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Peridigm: A New Paradigm in Computational Peridynamics

SIAM Conference on Mathematical Aspects of Materials Science

Mathematical and Computational Aspects of Peridynamics and Related Nonlocal Models

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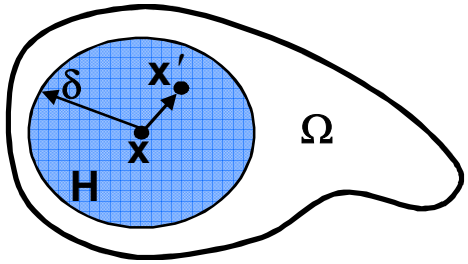
What is Peridynamics?



Point x interacts directly with all points x' within H

- **Peridynamics is a nonlocal extension of classical solid mechanics that permits discontinuous solutions**

- **Peridynamic equation of motion (integral, nonlocal)**

$$\rho\ddot{\mathbf{u}}(\mathbf{x},t) = \int_{H} \left(\mathbf{T}[\mathbf{x},t]\langle \mathbf{x}'-\mathbf{x} \rangle - \mathbf{T}[\mathbf{x}',t]\langle \mathbf{x}-\mathbf{x}' \rangle \right) dV_{\mathbf{x}'} + \mathbf{b}(\mathbf{x},t)$$

  - Replace PDEs with integral equations
  - Utilize same equation everywhere; nothing "special" about cracks
  - No assumption of differentiable fields (admits fracture)
  - Damage incurred when deformation criteria satisfied (critical stretch, etc.)
  - No obstacle to integrating nonsmooth functions
  - Integrand is "force" function; contains constitutive model
  - Integrand = 0 for points x,x' more than δ apart (like cutoff radius in MD!)
  - PD is "continuum form of molecular dynamics"

"It can be said that all physical phenomena are nonlocal. Locality is a fiction invented by idealists."

A. Cemal Eringen

- **Impact**
  - Nonlocality
  - Larger solution space than corresponding classical PDE-based models (fracture)
  - Account for material behavior at small & large length scales **(multiscale material model)**

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Part I
Brief Overview of Peridynamics

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Demonstration Computations

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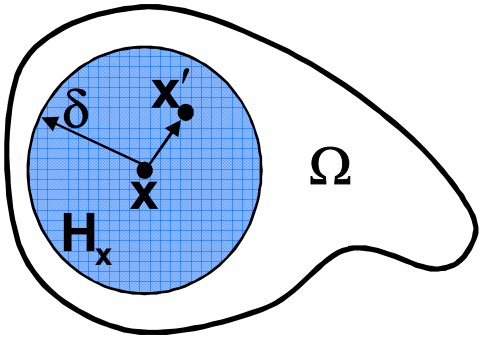
Peridynamics: The Basics

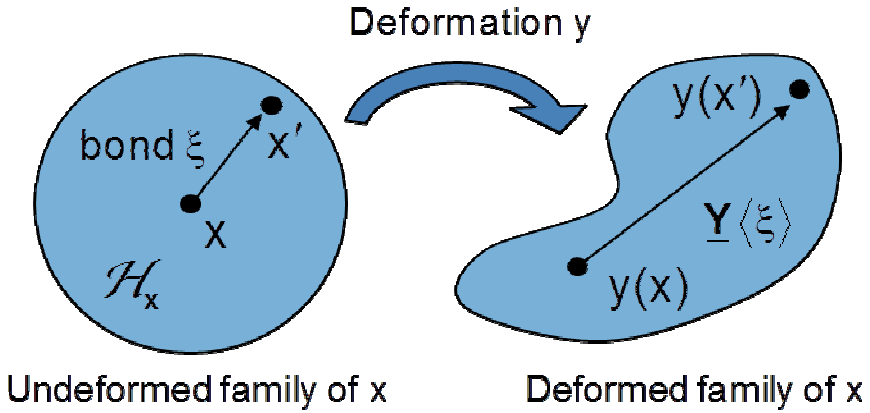
- **Horizon and family**
  - Point **x** interacts directly with all points with distance δ (***horizon***)
  - Material within distance δ of **x** is denoted H_x (***family of x***)



- **Bonds and bond forces**
  - Vector between **x** and any point in its family is called a ***bond:*** **ξ = x' – x**
  - Each bond has ***pairwise force density vector*** applied at both points: **f(x', x, t)**
  - This vector is determined jointly by collective deformation of $\mathbf{H_x}$ and collective deformation of $\mathbf{H_{x'}}$
  - Bond forces are antisymmetric: **f(x', x, t) = - f(x, x', t)**

- **Deformation state**
  - Deformation state operator **Y** maps each bond ξ into its deformed image

$$\underline{\mathbf{Y}}\langle\xi\rangle = \mathbf{y(x')} - \mathbf{y(x)}$$



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Peridynamics: The Basics

- **Bonds and states**
  - **f(x', x)** has contributions from material models at both **x** and **x'**

$$\mathbf{f}(\mathbf{x}',\mathbf{x}) = \mathbf{T}[\mathbf{x},t]\langle \mathbf{x}'-\mathbf{x}\rangle - \mathbf{T}[\mathbf{x}',t]\langle \mathbf{x}-\mathbf{x}'\rangle$$

  - $\underline{\mathbf{T}}[\mathbf{x}]$ is the ***force state*** – it maps bonds onto bond force densities
  - $\underline{\mathbf{T}}[\mathbf{x}]$ is determined by the constitutive model $\underline{\mathbf{T}} = \hat{\mathbf{T}}(\underline{\mathbf{Y}})$, where $\hat{\mathbf{T}}$ maps deformation state to force state
  - For elastic materials, $\underline{\mathbf{T}}[\mathbf{x}] = \mathbf{W}_{\underline{\mathbf{Y}}}$ (Fréchet derivative)

- **Peridynamics vs. standard equations**
  - Peridynamic operators and relationships between them are nonlocal analogues of standard theory

Relation	Peridynamic Theory	Standard Theory
Kinematics	$\underline{\mathbf{Y}}\langle \mathbf{x}'-\mathbf{x}\rangle = \mathbf{y}(\mathbf{x}')-\mathbf{y}(\mathbf{x})$	$\mathbf{F} = \frac{\partial \mathbf{y}}{\partial \mathbf{x}}(\mathbf{x})$
Linear Momentum Balance	$\rho\ddot{\mathbf{u}}(\mathbf{x}) = \int_{\mathcal{H}_\mathbf{x}} \{\underline{\mathbf{T}}[\mathbf{x},t]\langle \mathbf{x}'-\mathbf{x}\rangle - \underline{\mathbf{T}}[\mathbf{x}',t]\langle \mathbf{x}-\mathbf{x}'\rangle\}\, dV_{\mathbf{x}'} + \mathbf{b}(\mathbf{x})$	$\rho\ddot{\mathbf{u}}(\mathbf{x}) = \nabla\cdot\boldsymbol{\sigma}(\mathbf{x}) + \mathbf{b}(\mathbf{x})$
Constitutive Model	$\underline{\mathbf{T}} = \widehat{\mathbf{T}}(\underline{\mathbf{Y}})$	$\boldsymbol{\sigma} = \widehat{\boldsymbol{\sigma}}(\mathbf{F})$
Angular Momentum Balance	$\int_{\mathcal{H}_\mathbf{x}} \{\underline{\mathbf{Y}}\langle \mathbf{x}'-\mathbf{x}\rangle \times \underline{\mathbf{T}}\langle \mathbf{x}'-\mathbf{x}\rangle\}\, dV_{\mathbf{x}'} = 0$	$\boldsymbol{\sigma} = \boldsymbol{\sigma}^T$

