极端变形问题的数值模拟方法与软件

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Acknowledgement:

刘 岩，廉艳平，杨鹏飞，宫伟伟，
周双珍，刘 平，李全光，张 帆，
陈镇鹏，马 上，黄 鹏，吴 博

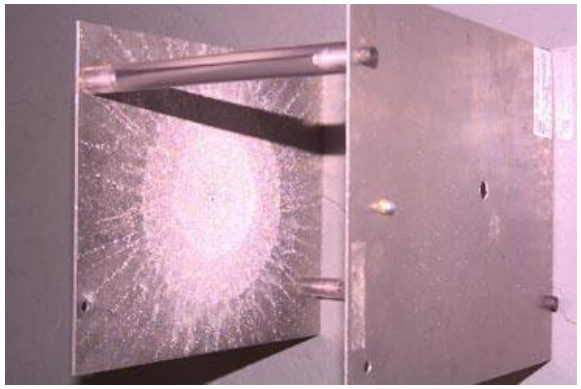
Outline

- **Introduction**
- Material Point Method
- Our Developments on MPM
- MPM3D – A 3D explicit MPM code
- Applications
- Concluding remarks

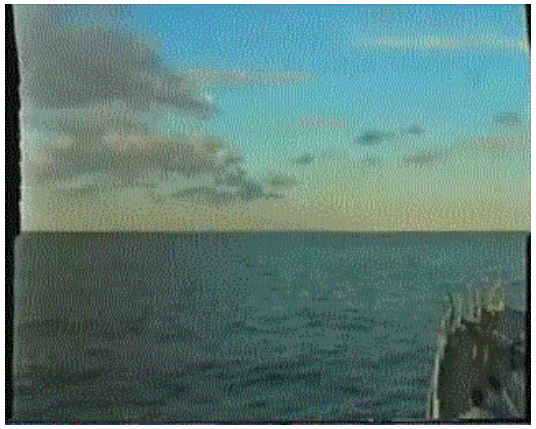
Introduction

Extreme deformation problems

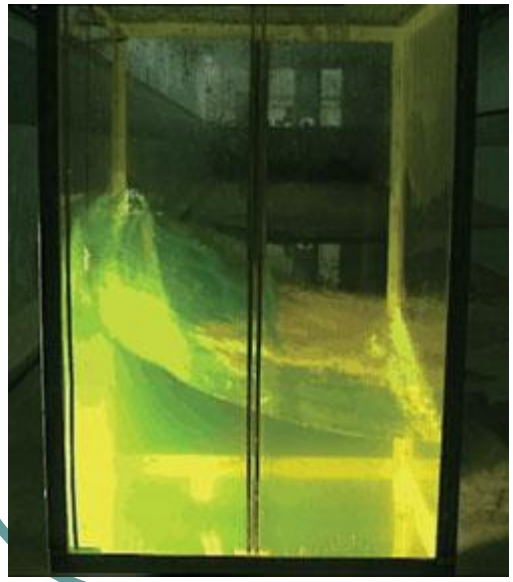
- Hyper velocity impact
- Impact and penetration
- Blast loading
- Metal cutting
- Friction stir welding
- Explosive welding
- Sloshing







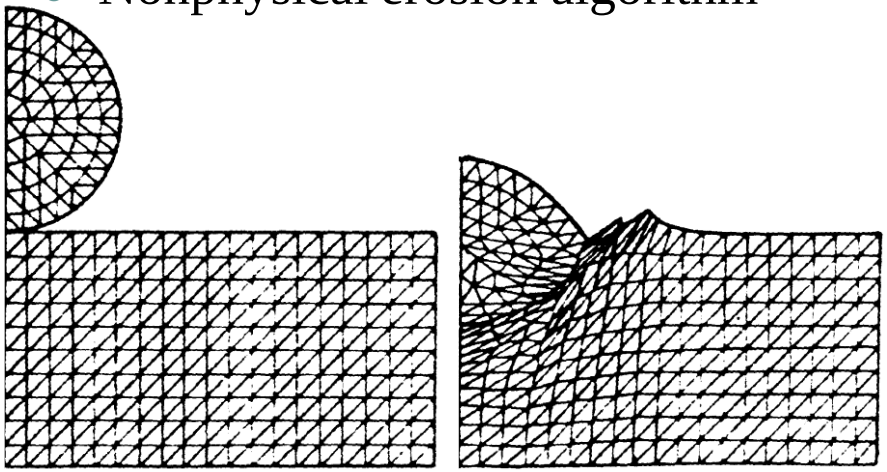






Introduction

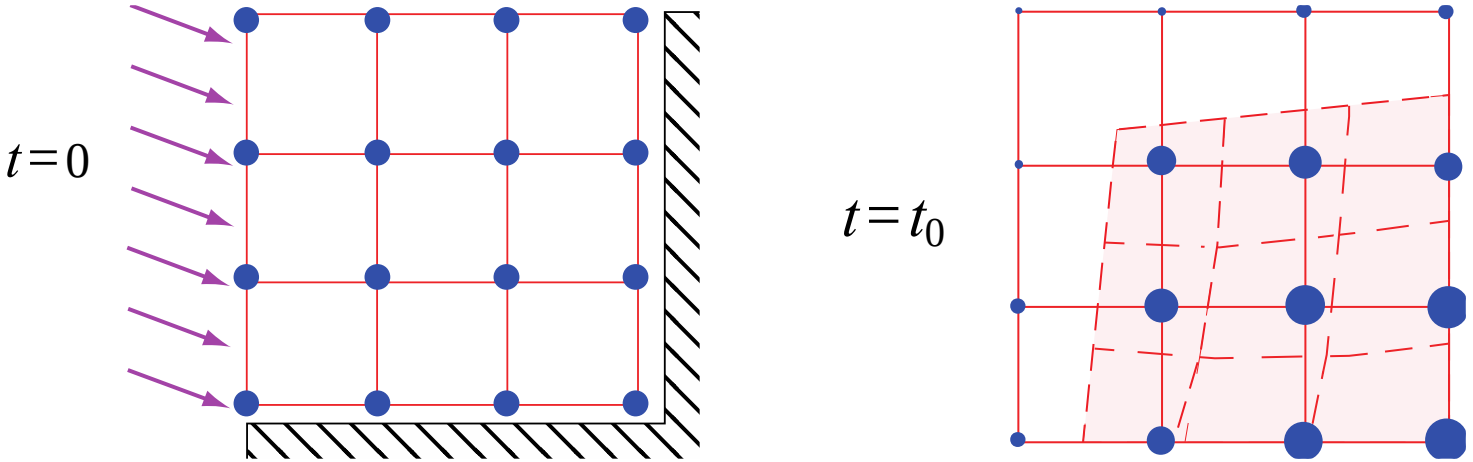
- Lagrangian method
  - FEM mesh is attached to the material
    - History-dependent constitutive models
    - Material free surfaces or material interfaces
  - Mesh distortion
    - Deteriorate accuracy
    - Decrease time step and increase computational cost
  - Fragmentation (discontinuity)
    - Nonphysical erosion algorithm





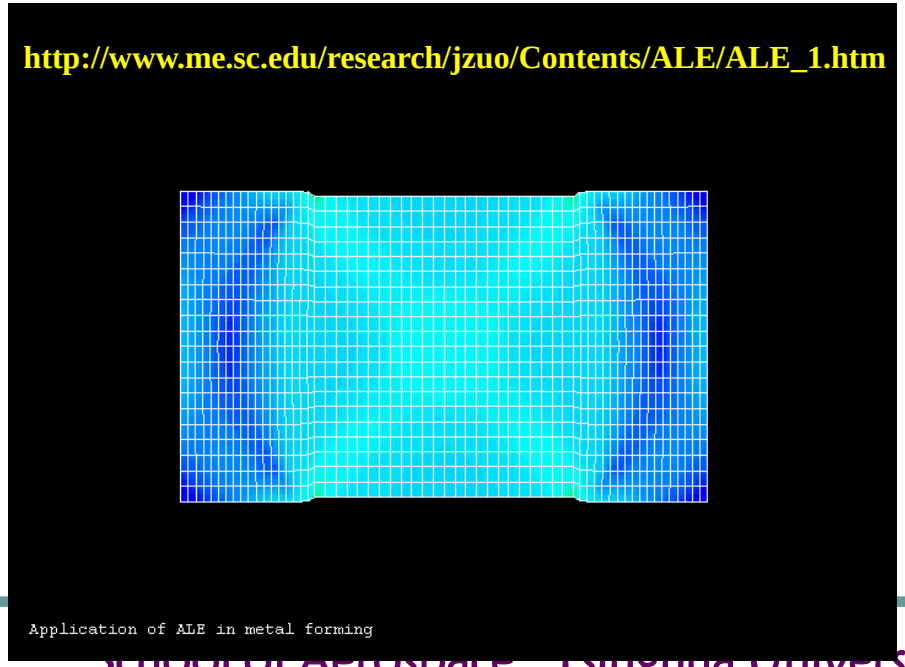
Introduction

- Eulerian method
  - Mesh is fixed in space
    - No element distortions
  - Difficulties
    - Advection term
    - Representation of free boundary and material interface
    - Tracking of material deformation history
    - Dissipation and dispersion problems



Introduction

- Hybrid Lagrangian-Eulerian methods
  - Arbitrary Lagrangian Eulerian (ALE)
    - The mesh is not fixed in space or attached to material
      - *Inside the domains*: Move arbitrarily to optimize element shape
      - *On the boundaries and interfaces*: Move along with materials to precisely track the boundaries and interfaces
    - Very complicated for 3D problems



Introduction

- Hybrid Lagrangian-Eulerian methods
  - PIC (Particle in Cell): Harlow and Evans, 1957
    - Fixed Eulerian cells are used to compute the conservation equations
    - Lagrange particles with mass and different material symbols are used to identify different materials
    - Particle position is updated by the four cells nearby

$$\boldsymbol{u}_k = \frac{A_1\boldsymbol{u}_{i+1,j+1} + A_2\boldsymbol{u}_{i,j+1} + A_3\boldsymbol{u}_{i,j} + A_4\boldsymbol{u}_{i+1,j}}{\Delta x \Delta y}$$

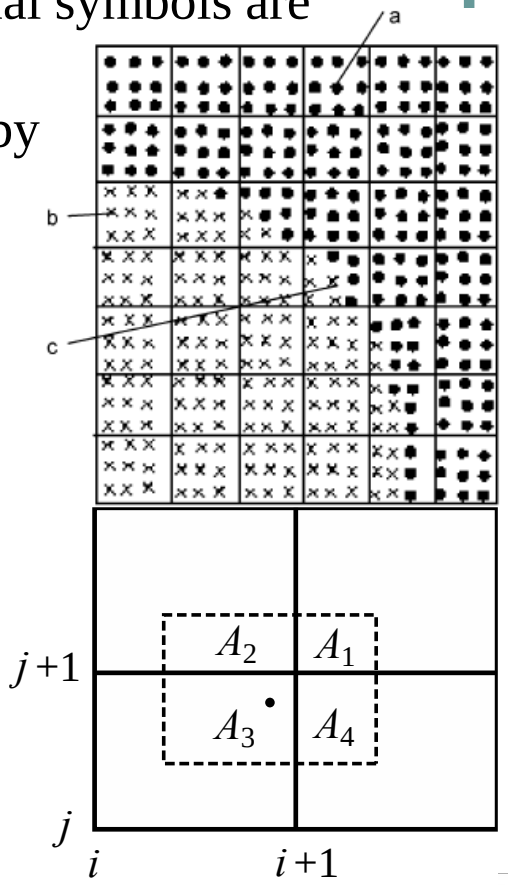
  - The computation of the transportation
    - Mass, momentum and energy are subtracted from the donor cell and added to the acceptor cell.

$$\Delta m_{\text{cell}} = m_k \qquad \Delta \boldsymbol{p}_{\text{cell}} = m_k \boldsymbol{v}_{\text{cell}}; \qquad \Delta E_{\text{cell}} = m_k e_{\text{cell}}$$

    - Mixed cell: internal energy increment can be divided by the volume percent

$$M_{\cdot} / r_{\cdot} + M_{\times} / r_{\times} = V$$

$$P = f(\rho_{\cdot}, e_{\cdot})_{\cdot} \qquad P = f(\rho_{\times}, e_{\times})_{\times}$$

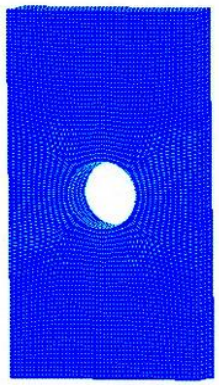


Computational Dynamics 计算动力学实验室

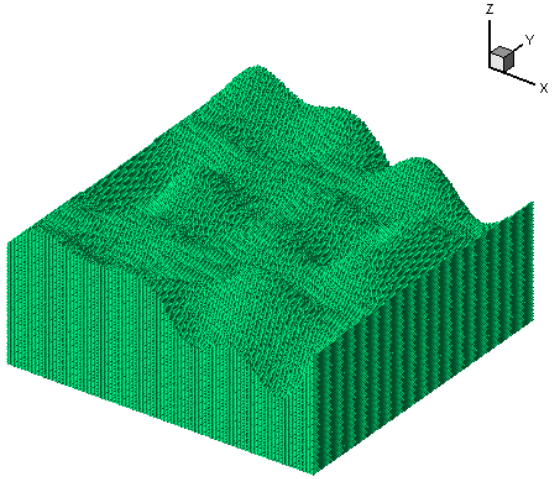
Introduction

- Meshfree methods
  - **SPH**
  - EFG
  - RKPM
  - MLPG
  - … …

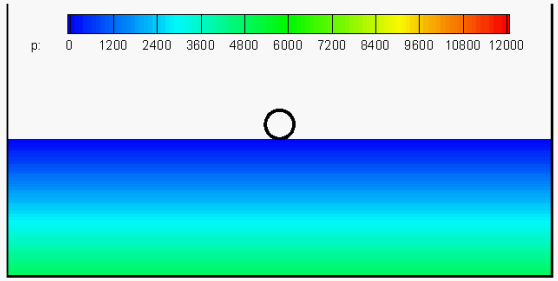
- 张雄, 刘岩, 马上. 无网格法的理论及应用, **力学进展**, 39(1):1-36, 2009
- 张雄, 刘岩著. **无网格法**. 清华大学出版社/Springer出版社, 2004



RKPM: SF Li et al.



SPH: 王裴



SPH: 刘谋斌

Introduction

- Meshfree methods — SPH

$$\nabla\cdot\boldsymbol{\sigma}=\rho\dot{\boldsymbol{v}}$$

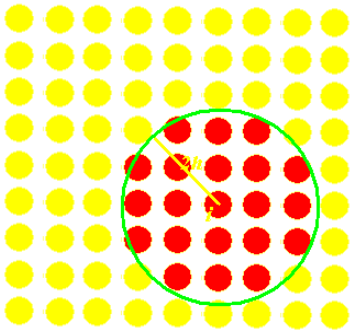
配点法 ⇓ 核函数近似 ⇐

$$(\nabla\cdot\boldsymbol{\sigma})_I=\rho_I\dot{\boldsymbol{v}}_I \Leftarrow \nabla\cdot\boldsymbol{\sigma}\approx\sum_{J=1}^{N}\frac{m_J}{\rho_J}\nabla w_J(x)\cdot\boldsymbol{\sigma}_J$$

$$\dot{\boldsymbol{v}}_I=\frac{1}{\rho_I}\sum_{J=1}^{N}\frac{m_J}{\rho_J}\nabla w_{IJ}\cdot\boldsymbol{\sigma}_J$$

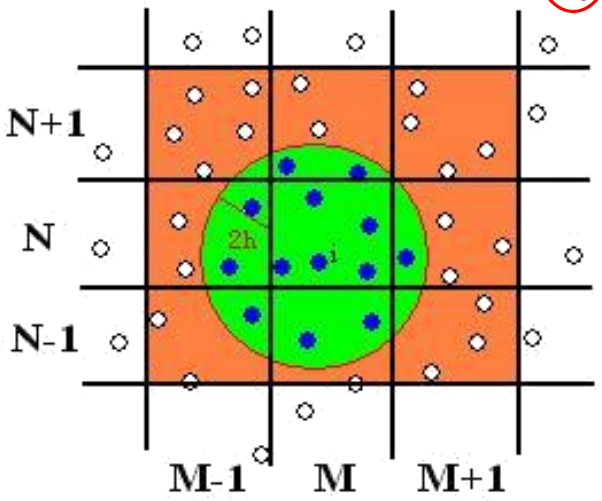
$$N\gg 8!$$

- Neighboring particles search – Time consuming
- Less efficient than mesh based Lagrangian methods



$$u(\boldsymbol{x})=\int_{\Omega} u(\bar{\boldsymbol{x}})\delta(\boldsymbol{x}-\bar{\boldsymbol{x}})\,\mathrm{d}\Omega_{\bar{x}}\;\Delta V_J$$

$$u^h(\boldsymbol{x})=\sum_{J=1}^{N} w_J(\boldsymbol{x})u_J\frac{m_J}{\rho_J}$$



Computational Dynamics 计算动力学实验室

Introduction

SPH

AUTODYN-3D v6.1 from Century Dynamics

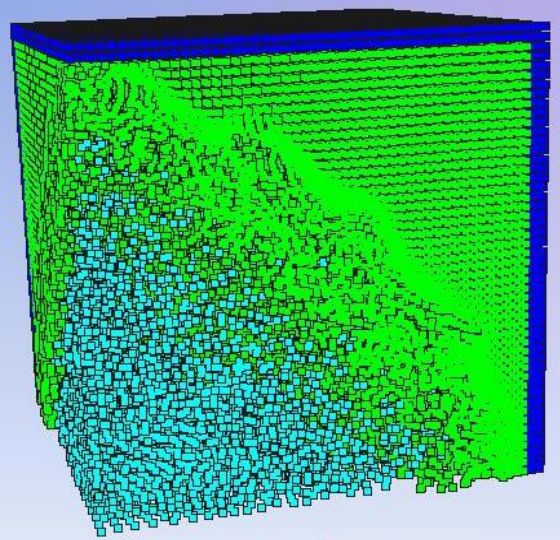
Material Location

CONC-35MPA

AIR

TNT

AUTODYN-3D中SPH求解器计算室内爆轰问题出现数值振荡导致误差过大





Error!

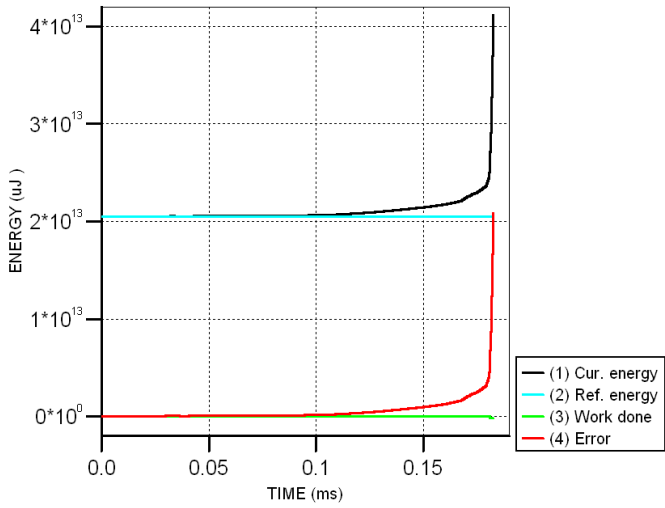
Problem terminated .... energy error too large

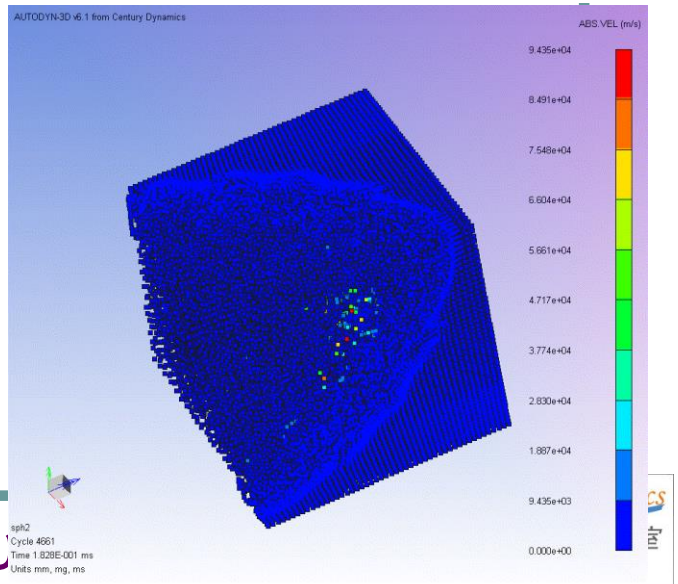
确定

sph2
Cycle 4661
Time 1.828E-001 ms
Units mm, mg, ms

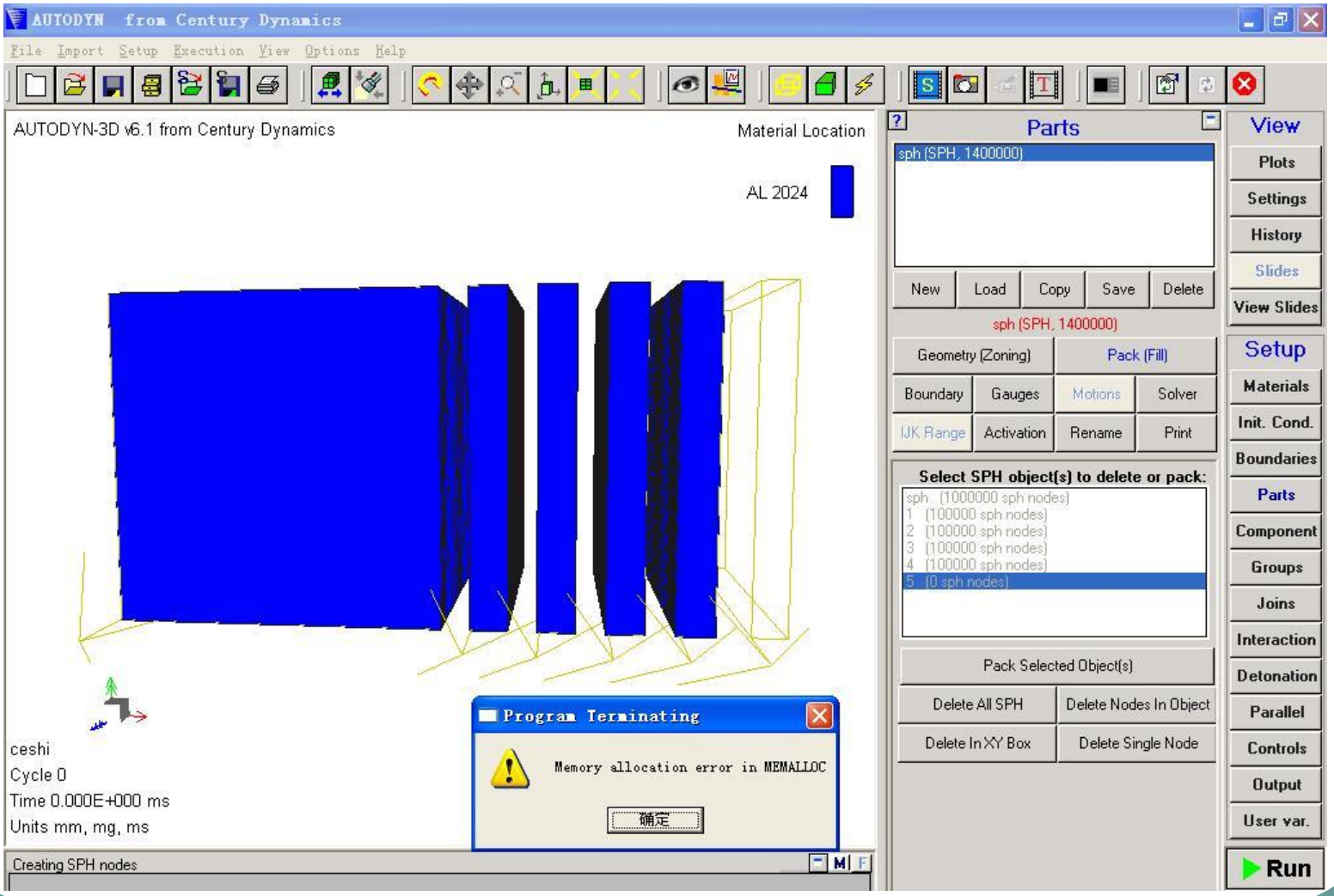
Problem terminated .... energy error too large

Energy Summary (sph2)





AUTODYN6.0中SPH粒子数不能超过150万 (11.0版为200万)，否则出错



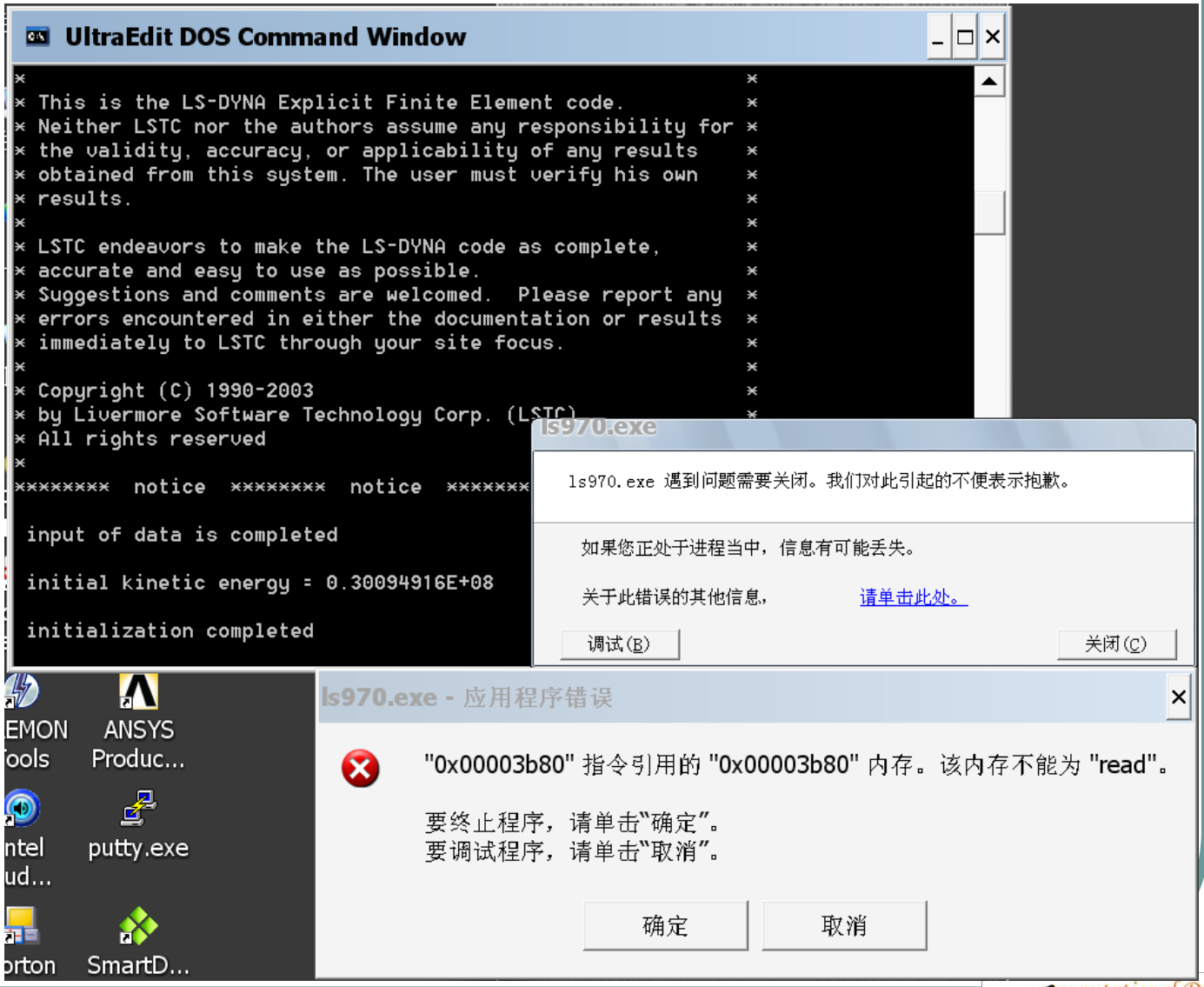
Introduction

SPH

1,274,376 质点

LS-DYNA
970.5434 出错

970s.6763.169
占用内存1.12G



Introduction

Research Interests

- 紧支径向基函数配点法 (CM)
- 最小二乘配点无网格法 (IJNME)
- 加权最小二乘无网格法 (力学学报)
- 伽辽金最小二乘无网格法
- 伽辽金配点无网格法
- 边界弱形式配点法
- 质点积分无网格伽辽金法

1997

侧重通用方法研究

教育部自然科学奖二等奖 (2009)

2004

聚焦极端变形问题
(超高速碰撞预研基金)

- 物质点法
- 冲击爆炸三维物质点法数值仿真软件**MPM3D** (2009SRBJ4761, 2008.8）
- 有限元法
- 有限差分法
- 多物质ALE法

2008.11

软件系统研发：联合总装工程设计研究所

2015.12

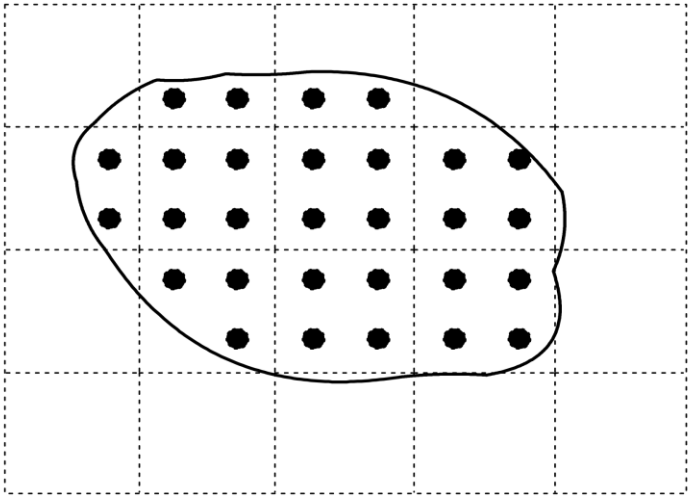
发布试用版MaPoss

Outline

- Introduction
- **Material Point Method**
  - 张雄等. **物质点法**, 清华大学出版社, 2013
  - 张雄等. ***The Material Point Method*** - A Continuum-Based Particle Method for Extreme Loading Case. Published by Elsevier, 2016.10
  - 开源代码：**MPM3D-F90**
    http://www.comdyn.cn/downloads/mpm-book
  - 试用软件：(截止日期2016-12-31)
    http://www.comdyn.cn/show/software/398-mpm3d-download
- **Our Developments on MPM**
- **MPM3D – A 3D explicit MPM code**
- **Applications**
- **Concluding remarks**

Material Point Method

- 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



Material Point Method

Basic Formulation

- In each time step
  - Particles are attached rigidly to a predefined regular grid. State variables of particles are mapped to the grid nodes to establish their momentum equations

FEM

$$m_I^k = \sum_p m_p N_{Ip}^k \qquad p_{iI}^{k-1/2} = \sum_p m_p v_{ip}^{k-1/2} N_{Ip}^k \qquad f_{iI}^{\text{int}} = -\sum_p N_{Ip,j}^k \sigma_{ijp} \frac{m_p}{\rho_p}$$

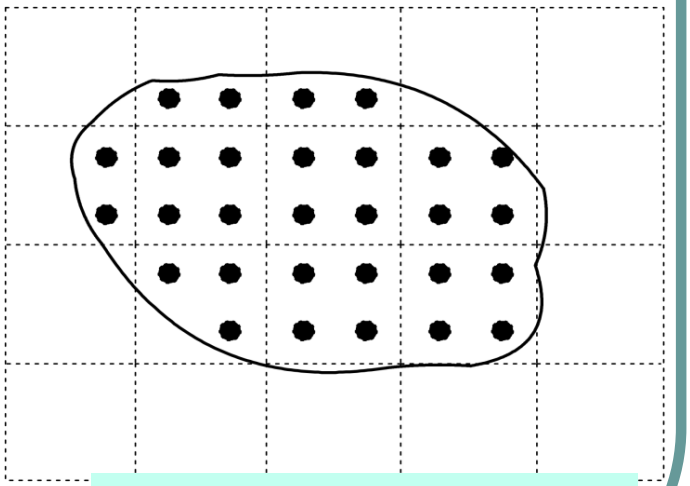
$$p_{iI}^{k+1/2} = p_{iI}^{k-1/2} + f_{iI}^k \Delta t^k$$

Particle quadrature

  - After solving momentum equations on grid nodes, results are mapped back to the particles to update their states.

$$v_{ip}^{k+1/2} = v_{ip}^k + \sum_I \frac{f_{iI}^k}{m_I^k} N_{Ip}^k \Delta t$$

$$x_{ip}^{k+1} = x_{ip}^k + \sum_I \frac{p_{iI}^{k+1/2}}{m_I^k} N_{Ip}^k \Delta t$$



  - The deformed grid is discarded, and a new regular grid is used

Remesh

$$N_g = \frac{1}{4}(1+\xi\xi_g)(1+\eta\eta_g)$$

Computational Dynamics 计算动力学实验室

Material Point Method

Basic Formulation

Material Point Method	Finite Element Method
$m_I^k = \sum_p m_p N_{Ip}, \quad p_{iI}^k = \sum_p m_p v_{ip}^k N_{Ip}$	Nodes carry mass, momentum
$f_{iI}^{k,\text{int}} = -\sum_p N_{Ip,j}\sigma_{ijp}\frac{m_p}{\rho_p}V_p$ Particle quadrature	$f_{iI}^{k,\text{int}} = -\int_\Omega N_{I,j}\sigma_{ij}\,\mathrm{d}V = -\sum_q N_{Iq,j}\sigma_{ijq}J_q w_q V_q$
$p_{iI}^{k+1/2} = p_{iI}^k + f_{iI}^k \Delta t$	$v_{iI}^{k+1/2} = v_{iI}^k + \frac{f_{iI}^k}{m_I}\Delta t$ $x_{iI}^{k+1} = x_{iI}^k + v_{iI}^{k+1/2}\Delta t$
$v_{ip}^{k+1/2} = v_{ip}^k + \sum_I \frac{f_{iI}^k}{m_I^k} N_{Ip}\Delta t$ $x_{ip}^{k+1} = x_{ip}^k + \sum_I \frac{p_{iI}^{k+1/2}}{m_I^k} N_{Ip}\Delta t$ Remesh	Gauss points keep fixed in a element, so it is unnecessary to recalculate their coordinates

Computational Dynamics 计算动力学实验室

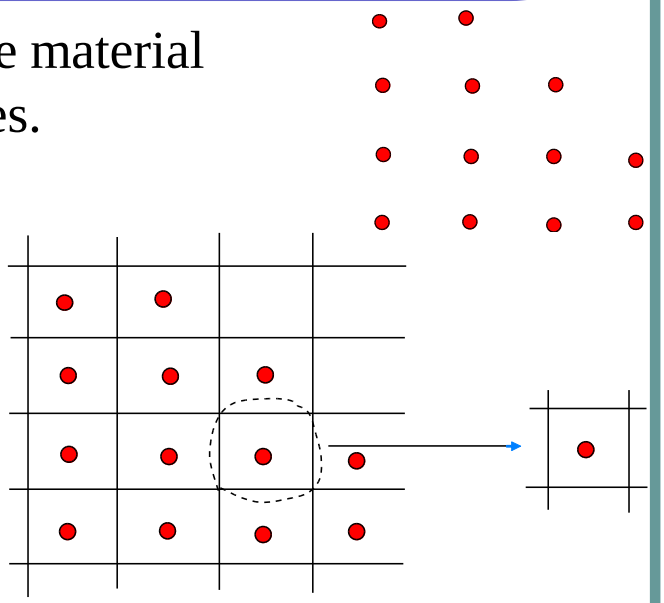
Material Point Method

Basic Formulation

- The MPM procedure begins by discretizing the material domain with a set of material points or particles.

$$r(x) = \sum_{p=1}^{n_p} m_p \delta(x_i - x_{ip})$$

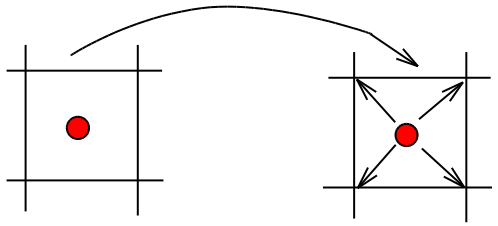
- Define a background computational mesh to cover the whole material domain



For each step:

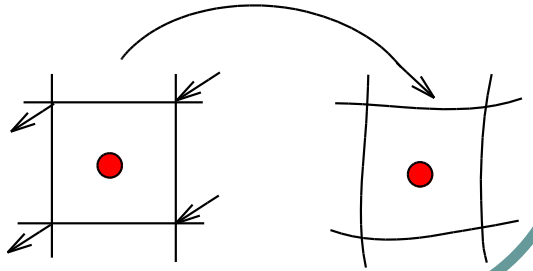
- Map the mass and velocities of the particles onto the background computational mesh

$$m_I^k = \sum_p m_p N_{Ip} \qquad p_{iI}^k = \sum_p m_p v_{ip}^k N_{Ip}$$



- Integrate the grid nodal momentum equations, and update the nodal velocities

$$f_{iI}^{k,\text{int}} = -\sum_p N_{Ip,j} s_{ijp} \frac{m_p}{r_p} \qquad p_{iI}^{k+1/2} = p_{iI}^k + f_{iI}^k \Delta t$$



