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PRACTICAL PERIDYNAMIC MODELING FOR DAMAGE AND FAILURE PREDICTION

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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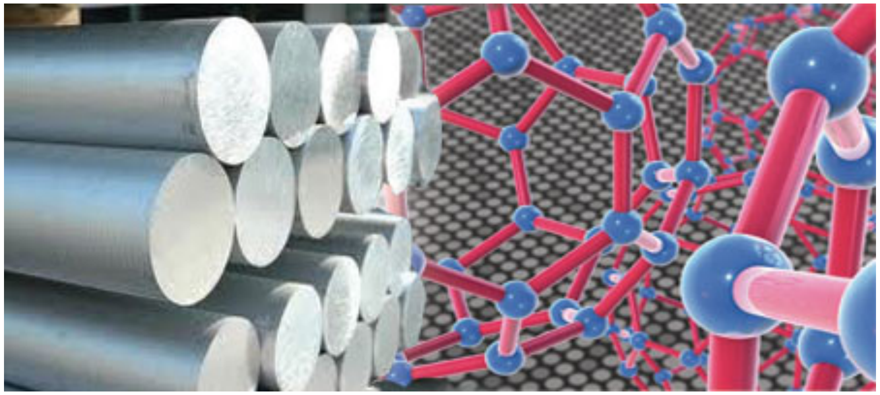
PROBLEM

- Predictive analysis of material damage and failure is a critical challenge in several industries (e.g., aerospace, automotive, medical devices, design, fashion and jewelry)
- Existing computer-aided engineering software based on the Finite Element Method (FEM) have received widespread acceptance for macroscale materials and traditional manufacturing processes
- Such software must deal with ambiguity of derivatives of displacement at discontinuities
- Damage models in existing software impose requirements on mesh size



- New materials damage analysis is critically needed for products of additive manufacturing which comprise 3-D heterogeneities and discontinuities (e.g., composites, porous metals/alloys)

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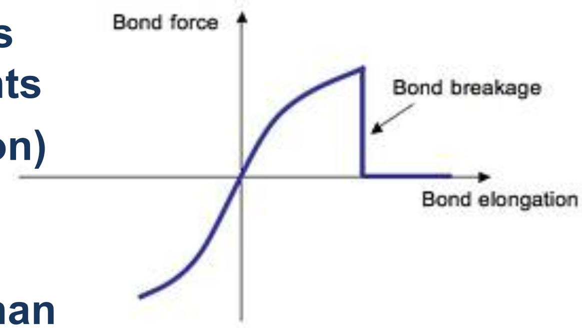
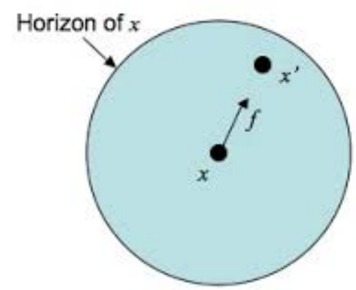
SOLUTION: COMMERCIALIZE PERIDYNAMICS

- Stewart Silling

- **Peridynamic theory originated at Sandia is based on direct interactions between points**
- **The maximum interaction distance (horizon) provides a length scale for the material model**
- **Peridynamics use displacements rather than displacement derivatives**
- **Peridynamic equations are valid everywhere, including discontinuities (e.g., voids, pores, pre-cracks)**
- **Peridynamic tensor converges to a Piola-Kirchhoff stress tensor when horizon → 0**





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PERIDIGM

- Sunergolab Inc. in collaboration with Sandia National Laboratories commercialize the Peridigm peridynamic software
- Peridigm (https://github.com/peridigm/Peridigm) is an open-source, highly efficient, massively-parallel C++ simulation code for solving 3-D problems in structural mechanics and material failure

Peridigm

https://peridigm.sandia.gov/

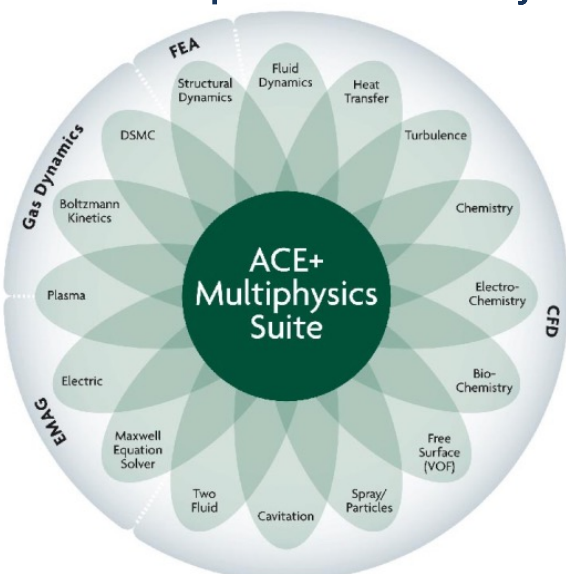
- Peridigm heavily leverages Sandia's Trilinos software project (e.g., parallel data structures, solvers, automatic differentiation package, I/O)
- Wide adoption of Peridigm is limited by
  - Lack of integration with commercial software
  - Difficulties with installation and use
  - Differences in the discretization process, selection of model parameters, and application of initial and boundary conditions from standard approaches
  - Computational cost

