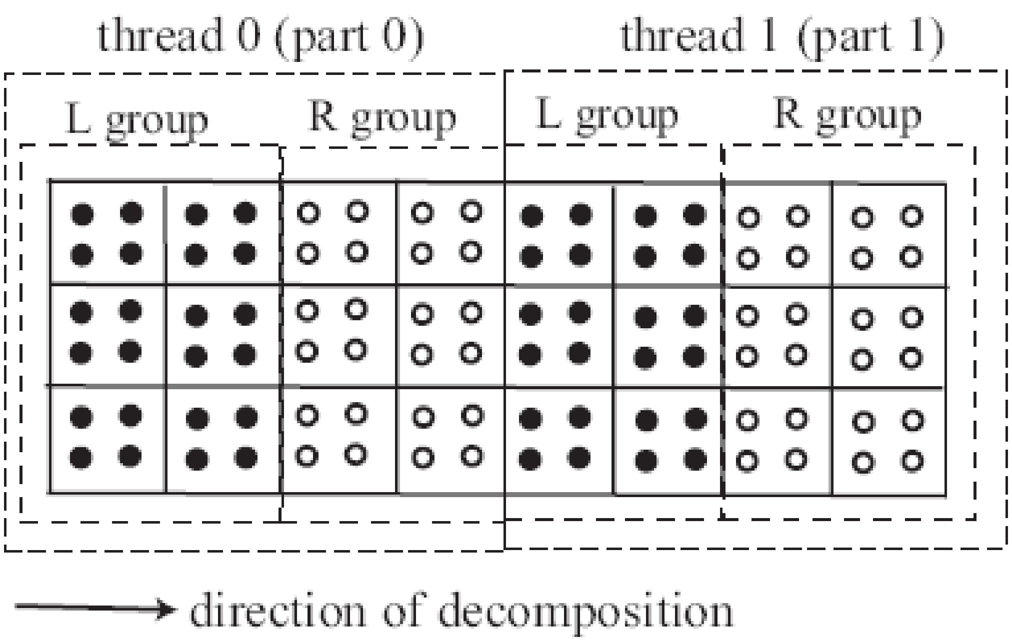
Parallelization based on OpenMP

Alternated grid updating method to avoid data race

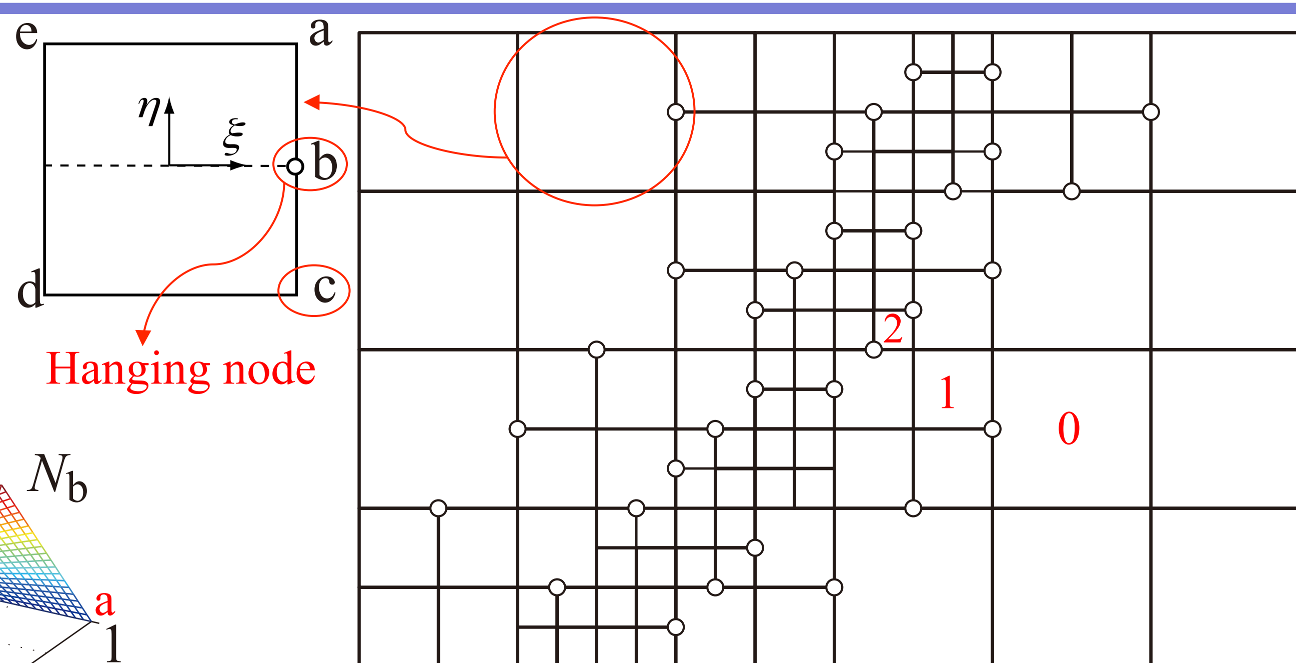
1. Divide the computing domain along the direction selected
2. Each part is further divided into two groups
3. Each thread update its **L** group
4. A barrier is set
5. Each thread upate its **R** group

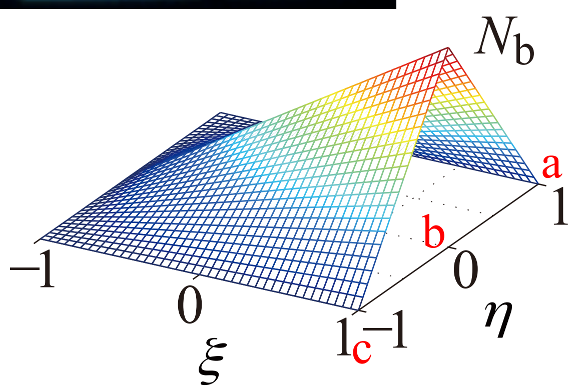
Requires minor modification to original code

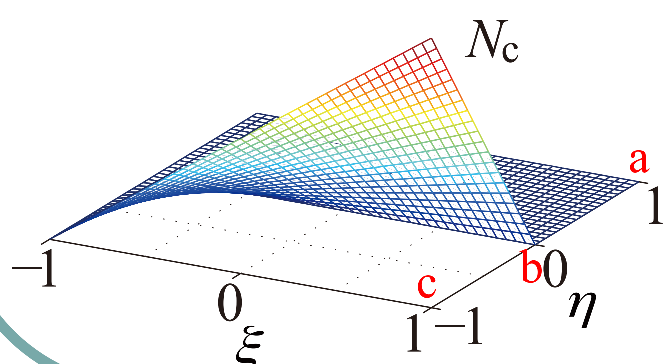
YT Zhang, X Zhang et al. An alternated grid updating parallel algorithm for material point method using OpenMP. *CMES* 69(2): 143-165, 2010



Multi-Level Grid Material Point Method







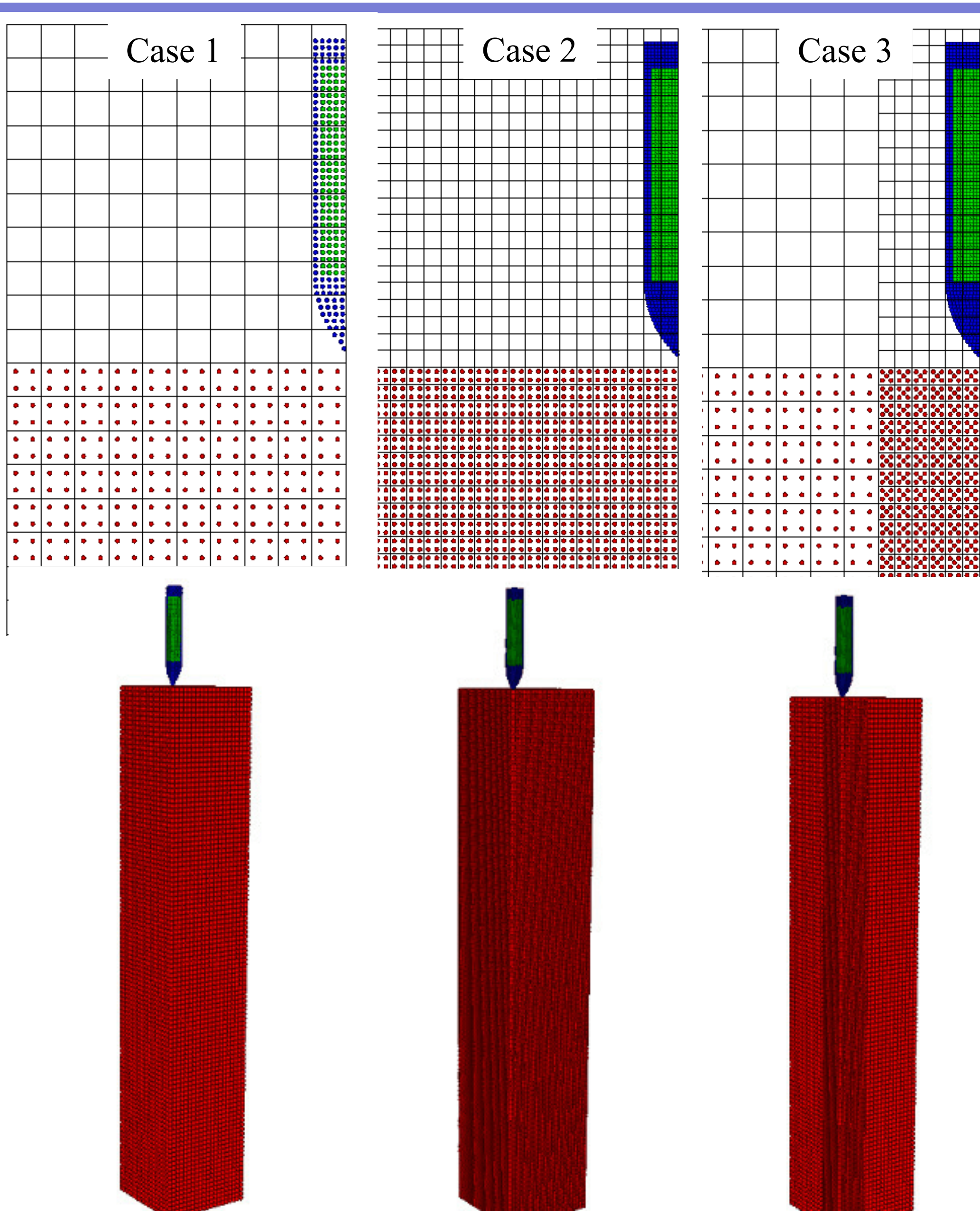
$$N_I(\xi_J,\eta_J)=\delta_{IJ}$$

$$N_b(\xi,\eta)=\frac{1}{2}(1+\xi)(1-|\eta|)$$

$$N_a(\xi,\eta)=N_a^L(\xi,\eta)-\frac{1}{2}N_b(\xi,\eta)$$

$$N_c(\xi,\eta)=N_c^L(\xi,\eta)-\frac{1}{2}N_b(\xi,\eta)$$

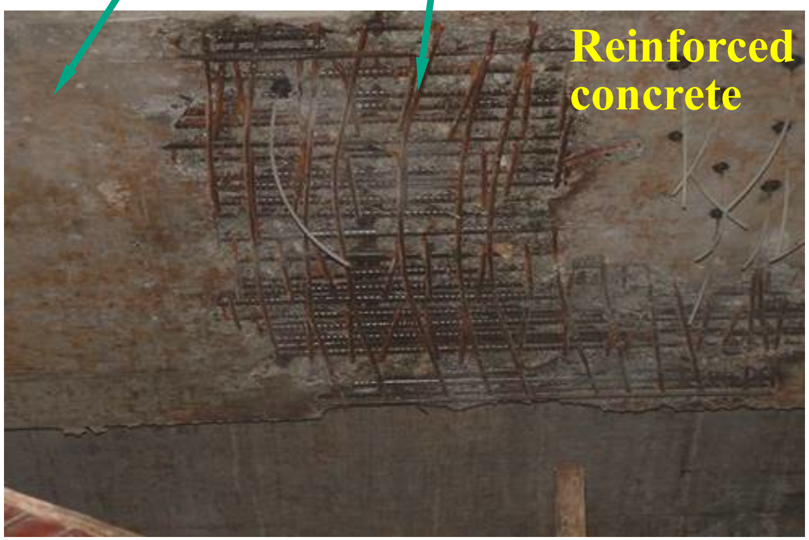
Multi-Level Grid Material Point Method

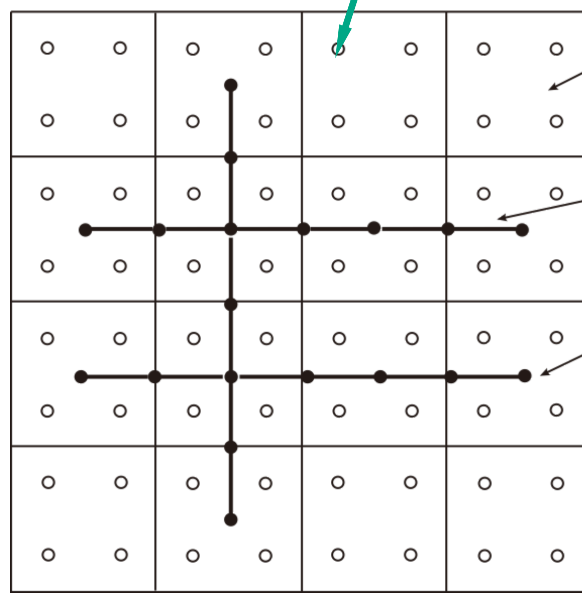


	No. grid nodes	No. particles	CPU time
Case 1	9075	45620	21 m
Case 2	72116	365206	5 h 25 m
Case 3	15176	79830	1 h 42 m

Hybrid FE-MP method

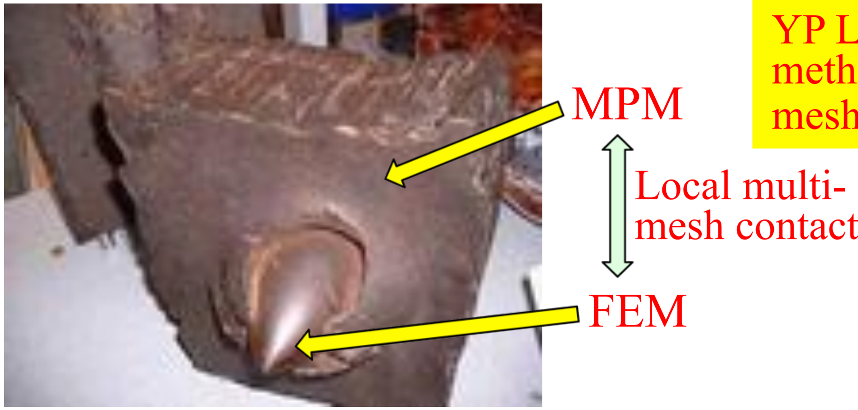
- Plain concrete is discretized into particles
- Rebars are discretized into bar elements (rebar elements)
  - Rebar nodes carry kinematic variables
  - Rebar elements carry history variables
- All the rebar nodes and particles move in the same single-valued velocity field



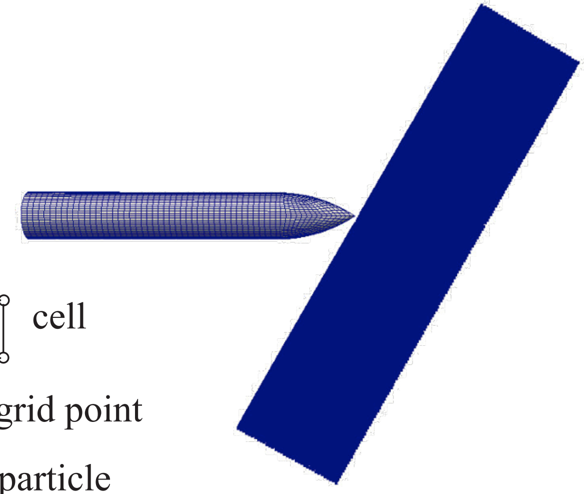


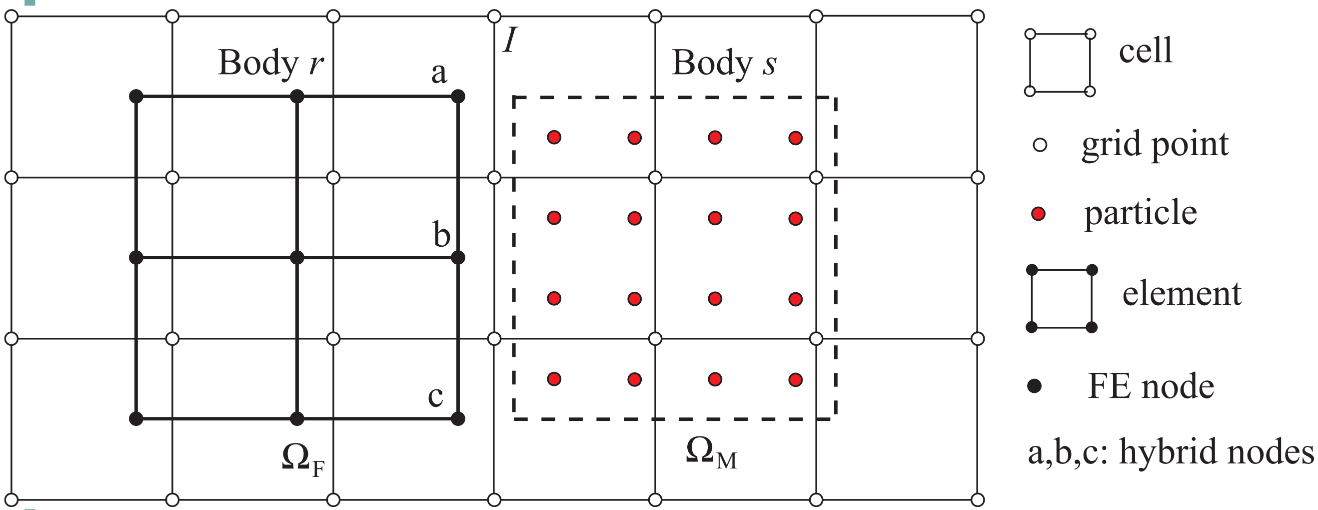
YP Lian, X Zhang et al. A FEMP method and its application in modeling dynamic response of reinforced concrete subjected to impact loading. *CMAME*, 200(17-20): 1659-1670, 2011.

