Meshless Computational tools for Damage and Failure Modeling

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ABSTRACT

Typical damage simulation approaches are usually based on traditional finite element methods (FEM), extended FEM (xFEM) and cohesive zone method, need prescription of crack topology and complicated algorithms to facilitate crack growth – which severely limit the applicability of these theories. This limitation is a consequence of the continuum mechanics based governing equations which are cast as partial-differential equations (PDEs) that are not well-defined at cracks or singularities. Recently, a new non-local formulation of continuum mechanics named a Peridynamics (PD) theory has been proposed, which replaces PDEs with equivalent integro-differential equations. The framework results in governing equations that do not require spatial derivatives and allows for treatment of solid-continua containing cracks/discontinuities in a unified meshless manner. In this talk, we will discuss recent advances in meshless Peridynamics-based crack/damage modeling and discuss the novel computational tools being developed Advanced Cooling Technologies, Inc. (ACT) for damage modeling. Using simple test cases we demonstrate the capabilities of the meshless approach to capture fatigue initiated damage and crack growth in composites. The mathematical structure of the PD approach automatically enables simulation of cracks propagation and failure, without the need for complicated crack path algorithms like that of XFEM or cohesive element method.

KEY WORDS: Peridynamics, Finite Element Analysis, Fiber Reinforced Composite, ABAQUS, Crack Propagation.

Introduction

In recent years, fiber reinforced composites (FRC) have grown important due to its advantages in strength and light-weight. However, crack initiation and propagation in FRC are not well understood. Failure in composites is a result of complex interactions between different damage mechanisms such as matrix cracking, fiber breakage, shear banding, kinking of fibers, fiber/matrix de-bonding and delamination. These damage mechanisms interact with each other by weakening of the material properties. The internal damage at constituent level accumulates under continuous or cyclic loads and results in macroscopic stiffness degradation, which in turns leads to load redistribution and progression of damage to cause ultimate catastrophic failure of the FRC structure.

Several studies have utilized finite element method (FEM) to model damage evolution in FRC. However, All FEM approaches need to solve partial differential equations, whose derivatives fail to exist along cracks or other material discontinuities. To circumvent this limitation, models based on extended finite element method (xFEM) [1] and cohesive zone element method [2] have been developed. However, they still need kinetic relation to inject elements along crack growth path., these methods are limited in their ability to track crack propagation.

Limitations of FEM have also led to research in other approaches like Material Point Method (MPM) [3], and Smoothed Particle Hydrodynamics [4] for modeling crack and fracture. While MPM is a particle based method with elegant aspects to model cracks, it does not account for mutual interaction between particles through multi-body interaction forces (i.e., does not account for nonlocal interactions). On the other hand, SPH method is a spin- off of research on fluid-structure interaction and are less suited for mechanics problems.

Peridynamics (PD) is a nonlocal continuum mechanics theory introduced by Silling [5] as a reformulation the classical elasticity theory for modeling materials with discontinuities. The theory replaces the partial differential equations of classical solid mechanics with integro-differential equations, shown in Eq. (1). The resulting numerical structure of the governing equations is amenable to crack growth, since the integral can be evaluated across discontinuities/cracks without any complicated meshing or crack-tracking algorithms.

$$\rho\ddot{\mathbf{u}}(\mathbf{x},\mathrm{t}) = \int_{\mathcal{H}_{\mathrm{x}}} \mathbf{f}\big(\mathbf{u}'-\mathbf{u},\, \mathbf{x}'-\mathbf{x}\big)dV + \boldsymbol{b}(\mathbf{x},\mathrm{t}) \qquad (1)$$

The PD equations are based on a model which treats the internal forces within a body as a network of interactions between material points. Within a horizon $\boldsymbol{\mathcal{H}}_{\mathbf{x}}$, the interaction between a pair of material points $\mathbf{x}'$ and $\mathbf{x}$ is called a *bond*, which can account for the long-range interaction between particles (nonlocality).

Consequently, the PD approach has been applied to several problems like modeling fracture [6], damage analysis of composite laminates [7,8], electro-migration [9], transient heat conduction [10], thermomechanical fracture [11], and accumulated crack propagation due to fatigue loads [12]. One of the drawback of PD simulation is that it is computationally expensive because of its small time step requirement.

Finite Element Based Peridynamics Models

In this work, a coupled Finite Element (FE) and Peridynamics (PD) based micro-damage dependent effective medium multiscale framework was developed. The framework describes the nature of interactions between PD material points within each lamina as a function of: (a) underlying fiber architecture (b) local damage state and (c) local content of micro-voids or porosity.