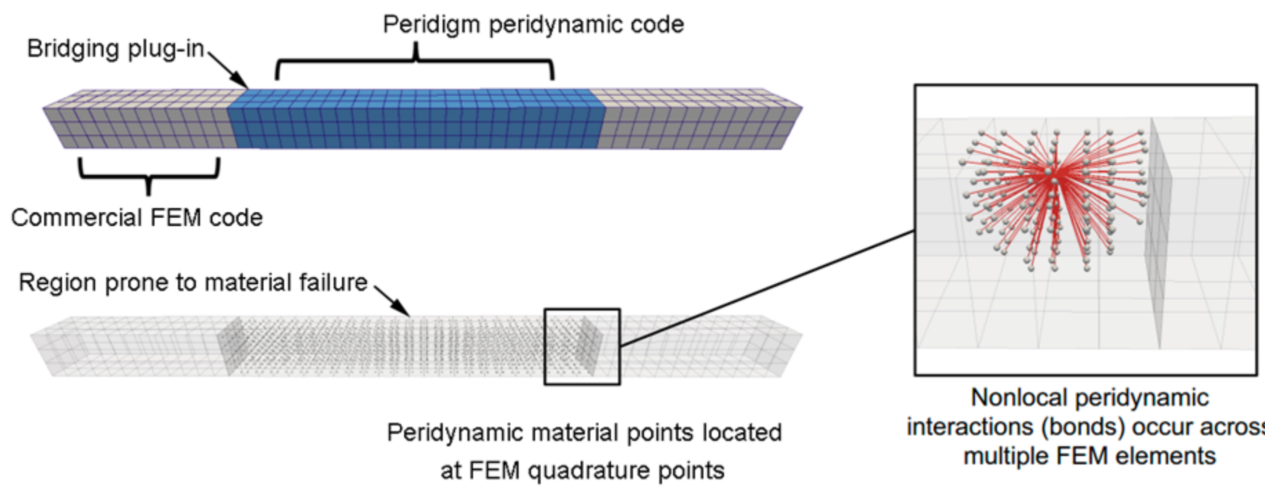
CURRENT USE OF PERIDYNAMICS IN INDUSTRY

- Peridynamic model called PDIFEA (Peridynamics Implemented Finite Element Analysis) was implemented in ABAQUS
- A few small-businesses pursue peridynamic approach:
  - 1) Global Engineering Research and Technologies, http://www.gertinnovation.com/, commercializing university's code
  - 2) Technical Data Analysis, Inc. (TDA), http://www.tda-i.com/, focusing on providing solutions using peridynamics to extend the useful life of aircraft
  - 3) Advanced Cooling Technologies, Inc., http://www.1-act.com/, develops thermal protection materials with peridynamic analysis
- Existence of direct competitors demonstrates the interest of potential customers to peridynamics software and reflects urgency in commercializing Peridigm

BLENDING PERIDIGM IN FEM SOFTWARE

- **Nonlocal-local coupling is currently being investigated as means to embed a peridynamic modeling within a larger ACE+ multi-physics simulation**
- **Such coupled approach achieves a desirable balance between the high fidelity of the peridynamic model and the computational efficiency of classical FEM**





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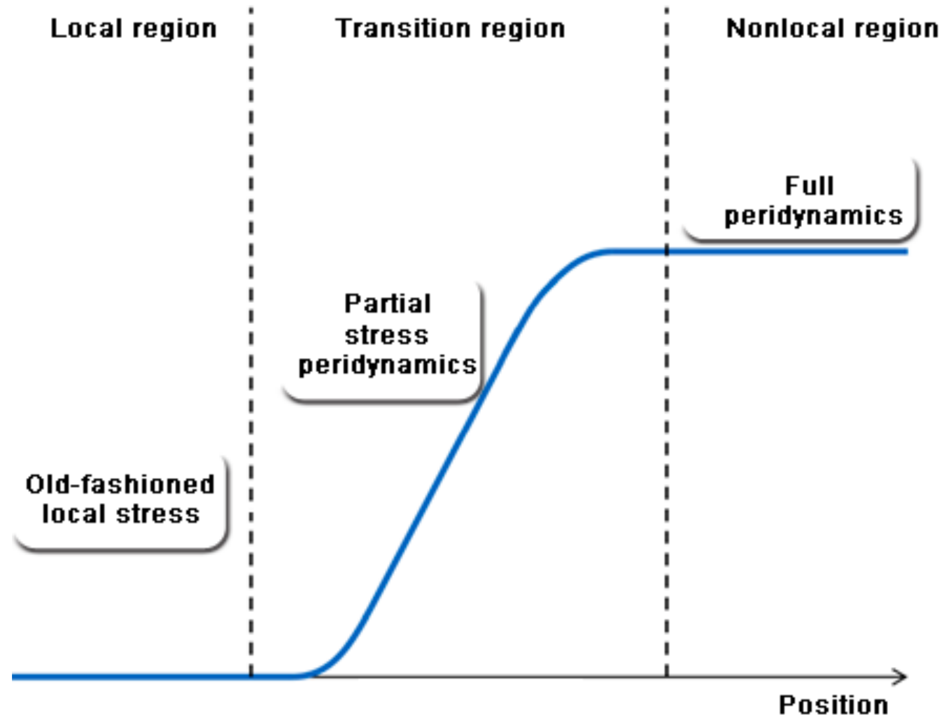
LOCAL/NONLOCAL COUPLING