Coupled FE-MP method



YP Lian, X Zhang et al. Coupling of finite element method with material point method by local multi-mesh contact method. ***CMAME*** 200: 3482-3494, 2011

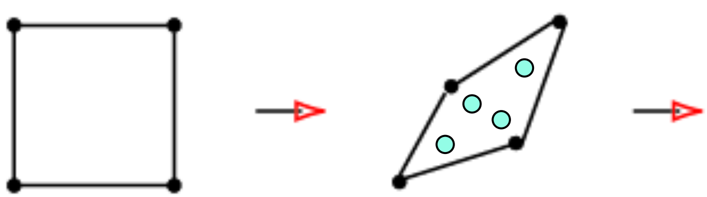


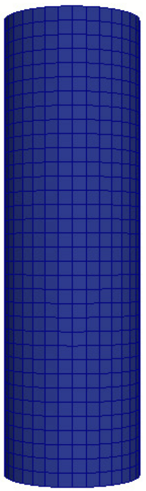


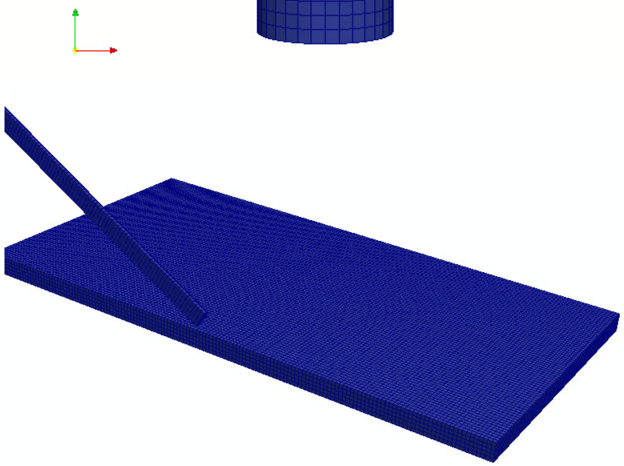
- Discretize different bodies by FEM and MPM, respectively
- Interaction between bodies is handled by the local multi-mesh contact method in the framework of MPM

Adaptive FE - MP Method

- Distorted elements are adaptively converted into MPM particles
  - When to convert – avoid element distortion
    - Effective plastic strain
    - Critical time step
  - How to convert
    - Conservation of mass/momentum/ energy
    - New particles are placed at (±0.5, ±0.5, ±0.5)







  - After conversion
    - Particles and remaining elements are coupled by the local multi-mesh contact method

YP Lian, X Zhang et al. An adaptive finite element material point method and its application in extreme deformation problems. *CMAME* 241-244 (1): 275~285, 2012

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MPM3D - 3D explicit MPM code

MPM3D-F90: Open source
http://www.mpm3d.com

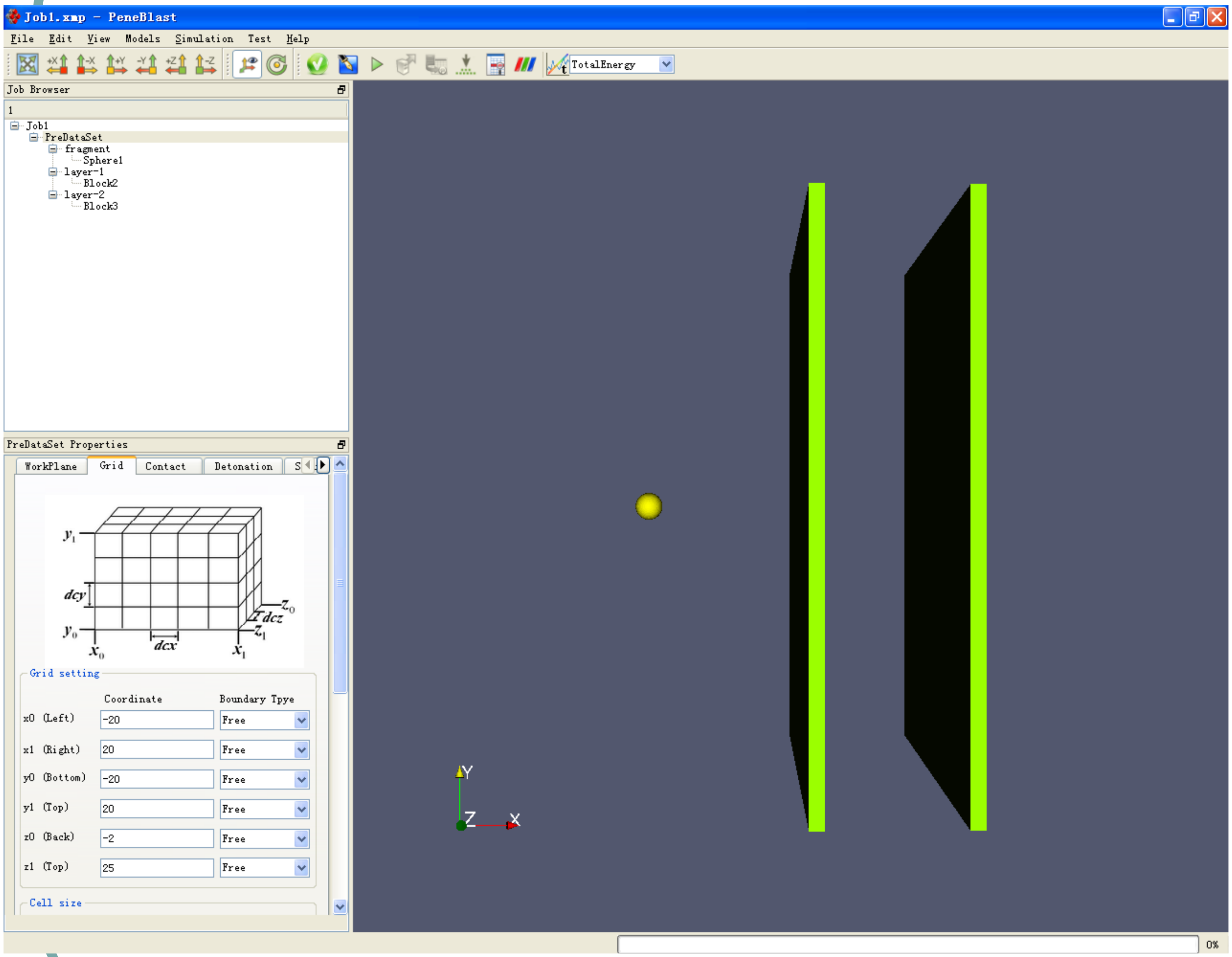
- MPM3D solver
  - Algorithm
    - MPM / GIMP (USF, USL & MUSL)
    - FEM
    - HFEMP、CFEMP and AFEMP
  - Material models
    - Elasticity, plasticity (hardening, temperature, strain rate)
    - Fluid, High explosive
    - Concrete, Ceramic, rubber, Foam, Soil …
  - Equation of states
    - Solid
    - Fluid
    - High explosive
  - Failure models
    - Hydrodynamic tensile failure; Effective plastic strain
    - Principal stress failure; Principal strain failure

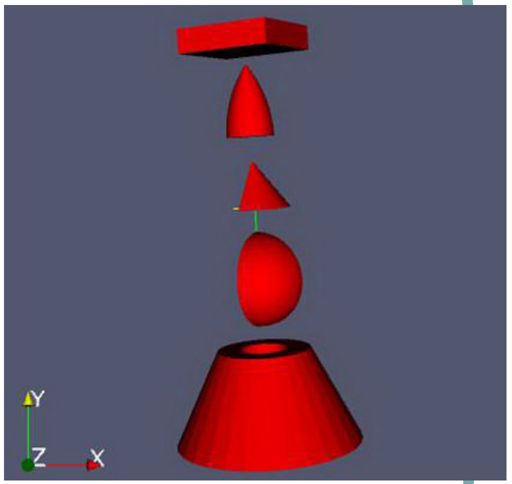
MPM3D - 3D explicit MPM code

- Graphical User Interface (GUI)
  - Preprocessor
    - Create 3D solid models & Particle discretization
    - Setup solution parameters
    - Generate input data for solver
  - Solution process monitor
    - Call MPM3D solver to solve the model
    - Real Time Monitoring (Energy, momentum, animation)
    - Interactive steering (Pause/Resume/Restart/Stop)
    - Auto-testing
  - Postprocessor
    - Solver ➔ ParaView (http://www.paraview.org)
  - Cross platform (Windows, Linux, Mac OS X)

