MODELLING DAMAGE EVOLUTION IN LAMINATED COMPOSITES USING COHESIVE ZONE MODELS

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ABSTRACT

One of the most difficult problems in designing composite structures is to ensure tolerance of severe damage. Current practice requires significant, time-consuming, and expensive testing to establish damage tolerance certification. In this study we shall discuss the application of cohesive zone modelling approach for analyzing the damage tolerance of laminated composites with or without the existence of stress concentrators. A 3D, mode-dependent cohesive zone model (CZM) is incorporated through the use of cohesive elements, which allow tractions to persist across displacement discontinuities (cracks or strain localizations), which arise after the attainment of a local failure condition. An essential feature of the formulation is that the existence and shapes of major crack systems need not be prescribed a priori. Successful applications will be reported to some practical problems in composite engineering, which cannot be adequately analyzed by conventional tools such as LEFM. It will be shown that the CZM simulations can successfully reproduce experimentally measured crack shapes that have been reported in the literature.

1. INTRODUCTION

When a laminated composite with a stress concentrator (hole, slit, or notch) is subjected to an in-plane tension load, a number of possible failure events (also referred to as sub-critical damage events) may develop during different loading stages. The first damage is usually matrix mediated failure events at locations of local stress concentration, including matrix tensile cracking and matrix shear cracking between fibers. Numerous such small cracks may develop into macroscopic splitting cracks in 0° ply, running parallel to the load axis and away from the edges of the stress concentrator (H cracks). Such splitting cracks often are accompanied by delaminations between the 0° ply and its neighboring plies and extensive matrix tensile cracks in the neighboring plies (Spearing [1]). These mechanisms are summarized in the schematic of Fig. 1. The delamination fronts and the splitting cracks sometimes (but not always) form triangular zones, which is the case depicted. As the load approaches the failure load, fiber rupture in 0° plies starts at the hole edge and propagates perpendicular to the loading direction. The propagation of this rupture zone generally culminates in catastrophic failure of the entire composite (Kortschot [2]; Chang [3]). If a compressive instead of tensile load is applied, the basic features of splitting and delamination crack development remain and off-axis plies are still prone to distributed shear microcracking. But tensile matrix cracking in 90° plies tends to be suppressed and ultimate failure will usually follow by buckling, either at the global or local level (Soutis [4]).

Among the four major damage modes, namely, shear cracking (split), matrix tensile cracking, fiber breakage (in tension) or microbuckling (in compression), and delamination, the first three are primarily in-plane damage events, because they typically occur in individual plies and are related mostly to in-plane stresses. Delamination between two adjacent plies is considered an out-of-plane damage mode (generally involving both opening and sliding delamination crack displacements) and its evolution is dictated by the interlaminar stresses. Previous models for predicting laminated composite failure are more or less divided along these two lines. For in-plane failure, various material property degradation models have been proposed in an effort to describe the load redistribution associated with damage accumulation ([3]; Shokrieh [5]). The out-of-plane damage mode has also been subjected to extensive studies using either strength-of-material based failure criteria (Pagano [6], Garg [7]) or energy based failure criteria from linear elastic fracture mechanics (Rybicki [8];Tay [9]). However, neither of these methods is capable of dealing with problems of engineering importance including free edge crack nucleation and propagation, and delamination in a composite panel due to low-velocity impact. The strength-of-material approach has lost credibility because many experimental observations showed that using point-wise stress/strain criteria is not sufficient. This is particularly true in the case of free-edge delamination around an open hole or a notch. Rather than using point stresses or strains, a characteristic length scale has to be introduced into the delamination criterion (Whitney [10]; Pipes [11]). The LEFM approach has enjoyed some success in delamination prediction, under the condition that there are pre-exist cracks of finite size (a condition does not hold on free-edge delamination initiation problems). However, the complicated and subjective mode-separation technique has greatly limited its applicability to realistic structural problems that often contain complicated mixed-mode 3D crack fronts [9].

Failure analyses considering both the in-plane failure modes and the interlaminar delamination are far fewer, largely due to the complex nature of the nonlinear coupling between in-plane and out-of-plane damage events. For example, the longitudinal splitting cracks are always accompanied by interlaminar debonding as sketched in Figure 1. Beaumont and his colleagues proposed a phenomenological model for the $(90_j/0_j)_{ns}$ family of laminated composites based on a steady-state energy balance approach [1,2,12]. Unfortunately, this approach cannot be generalized to predict the split and delamination laminated with arbitrary ply orientation, where a debonding crack usually propagates in a non-self-similar fashion.