One of the drawback of PD simulation is that it is computationally expensive because of its small time step requirement. Therefore, for elastic cases in which discontinuity is not present, it is not as efficient as the conventional Finite Element approach. To reduce the computational cost of PD simulation, recent studies focused on implementing PD to conventional finite element analysis (FEA) models as truss elements. In PD theory, the scalar bond stretch is defined as:

$$s = \frac{|\boldsymbol{\xi} + \boldsymbol{\eta}| - |\boldsymbol{\xi}|}{|\boldsymbol{\xi}|} \tag{2}$$

Such bond stretch is similar to the engineering strain in FE truss element. Hence, PD bonds can be implemented as truss element by setting fracture strain equal to the critical stretch, s_0. In another word, the strain of truss element is set to zero when it is equal or larger than the pre-defined critical stretch to simulate a broken bond. The algorithm for PD bond as FE truss element is shown below in Table 1.

Table 1: Algorithm for FE truss element based PD

- Determine the initial angle of the bonds.
- Apply additional variable svar (initially = 1), representing condition of the bonds.
  - If svar = 0 then strain = 0
  - Else then calculate strain for FE truss element
- Apply stiffness properties according to the initial angles.
- Solve bond force from strain and stiffness.
- Calculate the new length of the bond/truss
  - If the new length reaches critical stretch, then svar = 0 (bond break).
  - Else, svar = 1

Furthermore, the modeling domain can be divided into sub-domains where the region expected to failure is modeled using PD, the remainder of the domain is modeled in FEA framework, and the overlap region contains FE elements with small modulus properties, embedded with PD elements, as shown in Fig. 1.

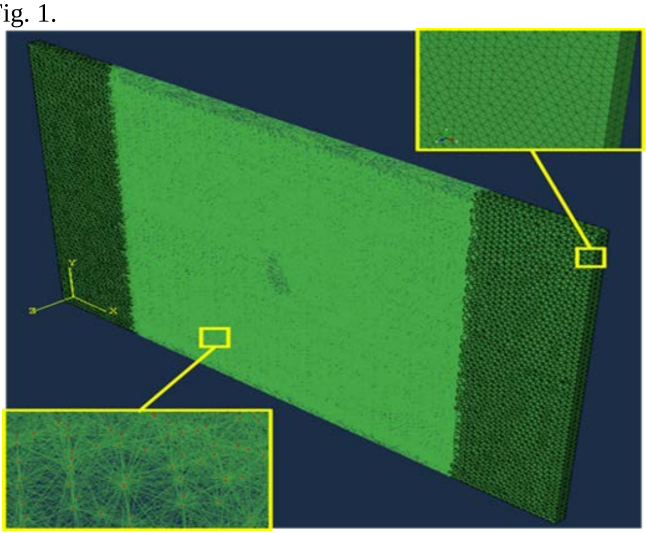

Fig. 1: FE Truss Element based Peridynamics. (ABAQUS)

Implementation of the PD framework into ABAQUS-CAE

The PD framework is implemented into the commercial software ABAQUS through user element (VUEL) and external database (VexternalDB) subroutines. The framework employs Smoothed Particle Hydrodynamics (SPH) kernel to generate neighbor list, and Explicit Finite Element kernel to solve the bond force between each pair of particles. The framework also utilizes effective modulus tensors superimposed with a spatially random correlation to account for discontinuities in material properties, representing defects due to manufacturing, as well as the micro-modulus functions dependent on damage variables to account for material degradation due to cumulative micro-scale damage from continuous loading.

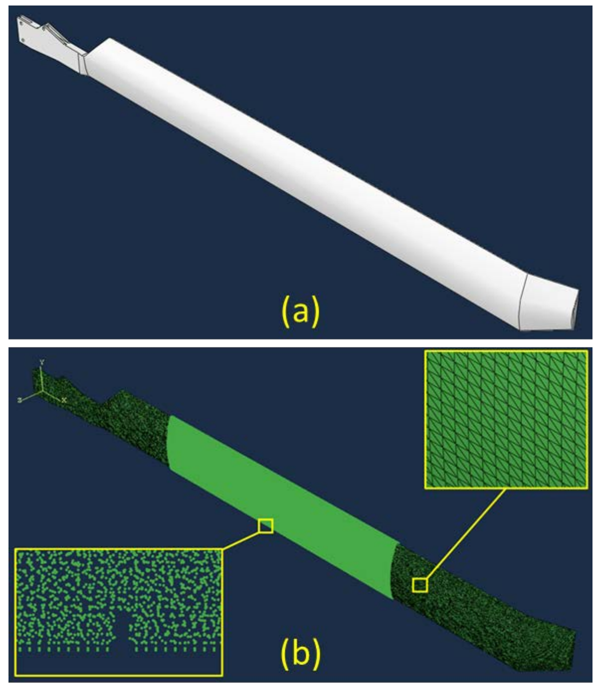

Fig. 2: (a) Sample 3-D Solidworks model of a rotor blade, (b) 3-D notched rotor blade with mesh 4-node tetrahedral FE elements (two sides) with PD elements (center).

