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Damage evolution in cross-ply laminates revisited via cohesive zone model and finite-volume homogenization

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ABSTRACT

The classical phenomenon of progressive cracking of 90° plies in polymeric matrix cross-ply laminates, and potential or subsequent delamination along the 0°/90° ply interface, is critically revisited using a finite-volume homogenization theory with damage evolution capability. Progressive separation of adjacent phases or subdomains as well as crack evolution may be simulated with this capability within a unified framework that employs discontinuity functions in conjunction with the cohesive-zone model. The finite-volume simulations of evolving damage in graphite/epoxy cross-ply laminates on the fly and its effect on the homogenized axial stress–strain and transverse Poisson's responses, as well as crack density, are compared with available experimental results, taking account of residual stresses, interfacial resin-rich region and variable strength of the 90° plies. The comparison demonstrates the theory's ability to capture the dramatic effect of transverse cracking on the homogenized transverse Poisson's ratio that increases with increasing 90° ply thickness, and the damage mode bifurcation from transverse cracking to interfacial delamination. Moreover, the finite-volume simulations indicate that many features observed in the transverse and through-thickness Poisson's response of graphite/epoxy cross-ply laminates may be related to the underpinning damage modes more readily than in the axial response. The developed finite-volume framework offers a unified methodology for simulating damage evolution in a class of composite laminates due to cracking and/or progressive interfacial degradation, and for identifying features observed in the homogenized response that reflect the underpining local failure mechanisms.

1. Introduction

Simulation of damage evolution in heterogeneous materials remains a challenging problem due to the myriad of failure mechanisms and modes that may be activated at different scales. In composite laminates comprised of differently-oriented unidirectional plies, for example, these modes are hierarchical and include microcracks, fiber/matrix debonding, ply cracking and interfacial delaminations, cf., [31,41]. To naturally track the evolution of localized failure modes, the cohesive zone model proposed by Ref. [7,8] for fracture of brittle materials, and subsequently extended by Ref. [23] for perfectly plastic materials, has been adopted by numerous researchers during the past 30 years. The model is based on a traction-interfacial separation relation which describes the interfacial degradation process between two adjacent phases or subdomains. As the interface separates, traction first increases until the interfacial strength is reached, and then decreases to zero, where complete separation occurs. The contributions of Needleman and coworkers [40,64] and Ortiz and coworkers [15,42] have spurred extensive use of this model in simulating fracture phenomena in a wide range of materials due to its ability to mimic spontaneous crack nucleation, crack branching and fragmentation, as well as crack propagation without an external fracture criterion, and in the absence of self-similar crack growth. Reviews of the different aspects and applications of the cohesive zone model have been provided by Ref. [5,24,43].

The majority of cohesive zone model applications are based on variational techniques. It is only relatively recently that the cohesive zone model has been incorporated into finite-volume based techniques to simulate damage evolution. The finite-volume method has proved an attractive alternative to the established finite-element analysis of boundary-value problems in solid mechanics, cf., [10]; following its origins in fluid mechanics, [58]. In

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contrast to variational techniques, local equilibrium is satisfied in integral sense at the discretized subdomain level in the finite-volume method, offering solution stability and other advantages, [18]. The different variants of the method have been applied to elastic and inelastic boundary-value problems, including fracture mechanics problems based on the classical approach, cf., [36]; and crack propagation with the cohesive zone model in bi-material constructs and heterogeneous materials, [2,16].

Large modulus contrast between constituent phases in heterogeneous materials produces high stress gradients at phase interfaces. Hence in order to correctly simulate crack opening and propagation with cohesive zone model using the displacement-based finite-element approach, convergence of both interfacial tractions and displacements requires extensive mesh refinement in the cohesive zone to ensure self-equilibrated stress fields. In contrast, the parametric finite-volume direct averaging micromechanics (FVDAM) theory was developed explicitly for heterogeneous materials with periodic microstructures, [48]. One advantage of the FVDAM theory over the finite-element method is the availability of closed-form relations between surface-averaged tractions and displacements along interfaces separating adjacent phases through a local stiffness matrix that governs the equilibrated response of a subdomain. These relations are determined from the assumed displacement field at the subdomain level following the elasticity approach, avoiding the problem of accurate stress extrapolation to the subdomain surfaces encountered in finite-element approaches. The analytical relations between interfacial tractions and displacements provided a natural path for cohesive zone model incorporation into the FVDAM framework, [56]; using a unified approach based on displacement discontinuity functions previously employed in the solution of interfacial crack problems, cf., [20]. This unified approach enables simulation of both progressive phase separation and crack growth within the same framework. The extended FVDAM theory was shown to faithfully capture the mechanics of interfacial debonding in metal/matrix composites with fiber/matrix interfaces degraded by the fabrication process.

