



Peridynamics for fatigue life and residual strength prediction of composite laminates



Y.L. Hu, E. Madenci*

Department of Aerospace and Mechanical Engineering, The University of Arizona, Tucson, AZ 85721, USA

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ABSTRACT

This study presents an application of peridynamics to predict damage initiation and growth in fiber reinforced composites under cyclic loading. The fatigue model utilizes standard S-N fatigue data for a lamina along with the critical energy release rate values. The fidelity of this model is established by simulating the tests conducted by the Air Force Research Laboratory under the Tech Scout Project. As part of this project, the AFRL tested open-hole composite laminates made of IM7/977-3 for three different layups under cyclic loads for strength and failure progression. The peridynamic predictions agree with the reduction in stiffness and strength as a function of number of load cycles. Also, the progressive damage predictions capture the general characteristics of the experimentally observed damage patterns.

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1. Introduction

Due the presence of different length scales and failure mechanisms as recently discussed by Talreja [1,2], residual strength and fatigue life prediction of fiber reinforced composite structures is extremely complex. Indeed, it requires a synergistic multi-scale analysis to reflect the nature of failure at the governing scale consistent with the characteristic structural scale. However, the standard test data for fatigue life prediction consists of the ply-level properties of fiber reinforced composites, G_{IC} and G_{IIC} as well as S-N fatigue data. Such data are necessary for the existing fatigue life, phenomenological, and progressive damage models. Fatigue life models employ the S-N data in conjunction with a fatigue failure criterion without accounting for the material degradation mechanisms under specified loading conditions. Phenomenological models employ a power law relation to describe the degradation in stiffness and strength as a function of number of cycles and empirical material parameters. Progressive damage models employ damage variables to quantify the degree of degradation and the nature of the damage such as matrix cracking and delamination. An in-depth review of such models can be found in review articles Degrieck and Paepegem [3] and Kaminski et al. [4].

Despite the development of many important concepts, the prediction of failure modes and strength of composite materials is still

a challenge within the framework of finite element method. Therefore, this study concerns the prediction of fatigue damage in composite laminates by using PeriDynamics (PD). Peridynamics introduced by Silling [5,6] allows damage initiation and propagation at multiple sites with arbitrary damage paths without special procedures; thus, making progressive failure analysis more practical. In peridynamics, the internal forces are expressed through nonlocal interactions between the material points, and these non-local interactions are referred to as “bonds”. When a particular failure criterion is satisfied, these bonds are removed to nucleate damage and its propagation.

Peridynamics has been successfully applied to predict damage in composites under quasi-static and dynamic loading conditions. The simplest PD approach to model a composite layer with directional properties is achieved by assigning different material properties in the fiber and other (remaining) directions. The interactions between neighboring layers are defined by using interlayer bonds. Askari et al. [7] predicted damage in laminated composites subjected to low-velocity impact. In addition, Xu et al. [8] considered notched laminated composites under biaxial loads. Also, Oterkus et al. [9] demonstrated that PD analysis is capable of capturing bearing and shear-out failure modes in bolted composite lap-joints. Xu et al. [10] analyzed the delamination and matrix damage process in composite laminates due to low-velocity impact. Askari et al. [11] considered the effect of both high- and low-energy hail impacts on a toughened-epoxy, intermediate-modulus, carbon-fiber composite. Also, Hu et al. [12] predicted the basic failure modes of fiber, matrix, and

* Corresponding author.

E-mail addresses: yilehu@email.arizona.edu (Y.L. Hu), madenci@email.arizona.edu (E. Madenci).

delamination in laminates with a pre-existing central crack under tension. The analytical derivation of the PD material parameters, including thermal loading conditions, was given by Oterkus and Madenci [13]. An alternative approach to model composites was introduced by Kilic et al. [14] by distinguishing fiber and matrix materials based on the volume fraction. Although this approach may bring certain advantages by taking into account the inhomogeneous structure discretely, it is computationally more expensive than the homogenized approach. Oterkus et al. [15] coupled PD with FEM to predict the failure loads in a curved, stiffened composite panel with a central slit subjected to uniaxial loading and an internal pressure. These studies demonstrate the ability of PD theory to accurately model both the progressive damage and final failure modes of composite laminates.

Recently, Hu and Madenci [16] developed a new bond-based peridynamic modeling of composite laminates without any limitation to specific fiber orientation and material properties in order to consider arbitrary laminate layups. They validated the PD predictions by considering the test data made available by the AFRL for three laminate layups with an open hole under quasi-static tension and compression loading.

There exist only a few PD models in the literature to predict fatigue damage with application to metals. Silling and Askari [17] introduced a PD model for fatigue cracking in metallic structures. It is based on the concept of remaining life, and it is capable of predicting life concerning crack initiation and fatigue crack growth. Another PD fatigue model was proposed by Oterkus et al. [18] that applies only to the growth phase of a crack. Recently, Zhang et al. [19] improved the computational efficiency of the model by Silling and Askari [17], and investigated the fatigue cracking in metals and two-phase composites. There exists no PD fatigue model to predict damage in fiber reinforced composite laminates.

This study employs the bond-based peridynamic approach introduced by Hu and Madenci [16] to predict fatigue damage in fiber reinforced composites. This approach is free of any limitation on the fiber orientation, stacking sequence, and constraints on material constants. It is classified as a bond-based PD approach because the force density vectors between two material points are in opposite directions with equal magnitudes. The PD approach captures accurate elastic constants such as E_1 , E_2 , G_{12} , G_{23} and Poisson's ratio such as ν_{12} , ν_{21} , ν_{23} removing any constraints on the material constants.