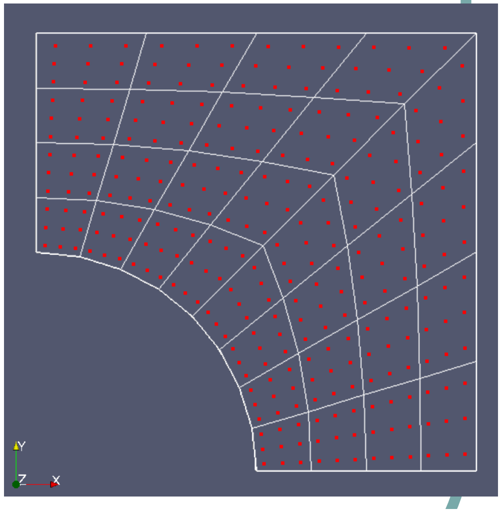
MPM3D - 3D explicit MPM code

Preprocessor - Modeling





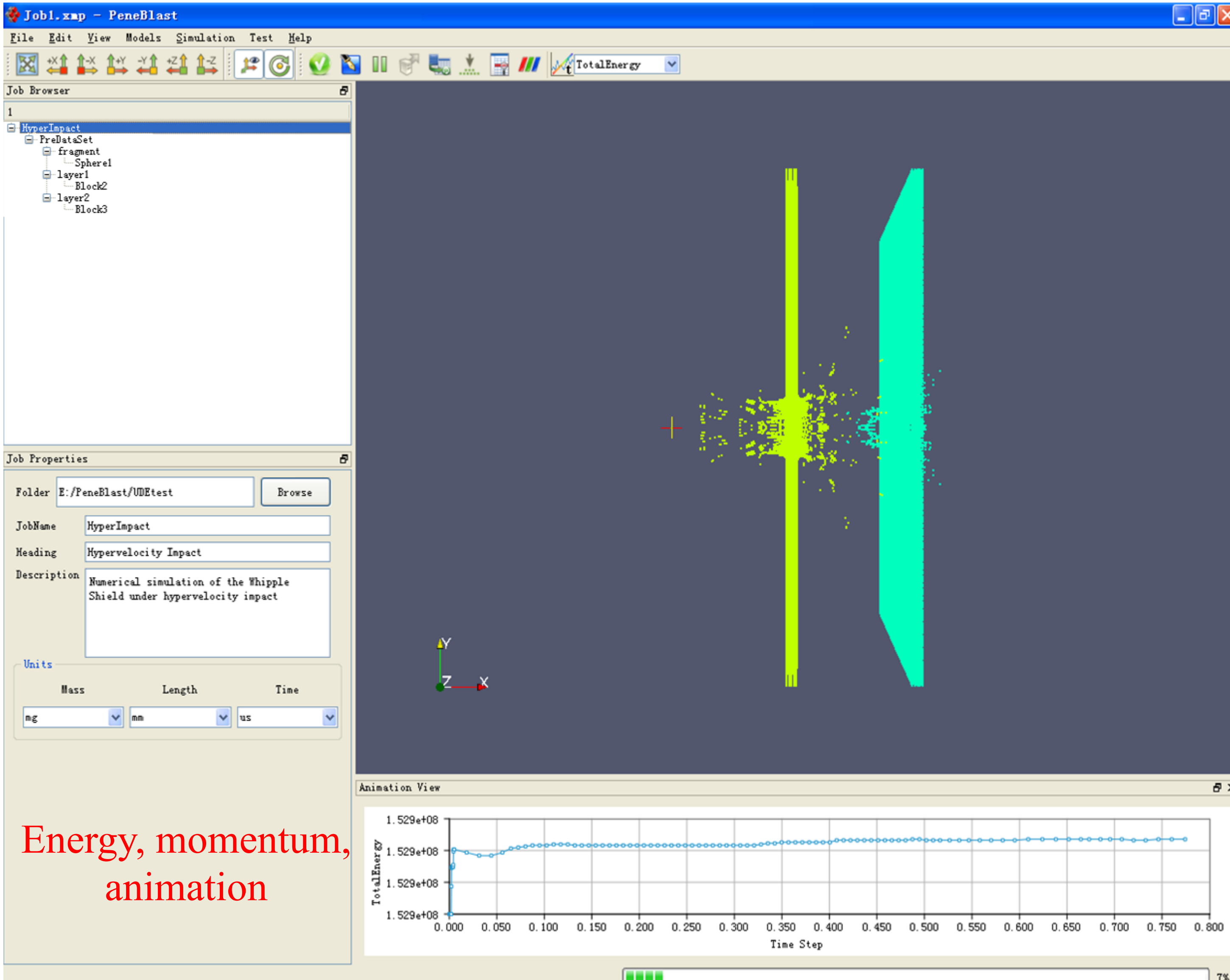
Regular Bodies



User-defined entity

MPM3D - 3D explicit MPM code

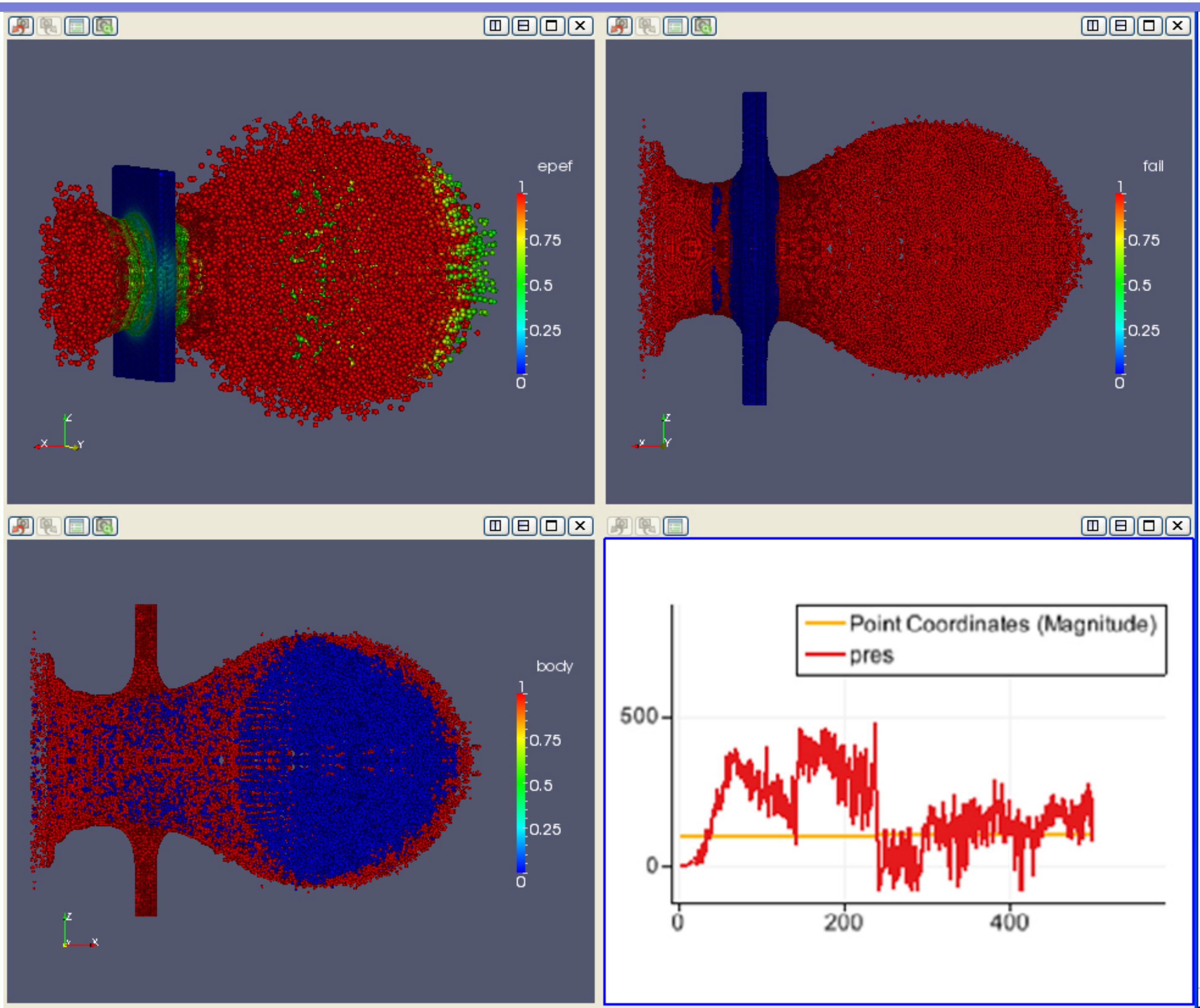
Real time monitoring



Energy, momentum, animation

MPM3D - 3D explicit MPM code

Postprocessor - ParaView



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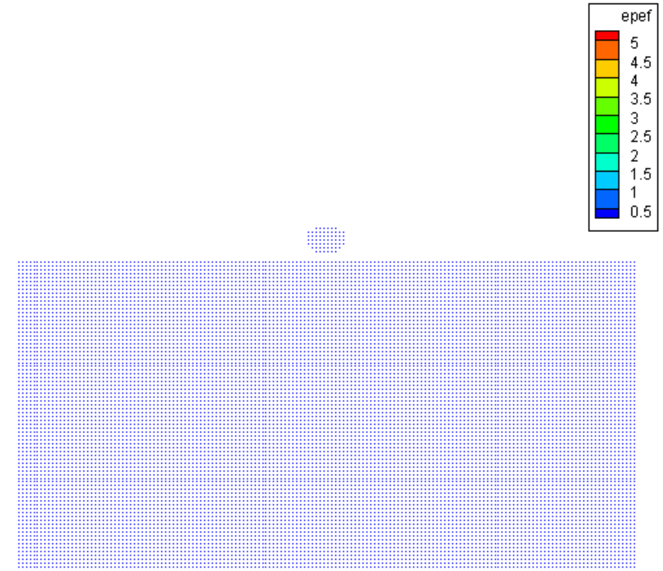
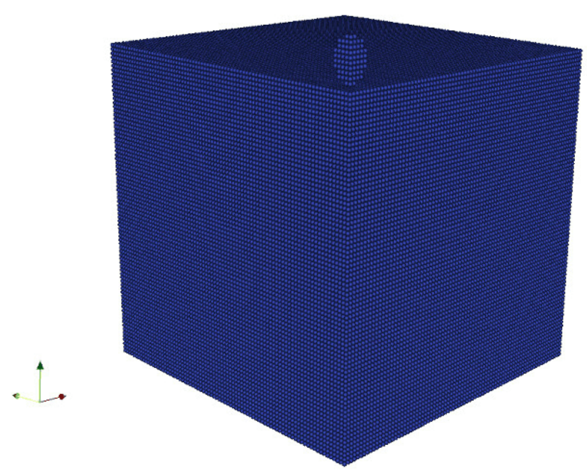
Applications

Crater forming

- Impact velocity： 6.0 km/s
- Projectile mass： 0.5 g
- *L* = 80mm, *H* = 40mm
- **1,024,224** particles
- Run 1h 55m in P4 2.8G PC for simulation time of 32ms
- Time step size = 46.2 μs
- Steps: 692 steps

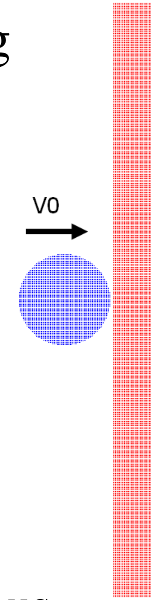
	Deepness (mm)	Crater diameter (mm)	Deepness/ Diameter
Experiment*	14	25.4	55
EPIC	18	24	75
MESA	15.9	28	57
SPH	17.3	26	67
CALE	15.1	24.4	62
MPM3D	14	25	56





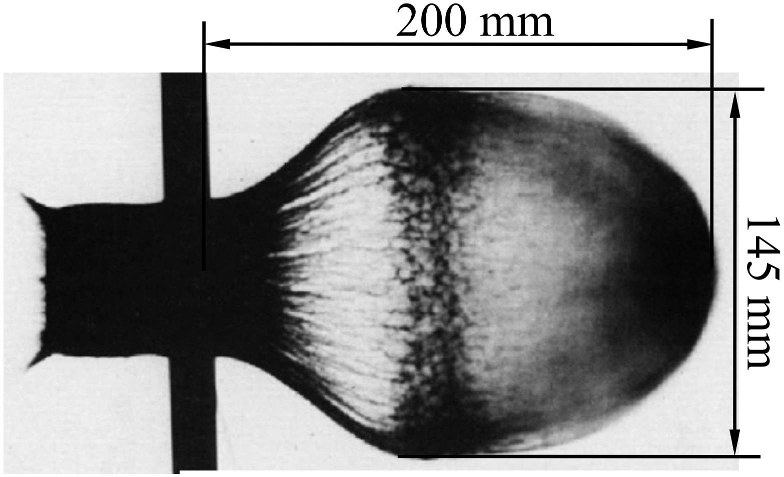
Applications

- Projectile: Lead sphere, r =7.5mm, m = 20g
- Target: Lead plate, t = 6.35 mm
- Impact velocity: v_0 = 6.58 km/s
- Material model
  - Elastic-plastic constitutive model
  - Mie-Grüneisen EOS
- Material failure model
  - Tensile Failure (P_{min} = −1500 MPa)
  - Plastic Strain Failure (ε_{pmax}= 3.0)

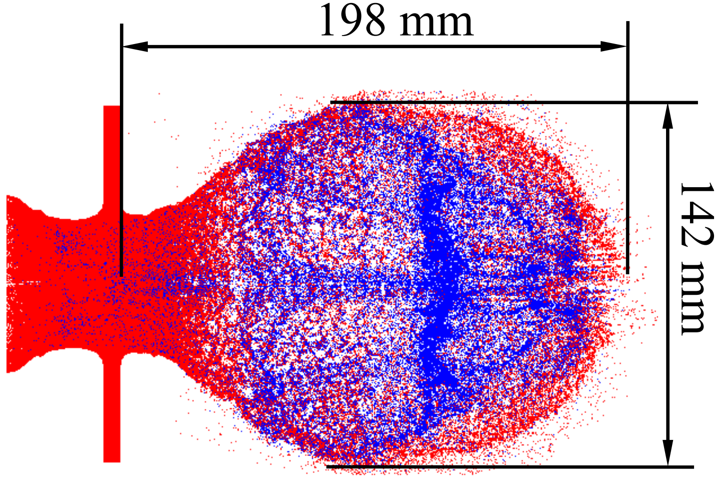


2 Quad-Core Xeon
2.66 GHz processors
(OpenMP): 1.93h

The debris cloud at 30.6 μs



Experimental radiograph (Anderson, 1990)

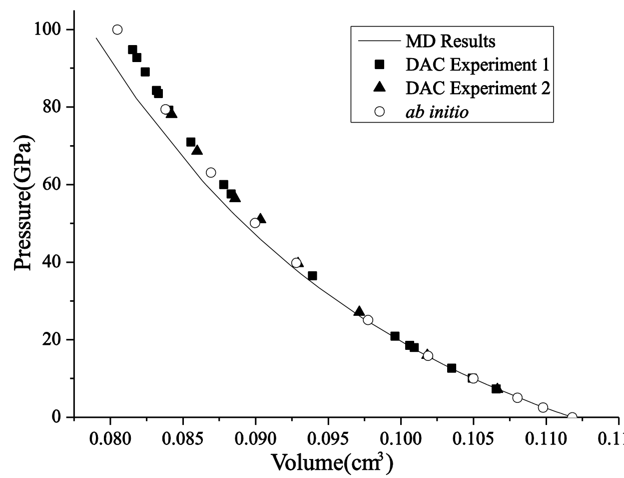


13,542,030 particles

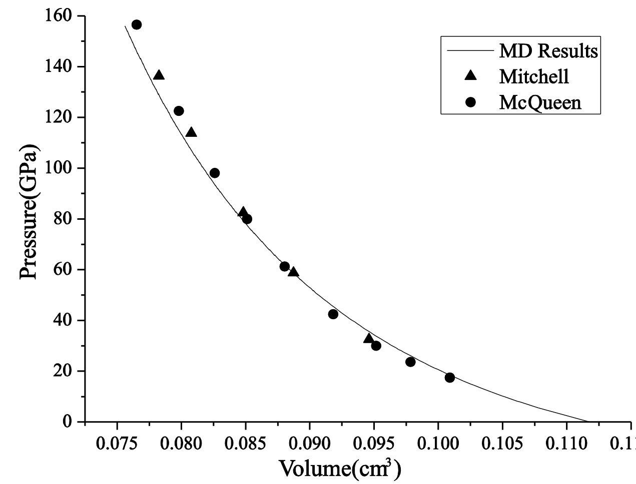
Applications

Phase transition (solid -> liquid -> gas) may occur in hypervelocity impact
Require an EOS covering a large range of points in the phase space

MD computation
↓
E, *V*, *P*, *T*
↓
Material constants of GRAY EOS
↓
MPM simulation



Isothermal compression curves at 293K



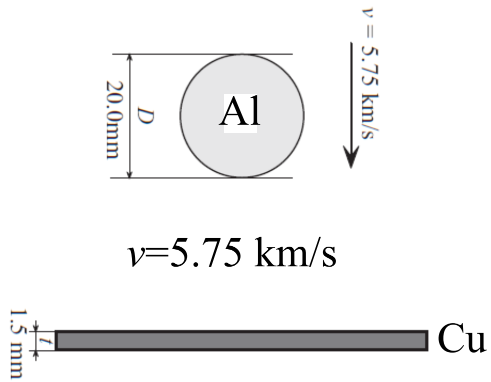
Hugoniot curves

Material constants of GRAY EOS

	V_0(cm³/g)	C(cm/μs)	S	γ_0	a	g_e(kJ/(moleK²))	T_m(K)
Experiment	0.1118	0.394	1.489	1.97	1.5	4.9×10^{-7}	1790
MD fitting	0.1119	0.398	1.301	1.86	1.7	8.3×10^{-7}	2006

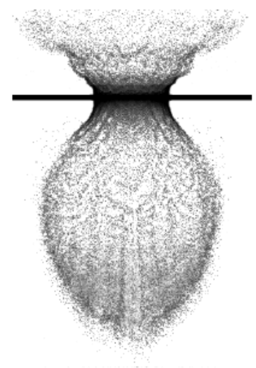
Y Liu, HK Wang, X Zhang. A Multiscale Framework for High-velocity Impact Process with Combined Material Point Method and Molecular Dynamics. ***International Journal of Mechanics and Materials in Design***. 9(2): 127-139, 2013