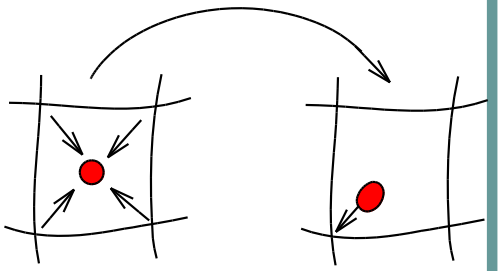
Material Point Method

Basic Formulation

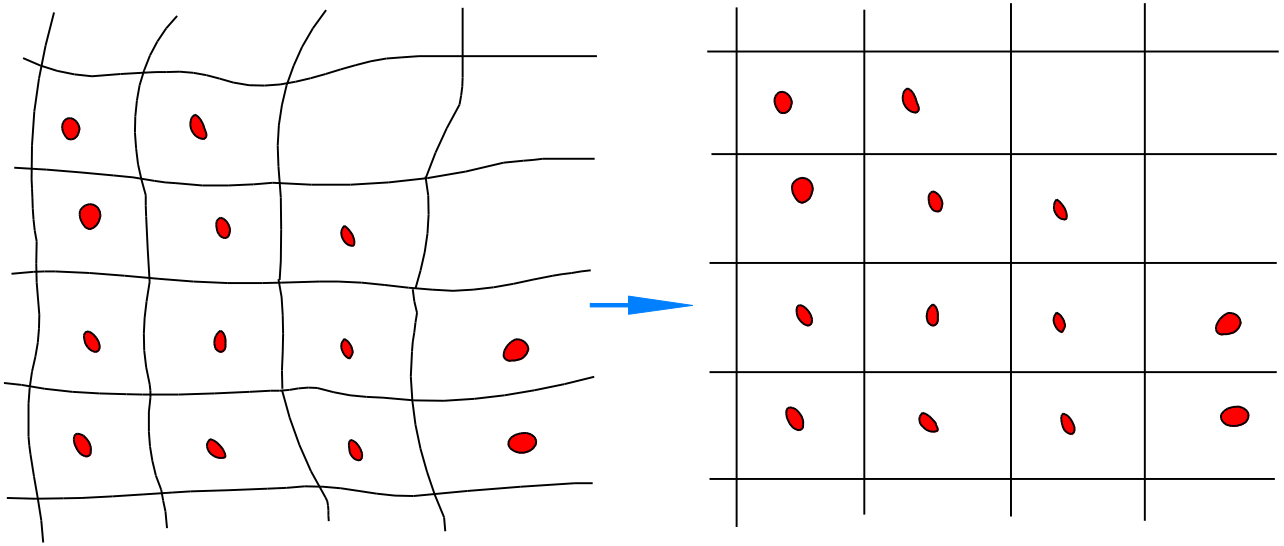
- Map the nodal results to the particles to update their velocity, position, strain, and stress

$$v_{ip}^{k+1/2} = v_{ip}^{k} + \sum_I \frac{f_{iI}^{k}}{m_I^{k}} N_{Ip} \Delta t \qquad x_{ip}^{k+1} = x_{ip}^{k} + \sum_I \frac{p_{iI}^{k+1/2}}{m_I^{k}} N_{Ip} \Delta t$$

$$\Delta e_{ijp}^{k+1/2},\ \Delta W_{ijp}^{k+1/2},\ r_p^{k+1},\ s_{ijp}^{k+1}$$



- Discard the deformed grid, and employ a new regular background grid in the next time step

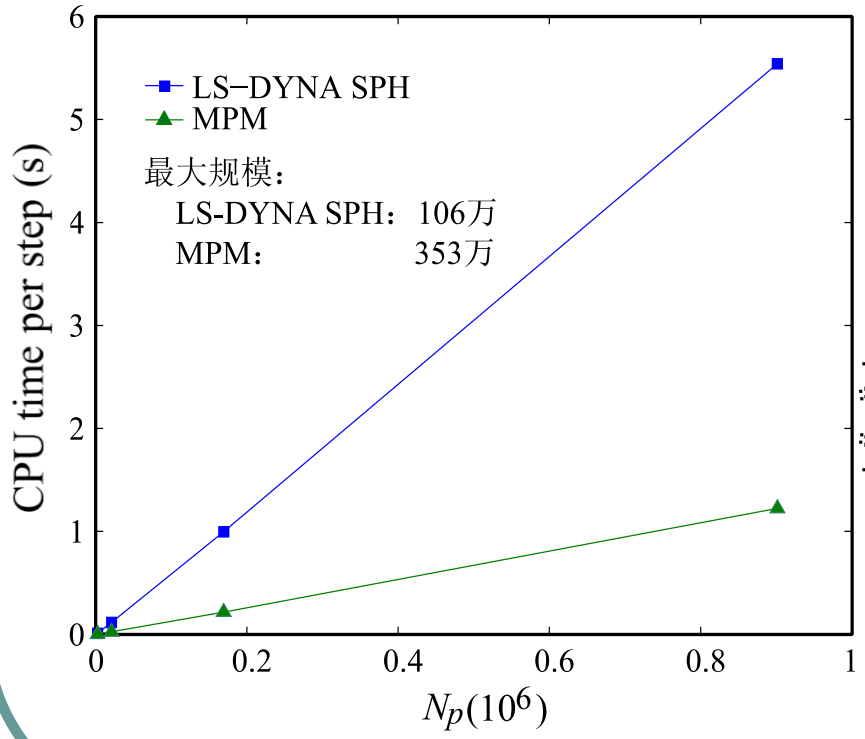


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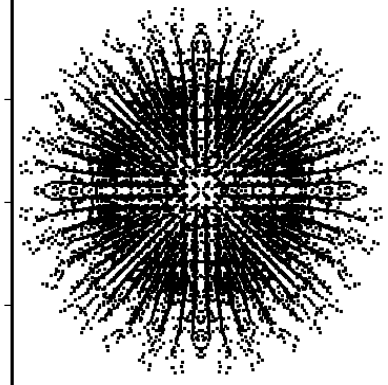
Material Point Method

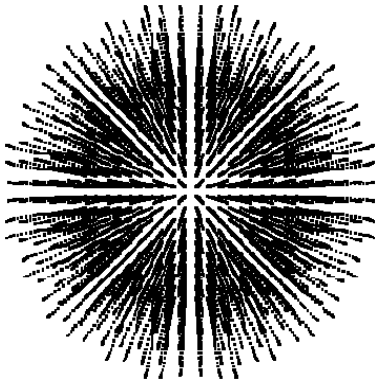
Comparison with SPH

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









SPH MPM

Final configuration of the bar (top view)

马上，张雄等. Comparison study of MPM and SPH in modeling hypervelocity impact problems. ***International Journal of Impact Engineering*** 36: 272-282, 2009

Material Point Method

- Combines the advantages of Lagrangian and Eulerian methods
  - No mesh distortion and element entanglement
  - History-dependent constitutive models
  - Free surfaces or multiple materials
  - Promising in modeling **extreme deformation** and material discontinuities
- Compared with FEM
  - Particle quadrature instead of Gauss quadrature
  - Remesh in every time step
  - Take use of both grid and particle data ⟹ ***Efficient implementation***
  - Less accurate, less efficient, and more storage usage for **small deformation problem** ⟹ ***Combined with other methods***

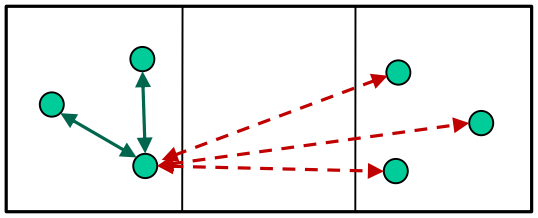
Outline

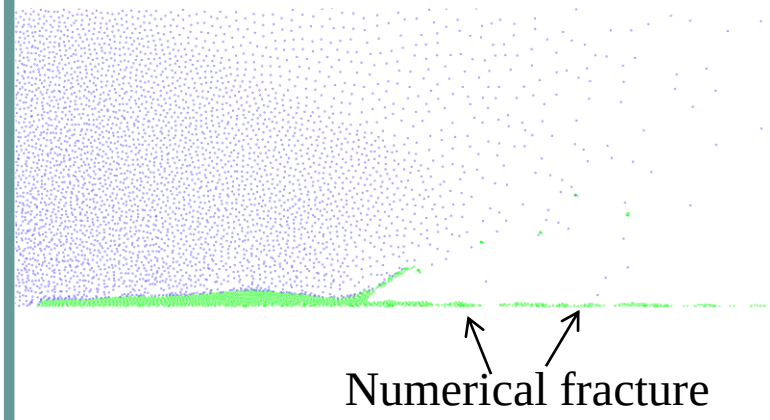
- Introduction
- Material Point Method
- Our Developments on MPM
  - Efficient implementation
    - Adaptive particle split
    - Improved Contact Method
    - Efficient implementation
    - Hanging Node Adaption
    - Moving Tied interface grid
    - Parallel MPM
  - Combined with other methods
    - Combined with Finite Element Method
    - Combined with Finite Difference Method
    - Combined with Molecular Dynamics
- MPM3D – A 3D explicit MPM code
- Applications
- Concluding remarks

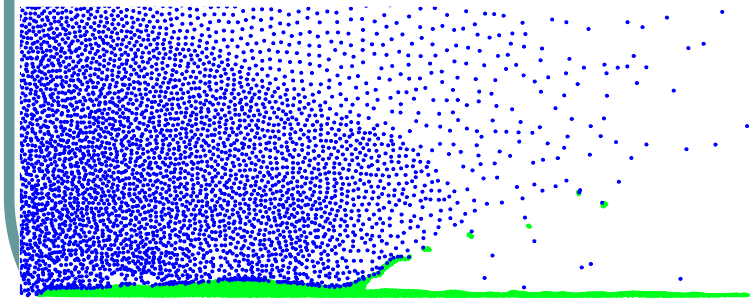
Our Developments on MPM

Adaptive particle split

Numerical fracture





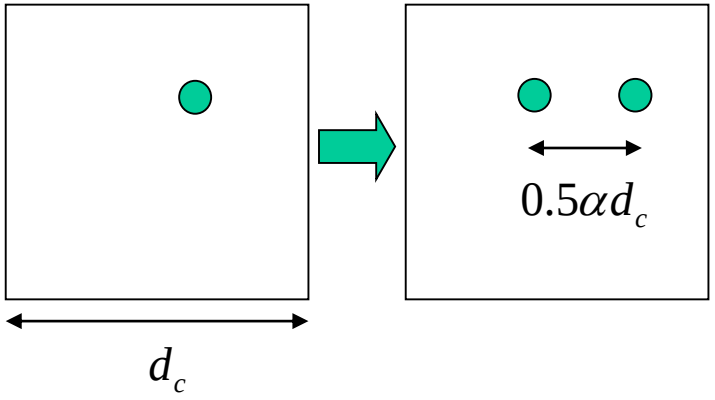


Accumulated strain: $e_{xx} = \sum_k \Delta e_{xx}^k = \sum_k D_{xx}^k \Delta t$

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

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

Split: mass, volume, internal energy

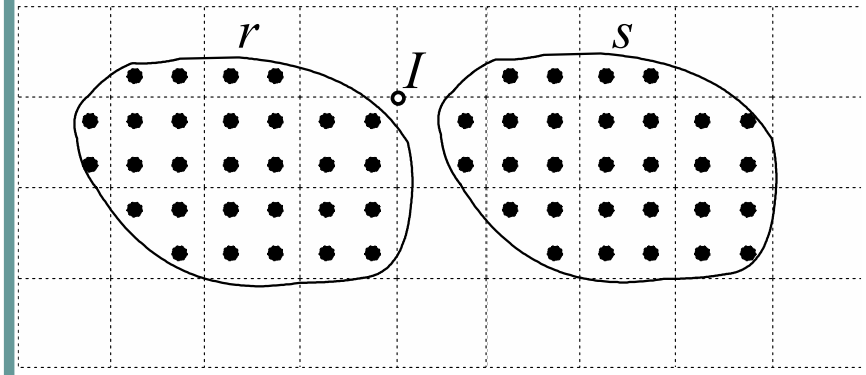


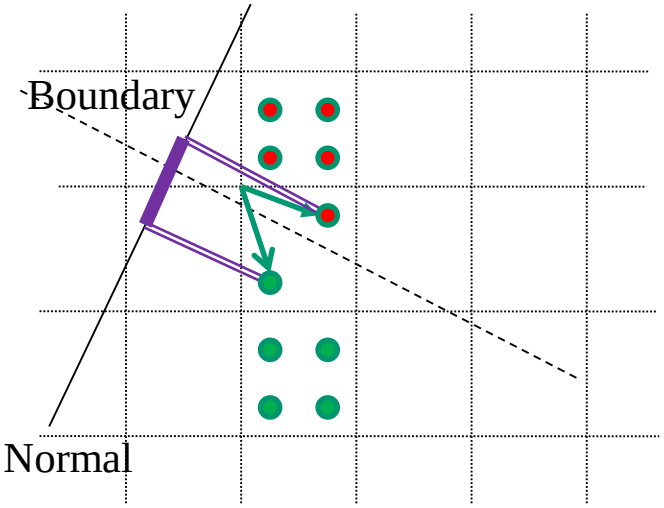
马上, 张雄等. Simulation of high explosive explosion using adaptive material point method. ***CMES*** 39(2):101-123, 2009

Our Developments on MPM

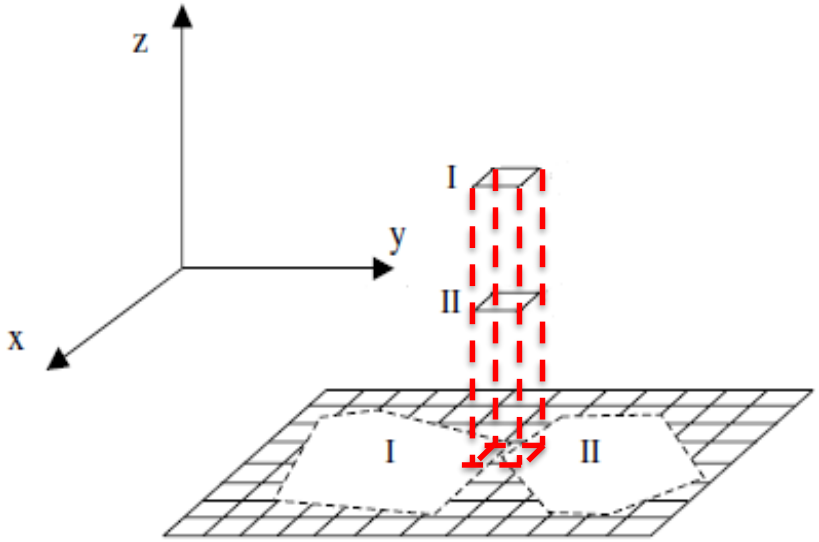
Improved Contact Method

- Improved contact detection





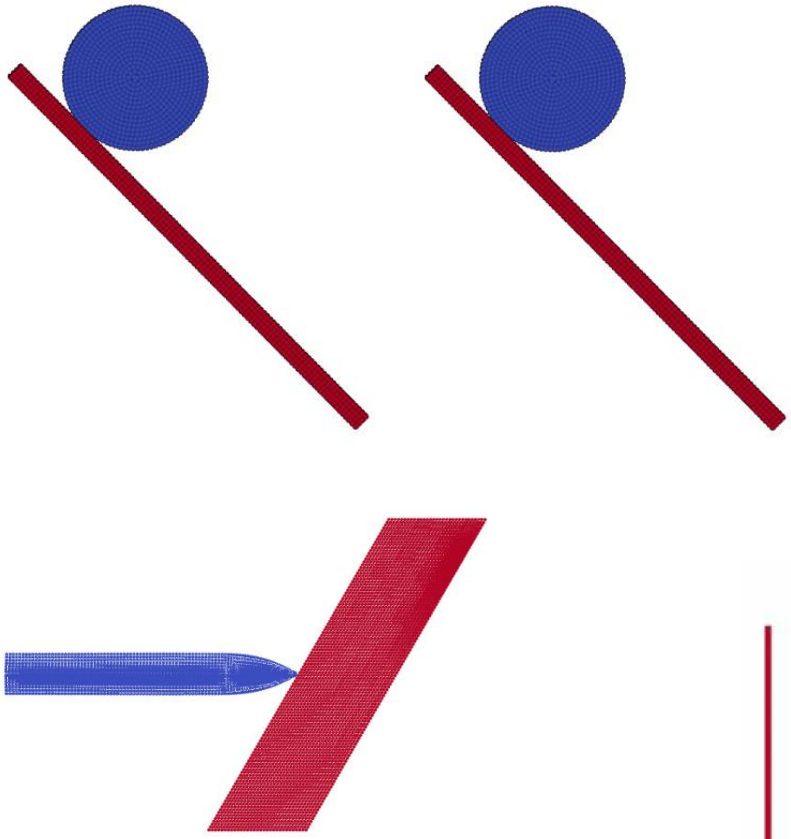
- Local multi-grid

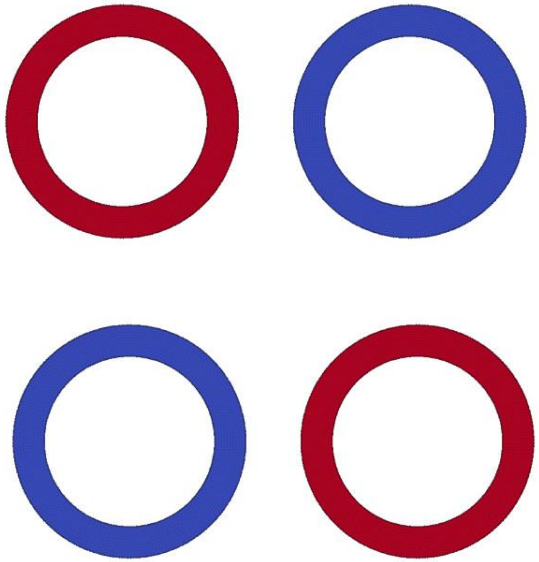


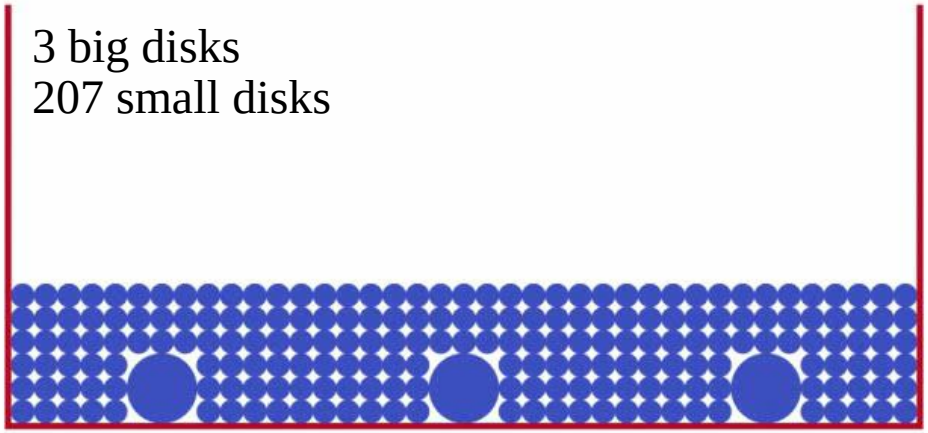
- 黄鹏, 张雄等. Contact Algorithms for the Material Point Method in Impact and Penetration Simulation. ***International Journal for Numerical Methods in Engineering*** 85(4): 498-517, 2011
- 马志涛, 张雄等. An Object-Oriented MPM Framework for Simulation of Large Deformation and Contact of Numerous Grains. ***CMES*** 55(1): 61-88, 2010.

Our Developments on MPM

Improved Contact Method







3 big disks
207 small disks

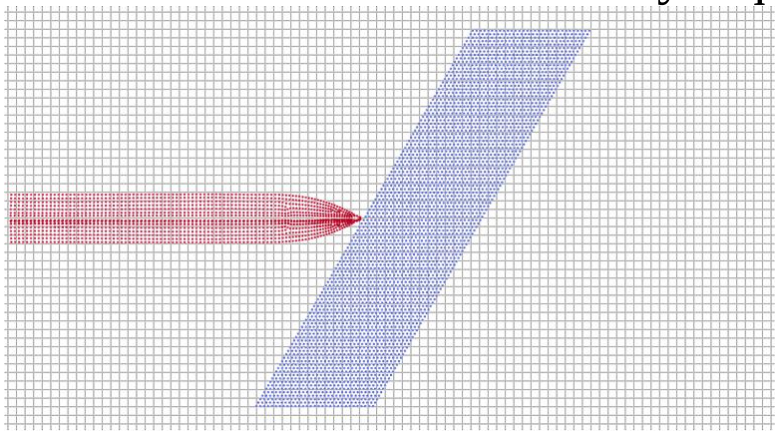
N_p / N_g	CPU time Reduced	Memory Reduced
200,864/ 170,688	88.8%	49.7%

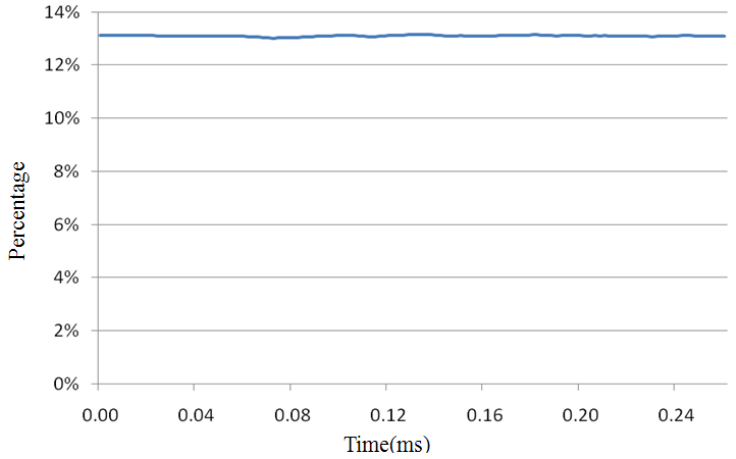
Computational Dynamics 计算动力学实验室

Our Developments on MPM

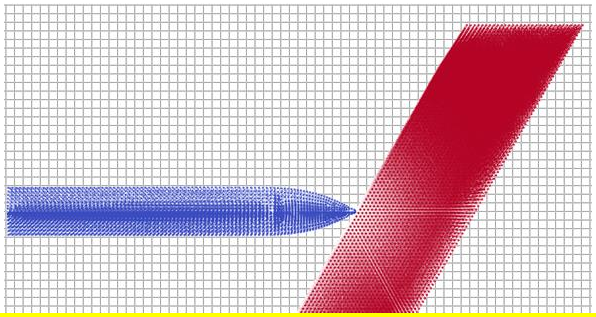
Efficient implementation

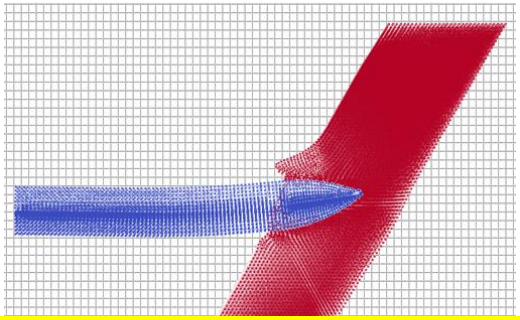
- Dynamic grid
  - Cells are dynamically created when occupied by at least one particle
  - Reduce CPU time and memory requirement significantly

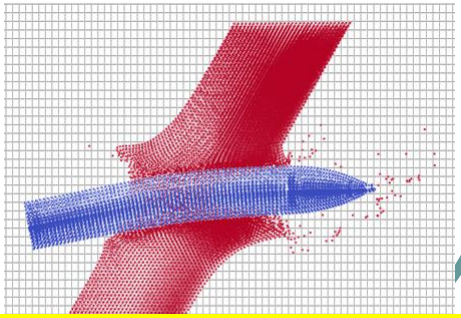




- Moving grid
  - Adjust grid according to the position of particles to just cove all bodies
  - Reduce the number of void cells



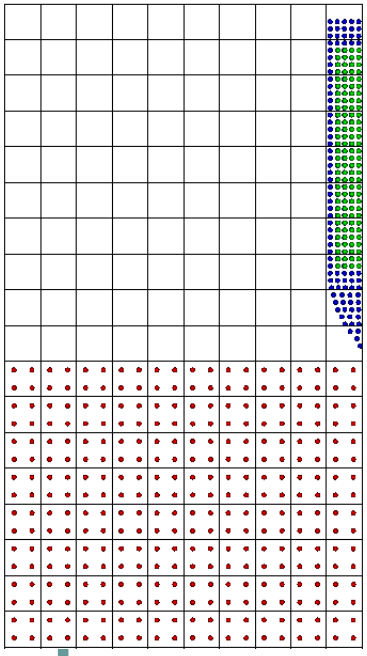




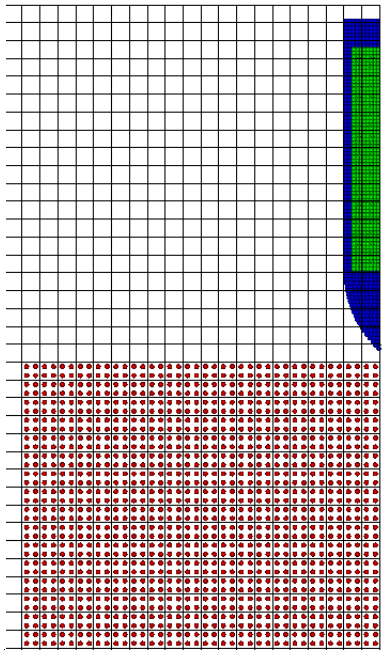
马志涛, 张雄等. An Object-Oriented MPM Framework for Simulation of Large Deformation and Contact of Numerous Grains. ***CMES***, 55(1): 61-88, 2010.

Our Developments on MPM

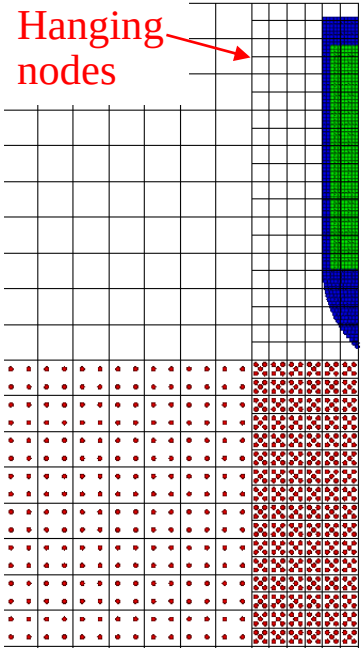
Hanging Node Adaption



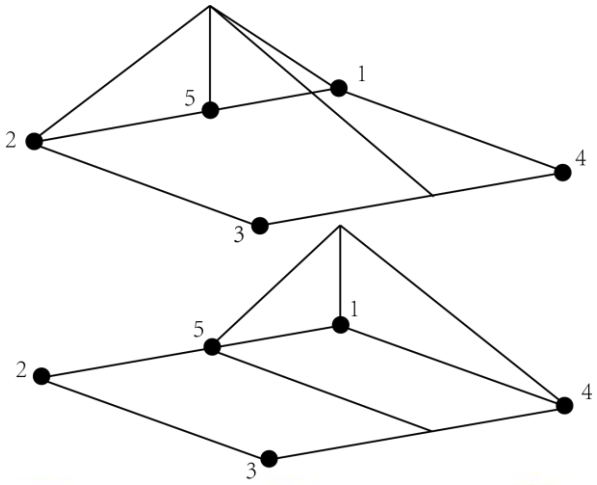
Case 1

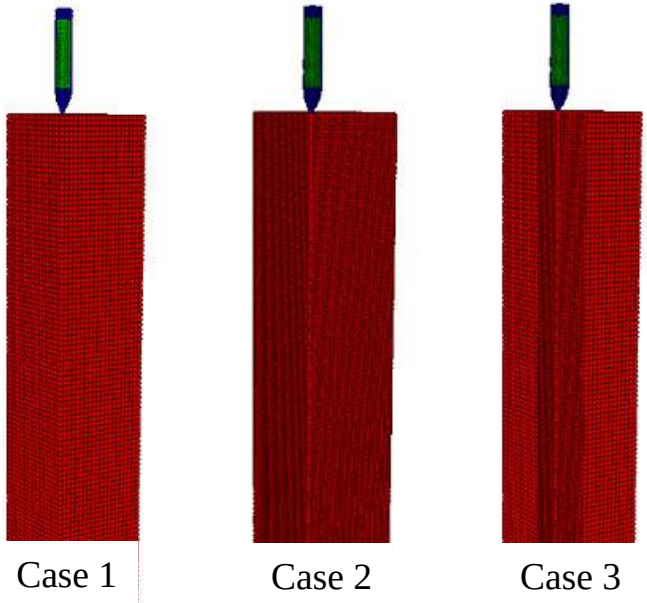


Case 2



Case 3





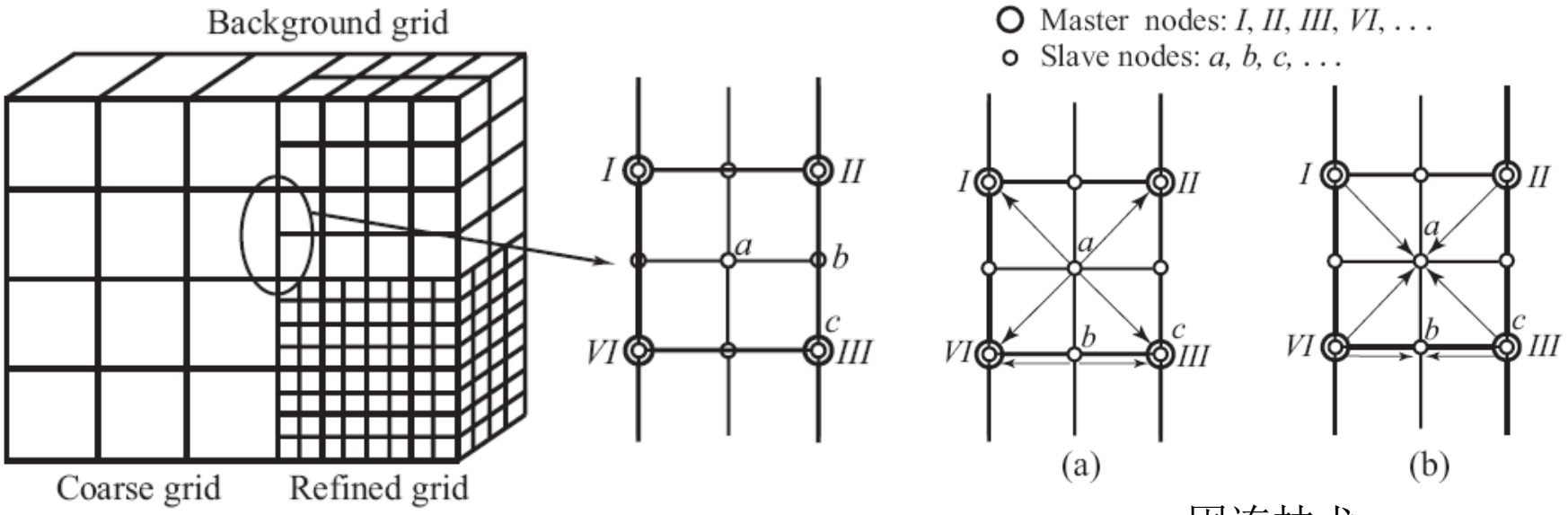
Case 1 Case 2 Case 3

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

廉艳平, 杨鹏飞, 张雄等. A Mesh-Grading Material Point Method and Its Parallelization for Problems with Localized Extreme Deformation. ***CMAME***. 289(1): 291–315, 2015.

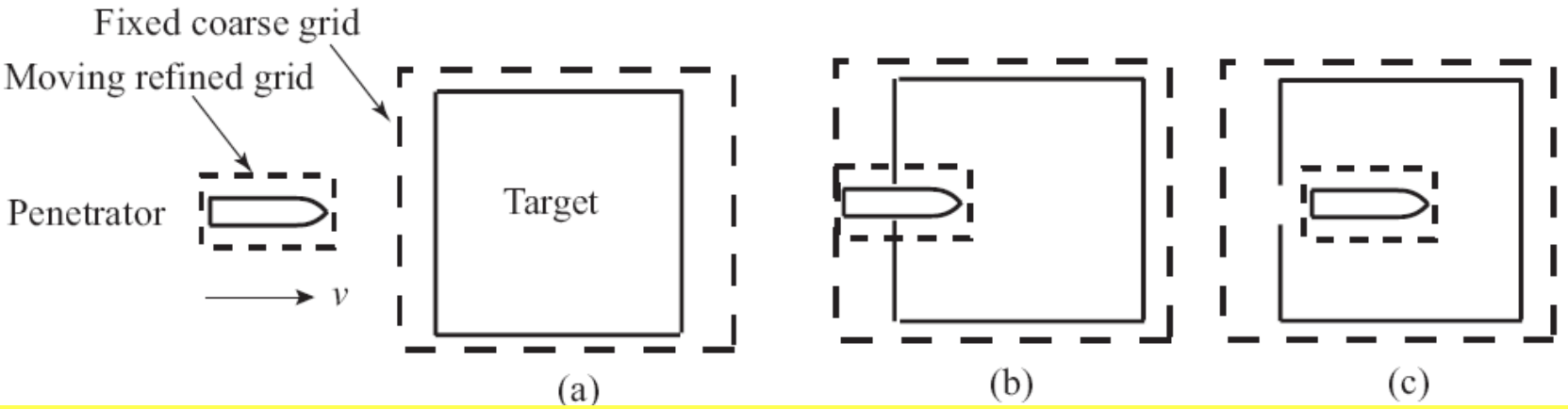
Our Developments on MPM

Moving Tied interface grid



固连接触多级背景网格

固连技术

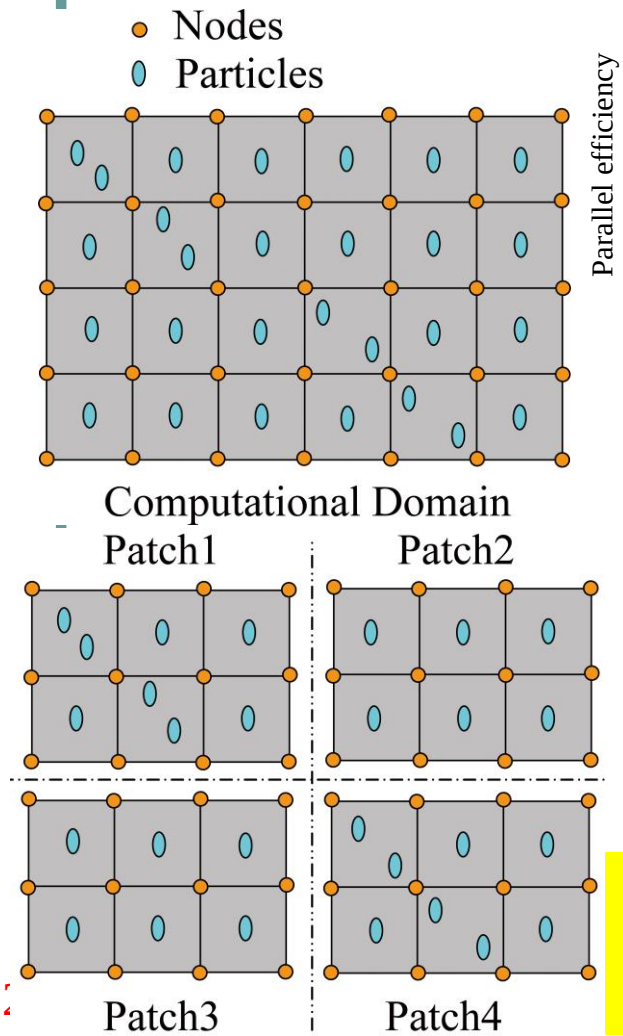


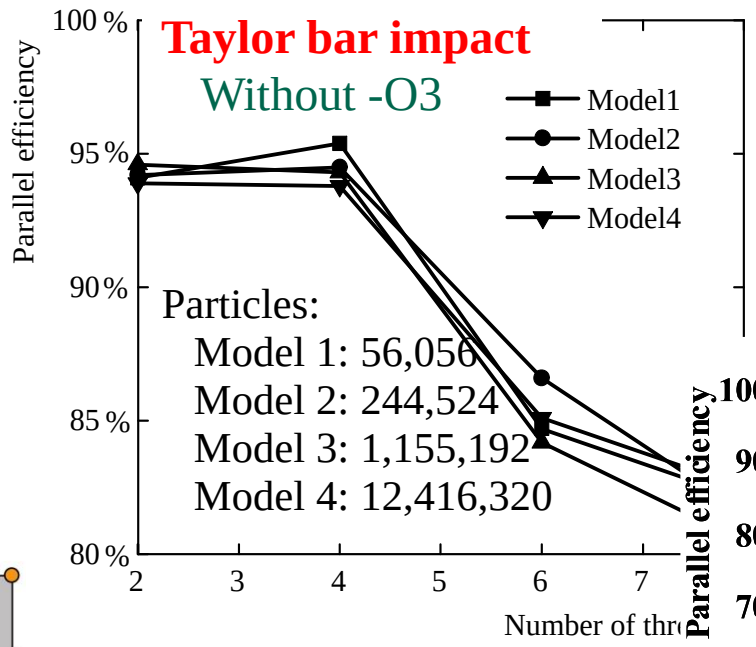
廉艳平, 张雄等. Tied interface grid material point method for problems with localized extreme deformation. ***International Journal of Impact Engineering***, 70:50-61, 2014.

