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Peridynamics in Sierra/SolidMechanics

David Littlewood

djlittl@sandia.gov

Multiphysics Simulation Technology

Org. 1444

Computational Solid Mechanics and Structural Dynamics

Org. 1542

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Outline

- Peridynamics in Sierra/SolidMechanics
  - Overview of peridynamics
  - Sierra/SolidMechanics implementation
  - Interface to Library of Advanced Materials for Engineering (LAME)
  - Interaction with classical FEM via contact
  - Setting up a peridynamics analysis
- Verification problems
  - Mesh independent response at material discontinuities
  - Verification of LAME interface
  - Patch tests
- Example applications
  - Fracture of brittle disk
  - Expanding tube simulation
  - Nonlocal crystal plasticity

Peridynamics

WHAT IS PERIDYNAMICS?

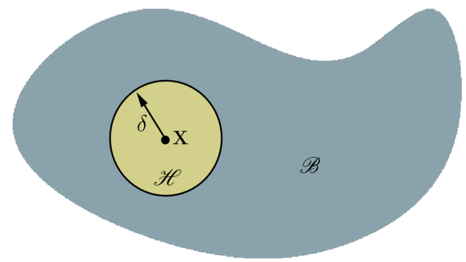
Peridynamics is a mathematical theory that unifies the mechanics of continuous media, cracks, and discrete particles.

HOW DOES IT WORK?

- Peridynamics is a *nonlocal* extension of continuum mechanics.
- Remains valid in presence of discontinuities, including cracks.
- Balance of linear momentum is based on an *integral equation*:

$$\rho(\mathbf{x})\ddot{\mathbf{u}}(\mathbf{x},t) = \underbrace{\int_{\mathscr{B}} \left\{\underline{\mathbf{T}}[\mathbf{x},t]\langle\mathbf{x}'-\mathbf{x}\rangle - \underline{\mathbf{T}}'[\mathbf{x}',t]\langle\mathbf{x}-\mathbf{x}'\rangle\right\} \, \mathrm{d}V_{\mathbf{x}'}}_{\text{Divergence of stress replaced with integral of nonlocal forces.}} + \mathbf{b}(\mathbf{x},t)$$

The point X interacts directly with all points within its horizon



S.A. Silling. Reformulation of elasticity theory for discontinuities and long-range forces. *Journal of the Mechanics and Physics of Solids*, 48:175-209, 2000.

Silling, S.A. and Lehoucq, R. B. Peridynamic Theory of Solid Mechanics. *Advances in Applied Mechanics* 44:73-168, 2010.

Peridynamics in Sierra/SolidMechanics

> Peridynamics is available in Sierra/SolidMechanics for the modeling of material failure

- Available for explicit dynamics
- Material models
  - Linear peridynamic solid material model
  - Interface to full set of Sierra/SM classical material models (LAME library)
- User defined peridynamic horizon and influence function
- Bond failure laws
  - Critical stretch bond failure rule
  - Bond failure based on element variables (e.g. material model data)
- Contact algorithm
- Full set of pre- and post-processing tools
  - Meshing, visualization, initialization of peridynamic bonds

Key feature: Interface to LAME material library

Full set of classical material models is available via peridynamics in Sierra/SolidMechanics

MATERIAL MODELS: LIBRARY OF ADVANCED MATERIALS FOR ENGINEERING (LAME)

- Traditional models: Elastic, Thermo-elastic, Elastic-plastic, others…
- Advanced models: Johnson-Cook, BCJ, K&C Concrete, others…
- Suitable for geo modeling: Soil and Crushable Foam, Orthotropic Crush, others…

APPROACH: NON-ORDINARY STATE-BASED PERIDYNAMICS

① Compute regularized deformation gradient

$$\bar{\mathbf{F}} = \left(\sum_{i=0}^{N} \underline{\omega}_i \, \underline{\mathbf{Y}}_i \otimes \underline{\mathbf{X}}_i \, \Delta V_{\mathbf{x}_i} \right) \mathbf{K}^{-1} \qquad \mathbf{K} = \sum_{i=0}^{N} \underline{\omega}_i \, \underline{\mathbf{X}}_i \otimes \underline{\mathbf{X}}_i \, \Delta V_{\mathbf{x}_i}$$

② Classical material model computes stress based on regularized deformation gradient