Applications

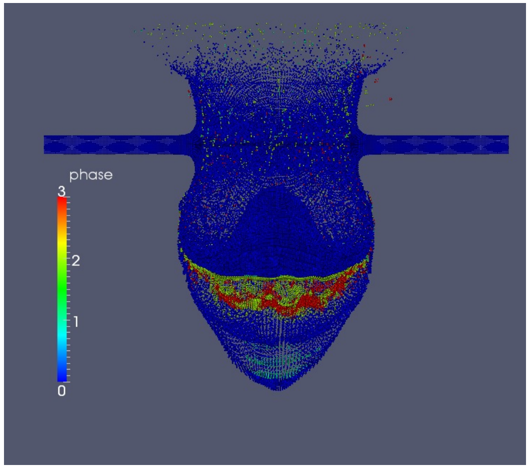


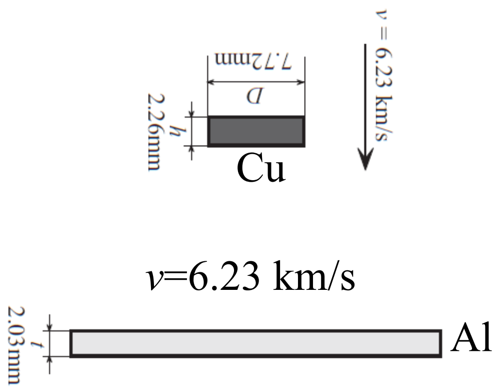
Experiment

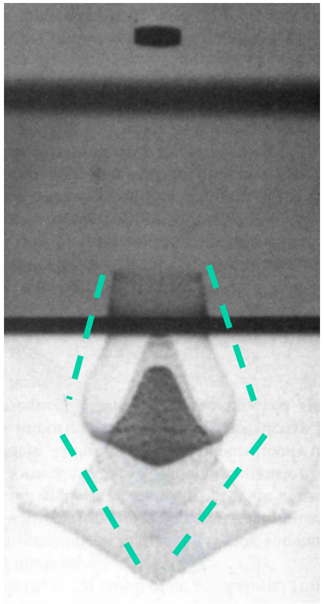
MPM3D



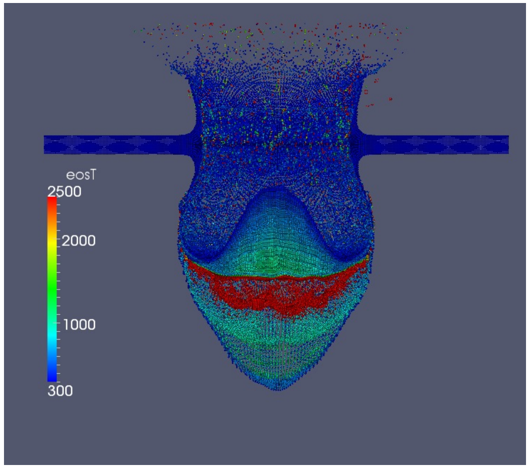
Phase transition







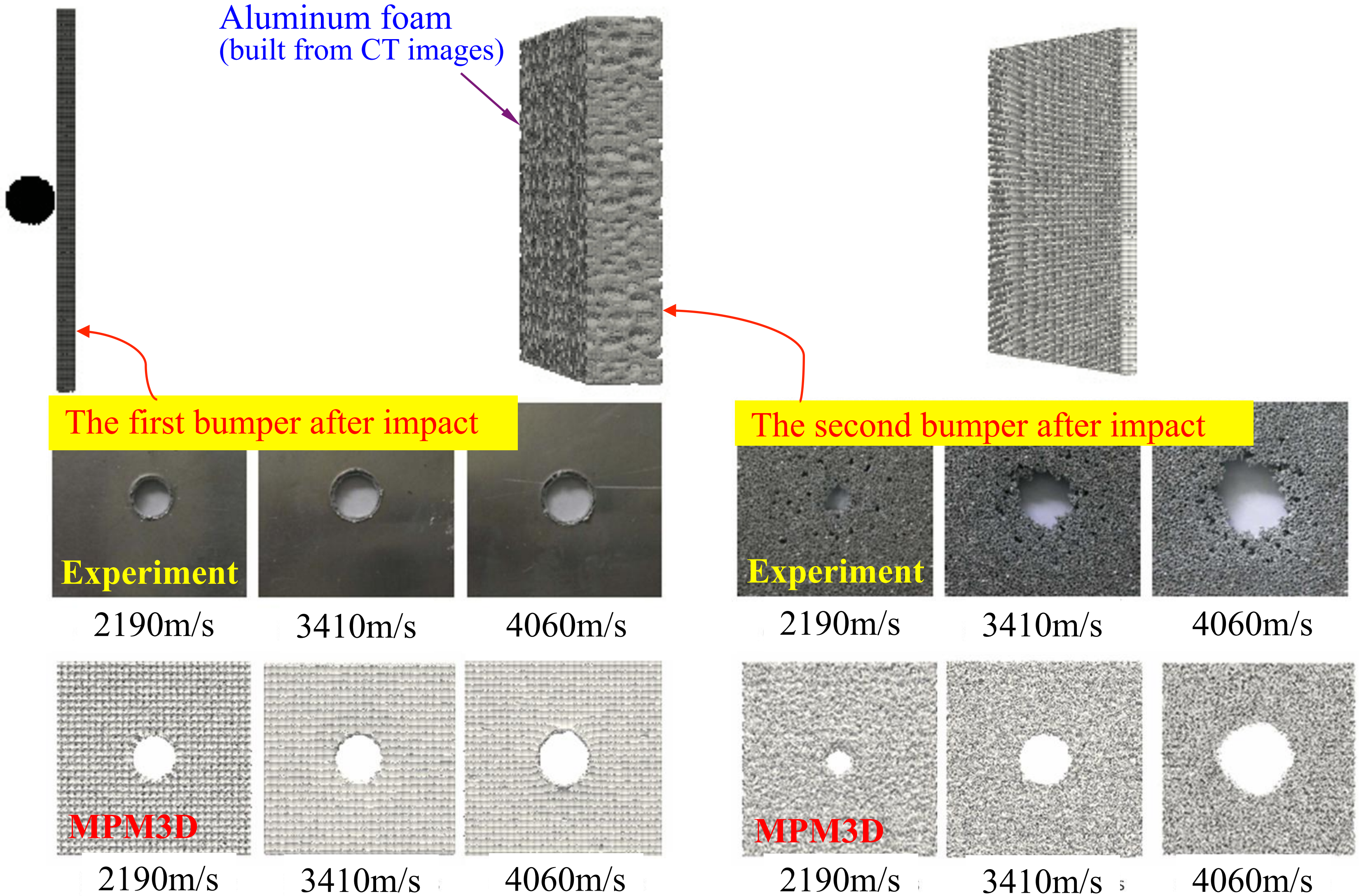
Temperature



Cu-Al

Applications

Space debris shielding



WW Gong, Y Liu, X Zhang. Numerical Investigation on Dynamical Response of Aluminum Foam Subject to Hypervelocity Impact With Material Point Method. *CMES* 83(5): 527-545, 2012

Applications

Penetration

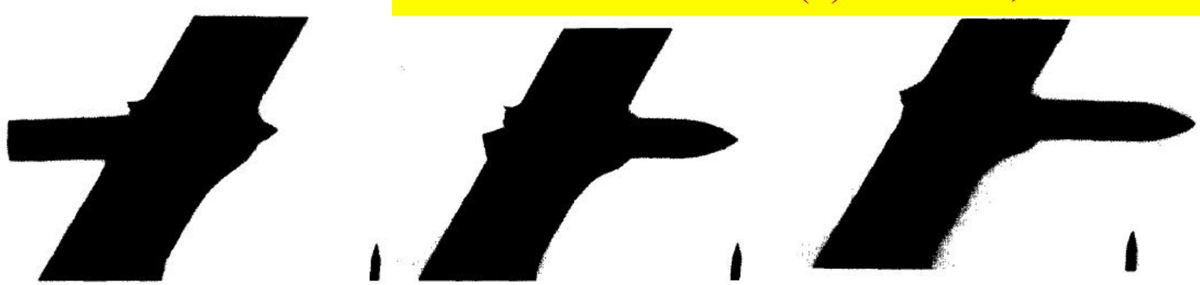
Projectile: Steel
- Length: 88.9 mm
- Diamete: 12.9 mm
- Velocity: 575 m/s
- Particles: 13,314

Target: Aluminium
- Thickness: 26.3mm
- Inclination: 30°
- Particles: 187,550

Projectile's residual velocity
- Experiment: 455 m/s
- MPM3D: 453.4 m/s

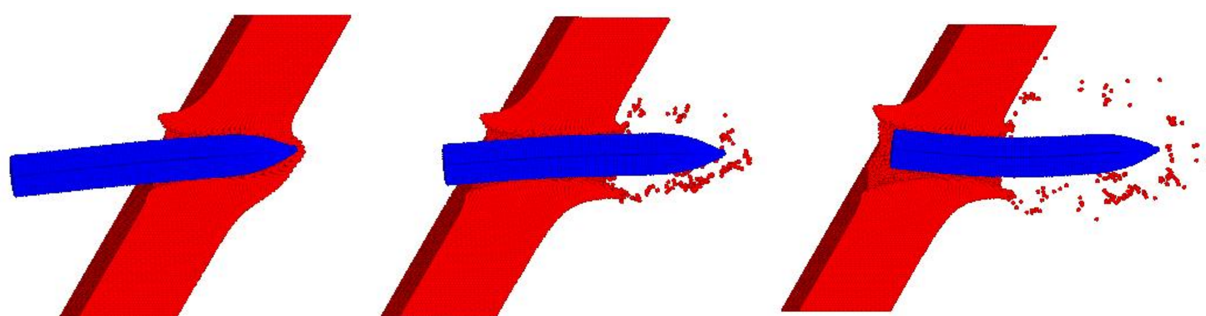
P Huang, X Zhang et al. Contact Algorithms for the Material Point Method in Impact and Penetration Simulation. ***IJNME*** 85(4): 498-517, 2011

Experiment: Piekutowski, Forrestal et al. ***IJIE*** 1996; 18: 877-887



t = 82.9 μs | *t* =152.8 μs | *t* =194.4 μs

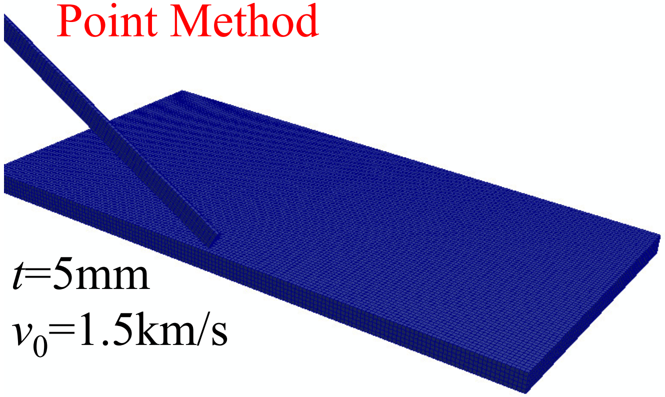
MPM3D



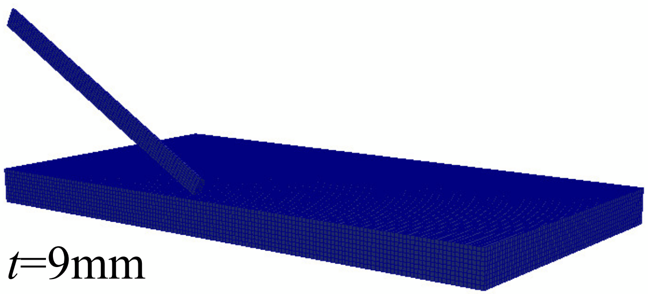
Applications

Penetration

Adaptive Finite Element Material Point Method



t=5mm
v_0=1.5km/s

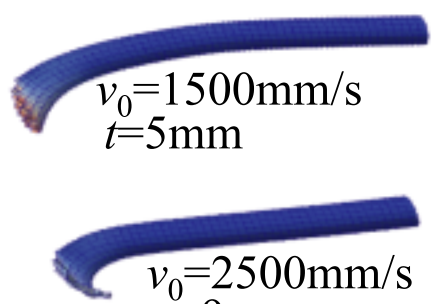


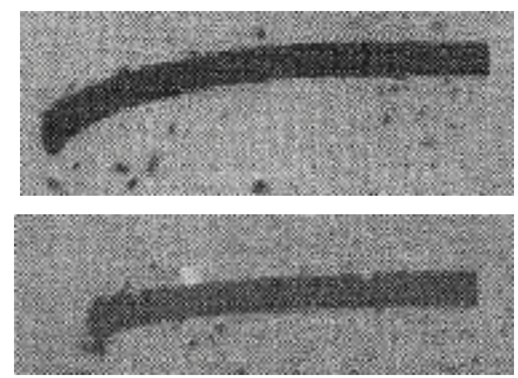
t=9mm
v_0=2.5km/s

Projectile: Tungsten alloy
L_0 = 75, D_0 = 5mm
v_0 = 1500 m/s
Incidence angle = 60°

Target: Armor steel
t = 5/9 mm
L_0=150 mm
W_0 = 150 mm

Cases		Residual length L/L_0	Residual velocity v/v_0
t=5 v_0=1.5	Experiment	0.85	0.97
	MPM3D	0.82	0.96
t=9 v_0=2.5	Experiment	0.76	0.99
	MPM3D	0.72	0.97





MPM3D **Experiment**

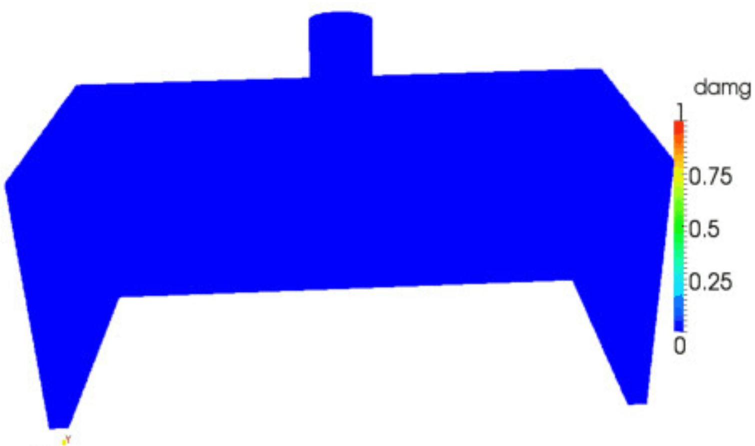
YP Lian, X Zhang et al. An adaptive finite element material point method and its application in extreme deformation problems. *CMAME* 241–244 (1): 275–285, 2012

Lars Holmberg, Patrik Lundberg et al. ***14th Inter. Sympo. Ballistics.*** 1993; 515-524

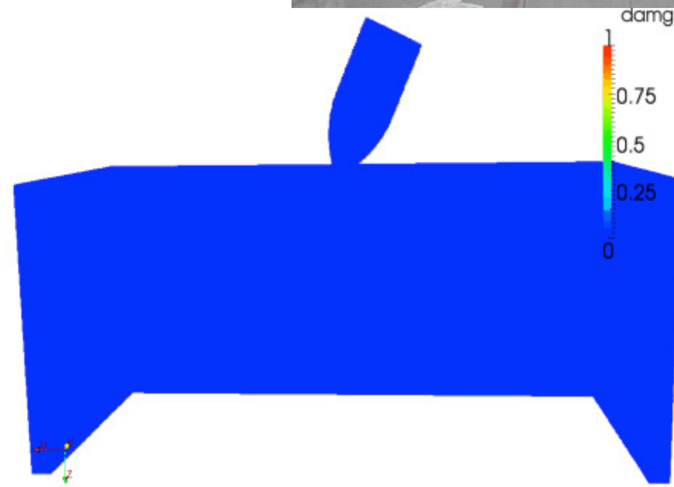
Applications

Impact Velocity (m/s)	Residual Velocity (m/s)		Perforation Pore Diameter (mm)	
	Experiment	MPM3D	Experiment	MPM3D
257.5	100.7	100	780×710	900×1000
248.3	83.7	83	930×730	1000×1000

Hybrid Finite Element Material Point Method



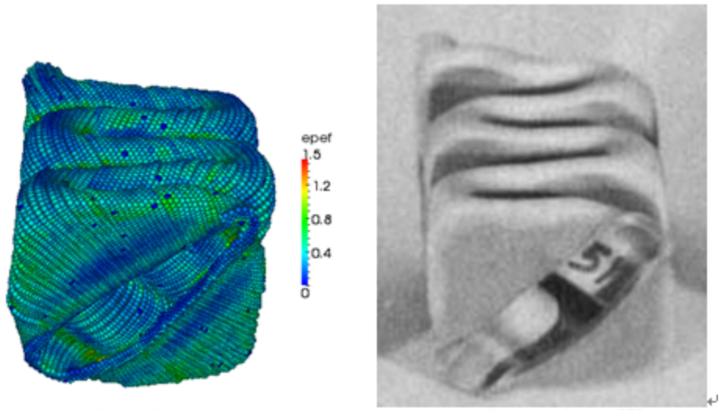
Impact velocity: 257.5 m/s
Incident angle: 1°



Impact velocity: 248.3 m/s
Incident angle: 24.5°

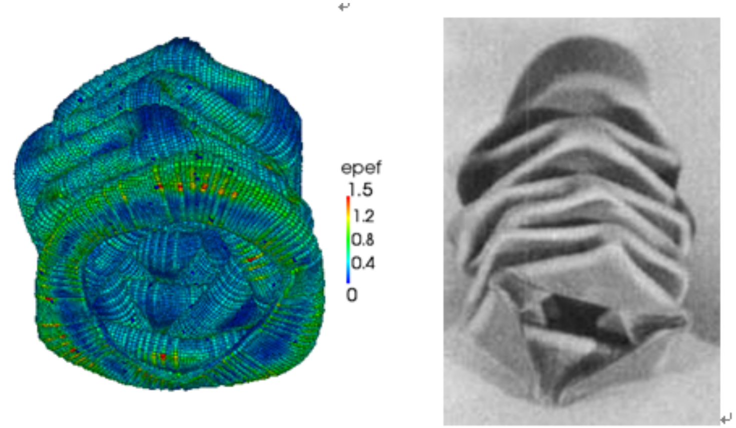
YP Lian, X Zhang et al. A FEMP method and its application in modeling dynamic response of reinforced concrete subjected to impact loading. ***Computer Methods in Applied Mechanics and Engineering***, 200(17-20): 1659-1670, 2011

PVC tube: Effect of normalized thickness/diameter ratio



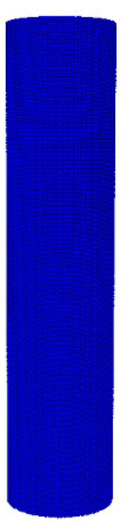
(a) simulation (b) experiment [7]

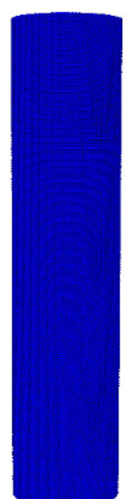
t/d=0.063 $\bar{P} = 2.7\text{kN}$



(a) simulation (b) experiment [7]

t/d=0.038 $\bar{P} = 1.0\text{kN}$





PF Yang, SA Meguid, X Zhang. Accurate modeling of the crush behavior of thin tubular columns using material point method. ***SCIENCE CHINA Physics, Mechanics & Astronomy***. 56(2): 1~11, 2013.