- **Fundamental challenge is discrepancy between finite length scale in peridynamics and zero-length scale of FEM**
- **This challenge was addressed with peridynamic partial stress approach that supports the use of variable horizon**
- **Here, peridynamic horizon can be reduced in the direct vicinity of the nonlocal-local interface, thus mitigating the discrepancy between local/nonlocal approaches**



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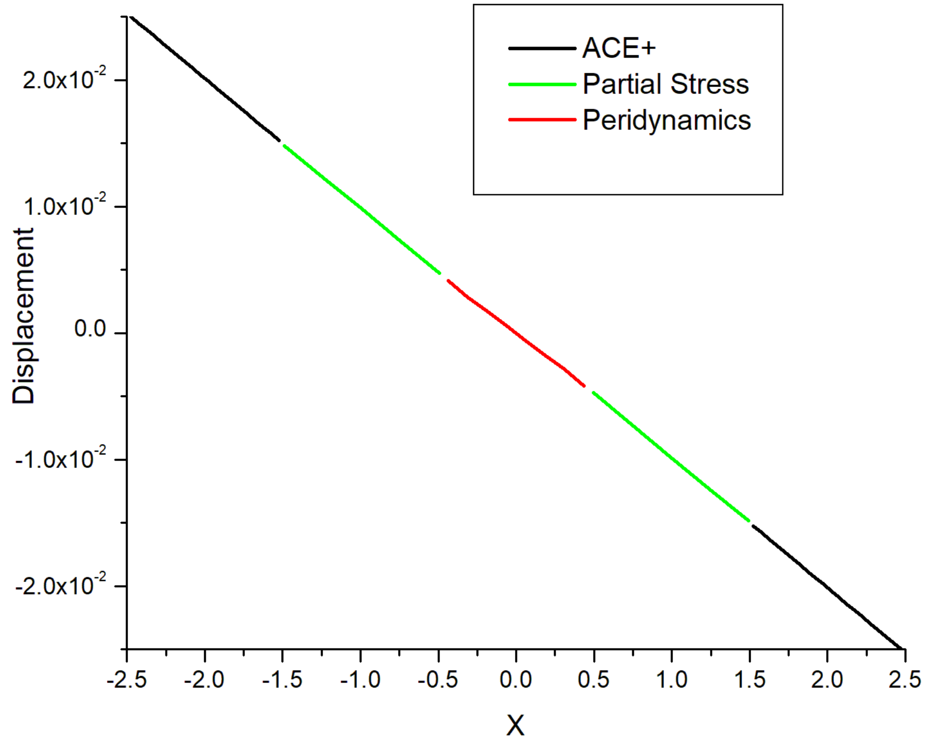
PERIDIGM/FEM COUPLING



- **Coupled ACE+/Peridigm simulation was demonstrated for a bar under tension problem**
- **A bar was discretized into five domains:**
  - **Meshfree peridynamics at the center**
  - **Peridynamic partial stress regions between FEM (ACE+) and meshfree peridynamics domains**
  - **Classical continuum mechanics regions at the ends of the bar**
- **Boundary conditions were applied in ACE+ software**
- **Simulation was performed with a linear elastic material model**