Peridynamic Material Modeling

- **Linear Peridynamic Solid (LPS)***
- Nonlocal analog to linear isotropic elastic solid
- k is bulk modulus, μ is shear modulus

$$\rho\ddot{\mathbf{u}}(\mathbf{x},t) = \int_{\mathbf{H}} \left(\mathbf{T}[\mathbf{x},t]\langle \mathbf{x}' - \mathbf{x} \rangle - \mathbf{T}[\mathbf{x}',t]\langle \mathbf{x} - \mathbf{x}' \rangle \right) dV_{\mathbf{x}'} + \mathbf{b}(\mathbf{x},t)$$

$$\mathbf{T}[\mathbf{x},t]\langle \mathbf{x}' - \mathbf{x} \rangle = \left(\frac{3k\theta}{m} \underline{\omega}\underline{\mathbf{x}} + \frac{15\mu}{m} \underline{\omega}\mathbf{e}^{\mathbf{d}} \right) \frac{\mathbf{x}' - \mathbf{x}}{\|\mathbf{x}' - \mathbf{x}\|}$$

- Many other peridynamic material models available: elastic-plastic, viscoelastic, etc.

- Can wrap classical material models (existing material libraries) in peridynamic "skin"

*S.A. Silling, M. Epton, O. Weckner, J. Xu, & E. Askari, Peridynamic States and Constitutive Modeling, J. Elasticity, 88, pp. 151-184, 2007.

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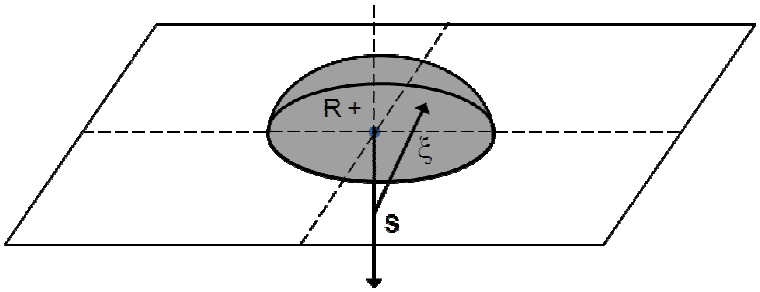
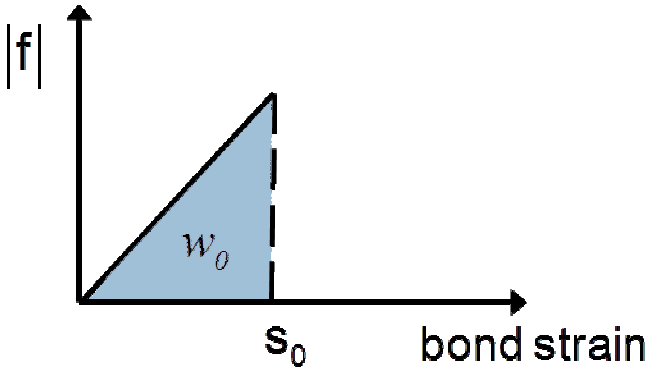
Peridynamic Fracture Modeling

- **Fracture ("Critical Stretch")**
  - Break bond if bond stretch **s** exceeds critical stretch s_0
  - If work to break bond ξ is $\mathbf{w_0(\xi)}$, then energy release rate found by summing this work per unit crack area



$$G = \int_0^{\delta} \int_{R_+} w_0(\xi) dV_\xi ds$$



  - Can then get the critical strain s_0 for bond breakage in terms of **G** (strain energy release rate), an experimentally measurable quantity

- **Fracture ("Critical Work")***
  - Break bond if work done on bond exceeds critical value*

- Many others possible…

* J.T. Foster, S.A. Silling, W. Chen, An energy based failure criterion for use with peridynamic states, J. Multi. Comp. Engng. 9 (6): 675–687 (2011).

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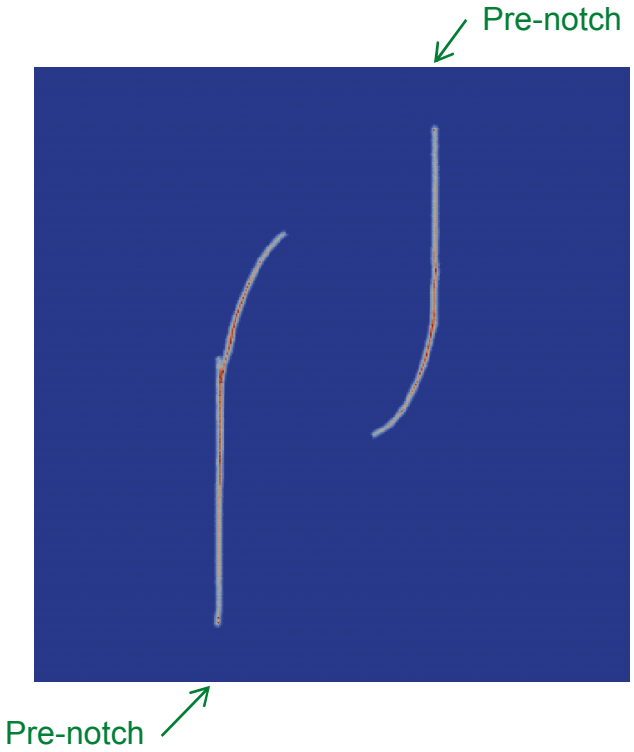
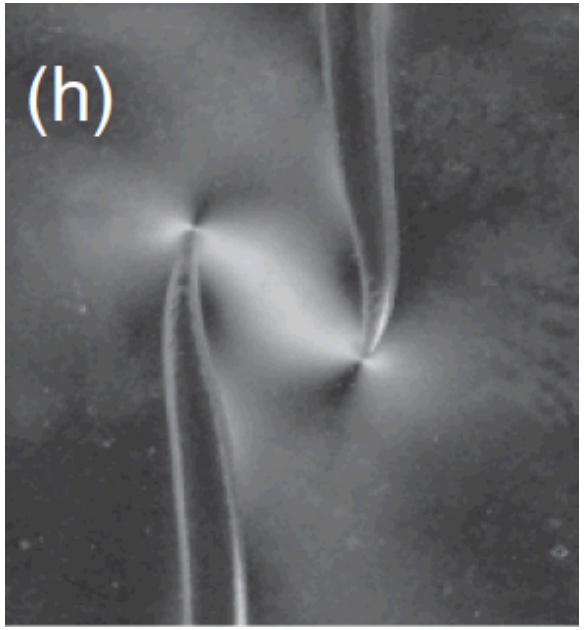
Simulation performed with PDLAMMPS

Two Interacting Cracks

- Offset notches thin rectangular elastic plate
- Uniaxial strain applied from sides
- Approaching cracks produce “en passant” crack pattern



Peridynamics



Physical Experiment*

* M. Fender, F. Lechenault, and K. Daniels, Universal Shapes Formed by Two Interacting Cracks, Phys. Rev. Lett. 105, 125505 (2010) .

