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A Mode I cohesive law characterization procedure for through-the-thickness crack propagation in composite laminates

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ABSTRACT

A method is proposed for the experimental characterization of through-the-thickness damage propagation in multidirectional carbon fiber reinforced polymer laminates. The compact tension specimen configuration is used to propagate damage stably while load and full-field displacements are recorded. These measurements are used to compute the fracture toughness and crack opening displacement from which a trilinear cohesive law is characterized. The proposed method provides a means to extrapolate to steady-state such that the cohesive law is characterized completely and accurately, even when the test specimens used for the characterization are too small to reach steady-state crack propagation. The characterized cohesive law is demonstrated through a prediction of the structural response and fracture of a geometrically-scaled test specimen.

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1. Introduction

Damage tolerance requirements for transport aircraft often mandate that a structure be capable of sustaining a specified load level with a through-the-thickness notch (e.g., Ref. [1]). Damage may propagate from a pre-existing notch in a fiber reinforced polymer (FRP) laminated structure by a variety of modes, such as matrix cracks, fiber breaks, and delaminations [2], as shown in Fig. 1. Each damage mode develops under a different range of crack opening displacement, δ. Together, the damage modes act through a fracture process zone (FPZ) with length, l_{FPZ}. Catastrophic failure occurs only after a critical amount of damage has accumulated. In structures designed for damage tolerance, propagating damage may be arrested by structural features such that additional load is required to precipitate catastrophic failure [3–5]. Therefore, to predict load carrying capability, it is necessary to capture the damage propagation and corresponding stress redistributions up to the catastrophic failure of the structure.

Analysis methods that idealize damage at the scale of the ply (i.e. mesoscale) have been introduced to analyze damage propagation from a through-the-thickness notch [6–9]. These methods have the advantage of providing insight into the effect of the layup on the performance of the structure. However, the applicability of mesoscale models has been restricted to coupon scale structures due to the large number of degrees of freedom and consequently high computational cost inherent to this scale of idealization.

Idealization of damage at the laminate scale (i.e. macroscale) offers a coarser but computationally less expensive alternative to mesoscale models. Macroscale idealizations of laminate through-the-thickness crack propagation lump all of the damage modes that develop in the FPZ into an effective through-the-thickness crack (through-crack). The through-crack is assumed to propagate self-similarly under Mode I loading at a particular orientation with respect to the layup. The macroscale analysis approaches that have been proposed to model the crack propagation include linear elastic fracture mechanics (LEFM) [10,11], bridged crack models [12–16], and cohesive zone models (CZM) [17–22], as shown schematically in Fig. 2. Since l_{FPZ} is on the order of relevant structural dimensions (e.g., laminate thickness), a LEFM analysis is not applicable [3,23]. Crack bridging models augment LEFM with closure tractions behind the crack tip that represent the effect of bridging mechanisms in the FPZ. Whereas crack bridging models assume a pre-existing sharp crack and therefore cannot predict damage initiation, the CZM eliminates the crack tip singularity and replaces it with a cohesive zone of closure tractions acting on the interface ahead of the opening crack [24–26]. The CZM collapses all of the damage modes that develop around the notch tip to an

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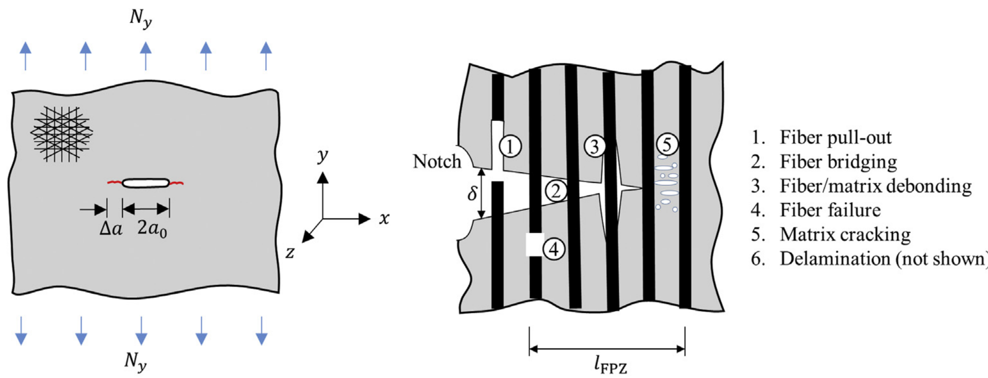
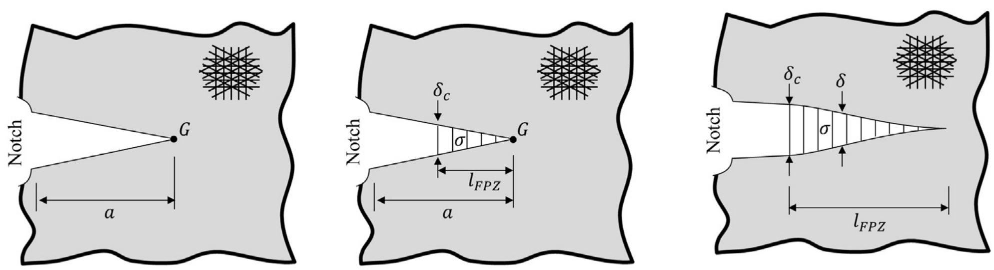