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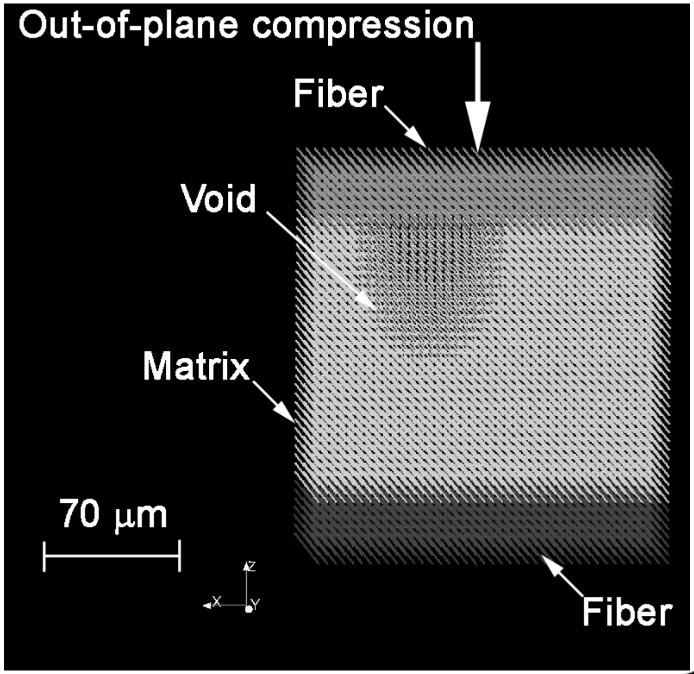
CARBON FIBER-REINFORCED SiC-MATRIX COMPOSITE

- **Carbon fiber-reinforced SiC-matrix composite (C/SiC) is a key material for thermal protection in aeronautics and astronautics**
- **Geometry represents a slice of unidirectional C/SiC, where fibers are aligned along the longitudinal direction**
- **Time-dependent displacement boundary conditions were prescribed at the top of domain, while the bottom boundary was fixed in transverse direction**
- **The anisotropic bond-based model was used to model interactions between points in the fiber regions**
- **A peridynamic plasticity model was used in the matrix region**
- **The plasticity model includes an explicit dependence on collective effects such as a shear band of plastic nature, which typically develop during severe deformation of the matrix ductile material**



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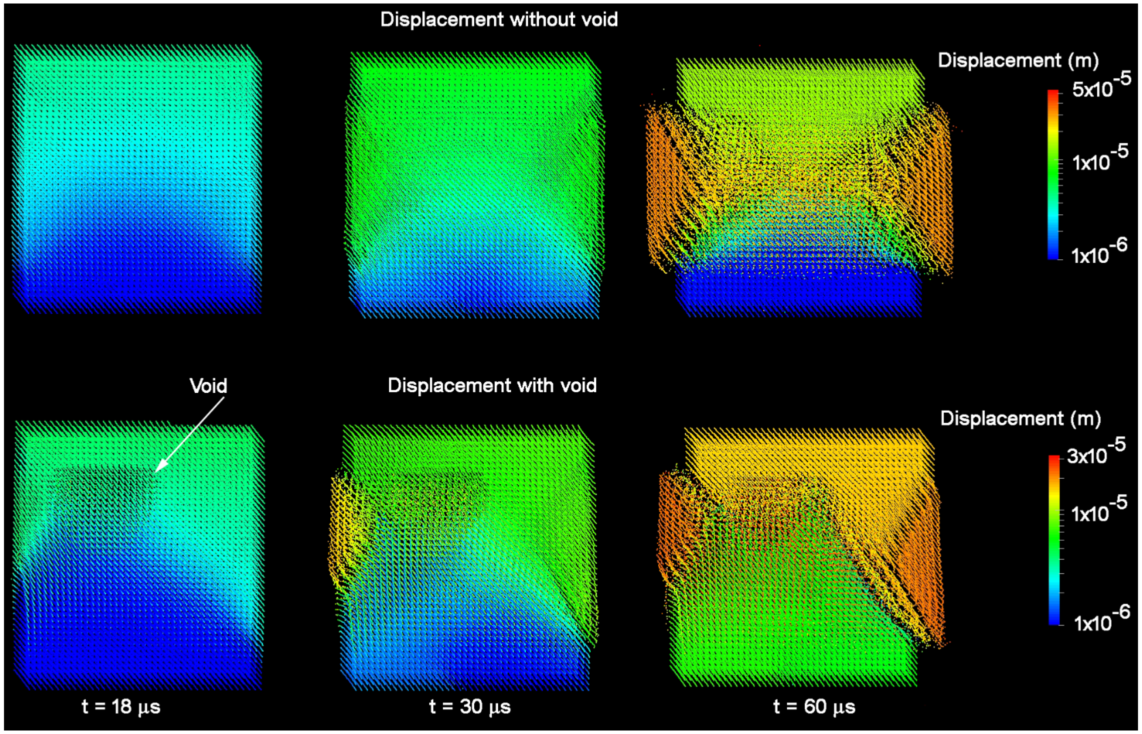
OUT-OF-PLANE COMPRESSION LOADING: DISPLACEMENT



- At 18 µs, displacement peaks near the void due to inhomogeneous deformation
- At 30 µs, systems are visibly deformed with a pronounced peak of displacement in matrix in comparison to the fiber regions due to a larger longitudinal elastic modulus in latter
- At 60 µs, damage for systems without and with void is clearly pronounced along the peak of shear stress direction that is about 45 degrees relative to the loading direction