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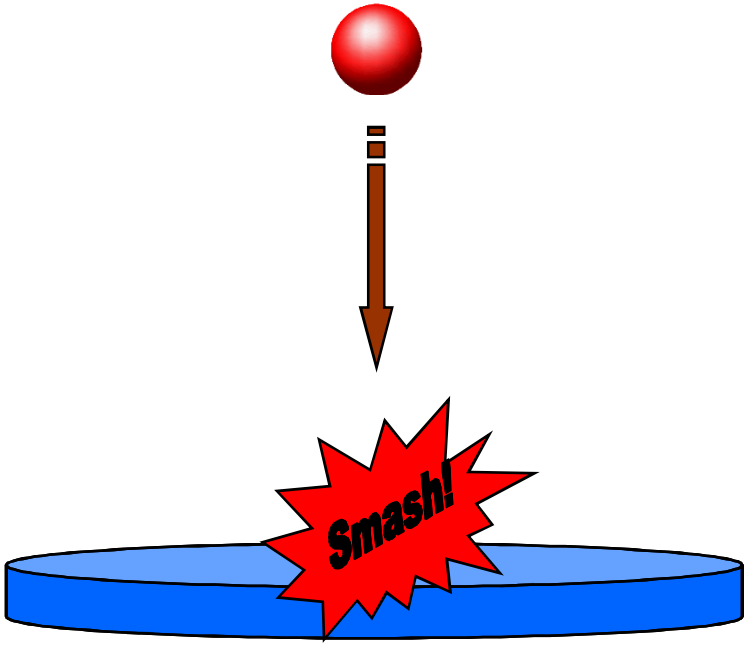
Simulation performed with Peridigm

Hard Sphere Impact on Brittle Disk*

- Projectile
  - Sphere (diameter 0.01 m)
  - Velocity 100 m/s
- Target
  - Disk: diameter 0.074 m,
  - thickness 0.0025 m
- Elastic modulus 14.9 GPa
- Density 2200 kg/m3



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

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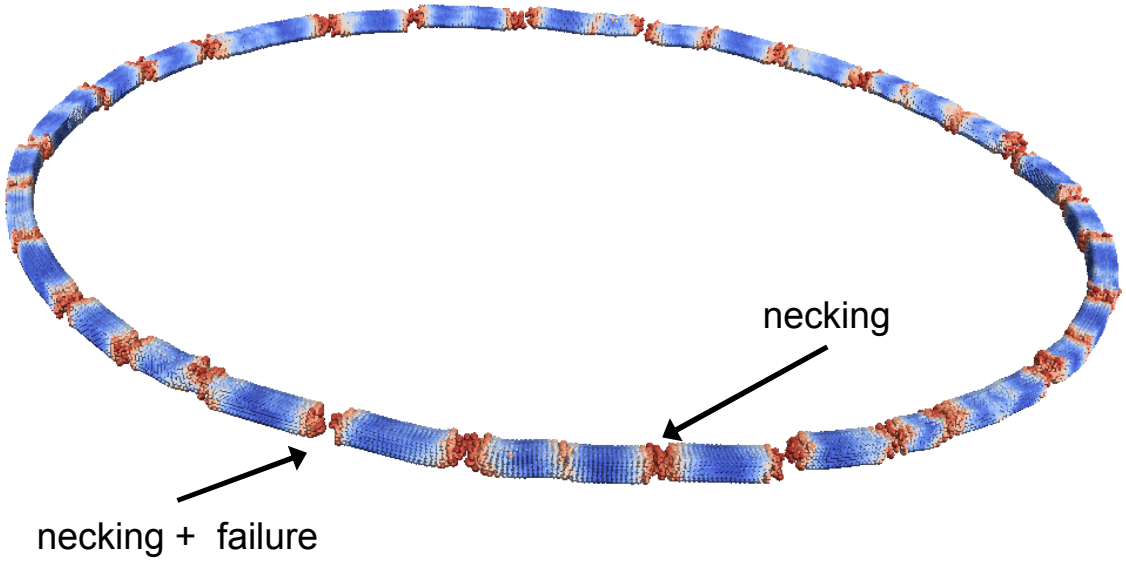
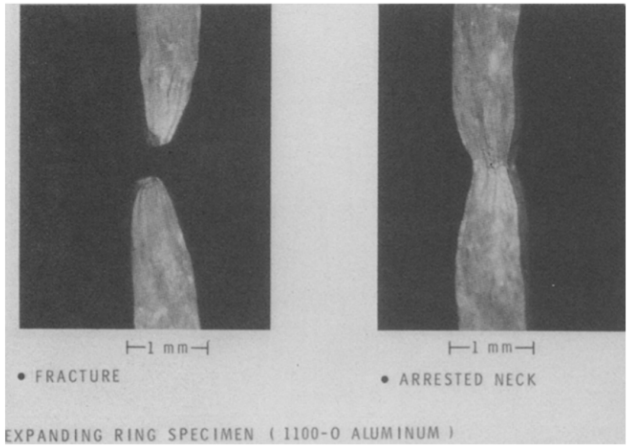
Simulation performed with Peridigm

Electromagnetically loaded ring

- 1100-0 aluminum ring (ductile)
- Motivated by ring fragmentation experiments of Grady & Benson*
- Used peridynamic elastic/plastic model**





Fracture and arrested neck region from dynamic expansion of ring*

* D. Grady, D. Benson, Fragmentation of metal rings by electromagnetic loading, Experimental Mechanics, 23(4), pp. 393-400, 1983
** J. Mitchell, A Nonlocal, Ordinary, State-Based Plasticity Model for Peridynamics, SAND2011-3166, 2011.

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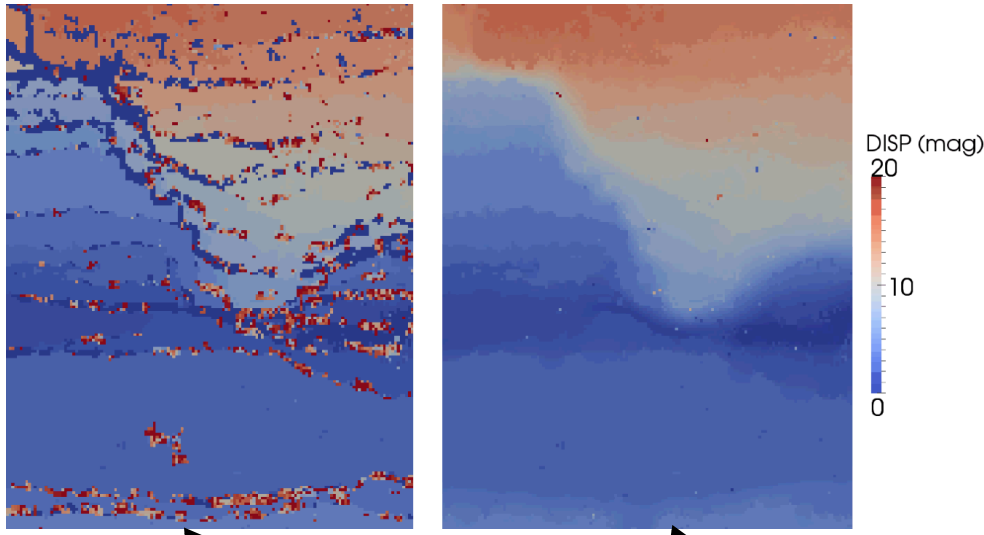
Improved Digital Image Correlation (DIC) Using Peridynamic Damage Modeling (Dan Turner)