Herein, we employ the FVDAM theory with the incorporated cohesive zone model to revisit the classical problem of damage evolution in symmetric cross-ply laminates under unidirectional loading due to progressive cracking of the transverse plies which may lead to delamination between the outer and inner plies when the transverse cracks reach saturation density, [22,49]. This hypothesis has been accepted by a number of researchers, but universal acceptance remains lacking, [39]. The above well-investigated problem serves as a model problem against which new damage evolution approaches may be gauged. It also provides a foundation for understanding damage evolution in symmetric laminates other than composites, such as those found in the microelectronics industry.

Hence the objectives of this investigation are several-fold. One objective is to demonstrate the finite-volume theory's ability to track the evolution of dispersed damage caused by the combined effects of transverse cracking and interfacial delamination, while accounting for the important effects of transverse ply strength variability and fabrication cooldown. Successful demonstration of this capability is intimately related to establishing the relationship between the homogenized response and the underpinning damage mechanisms, an ultimate goal of this investigation. In contrast with still-life approaches widely employed to assess the impact of damage on homogenized moduli and damage mode transition, the damage evolution in our approach is monitored on the fly within a unified homogenization framework that admits multidirectional loading. While it is known that certain homogenized moduli are substantially more sensitive to damage than others based on snapshot analyses of cracked laminates at fixed crack densities, herein we demonstrate on the fly during continuing loading that this sensitivity has dramatic impact on the homogenized Poisson's response features. This observation suggests a diagnostic tool for damage initiation detection and correlation with underpinning local failure mechanisms. We start with a brief historical survey of the literature to place our contribution and simulation approach in perspective.

2. A brief historical perspective

The occurrence of successive cracks in the 90° plies of symmetric cross-ply or $[0_m/90_n]_s$ laminates loaded axially has been documented as early as the mid 1960's, see Ref. [57] and the references therein. An approximate analytical model constructed by these authors based on the variational approach revealed that a system of cracks a distance π/k_2 apart develops in the 90° layers when the ply strength is initially reached, where k_2 depends on the thickness and material properties of the 0° and 90° plies (see the Appendix). Subsequent loading produces additional cracks in the 90° plies halfway between the first set when the axial stress in these locations again reaches the ply strength. The resulting homogenized axial stress–strain curve is characterized by jogs that correspond to the successive occurrence of transverse cracks in the 90° plies until sufficient stress is reached in the 0° plies to cause catastrophic failure. The severity of these jogs that correspond to the energy released by the catastrophic fracture of 90° plies depends on the relative proportion of the two sets of plies, and hence the energy associated with the stresses carried by the 90° plies. This form of damage also degrades the homogenized moduli with the ensuing implications relative to structural analysis and integrity, and has been an intense area of research since then.

The above phenomenon has been re-discovered by [4,25,33,46]; and others. The period that followed was characterized by the development of numerous analytical and numerical models aimed at predicting moduli degradation of cross-ply and related symmetric laminates as a function of crack density, cf [11,27,28,37,38,54,59–61]. The various models were based on shear lag assumptions of varying complexity, approximate elasticity-based analytical and variational approaches, and finite-element solutions. The variational approach employed by [57] was reproduced by [29,30]; and applied to calculate homogenized moduli of symmetric cross-ply laminates with uniform crack spacing. It has been used extensively as a benchmark for comparison with other solutions as well as experimental data. More recently, boundary-element and finite-element solutions of unit cells representative of symmetric cross-ply laminates with evenly spaced transverse cracks have been reported, [1,44,45]; as well as exact elasticity solutions based on the singular integral approach, [62]; and non-singular series expansion, [35].

While the calculation of stiffness degradation due to transverse cracking in this class of laminates is well-established, the evolution of damage continues to receive considerable attention, [6]. The problem is complicated by the occurrence of interfacial delaminations between the outer 0° and inner 90° plies which may arise when the transverse crack density reaches a saturation point, attributed to the occurrence of compressive normal stress between two adjacent transverse cracks that develops with sufficient crack density, [49]. This compressive stress may be used as a criterion to determine at what point along the loading history the damage mode switches from transverse cracking to interfacial delaminations in order to calculate the effect of the combined damage on stiffness degradation, [22]. While the majority of simplified analytical and finite-element unit cell models are based on uniform crack spacing, the in-situ 90° ply strength has a statistical