# An Overview of the MPM over the Last 15 Years

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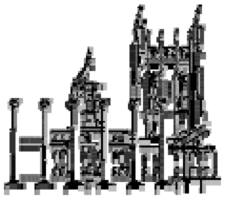
John Nairn at Oregon State University



# *Outline*

1. **Introduction**
2. **Statistical Data**
3. **Our Recent Work**
4. **Concluding Remarks**

**Recent Collaborators:**

Prof. Joe Labuz, University of Minnesota

Dr. E. Fang, Sandia National Laboratories

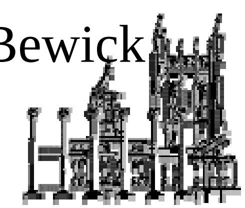
Prof. Y.-W. Mai, Sydney University, Australia

Prof. F. Oka, Kyoto University, Japan

Prof. H.W. Zhang, Dalian University of Technology, China

Prof. X. Zhang, Tsinghua University, China

Former and Current Ph.D. Students: W. Hu, L. Shen, Y. Gan, B. Bewick



# 1. Introduction

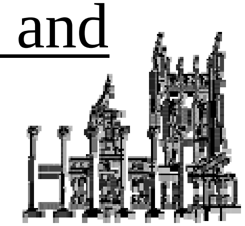
**Historical Notes –**

Motivated by the need for better simulating penetration problems

Inspired by Sulsky's seminar on simulating particle suspension in flow with the PIC method

Initially funded by Sandia National Laboratories ("The Application of New Numerical Techniques and Constitutive Equations to the Analysis of Penetration," PI Schreyer with Co-PIs Sulsky and Chen, 1992-1993)

First published in 1994 (Sulsky, D., Chen, Z., and Schreyer, H.L., "A Particle Method for History-Dependent Materials," Computer Methods in Applied Mechanics and Engineering, Vol. 118, pp. 179-196, 1994)



# 1. Introduction *(continued)*

**Remark 1** – The MPM is an extension from the PIC method in computational fluid dynamics to computational solid dynamics with the two key differences:

a. *The MPM is formulated in the weak form similar to that for the FEM so that both the FEM and MPM could be combined together for large-scale simulations.*

b. *History-dependent constitutive models could be formulated on the material points*, *which results in a robust spatial discretization method for multi-phase and multi-physics problems*, *including the transition from continuous to discontinuous failure modes*.

**Remark 2** – The original MPM employs a *regular* background mesh, and an *explicit* time integration scheme.

# 1. Introduction *(continued)*

**Remark 3** – The major milestones in improving the original framework of the MPM are as follows:

a. *Implicit time integration* (Cummins and Brackbill, 2002; among others)

b. *Adaptive background mesh* (Tan and Narin, 2002; among others)

c. *The generalized interpolation material point (GIMP) method* (Bardenhagen and Kober, 2004)

d. *Multi-scale framework* (Ayton et al., 2001; among others)

# 2. Statistical Data

**In about 120 papers published in the last 15 years, the domestic authors represent the following schools, national labs and companies:**

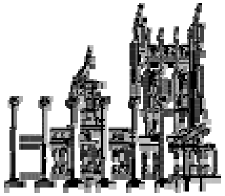
<u>The US Schools (in alphabetic order)</u>

CalTech, Indiana University-Purdue University in Indianapolis, MIT, New York University, Northwestern University, Oklahoma State University, Oregon State University, University of Alaska, University of Arizona, University of California at Los Angeles, University of Florida, University of Illinois at Urbana-Champaign, University of Iowa, University of Minnesota, University of Missouri, University of Nebraska-Lincoln, University of New Mexico, University of Oklahoma, University of Texas at Austin, University of Texas at San Antonio, University of Utah, University of Washington, and Washington State University

# 2. Statistical Data *(continued)*

The US National Labs and Companies (in alphabetic order)

- Air Force Research Laboratory
- Altair Engineering, Inc.
- Applied Research Associates
- Baker Engineering and Risk Consultants, Inc.
- Caterpillar, Inc.
- General Motors
- Jet Propulsion Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- Northwest Research Associates
- Sandia National Laboratories
- Schlumberger



# 2. Statistical Data *(continued)*

**The foreign authors are from the following countries (in alphabetic order):**

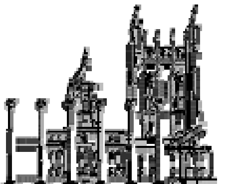
Argentina, Australia, Belarus, Brazil, Canada, China, France, Germany, India, Israel, Italy, Japan, Poland, Spain, Sweden, South Africa, and South Korea.

# 2. Statistical Data *(continued)*

## Numbers of the papers in each category

*Algorithms and Performance –*

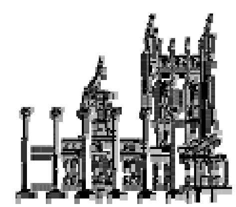
- Generalized (Interpolation) MPM: 4 papers
- Implicit Time Integration: 5 papers
- Improved Contact/Interface Schemes: 4 papers
- Improved Mapping Scheme: 1 paper
- Implementation Consideration: 5 papers
- Visualization: 2 papers
- Error Analysis: 1 paper
- Combined MPM and FEM: 1 paper
- Multiscale Approaches: 8 papers



# 2. Statistical Data *(continued)*

*Applications* –

- •Large deformation/Failure Evolution/Fracture: 18 papers
- •Extreme Loading Conditions (Fire, Explosion, Impact and Penetration): 22 papers
- •Geological/Granular Materials: 18 papers
- •Biological /Cellular Materials: 9 papers
- •Metal Forming and Processing: 4 papers
- •Solid-Fluid Interaction: 6 papers
- •Ice Dynamics: 4 papers



# 3. Our Recent Work

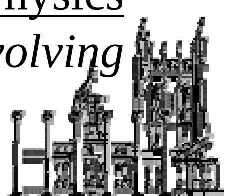
**Our Journal Papers Related to the Development of the MPM over the Last 10 Years:**

Zhou, S.J., Stormont, J., and Chen, Z., “Simulation of Geomembrane Response to Settlement in Landfills by Using the Material Point Method,” International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 23, pp. 1977-1994, 1999. – *Large Deformation*

Chen, Z., Hu, W., Shen, L., Xin, X., and Brannon, R., “An Evaluation of the MPM for Simulating Dynamic Failure with Damage Diffusion,” Engineering Fracture Mechanics, Vol. 69, pp. 1873-1890, 2002. – *Multi-Physics Simulation*

Hu, W., and Chen, Z., “A Multi-Mesh MPM for Simulating the Meshing Process of Spur Gears,” Computers & Structures, Vol. 81, pp. 1991-2002, 2003. – Contact Scheme

Chen, Z., Shen, L., Mai, Y.-W., and Shen, Y.-G., “A Bifurcation-based Decohesion Model for Simulating the Transition from Localization to Decohesion with the MPM,” Journal of Applied Mathematics and Physics (ZAMP), Vol. 56, pp. 908-930, 2005. – *Failure Evolution Involving Continuous and Discontinuous Modes*



# 3. Our Recent Work *(continued)*

Shen, L., and Chen, Z., “A Multi-Scale Simulation of Tungsten Film Delamination from Silicon Substrate,” International Journal of Solids and Structures, Vol. 42, pp. 5036-5056, 2005. – *Multi-Scale Simulation*

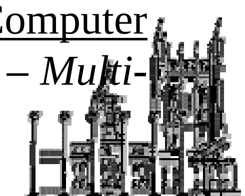
Shen, L., and Chen, Z., “A Silent Boundary Scheme with the Material Point Method for Dynamic Analyses,” Computer Modeling in Engineering & Sciences, Vol. 7, pp. 305-320, 2005. – *Large-Scale Dynamic Analyses*