Our Developments on MPM

- Massive Parallel Processing (MPI)

  Background grid decomposition

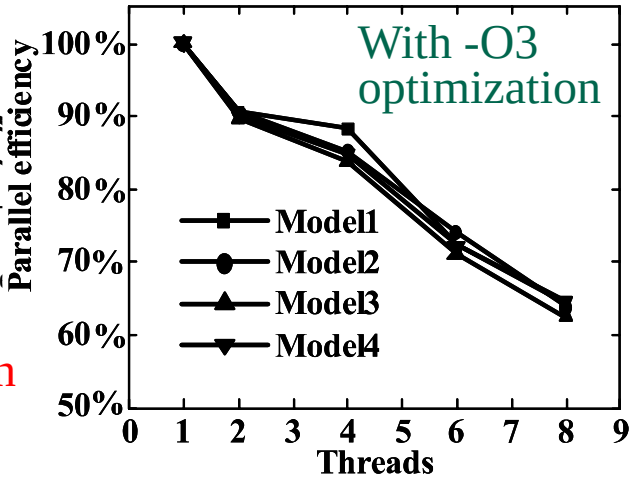




Requires significant modification to the original code

HP DL140G3 server

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



黄鹏，张雄等. Shared Memory OpenMP Parallelization of Explicit MPM and Its Application to Hypervelocity Impact. ***CMES*** 38(2):119-148, 2008

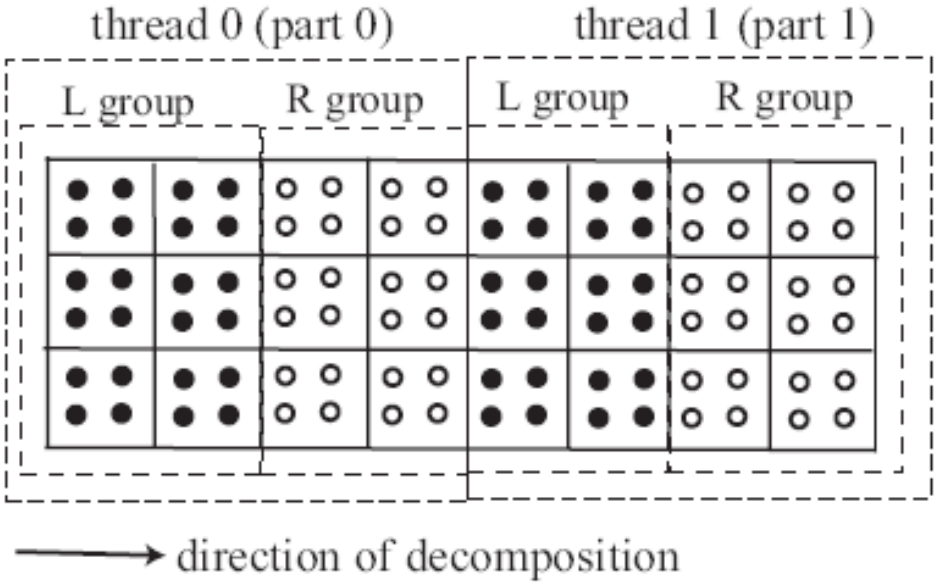
Our Developments on MPM

- Symmetric multiprocessing (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

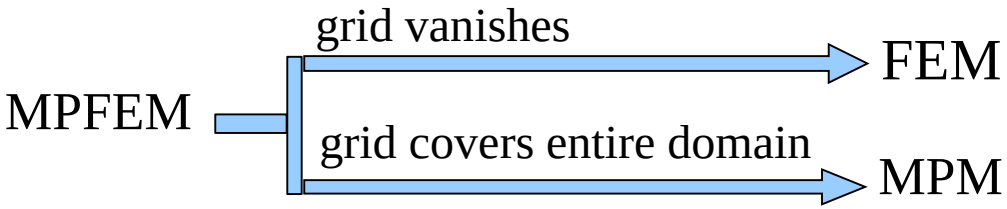


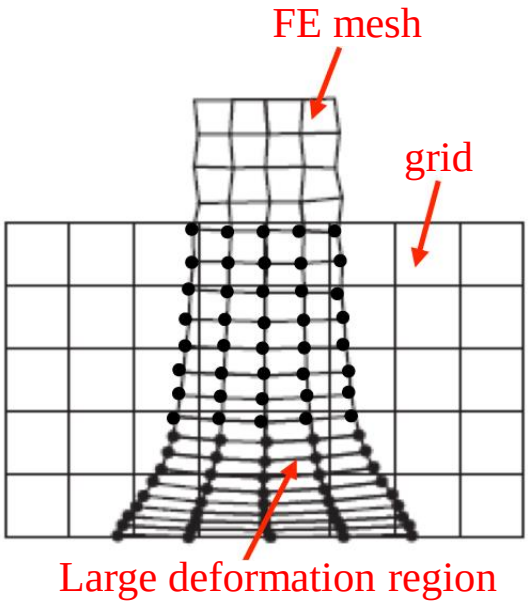
张衍涛, 张雄等. An alternated grid updating parallel algorithm for material point method using OpenMP. ***CMES: Computer Modeling in Engineering & Sciences***, 69(2): 143-165, 2010

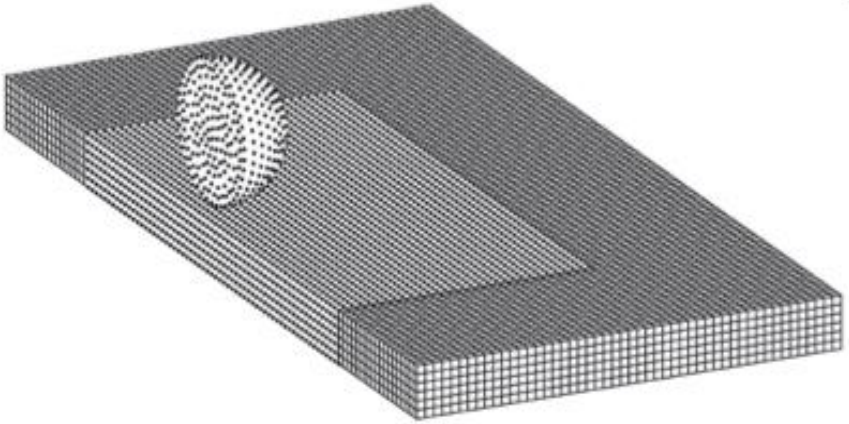
Our Developments on MPM

Material Point Finite Element Method

- Material domain is discretized by a mesh of finite elements
- A predefined grid is placed in the potential large deformation zone
- Momentum equations are solved on
  - Background grid — large deformation zone
  - FE mesh — elsewhere





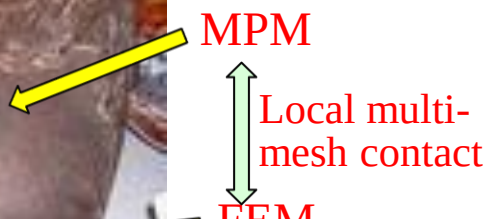


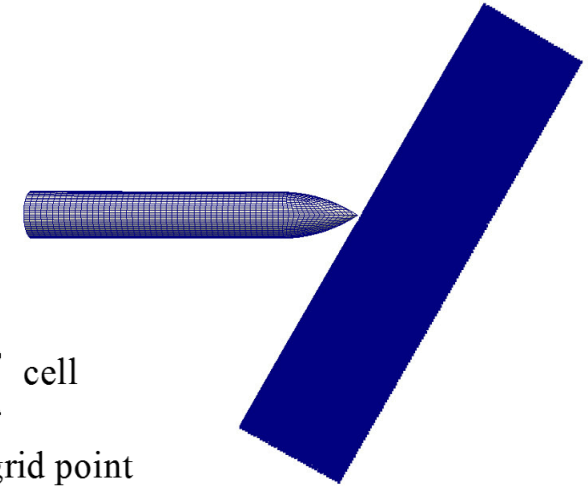
张雄，KY Sze 等. An explicit material point finite element method for hyper velocity impact. ***International Journal for Numerical Methods in Engineering*** 66: 689 ~706, 2006

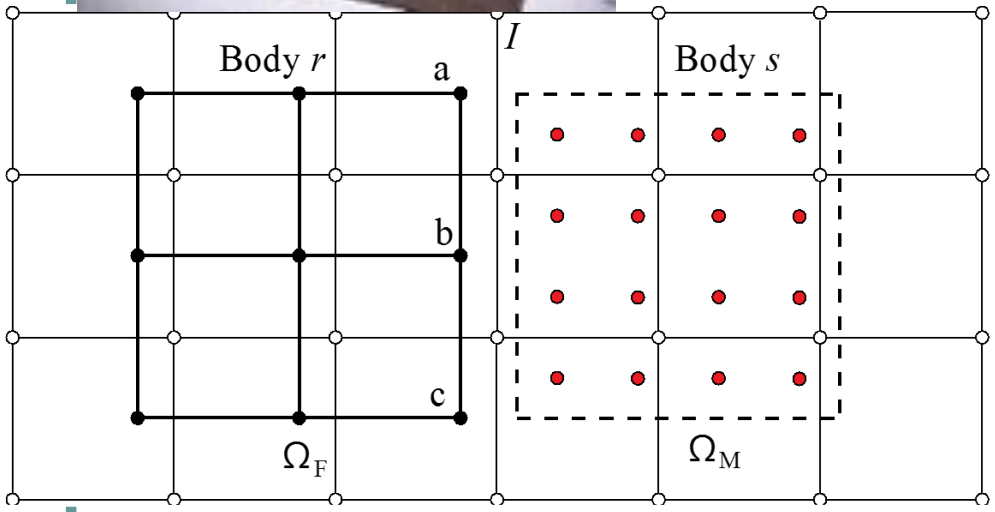
Our Developments on MPM

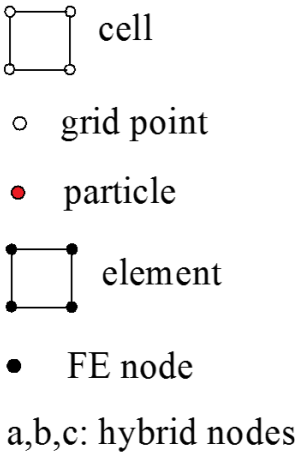
Coupled FE-MP method











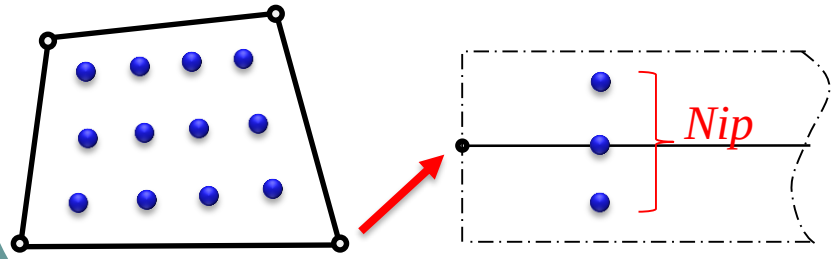
- Discretize different bodies by FEM and MPM, respectively
- Interaction between bodies is handled by ***contact methods***

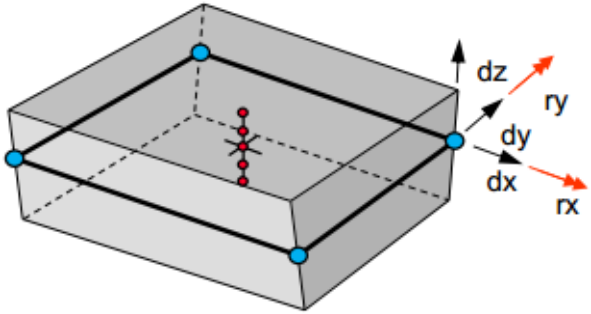
- 廉艳平，张雄等. Coupling of finite element method with material point method by local multi-mesh contact method. ***CMAME*** 200: 3482-3494, 2011
- 陈镇鹏，邱信明，张雄等. Improved coupling of finite element method with material point method based on a particle-to-surface contact algorithm. ***CMAME*** 293(15): 1-19, 2015

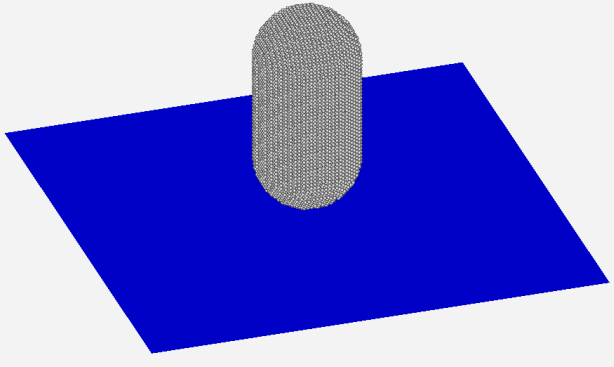
Our Developments on MPM

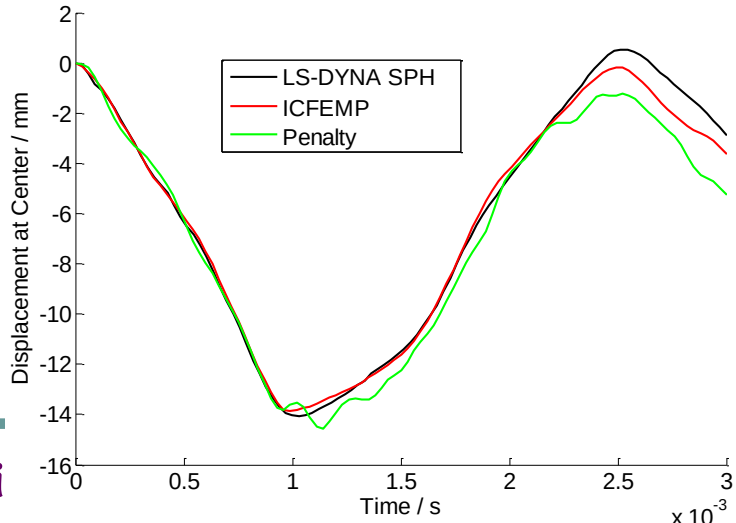
Coupled shell-particle

- **Coupled shell-particle method**
  - Belytschko and Tsay 1981
    - Point-surface contact
- Adaptive shell-particle method
  - Conversion criteria
    - Element aspect ratio
    - Plastic strain
  - Conversion method
    - *Nip* layers in the thickness direction
    - *Nx* × *Ny* particles in each layer





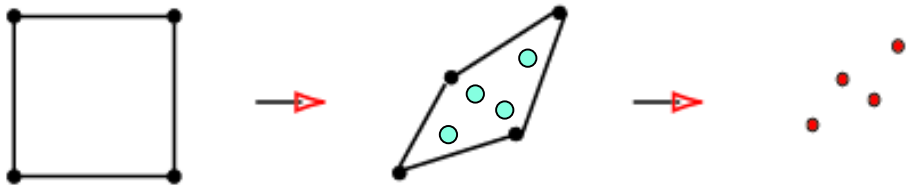




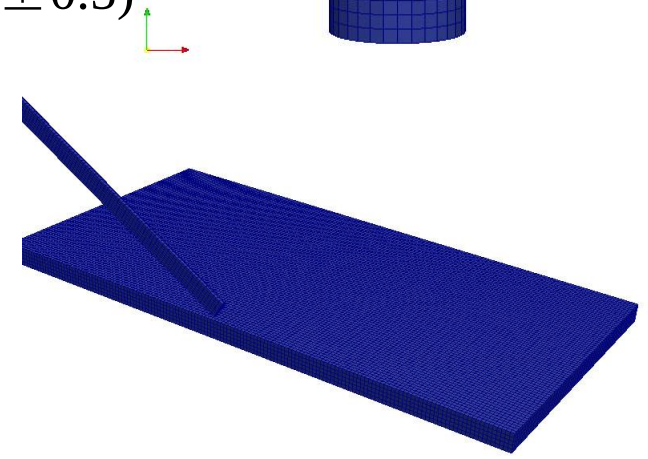
Our Developments on MPM

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 ($\pm 0.5, \pm 0.5, \pm 0.5$)







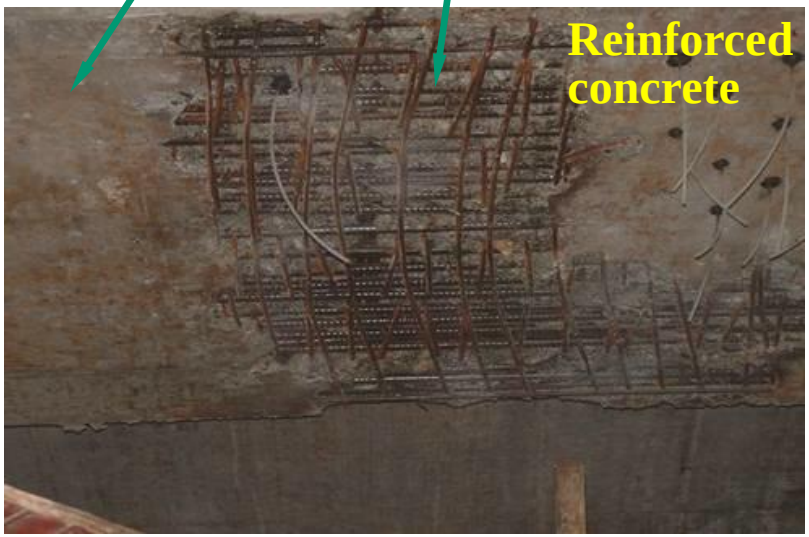
  - After conversion
    - Particles and remaining elements are coupled in a similar way to that used in MPFEM

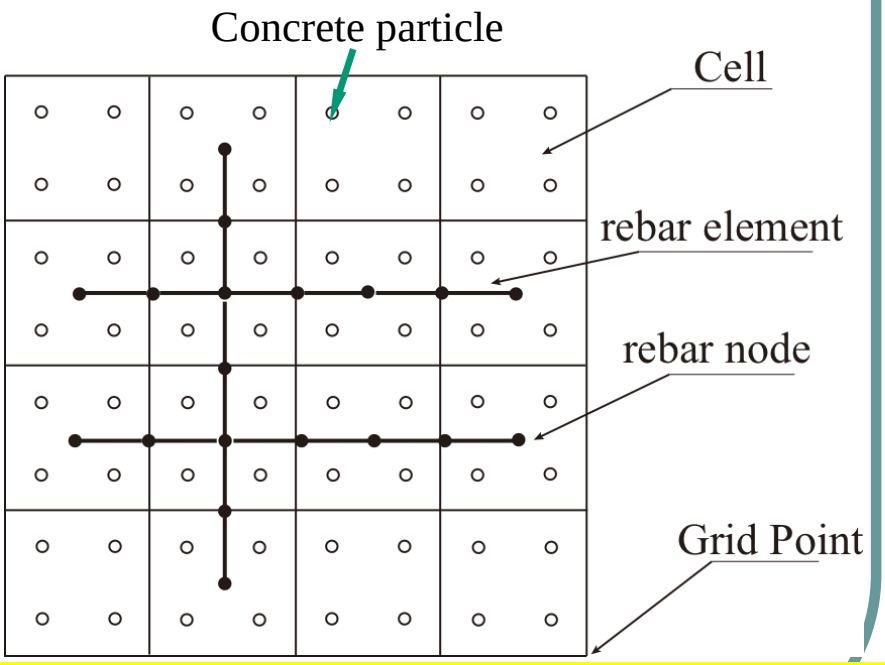
YP Lian, X Zhang, et al. An adaptive finite element material point method and its application in extreme deformation problems. ***CMAME*** 241-244 (1): 275~285, 2012
ZP Chen, XM Qiu, X Zhang, et al. Improved coupling of finite element method with material point method based on a particle-to-surface contact algorithm. ***CMAME*** 293(15): 1-19, 2015

Our Developments on MPM

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





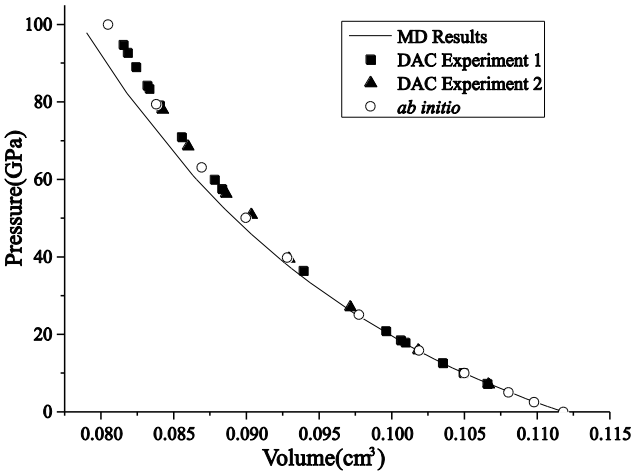
廉艳平，张雄等. A FEMP method and its application in modeling dynamic response of reinforced concrete subjected to impact loading. ***Computer Methods in Applied Mechanics & Engineering***, 200(17-20): 1659-1670, 2011.

Our Developments on MPM

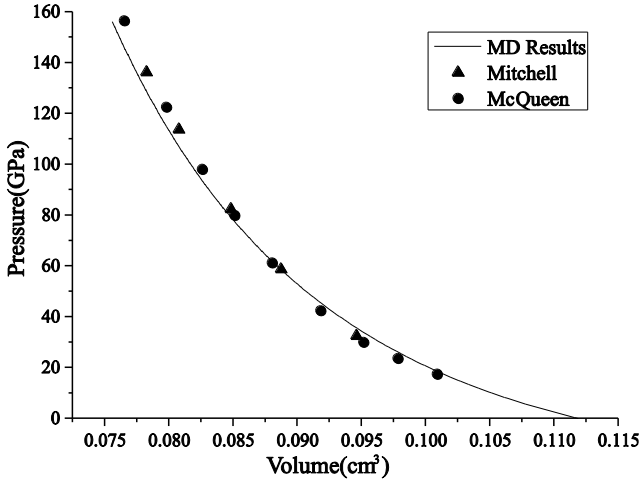
MPM-MD
Hierarchical multiscale

超高速碰撞会发生相变，需要状态方程能够描述相变

MD 模拟
↓
E, V, P, T
↓
GRAY 参数
↓
GRAY EOS
↓
MPM



293K等温压缩曲线



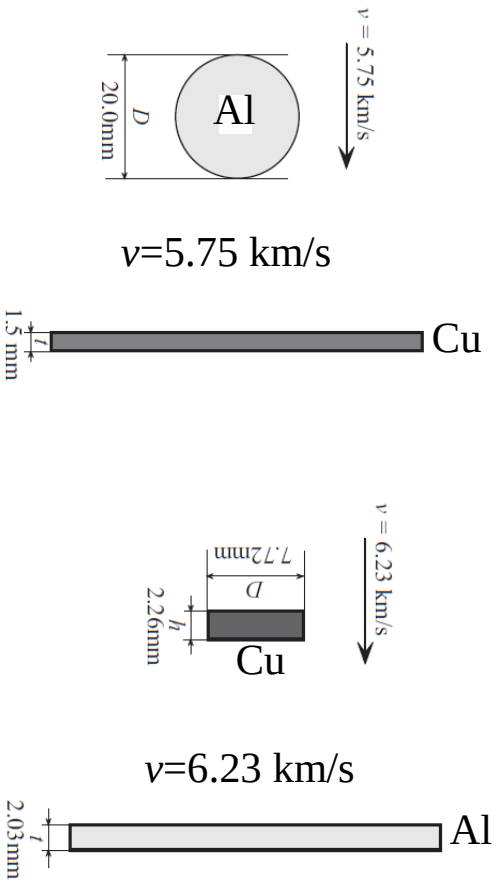
Hugoniot曲线

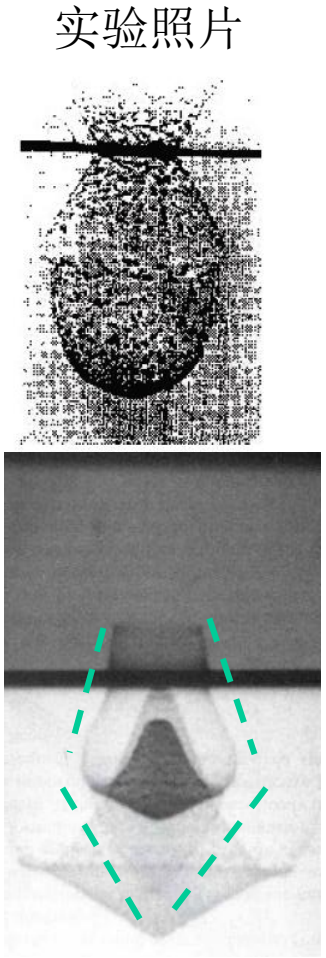
GRAY参数	V_0(cm^3/g)	C(cm/μs)	S	γ_0	a	g_e(kJ/(moleK^2))	T_m(K)
文献数值	0.1118	0.394	1.489	1.97	1.5	4.9×10^{-7}	1790
MD拟合值	0.1119	0.398	1.301	1.86	1.7	8.3×10^{-7}	2006

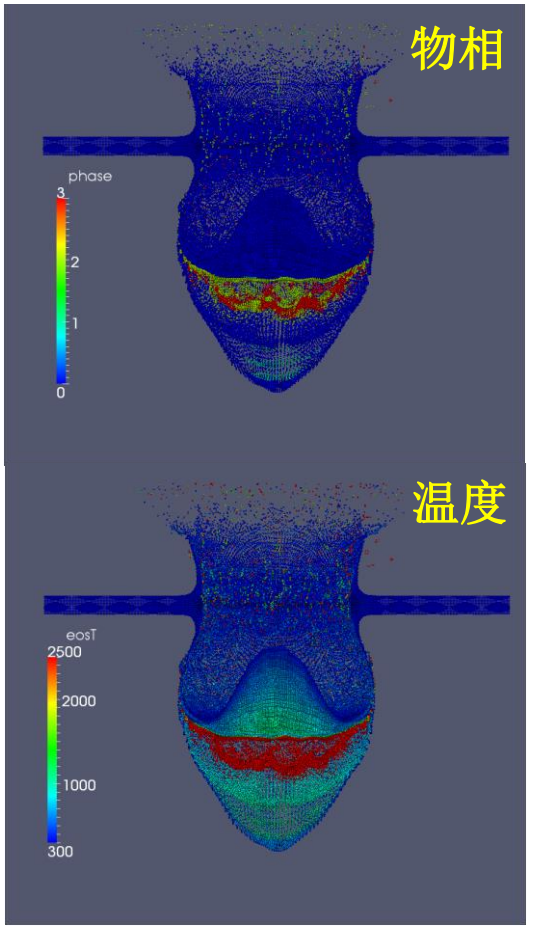
刘岩，王汉奎，张雄. A Multiscale Framework for High-velocity Impact Process with Combined Material Point Method and Molecular Dynamics. International Journal of Mechanics and Materials in Design. 9(2): 127-139, 2013.

Our Developments on MPM

MPM-MD
Hierarchical multiscale







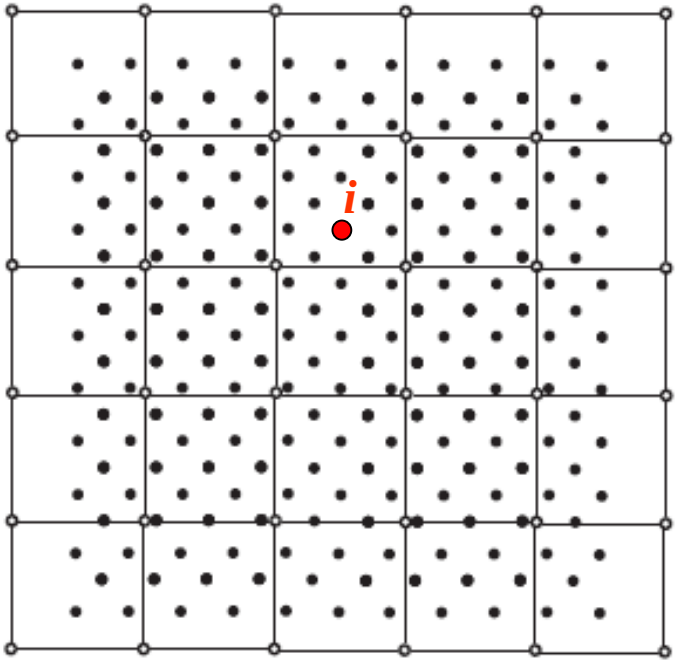
Cu-Al

Computational Dynamics 计算动力学实验室

Our Developments on MPM

Smoothed Molecular Dynamics

- The high-frequency components can be eliminated by
  - a mean force field approach in which the force field is obtained by an averaging process over the fastest degrees of motion. [Reich (1995)]
  - attaching the atoms to a regular background grid



The grid filter out the high frequency motion that can not be represented by the grid, which depends on the grid cell size

$$f_i = \sum_J N_J(\boldsymbol{r}_i) f_J$$

$$\dot{\boldsymbol{r}}_i = \sum_J N_J(\boldsymbol{r}_i) \dot{\boldsymbol{r}}_J$$

$$\ddot{\boldsymbol{r}}_i = \sum_J N_J(\boldsymbol{r}_i) \ddot{\boldsymbol{r}}_J$$

⇨ The motion of atoms are smoothed

Y Liu, X Zhang, et al. Smoothed Molecular Dynamics for Large Step Time Integration. ***CMES***, 20(3): 177-192, 2007

Our Developments on MPM

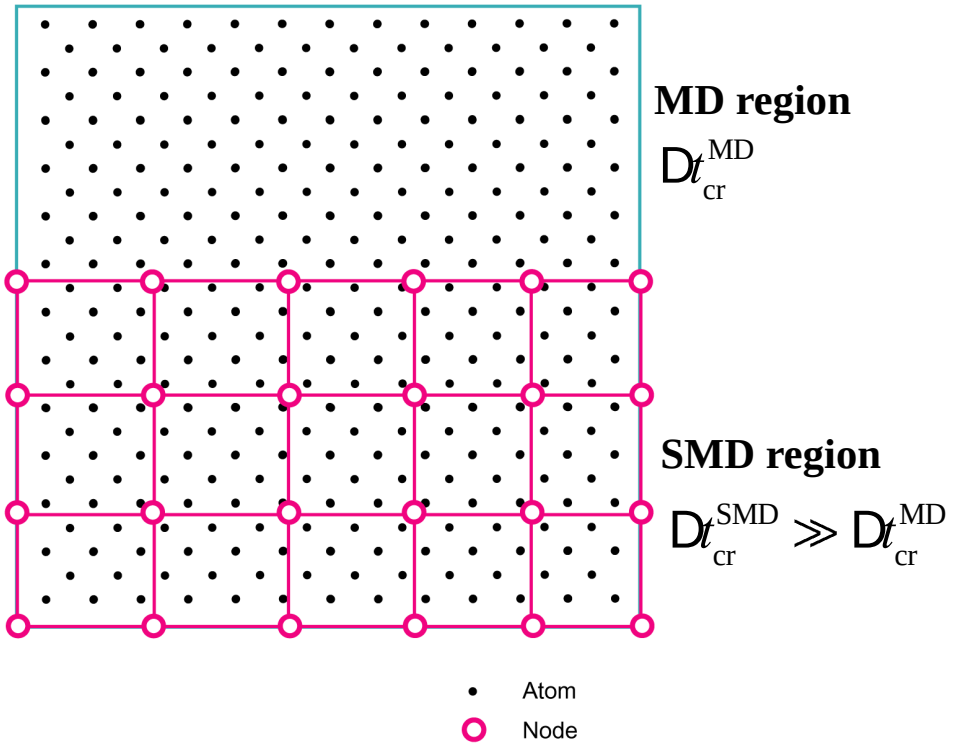
Combination of MD and SMD

- The grid filter out the high frequency motion that cannot be represented by the grid
- SMD fails in some case where the atomic resolution is required to capture the high frequency motion
  - dislocation
  - crack
  - bond breakage
  - bond formation
- No interface zone
- No need to reduce mesh size

MD + **SMD**

(Localized region) **(Far-field region)**

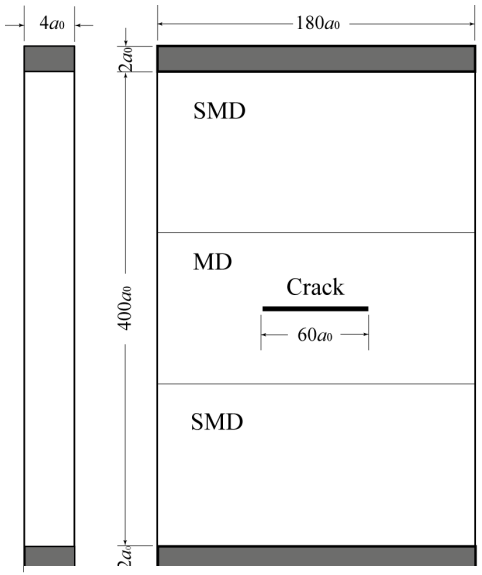
Concurrent multiscale coupling

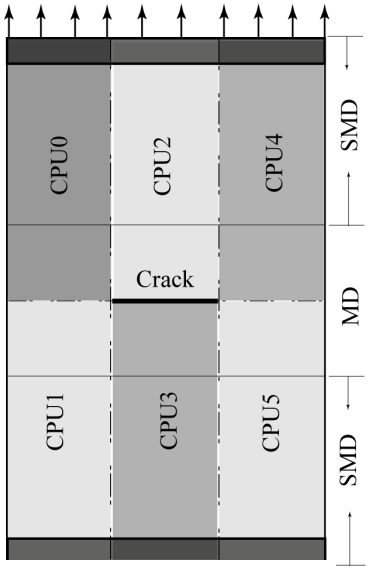


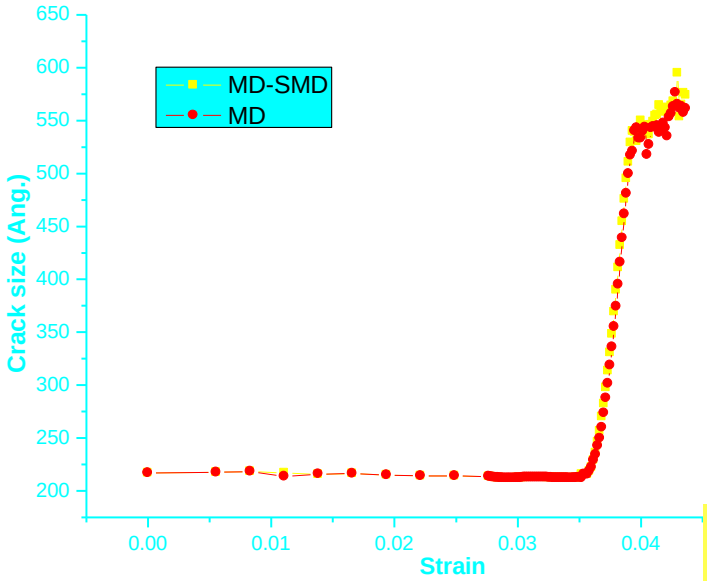
Multiple-time-step coupling of MD and SMD

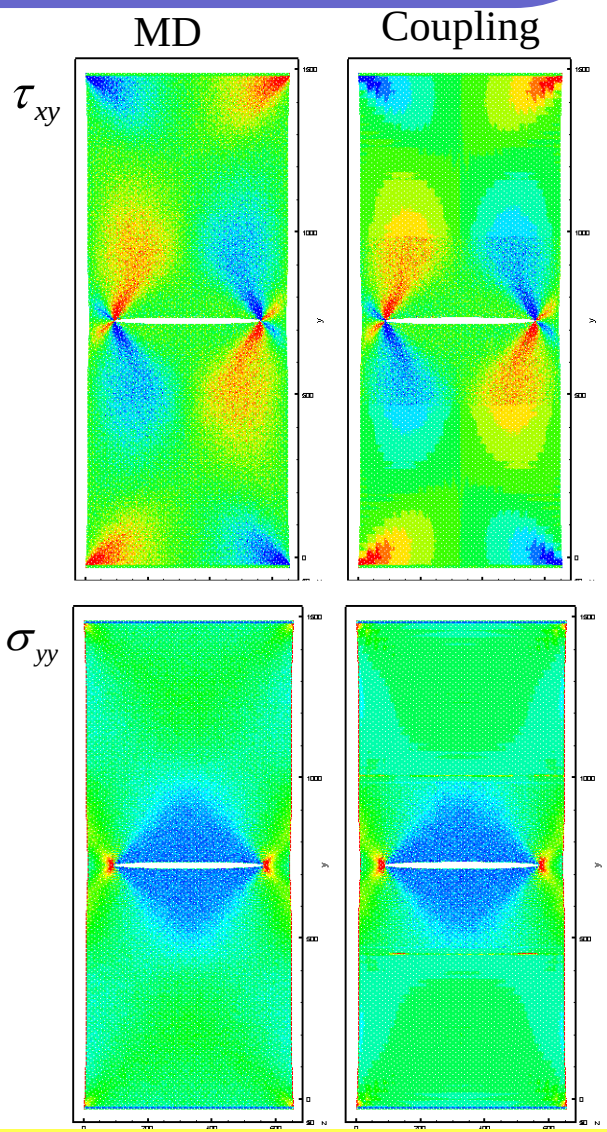
Our Developments on MPM

Crack Propogation







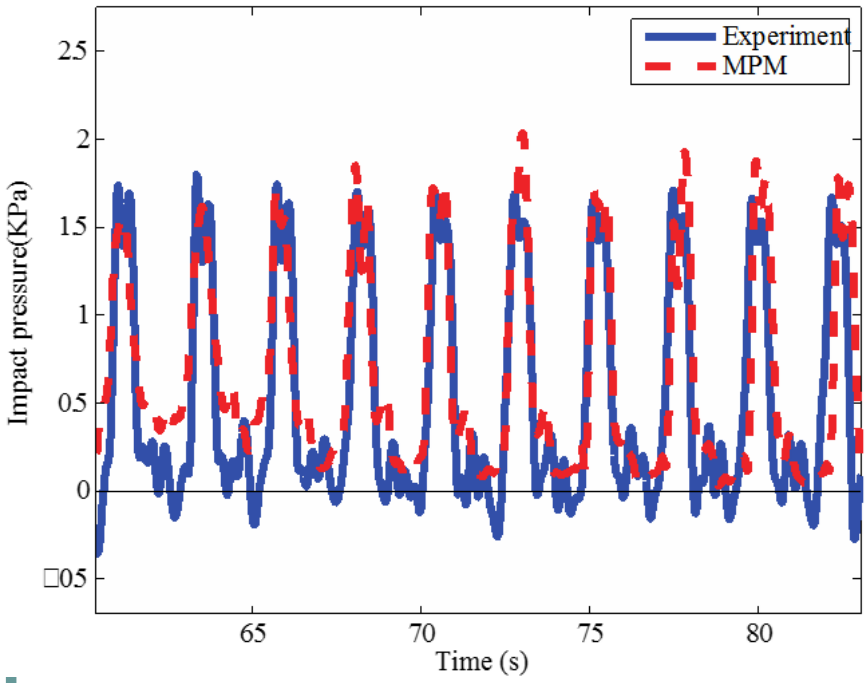


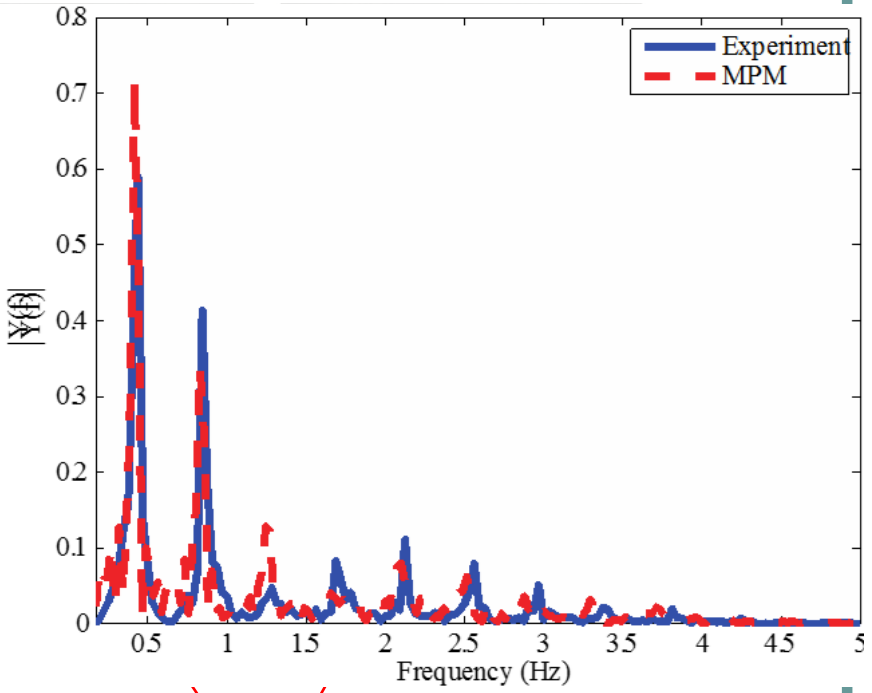
王汉奎，张雄，刘岩. 并行化光滑分子动力学方法及其与分子动力学的耦合. 计算物理，25(6): 718-724，2008

Our Developments on MPM

Weakly compressible EOS $p = c^2 r$

Density fluctuation: $\delta = \Delta\rho / \rho_0 = v_f^2 / c^2$ $d £ 1\%$ ⇒ $c ³ 10 v_f$





t = 63.69s t = 64.28s t = 64.87s t = 65.46s

$Dt = 5.5 \times 10^{-5}$ s

Pressure is not smooth

JG Li, Y Hamamoto, Y Liu, X Zhang. Sloshing impact simulation with material point method and its experimental validations. ***Computers & Fluids***, 103(1): 86 ~ 99, 2014

Our Developments on MPM

Incompressible fluid

$$\frac{d\boldsymbol{v}}{dt} = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla\cdot\boldsymbol{\tau} + \boldsymbol{b}$$

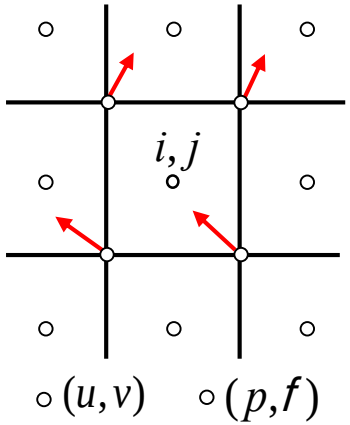
Operator split:

$$\frac{d\boldsymbol{v}}{dt} = \frac{1}{\rho}\nabla\cdot\boldsymbol{\tau} + \boldsymbol{b} \Longrightarrow \boldsymbol{v}^* = \boldsymbol{v}^n + \Delta t\left(\frac{1}{\rho}\nabla\cdot\boldsymbol{\tau} + \boldsymbol{b}\right) \text{ (explicit MPM)}$$

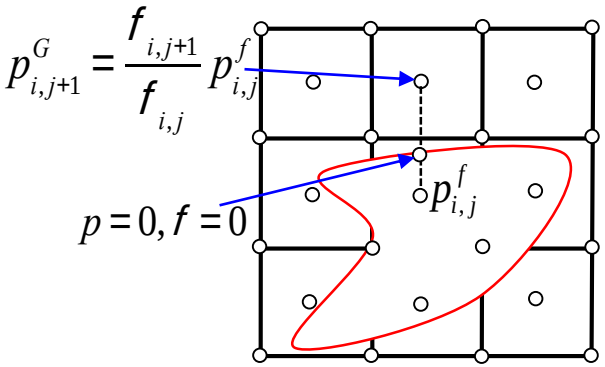
$$\frac{d\boldsymbol{v}}{dt} = -\frac{1}{r}\nabla p \Longrightarrow \boldsymbol{v}^{n+1} = \boldsymbol{v}^* - \mathrm{D}t\frac{1}{r}\nabla p^{n+1} \xrightarrow{\nabla\cdot\boldsymbol{v}^{n+1}=0} \nabla^2 p^{n+1} = \frac{r}{\mathrm{D}t}\nabla\cdot\boldsymbol{v}^*$$

(pressure Poisson equation)

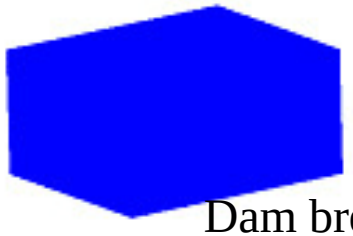
- PPE is solved by collocating at cell centers
- Level set is used to construct the free surface



Semi-Staggered grid



Pressure boundary condition



Dam break simulation

F Zhang, X Zhang, et al. Incompressible material point method for free surface flow. ***Journal of Computational Physics***. 330: 92–110, 2017.