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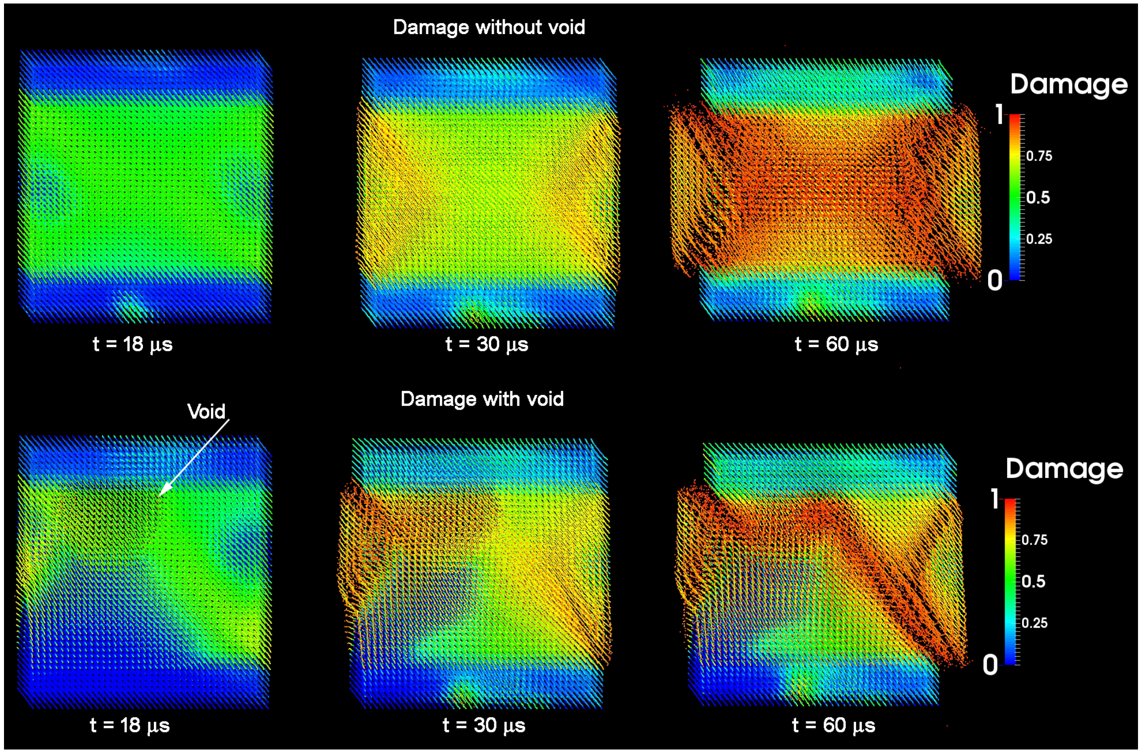
OUT-OF-PLANE COMPRESSION LOADING: DAMAGE



- At 18 μs, damage is spatially homogeneous for a system without void owing to homogeneous deformation
- At 30 μs, damage is concentrating near the void boundary when the void is present
- At 60 μs, damage for the system without void spreads to the center of the system owing to inhomogeneous deformation
- For the system with void, a fracture is visible along the peak of shear stress direction, while damage in the fiber regions remains relatively low

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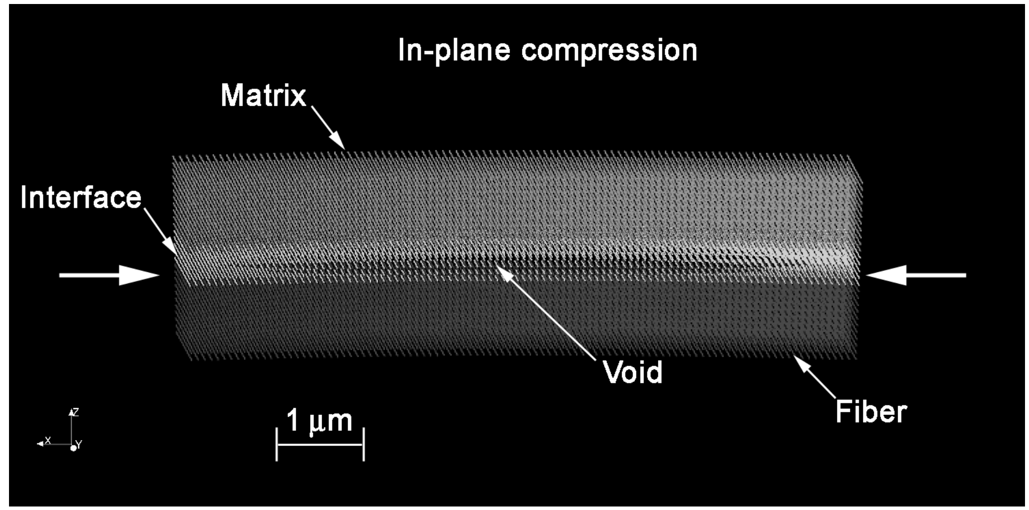
IN-PLANE COMPRESSION LOADING OF C/SIC