(a) Laminate through-crack propagation (b) Typical damage modes, after [2]

Fig. 1. A composite laminate with a through-the-thickness notch of initial length $2a_0$ and typical damage modes.



(a) LEFM (b) Crack bridging model (c) CZM

Fig. 2. Three models for through-crack propagation.

interface. By introducing a cohesive strength, the CZM has the benefit of predicting both initiation and propagation. The CZM has been applied successfully to predict damage initiation and propagation in center notched, edge notched, compact tension (CT), and three-point bend configurations [17–22,27]. Furthermore, it has been advocated as an appropriate model for through-crack propagation in larger structures [28] and applied successfully for this purpose by the authors [29]. The use of the CZM for modeling through-crack propagation is referred to as the laminate cohesive approach (LCA) herein.

The key challenge for application of the LCA for modeling through-crack propagation in composite laminates is characterizing the cohesive law

$$\sigma = \sigma(\delta) \tag{1}$$

that governs the cohesive tractions as a function of separation. An important limitation of the macroscale LCA is that a different cohesive law must be characterized for every layup and notch orientation of interest. Since several layups and notch orientations are needed for practical design, a simple and efficient cohesive law characterization methodology is required for practical application of LCA.

A variety of experimental methods have been proposed to characterize cohesive laws for through-crack propagation in FRP laminates, including iterative trial-and-error approaches [21,22,30], *R*-curve methods [31,27], inverse constitutive law methodologies [32], and J-integral methods [20,33–35]. In trial-and-error methods, the parameters that define an assumed cohesive law form are determined by iteratively minimizing the error in load–displacement response between test and analysis. Dopker et al. [30] introduced this approach and demonstrated that an *a priori* assumption for the cohesive law as a trilinear form is sufficiently general to capture the behavior in a variety of laminates. Li et al. showed that a trilinear cohesive law calibrated with CT tests could be used to predict the structural response of single-edge-notch tension tests accurately [21]. However, iterative methods are time consuming to apply, which precludes widespread adoption.

Another class of methods is based on measurement of the fracture toughness as a function of crack extension (known as the *R*-curve). Several researchers have attempted to measure *R*-curves for through-crack propagation in carbon/epoxy laminates (e.g., Refs. [36–40]). The *R*-curve methods approximate the cohesive law by relating l_{FPZ} and the measured *R*-curve to the cohesive law. These methods require experimental measurement of crack extension or the steady-state l_{FPZ} [27], which are difficult quantities to measure accurately. Furthermore, while a cohesive law is a laminate-level material property that is independent of the structural response, measured *R*-curves can be affected by the configuration of the structure [13,14,41,42]. Therefore, cohesive laws derived from *R*-curves can inherit the same structural dependence.

Inverse constitutive approaches use strain data measured with digital image correlation (DIC) and an assumed stress state to determine a stress–strain softening law without any *a priori* assumption of the form of the softening law [32]. Softening laws obtained from this approach can be related to a cohesive law [43]. Interestingly, using the inverse constitutive approach, Zobeiry et al. confirmed that through-crack propagation is approximated well by a trilinear form [32]. This conclusion validates the suggestion made in earlier works [27,30] that a trilinear cohesive law is sufficiently general. An important limitation of the inverse constitutive