Due to robustness of ABAQUS software and SPH neighbor list generator, complex structure from other CAD software could be imported and meshed. Fig. 2(a) presents a sample of a rotor blade created in Solidworks. The rotor blade is meshed in PD particles coupled with FE elements effortlessly, as shown in Fig. 2(b). The pre-existing crack in the center of the blade can be created by deleting the respected PD nodes. The overlap region include both PD and FE elements, where FE elements have a small value to elastic modulus to reduce the stiffness.

Numerical Simulations

Here we demonstrate the capabilities of the developed FE based PD framework through 3-D simulations of FRC thin plate. Case studies include crack propagation in: uni-directional fiber orientation FRC, multi-directional fiber orientation FRC, FRC with pre-existing defects, multi-ply FRC, and FRC with complex geometries.

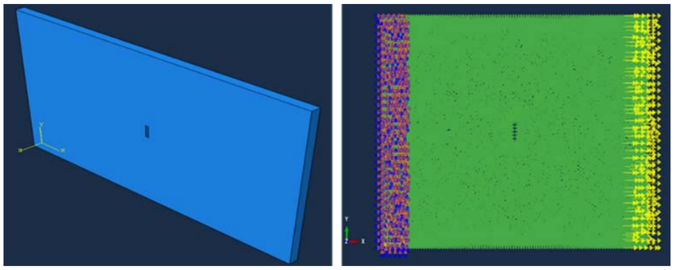

Fig. 3: 3-D single-ply unidirectional composite.

As shown in Fig. 3 (Left), the crack propagation of a 3-D thin plate with a centered crack is investigated. The plate has fixed boundary condition on the left and continuous loading on the right. The material properties applied are similar to E Glass where E11 = 40 (GPa), E22 = 8 (GPa), ρ = 1.9 (g/cm3), and critical stretch = 0.1. The force applied is F = 1.2 e6 (N). The mesh in Fig. 3 (Right) includes 30,634 material points (nodes), which generates nearly 900 thousand bonds (elements). The Abaqus simulation using 12 core computer took about 2 hours to simulate 1 second.

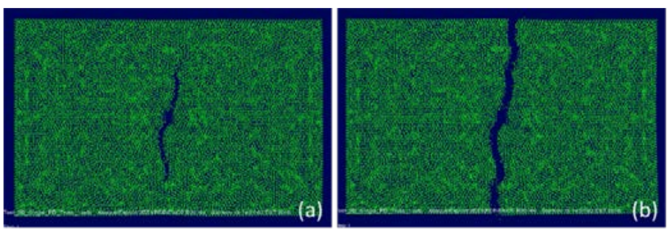

Fig. 4: Crack propagation of 0° fiber orientation at (a) time t = 0.25 s, (b) time t = 0.4 s.

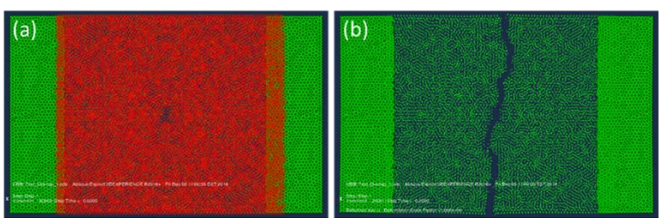

Fig. 5: Crack propagation of 0° fiber orientation at time (a) t = 0 s, (b) t = 0.4 s. (FE and PD coupling).

First, the plate is applied with a single ply unidirectional composite with horizontal (0°) fiber orientation. As shown in Fig. 4, the centered crack starts propagating in vertical direction when the applied force is parallel to the fiber orientation of a unidirectional lamina. Similarly, the FRC with horizontal fiber orientation is simulated with coupling between FE and PD framework. The plate is divided into FE region (green color), PD region (red color), and overlap region (both color), as shown in Fig. 5. The crack propagation is similar to that of Fig. 4; however, the computational cost is greatly reduced due to much less elements to solve.