③ Convert stress to peridynamic force densities

$$\underline{\mathbf{T}} \langle \mathbf{x}' - \mathbf{x} \rangle = \underline{\omega} \, \sigma \mathbf{K}^{-1} \langle \mathbf{x}' - \mathbf{x} \rangle$$

④ Apply peridynamic hourglass forces as required to stabilize simulation (optional)

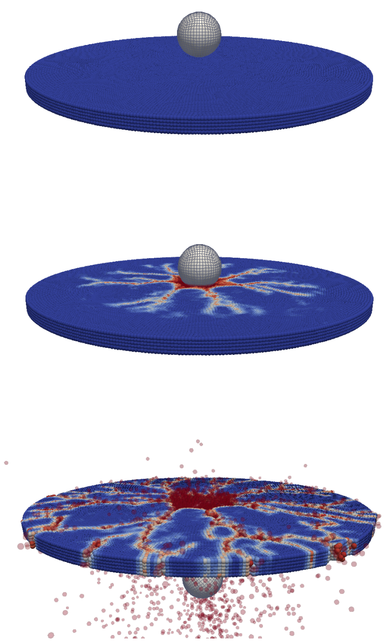
S. Silling, M. Epton, O. Weckner, J. Xu, and E. Askari. Peridynamic states and constitutive modeling. *Journal of Elasticity*, 88(2):151-184, 2007.

Key feature: Contact algorithm

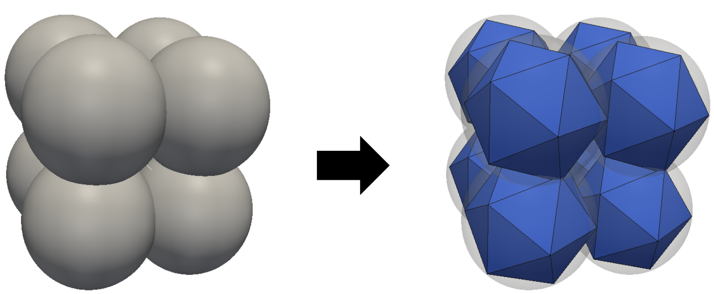
PERIDYNAMICS INTEGRATED WITH STANDARD SIERRA/SM CONTACT ALGORITHM

- Iterative penalty contact algorithm for explicit dynamics
- General and self contact
  - Peridynamic / peridynamic contact across block boundaries
  - Peridynamic / classical FEM contact across block boundaries
  - Peridynamic self contact within a block (disallowed for bonded elements)
- Contact algorithm operates on planar facets
  - Lofted contact geometry assigned to sphere elements