The fatigue loading is simulated by considering incremental static analyses of cyclic loads with constant amplitude. The incremental PD equilibrium equation is linearized and solved by employing implicit techniques [16,20]. The peridynamic analysis provides distinct energy release rates due to mode I, II and III deformations [21,22]; thus, it permits fatigue damage prediction under mixed-mode deformation. The onset and propagation of matrix cracking and delamination under mixed-mode deformation are predicted by employing energy based criteria in the form of Benzeggagh and Kenane [23,24] and Paris-Erdogan [25] along with the experimental S-N data. The simulation yields the number of cycles till the onset of damage, and the number of cycles for the extent of damage propagation.

After a specified number of cyclic loading, analysis can be performed to determine the residual laminate stiffness and strength. The mixed implicit-explicit solver introduced by Hu and Madenci [16] is employed. The analysis is implemented by employing implicit techniques until fiber failure occurs. Subsequently, the solution is achieved by using standard explicit time integration techniques until final failure.

This approach is validated by simulating the tests conducted by the Air Force Research Laboratory (AFRL) under the Tech Scout Project. As part of this project, the AFRL tested open-hole composite laminates made of IM7/977-3 for three different layups under

cyclic loads for strength and failure progression. The participants in this project reported their predictions and comparison with test results in a series of papers during AIAA SciTech 2016 [26–31]. This study presents the stiffness, strength and damage progression predictions as a function of number of load cycles.

2. Peridynamic model of a laminate

2.1. Peridynamic theory

The PD theory [5,6] concerns the physics of a material point that interacts with other material points within a certain range. The position of a material point in the undeformed configuration is denoted as $\mathbf{x}_{(i)}$ where the subscript (i) represents the material point index. The interaction domain of material point $\mathbf{x}_{(i)}$ is defined by its horizon, δ . Material points $\mathbf{x}_{(j)}$, located within the interaction domain are called the *family members* of $\mathbf{x}_{(i)}$. At any instant of time t , equilibrium between the acceleration term, internal force and external force must exist at each material point of a continuum given by

$$\rho_{(i)} \ddot{\mathbf{u}}_{(i)} = \sum_{j=1}^{N_{(i)}} \mathbf{f}_{(i)(j)}(\mathbf{u}_{(i)}, \mathbf{u}_{(j)}, \mathbf{u}_{(k)}, \mathbf{u}_{(l)}, \dots, \mathbf{x}_{(i)}, \mathbf{x}_{(j)}, \mathbf{x}_{(k)}, \mathbf{x}_{(l)}, \dots, t) V_{(j)} + \mathbf{b}_{(i)} \quad (1)$$

where $\rho_{(i)}$ is the density of material, and $\mathbf{u}_{(i)}$ is the displacement of material point $\mathbf{x}_{(i)}$. $N_{(i)}$ represents the number of family members of material point $\mathbf{x}_{(i)}$. The volume of material point $\mathbf{x}_{(j)}$ is denoted by $V_{(j)}$, and $\mathbf{b}_{(i)}$ is the external force density vector. As shown in Fig. 1, a pairwise force density vector, \mathbf{f} arises from the interaction of material points \mathbf{x} and \mathbf{x}' in opposite directions. The force density vector, $\mathbf{f}_{(i)(j)}$ for laminated composites with arbitrary fiber orientation and stacking sequence is derived in detail by Hu and Madenci [16].

The PD laminate model developed by Hu and Madenci [16] considers the interaction of material points within each ply as well as their interactions with other material points in the adjacent plies. The interactions are achieved through in-plane bonds and inter-layer bonds as depicted in Fig. 2. These bonds describe normal and shear deformation.

Bond forces arise from the deformation of in-plane and inter-layer bonds between the material points $\mathbf{x}_{(i)}$ and $\mathbf{x}_{(j)}$. The force density vectors, in the x -, y - and z - directional bonds, are denoted by \mathbf{f}^α with ($\alpha = x, y, z$). For the face diagonal shear bonds in the xy -, yz - and xz - planes, they are denoted by $\mathbf{f}^{\alpha\beta}$ with ($\alpha, \beta = x, y, z$) and ($\alpha \neq \beta$). In the case of a space diagonal shear bond, it is denoted by \mathbf{f}^d . These forces associated with a bond between the material points $\mathbf{x}_{(i)}$ and $\mathbf{x}_{(j)}$ are explicitly expressed as

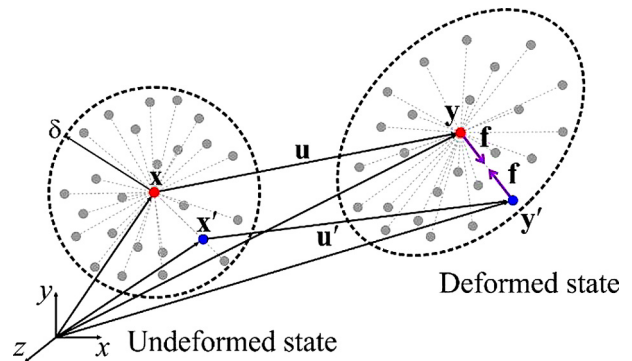


Fig. 1. Nonlocal interactions between \mathbf{x} and its family member \mathbf{x}' .

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