- DIC often fails near cracks or discontinuities
- Displacements obtained by interpolation across a crack are highly inaccurate
- Use peridynamics to compute displacements in regions where DIC fails
- Treat the quality DIC displacements as a boundary condition and solve for rest of domain as if it were a peridynamic material

Failure of fiber-reinforced concrete tensile specimens



Standard DIC algorithm (Dark blue regions represent failed correlation, spurious colors represent inaccurate displacements)

Peridynamics enhanced result

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Improved Digital Image Correlation (DIC) Using Peridynamic Damage Modeling (Dan Turner)

- ❑ Computed damage profile closely matches experimental results
- ❑ Displacement (strain) accuracy is considerably improved

Failure of fiber-reinforced concrete tensile specimens

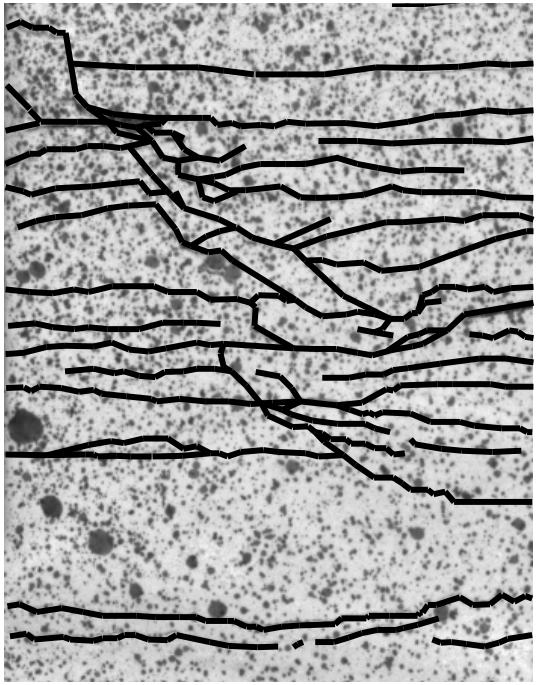
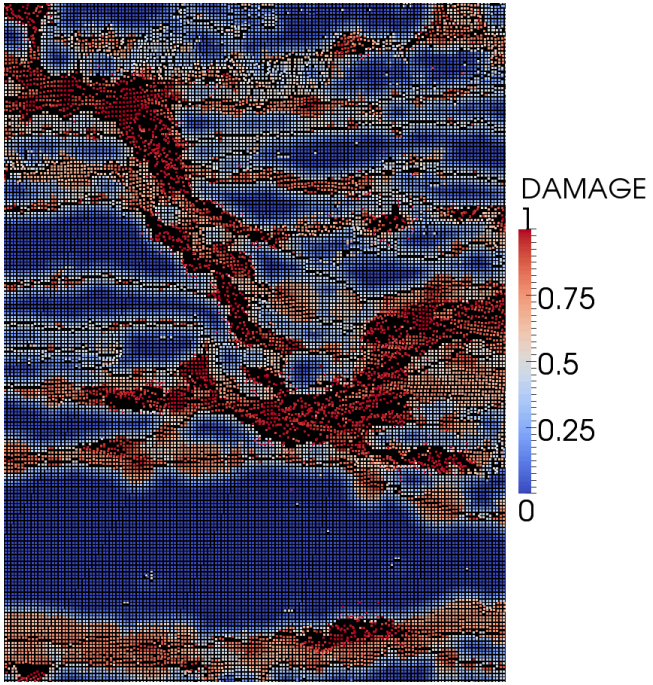


Photo of damaged concrete specimen (lines represent cracks)



Damage profile computed using peridynamics

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Peridigm

- **Peridigm** (Open Source, C++)
- Developers: Parks, Littlewood, Mitchell, Silling
- **https://software.sandia.gov/trac/peridigm**
- Intended as Sandia's primary open-source PD code
- Built upon Sandia's Trilinos Project (**trilinos.sandia.gov**)

- **Features/Capabilities**
- Massively parallel
- Exodus mesh input
- Multiple materials (only state based)
  - elastic, elastic-plastic, elastic-plastic with hardening, viscoelastic
- Explicit time integration (Velocity-Verlet)
- Implicit time integration (Newmark-beta method)
- Quasistatics (Nonlinear, via Newton/Krylov or nonlinear CG)
- Linear (preconditioned Krylov subspace methods)
- Automatic differentiation Jacobians
- DAKOTA interface for UQ/optimization/calibration, etc. (dakota.sandia.gov)

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Peridigm: Peridynamics via Agile Components

Peridigm

Software Quality Tools

Mailing Lists

SUBVERSION

Version Control

CMake

Build System

Testing (CTest)

UQ

Optimization

Error Estimation

Calibration

ParaView

Visualization

trac
Integrated SCM & Project Management

Project Management

Issue Tracking

Wiki

Parallelization Tools

Data Structures (Epetra)

Load Balancing (Zoltan)

Analysis Tools

UQ (Stokhos)

Optimization (MOOCHO)

Services

Interfaces (Thyra)

Tools (Teuchos, TriUtils)

Field Manager (Phalanx)

DAKOTA Interface (TriKota)

Solver Tools

Iterative Solvers (Belos)

Direct Solvers (Amesos)

Nonlinear Solvers (NOX)

Eigensolvers (Anasazi)

Preconditioners (IFPack)

Multilevel (ML)

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Peridynamic Codes

- **EMU** (Export controlled, F90)
  - Developer: Silling (www.sandia.gov/emu/emu.htm)
  - Research code
- **PDLAMMPS (Peridynamics-in-LAMMPS)** (Open source, C++)
  - Developers: Parks, Seleson, Plimpton, Silling, Lehoucq
  - Particular discretization of PD has computational structure of molecular dynamics (MD)
  - LAMMPS: Sandia's open-source massively parallel MD code (lammps.sandia.gov)
  - More info & user guide: www.sandia.gov/~mlparks
- **Peridigm** (Open Source, C++)
  - Developers: Parks, Littlewood, Mitchell, Silling
  - Intended as Sandia's primary open-source PD code
  - Built upon Sandia's Trilinos Project (trilinos.sandia.gov)
  - Massively parallel, Exodus mesh input, Multiple material blocks
  - Explicit, implicit time integration
  - State-based linear elastic, elastic-plasticity, viscoelastic models
  - DAKOTA interface for UQ/optimization/calibration, etc. (dakota.sandia.gov)
- **Peridynamics in Sierra/SolidMechanics** (Export controlled, C++)
  - Developer: Littlewood
  - Sandia engineering analysis code
- **Peridynamics is a capability that can be added to (almost) any analysis code!**