Contact between peridynamics and classical FEM



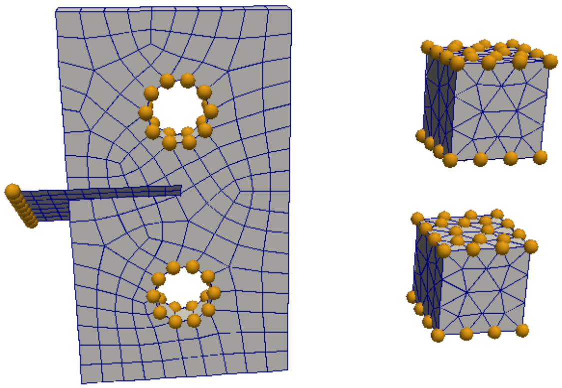
Brittle fracture simulation



Lofted geometry utilized for peridynamics contact

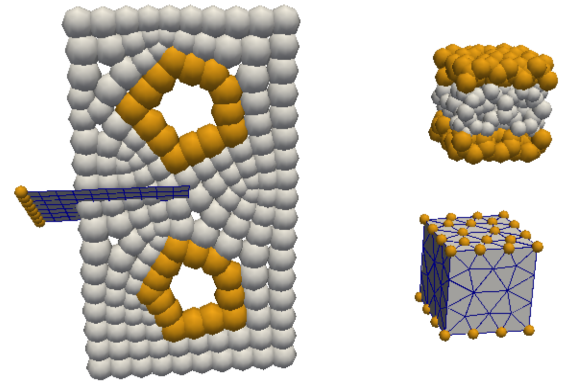
Setting up a peridynamics analysis

STEP ONE: CREATE MESH FILE WITH SPHERE ELEMENTS



Initial mesh
generated in Cubit

Apply peridynamics
pre-processing tools



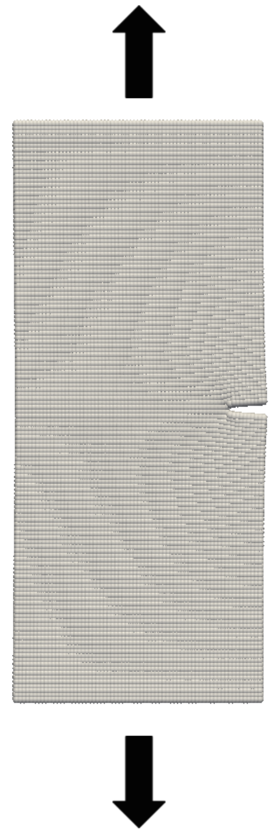
Peridynamics blocks converted
to sphere elements

STEP TWO: ADD PERIDYNAMICS SECTION TO INPUT DECK

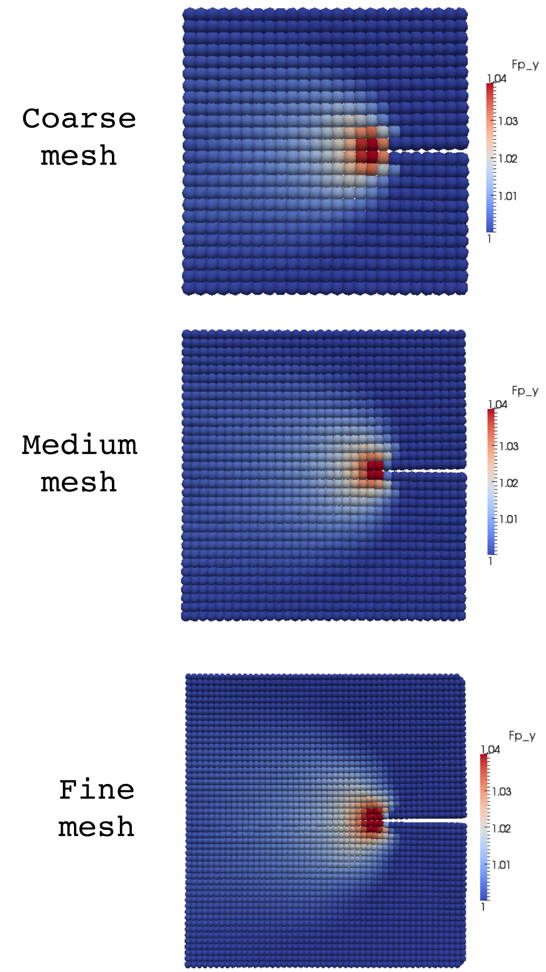
```
BEGIN PERIDYNAMICS SECTION section_name
   MATERIAL MODEL FORMULATION = CLASSICAL|PERIDYNAMICS
   HORIZON = horizon_value
   INFLUENCE FUNCTION = influence_function_name
   BOND DAMAGE MODEL = CRITICAL_STRETCH|ELEMENT_VARIABLE|NONE
   HOURGLASS STIFFNESS = stiffness_value
   BOND CUTTING BLOCK = block_names
   BOND VISUALIZATION = OFF|ON
END
```

Verification: Mesh independent plastic zone

- The peridynamic horizon introduces a length scale that is independent of the mesh size
- Decoupling from the mesh size enables consistent modeling of material response in the vicinity of discontinuities
- Example: Mesh independent plastic zone in the vicinity of a crack