Our Developments on MPM

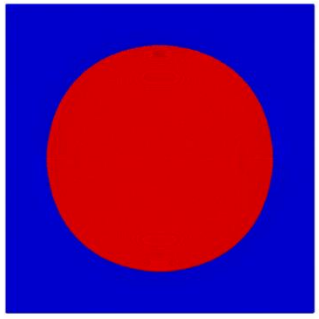
交替物质点有限差分法

- 有限差分法（FDM）求解冲击波传播阶段
- MPM求解起爆阶段和流固耦合阶段
- 发展了MPM与FDM之间的无缝转化方法
- 充分发挥了FDM和MPM在爆炸问题各阶段的优势

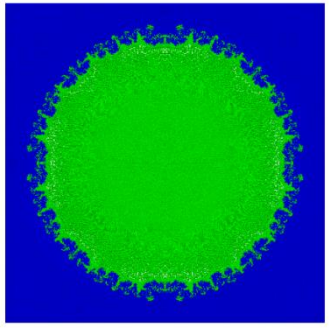
炸药起爆 → 冲击波传播 → 冲击波与结构相互作用

MPM　　FDM(cell-centered)　　MPM

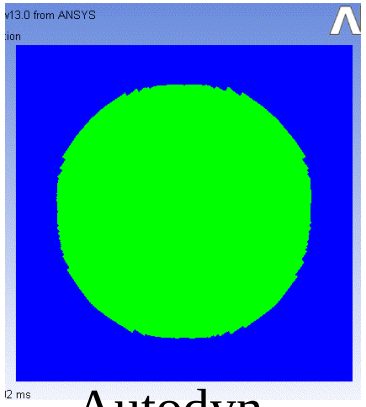
2维TNT空中爆炸



MPM-FDM



MPM



Autodyn

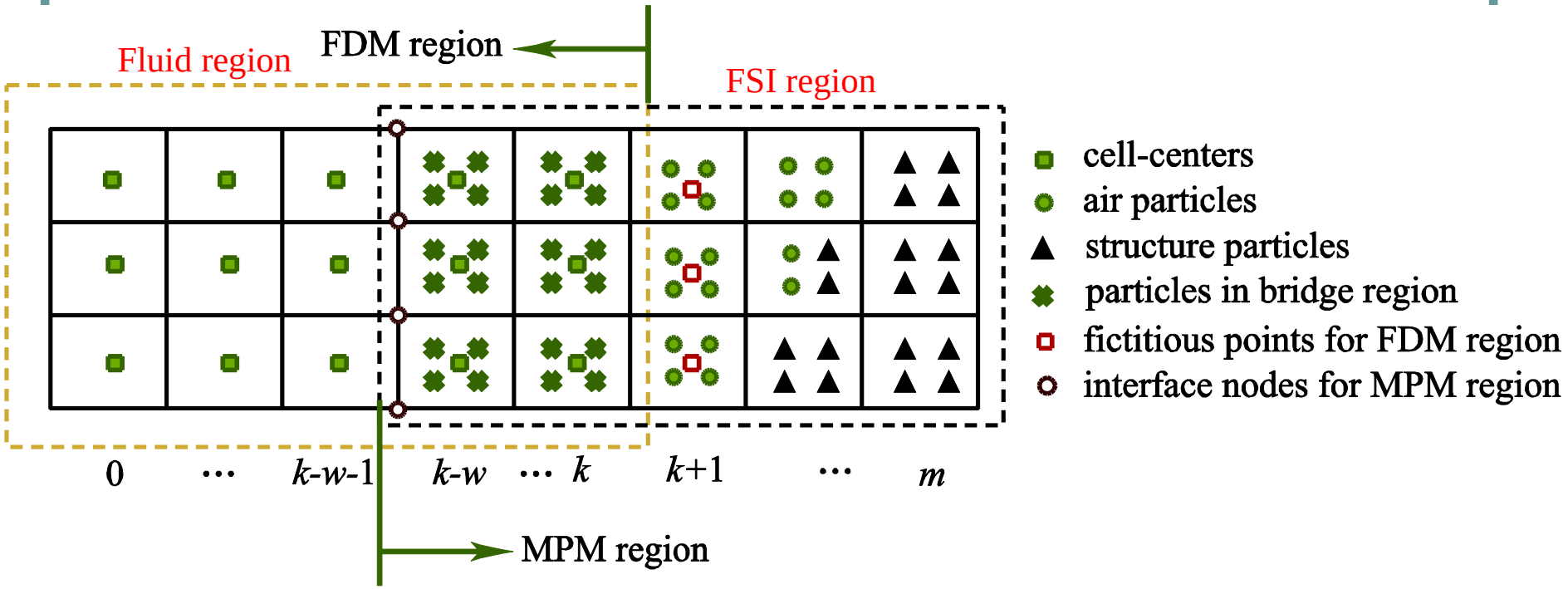
崔潇骁，张雄等. An alternating finite difference material point method for numerical simulation of high explosive explosion problems. ***CMES***, 92(5): 507-538, 2013

Our Developments on MPM

耦合物质点有限差分法

流体区域 → 过渡区域 ← 流固耦合区域

FDM　　“握手区”　　MPM



1. 两个区域间物质交换、能量交换的守恒性保证
2. 两个区域间波反射效应的控制

崔潇骁, 张雄等. A coupled finite difference material point method and its application in explosion simulation, ***CMES: Computer Modeling in Engineering & Sciences***. 98(6): 565-599, 2014

Outline

- Introduction
- Material Point Method
- Our Developments on MPM
- **MPM3D – A 3D explicit MPM code**
- Applications
- Concluding remarks

MPM3D - 3D explicit MPM code

- 开发工具
  - CMake — 跨平台的程序构建和打包系统；
    http://www.cmake.org
  - VTK — 跨平台、支持并行的可视化工具库；
    http://www.vtk.org
  - Qt — 跨平台的C++图形用户界面应用程序框架；
    http:/qt.digia.com
  - SVN、Git — 源代码版本控制（历史记录、团队开发）；
    http://subversion.tigris.org
    http://git-scm.com
  - ParaView — 跨平台的二维和三维数据分析和可视化程序(并行)；
    http://www.paraview.org
  - QXMLEdit — 跨平台的xml编辑器；
  - Kdiff、DiffMerge — 文本文件比较与合并工具；

MPM3D - 3D explicit MPM code

- MPM3D solver
  - Algorithm
    - MPM / GIMP (USF, USL & MUSL); iMPM
    - FEM / FEM-MPM
    - FDM / FDM-MPM
  - Material models
    - Elasticity, plasticity (hardening, temperature, strain rate)
    - Fluid, High explosive
    - Metal, 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-F90:** Open source version
- **MPM3D:** Free trial until 12-31-2016
  http://mpm3d.comdyn.cn

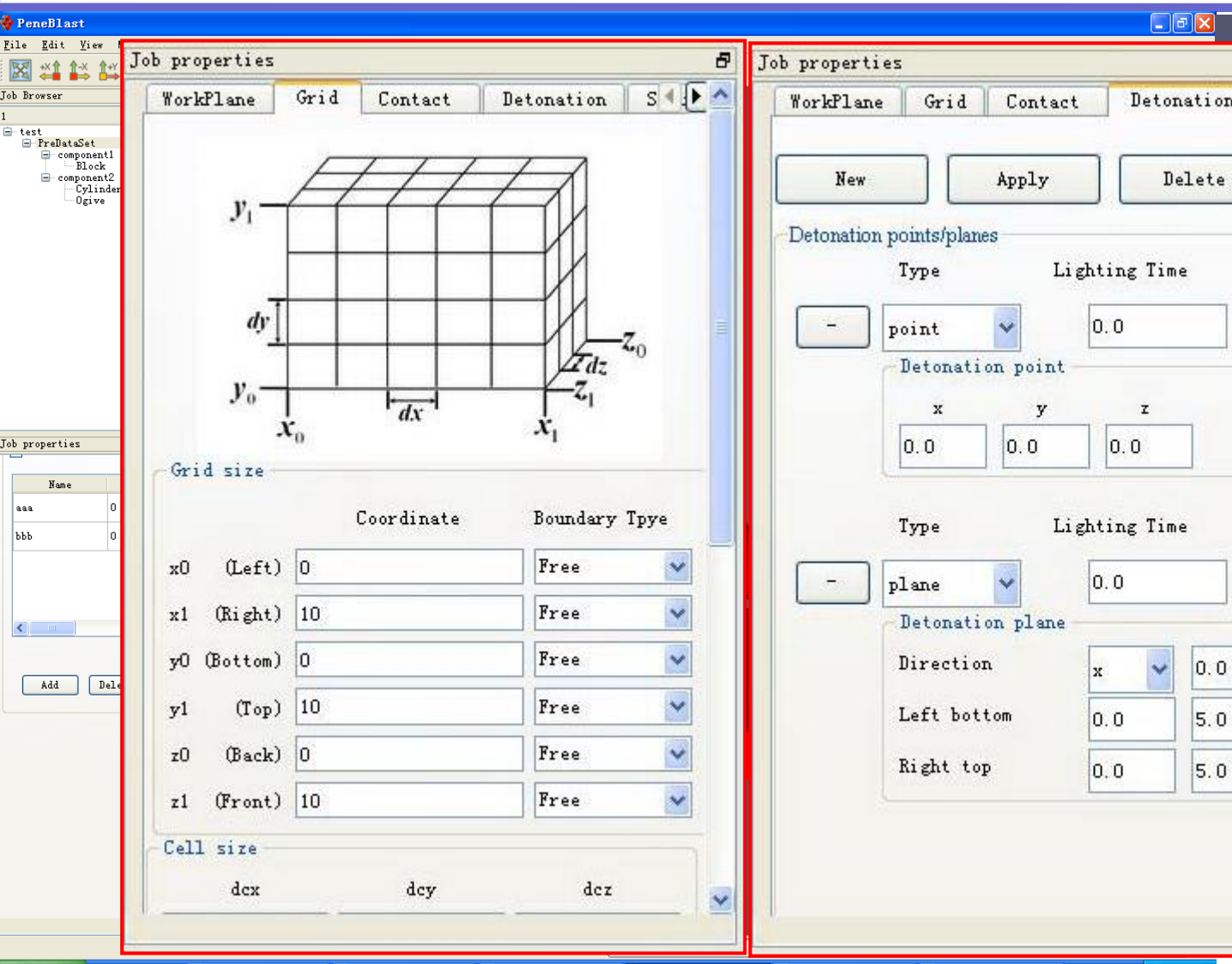
- 张雄等. 物质点法. 清华大学出版社, 2013.9
- 张雄等. ***The Material Point Method*** - A Continuum-Based Particle Method for Extreme Loading Case. Published by Elsevier, 2016.11.

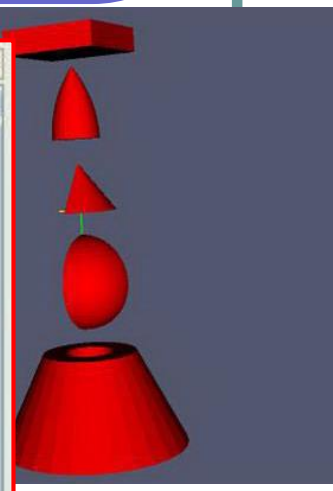
MPM3D - 3D explicit MPM code

- 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)

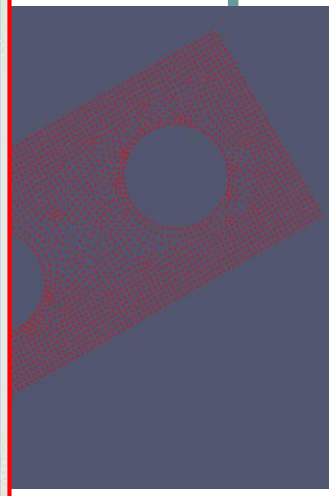
MPM3D - 3D explicit MPM code

Preprocessor





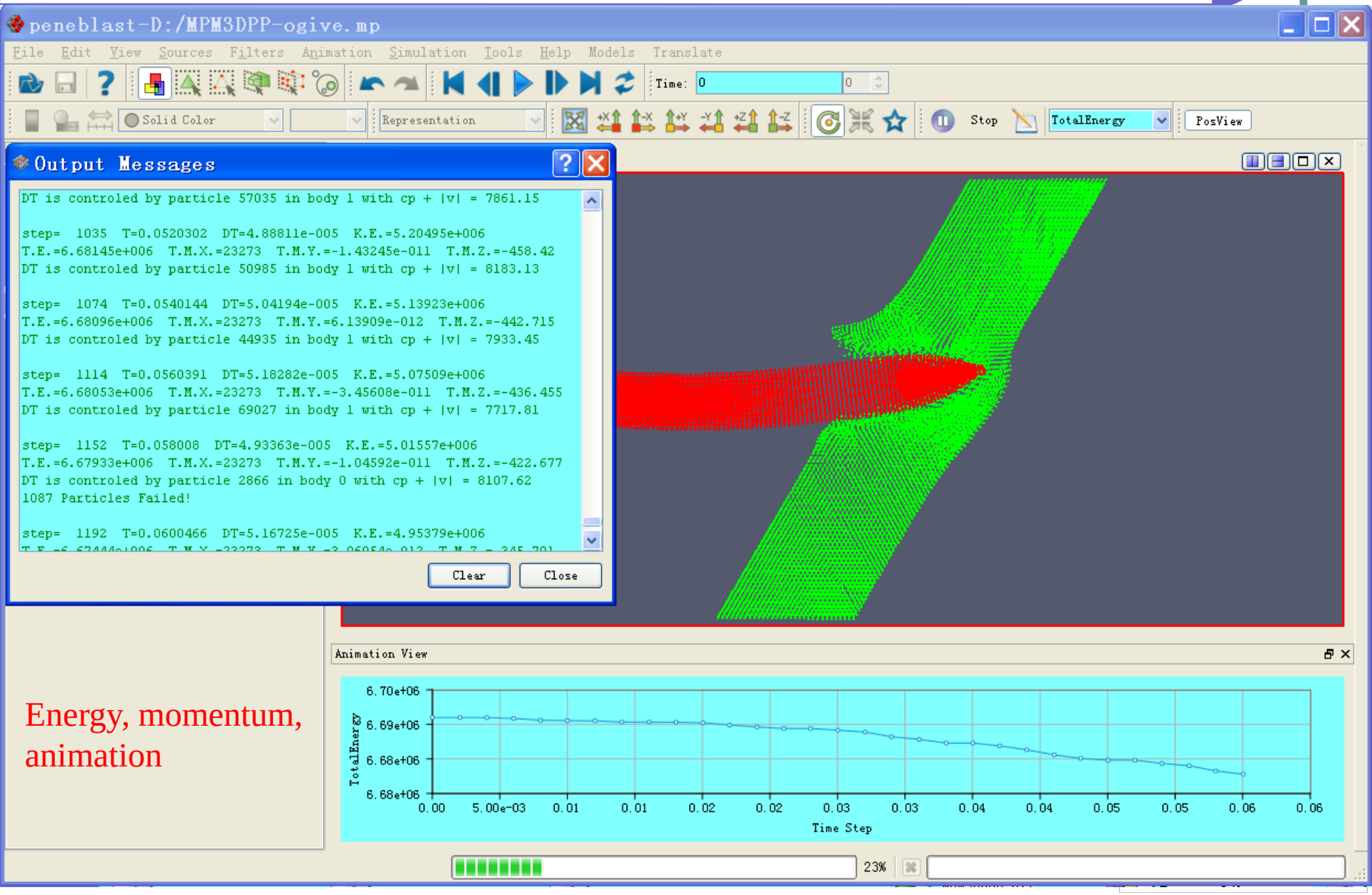
ular Bodies



defined entity

MPM3D - 3D explicit MPM code

Real time monitoring

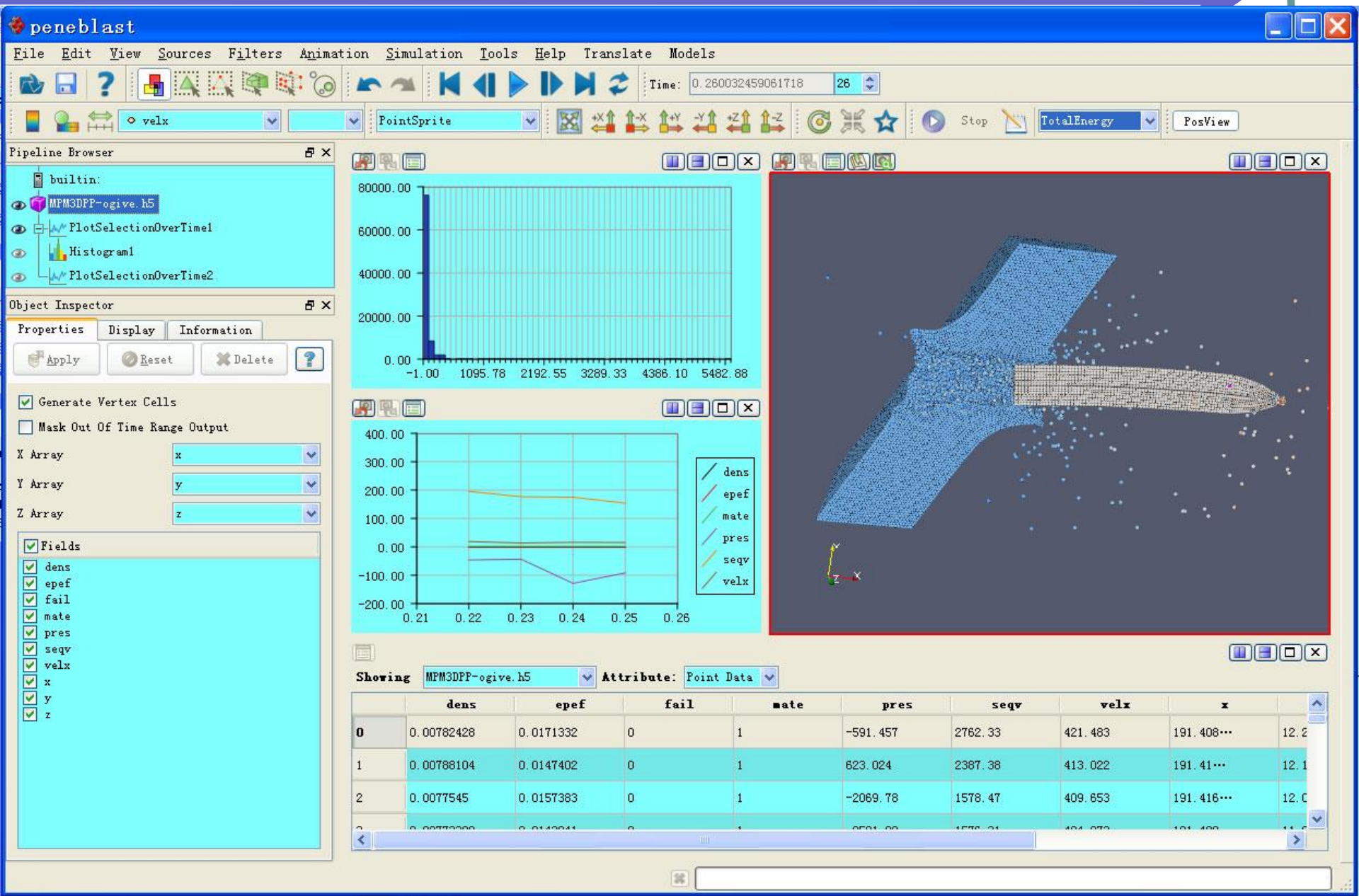


Energy, momentum, animation

http://www.comdyn.cn

MPM3D - 3D explicit MPM code

Postprocessor
ParaView



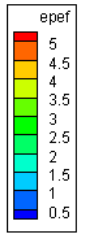
Outline

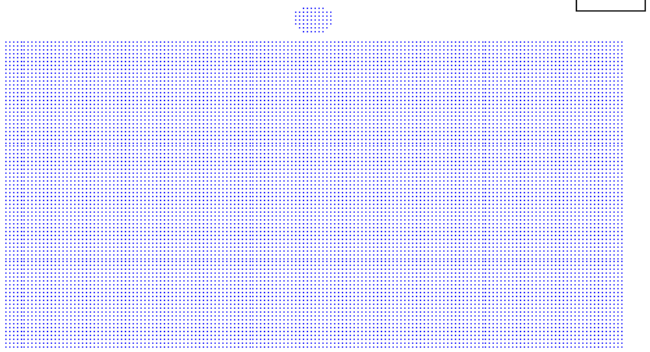
- Introduction
- Material Point Method
- Our Developments on MPM
- MPM3D – A 3D explicit MPM code
- **Applications**
  - **Hypervelocity impact**
  - **Impact/Penetration**
  - **Blast loading**
  - **Slope failure**
  - **Metal cutting**
  - **Fracture simulation**
  - **Free surface flow**
  - **Fluid-structure interaction**
- Concluding remarks

Applications

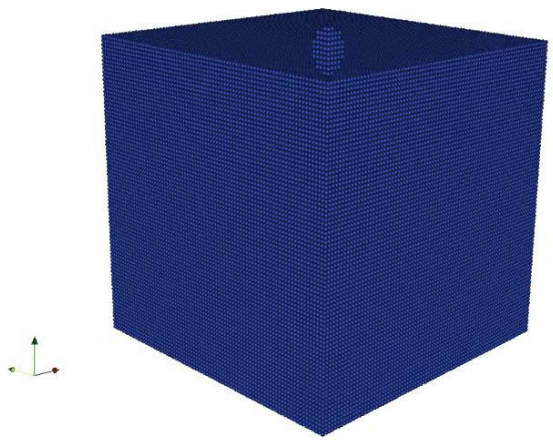
Crater forming

- 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





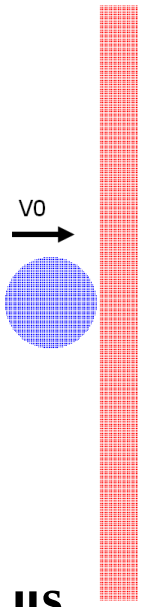
	Deepness (mm)	Crater diameter (mm)	Deepness/Diameter
Experiment*	14	25.4	55
EPIC	18	24	75
MESA	15.9	28	57
SPH	17.3	26	67
CALE	15.1	24.4	62
MPM3D	14	25	56



Applications

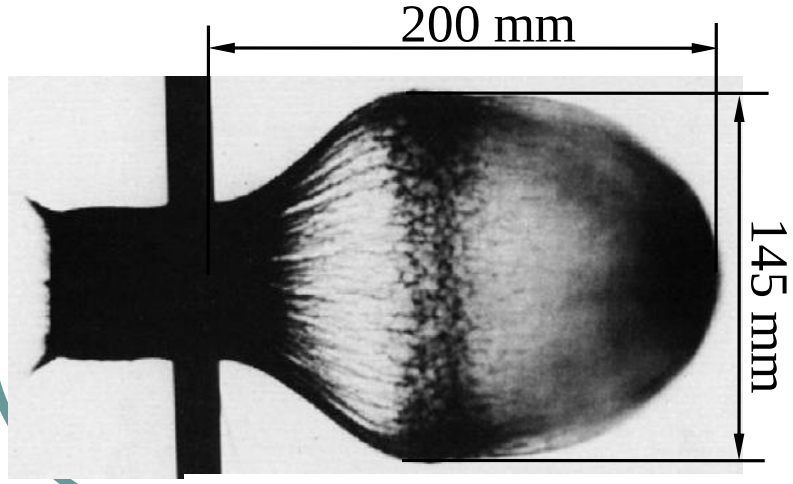
Debris cloud

- 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)

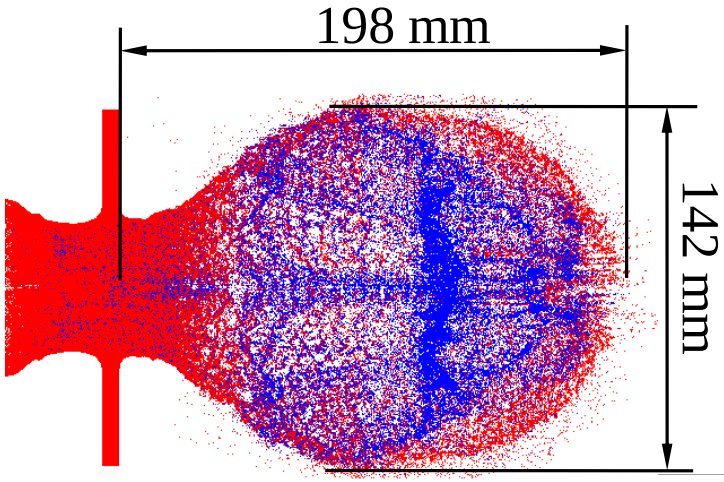


2 Quad-Core Xeon 2.66 GHz processors (OpenMP): 1.93h

The debris cloud at 30.6 μs



Experimental radiograph (Anderson, 1990)

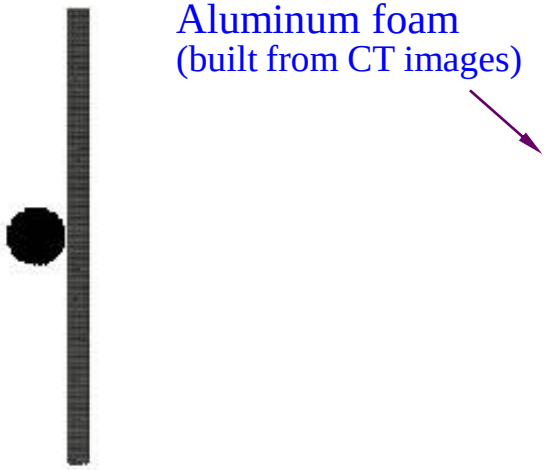


13,542,030 particles

Computational Dynamics 计算动力学实验室

Applications

Space debris shielding



Aluminum foam
(built from CT images)





The first bumper after impact



2190m/s 3410m/s 4060m/s

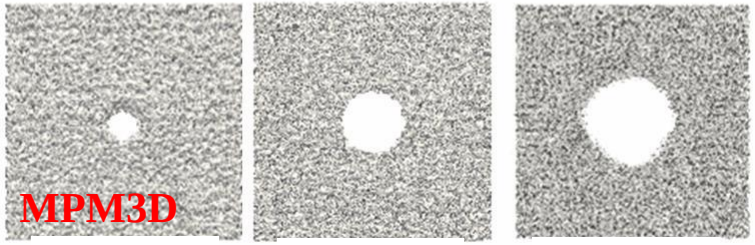
The second bumper after impact



2190m/s 3410m/s 4060m/s



2190m/s 3410m/s 4060m/s

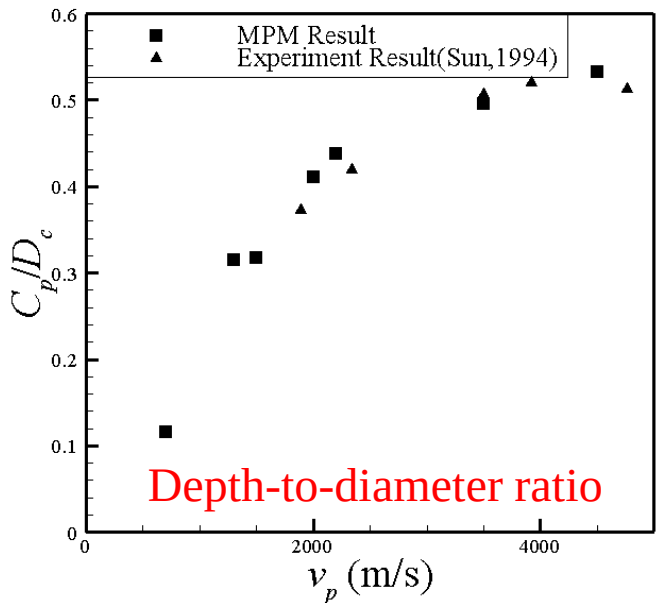


2190m/s 3410m/s 4060m/s

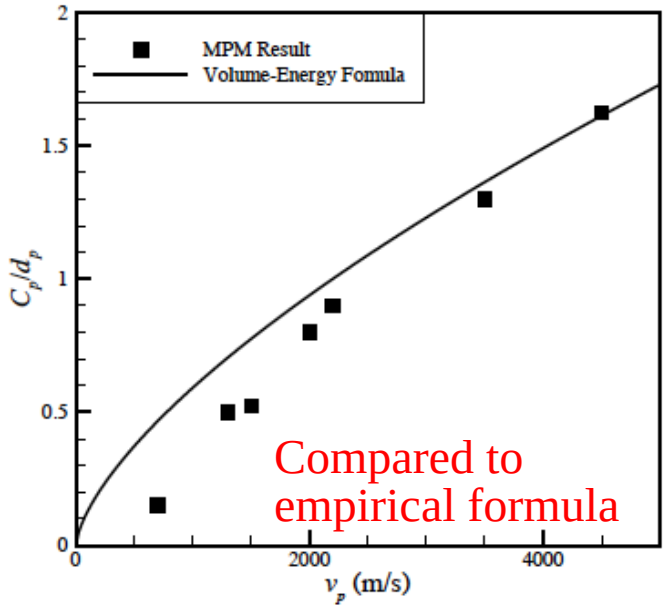
宫伟伟，刘岩，张雄等. Numerical Investigation on Dynamical Response of Aluminum Foam Subject to Hypervelocity Impact With Material Point Method. ***CMES*** 83(5): 527-545, 2012

Applications

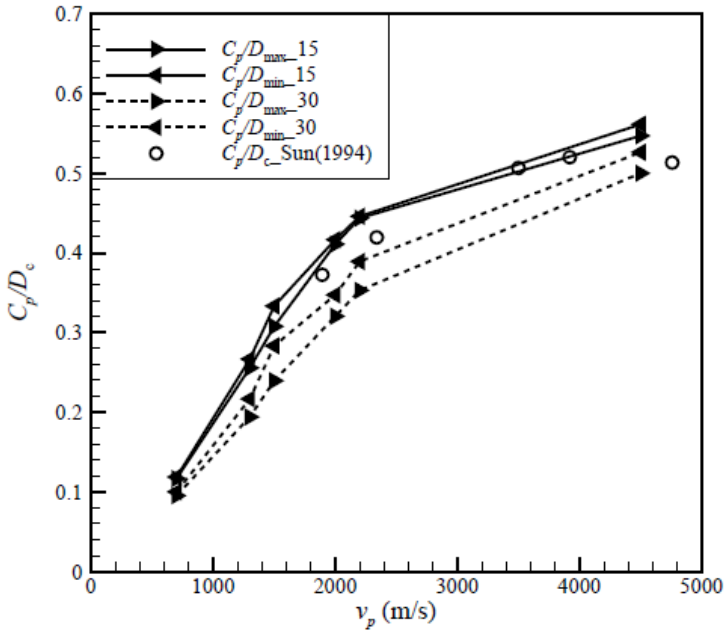
单颗粒正斜高速撞击厚靶



Depth-to-diameter ratio



Compared to empirical formula



Oblique impact: the depth-to-diameter ratio

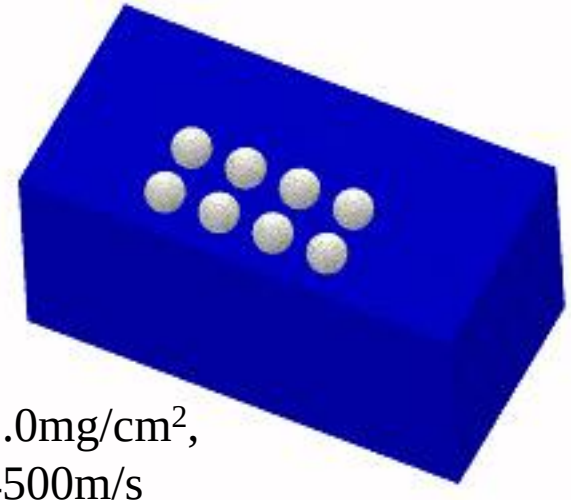
- 正撞击结果与实验、经验公式吻合良好
- 给出了斜撞击坑深、坑型的变化规律

刘平, 刘岩, 张雄. Investigation on High-Velocity Impact of Micron Particles using Material Point Method. ***International Journal of Impact Engineering***. 75: 241–254, 2015