Hu, W., and Chen, Z., “Model-Based Simulation of the Synergistic Effects of Blast and Fragmentation on a Concrete Wall Using the MPM,” International Journal of Impact Engineering, Vol. 32, pp. 2066-2096, 2006. – *Coupled CFD and CSD Simulation*

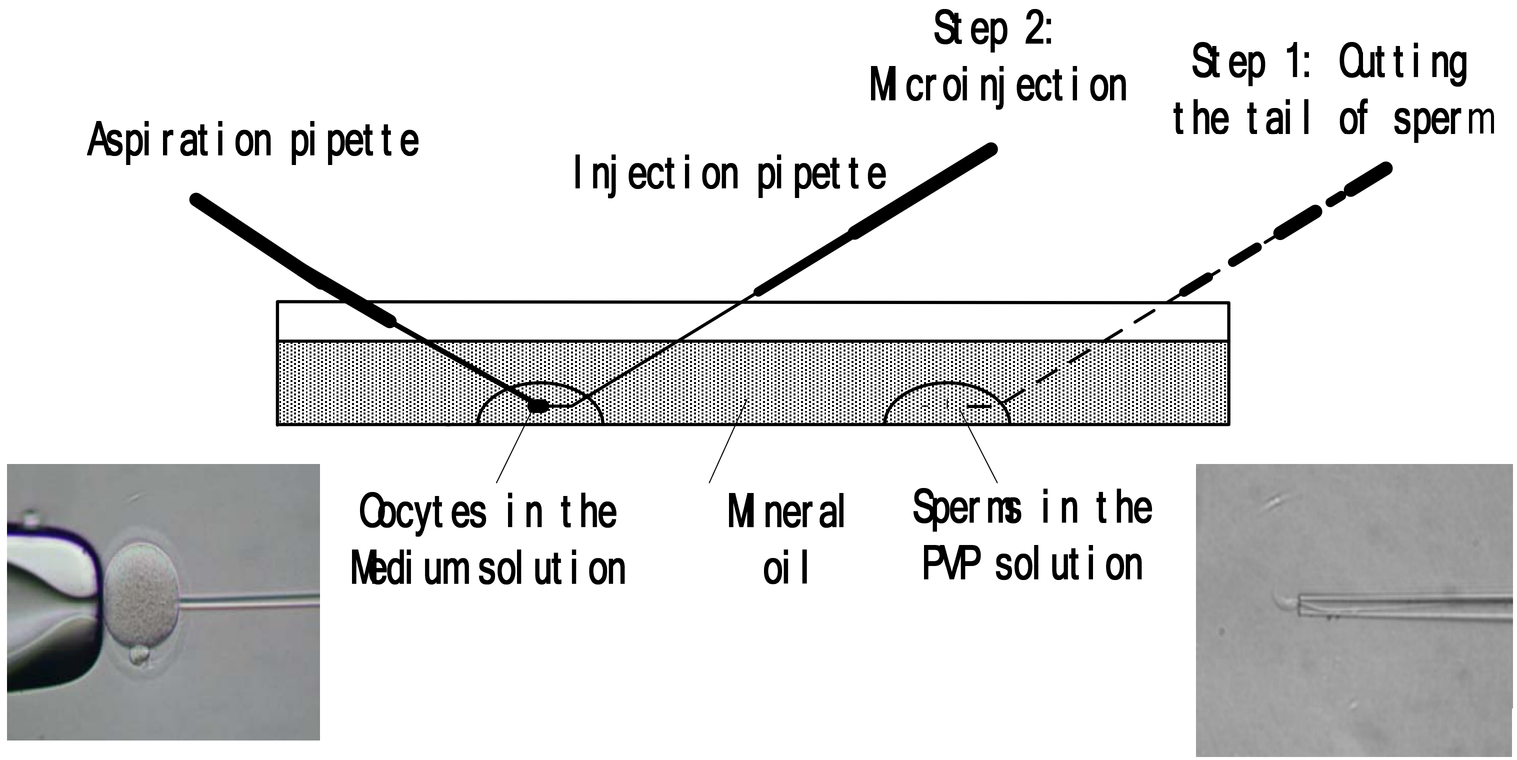
Chen, Z., Gan, Y., and Chen, J.K., “A Coupled Thermo-Mechanical Model for Simulating the Material Failure Evolution Due to Localized Heating,” Computer Modeling in Engineering and Sciences, Vol. 26, pp. 123-137, 2008. – *Coupled Thermo-Mechanical Simulation*

Gan, Y., and Chen, Z., “A Study of the Zona Piercing Process in Piezodriven Intracytoplasmic Sperm Injection,” Journal of Applied Physics, Vol. 104, pp. 044702-1-8, 2008. (This paper has been selected for publication in Virtual Journal of Biological Physics Research – Physical Studies of Cell Mechanics, Vol. 16, Issue 5, 2008.) – *Cell Penetration Mechanics*

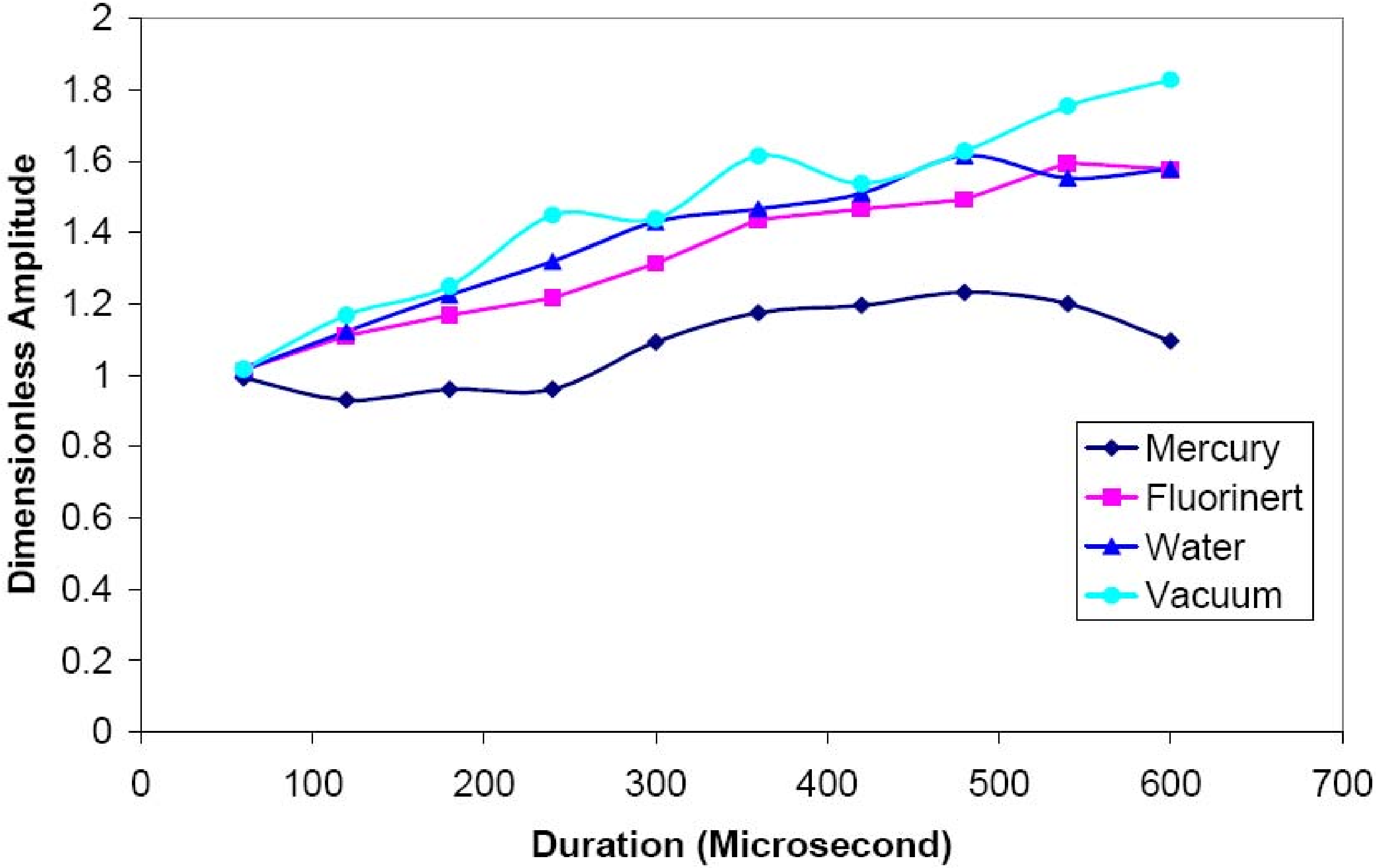
Zhang, H.W., Wang, K.P., and Chen, Z., “Material Point Method for Dynamic Analysis of Saturated Porous Media under External Contact/Impact of Solid Bodies,” Computer Methods in Applied Mechanics and Engineering, Vol. 198, pp. 1456-1472, 2009. – *Multi-Phase Interaction*