Pre-cracked specimen loaded in tension

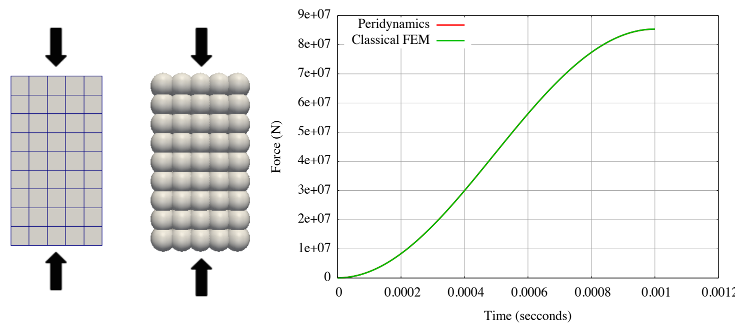


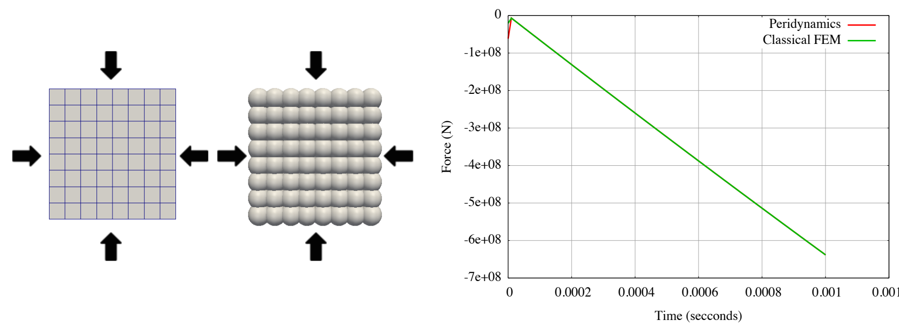
Component of plastic deformation gradient in loading direction

Verification: Patch tests

Uniaxial and hydrostatic compression

- Tests constructed such that peridynamics and classical FEM should yield same result
- Simulation results verified for numerous material models

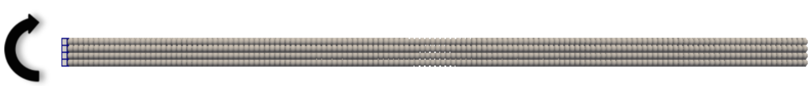




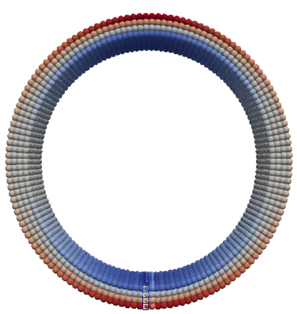
Beam bending

- Test peridynamics with neo-Hookean material model against classical beam bending theory
- Simulation gives expected bending response and stress distribution

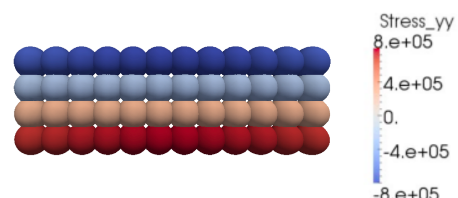
Applied rotation



Fixed support



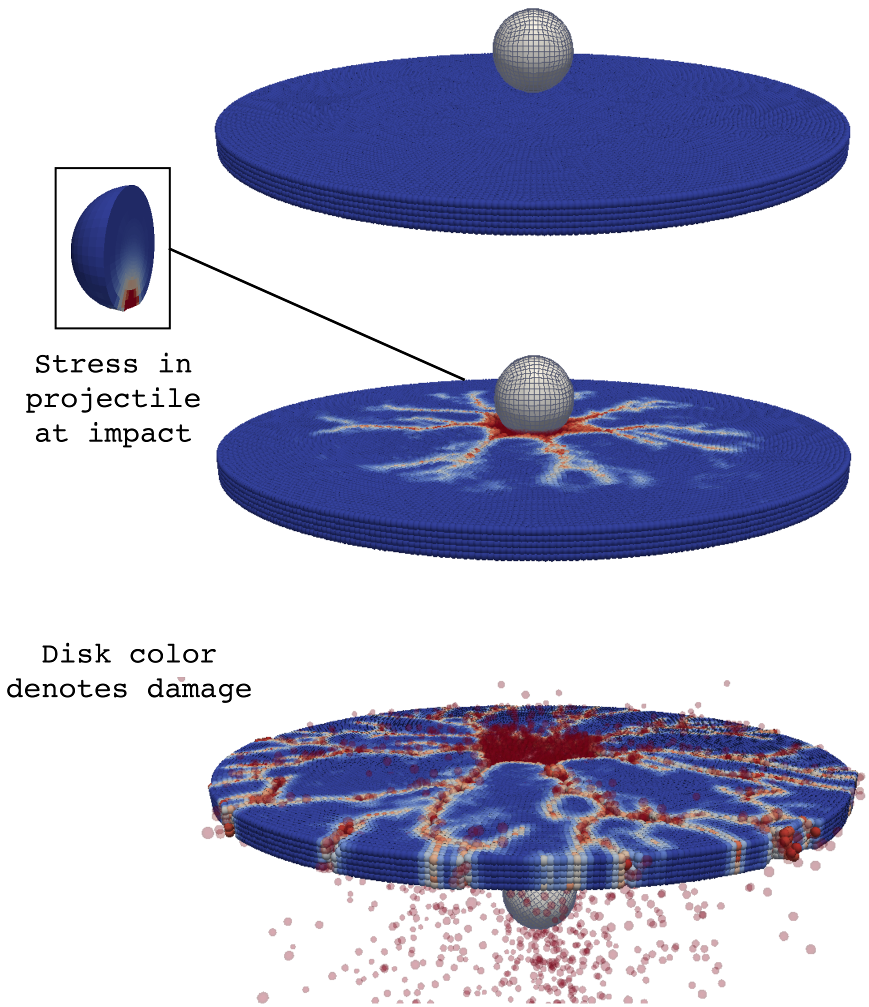
Increased pure bending eventually produces circle