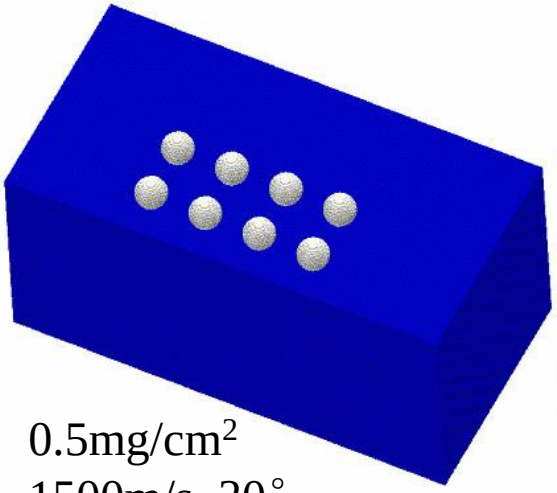
Applications

碎片群撞击厚靶

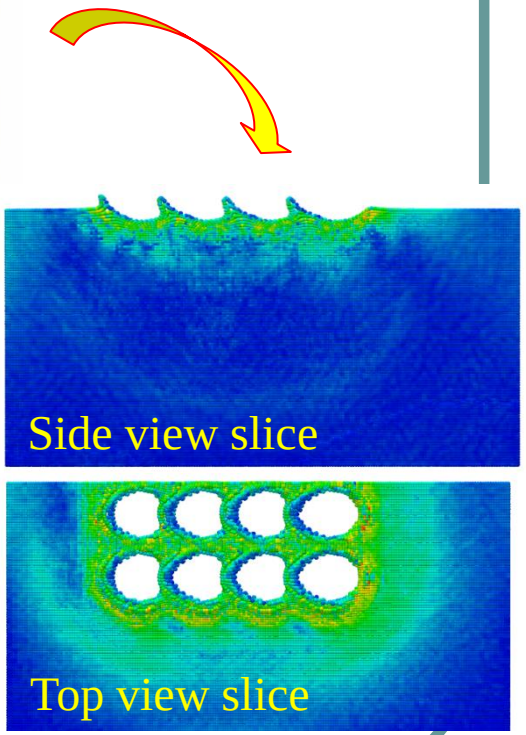
- 提出了正撞击的四种坑型模式、斜撞击的七种坑型模式
- 给出了坑深随质量流量密度、撞击速度变化的经验公式



1.0mg/cm^2,
4500m/s



0.5mg/cm^2
1500m/s, 30°

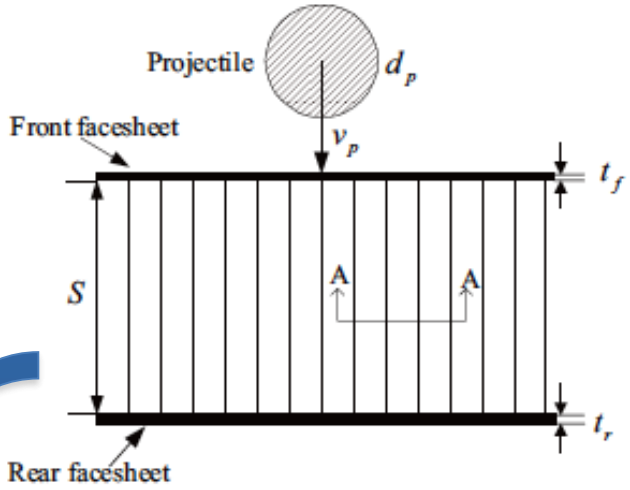


刘平, 刘岩, 张雄. Investigation on High-Velocity Impact of Micron Particles using Material Point Method. ***International Journal of Impact Engineering***. 75: 241–254, 2015

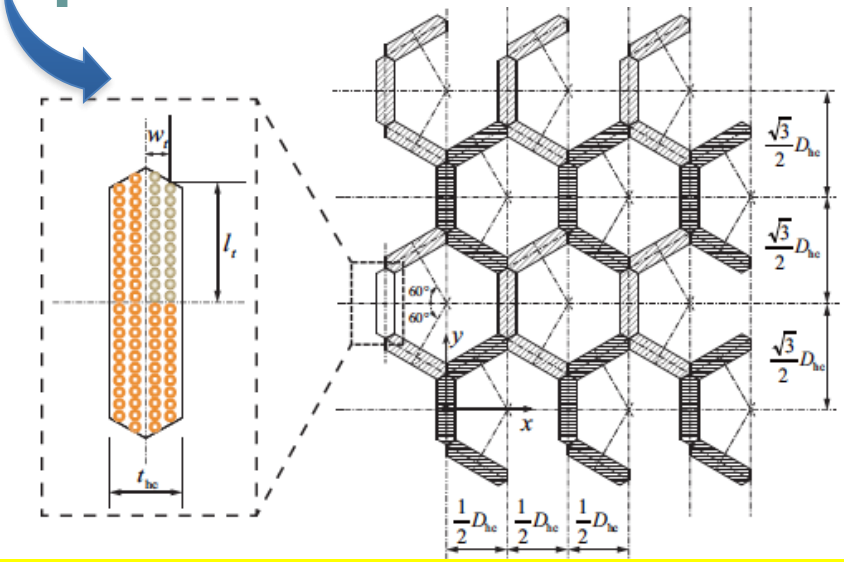
Applications

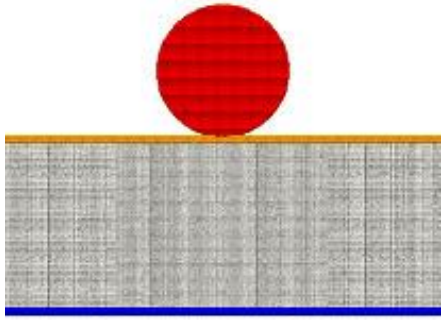
Honeycomb

基于细观结构模型的直接模拟：蜂窝材料



- 芯质-面板连接处离散便利，模型易于加密
- 结果与实验、经验公式吻合
- 易于研究芯质的拢聚效应







芯质孔洞形态

$m = 2\mathrm{g}$

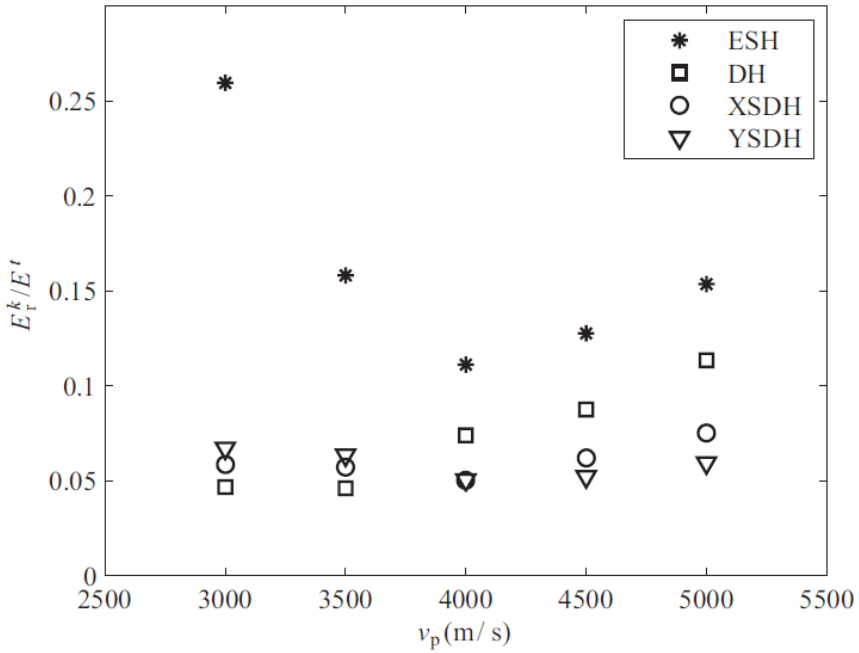
$v_p = 4500\mathrm{m/s}$

刘平, 刘岩, 张雄. Internal-structure-model Based Simulation Research of Shielding Properties of Honeycomb Sandwich Panel Subjected to High-Velocity Impact. ***IJIE***. 77:120 - 133, 2015.

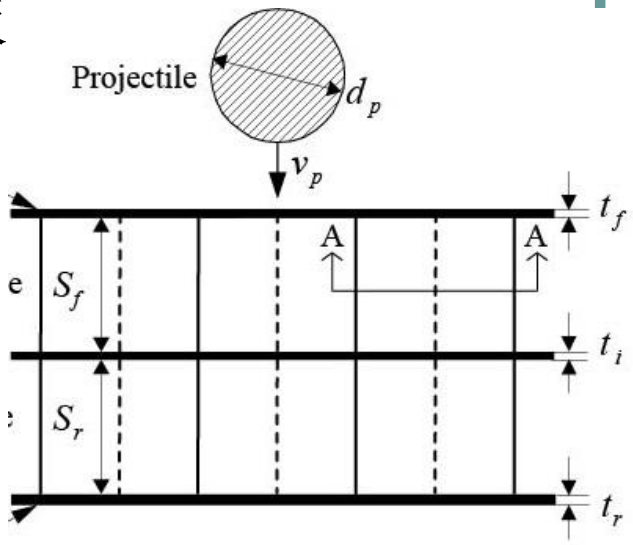
Applications

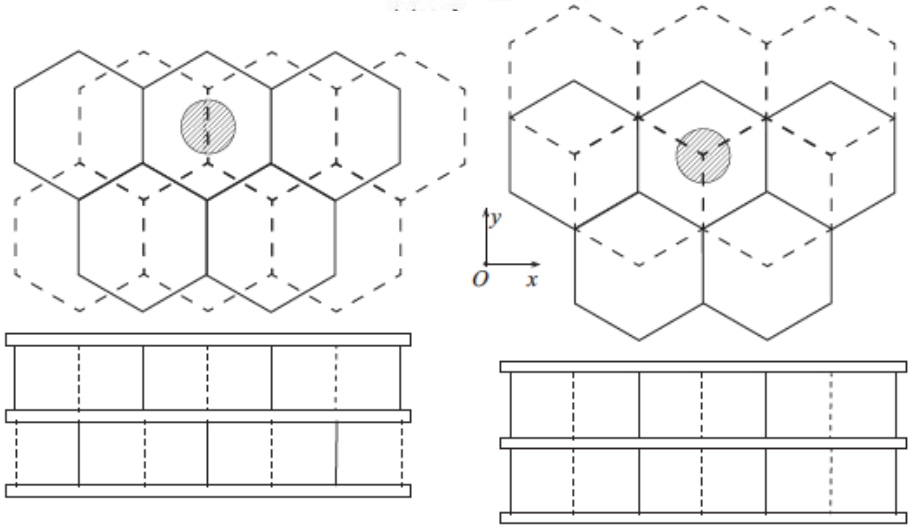
Honeycomb

蜂窝夹芯防护结构的改进：芯质交错双层蜂窝板



The residual energy is obviously decreased





- 刘平, 刘岩, 张雄. ***Mechanics Research Communications***. 69:34~39, 2015.
- 刘平, 刘岩, 张雄. ***International Journal of Mechanics and Materials in Design***. 12(2): 241-254, 2016

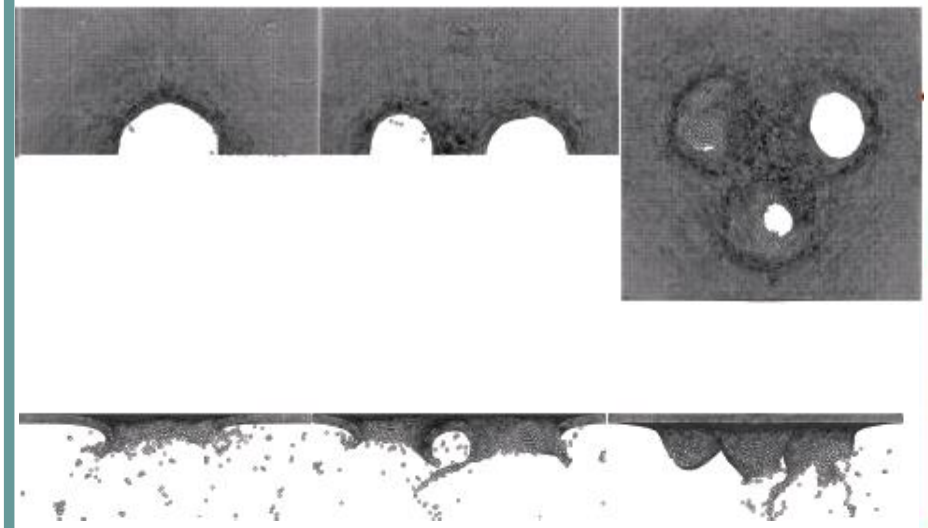
Applications

Honeycomb

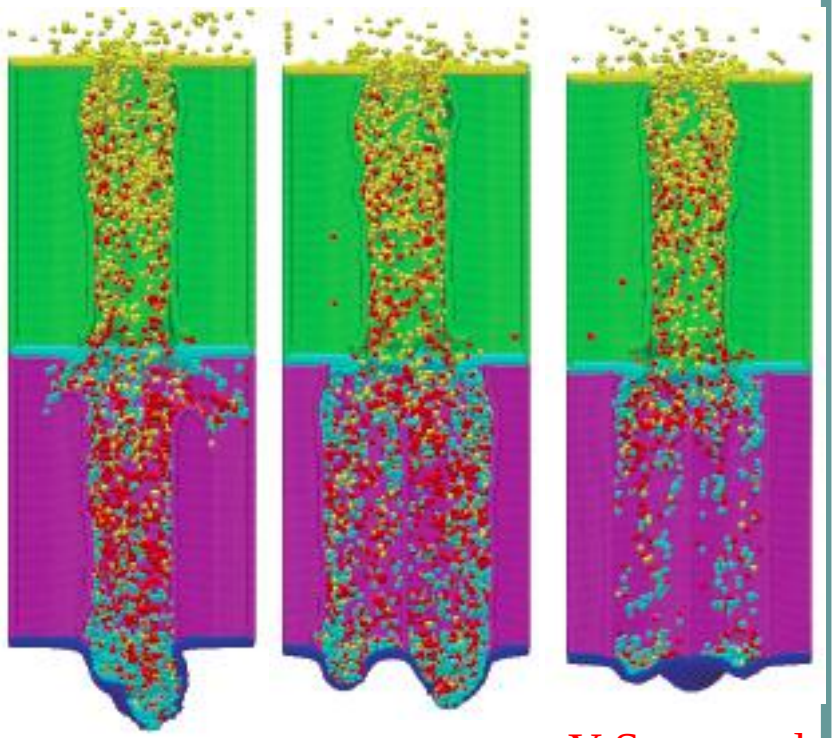
蜂窝夹芯防护结构的改进：芯质交错双层蜂窝板

碎片二次粉碎效果明显，
孔洞尺寸大幅减少

$v = 5\text{km/s}, t = 18\text{ms}$



Final configurations



DH panel

X-Staggered DH panel

Y-Staggered DH panel

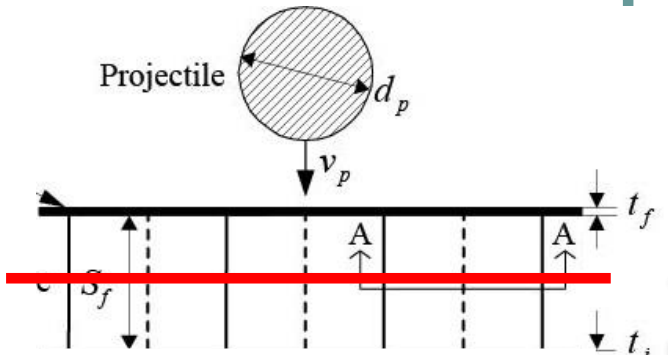
- 刘平, 刘岩, 张雄. ***Mechanics Research Communications***. 69:34~39, 2015.
- 刘平, 刘岩, 张雄. ***International Journal of Mechanics and Materials in Design***. 12(2): 241-254, 2016

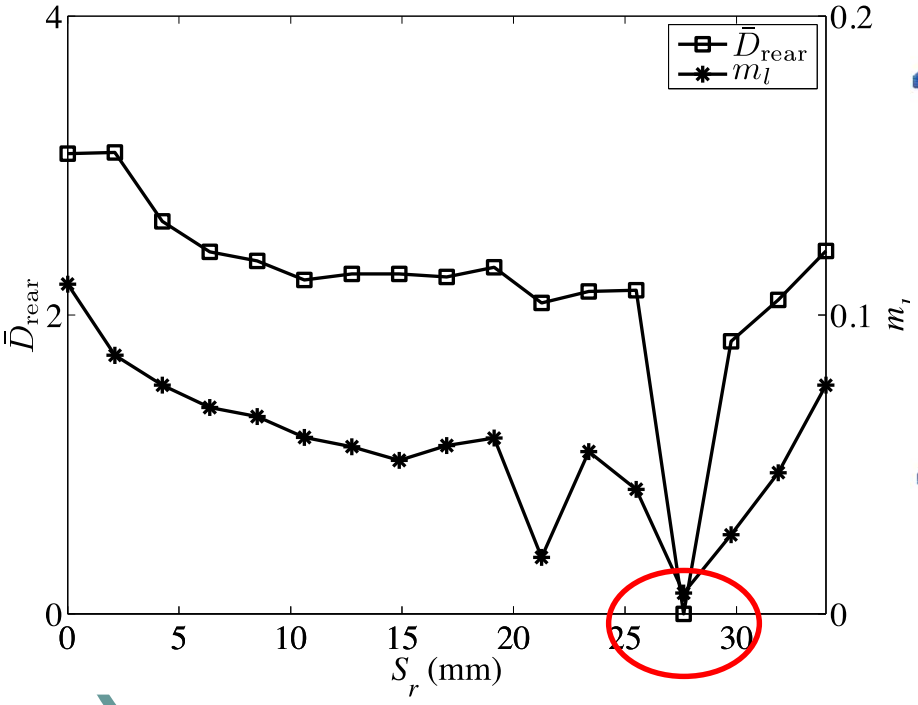
Applications

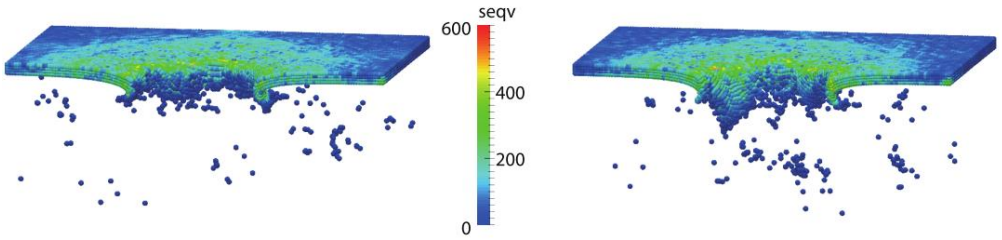
Honeycomb

蜂窝夹芯防护结构的改进：非等距双层蜂窝板

合适距离下可达到非穿透效果

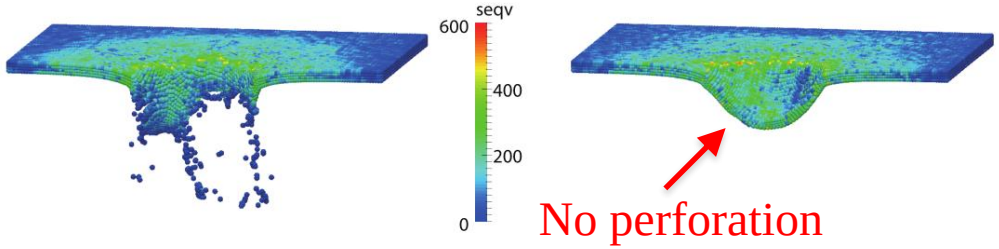






(a) S_r = 8.5 mm

(b) S_r = 17.0 mm



(c) S_r = 25.5 mm

(d) S_r = 27.625mm

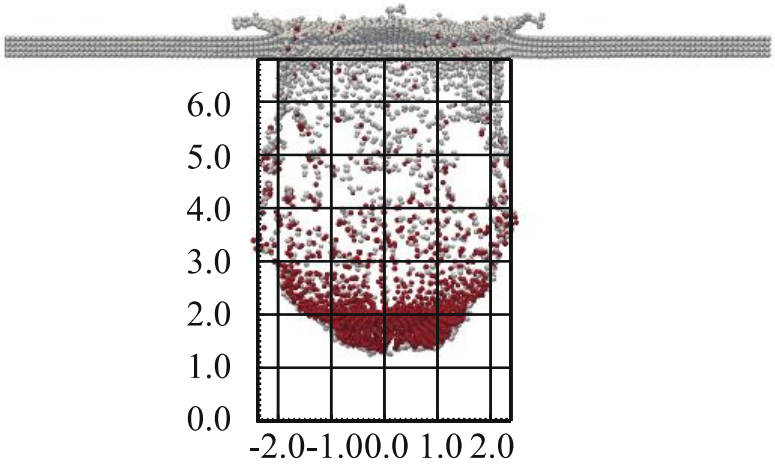
- 刘平, 刘岩, 张雄. ***Mechanics Research Communications***. 69:34~39, 2015.
- 刘平, 刘岩, 张雄. ***International Journal of Mechanics and Materials in Design***. 12(2): 241-254, 2016

Applications

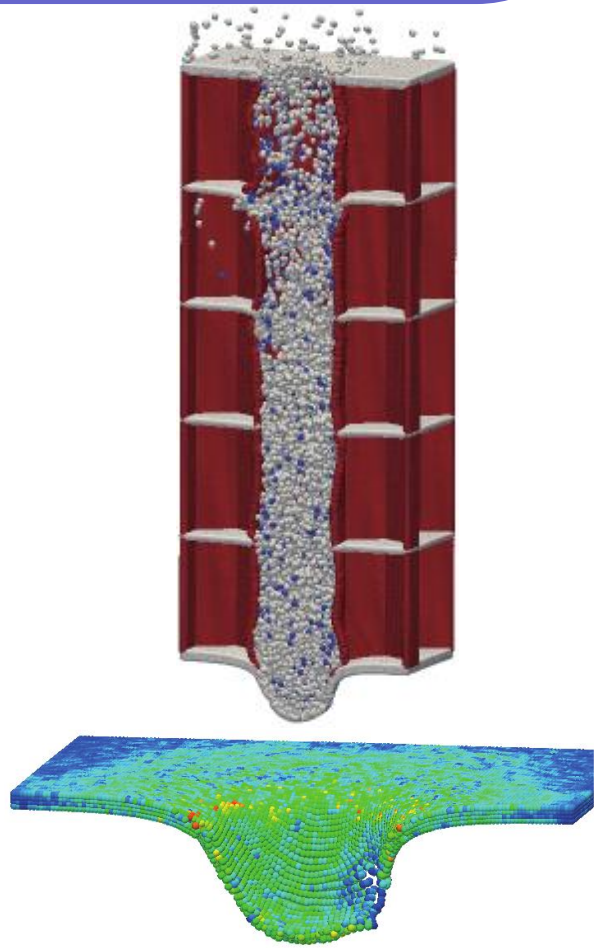
Honeycomb

蜂窝夹芯防护结构的改进：非等距双层蜂窝板

给出了指定条件下最优距离的计算方案
进一步提出了**具有最优防护效能的**
多层交错蜂窝夹芯防护结构



(b) v_p = 5000m/s



没有任何质量增加，5km/s
速度撞击下未穿透！

- 刘平, 刘岩, 张雄. ***Mechanics Research Communications***. 69:34~39, 2015.
- 刘平, 刘岩, 张雄. ***International Journal of Mechanics and Materials in Design***. 12(2): 241-254, 2016

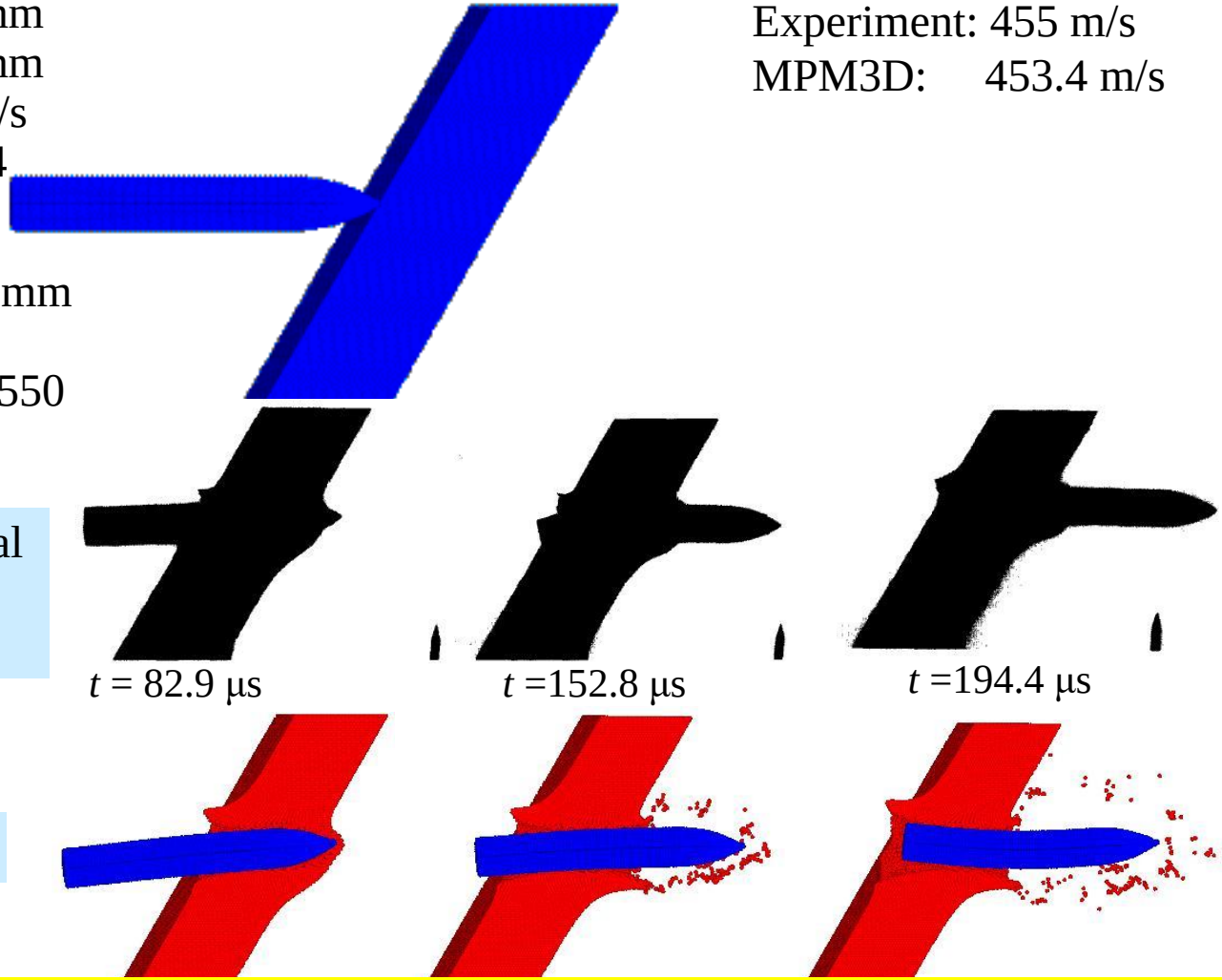
Applications

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



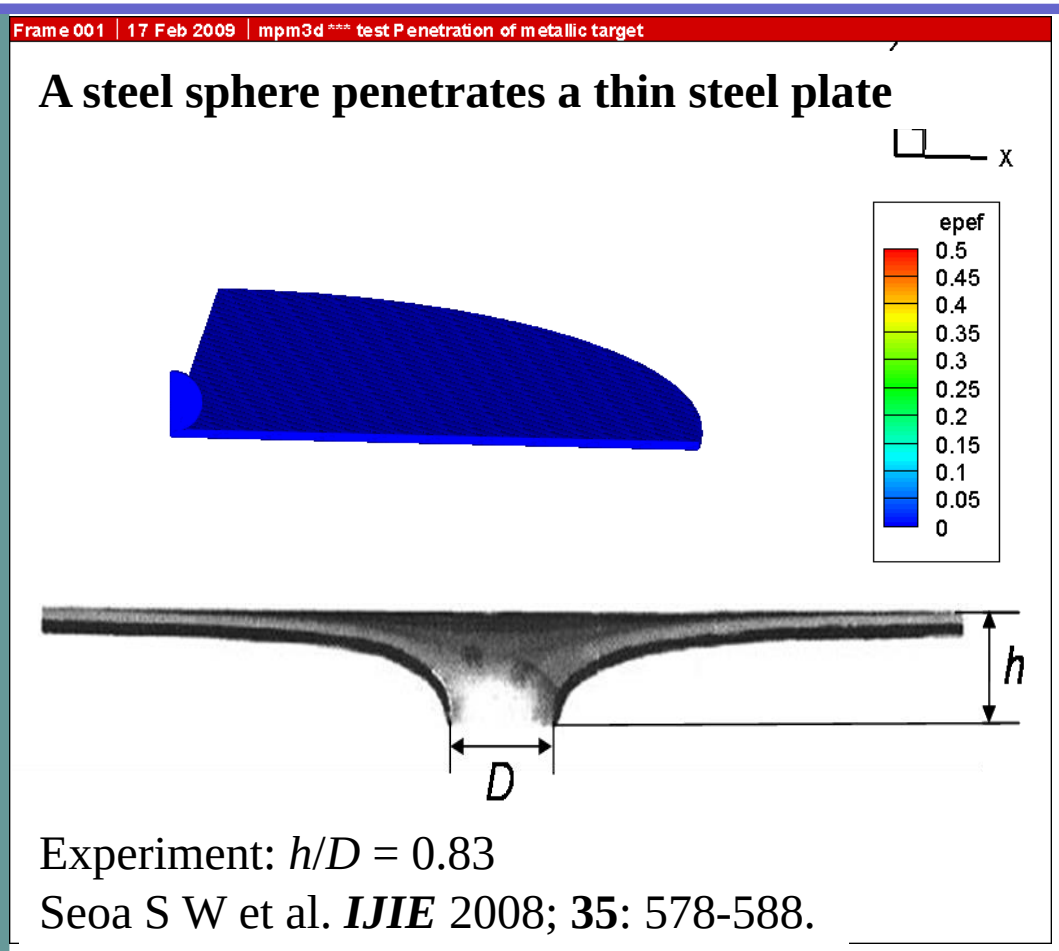
Piekutowski, Forrestal et al. ***IJIE*** 1996; 18: 877-887

MPM3D

黄鹏, 张雄等. Contact Algorithms for the Material Point Method in Impact and Penetration Simulation. ***International Journal for Numerical Method in Engineering*** 85(4): 498-517, 2011

Applications

Penetration



Experiment: $h/D = 0.83$

Seoa S W et al. ***IJIE*** 2008; **35**: 578-588.



MPM3D: $h/D = 0.87$

Steel sphere

Diameter: 10mm

Velocity: 200m/s

Particles: 32,768

Steel plate：

Thickness: 1mm

Diameter: 178mm

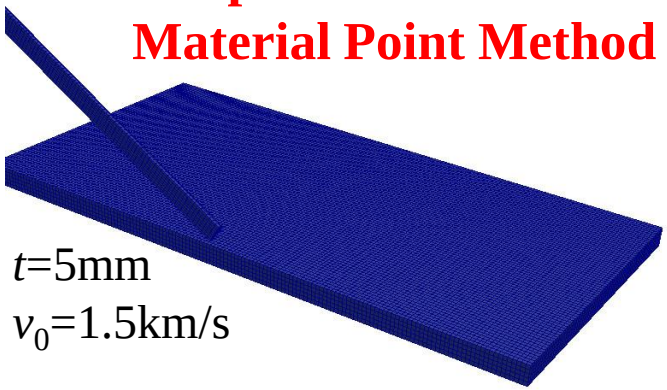
Particles: 398,184

Effective plastic strain at failure： 0.5

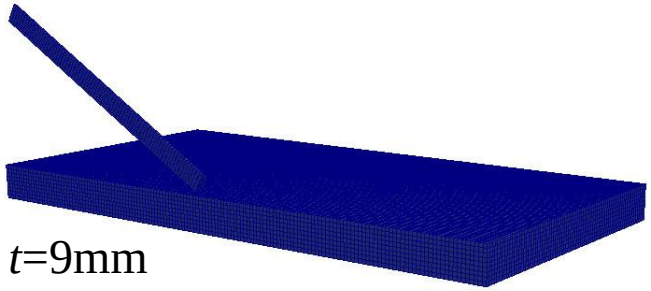
Applications

Penetration

Adaptive Finite Element Material Point Method



t=5mm
v_0=1.5km/s



t=9mm
v_0=2.5km/s

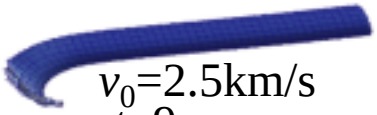
Projectile: Tungsten alloy
L_0 = 75, D_0 = 5mm
v_0 = 1500 m/s
Incidence angle = 60°

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

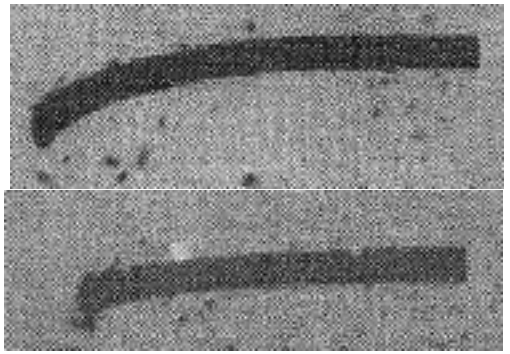


v_0=1.5km/s
t=5mm



v_0=2.5km/s
t=9mm

MPM3D



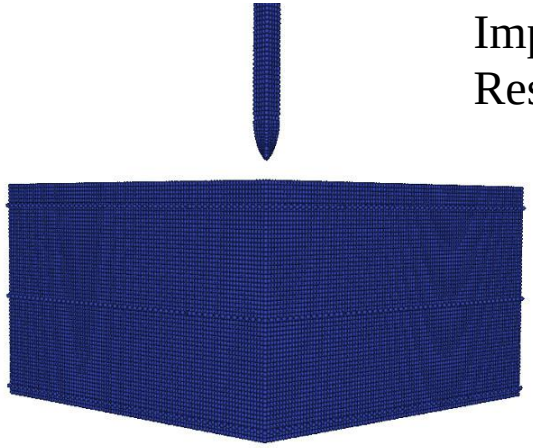
Experiment (Holmberg, Lundberg et al. 1993)

廉艳平, 张雄等. An adaptive finite element material point method and its application in extreme deformation problems. ***CMAME*** 241–244 (1): 275–285, 2012

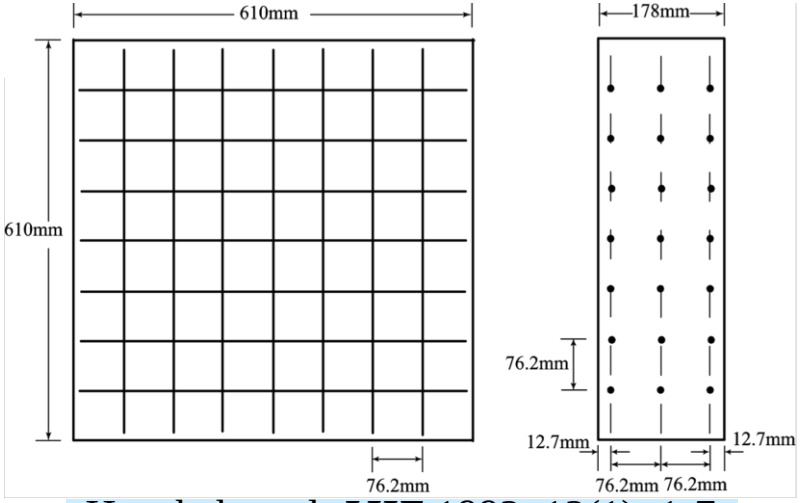
Applications

Penetration: C48 RC

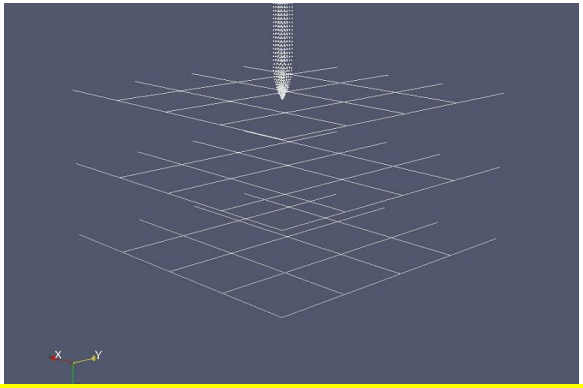
Hybrid Finite Element Material Point Method

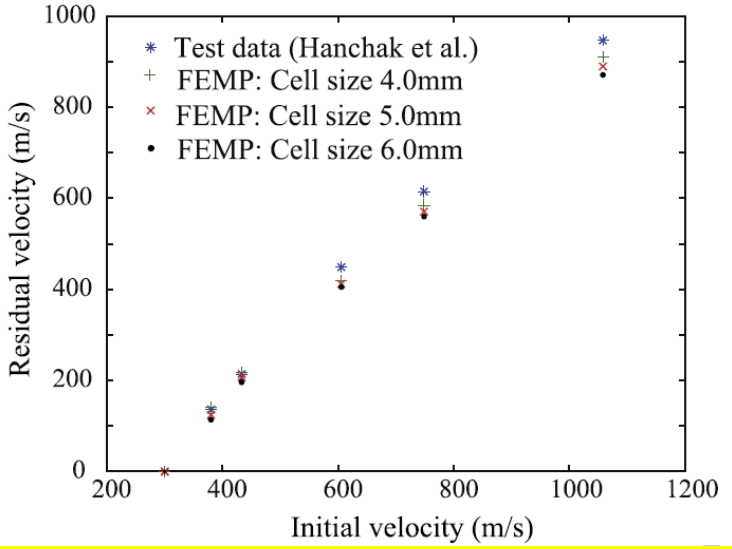


Impact velocity: 746 m/s
Residual velocity
Experiment: 615m/s
MPM3D: 585m/s



Hanchak et al. ***IJIE*** 1992; 12(1): 1-7





廉艳平, 张雄等. A FEMP method and its application in modeling dynamic response of reinforced concrete subjected to impact loading. ***CMAME*** 200(17-20), 1659-1670, 2011