Gan, Y., and Chen, Z., “A Study of the Zona Piercing Process in Piezodriven Intracytoplasmic Sperm Injection,” Journal of Applied Physics, Vol. 104, pp. 044702-1-8, 2008.



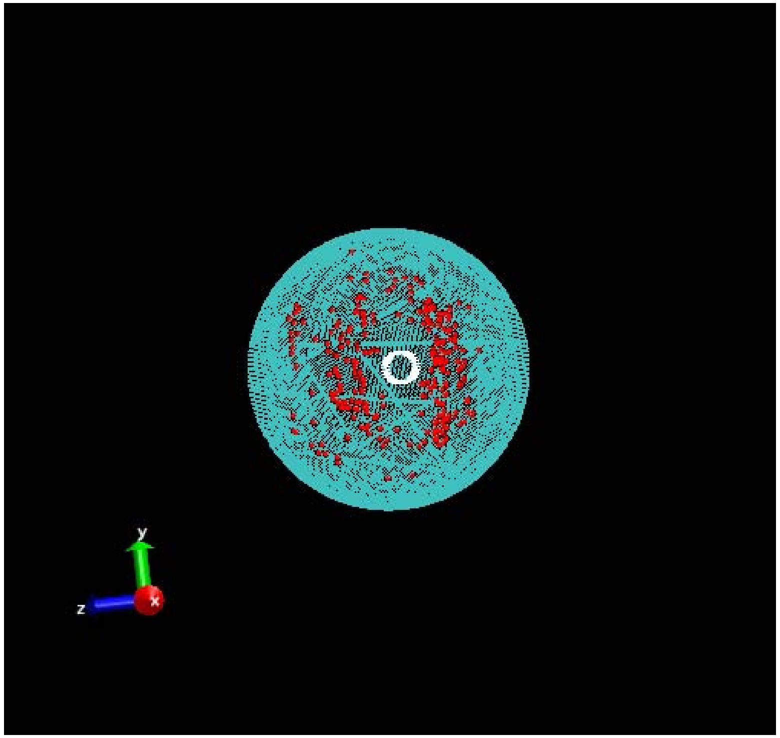
# The Effect of Mercury on Lateral Vibration