Linear stress distribution through cross section

Application: Fracture of brittle disk

RECREATION OF IMPACT SIMULATION FIRST PUBLISHED BY SILLING AND ASKARI [2005]



- Disk modeled with peridynamics
  - Peridynamic linear solid material model
  - Critical stretch bond breaking law
- Projectile modeled with classical FEM
  - Linear elastic material model
- Bodies interact via contact algorithm

S. A. Silling and E. Askari. A meshfree method based on the peridynamic model of solid mechanics. *Computers and Structures*, 83:1526-1535, 2005.

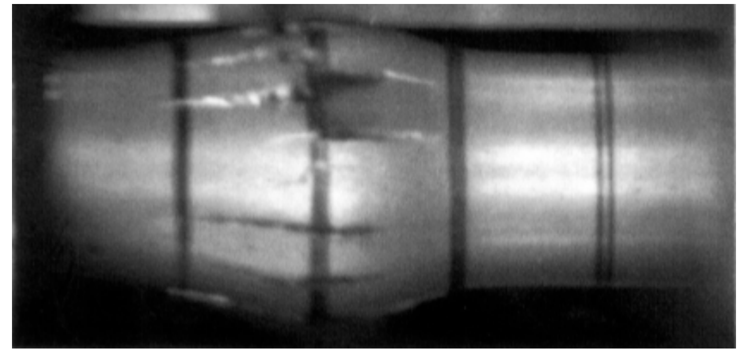
Application: Expanding tube experiment

Experimental Setup

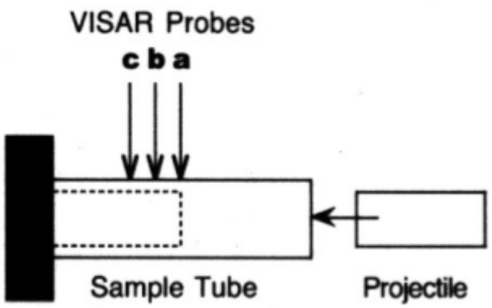
- Tube expansion via high-velocity collision of Lexan projectile and plug within AerMet tube

Modeling Approach

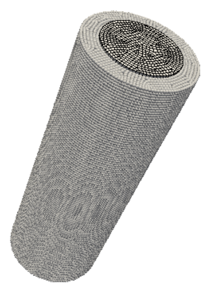
- AerMet tube modeled with peridynamics
- Lexan plugs modeled with classical FEM
- Interaction via contact algorithm



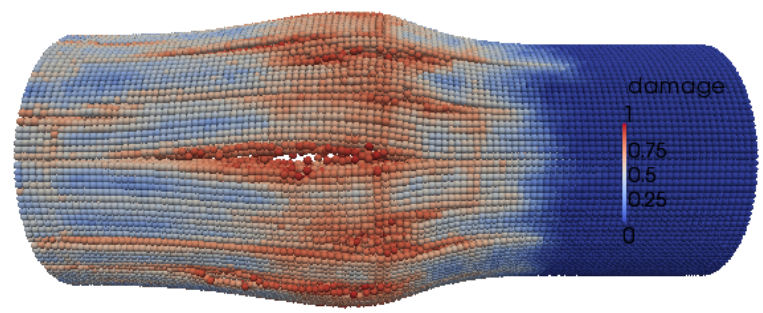
Experimental image at 15.4 microseconds
[Vogler et. al]



Experimental setup
[Vogler et. Al]



Model
discretization



Simulation at 15.4 microseconds
Color denotes percent of broken bonds

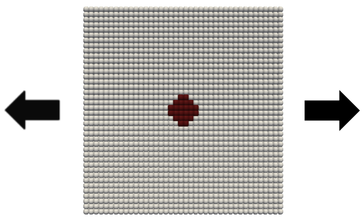
Vogler, T.J., Thornhill, T.F., Reinhart, W.D., Chhabidas, L.C., Grady, D.E., Wilson, L.T., Hurricane, O.A., and Sunwoo, A. Fragmentation of materials in expanding tube experiments. *International Journal of Impact Engineering*, 29:735-746, 2003.