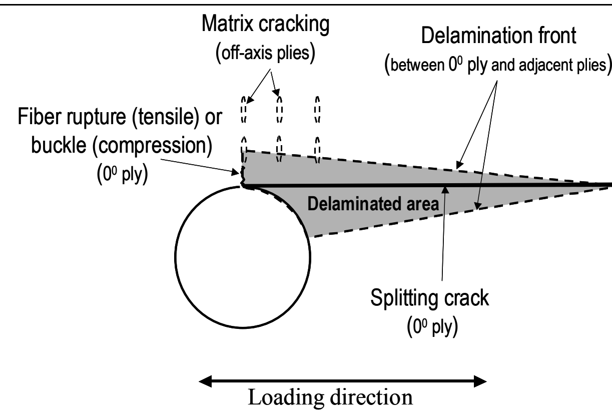


Figure 1. A sketch of possible failure events around an open hole in a laminar composite panel.

Recently, the concept of cohesive zones has received revived interest and the cohesive zone modeling (CZM) approach has emerged as a powerful analytical tool for nonlinear fracture processes. This type of model has been used for studying the so-called quasi-brittle fracture process zone in concrete materials and macromolecular based polymer materials (de Borst [13], Elices [14]). Applications to other material systems such as adhesively bonded joints (Wei [15; Yang [16]), bimaterial interfaces (Needleman [17], Tvergaard [18]), and the dynamic fracture of homogeneous materials (Xu [19], Needleman [20]) have also been very successful. Cohesive zone models have also been used to analyze composite delamination problems. Problems of delamination in the absence of large notches or holes have been studied (Corigliano [21]. Schellekens [22], Borg [23]) and also, more pertinently to the present work, in the presence of a notch (Wisnom [24]). In laminate problems, cohesive zone models offer the prospect of determining important issues such as the influence of stacking sequence on delamination crack propagation, free edge delamination initiation and propagation, and damage and delamination around pinned holes. Furthermore, if the damage mechanics based in-plane failure modes are incorporated into the solid continuum elements representing the plies, it is possible to study the coupling effects between in-plane damage and out-of-plane delamination simultaneously, which is a topic that has not been adequately addressed to date.

In this work, some motivating calculations will be demonstrated using a relatively simple cohesive law. Even with such a simple law (and recognizing that further considerations may lead to more complex laws), the results encourage the idea that the cohesive modeling approach can create remarkably realistic simulations of complex damage evolution. The mode-dependent CZM proposed by Yang [16] for other de-adhesion problems will be extended to account for 3D fracture, i.e., mixed mode I, mode II and mode III fracture. Numerical examples will be shown that such a CZM can adequately reproduce experimentally measured crack shapes that have been reported in the literature.

2. 3D COHESIVE ZONE MODEL FOR DELAMINATION

The mixed-mode cohesive zone model (CZM) shown in Figure 2 was shown by Yang and Thouless [16] to lead to accurate predictions of mixed mode fracture of adhesively bonded joints with large nonlinear deformations. The law summarizes the mechanics of the deformation and failure of a polymer-based adhesive within a nonlinear crack process zone. The length of the zone is not specified a priori, but will depend on the stress distribution near the crack tip in a particular loading geometry. The law is generalized here to treat 3D fracture (mixed mode I, II, and III).

The CZM is implemented in elements that allow it to represent a weak layer of material that may be assigned either nonzero or zero thickness. The elements can be embedded in a commercial finite element code.

3D Mode-Dependent Cohesive Zone Model

The CZM uses independent cohesive laws for the opening mode (mode I) and shear modes (modes II and III), so that the toughnesses (total area underneath the cohesive laws) and cohesive strengths for the three modes can be different (Fig. 2a). Dependence on mode of toughness and strength is typically the case for interlaminar cracks [23]. The CZM accommodates separation of the total energy absorbed during fracture, $\mathcal{G}$, into the opening and shear components, $\mathcal{G}_{\mathrm{I}}$, $\mathcal{G}_{\mathrm{II}}$, and $\mathcal{G}_{\mathrm{III}}$:

$$\mathcal{G} = \mathcal{G}_{\mathrm{I}} + \mathcal{G}_{\mathrm{II}} + \mathcal{G}_{\mathrm{III}} \tag{1}$$

where the separate components can be calculated by integration of the mode I, II and III traction-separation curves (Fig. 2a):

$$\mathcal{G}_I(\delta_n) = \int_0^{\delta_n} \sigma(\delta_n')\,d\delta_n'; \tag{2a}$$

$$\mathcal{G}_{II}(\delta_{tx}) = \int_0^{\delta_{tx}} \tau_x(\delta_{tx}')\,d\delta_{tx}' \tag{2b}$$

$$\mathcal{G}_{III}(\delta_{ty}) = \int_0^{\delta_{ty}} \tau_y(\delta_{ty}')\,d\delta_{ty}' \tag{2c}$$