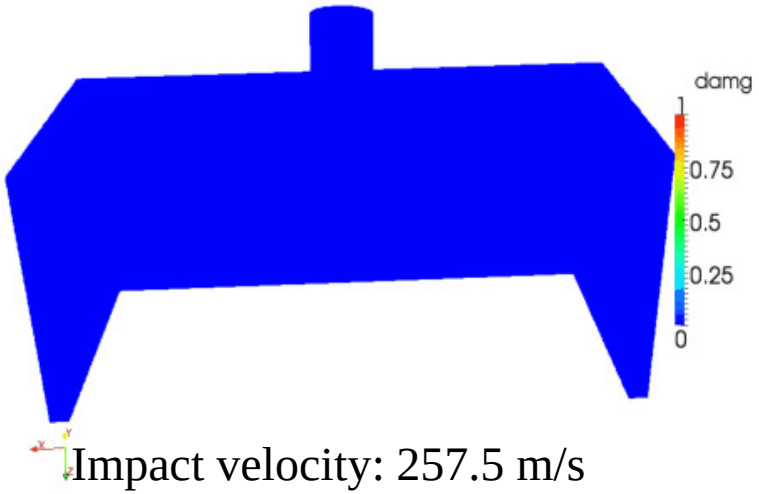
Applications

Reinforced Concrete

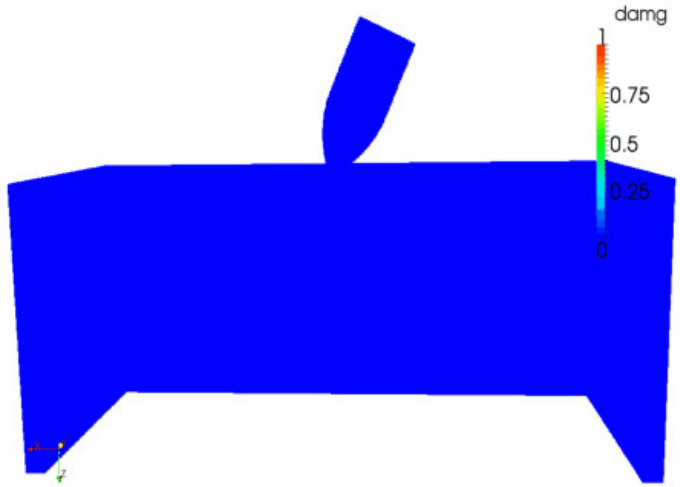
Impact Velocity (m/s)	Residual Velocity (m/s)		Perforation Pore Diameter (mm)	
	Experiment	MPM3D	Experiment	MPM3D
257.5	100.7	100	780×710	900×1000
248.3	83.7	83	930×730	1000×1000



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°

Applications

Cohesive soil impact

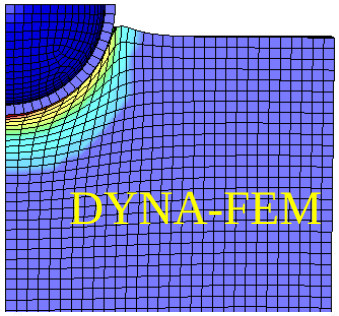


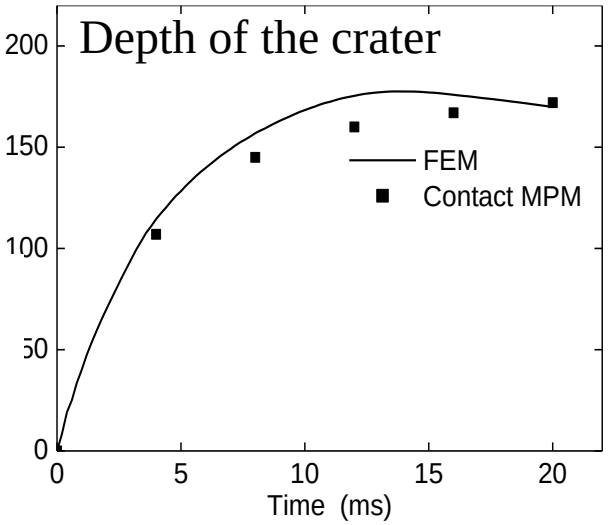
Half spherical shell:
- Diameter: 0.408m
- Mass: 12kg
- Al alloy

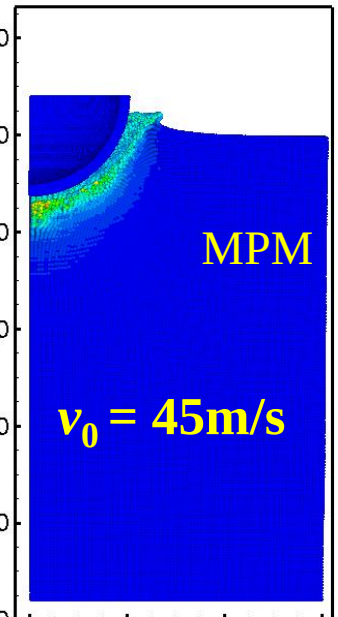
Fasanella E L, et al. AIAA, 2001

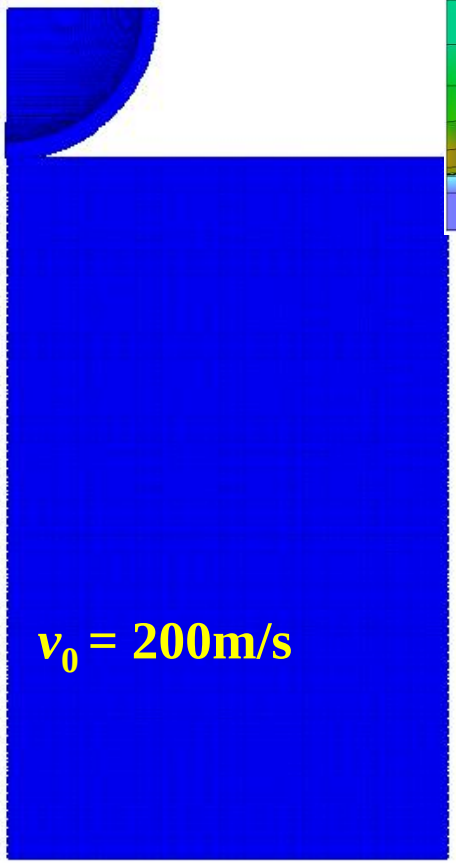
Particles for spherical shell: 26385
Particles for target: 1600000

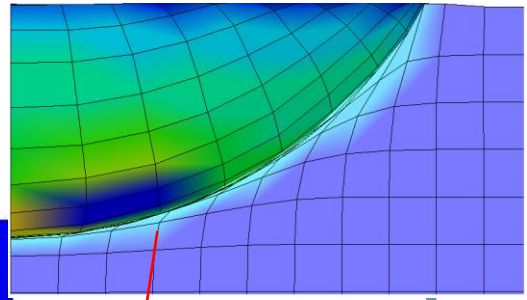
LS-DYNA FEM calculation terminated abnormally due to element distortion

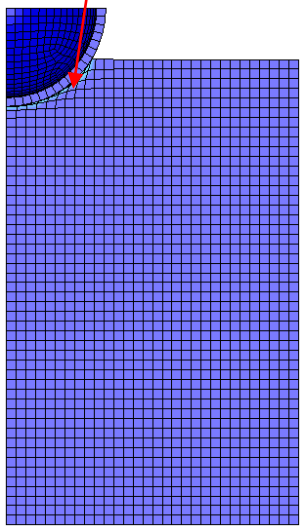










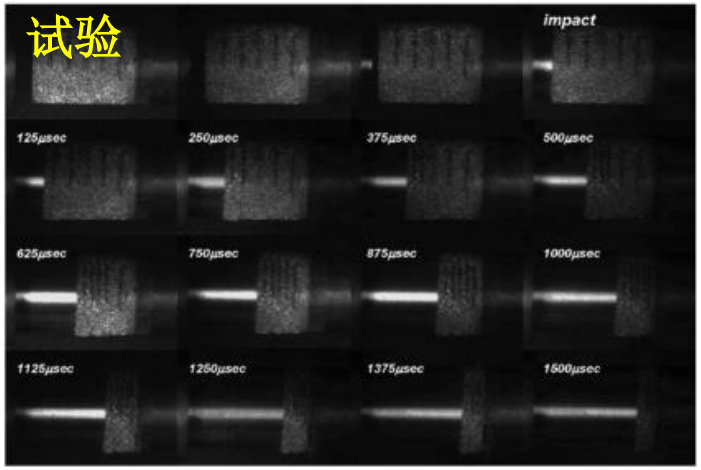


Applications

Compression of Aluminum Foam

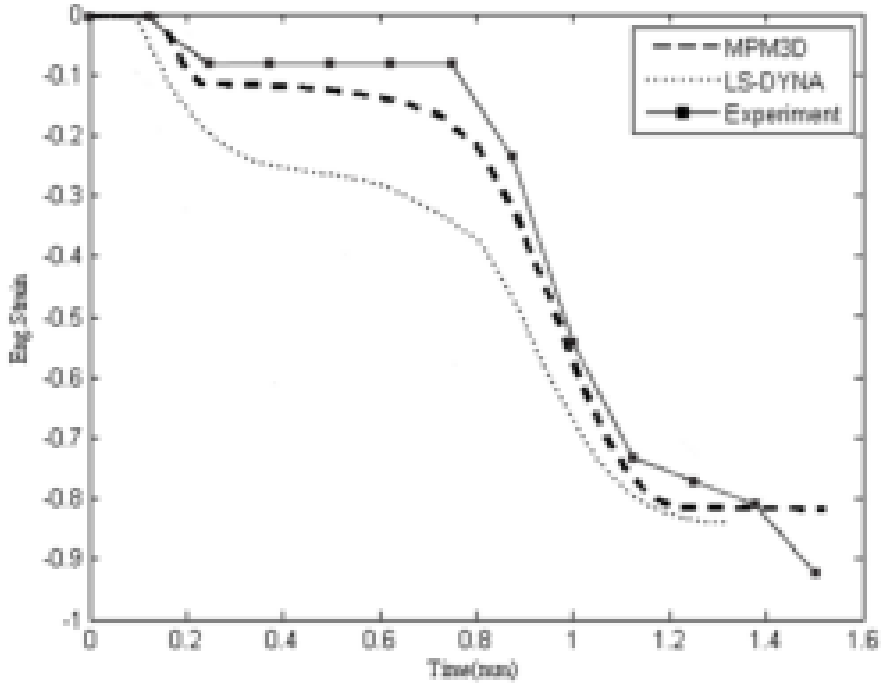
泡沫铝动态压缩物质点法模拟：Deshpande-Fleck模型

泡沫铝压缩试验：速度52.6m/s



MPM3D





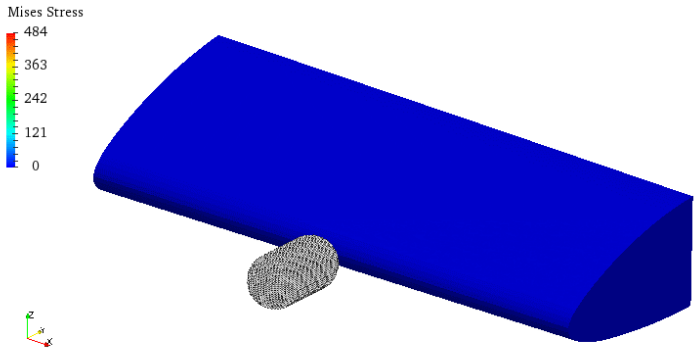
输出杆端工程应变时程曲线

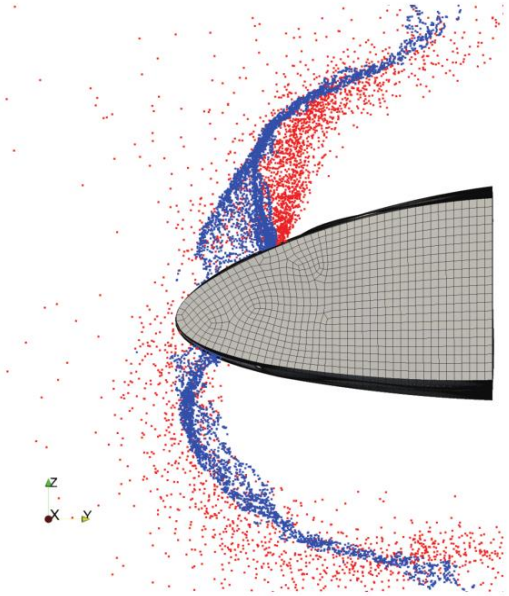
LS-DYNA在1.3ms后因网格畸变而终止

宫伟伟，张雄等. Numerical Study of Dynamic Compression Process of Aluminum Foam with Material Point Method. ***CMES*** 82(3-4): 195-213, 2011

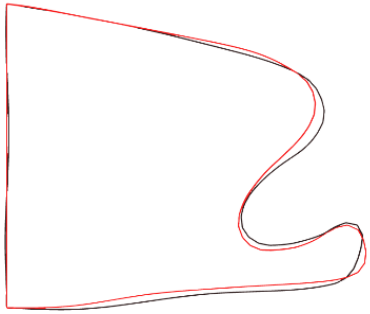
Applications

Bird Strike Leading Edge

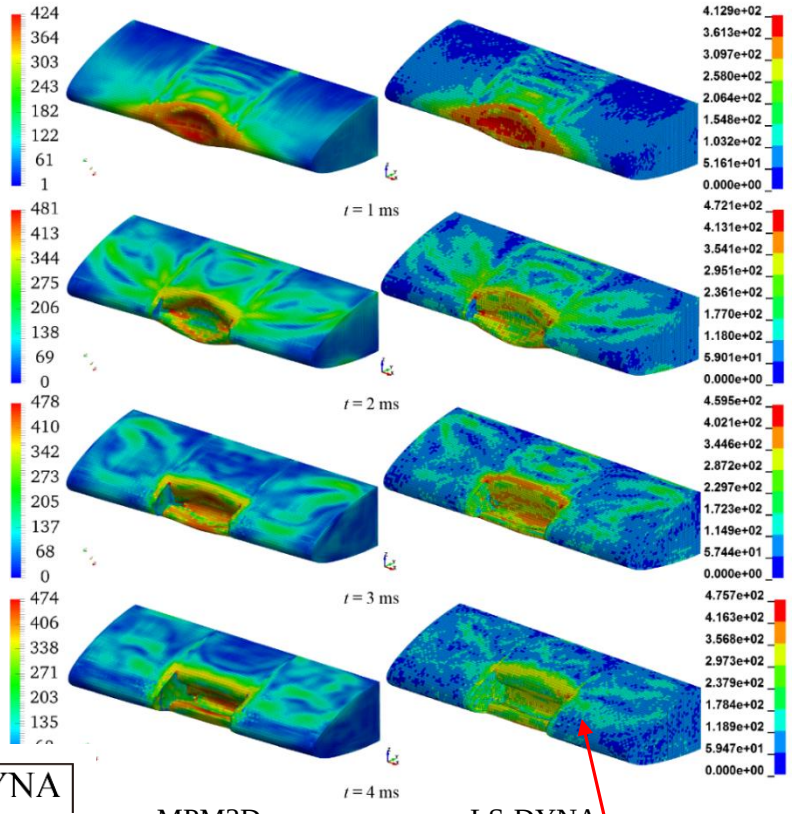




Bird deformations at 4 ms
- Red: DYNA-SPH bird
- Blue: MPM bird



Cut shapes at 4 ms



DYNA
MPM3D

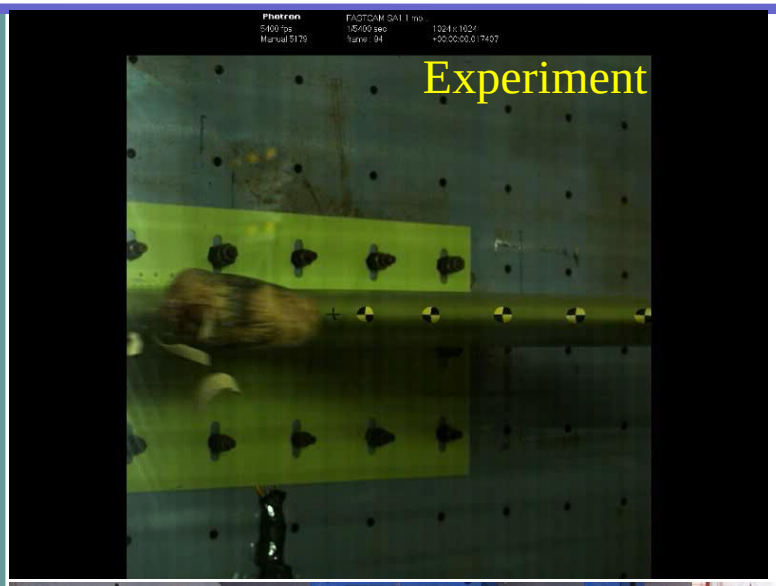
MPM3D LS-DYNA

von Mises stress

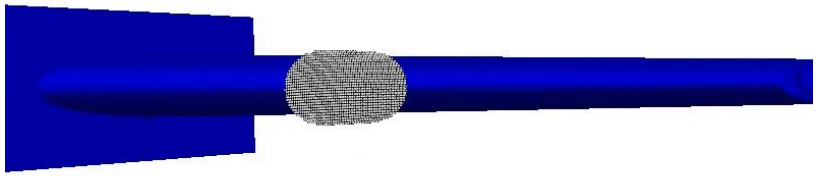
noisy

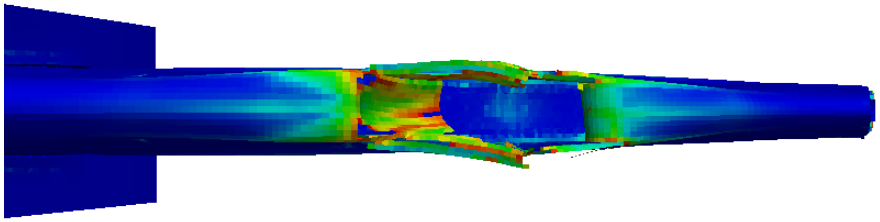
Applications

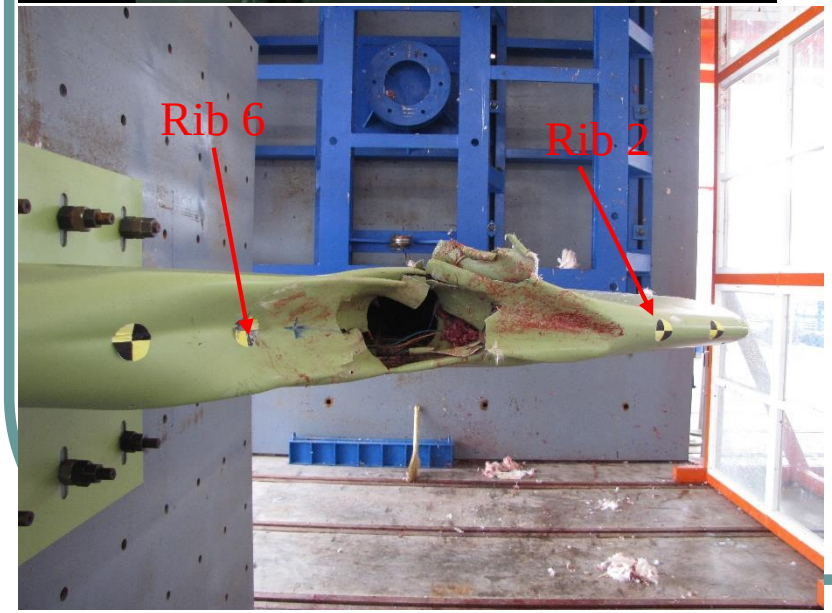
Bird Strike Empennage

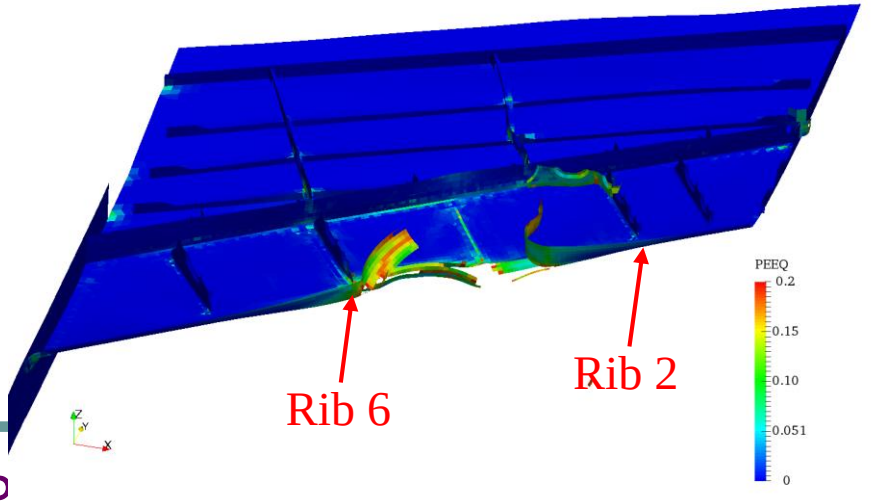


MPM3D



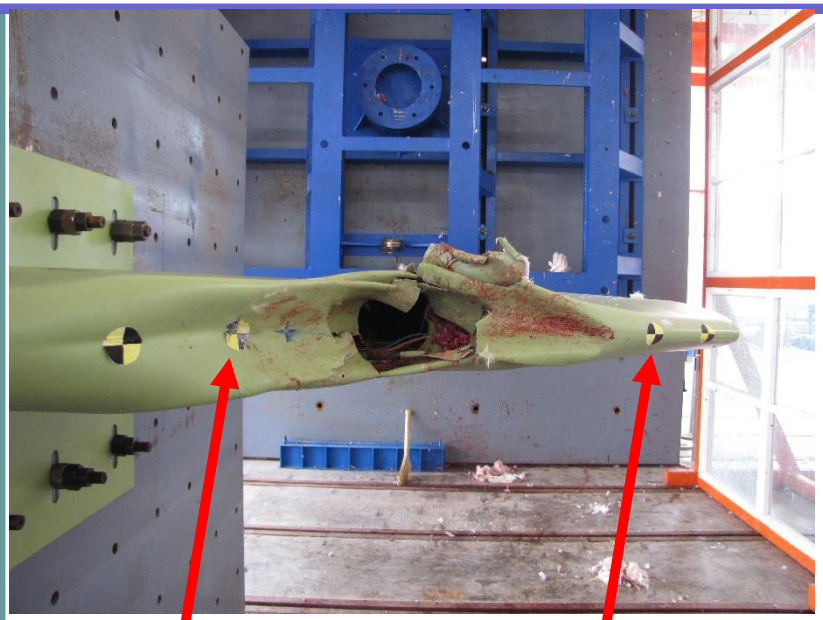


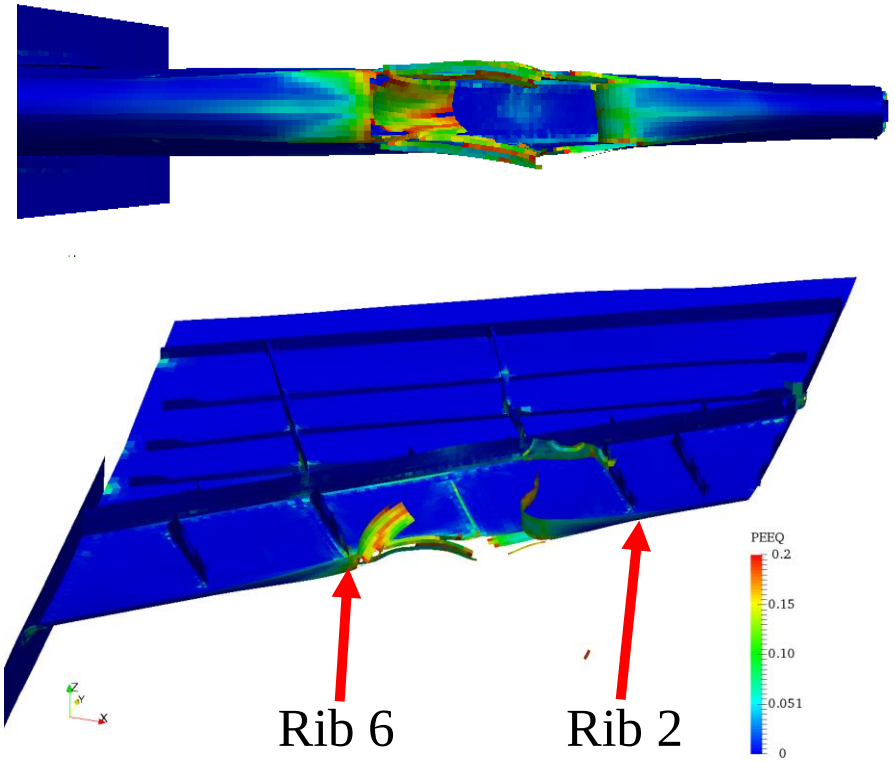




Bird Strike Simulations

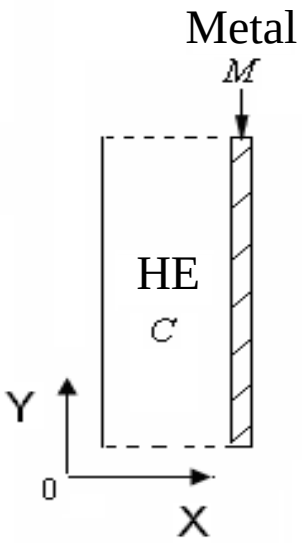
鸟撞尾翼结构

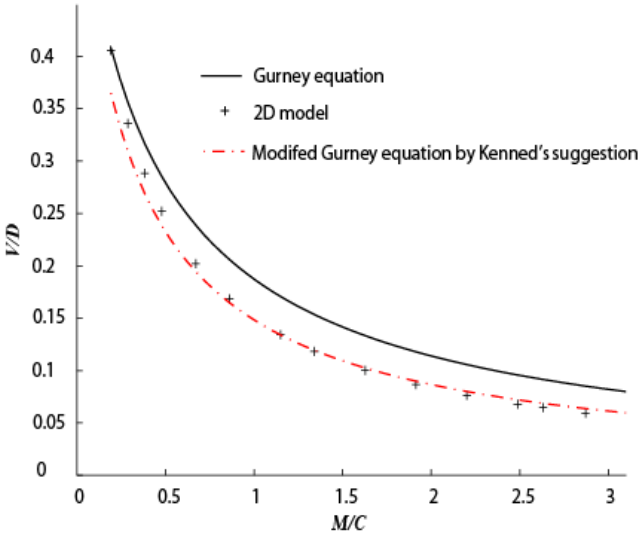


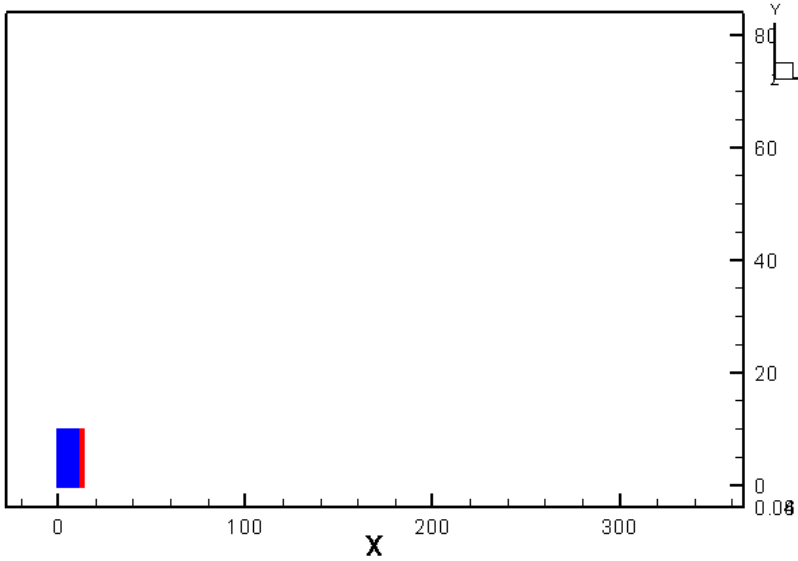


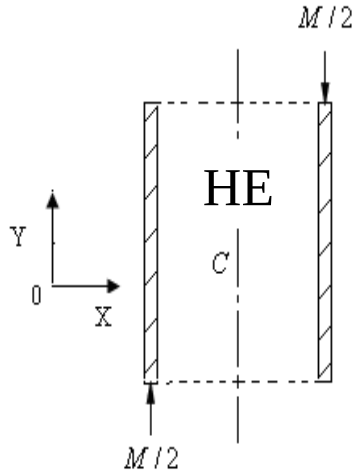
Applications

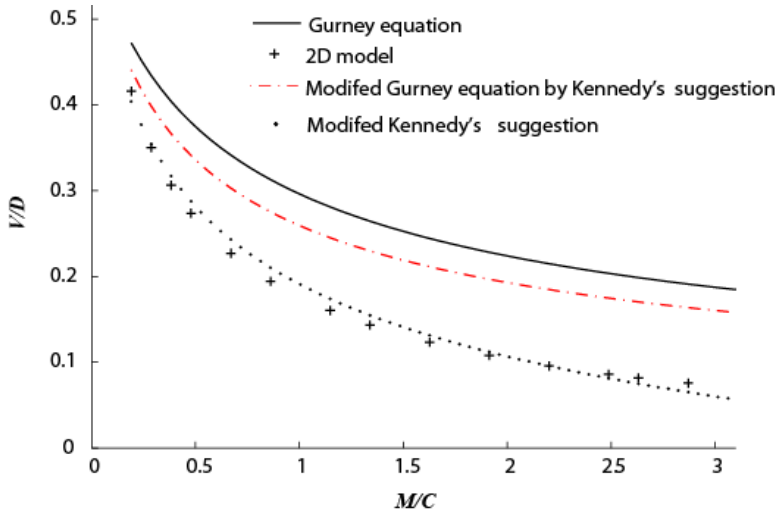
Explosive driven Metal









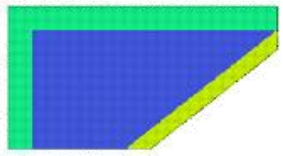


廉艳平，张雄等. Numerical Simulation of Explosively Driven Metal by Material Point Method. ***IJIE*** 38(4): 237-245, 2011

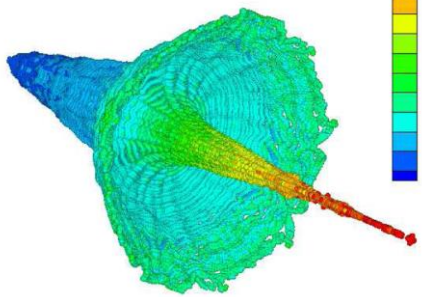
Applications

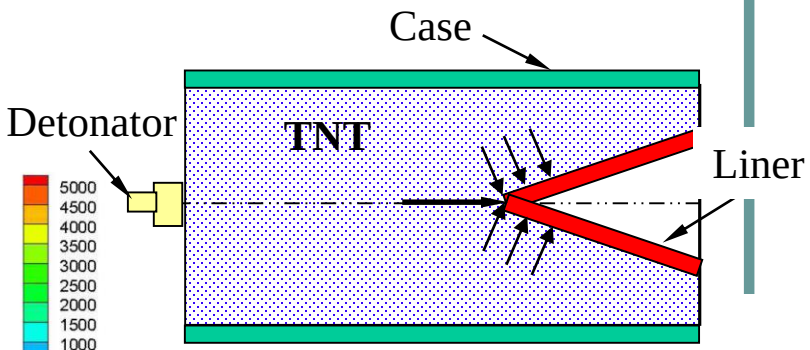
Shaped charge

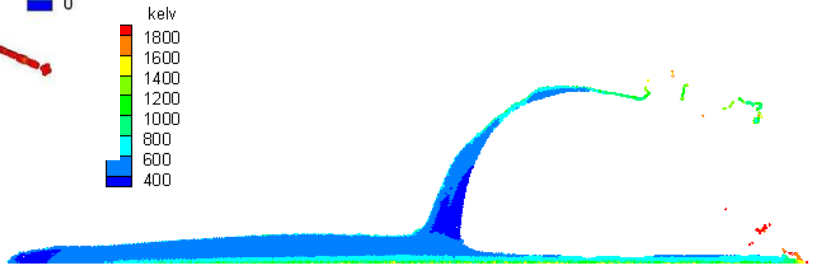
- Shaped charge
  - A cylinder of high explosive with a cone-shape thin metal liner in one end
  - Intense pressure ➔ Collapse of the liner ➔ A jet with extreme high velocity (> 10 km/s)
- Application
  - Armor penetration
  - Metal cutting
  - Oil well perforation



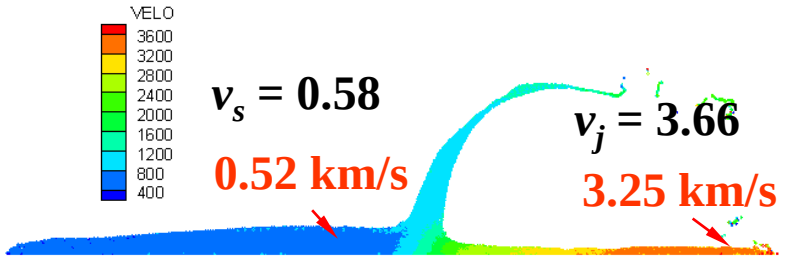








Temperature distribution



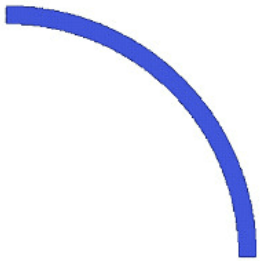
Velocity distribution

马上，张雄，廉艳平，周旭. Simulation of high explosive explosion using adaptive material point method. ***CMES*** 39(2):101-123, 2009

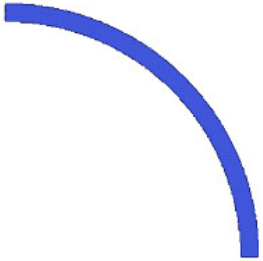
Applications

Fragmentation driven by explosion

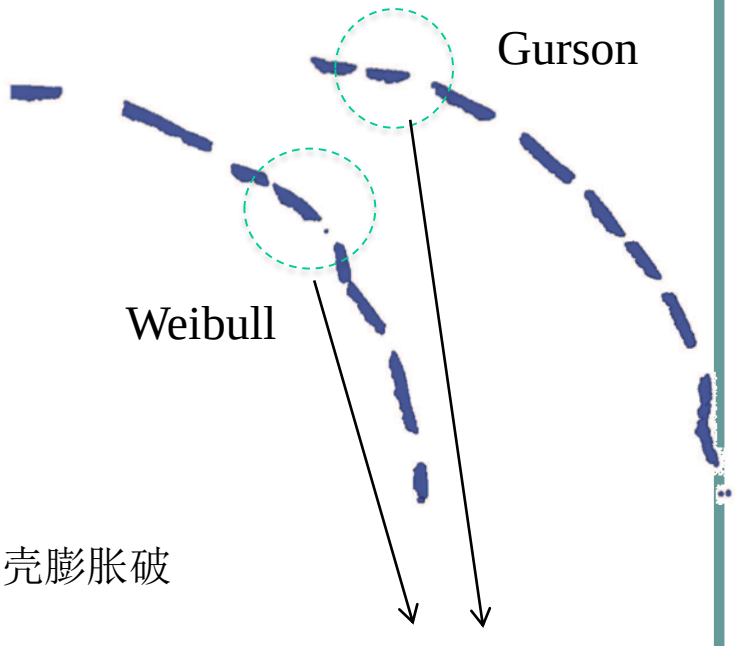
Metal shell driven by High explosive



Weibull random failure

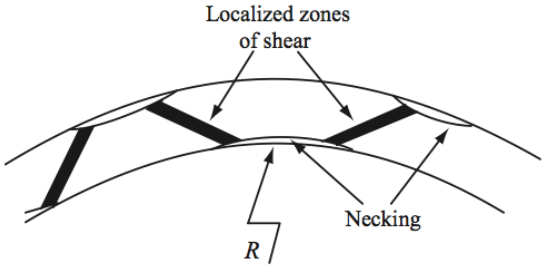


Gurson model



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



杨鹏飞, 刘岩， 张雄等. Simulation of Fragmentation with Material Point Method Based on Gurson Model and Random Failure. ***CMES*** 85(3): 207-236, 2012

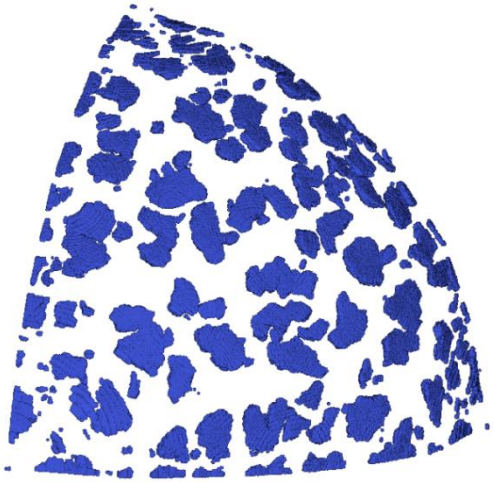
Applications

Fragmentation driven by explosion

Weibull random failure

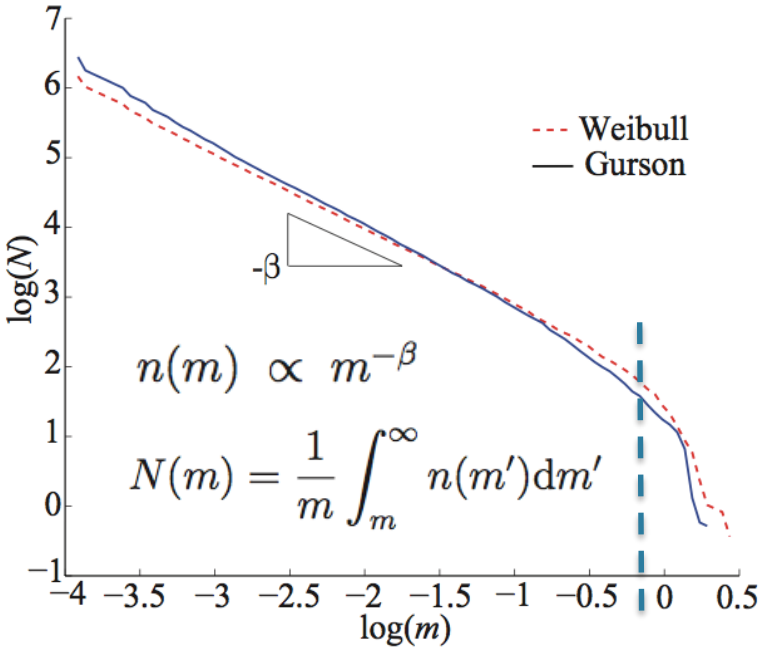


Gurson model





Cumulative mass distribution of fragments



$$n(m) \propto m^{-\beta}$$

$$N(m) = \frac{1}{m}\int_{m}^{\infty} n(m')\mathrm{d}m'$$

$$\beta_w = 1.06 \quad \beta_g = 1.11$$

characteristic cutoff mass

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

杨鹏飞, 刘岩，张雄等. Simulation of Fragmentation with Material Point Method Based on Gurson Model and Random Failure. ***CMES*** 85(3): 207-236, 2012