Peridigm Material Models

- **Linear Peridynamic Solid (LPS)***
  - Nonlocal analog to linear isotropic elastic solid
  - k is bulk modulus, μ is shear modulus

$$\rho\ddot{\mathbf{u}}(\mathbf{x},t) = \int_{\mathbf{H}} \left(\mathbf{T}[\mathbf{x},t]\langle \mathbf{x}'-\mathbf{x}\rangle - \mathbf{T}[\mathbf{x}',t]\langle \mathbf{x}-\mathbf{x}'\rangle \right) dV_{\mathbf{x}'} + \mathbf{b}(\mathbf{x},t)$$

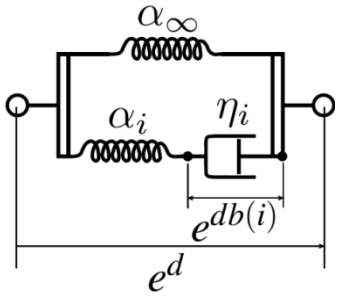
$$\mathbf{T}[\mathbf{x},t]\langle \mathbf{x}'-\mathbf{x}\rangle = \left(\frac{3k\theta}{m}\omega\underline{\mathbf{x}} + \frac{15\mu}{m}\omega\mathbf{e}^{\mathbf{d}} \right) \frac{\mathbf{x}'-\mathbf{x}}{\|\mathbf{x}'-\mathbf{x}\|}$$

- Many other peridynamic material models available:

- **Elastic-Plastic Model****
  - Nonlocal analogue to perfect plasticity model

- **Elastic-Plastic Model with Hardening (J. Foster, UTSA)**

- **Viscoelastic Model*****
  - Nonlocal analog to standard linear solid



*S.A. Silling, M. Epton, O. Weckner, J. Xu, & E. Askari, Peridynamic States and Constitutive Modeling, J. Elasticity, 88, pp. 151-184, 2007.
**J. Mitchell, A Nonlocal, Ordinary, State-Based Plasticity Model for Peridynamics, SAND2011-3166, 2011.
***J. Mitchell, A Non-local, Ordinary-State-Based Viscoelasticity Model for Peridynamics, SAND2011-8064, 2011.

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Peridigm: Structure & User Interface

- Peridigm designed to be user extensible
  - User defined material models, compute classes, etc.

- Compute class: Compute any user-defined quantity
  - Class must declare what data it needs allocated
    - Examples: per-element or per-node scalar, vector, tensor, etc.
  - Class must provide routine that computes user-defined quantity
  - User writes only serial code -- parallel communication handled “auto-magically”
- Example: Compute Acceleration (for output)

```
//! Fill the acceleration vector
int PeridigmNS::Compute_Acceleration::compute( Teuchos::RCP< std::vector<Block> > blocks ) const {
  int retval(0);

  Teuchos::RCP<Epetra_Vector> force, acceleration;
  std::vector<Block>::iterator blockIt;
  for(blockIt = blocks->begin() ; blockIt != blocks->end() ; blockIt++){
    force        = blockIt->getData(m_forceDensityFieldId, PeridigmField::STEP_NP1);
    acceleration = blockIt->getData(m_accelerationFieldId, PeridigmField::STEP_NP1);
    *acceleration = *force;
    double density = blockIt->getMaterialModel()->Density();
    // Report if any calls to Scale() failed.
    retval = retval || acceleration->Scale(1.0/density);
  }

  return retval;
}
```

- Declare “acceleration” as output field in input deck
  - Only specified fields are computed

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Peridigm: Structure & User Interface

- Peridigm material models: Create your own!

```
 //! Returns a vector of field specs that specify the variables associated with the material
 virtual Teuchos::RCP< std::vector<Field_NS::FieldSpec> > VariableSpecs() const = 0;

//! Initialize the material model.
virtual void initialize(const double dt,
                        const int numOwnedPoints,
                        const int* ownedIDs,
                        const int* neighborhoodList,
                        PeridigmNS::DataManager& dataManager) const {}


//! Evaluate the forces on the cells
virtual void computeForce(const double dt,
                          const int numOwnedPoints,
                          const int* ownedIDs,
                          const int* neighborhoodList,
                          PeridigmNS::DataManager& dataManager) const = 0;


//! Evaluate the Jacobian
virtual void computeJacobian(const double dt,
                             const int numOwnedPoints,
                             const int* ownedIDs,
                             const int* neighborhoodList,
                             PeridigmNS::DataManager& dataManager,
                             PeridigmNS::SerialMatrix& jacobian) const;


// other routines
```

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Surface Correction Factor (John Mitchell)

- PD material models developed to get linear bulk response correct (i.e., match classical response).
- In PD, points close to surface have fewer bonds than points in bulk
  - Model response is different near the surface!
- **Surface effects conflict with engineering analyst expectations!**
- Modify model near surface to correct for "missing" bonds
  - Introduce a "surface correction factor"

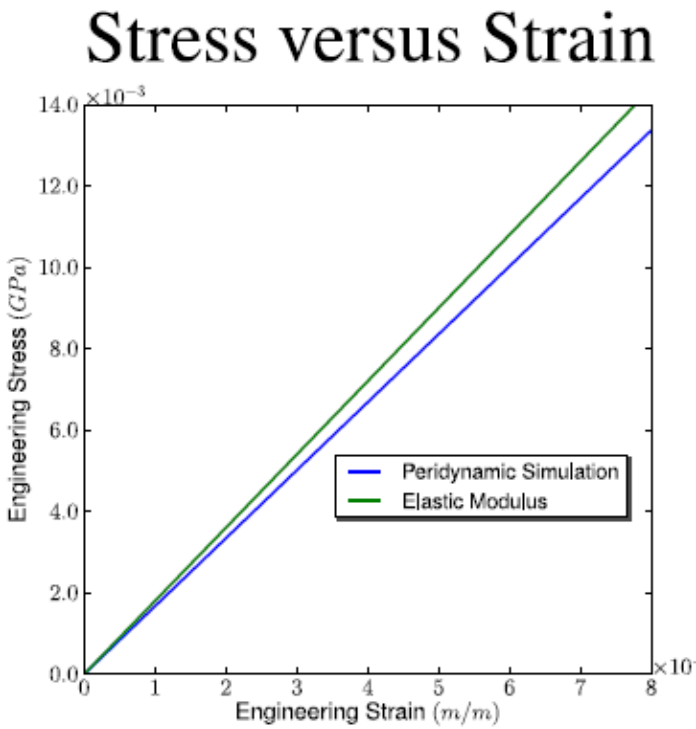
- Demonstration: Applied strain to dogbone

Axial Displacement

Stored Elastic Energy

Sources of Error:

1) Geometric surface effects
2) Nonlocal model (dilatation on surface) and related model properties
3) Discretization error



Thermal Stress (Dave Littlewood)

- Introduce thermal stress due to specified temperature field
  - Modify bond extension to account for temperature change
  - Demonstration: Precracked plate clamped at top & bottom subjected to $-\Delta T$