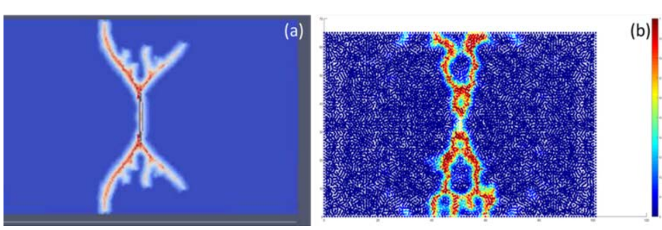

Fig. 6: 0°/90° cross-ply woven composite: (a) previous PD model, (b) current FE based PD model.

The thin plate with centered crack is then applied with a 0°/90° cross-ply woven composite. The crack propagates initially in diagonal direction, then in time changes direction toward vertical (Fig. 6). The damage map of the current FE-PD model matches well with ACT's existing PD model developed under a previous Navy Phase I SBIR program for PD modeling of thick composite [13].

In the case of five-ply laminate FRC, the plate is increased in thickness and applied five different angles of fiber orientation, 0°/45°/90°/-45°/0°. The mesh created includes 66,240 material points (nodes), generating nearly 1.42 million bonds (elements). Due to ABAQUS' robust user subroutine kernel, five different user elements (VU1, VU2, VU3, VU4, and VU5) with each angle is identified in only one user element subroutine (VUEL).

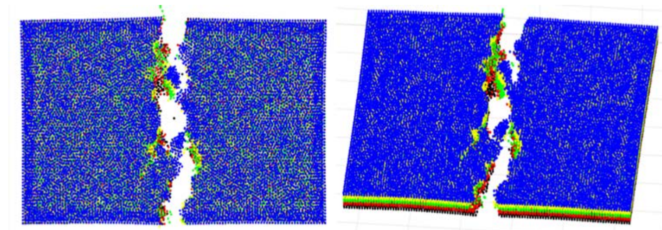

Fig. 7: Crack Propagation of Five-ply laminate with fiber orientation of 0°/45°/90°/-45°/0°, (Left) 2-D and (Right) 3-D view. Each ply is presented by each color (blue, yellow, green, red, and black).

Fig. 7 shows the displacement of PD nodes in each ply, colored respectively in blue, yellow, green, red, and black. From the center crack, each ply propagates in different crack path. Furthermore, the top and bottom ply (in blue and black) are both at 0° orientation; however, they propagate differently. That is because one ply is connected to 45° ply, while the other is connected to -45° ply. This difference demonstrates the inter-ply effect in or FE based PD model.

To demonstrate the effect of pre-existing material defect, the sample in this case is a thin plate with a notched crack on the left side, and a sub-region on the right side with 10% to 30% broken bonds distributed randomly, as shown in Fig. 8. The plate is under continuous loading on both side. The material properties applied are similar to E Glass, and the composite structure is 0°/90° cross-ply woven.

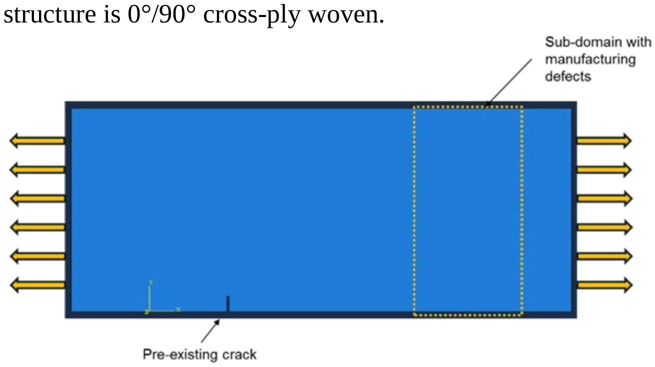

Fig. 8: 3D notched plate with pre-existing material defect under continuous loading.

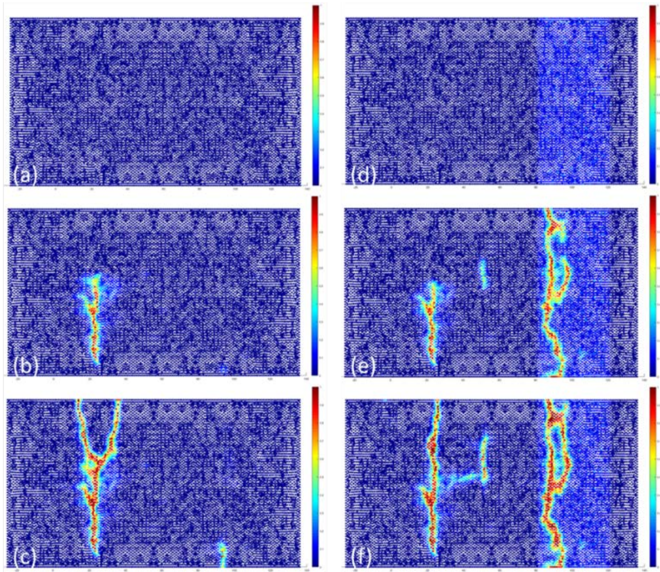

Fig. 9: Damage map comparison between: (a), (b), (c) non-defected plate, and (d), (e), (f) 10% defected plate. (a), (d) time t = 0 s. (b), (e) time t = 0.1 s. (c), (f) time t = 0.5 s.