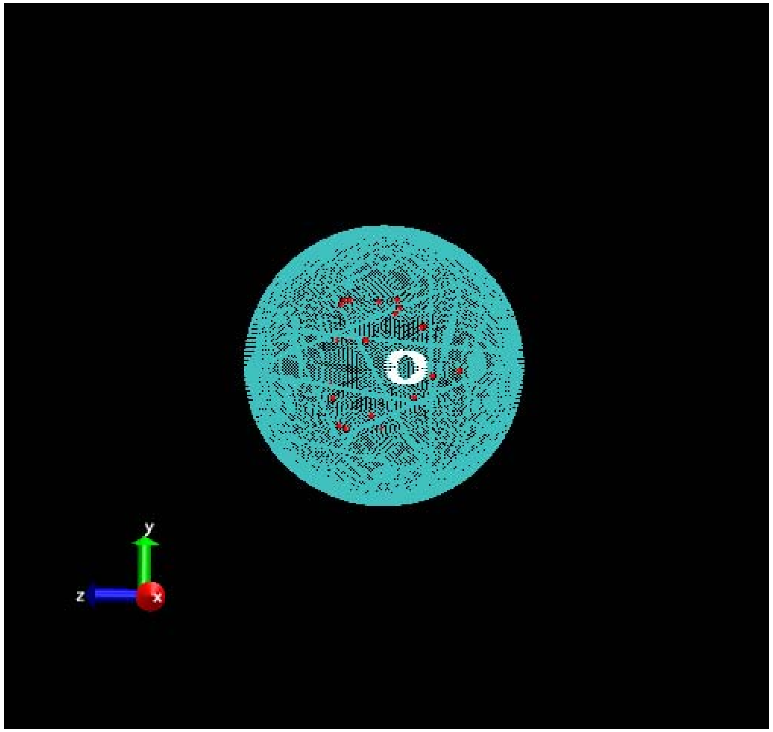


# Coupled CFD and CSD Simulation

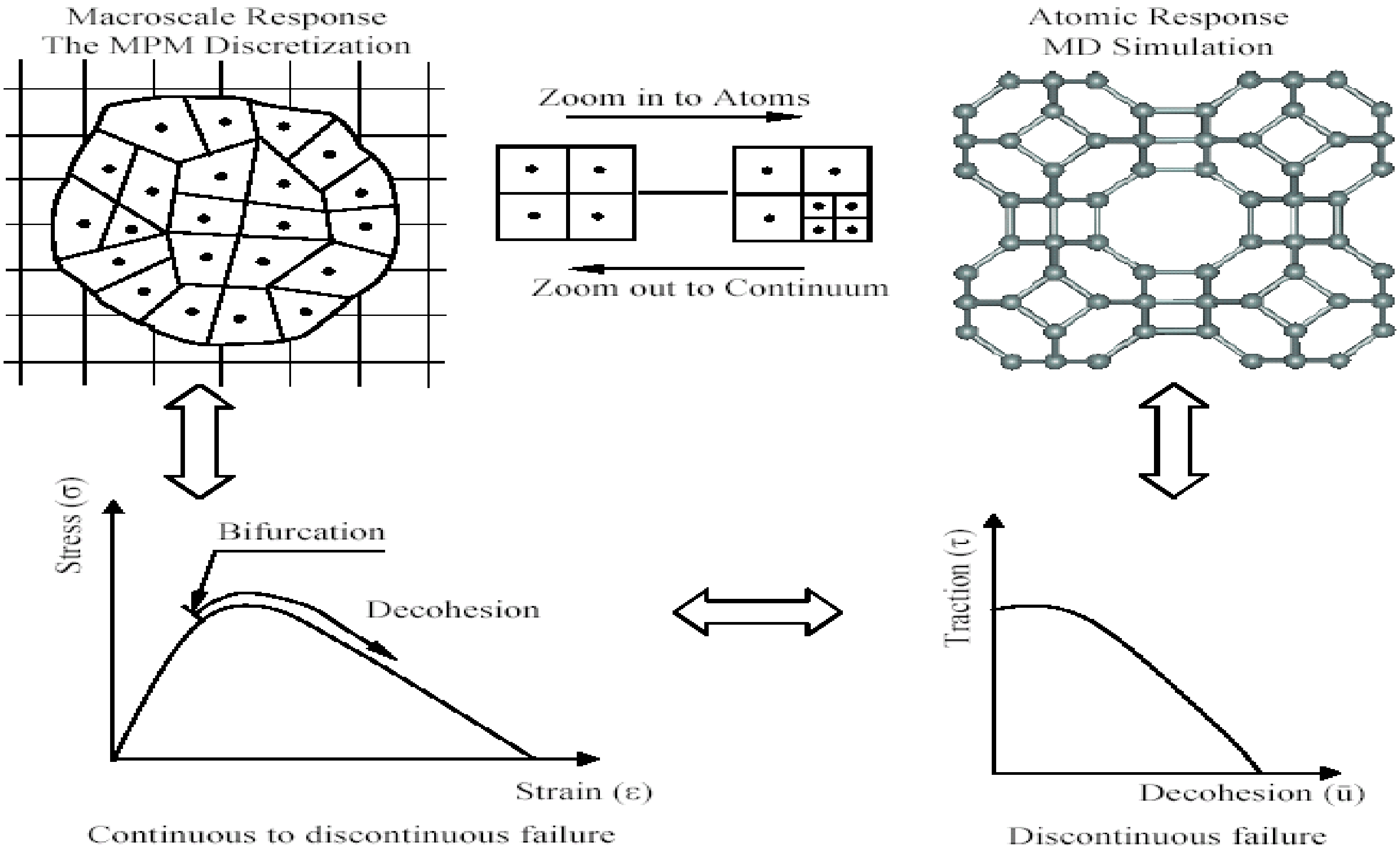
*Left: Penetration with lateral oscillation*

*Right: Penetration without lateral oscillation*



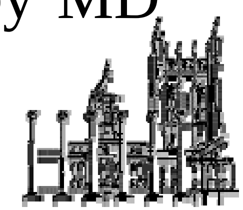



# A Multi-Scale Model-Based Simulation Procedure
## *Based on the MPM and Hyper-surface*



# *Background Information*

- Much research has been performed to study the size (nano-micro-meso-macro), rate (static-dynamic-impact-shock) and thermal (isothermal-heat conduction-thermal shock) effects on material properties, *respectively*.
- Research focus has usually been on the size effect, with a recent shift to combined size and rate effects due to the need for multi-scale structural safety under extreme loading conditions.
- The length and time scales that can be probed by the molecular level simulation are limited due to the computational capability available. On the other hand, the current experimental facilities can not provide the data in the range of sizes and rates that could be handled by MD simulation.



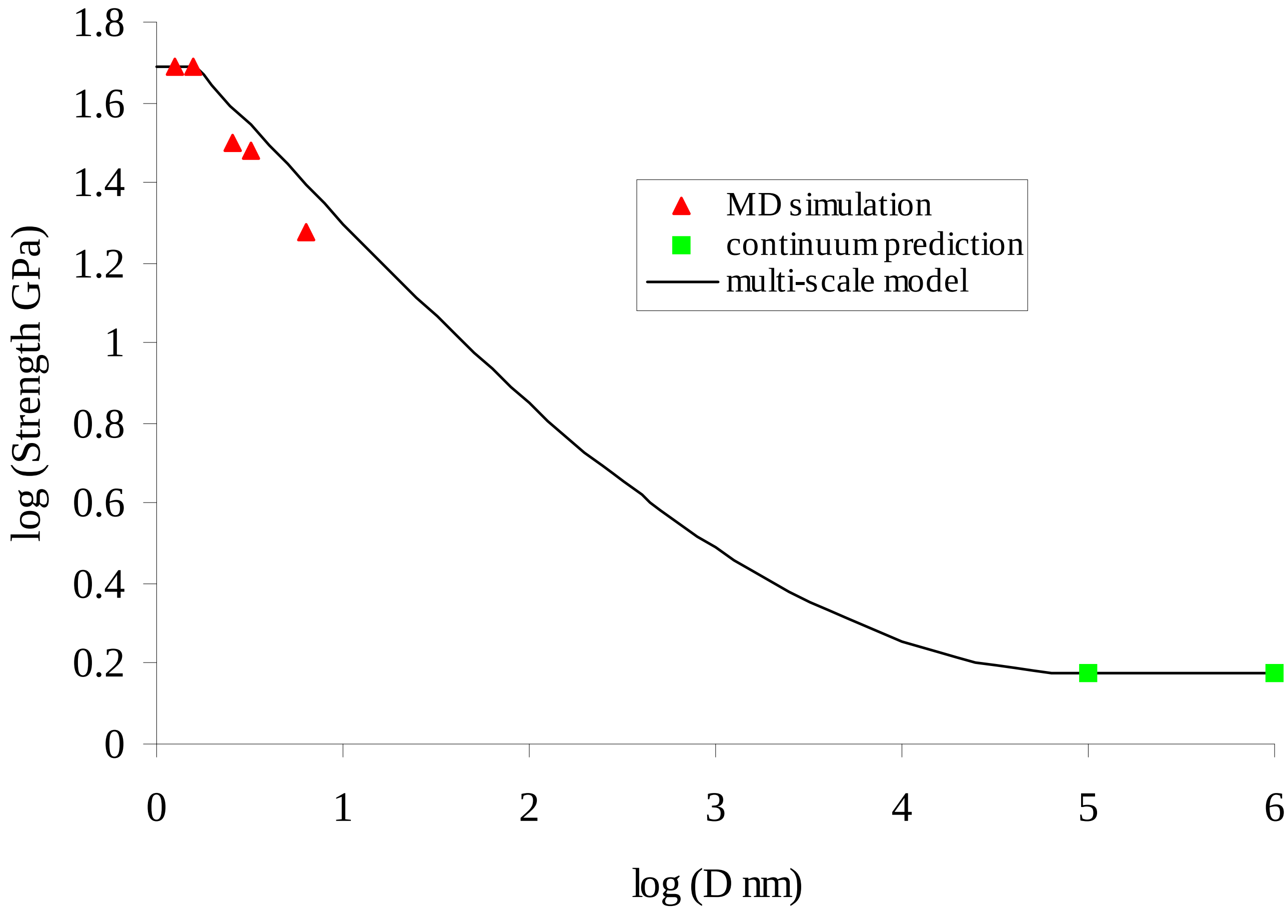
# *A Simple Model-Based Simulation Approach*

- Little work has been done to investigate combined size, rate and thermal effects on material properties, although there exists an urgent need for multi-physics simulation in homeland security and space exploration.