where δ_{n}, δ_{tx}, and δ_{ty} denote the mode I, II, and III displacement jumps across the interface and σ, τ_{x}, and τ_{y} the corresponding mode I, II, and II cohesive tractions, respectively. The energy release rate components are not independent parameters; they evolve together as a natural result of the interplay between the deformation of the adherends and the physics embedded in the traction-separation laws. A failure criterion is required to specify conditions for separation (failure) in the CZM. The criterion used here is a simple one:

$$\mathcal{D} = \mathcal{G}_I / \mathcal{G}_I(\delta_{nc}) + \mathcal{G}_{II} / \mathcal{G}_{II}(\delta_{txc}) + \mathcal{G}_{III} / \mathcal{G}_{III}(\delta_{tyc}) = 1 \tag{3}$$

where $\mathcal{D}$ is a damage measure ranging from 0 (undamaged) to 1 (fully debonded). The assumption that the same cohesive traction law is appropriate for modes II and III is made in the absence of experimental information about mode III delamination fracture in the literature. The

CZ element is shown in Figure 2(b). A detailed formulation and implementation of such elements in a standard commercial FE package (ABAQUS) can be found in Yang [25].

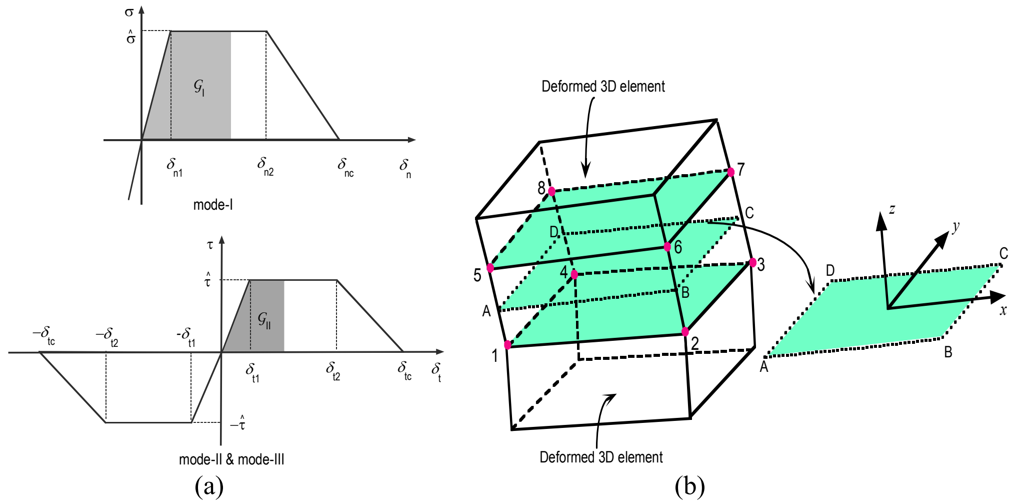


Figure 2. (a) A mode-dependent cohesive zone model proposed by Yang [16], and (b) Definition of the 3D CZM elements. The element has 4 node-pairs that link to its surround solid elements. The tractions between each load pair are shown in (a).

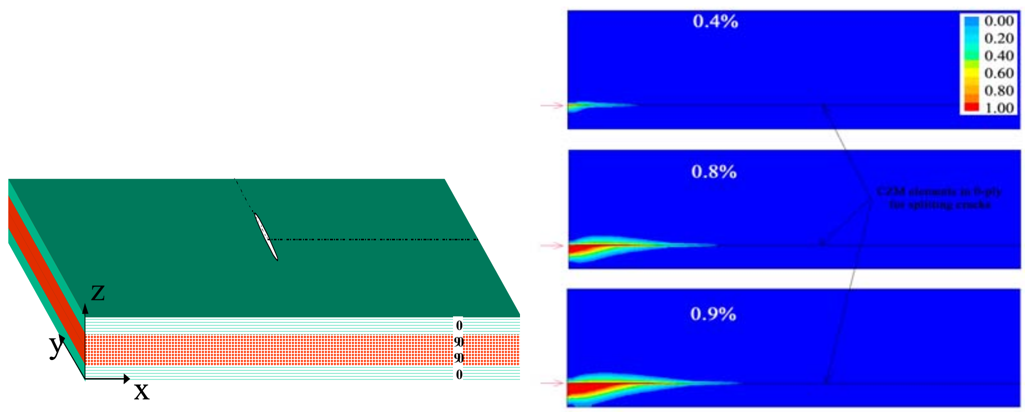
During a deformation process, displacement increments will be passed on to the cohesive element, within which the separations and tractions are updated according to the cohesive laws. The updated nodal force vectors and stiffness matrix are then added to the global stiffness matrix to check the total force balance. Iteration continues until an equilibrium condition is satisfied for each displacement increment.