Fig. 9 shows the comparison in crack propagation between a normal plate on the left (a,b,c), and a defected plate on the right (d,e,f). The first row represents initial time t = 0 s, the second row represents time t = 0.1 s, and the last row represents time t = 0.5 s. As stated above, the damage is from 0 (no damage, blue color) to 1 (fully damage, in red). In the normal plate, the crack propagates from the notch diagonally, then vertically, and diagonally again at the end. At t = 0.5 s, the normal plate experiences a new crack on the right side. In Fig. 9(d), the initial damage is shown on the right side of the plate in lighter blue color. The initial defect not only changes the path of the main crack from the notch but also generates additional cracks in the center.

A sample of a rotor blade is used to simulate crack propagation in FRC with complex geometries. The rotor blade is created in Solidworks as a STEP file. Again, the material properties applied are similar to E Glass, and the composite structure is 0°/90° cross-ply woven. The blade is under fixed condition at the root and continuous drag loading at the tip of trailing edge. A pre-existing crack is initialized at the center of leading edge, as shown in Fig. 10. The mesh created includes 337,407 material points (nodes), generating nearly 8.53 million PD bonds (elements).

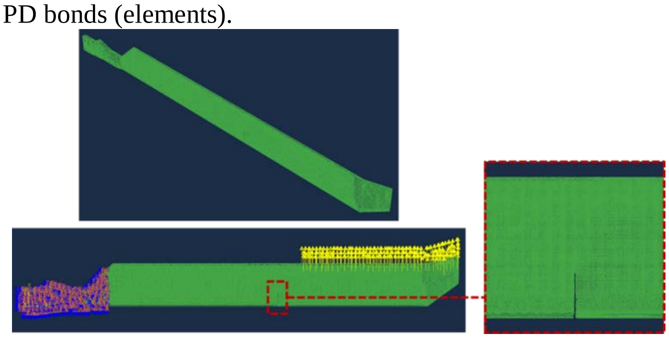
Fig. 10: PD mesh of a rotor blade with pre-existing notch and continuous drag.

Fig. 11 shows the deformation and crack propagation of a notched rotor blade under continuous drag loading. As the drag begins to bend the rotor blade, the initial crack propagates as a result. The crack path is in a diagonal and vertical path, similar to that of a woven composite structure in Fig. *9*(c).

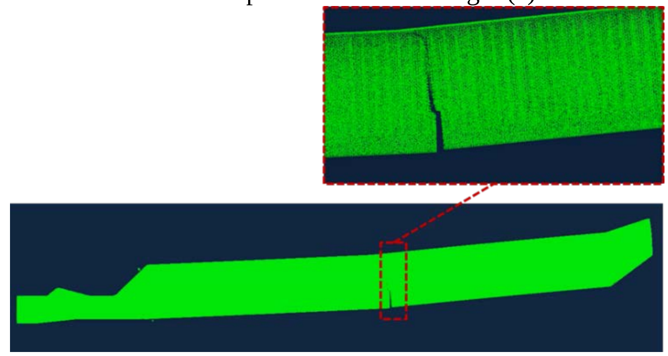
Fig. 11: Crack propagation in a notched rotor blade.

Summary & Conclusions

In this work, a coupled Finite Element (FE) and Peridynamics (PD) based multi-scale framework was developed which can accurately predict 3-D crack propagation paths of fiber-reinforced composite structures. The PD framework has the capability to estimate effective modulus of complex FRC structure as well as to account for material defect from manufacturing, and material degradation from continuous loadings. The PD framework is implemented into ABAQUS software through user subroutines. The robustness of ABAQUS kernel assist our developed model in setup simulation cases effortlessly. In addition, coupling between FE and PD framework can be performed to enhance the model efficiency.

To employ the developed modeling framework in practical applications of interest, there is a need benchmark the predictions with suitable experiments. However, the lack of directly comparable experimental data limits the benchmarking effort. This will the focus of future work.

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