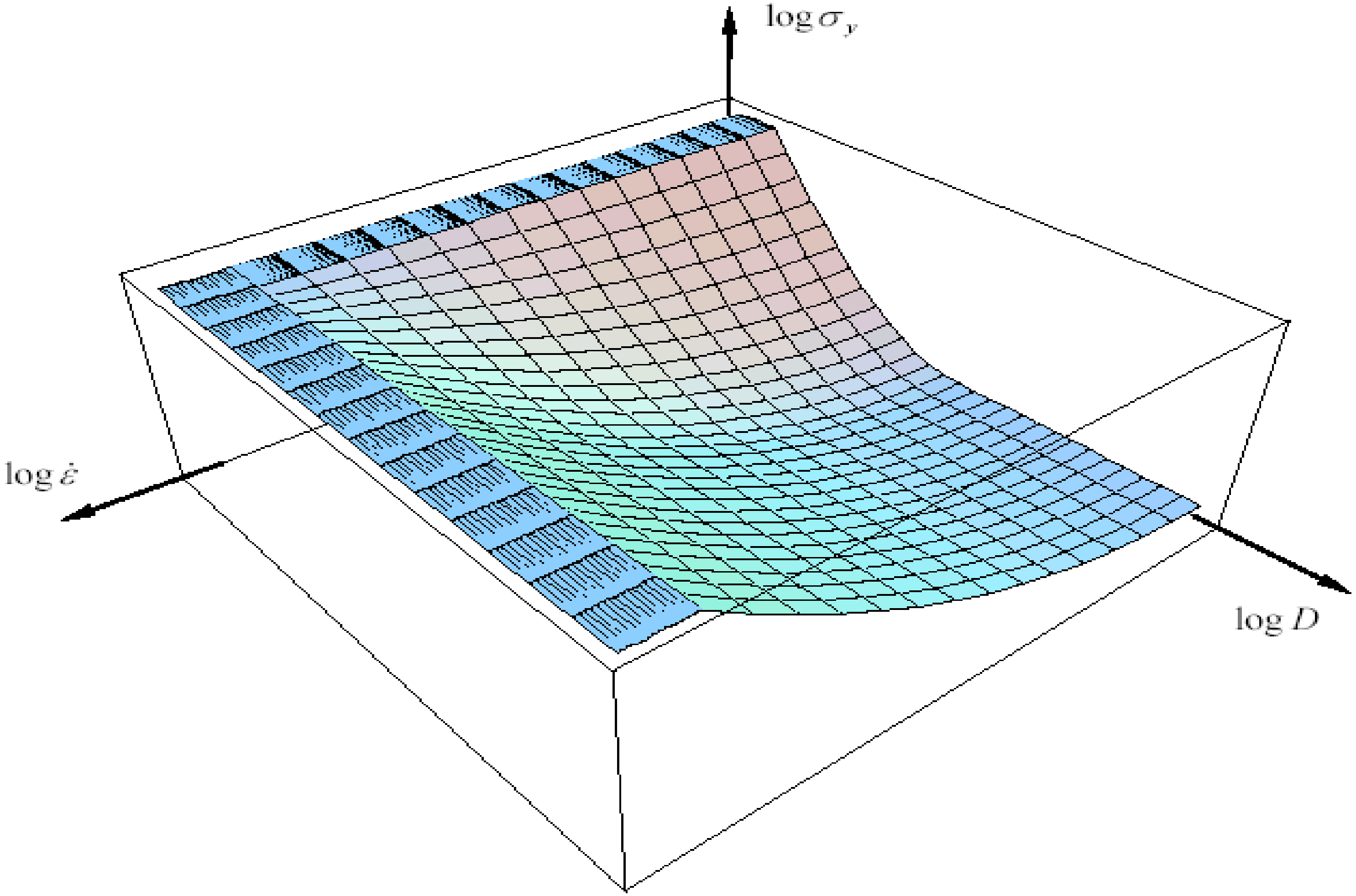
- We propose to formulate a hypersurface to predict combined size, rate and thermal effects, which could yield a simple design tool for engineering practice.

- The size effect is also important in evaluating the impact of nano-technology on the environment, as shown in the recent study on bio-nano interactions, as well as in effective energy generation with energetic nanoparticles.

# Size Effect on the Material Strength

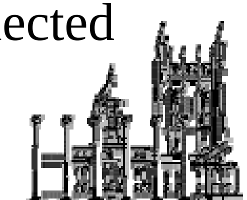


# A hyper-surface of the material property as a function of the spatial size and strain rate



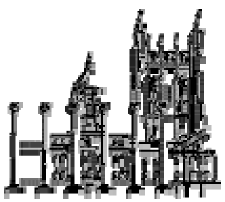
# Determination of the Hypersurface Based on the Available Experimental and Computational Capabilities

1. Under quasi-static loading, the continuum level data could be obtained by using the Weibull statistics, and the molecular level data could be found with molecular mechanics tools.
2. At the continuum level, quasi-static, dynamic and impact experiments could be conducted to determine the rate-dependent responses.
3. Assuming that there is no sudden change in material properties, i.e., no local minina or maxima, a monotonic hypersurface of material properties, as a function of the rate and size, could be formulated via analytical geometry for given boundary conditions.
4. For different materials, the hypersurface exhibits different changes in curvature, which must be determined by selected data points on the surface.