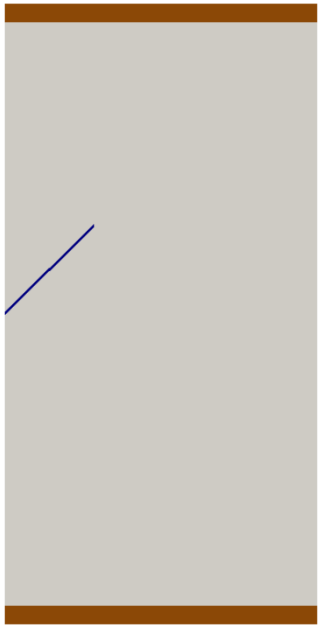
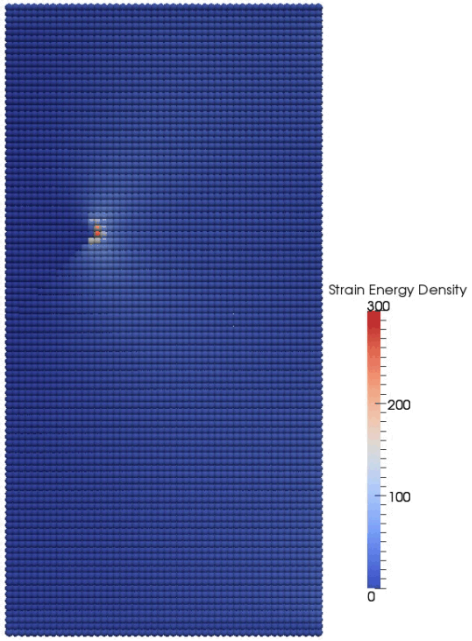


Plate with precrack



Strain energy density after temperature change

  - Can simulate thermally driven fracture, etc.

- Required bond-cutting planes (John Mitchell, Dave Littlewood)
  - Break all bonds across a plane to introduce precrack

New Input Deck Format (John Foster)

- More readable input deck format (.peridigm format)
  - Use human-readable plain text instead of XML Teuchos ParameterList format
  - Sublists indicated by indentation, as in python

Old Format

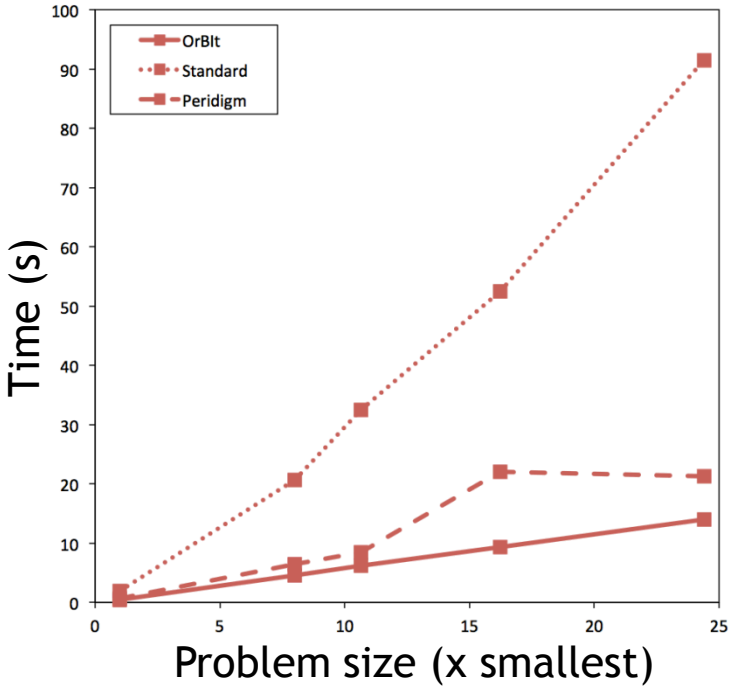
```
<ParameterList>
  <Parameter name="Verbose" type="bool" value="false"/>

  <ParameterList name="Discretization">
        <Parameter name="Type" type="string" value="Exodus" />
        <Parameter name="Horizon" type="double" value="0.1900"/>
        <Parameter name="Input Mesh File" type="string" value="tensile_test.g"/>
  </ParameterList>

  <ParameterList name="Materials">
        <ParameterList name="My Material">
          <Parameter name="Material Model" type="string" value="Elastic"/>
          <Parameter name="Density" type="double" value="8.0"/>
          <Parameter name="Bulk Modulus" type="double" value="1.500e12"/>
          <Parameter name="Shear Modulus" type="double" value="6.923e11"/>
        </ParameterList>
  </ParameterList>

  <ParameterList name="Blocks">
        <ParameterList name="My Block">
          <Parameter name="Block Names" type="string" value="block_1 block_2
block_3"/>
          <Parameter name="Material" type="string" value="My Material"/>
        </ParameterList>
  </ParameterList>

  <ParameterList name="Boundary Conditions">
    <ParameterList name="Prescribed Displacement Bottom">
          <Parameter name="Type" type="string" value="Prescribed Displacement"/>
          <Parameter name="Node Set" type="string" value="nodelist_1"/>
          <Parameter name="Coordinate" type="string" value="y"/>
          <Parameter name="Value" type="string" value="y*0.01*t"/>
```

New Format

```
Verbose "false"

Discretization
    Type "Exodus"
    Horizon {0.1900*2.0/2.0}
    Input Mesh File "tensile_test.g"

Materials
    My Material
      Material Model "Elastic"
      Density 8.0
      Bulk Modulus 1.500e12
      Shear Modulus 6.923e11

Blocks
    My Block
        Block Names "block_1 block_2 block_3"
        Material "My Material"

Boundary Conditions
    Prescribed Displacement Bottom
        Type "Prescribed Displacement"
        Node Set "nodelist_1"
        Coordinate "y"
        Value "y*0.01*t"
```

Matrix Assembly via Bond Iteration (Dan Turner)

- Ongoing algorithmic research into assembly of nonlocal tangent stiffness matrices
- Bond iteration provides 3-4 x speedup over cell iteration in assembly time
- Broken bonds can be removed from iteration loop
- Computes sensitivities for a single row at a time (saves on sparse matrix insertion)*
- Controlling damage propagation to achieve convergence is simpler
- Avoids repetitious computing of contributions from neighbors that share a bond
- Can be done using standard cell based fields



Serial Assembly Time Comparison

*This provides the greatest performance improvement

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Part I
Brief Overview of Peridynamics

Part II
Demonstration Computations

Part III
Peridigm: A Computational Peridynamics Code

Part IV
Peridigm: Recent Developments

Part V
Peridigm: Tutorial and Example

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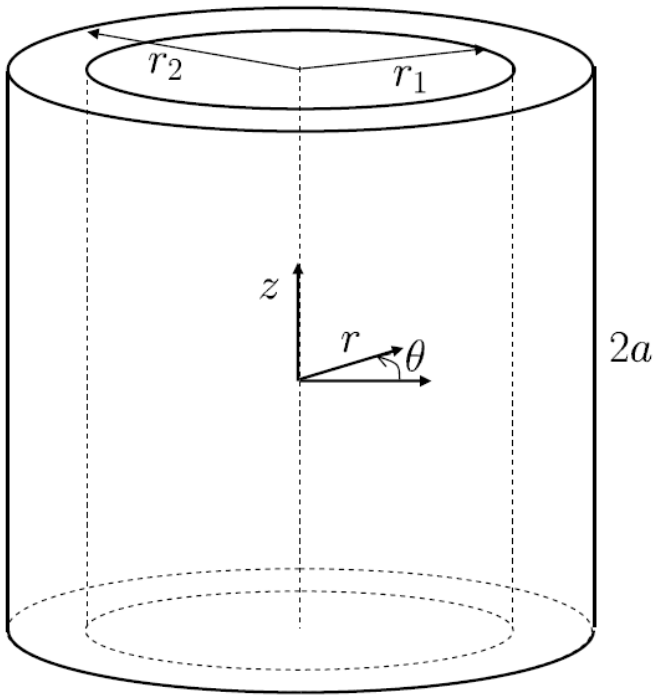
Fragmenting Cylinder