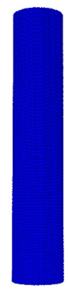
Applications

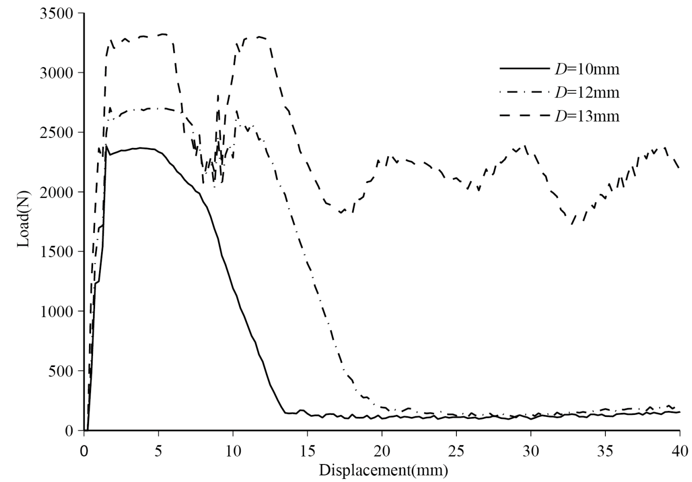
Crush of Thin Tubular Columns

PVC tube: Effect of normalized Length/Diameter ratio

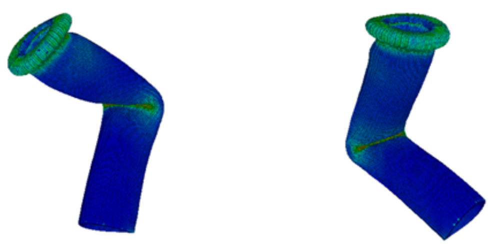
l/d=5.4

(a)with random weak particles (b) without random weak particles

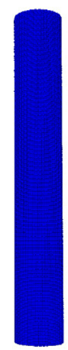




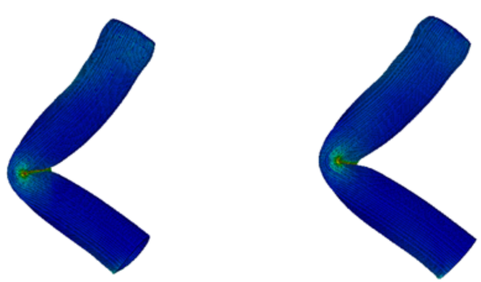
l/d=6.4



(a)with random weak particles (b)without random weak particles



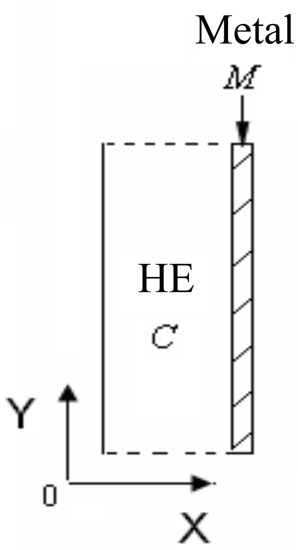
l/d=7.6

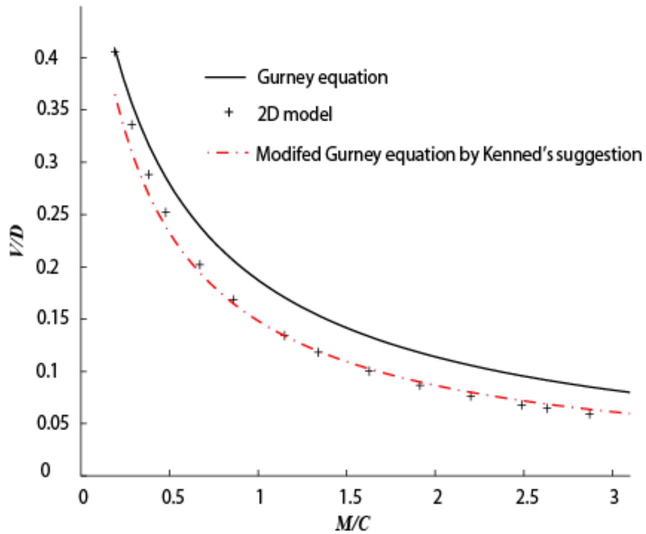


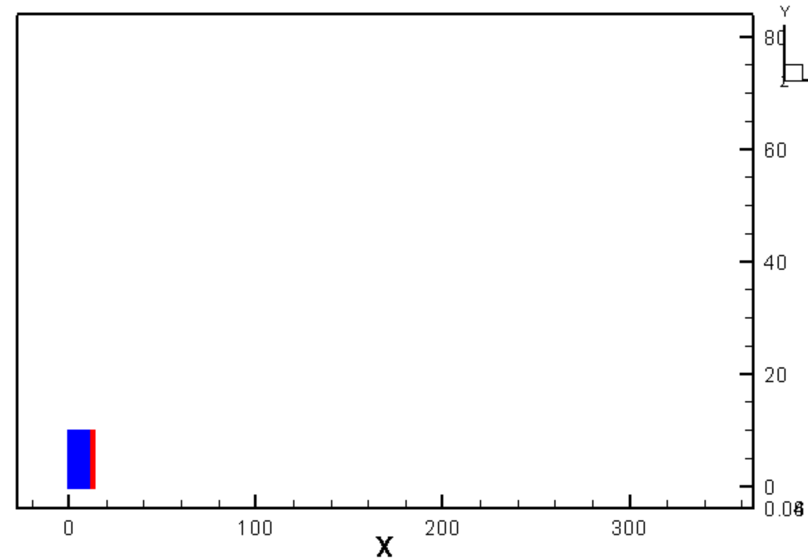
(a)with random weak particles (b) without random weak particles

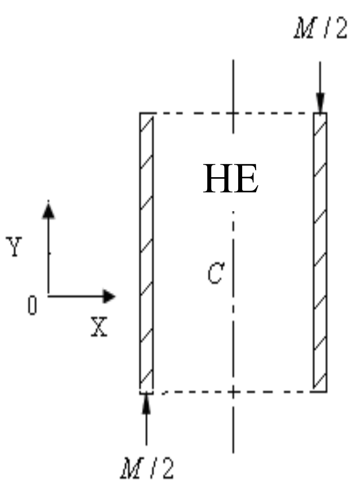
Applications

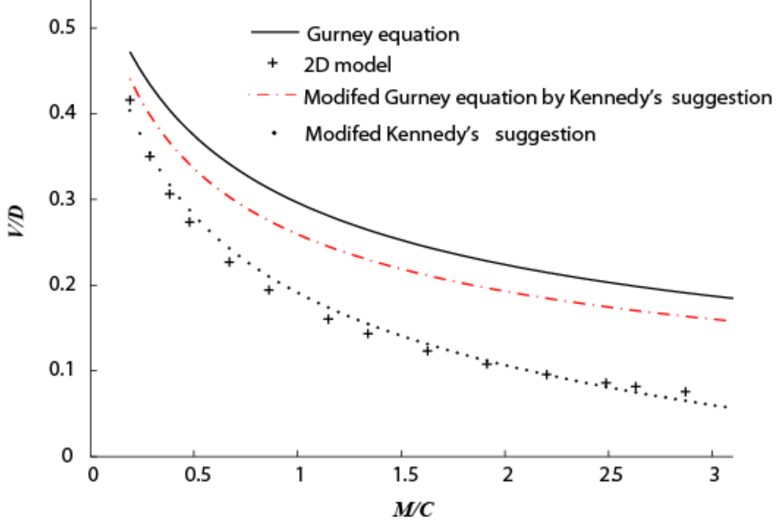
Explosive driven Metal







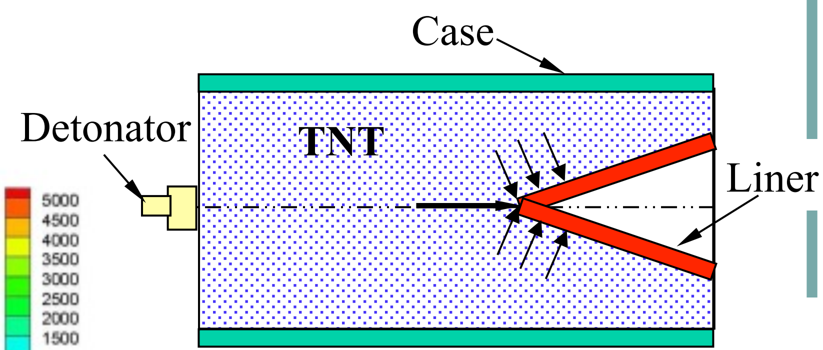


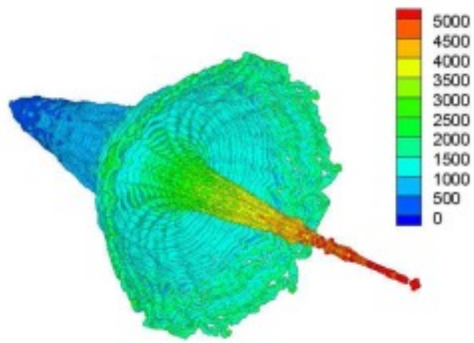


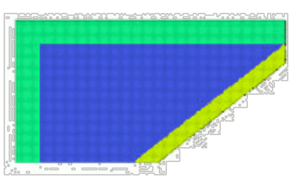
YP Lian, X Zhang et al. Numerical Simulation of Explosively Driven Metal by Material Point Method. ***International Journal of Impact Engineering***, 38(4): 238-246, 2011

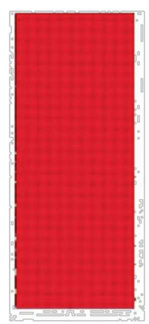
Applications

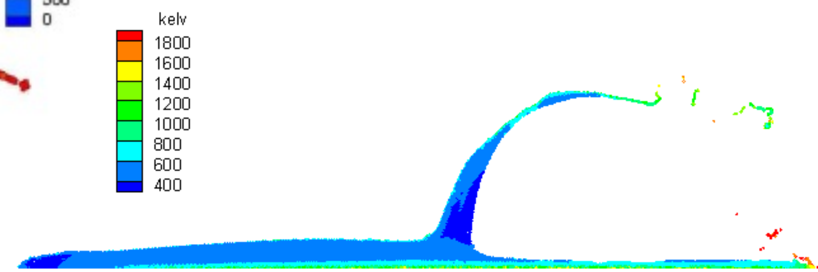
- Shaped charge
  - A cylinder of high explosive with a cone-shape thin metal liner in one end
  - Intense pressure ➔ Collapse of the liner ➔ A jet with extreme high velocity (> 10 km/s)
- Application
  - Armor penetration
  - Metal cutting
  - Oil well perforation



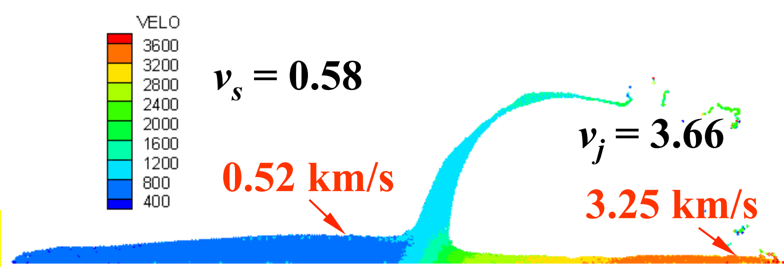








Temperature distribution



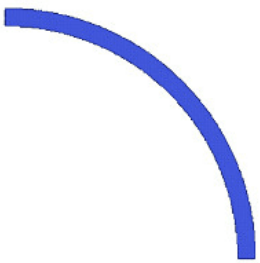
Velocity distribution

S Ma, X Zhang et al. Simulation of high explosive explosion using adaptive material point method, ***CMES: Computer Modeling in Engineering & Sciences***, 39(2): 101-123, 2009

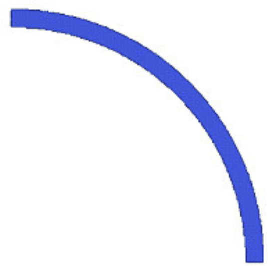
Applications

Fragmentation driven by explosion

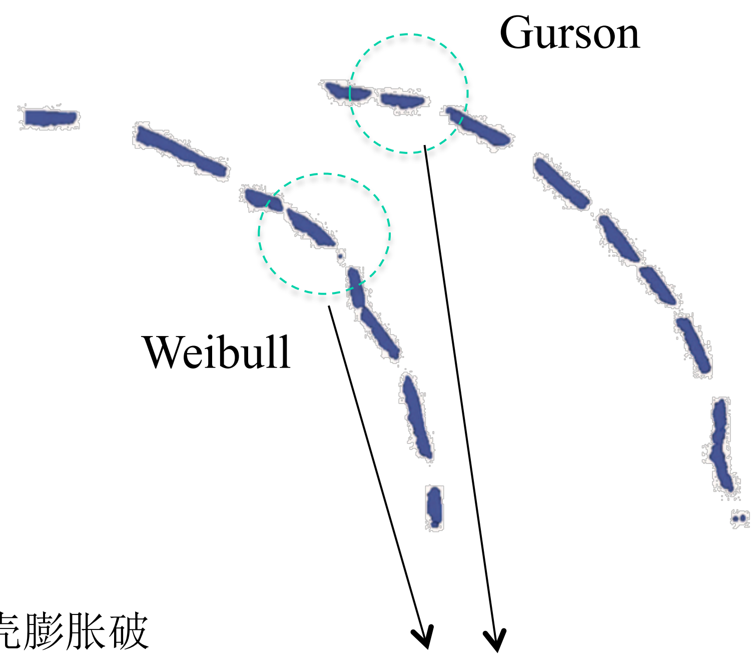
Metal shell driven by High explosive

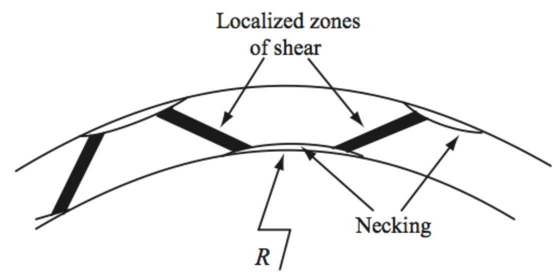


Weibull random failure



Gurson model





Experiment: 汤铁钢, 谷岩, 李庆忠. 爆轰加载下金属柱壳膨胀破裂过程研究. 爆炸与冲击, 2003, 23:529-533

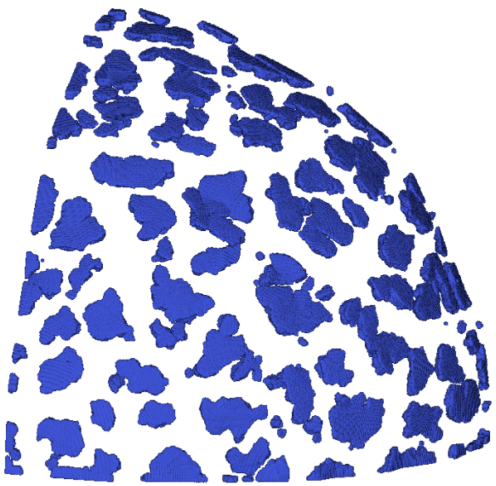
	Experiment	MPM3D with Weibull	MPM3D with Gurson
Fragmentation time (μs)	15.4	15.0	15.5

PF Yang, Y Liu, X Zhang et al. Simulation of Fragmentation with Material Point Method Based on Gurson Model and Random Failure. ***CMES: Computer Modeling in Engineering & Sciences***, 85(3): 207-236, 2012.