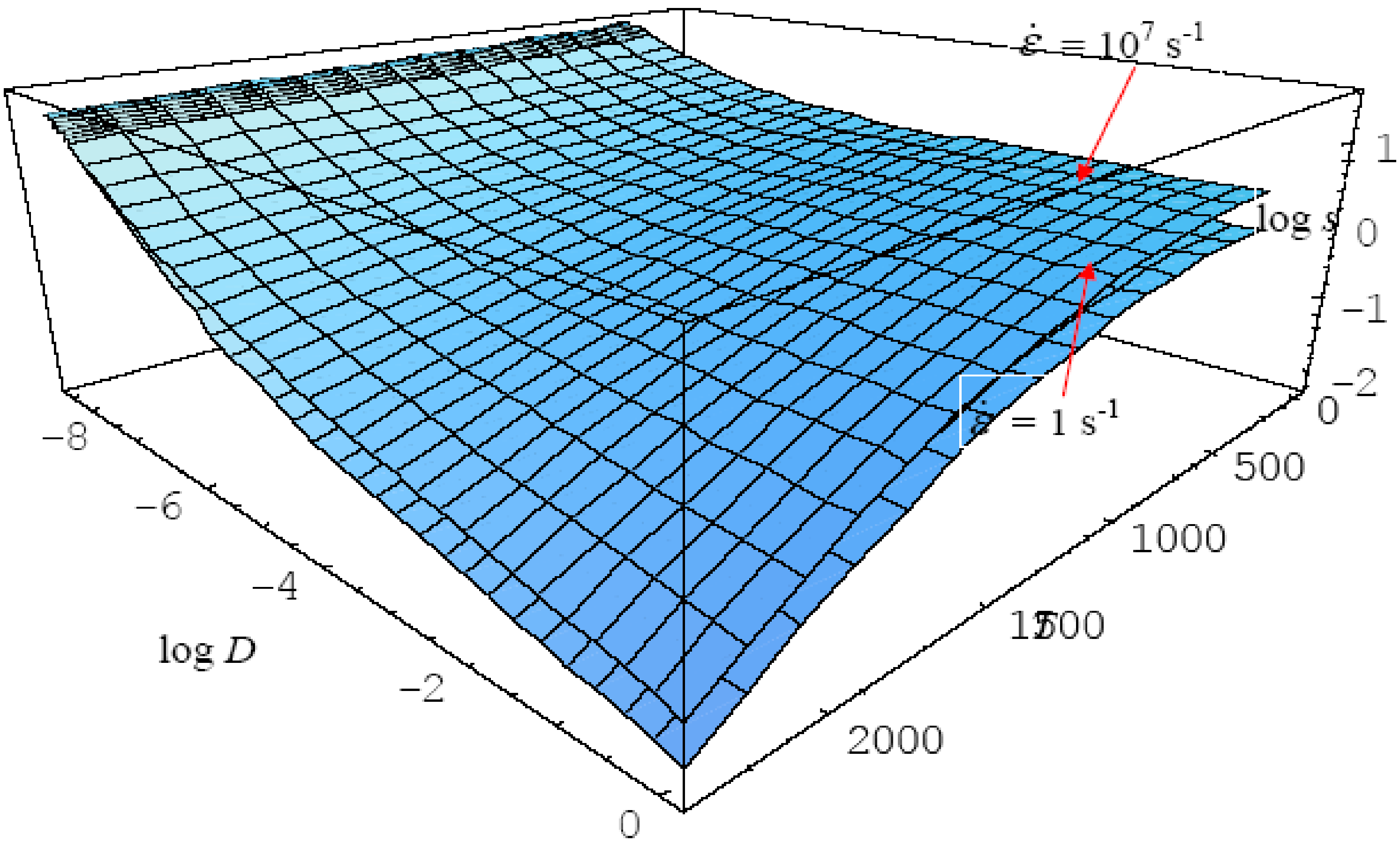


# Combined Rate, Size and Thermal Effects

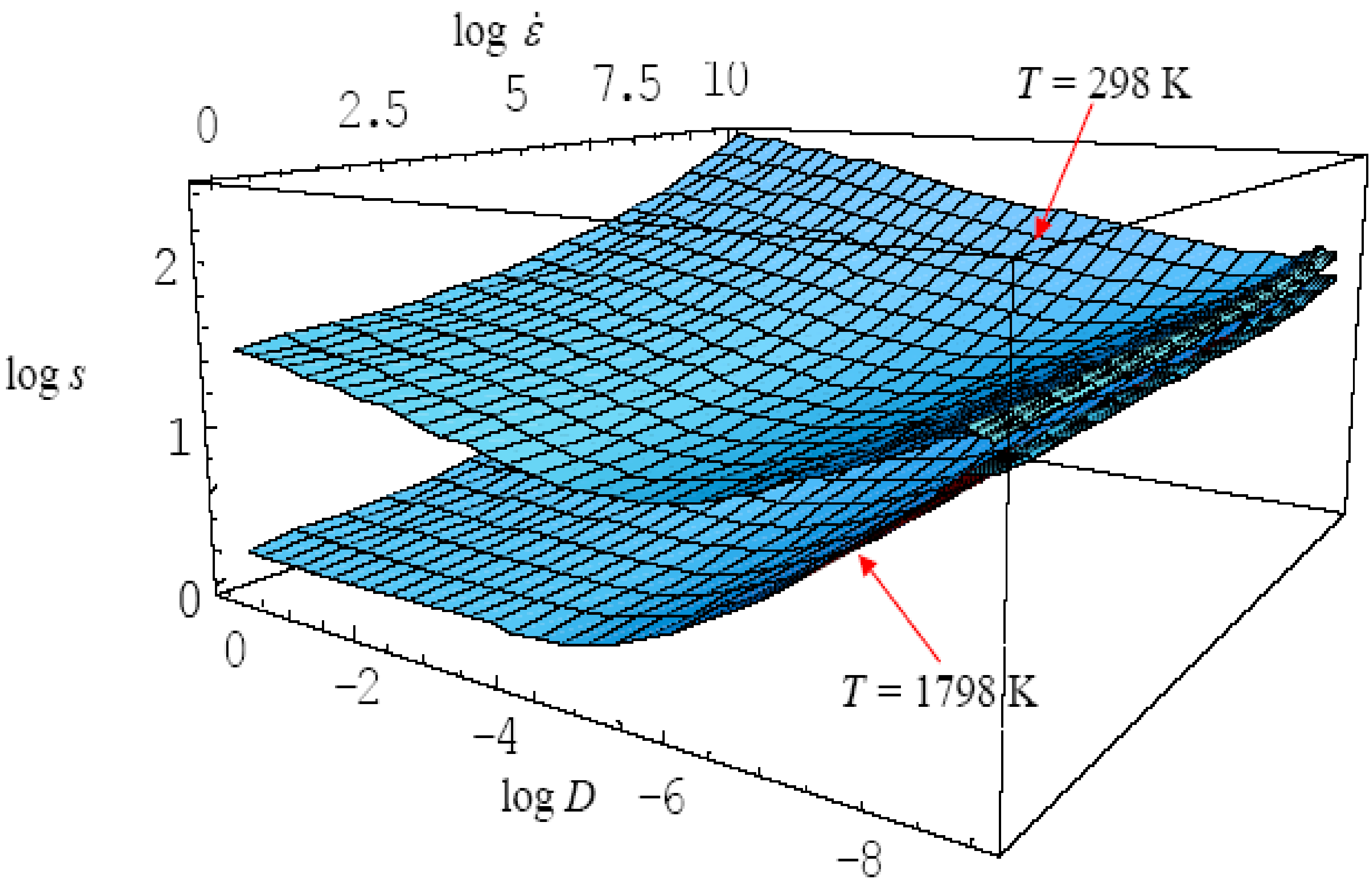
1. Thermal-activated mechanisms play an important role in the onset and evolution of material failure.
2. Assuming that no phase transition is considered, a hypersurface, as a function of rate, size and temperature, could be formulated to predict the material strength.
3. For tungsten, the Embedded Atom Method is used for MD calculation with the temperature being kept constant in the simulation box via a velocity scaling technique.
4. Both molecular and continuum level data are used to describe the thermal-mechanical response.



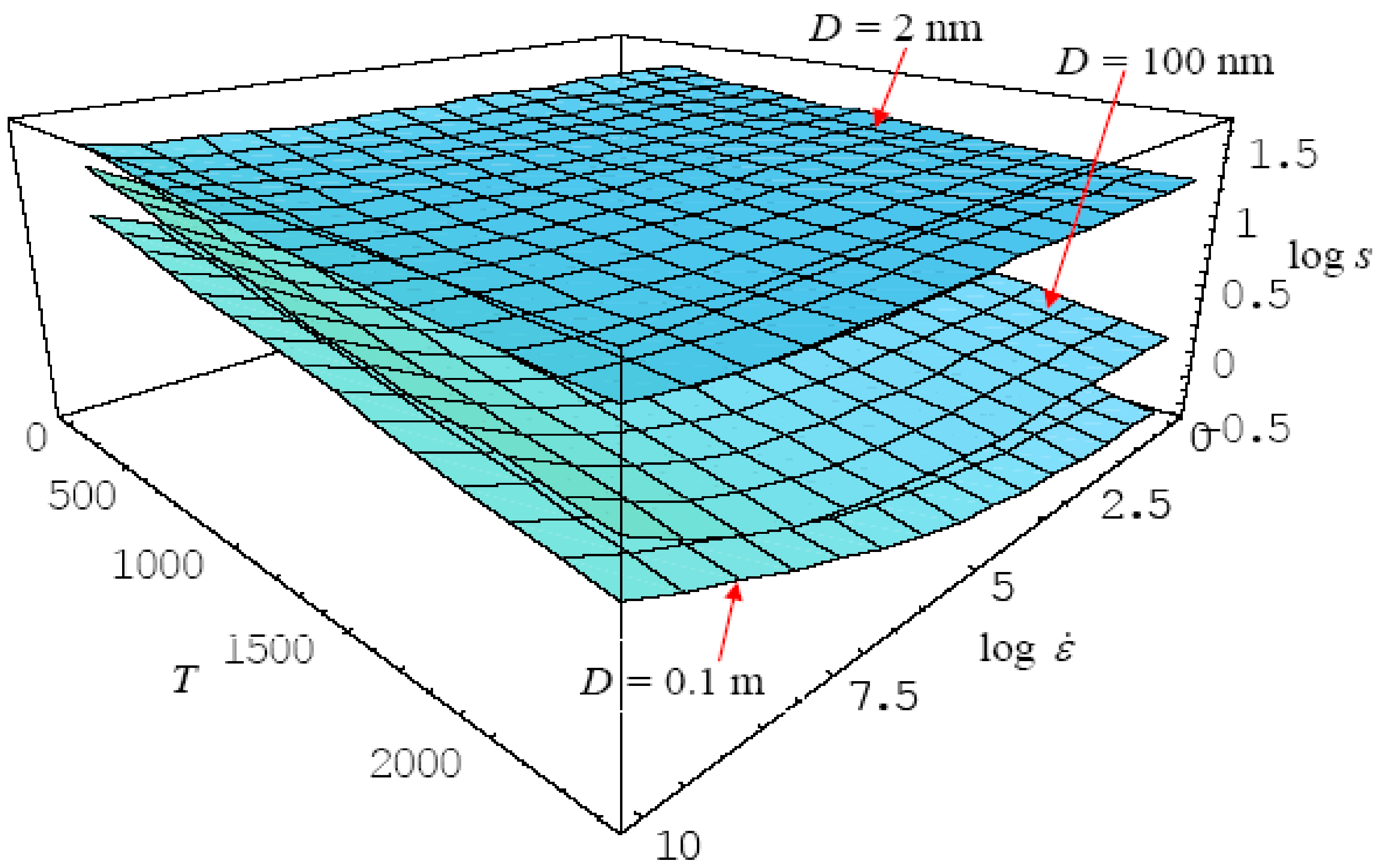
The hypersurfaces in a log$D$ (m)-$T$(K)-log $s$(GPa) space under strain rates of  = 1 $s^{-1}$ and $10^7$ $s^{-1}$, respectively.