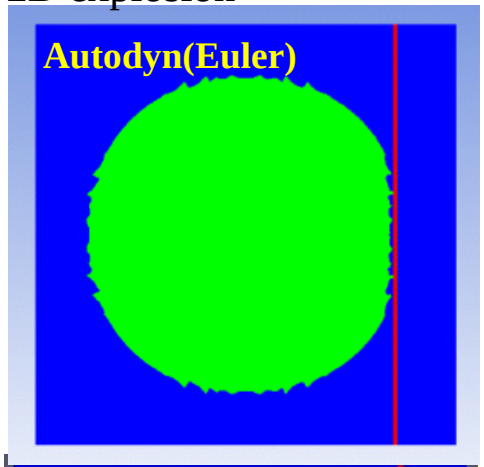
Applications

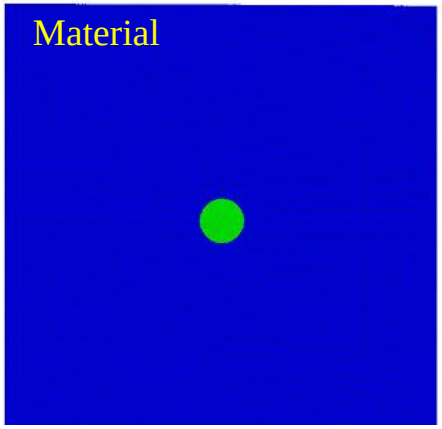
Shock-structure interaction

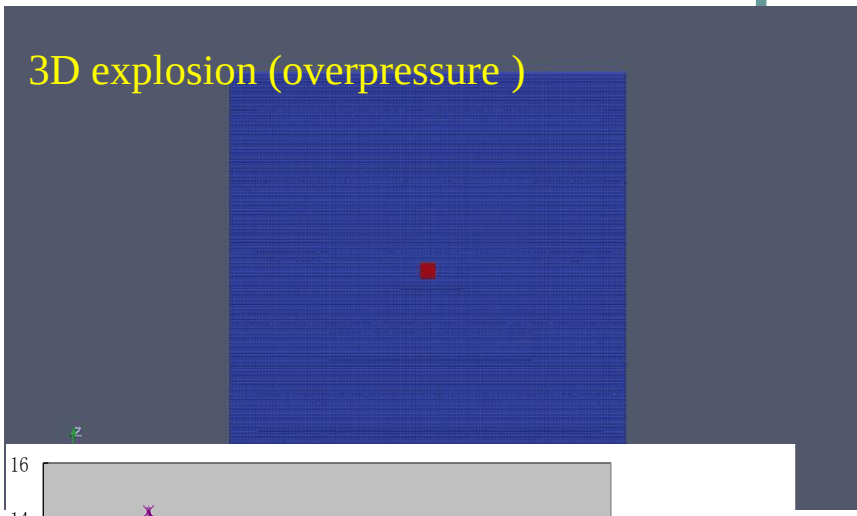
Detonation → Shock wave propagation → Shock-structure interaction

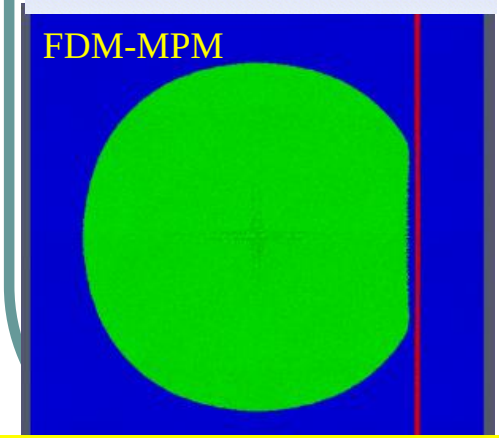
MPM — FDM + markers — MPM

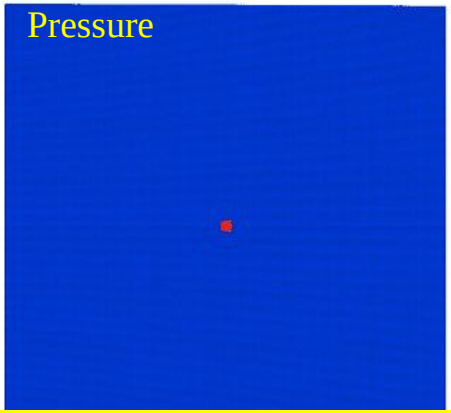
2D explosion

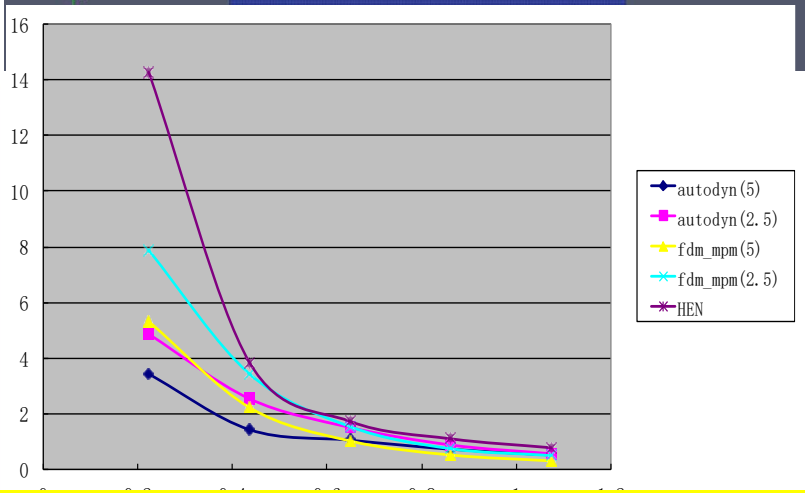






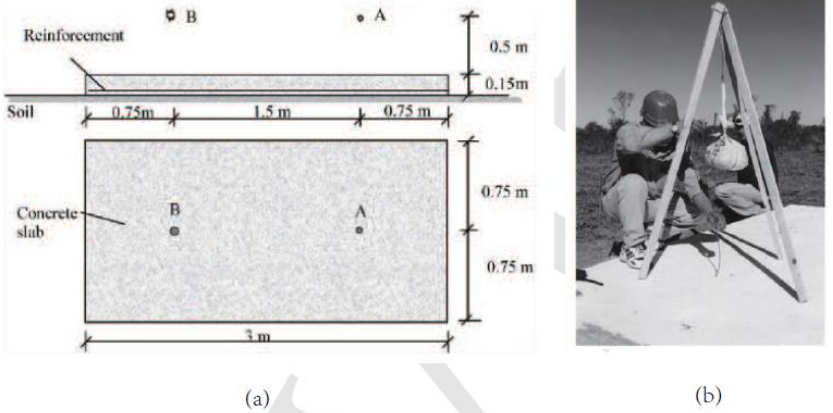




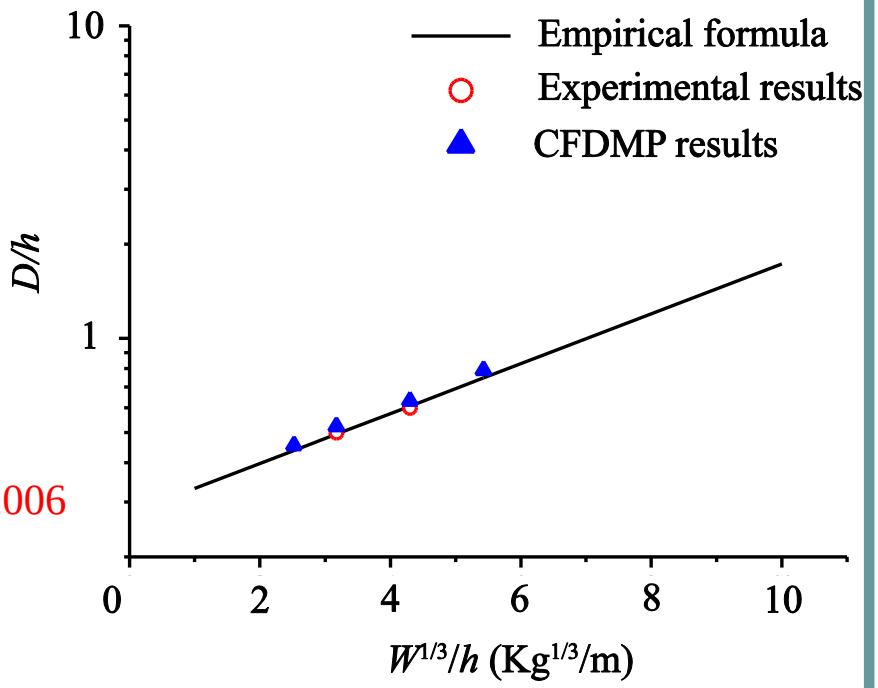


崔潇骁, 张雄等. An alternating finite difference material point method for numerical simulation of high explosive explosion problems. ***CMES***, 92(5): 507-538, 2013

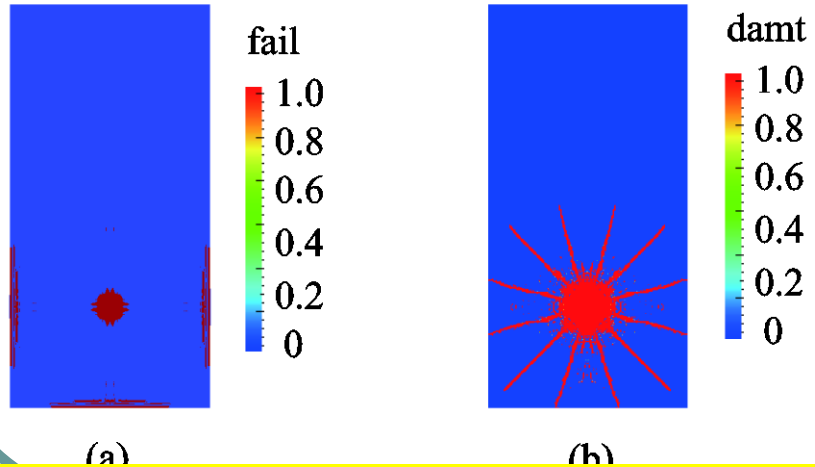
Applications



B M Luccioni, M Luege. ***IJIE*** 32: 1248-1266, 2006



$$\ln(3.63D/h) = 0.1838(W^{1/3}/h)$$

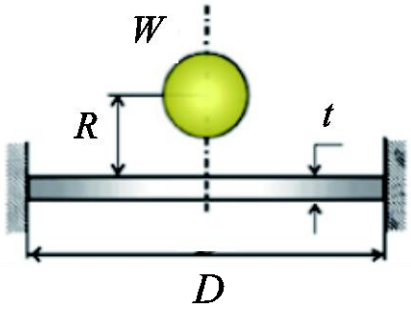


崔潇骁, 张雄等. A coupled finite difference material point method and its application in explosion simulation, ***CMES: Computer Modeling in Engineering & Sciences***. 98(6): 565-599, 2014

Applications



(a)

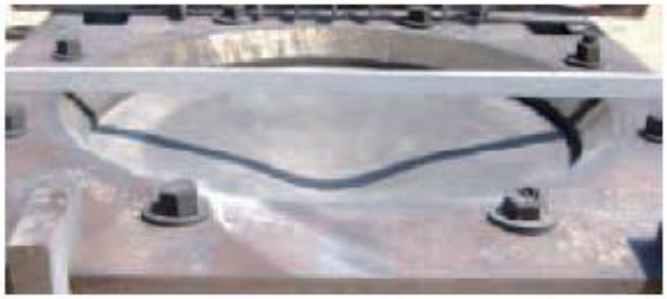


(b)

A Neuberger, S Peles, D Rittel. ***IJIE*** 34(5): 874-882, 2007

最大相对挠度δ /t

缩比	实验值	CFDMP
4	2.60	2.69
2	2.70	2.71
1	-	2.68
4	4.85	5.20
2	5.35	5.45
1	-	5.63





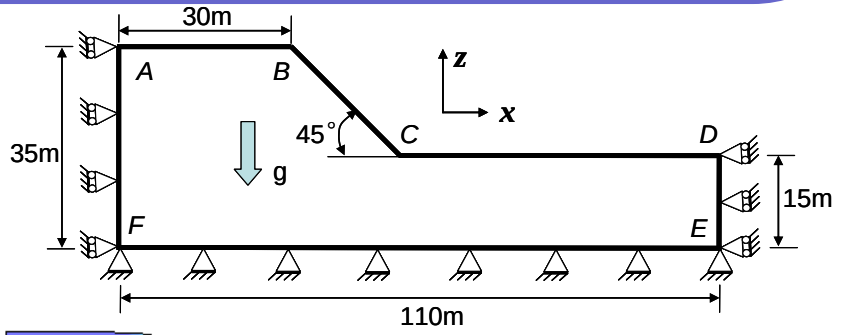
Applications

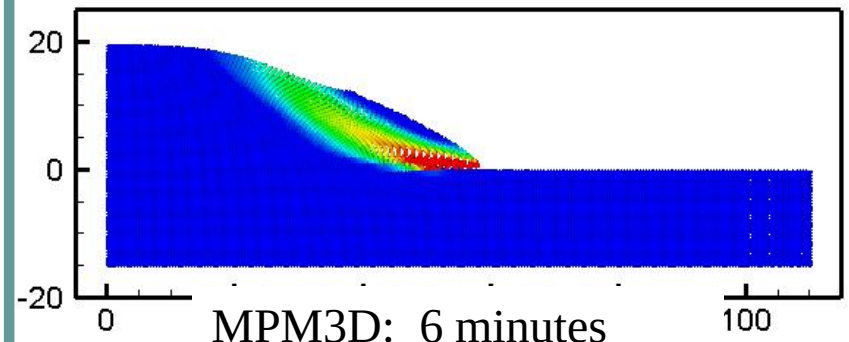
Soil slope failure

- **Cohesive soil**

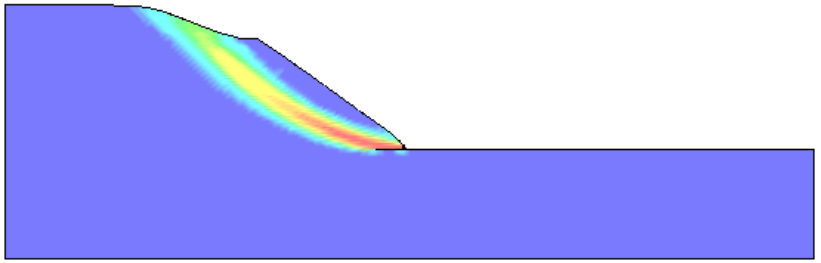
$\phi = 20^\circ$; $\psi = 0^0$; $c = 10.0$ kPa

E=70MPa, ν =0.3, ρ =2.1 g/cm3





MPM3D: 6 minutes

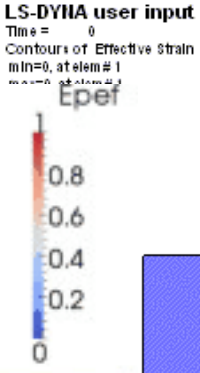


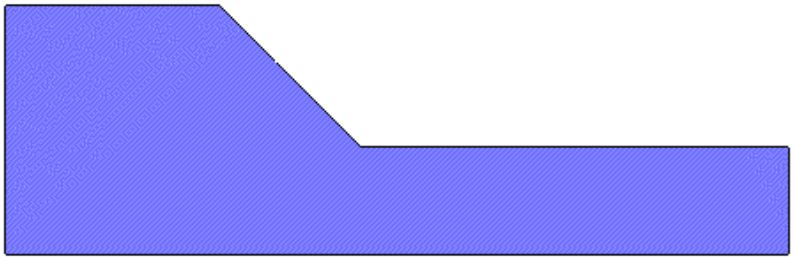
LS-DYNA (FEM): 262 minutes

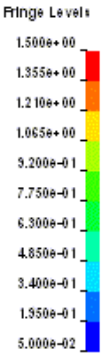
- **Non-cohesive soil**

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







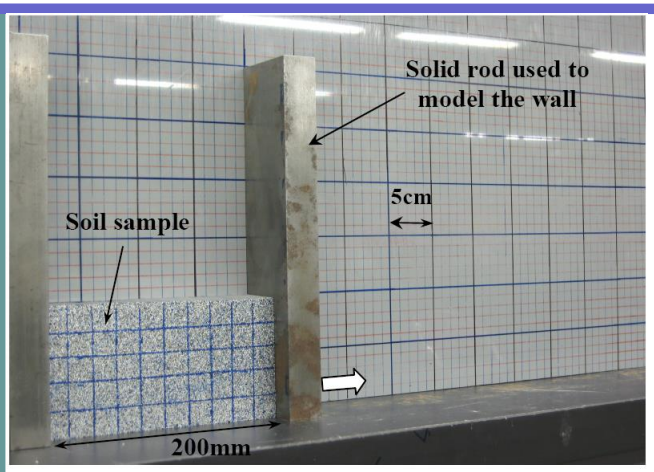


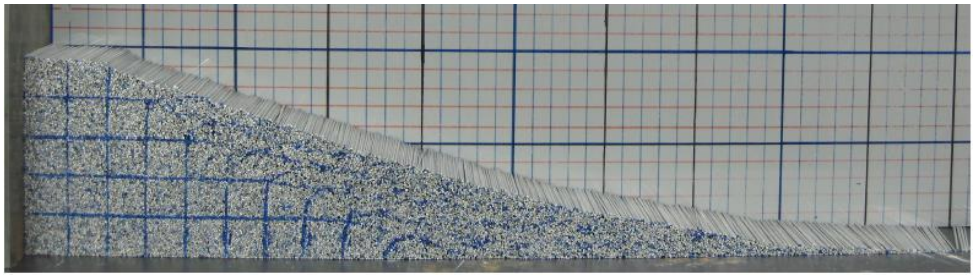
MPM3D: 6 minutes

LS-DYNA (FEM): 19.8 hours

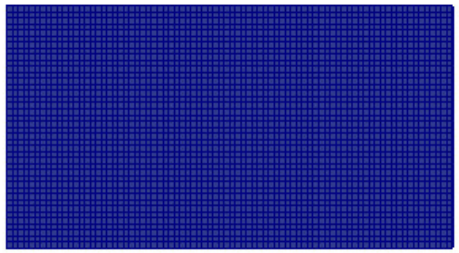
Applications

Failure process of non-cohesive soil





Bui H H, Japan: Ritsumeikan University, 2006

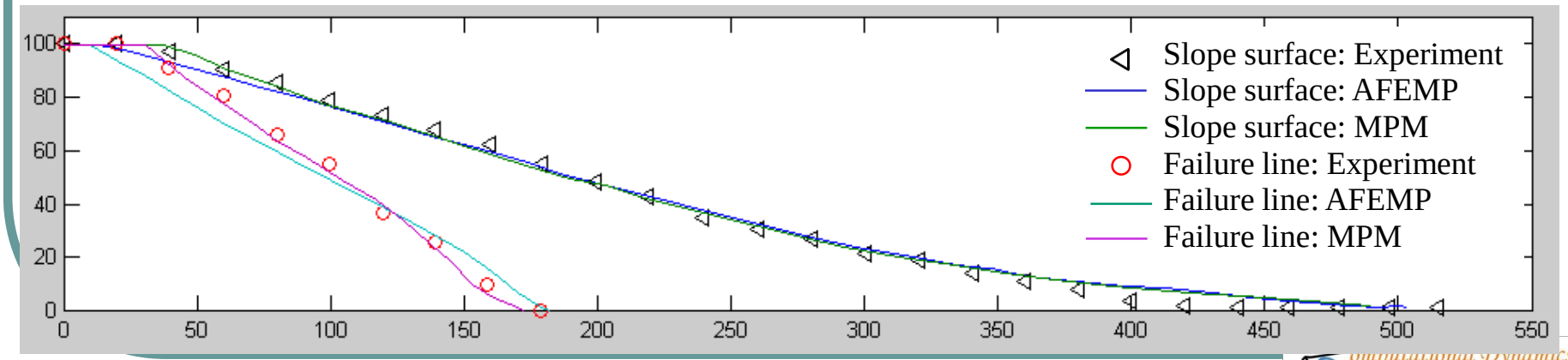


K=0.7MPa，ρ=2.65 g/cm^3

φ = 19.8° ; c = 0kPa;

ψ =0°

Adaptive Finite Element Material Point Method

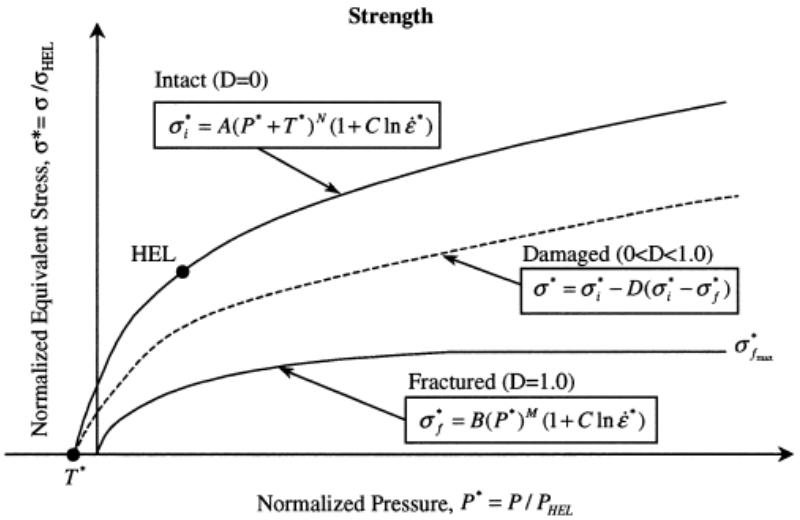


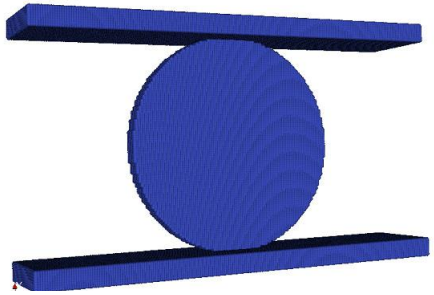
Computational Dynamics 计算动力学实验室

Applications

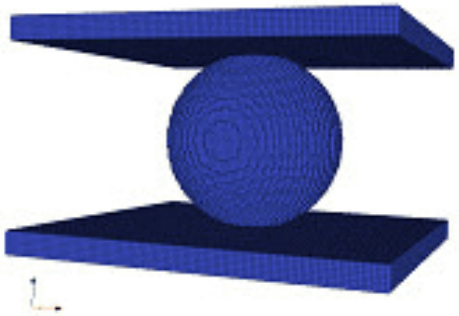
Ceramic Material

LS-DYNA MAT_110: JH-2

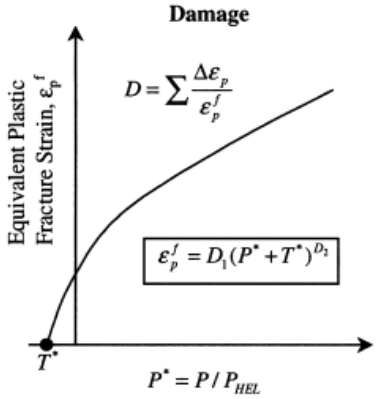


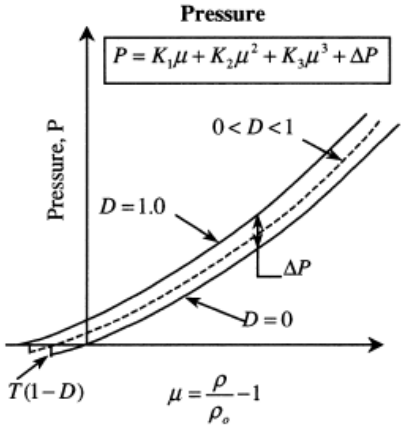


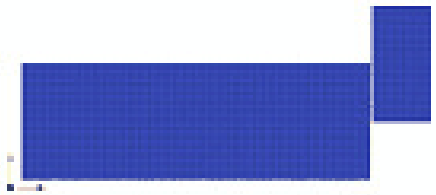
Crush ceramic plate



Crush ceramic ball





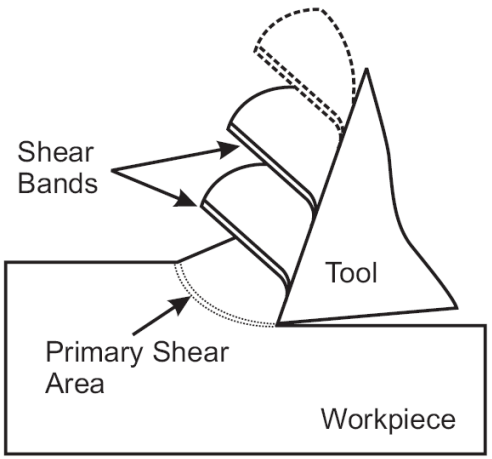


Cut ceramic block

Computational Dynamics 计算动力学实验室

Applications

Metal cutting process





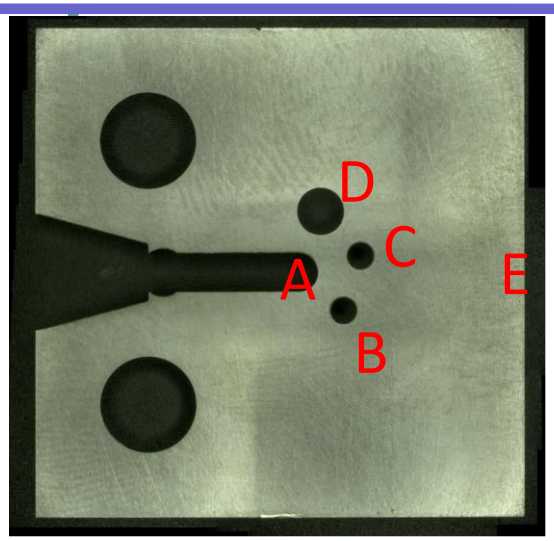




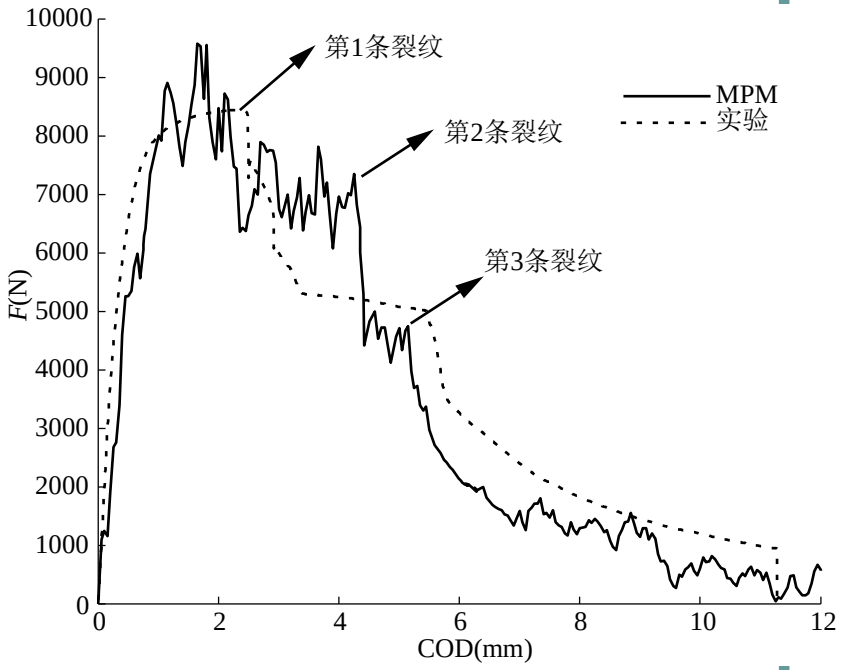
R. Ambati, 袁荒, 潘小飞, 张雄, Application of material point methods for cutting process simulations. ***Computational Materials Science*** 57: 102-110, 2012

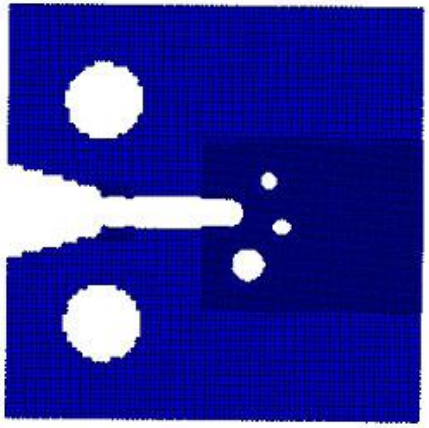
Applications

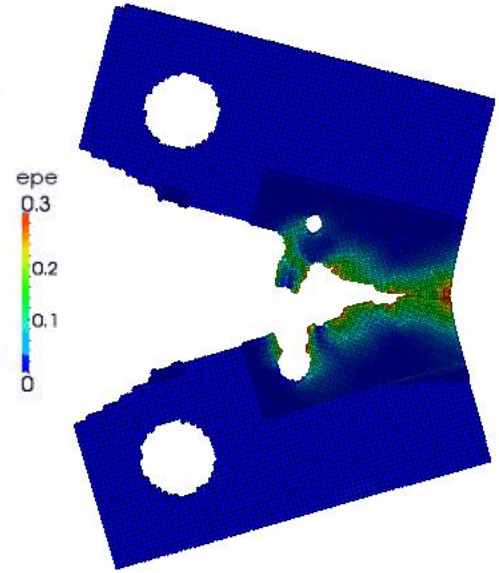
Sandia fracture challenge



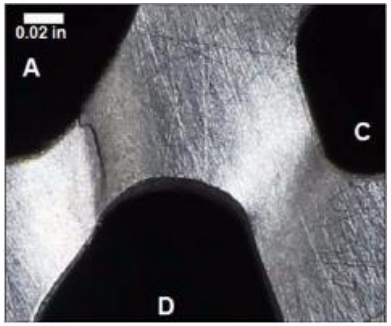


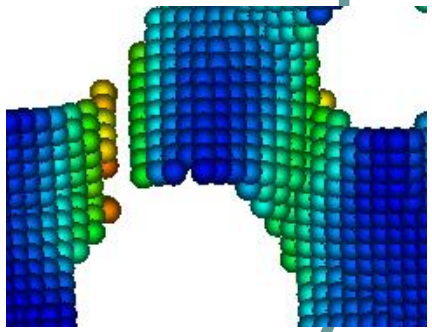










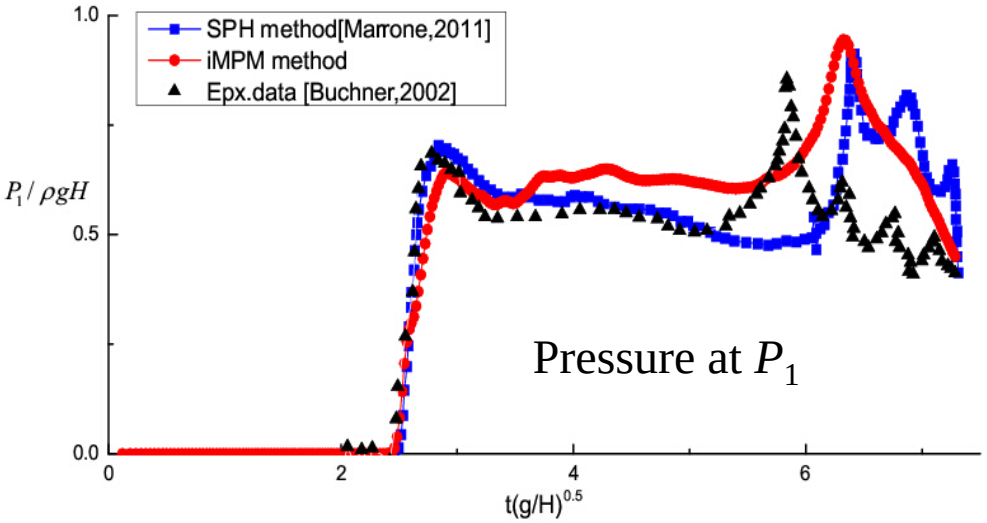


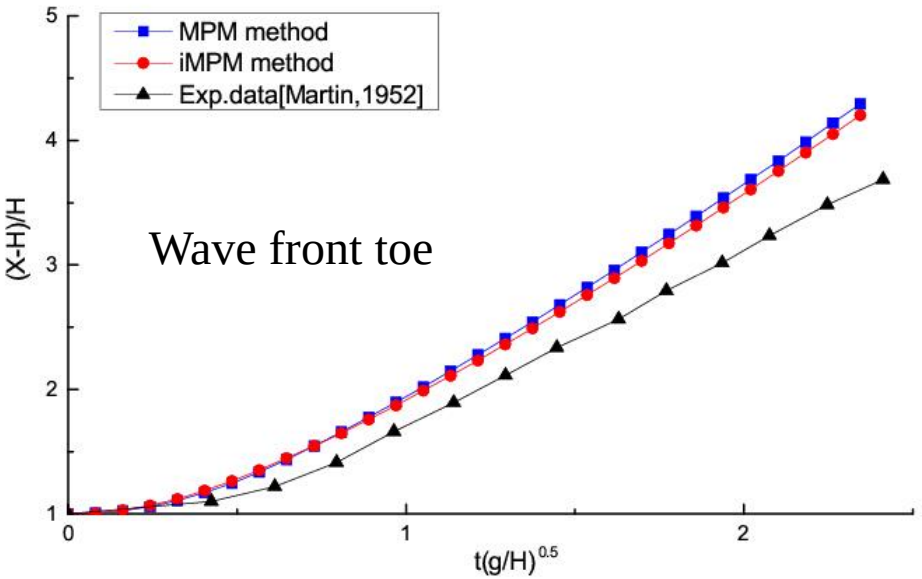
2nd Crack

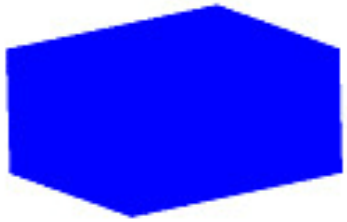
- *PF Yang, Y Gan, X Zhang, et al.* ***International Journal of Fracture***. 186(1-2): 177-184, 2014
- *B. L. Boyce, et al.* ***International Journal of Fracture***. 186(1-2): 5-68, 2014

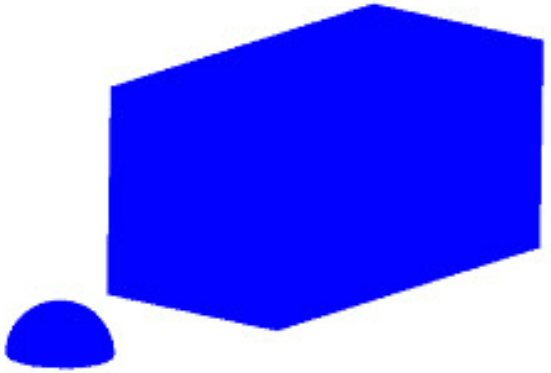
Applications

Dam break







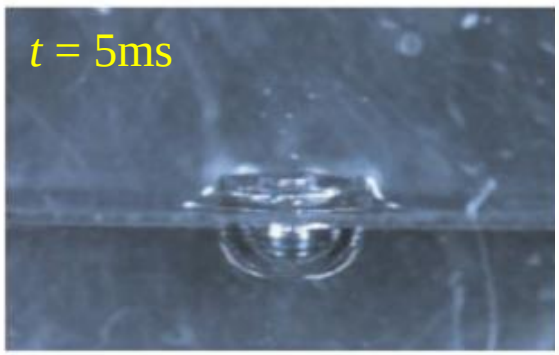


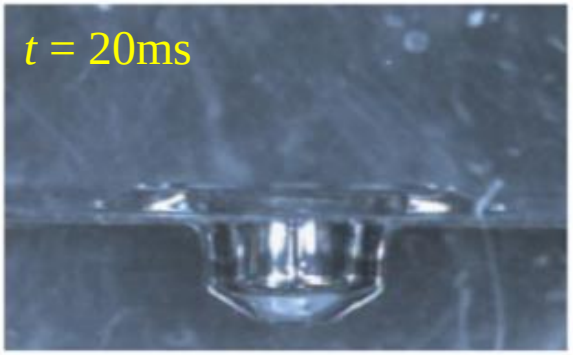
Dam break with a obstacle

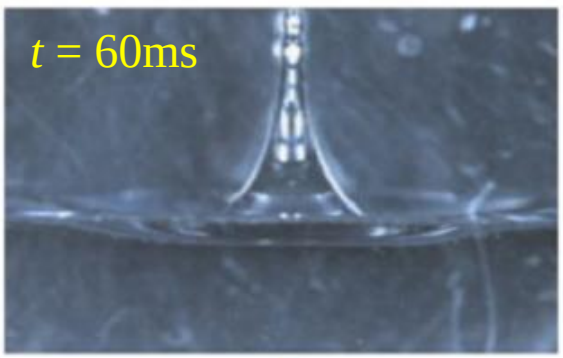
F Zhang, X Zhang, YP Lian, et al. Incompressible material point method for free surface flow. ***Journal of Computational Physics***. 330: 92–110, 2017.