- **Fragmenting Brittle Cylinder**
  - Motivated by tube fragmentation experiments of Winter (1979), Vogler (2003)*

- **Material properties**
  - Inner radius r1 = 0.020 m
  - Outer radius r2 = 0.025 m
  - Length 2a = 0.1 m
  - Density ρ = 7800 kg/m^3
  - Bulk modulus k = 130 GPa
  - Shear modulus μ = 78 GPa
  - Yield stress Y = 500 GPa
  - Ultimate stress σ = 700 GPa
  - Elongation at failure ε = 0.02



- **Initial Velocity**
  - **$v(r) = V_{r0} - V_{r1}(a/z)^2$**
  - **$v(z) = V_{z0}(a/z)$**
  - **$v(\theta) = 0$**

  where **V_{r0} = 200 m/s, V_{r1} = 50 m/s, V_{z0} = 100 m/s**

* D. Grady, Fragmentation of Rings And Shells: The Legacy of N.F. Mott, Springer, 2006.

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Running Peridigm

- **Usage:**

```
Peridigm input.peridigm
```

where input.peridigm is a properly formatted input deck.

- **An input deck contains these sections:**

```
[Discretization Section]
[Materials Section]
[Damage Models Section]
[Blocks Section]
[Contact Section]
[Boundary Conditions Section]
[Solver Section]
[Output Sections]
```

Running Peridigm

❑ Input Deck

```
Discretization
    Type "PdQuickGrid"
    Horizon "0.00417462"
    NeighborhoodType "Spherical"
    TensorProductCylinderMeshGenerator
        Type "PdQuickGrid"
        Inner Radius 0.020
        Outer Radius 0.025
        Cylinder Length 0.100
        Ring Center x 0.0
        Ring Center y 0.0
        Z Origin 0.0
        Number Points Radius 5

Materials
    My Linear Elastic Material
        Material Model "Elastic"
        Density 7800.0
        Bulk Modulus 130.0e9
        Shear Modulus 78.0e9

Damage Models
    My Critical Stretch Damage Model
    Damage Model "Critical Stretch"
    Critical Stretch 0.02
```

Alternative: Read from Exodus/Genesis mesh generated by meshing tool (example: CUBIT)

Material properties

Damage model properties

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Running Peridigm

```
Blocks
    My Group of Block
        Block Names "block_1"
        Material "My Linear Elastic Material"
        Damage Model "My Critical Stretch Damage Model"
```

Used to associate blocks of elements with specific material models

```
Boundary Conditions
    Initial Velocity X
        Type "Initial Velocity"
        Node Set "All"
        Coordinate "x"
        Value "(200 - 50*((z/0.05)-1)^2)*cos(atan2(y,x)) + rnd(5)"
    Initial Velocity Y
        Type "Initial Velocity"
        Node Set "All"
        Coordinate "y"
        Value "(200 - 50*((z/0.05)-1)^2)*sin(atan2(y,x)) + rnd(5)"
    Initial Velocity Z
        Type "Initial Velocity"
        Node Set "All"
        Coordinate "z"
        Value "(100*((z/0.05)-1)) + rnd(5)"
```

Function parser: Enter any mathematical function to specify initial velocities or boundary conditions as a function of space & time

Alternative: Specify nodesets in exodus/genesis database

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Running Peridigm

```
Solver
    Verbose "false"
    Initial Time 0.0
    Final Time 2.5e-4
    Verlet
        Fixed dt 1.0e-8

Output
    Output File Type "ExodusII"
    Output Format "BINARY"
    Output Filename "fragmenting_cylinder"
    Output Frequency 250
    Parallel Write "true"
    Output Variables
        Proc_Num
        Displacement
        Velocity
        Acceleration
        Force_Density
        Element_Id
        Dilatation
        Damage
        Weighted_Volume
```

Alternative: Implicit time integrator (Newmark-Beta) or quasistatic solver (damped Newton)

Output from compute class defined earlier

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Simulation performed with Peridigm

The Results…

- Fragmenting Brittle Cylinder

Before

After (brittle)

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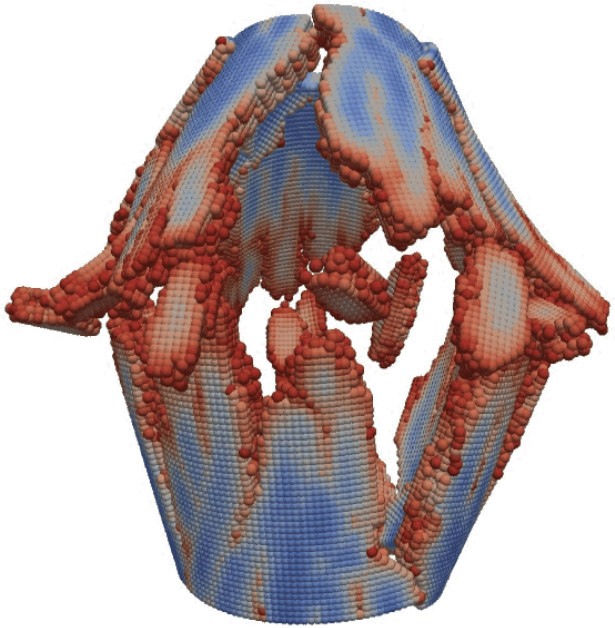
Simulation performed with Peridigm

The Results…

- Fragmenting Brittle Cylinder

Before



After (brittle)

- What about ductile failure?

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Running Peridigm

- **Modify the material section and damage model**

```
Materials
    My Elastic Plastic Material
        Material Model "Elastic Plastic"
        Density 7800.0
        Bulk Modulus 130.0e9
        Shear Modulus 78.0e9
```

Change material type and parameters

```
Damage Models
    My Critical Stretch Damage Model
    Damage Model "Critical Stretch"
    Critical Stretch 0.12
```

Increase critical stretch to be consistent with elongation at failure for material.

Allows material to yield plastically before failure.