David Littlewood. 2010. Simulation of dynamic fracture using peridynamics, finite element modeling, and contact. Proceedings of the ASME 2010 International Mechanical Engineering Congress and Exposition, British Columbia, Canada.

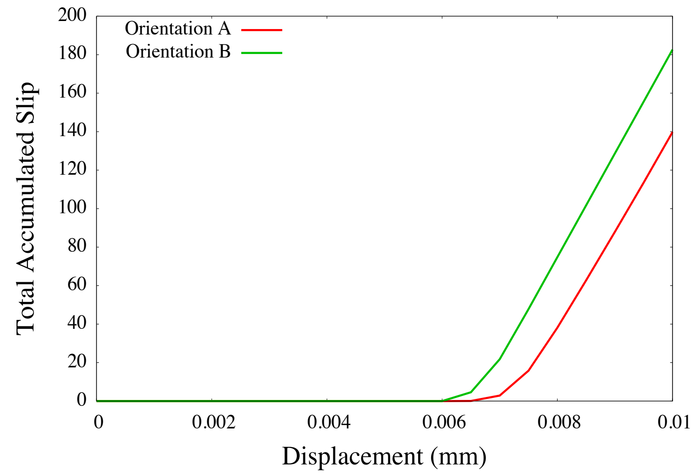
Application: Nonlocal crystal plasticity

Proof-of-concept simulation

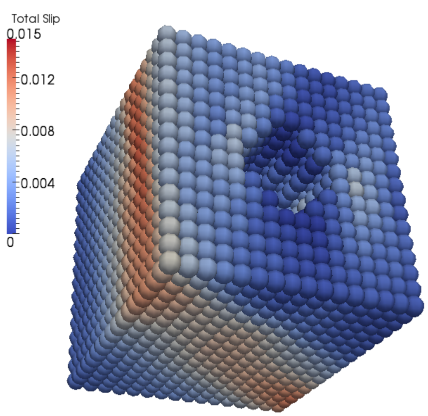
- Tensile loading applied to single crystal with hard elastic inclusion



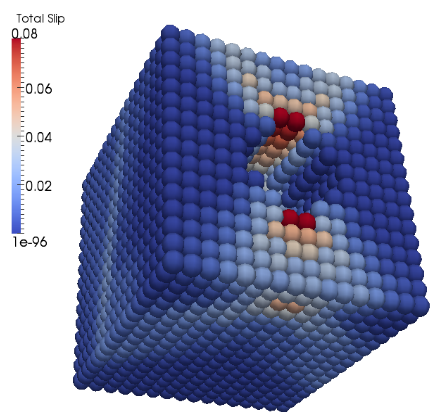
- Crystallographic slip highly dependent on lattice orientation



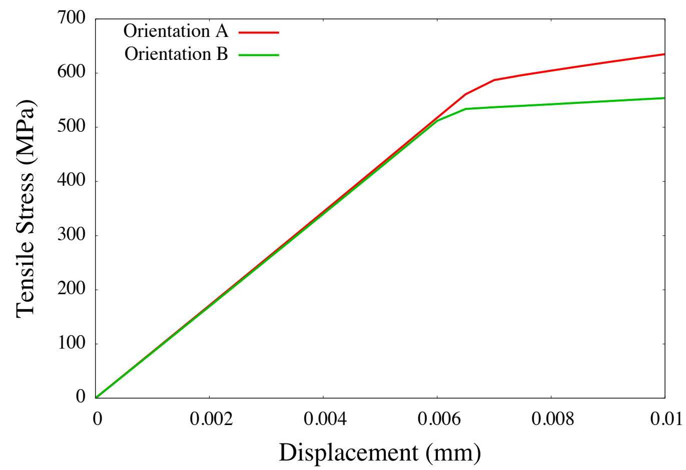
Total accumulated slip in crystal



Orientation A



Orientation B



Tensile stress in particle

David Littlewood. 2011. A nonlocal approach to modeling crack nucleation in AA 7075-T651. Proceedings of the ASME 2011 International Mechanical Engineering Congress and Exposition, Denver, Colorado. *To appear*.

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