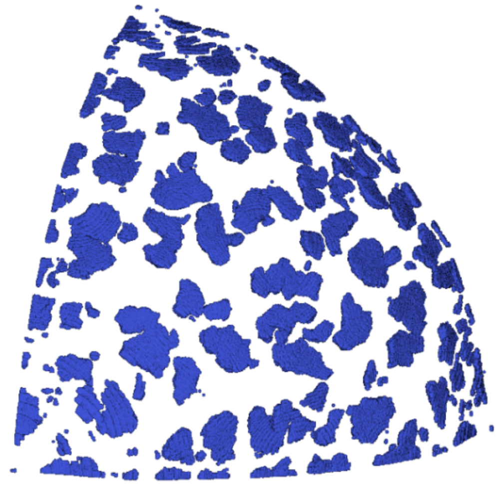
Applications

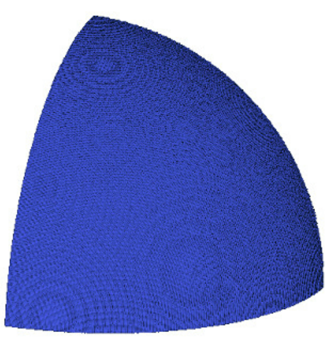
Fragmentation driven by explosion

Weibull random failure

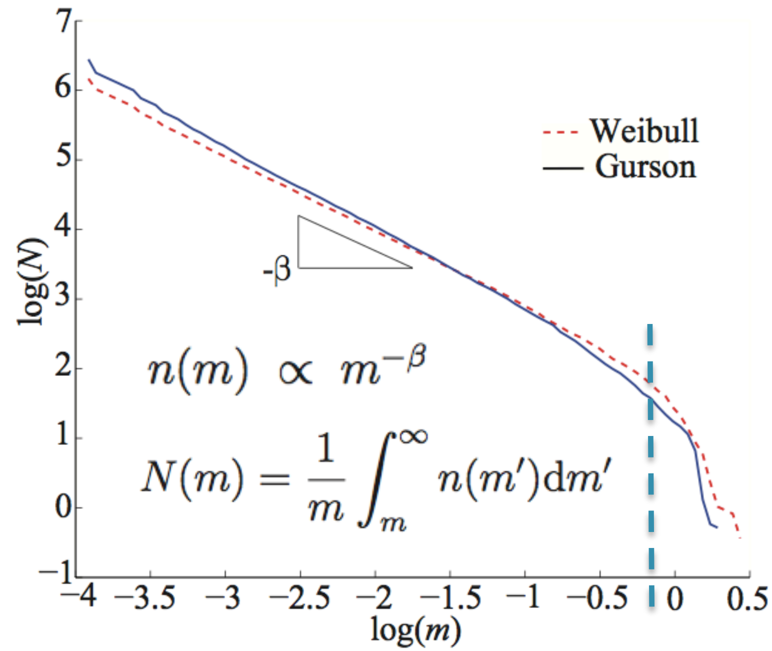


Gurson model





Cumulative mass distribution of fragments



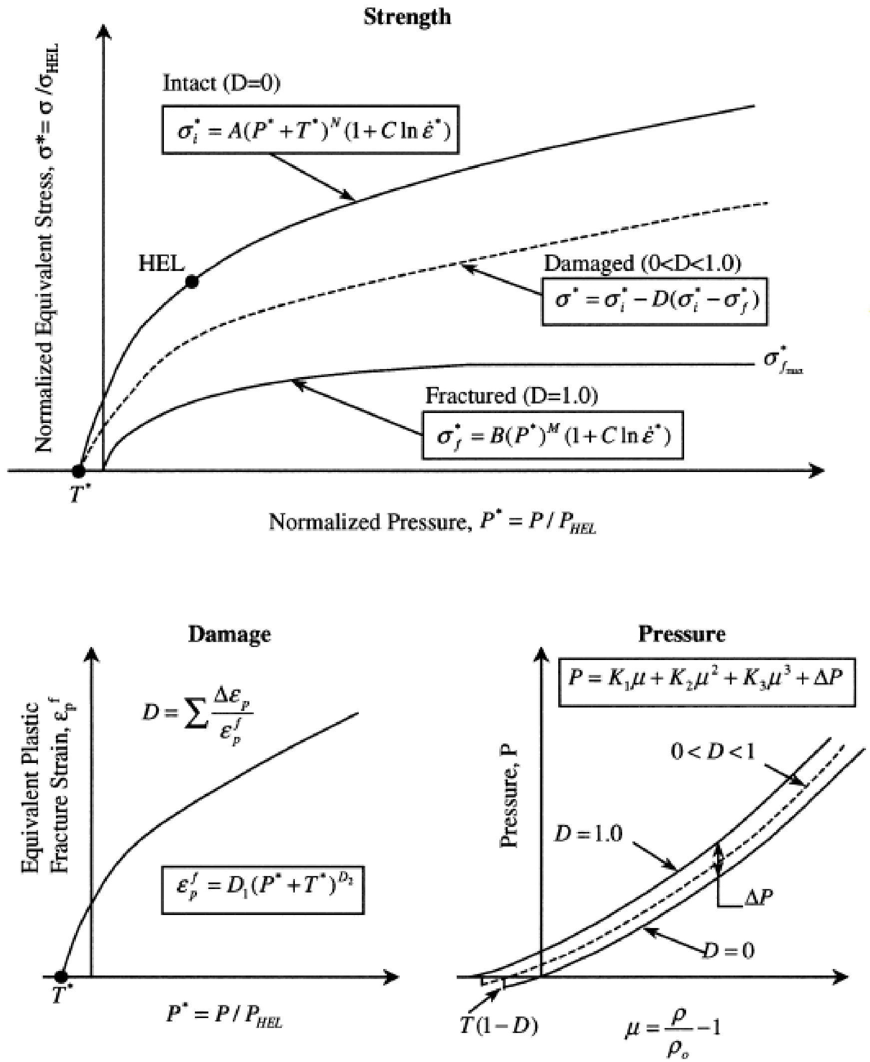
$$\beta_w = 1.06 \qquad \beta_g = 1.11$$

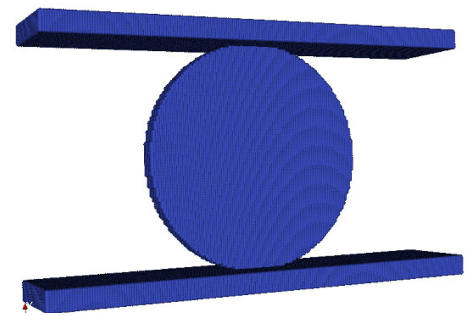
characteristic cutoff mass

$$m_0 = \rho h^3 = 0.4992\mathrm{g}.$$

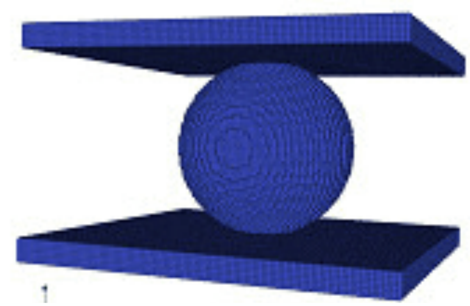
Applications

LS-DYNA MAT_110: JH-2





Crush of a ceramic plate

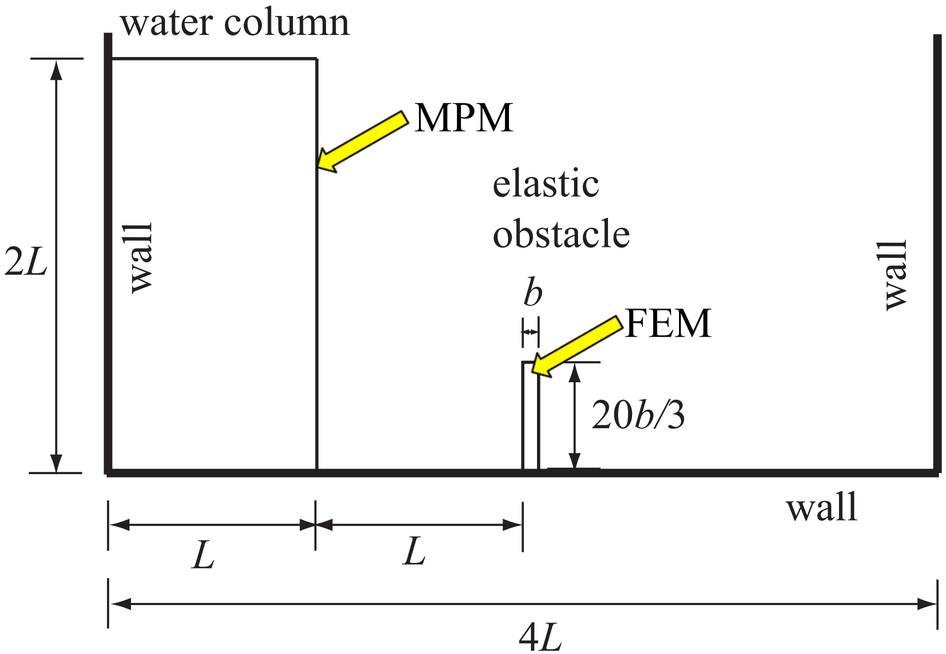


Crush of a ceramic ball

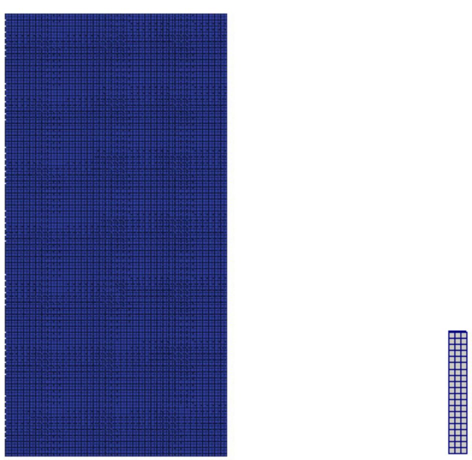
Cutting a ceramic block

Applications

Collapse of water column with a flexible obstacle



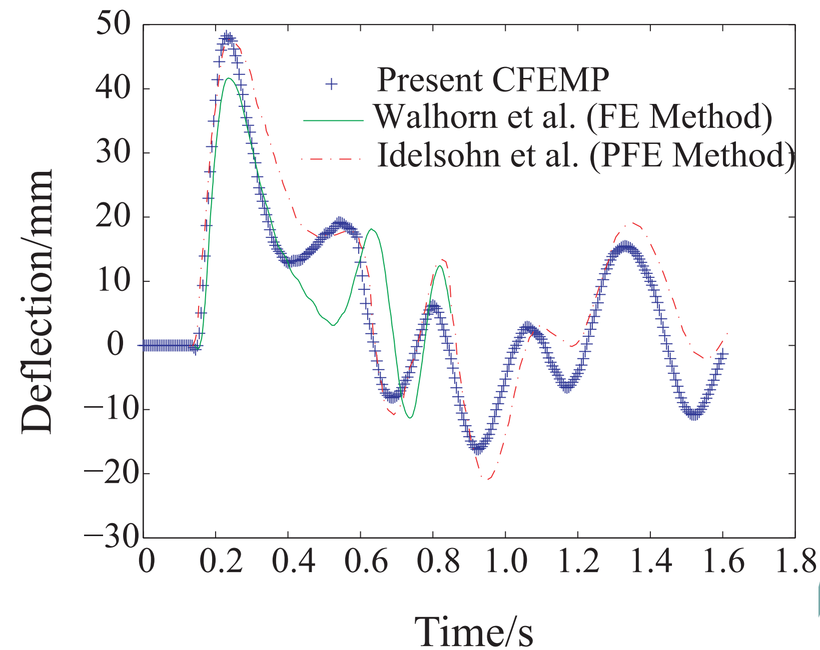
Coupled Finite Element Material Point Method



YP Lian, X Zhang. Coupling of finite element method with material point method by local multi-mesh contact method. *CMAME* 200: 3482-3494, 2011

Water column:
Particles: 21,316

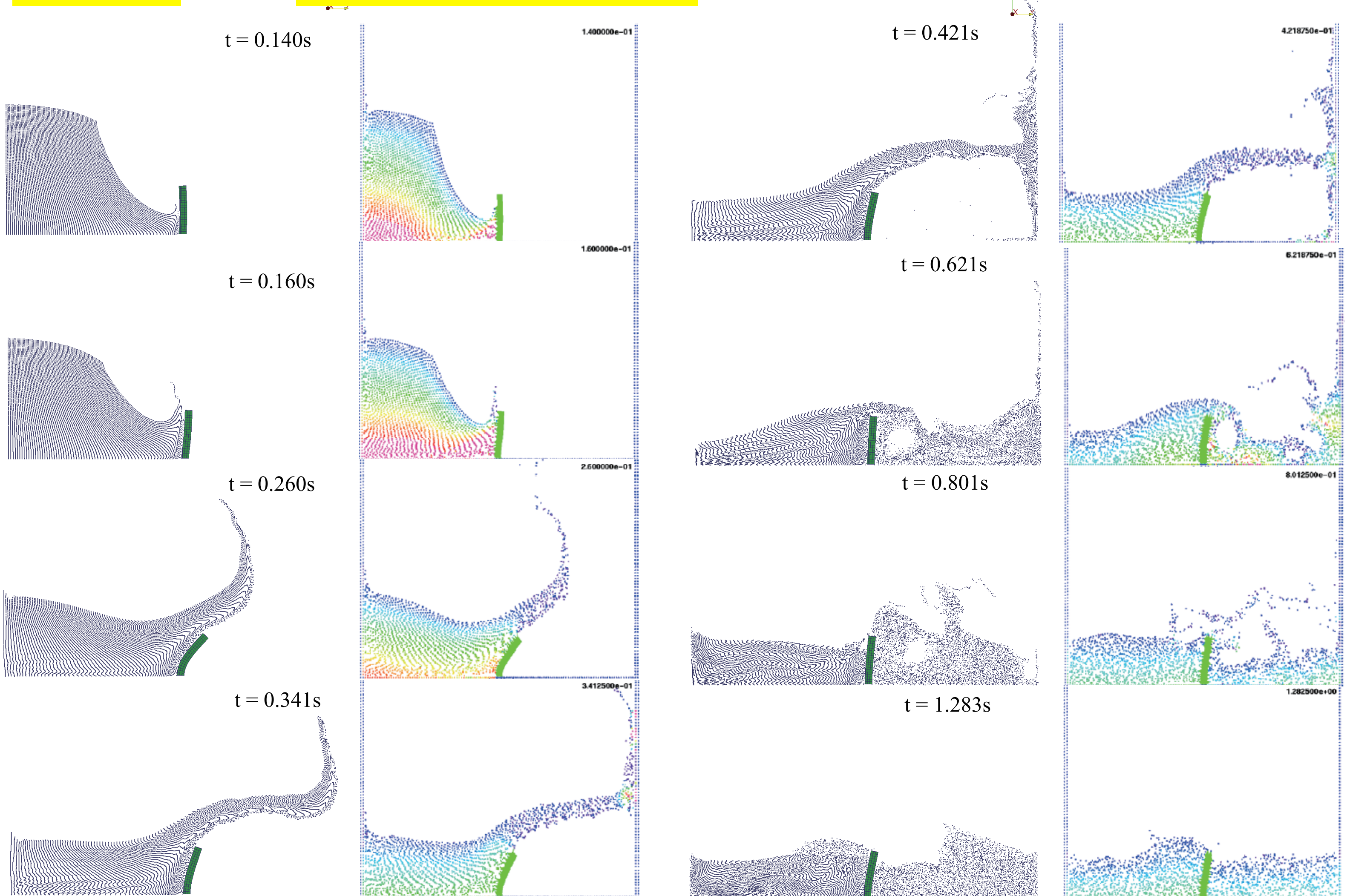
Flexible obstacle:
Elements: 120



Time history of the displacement of the upper left corner of the obstacle

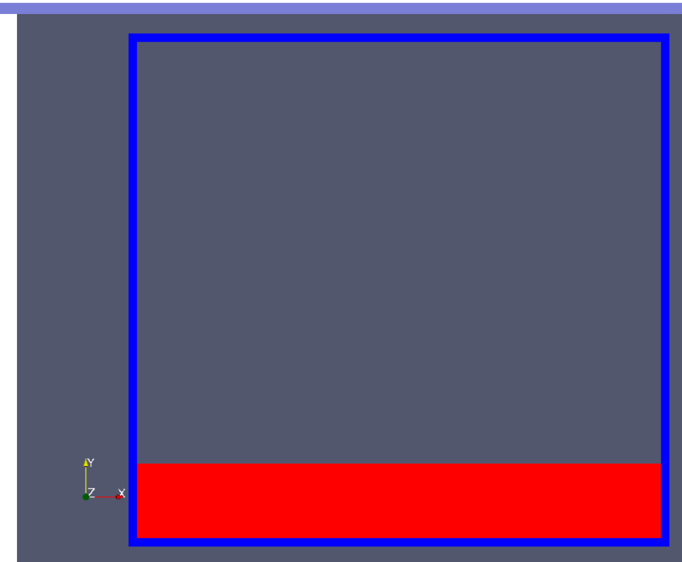
Applications

CFEMP PFEM(Idelsohn 2008)