Simulation performed with Peridigm

The Results…

- Fragmenting Ductile Cylinder

Before

After (ductile)

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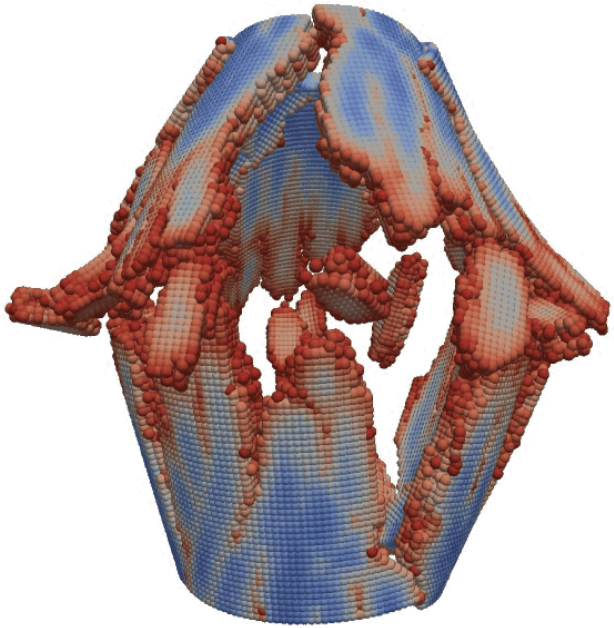
Simulation performed with Peridigm

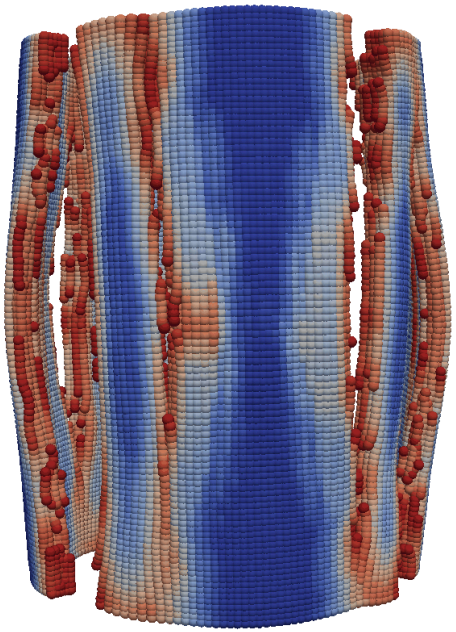
The Results…

- Fragmenting Cylinders
  - Brittle fracture characteristically different from ductile fracture

Before



After (brittle)



After (ductile)

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Summary

- Peridynamics overview
- Example computations
- Peridigm overview
- Peridigm fragmenting cylinder demonstration
  - Input deck distributed with Peridigm…
  - Other interesting examples (disk impact, tensile test)

- Peridigm
  - https://software.sandia.gov/trac/peridigm

- Contact me for more info: mlparks@sandia.gov

- Papers, etc.: www.sandia.gov/~mlparks

- **Thank you!**

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Simulation performed with Peridigm

Tensile Test

- Stainless steel dogbone specimen.
- Apply displacement boundary conditions until dogbone yields.
- Quasistatic solve

before

after

Color proportional to yield.

Displacement exaggerated 10□

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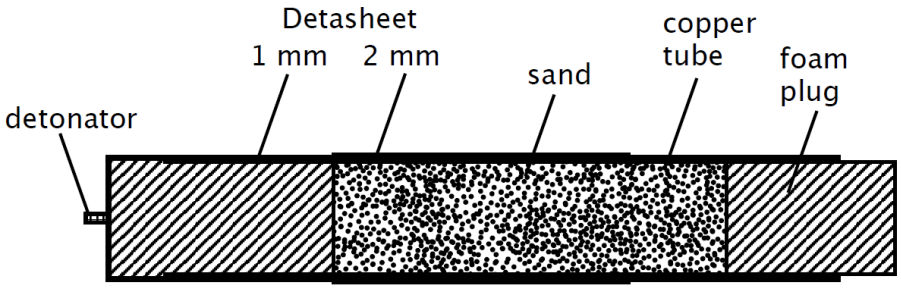
Simulation performed with Peridigm

Explosively Compressed Cylinder*

- Motived by experiments of Vogler & Lappo*
- Commonly used for consolidation of powders
- Copper cylinders filled with granular material and wrapped with Detasheet explosive
- Polyurethane foam plugs used to keep granular sample in tube.

- Geometry and Material Properties
- Copper tubes 305 mm long, ID 50.8 mm, wall thickness of 1.52 mm
- PETN based Detasheet with thicknesses of 1, 2, 4, or 6 mm were used, and a
- Detonation traveled down length of tube, compressing both tube and sand fill



Cylinder schematic

Cylinder after compression

* T.J. Vogler and K.M. Lappo, Cylindrical Compaction of Granular Ceramics: Experiments and Simulations, The 12th Hypervelocity Impact Symposium. 2012.

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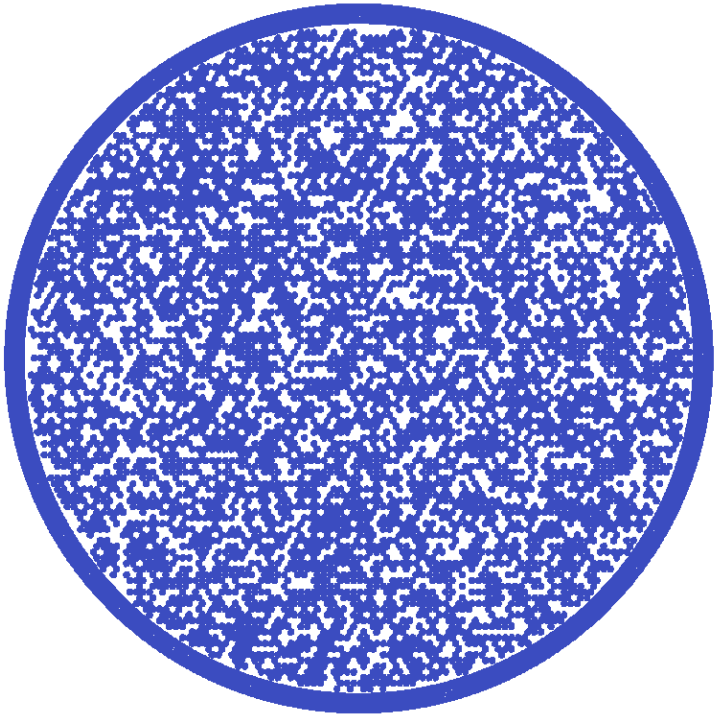
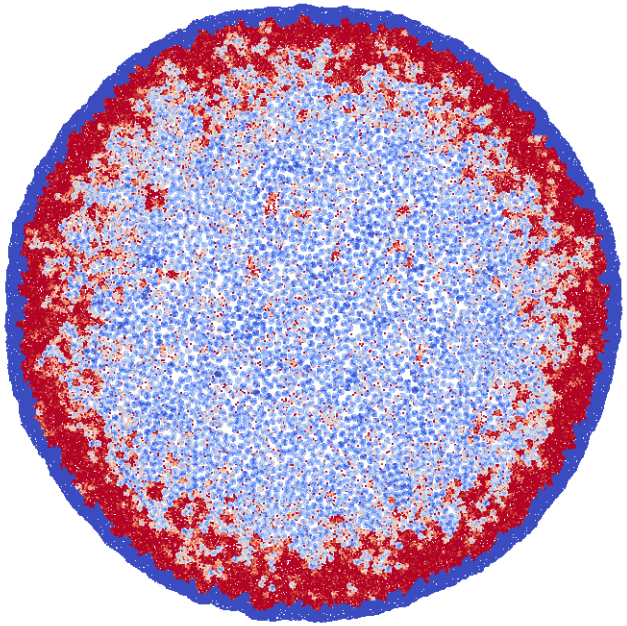
Simulation performed with Peridigm

Explosively Compressed Cylinder

- Peridigm computational results (with C. Hoffarth (ASU), D. Littlewood (SNL))
  - Color indicates damage (blue = undamaged, red = damaged)



Before



After

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