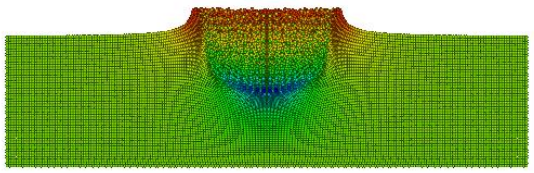
Applications

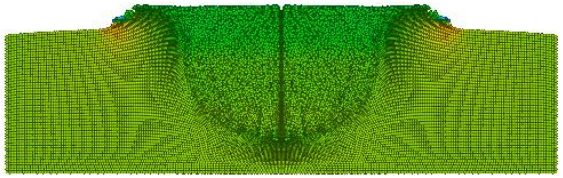
Water droplet impact

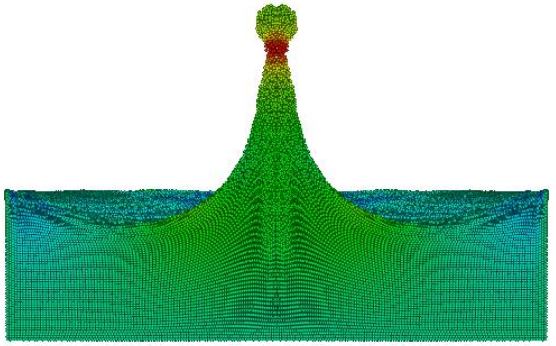


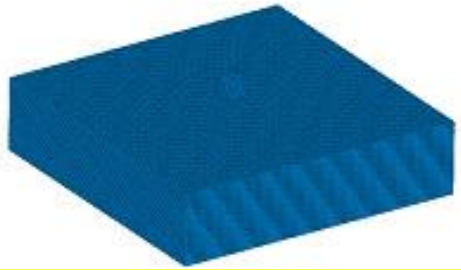


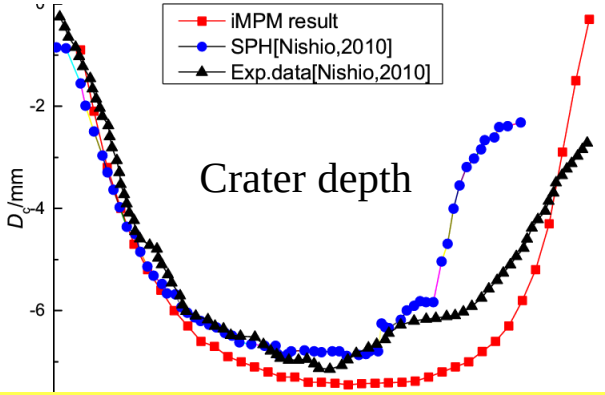








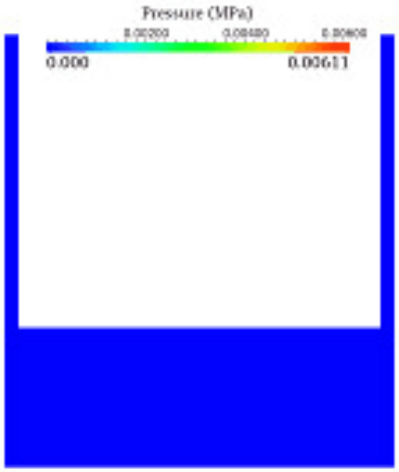




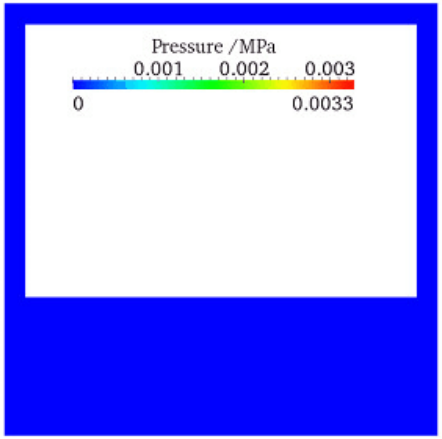
F Zhang, X Zhang, YP Lian, et al. Incompressible material point method for free surface flow. ***Journal of Computational Physics***. To be appeared.

Applications

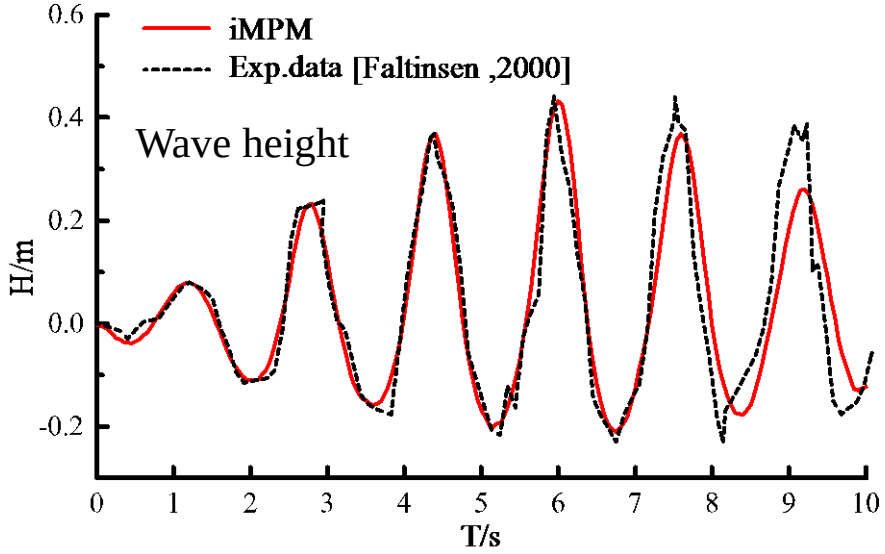
Sloshing due to excitation

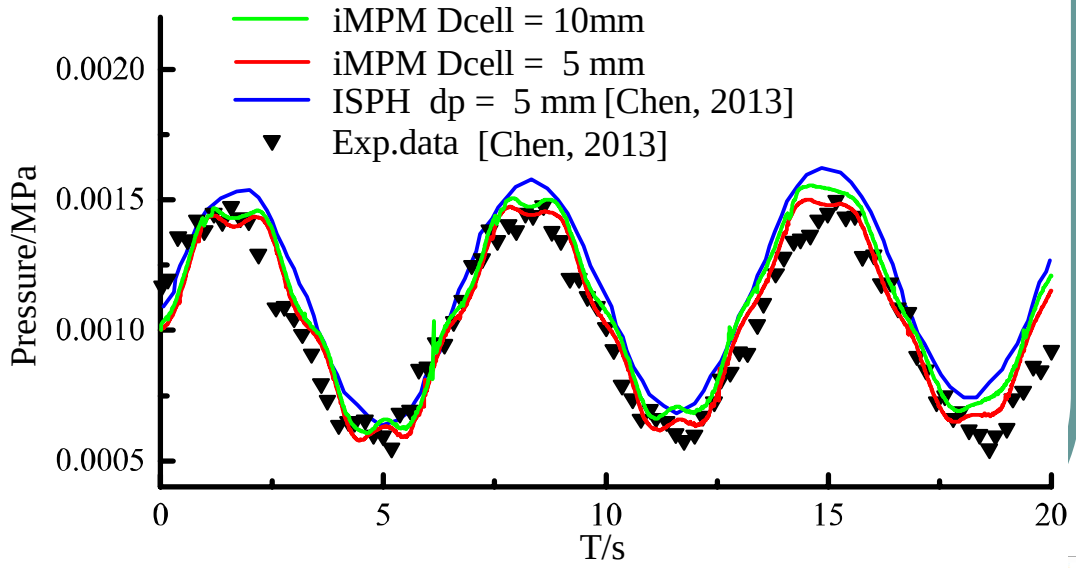


Horizontal excitation



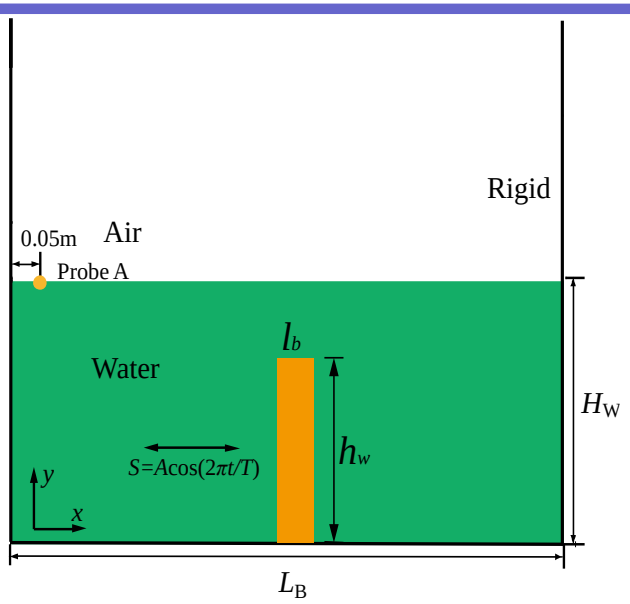
Rolling excitation

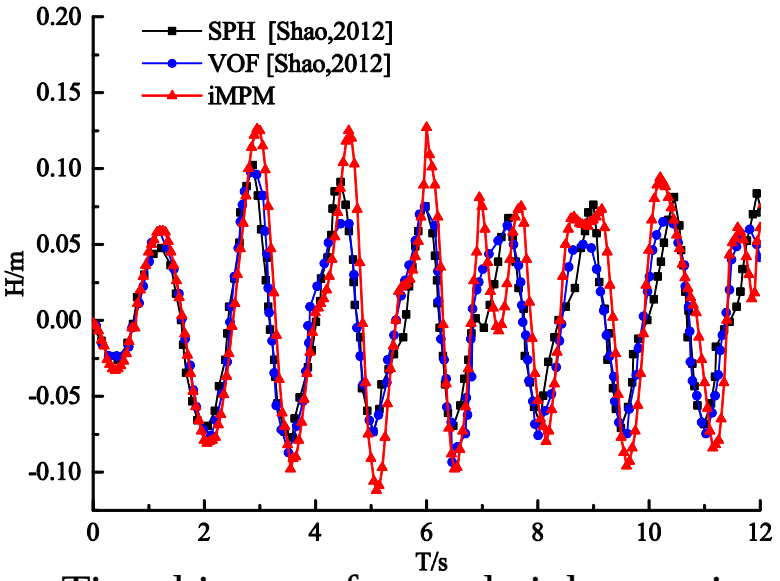




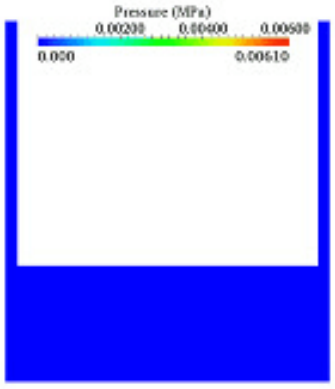
Applications

Sloshing with a middle baffle

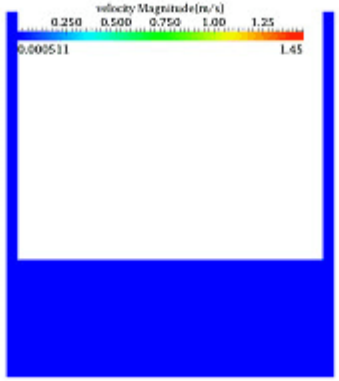




Time history of wave height at point A



Distribution of pressure

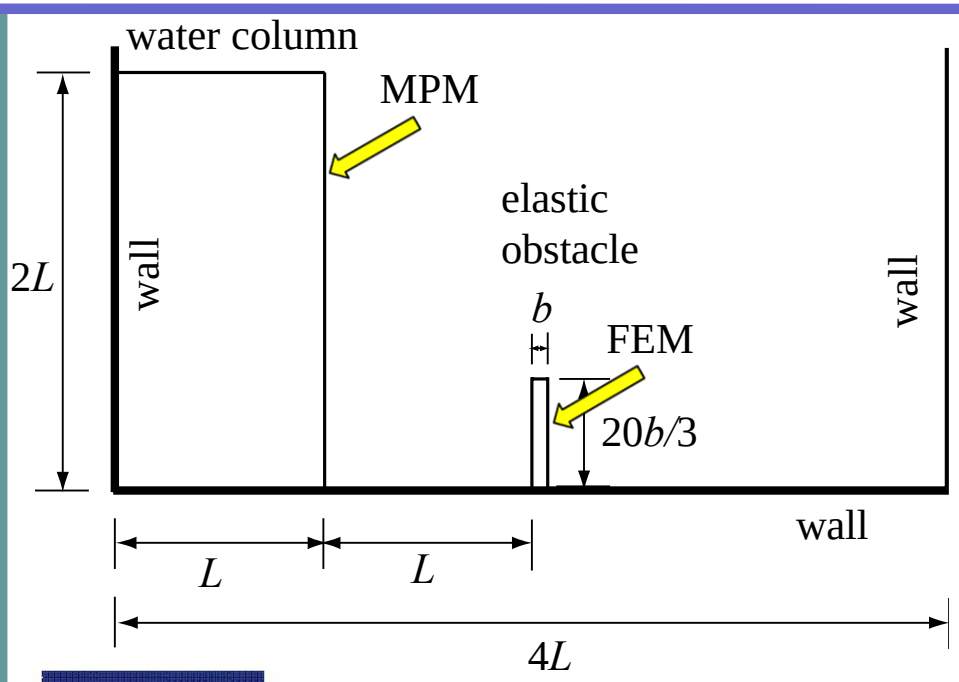


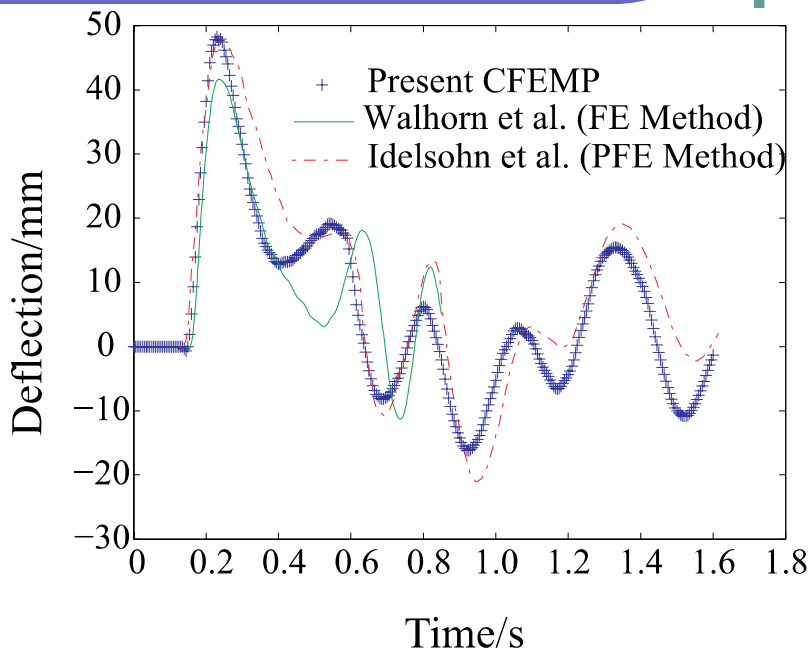
Distribution of velocity

Computational Dynamics 计算动力学实验室

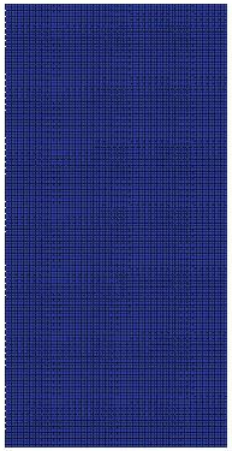
Applications

Collapse of water column with a flexible obstacle

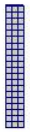




Time history of the displacement of the upper left corner of the obstacle



Coupled Finite Element Material Point Method

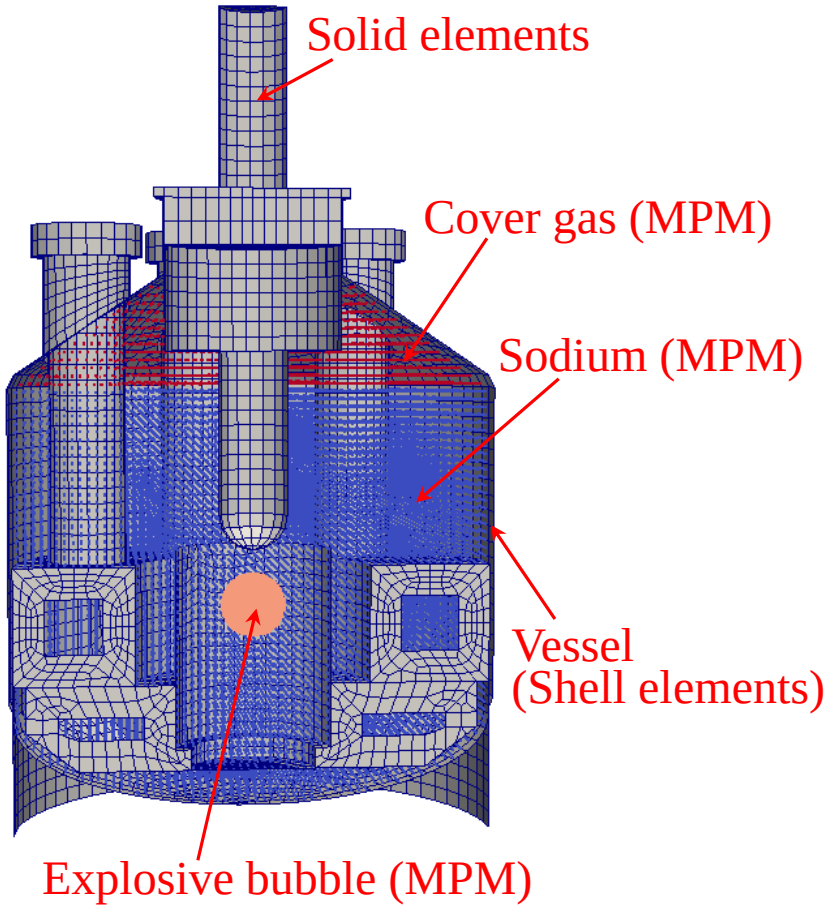


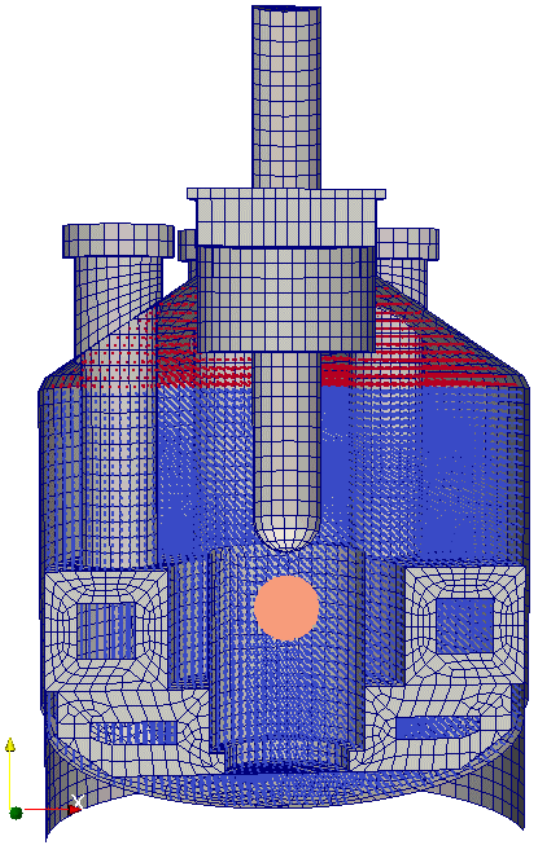
廉艳平, 张雄等. Coupling of finite element method with material point method by local multi-mesh contact method. ***CMAME*** 200: 3482-3494, 2011

Applications

HCDA in a fast reactor

Coupled Finite Element Material Point Method





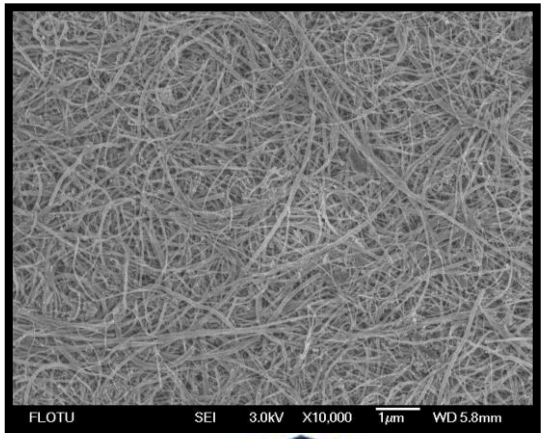
Hypothetical Core Disruptive Accident in a fast reactor

Computational Dynamics 计算动力学实验室

Applications

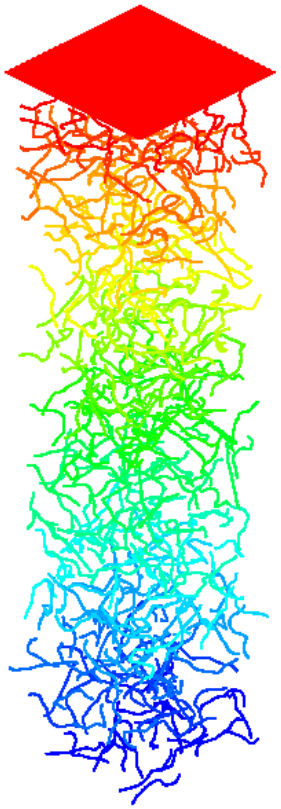
Carbon Nanotube Composite

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





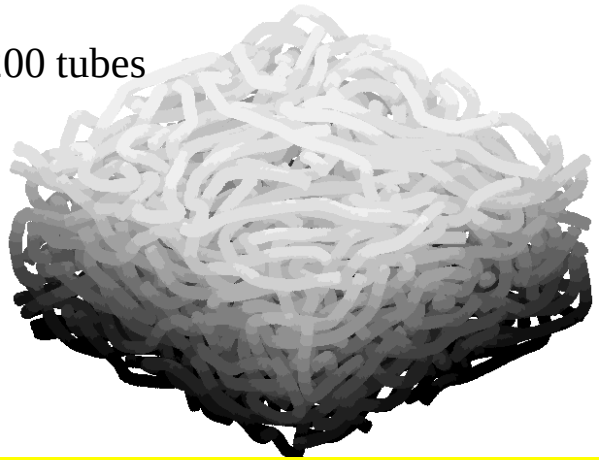
Pan, Iorga et al. 2008



400 tubes

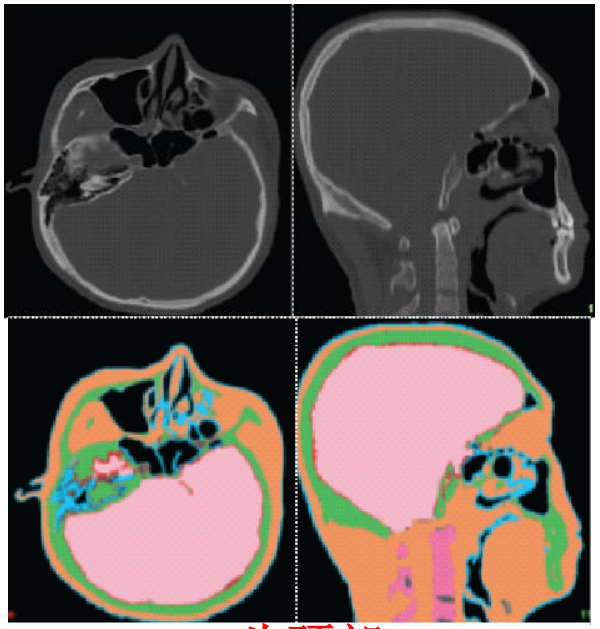


200 tubes

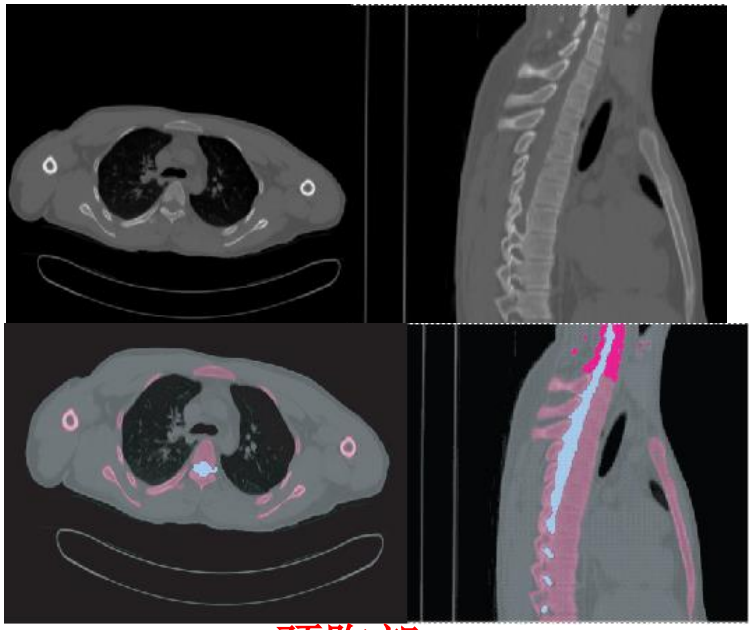


王汉奎, 刘岩, 张雄. Numerical simulation of carbon nanotube reinforced composite by material point method. ***CMS*** 57: 23-29, 2012

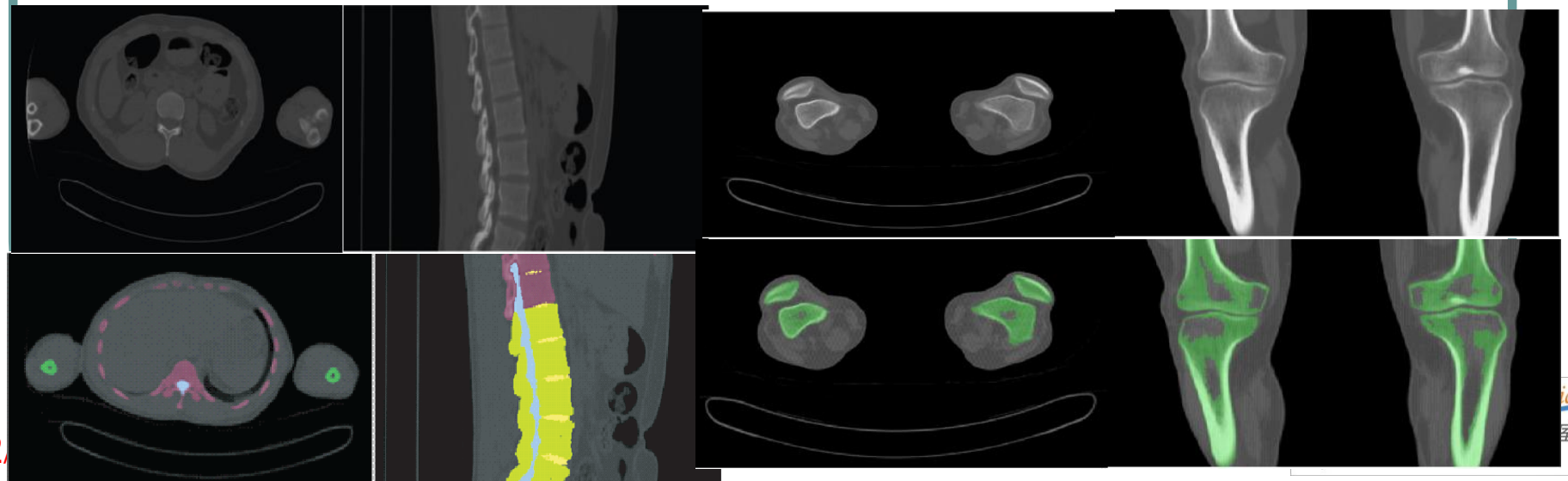
Applications



头颈部

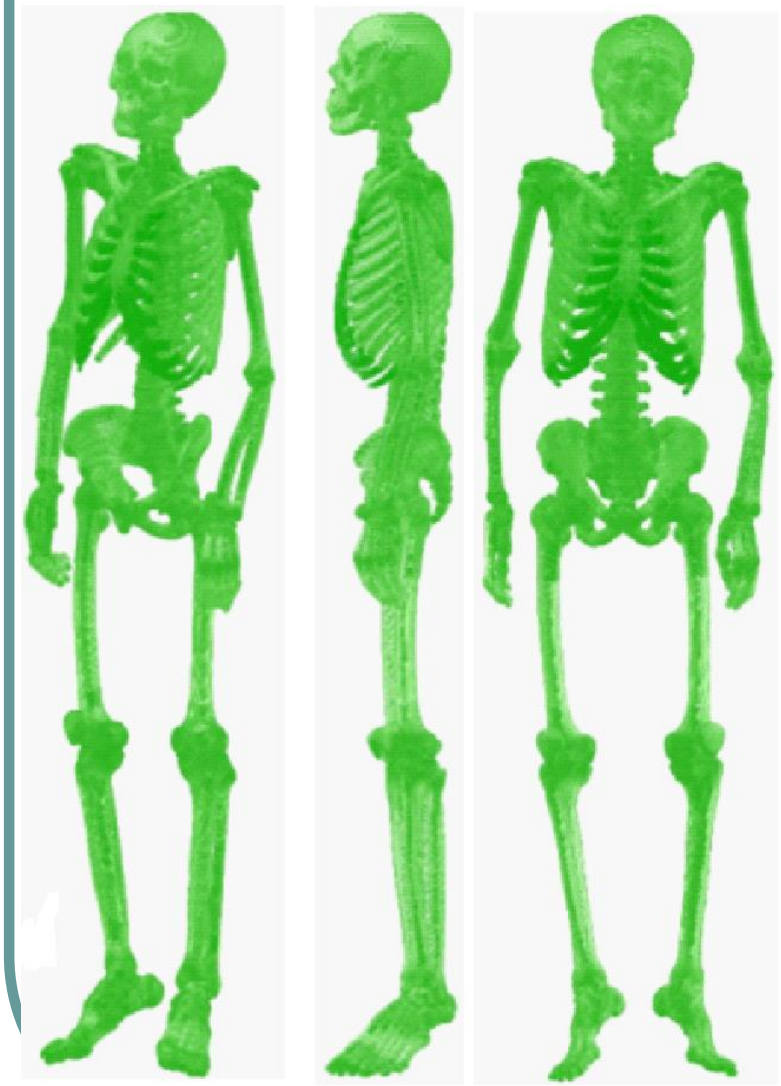


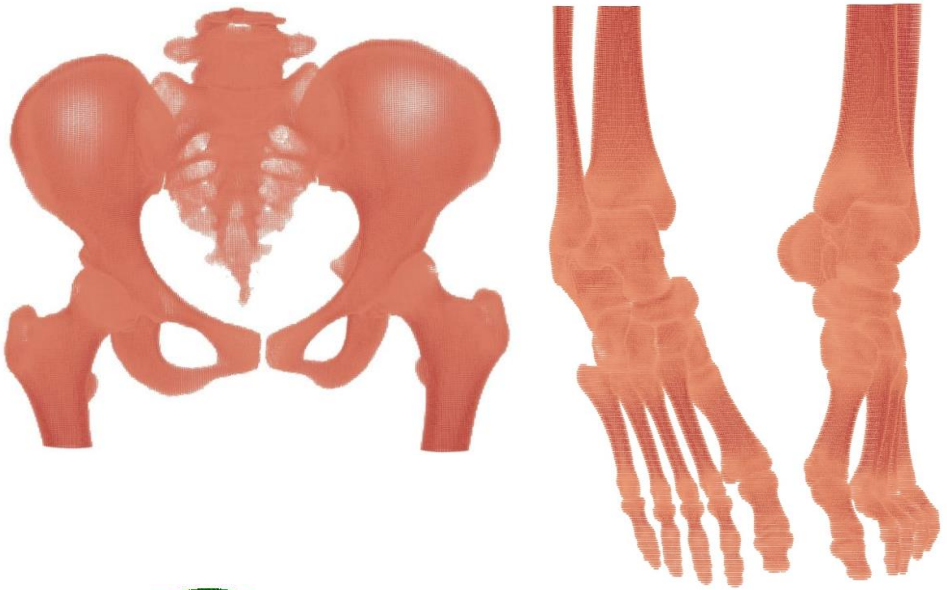
颈胸部

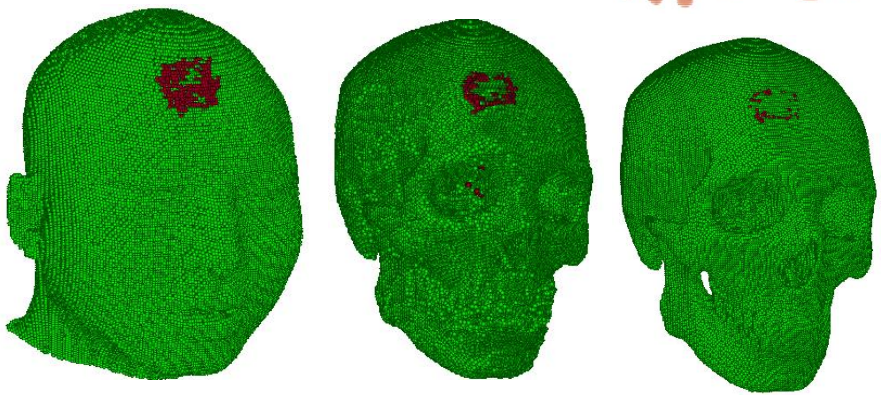


Applications

Biomechanics







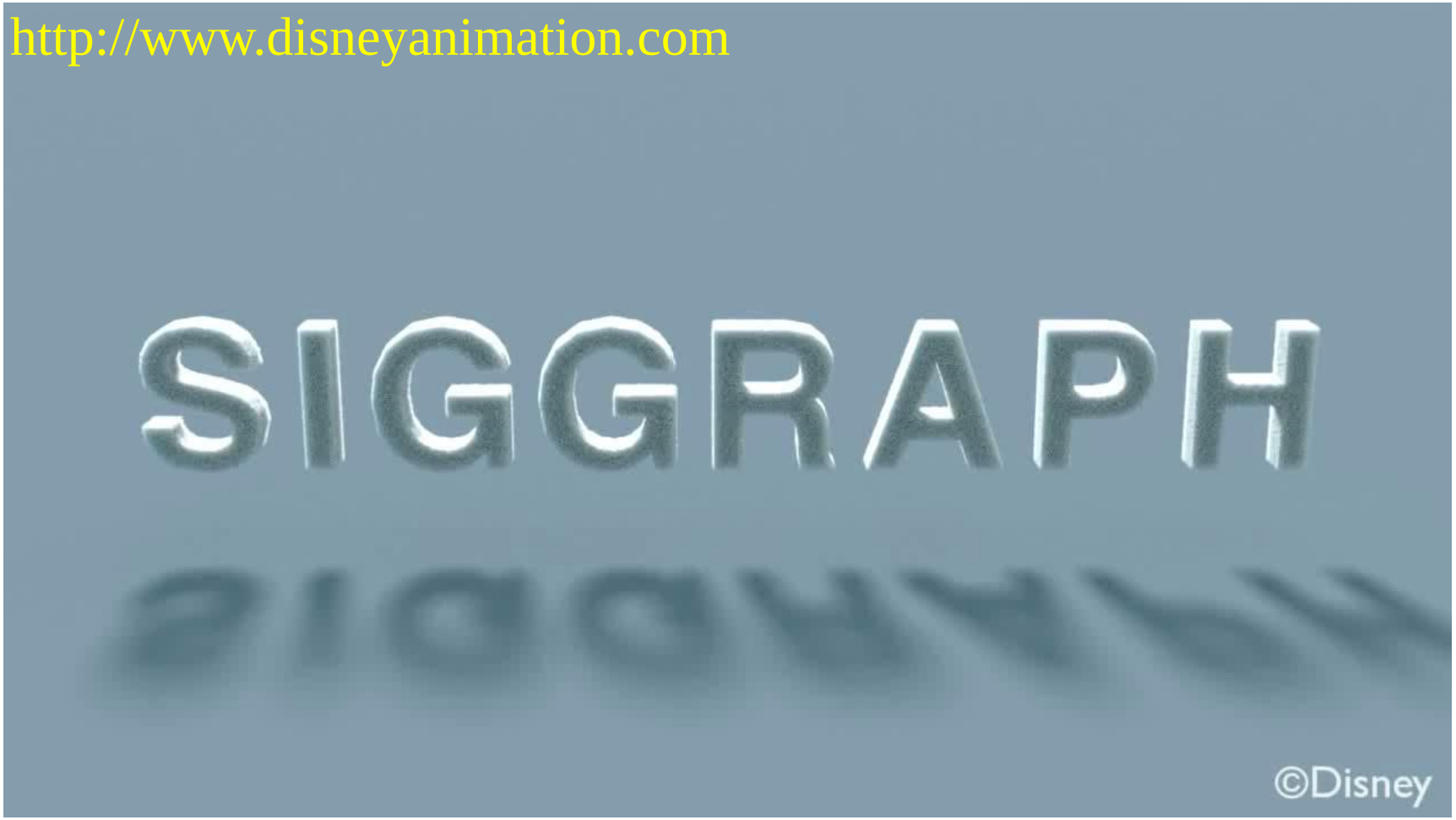
Muscle Membrane Skull

周双珍, 张雄等. Numerical Simulation of Human Head Impact Using the Material Point. ***International Journal of Computational Methods***. 10(4), 2013

Applications

Snow Simulation

http://www.disneyanimation.com



How Disney made their snow look real

Outline

- Introduction
- Material Point Method
- Our Developments on MPM
- MPM3D – A 3D explicit MPM code
- Applications
- **Concluding remarks**

Concluding Remarks

- MPM Combines the advantages of Lagrangian and Eulerian methods
  - No mesh distortion and element entanglement
  - History-dependent constitutive models
  - Free surfaces or multiple materials
  - Promising in modeling extreme deformation and material discontinuities
- MPM3D is much more efficient and robust than SPH in LS-DYNA and AUTODYN
  - Large time step
  - No neighbor search
- MPM is a FEM based particle method
  - Particle quadrature rather than Gauss quadrature
  - Remesh in each time step
  - Easy to be combined with FEM





Thank you for your attention !





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