- Time-dependent external force at the side boundaries was used to represent an in-plane loading
- Fiber was aligned along the compression direction shown by the thick arrows
- An isotropic bond-based peridynamic model was used to model interactions between points in the matrix region
- An anisotropic bond-based peridynamic model was used in the fiber and interface regions
- Stiffness of interface structure was represented by a combination of fiber bonds along the compression direction and matrix bonds in all other directions



- Damage processes in the fiber-interface-matrix system were resolved by iterating fast implicit quasi-static time integration with slow explicit dynamics

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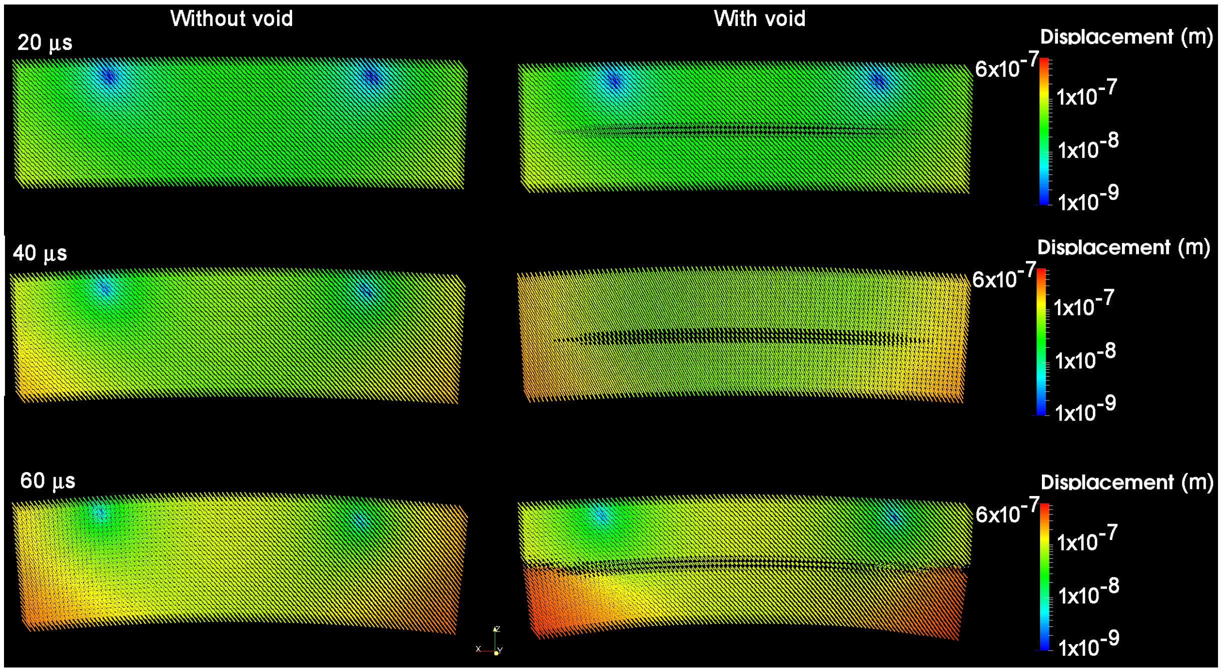
IN-PLANE COMPRESSION LOADING



- **At 20 µs, displacement is spatially homogeneous except the region near the side boundaries where displacement peaks due to the directional deformation**
- **There are two spots with low displacement magnitude where deformation along the longitudinal direction is negated by that along the transverse direction**
- **Systems are deformed at 40 µs with a pronounced peak of displacement in the fiber region due to the small transverse elastic modulus**
- **At 60 µs, fracture is visible in the case of the system with void, while the system without void is deformed, but not cracked**

