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Peridynamic modeling of delamination growth in composite laminates

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ABSTRACT

Delamination growth predictions in previous peridynamic models were based on the assumption of constant critical stretch for each interlayer bond interaction. This study presents a new approach to terminate the interlayer peridynamic bonds. The critical stretch of a bond is implicitly determined by using the measured critical energy release rate values for different modes of deformation, and can vary depending on the degree of deformation. The bond failure occurs when the amount of energy required to remove the bonds across a unit surface equals the critical energy release rate of the interface between the two layers. This approach is applied to model delamination growth in double cantilever beam (DCB) (Mode I) and transverse crack tension (TCT) (Mode II dominated) specimens. The peridynamic predictions correlate well with the numerical and experimental results available in the literature.

1. Introduction

Complex nonlinear material behavior of advanced composites cannot be described by simple constitutive models. In addition, the presence of dynamic and cyclic loading conditions further complicates their failure analysis for strength prediction. Currently, there is no modeling strategy that can predict all possible damage modes (matrix cracking, fiber breakage, fiber kinking, delamination) and their complex interactions under multi-axial loading conditions and multiple-load paths. Matrix-rich interfaces between plies can be considered the weakest link in fiber-reinforced polymer composites. Composites often contain defects, which occur at these interfaces. Upon loading these defects can grow and coalesce leading to the separation of layers. This process is known as delamination and can significantly reduce the laminate's performance, namely its residual strength and stiffness. Therefore, accurate modeling and evaluation of the influence of a delamination on damage initiation and growth in fiber-reinforced composite laminates under complex loading conditions is a primary design concern.

The finite element (FE) method is widely applied in predicting failure initiation and propagation, and is often used in conjunction with a fracture mechanics approach. However, the FE method relies on the equations of motion that include spatial derivatives [1]. The fundamental difficulty is that the derivatives of displacement fields are not defined at the crack surface or tip. Hence, modeling crack growth within the FE method requires the use of extrinsic criteria and modeling approaches. The virtual crack closure technique (VCCT) [2–6] and cohesive zone model (CZM) [7–11] are the most commonly accepted approaches for predicting delamination onset and growth.

The VCCT is a technique proposed to determine the energy release rates at the crack front based on forces and displacements obtained from an FE analysis. When used to model growth, it is typically assumed that growth occurs if the energy released for a delamination to grow is equal to the energy required to close the delamination at its original length [2,3]. Although it provides accurate results for delamination propagation, it requires the modeling of a pre-existing delamination [11–13] and invokes the assumption of self-similar growth [12]. An alternative to VCCT is the CZM. In CZM approaches, a process zone is assumed along the delamination front. Delamination growth is guided through a cohesive traction-displacement relation. Although CZM permits non-self-similar delamination growth [8,13], convergence issues may arise as a result of singular finite element stiffness matrices [11,12,14] as well as mesh size effects due to the characteristic length of cohesive zones [8,11]. In the case of thick composites, it can also become impractical to place Cohesive Zone Elements (CZE) in between each ply for delamination and in-plane matrix cracking.

Failure in composite materials typically results from the interaction of multiple damage modes, such as matrix cracking (intra-ply) and delamination. Within the FE context, the different damage modes are often modeled with damage mechanics as shown in references [15–17]. Using damage mechanics, the damage modes (cracks) or their interaction are not explicitly

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represented. Instead, the stiffness of the finite elements is degraded according to pre-defined initiation and propagation criteria. Alternatively, higher-fidelity approaches, capable of explicitly modeling different damage modes and resulting crack networks, have also been proposed. In one of such approaches, Cohesive Zone Elements (CZE) are placed "a priori" along assumed crack paths/locations, and used to model damage initiation and progression, exampled in references [18,19]. This strategy requires "a priori" knowledge of the crack propagation path for CZE placement. Addressing this constraint, several mesh-independent FE based techniques have been proposed [20–23]. However, all of these techniques require extrinsic damage initiation and propagation criterion. Furthermore, they often rely on limiting assumptions such as pre-determined crack spacing [21] or crack path [20–22], fixed maximum number of cracks [21,22], and/or are limited to 2D or quasi-2D problems [20–24].

The peridynamic (PD) theory [25–27] has been proposed to overcome the weaknesses of the existing methods, in particular the difficulties associated with modeling initiation and growth of multiple discontinuities (cracks) in solids. The PD theory uses an integral representation of the equilibrium equation rather than its differential form. This avoids the computation of derivatives of displacement, and therefore the equilibrium equations are valid in the entire domain even in the presence of cracks. When damage emerges in structures, the interactions between material points progressively break, and their corresponding contributions in the integral representation are simply removed. PD provides the following major advantages: (a) damage initiation in unguided locations, (b) damage propagation along unguided paths, (c) emergence of multiple damage sites and their complex interactions, and (d) no numerical difficulties after damage occurs. Therefore, PD theory is particularly suitable for modeling complex failure mechanisms such as the ones verified in composite structures under general dynamic and static loading conditions. PD is capable of capturing all failure modes without simplifying assumptions. Damage prediction is achieved by monitoring the stretch of bonds connecting material points, and comparing against a critical stretch value. If the stretch of a bond exceeds a critical value, it no longer interacts with the other material points; thus, the PD force vanishes. Hence, damage is inherently calculated in a PD analysis without special procedures, making progressive failure analysis more practical. It is a fundamental breakthrough in computational analysis, alleviating difficulties associated with discontinuities.