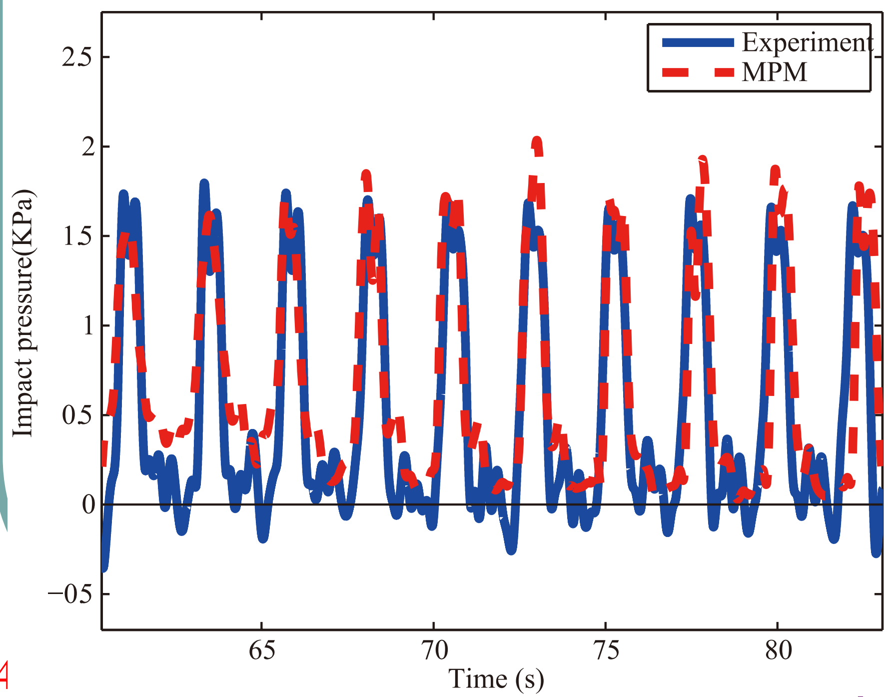


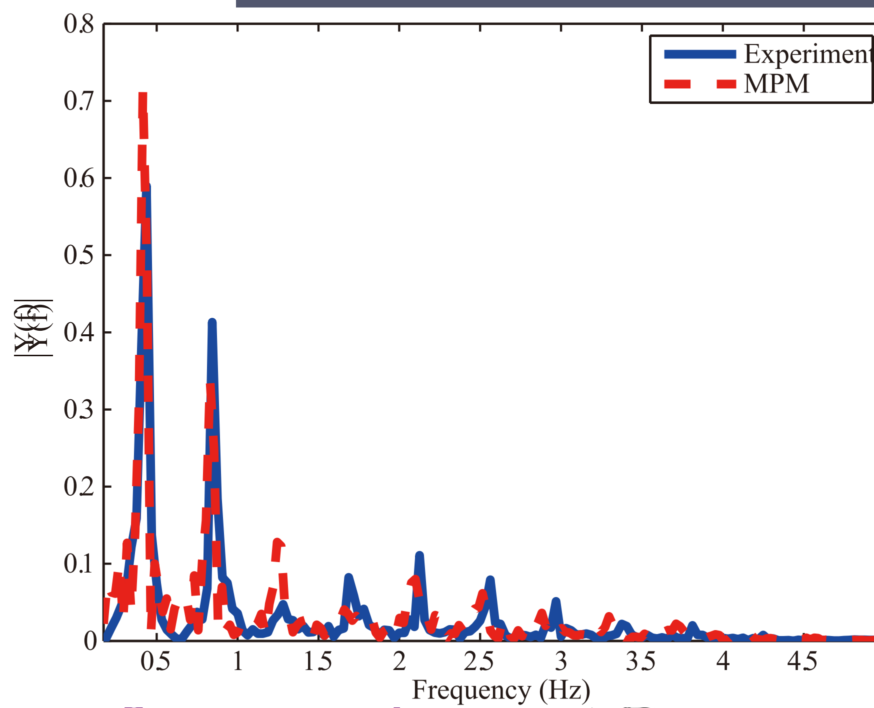
Applications

Fluid-Structure Interaction



Collaborated with Y Hamamoto. IHI, Japan.





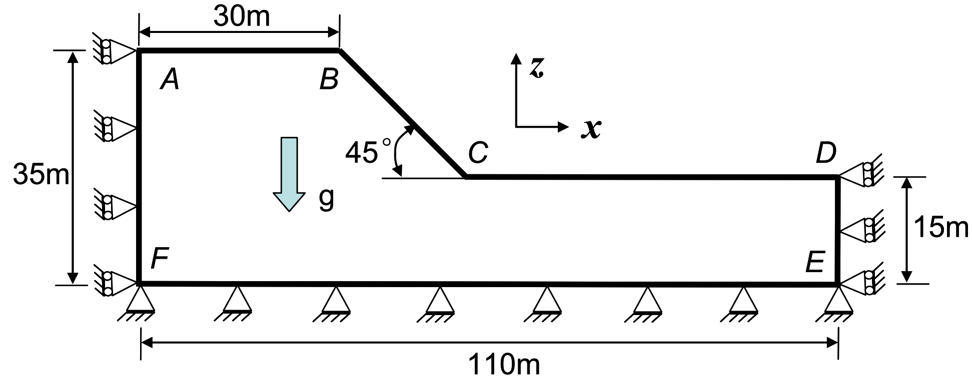
Applications

- **Non-cohesive soil**

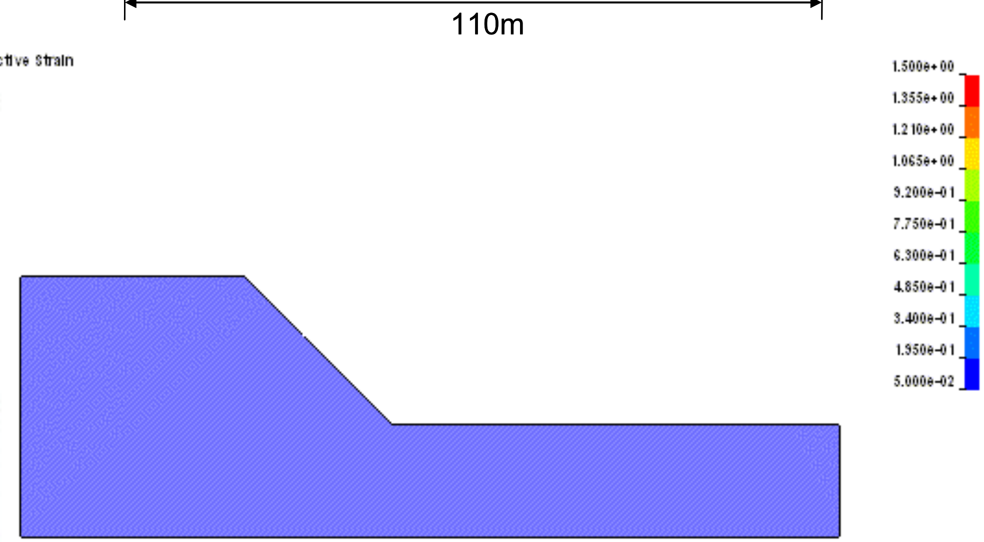
  Drucker-Prager model

  $\phi = 20°$; $\psi = 0^0$; $c = 0.1$ kPa

  E=70MPa, ν =0.3, ρ =2.1 g/cm3



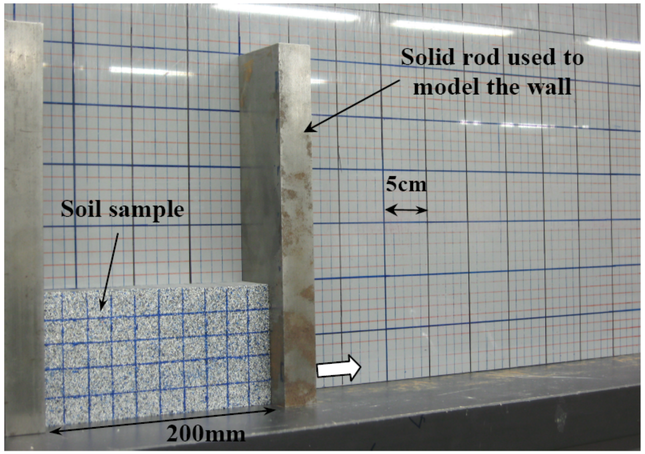
MPM3D： 9 minutes

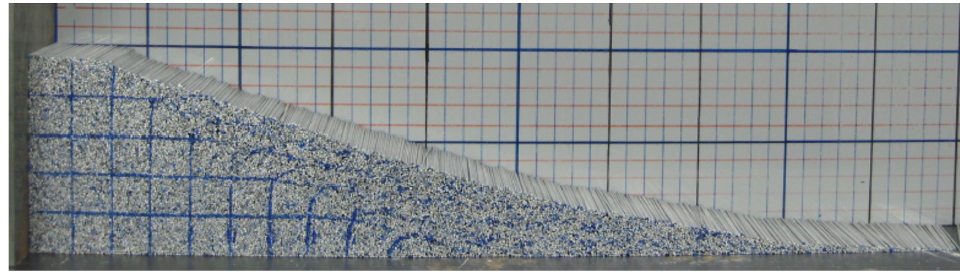


LS-DYNA (FEM): 468 minutes

Applications

Failure process of non-cohesive soil



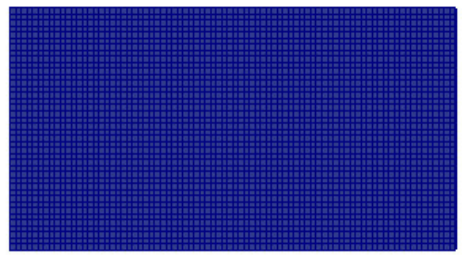


Bui H H, Japan: Ritsumeikan University, 2006

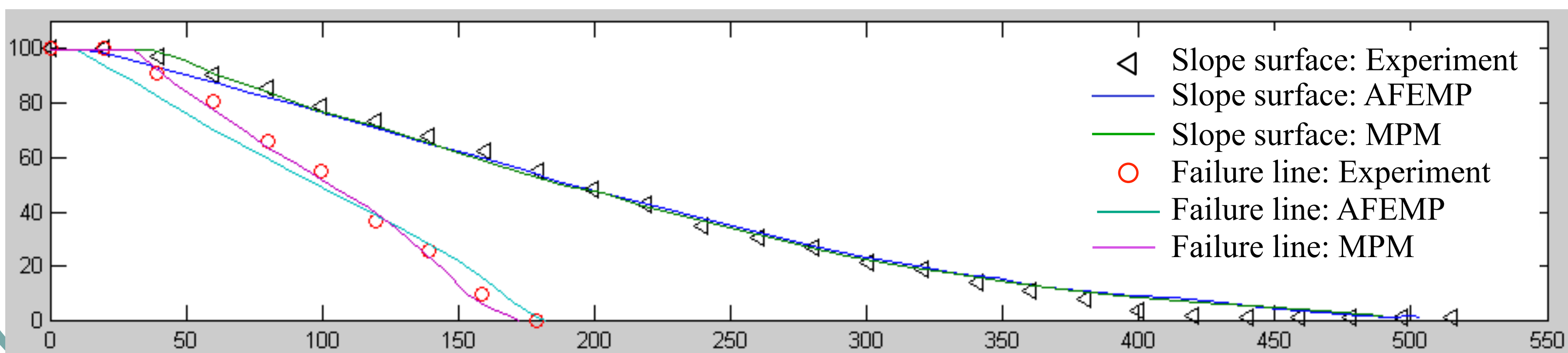
K=0.7MPa，ρ=2.65 g/cm^3

φ = 19.8° ; c = 0kPa;

ψ =0°

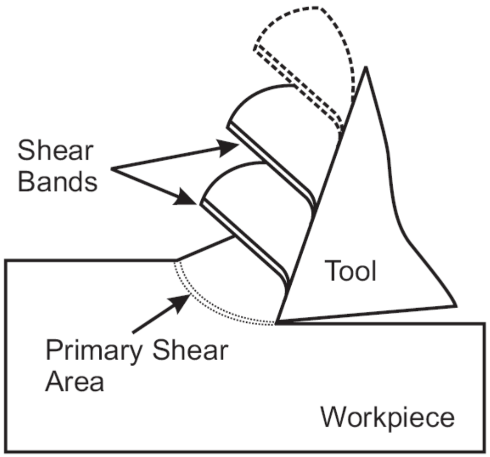


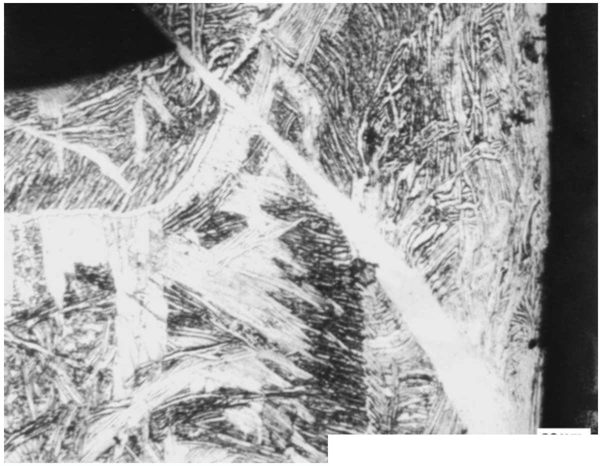
Adaptive Finite Element Material Point Method



Applications

Metal cutting process

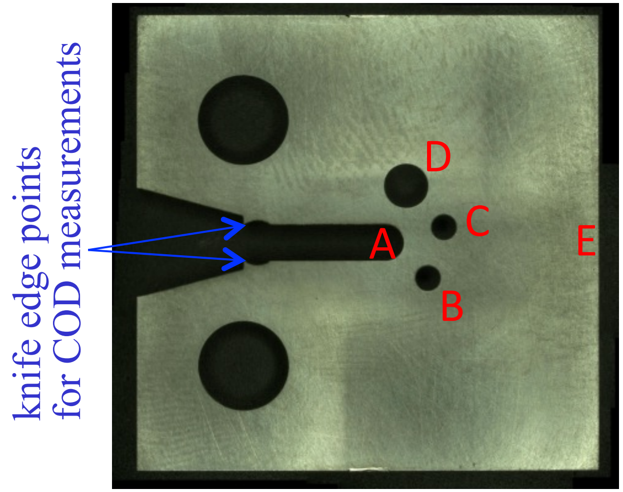




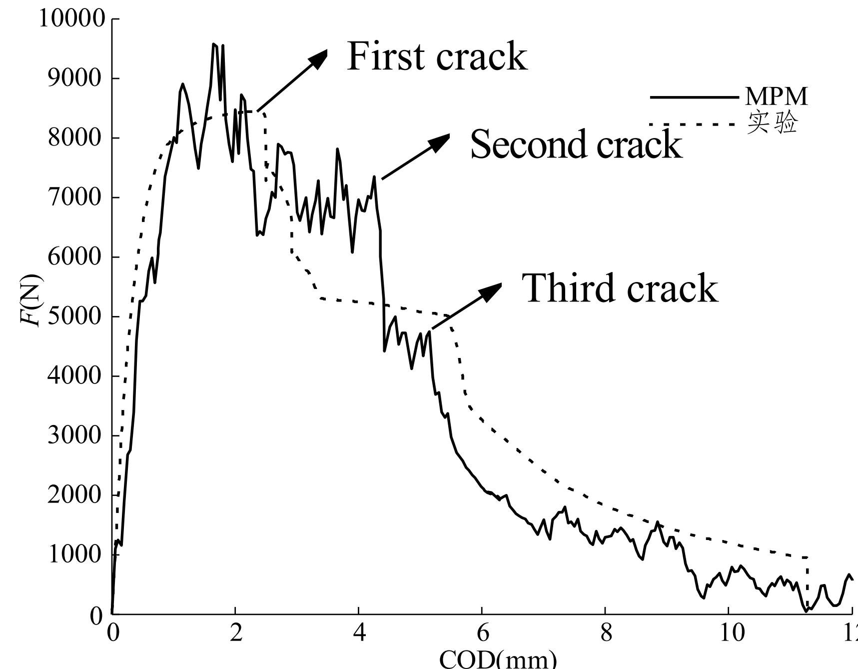
R. Ambati, H Yuan, XF Pan, X Zhang, Application of material point methods for cutting process simulations. ***CMS*** 57: 102-110, 2012