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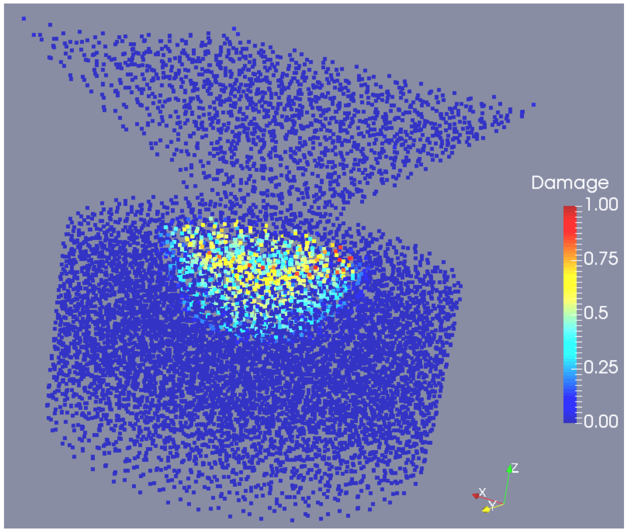
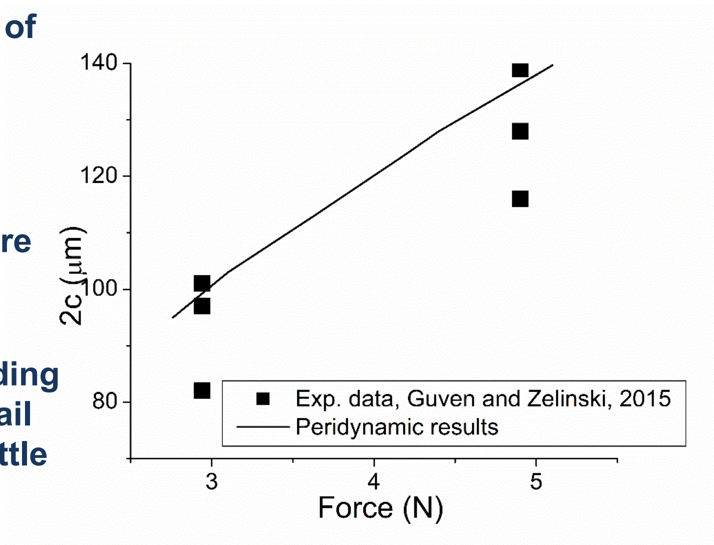
MODELING ELASTO-PLASTIC INDENTATION ON ZnS SUBSTRATE



- **Structural virtual analysis of missile materials was conducted in past using empirical impact material response models**
- **However, such models were developed only for simple materials such as metals**
- **Advanced materials including ceramic composites can fail due to microcracks with little appreciable mass loss**



- **Vickers hardness test measurements reported by Guven and Zelinski, 2015 were used to validate peridynamics results**
- **Peridynamic model consisted of an indentor and a ZnS ceramic substrate**
- **A peridynamic plasticity model was used for the substrate**

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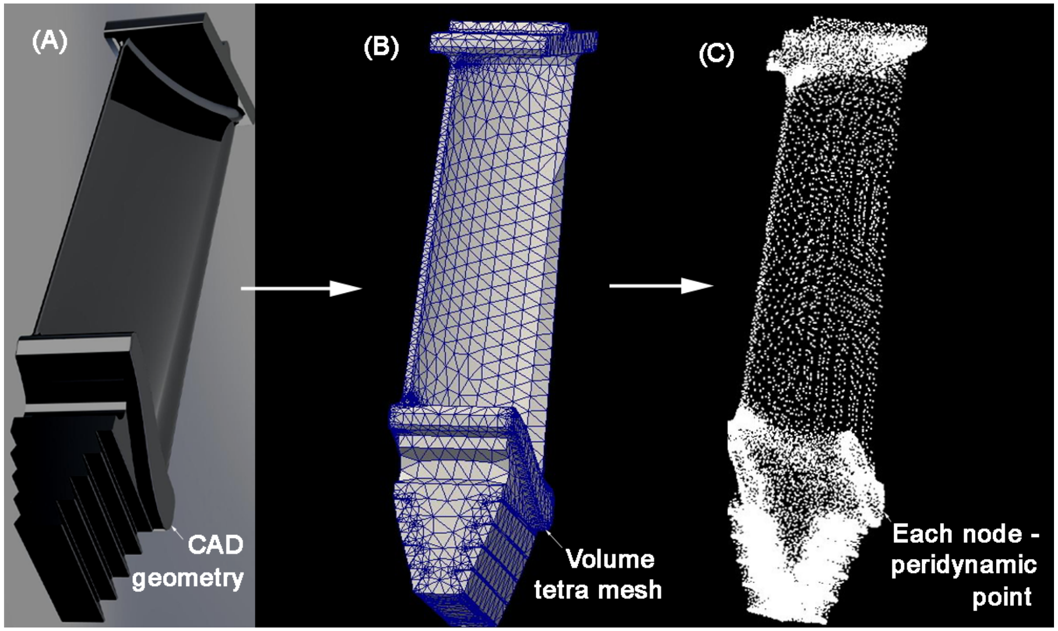
FATIGUE DAMAGE ANALYSIS OF GAS TURBINE BLADE

- **Peridynamic calculations are almost always done for mesh with nearly constant node spacing**
- **This makes peridynamic simulation unpractical for complex geometry**
- **Peridigm can handle a non-uniform mesh provided in Exodus/Genesis mesh input**
- **This feature is demonstrated by fracture analysis of a blade of gas-turbine engine**
- **(A) - CAD geometry**
- **(B) - Unstructured grid**
- **(C) – Peridynamic points**