The critical stretch is typically not measured directly and has often been determined using an inverse approach [28,29]. Unlike previous peridynamic models [30–37], this study presents an approach to determine the critical stretch of a bond in an implicit manner based on the degree of deformation, and correlating it with properties measured by standard methods, and hence not requiring an inverse approach. The critical stretch of an interlayer bond can vary according to the local deformation, and is not defined a priori. This enables capturing the variation of critical energy release rate with mode-mixity, observed in mixed mode delamination [38]. The empirical relationship proposed by Benzeggagh and Kenane [38] was adopted to account for increase in critical energy release with mode-mixity. The predictions concerning delamination growth in a double cantilever beam (DCB, Mode I) [39–41] and transverse crack tension (TCT, Mode II) [42–44] specimens are compared with the numerical and experimental results available in the literature [40–44].

2. Peridynamics

The peridynamic theory [25–27] concerns the physics of a material point that interacts with other material points within a certain range, as shown in Fig. 1. The coordinates of a material point in reference and deformed configurations are denoted as $\mathbf{x}$ and $\mathbf{y}$, respectively. The interaction range H_x is called the "horizon" of material point $\mathbf{x}$, defined by a radius, δ. Material points, $\mathbf{x}'$, located within the horizon are called "family members" of $\mathbf{x}$. For a bond-based PD method, the interactions between material point $\mathbf{x}$ and its family members $\mathbf{x}'$ are described through a pair of force functions, $\mathbf{f}$, which are in opposite directions with equal magnitudes.

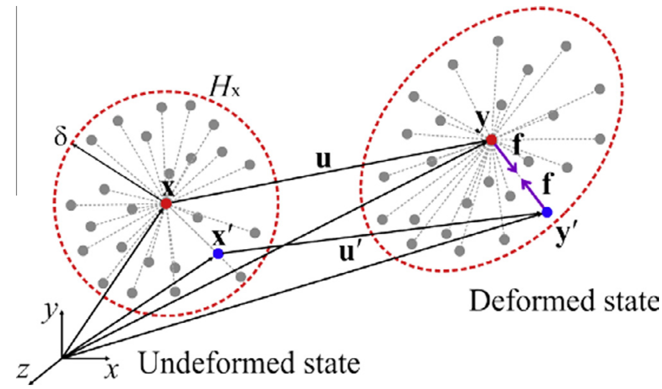

Fig. 1. Pairwise interaction of peridynamic bonds.

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

$$\rho\ddot{\mathbf{u}}(\mathbf{x},t) = \int_{H_x} \mathbf{f}(\mathbf{u},\mathbf{u}',\mathbf{x},\mathbf{x}',t)dV_{x'} + \mathbf{b}(\mathbf{x},t) \tag{1}$$

where ρ is the density of the material, $\mathbf{u}$ and $\mathbf{u}'$ are displacements of material points $\mathbf{x}$ and $\mathbf{x}'$, respectively. The volume of material point $\mathbf{x}'$ is denoted by $V_{x'}$ and $\mathbf{b}$ is the external force density. The vector $\mathbf{f}$ in Eq. (1) represents the peridynamic force between the bonds and can be expressed as [25,27].

$$\mathbf{f}(\mathbf{u},\mathbf{u}',\mathbf{x},\mathbf{x}',t) = \mu c s \frac{\mathbf{y}'-\mathbf{y}}{|\mathbf{y}'-\mathbf{y}|} \tag{2}$$

where $\mathbf{y} = \mathbf{x} + \mathbf{u}$ and $\mathbf{y}' = \mathbf{x}' + \mathbf{u}'$, and μ is a variable indicating the status (intact or broken) of a bond. The stretch, s, is defined as

$$s = \frac{|\mathbf{y}'-\mathbf{y}| - |\mathbf{x}'-\mathbf{x}|}{|\mathbf{x}'-\mathbf{x}|} \tag{3}$$

The status variable, μ, is defined as

$$\mu = \begin{cases} 1, & s < s_c \text{ no damage} \\ 0, & s \geqslant s_c \text{ damage} \end{cases} \tag{4}$$

with representing the critical value for bond breakage.

The *micromodulus*, in Eq. (2), defines the "modulus" of a bond. Due to the directional properties of fiber-reinforced laminates, there exist fiber bonds, matrix bonds, and interlayer bonds with distinct *micromoduli* values. This is the simplest approach to model a composite laminate with directional properties. It is achieved by assigning different *micromoduli* values in the fiber and other (remaining) directions. The interactions between neighboring layers are defined by using interlayer bonds.

Based on such a simple model, Askari et al. [30] predicted damage in notched laminated composites subjected to uniaxial loading. In addition, Xu et al. [31] analyzed the delamination and matrix damage process in composite laminates due to low-velocity impact. Also, Oterkus et al. [32] demonstrated that PD analysis is capable of capturing bearing and shear-out failure modes in bolted composite lap joints. More recently, Askari et al. [33] considered the effect of both high- and low-energy hail impacts against a