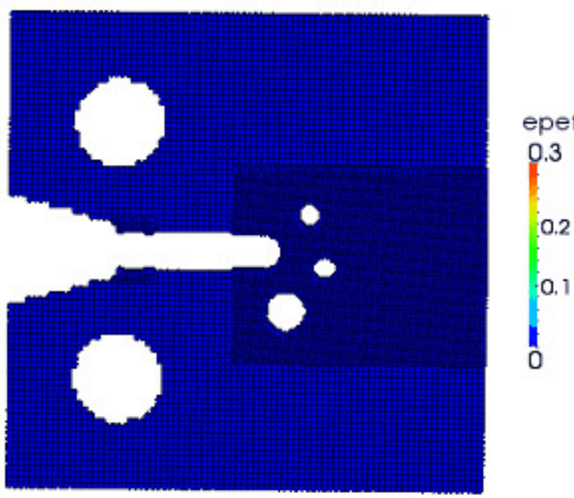
Applications

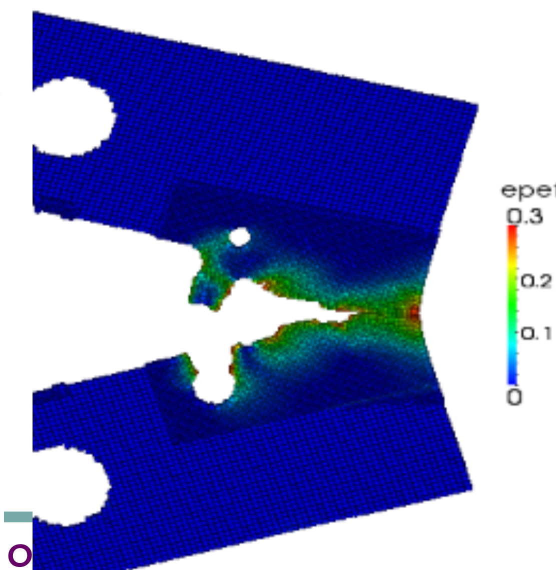
Fracture of ductile metal
The 2012 Sandia Fracture Challenge



Alloy 15-5 PH

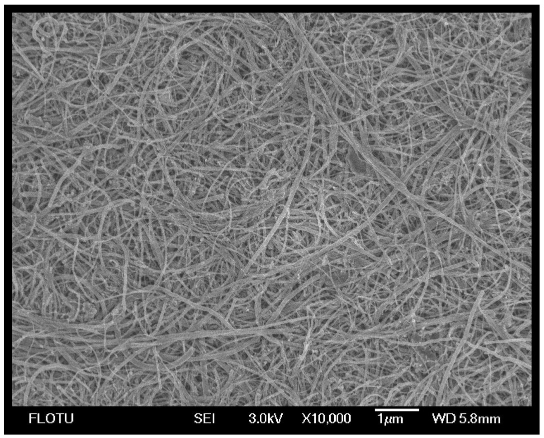


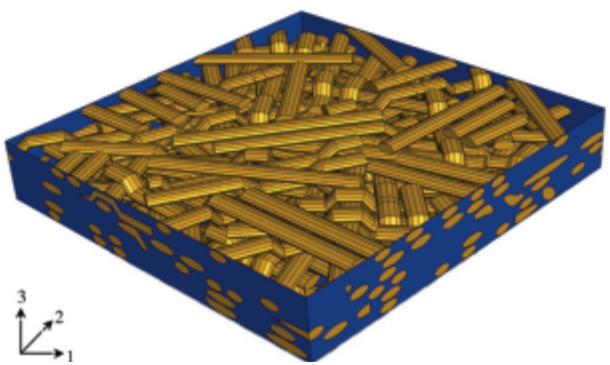




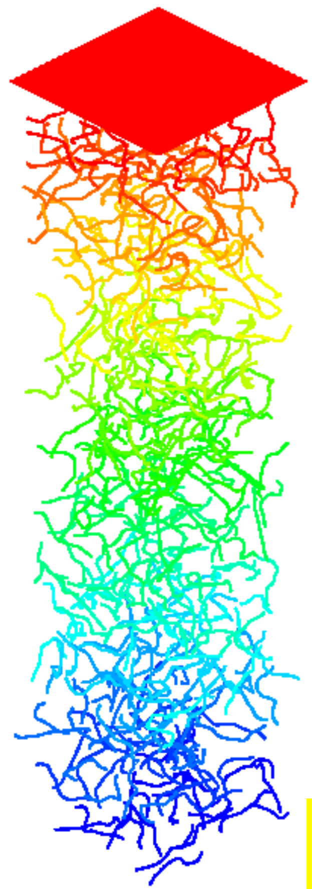
Applications

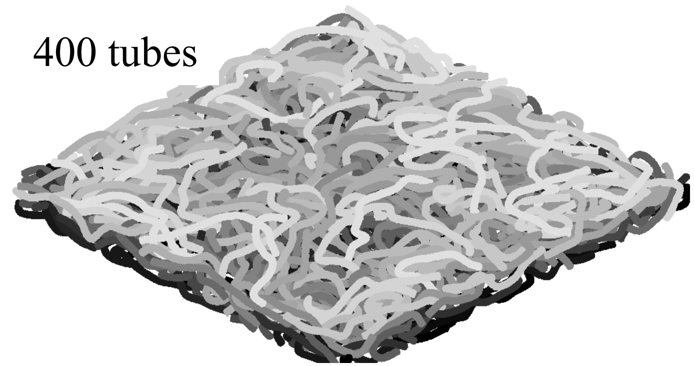
- Carbon nanotube
  - Exceptionally high stiffness, strength and resilience
  - Ideal to act as the reinforcing materials
    - 1% CNTs ➔ stiffness ↑40%, tensile strength ↑ 25%

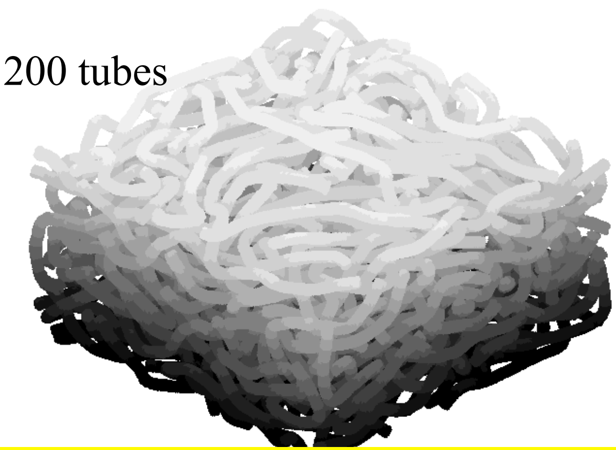




Pan, Iorga et al. ***Composites Science and Technology*** 68: 2792-2798, 2008

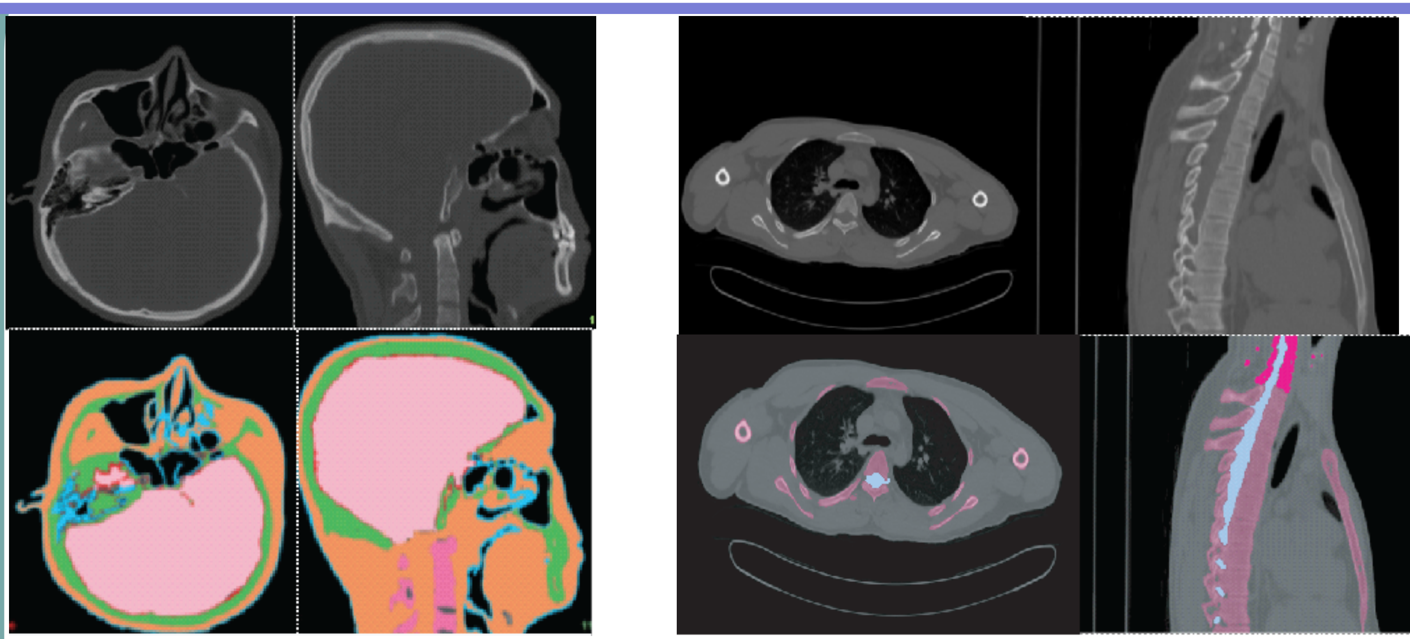




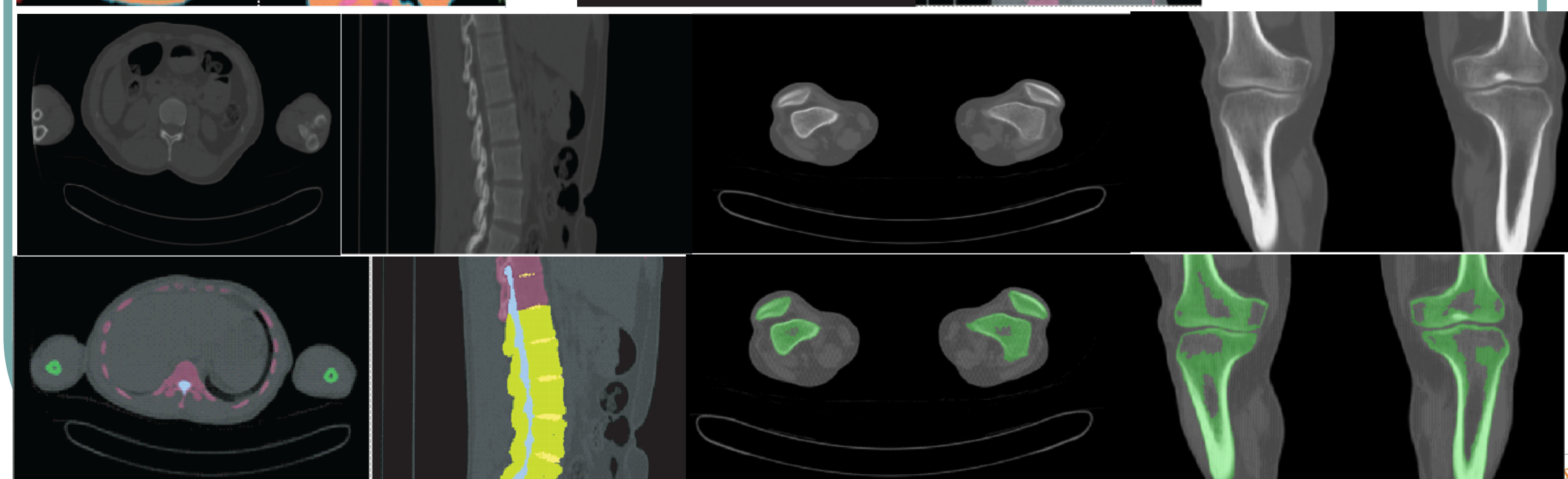


HK Wang, Y Liu, X Zhang. Numerical simulation of carbon nanotube reinforced composite by material point method. ***CMS*** 57: 23-29, 2012

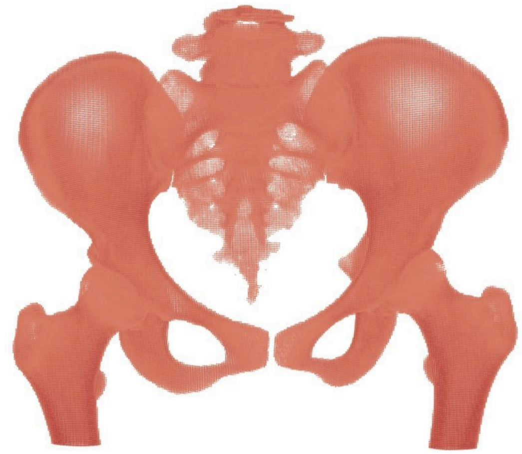
Applications

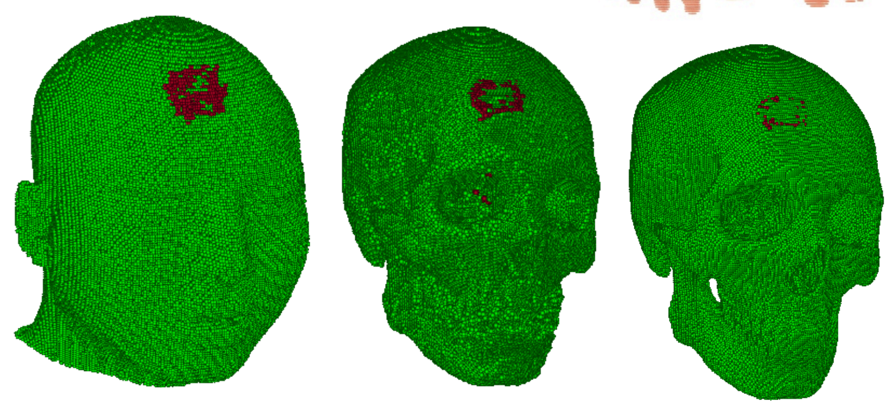


CT images of human body



Applications





SZ Zhou, X Zhang. Numerical Simulation of Human Head Impact Using the Material Point. ***International Journal of Computational Methods***. 10(4): 1350014 (2013).

Outline

- Introduction
- Our improvements on MPM
  - Efficient implementation of MPM
  - Improved contact method
  - Adaptive Material Point Method
  - Parallel based on OpenMP
  - Multi-Level Grid Material Point Method
  - Hybrid FE-MP method
  - Coupled FE-MP method
  - Adaptive FE-MP method
- MPM3D – A 3D explicit MPM code
- Applications
  - Impact
  - Explosion
  - Fluid-Structure Interaction
  - Nano- & Bio- Mechanics
- **Concluding remarks**

Concluding Remarks

- Less accurate, less efficient, and more storage usage for small deformation problem
  - Efficient implementation of MPM
  - Parallel computing
  - Combined with FEM
  - Combined with FDM
- Combines the advantages of Lagrangian and Eulerian methods
  - Impact simulation
  - Cutting simulation
  - Crush simulation
  - Blast simulation
- Much easier to generate MPM particles than FEM mesh
  - Carbon nanotube composite
  - Digital human modeling

Thanks for your attention !