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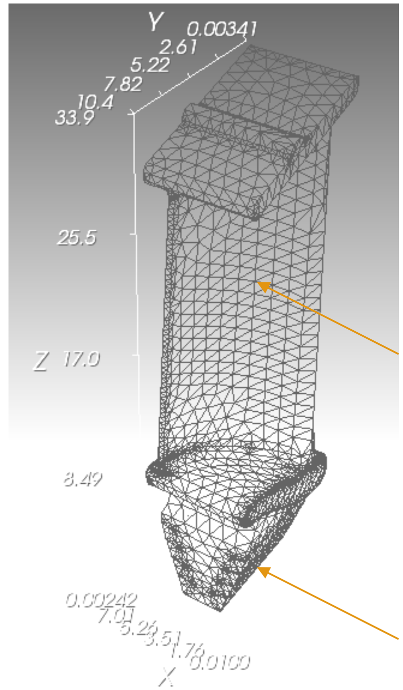
SET-UP AND BOUNDARY CONDITIONS

- **Modeling was performed for a blade made from a Ti–6Al–4V alloy**
- **Temperature was prescribed as a function of height**
- **Temperature varied from 400°C at the bottom to 500°C at the top**
- **Single cycle was modelled with explicit Verlet integration method with a stable time step of 2.0 x 10^{-7}**
- **Explicit solution provided an initial guess to the implicit method**



Prescribed Force of

Fx = 10^3 sin(2π RPM t) [Lift]

Fy = 10^3 cos(2 π RPM t) [Drag]

Prescribed zero displacement for disk/blade segment

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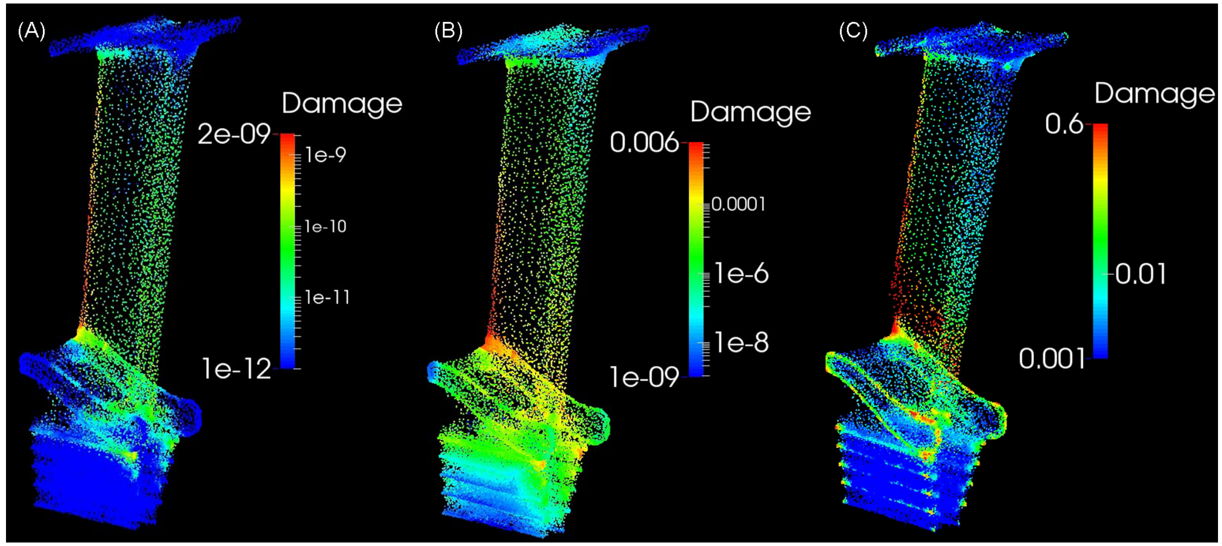
DAMAGE VS NUMBER OF CYCLES (N)

- **Damage resulting from fatigue of blade had a strong dependence on the number of cycles**
- **Damage peaked at the bottom of the trailing edge of the blade**
- **It is likely that cracks would form in this area at a larger number of cycles**
- **There was also some damage accumulated at the blade/disk interface**



- **(A) - N=1**
- **(B) - N=1,000**
- **(C) - N=30,000**
- **RPM - 15,000**

- **Prescribed Force:**
  - **Fx = 10^3 sin(2π RPM t) [Lift]**
  - **Fy = 10^3 cos(2 π RPM t) [Drag]**

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SUMMARY

- **Peridynamics is a novel mathematical theory that unifies the mechanics of continuous media, cracks and discrete particles**
- **Peridynamic damage analysis is particularly valuable for products of additive manufacturing which comprise 3-D heterogeneities and discontinuities**
- **Nonlocal-local coupling was demonstrated as means to embed peridynamic modeling within a larger FEM simulation**
- **Peridynamic software was used to reproduce trends from the literature for fracture formation during the out-of-plane and in-plane compression loadings**
- **For out-of-plane loading, fracture was formed via void collapse and shear damage banding owing to compression**
- **For in-plane loading, fracture was caused by the directional delamination**
- **Peridynamic modeling can provide predictive insight to composite nosecones and radomes applications**
- **The use of non-uniform node spacing made the peridynamic simulations practical for high-cycle fatigue damage analysis of a turbine blade**

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