The hypersurfaces in a log$D$ (m)-log($s^{-1}$)-log $s$ (GPa) space under temperatures of $T$ = 298 K and 1798 K, respectively.

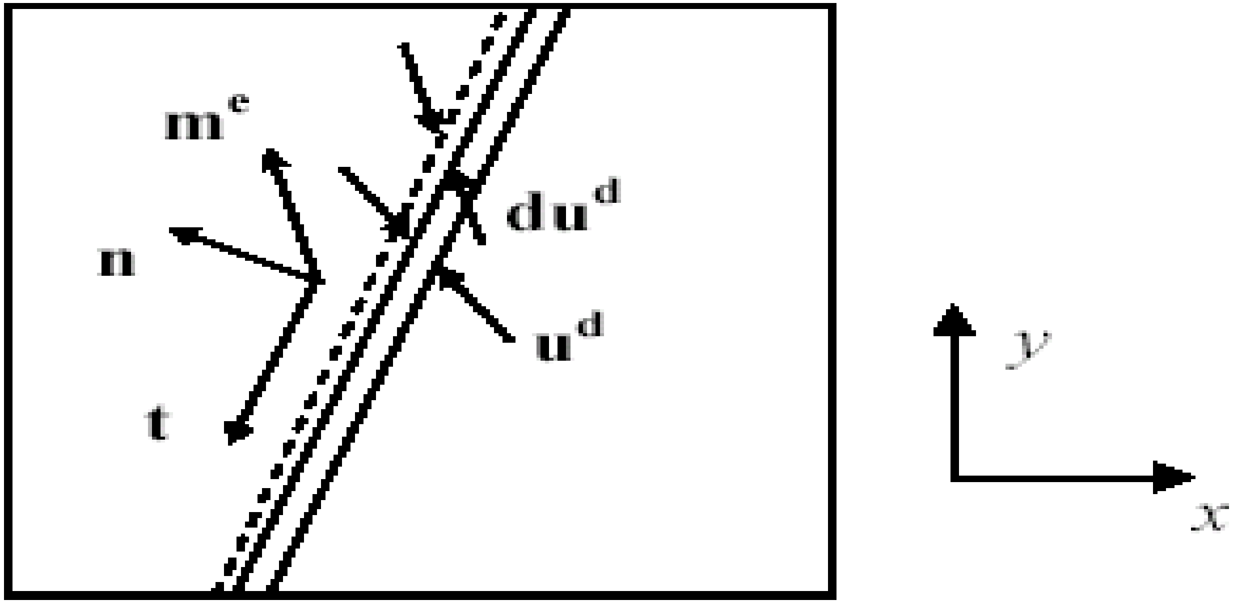


The hypersurfaces in a log($s^{-1}$)-$T$ (K)-log $s$ (GPa) space with specimen sizes of $D$ = 2 nm, 100 nm and 0.1m, respectively.

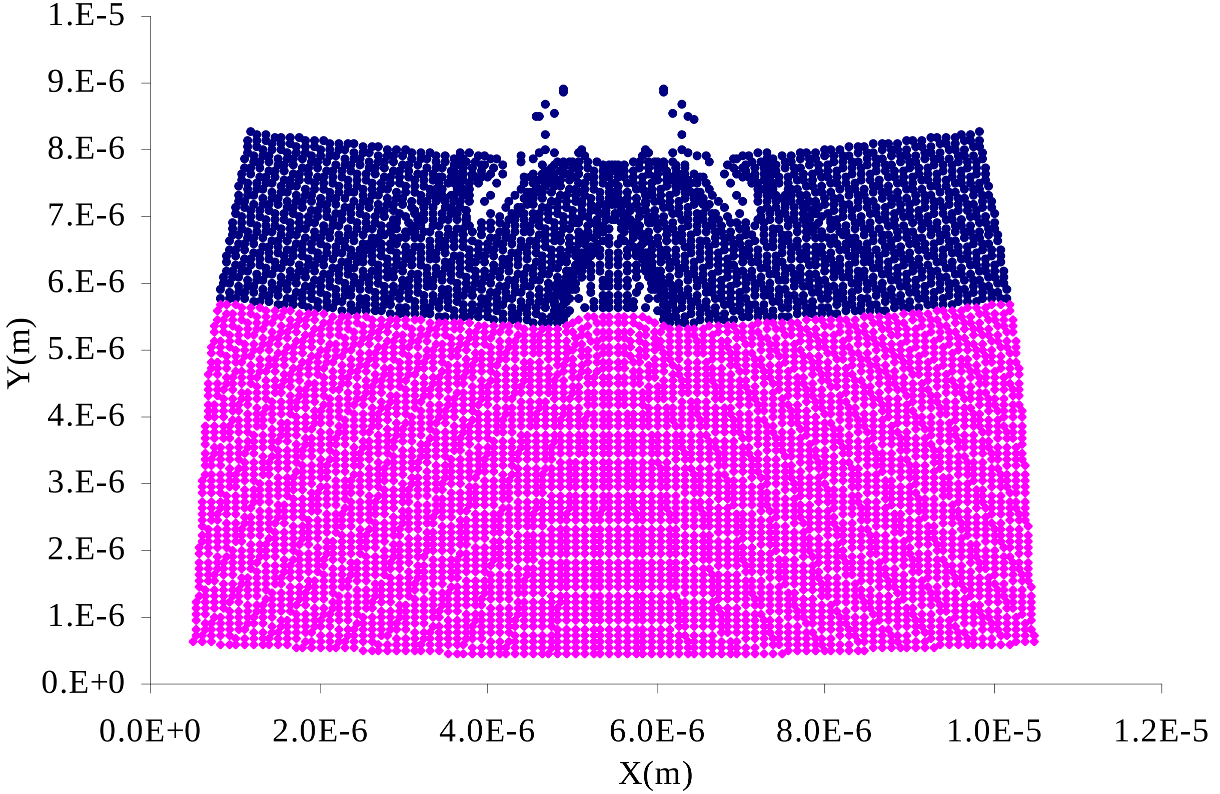


# A Material Element with Multiscale Decohesion in a Plane Strain Problem

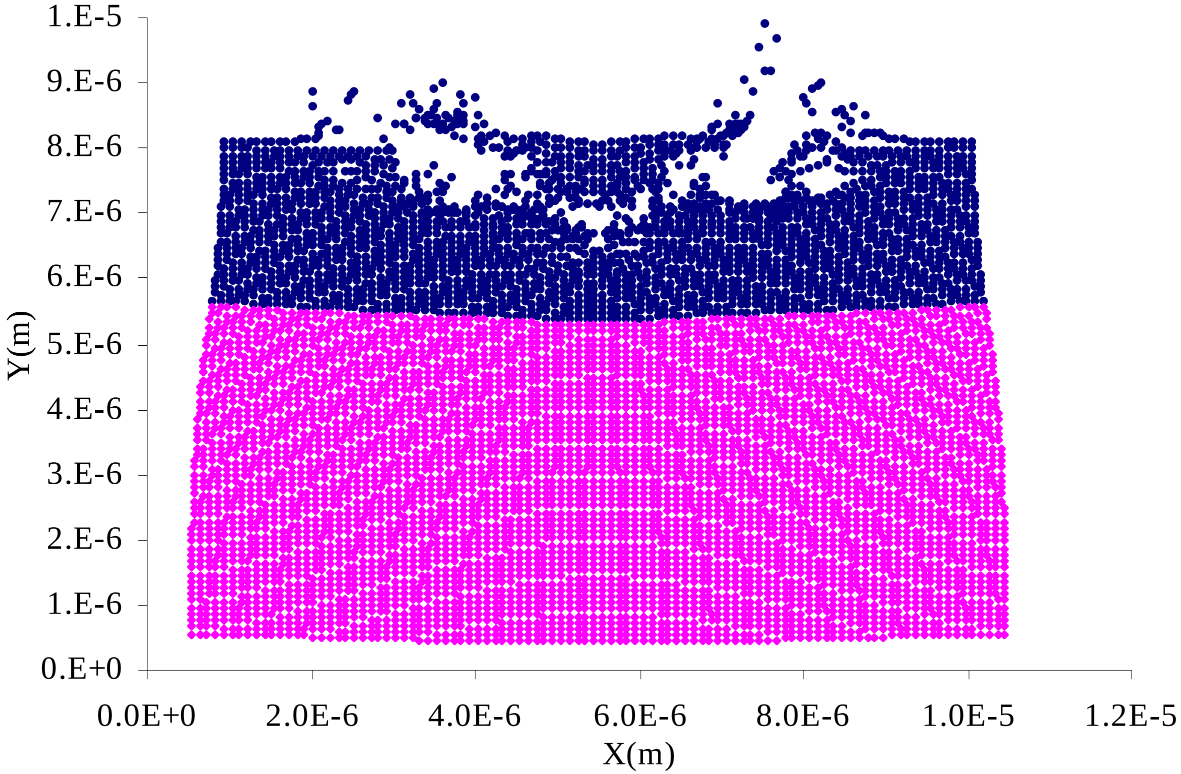
*The critical state depends on the hyper-surface*



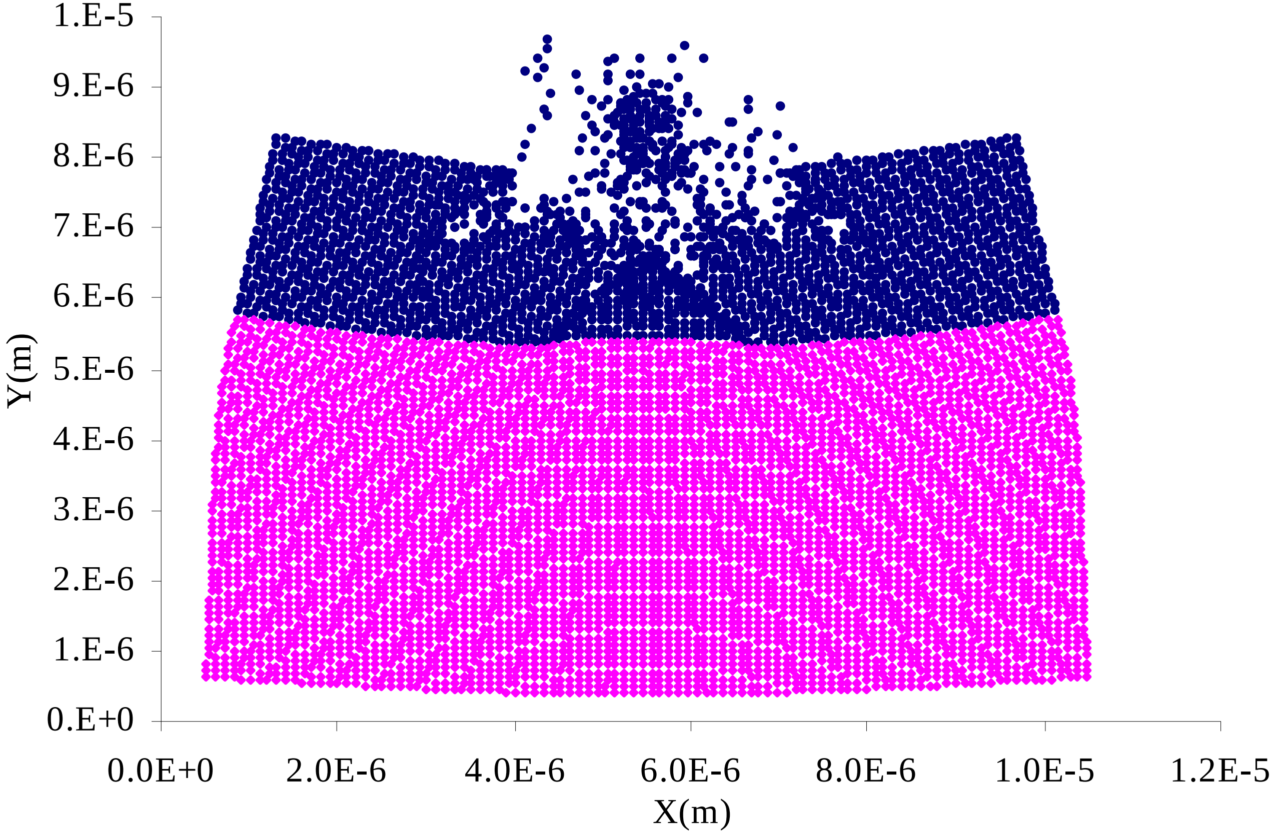
# Failure pattern with mode I being dominant



# Failure pattern with mode II being dominant



# Failure pattern with mixed modes



# 4. Concluding Remarks

- The MPM is now 15 years old, and has demonstrated a great potential in promoting Simulation-Based Engineering Science (SBES).
- More and more international players are entering into the MPM arena so that a regular international workshop and update of the MPM website might be necessary.
- Several research centers/institutes and companies are developing user-friendly MPM codes, some of which are free and available online.
- For the MPM to become robust in multi-scale simulation of multi-physical phenomena, much research remains to be done via an interdisciplinary team effort.
- The advancement of SBES needs to take advantage of different numerical methods for different problems.