Most emphatically, it is inappropriate to regard the above CZM element as a simple spring element connecting single pairs of nodes. In the cohesive element, the separations and nodal forces of the four node-pairs are inter-related, because the nodal forces are integrated from cohesive tractions that are distributed along the entire cohesive surfaces. For a spring element the nodal forces between two points depend only on the relative displacements of that node-pair; and the relation to continuously distributed tractions is therefore inaccurately represented, especially at mesh discontinuities, such as free edges.

A Numerical Example: Coupled Splitting and Delamination in A [0/90/90/0] Laminate

Figure 3 shows the damage evolution in a [0/90/90/0] laminate with a sharp slit in the center (Fig. 3a), for which both in-plane (delamination) and through-thickness (splitting) fracture events can be expected. The splitting cracks will initiate first in the 0° plies. Since the splitting cracks are known from experiments to initiate at the tips of the slit and propagate parallel to the loading direction (the so-called H-crack configuration), their locus was pre-determined by planting a string of CZM elements along these paths within the 0° plies. The same CZM parameters were used for these and the inter-ply elements. The ply elastic constants and cphesive law parameters can be found in [25]. The two symmetry planes, *z-x* and *y-z*, were used to reduce the size of the problem, but not the symmetry plane *x-y*.

Figure 3(b) shows the damage evolution at a 0/90° interface. The line shows the locus of CZM elements planted in the 0° ply to permit a splitting crack. The (pink) arrow indicates the tip of the slit. Under longitudinal tension, interlaminar damage accumulates initially at the tip of the slit. Simultaneously, damage develops in the CZM elements along the splitting crack line. The existence of the splitting damage can be discerned in Fig. 3b as a discontinuity in the damage variable contours for the delamination damage. The splitting damage extends to the furthest manifestation of the delamination damage. At some applied strain, the delamination damage matures into a traction-free delamination crack (red zone). The splitting damage also matures into a traction-free crack (not visible in Fig. 3b). The delamination damage zones above and below the splitting crack grow in an approximately self-similar fashion (although of course they are free to develop any shape in the simulations) until the lower zone hits the symmetric boundary (y = 0). The shapes are qualitatively consistent with experimental observations of Spearing and Beaumount [1] for fatigue damage evolution in specimens of this geometry. In addition, the angle formed by the front of the damage zones is roughly 10°, which again agrees with the experimental observation of 10^0-15^0 range [1].



(a) (b)

Figure 3 (a) A $[0/90]_S$ laminate panel containing a through thickness narrow slit, and (b) Approximately self-similar delamination damage growth between the 0° and 90° plies influenced by a splitting crack in the 0° ply of the $[0/90]_S$ laminate.

3. CONCLUSIONS

A cohesive zone model (CZM) has been formulated that represents mixed mode (modes I, II, and II) damage in a fracture process zone in a layer that can have finite or zero thickness. The CZM discussed here has been motivated by problems of delamination and intra-ply splitting cracks in laminated composites, but has other applicability. The CZM is easily integrated into a commercial finite element code through the use of user-defined element.

The CZM has been formulated not as springs coupling individual pairs of nodes according to local laws (as in prior studies of delamination using cohesive models [24], but as tractions that are evaluated by integrating formally over an entire element, using interpolation between pairs of nodes. This definition avoids spurious cohesive traction concentrations at mesh discontinuities, such as free edges. Correct simulation of damage initiation from free edges (and other fracture characteristics) is therefore made possible.

Simulation of mixed mode damage evolution has been demonstrated for a practical problem in composite engineering, i.e., simultaneous interply delamination and intra-ply splitting crack evolution near a through thickness slit. The problem can not be adequately analyzed by traditional tools such as LEFM and VCCT. The CZM simulation successfully reproduced experimentally measured crack shapes that have been reported in the literature.

Acknowledgments

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References:

1. Spearing, S. M. and P. W. R. Beaumont (1992). Composites Science and Technology **44**: 159-168.
2. Kortschot, M. T. and P. W. R. Beaumont (1990). Composites Science and Technology **39**: 289-301.
3. Chang, K. Y., S. Liu, et al. (1991). Journal of Composite Materials **25**: 274-301.
4. Soutis, C., F. C. Smith, et al. (2000). Composites: Part A **31**: 531-536.
5. Shokrieh, M. M. and L. B. Lessard (2000). Journal of Composite Materials **34**(13): 1056-1080.
6. Pagano, N. J. and G. A. Schoeppner (2000). Delamination of ploymer matrix composites: problems and assessment. Comprehensive Composite Materials. A. Z. C. Kelly. Oxford, Elsevier Science. **2:** 433-528.
7. Garg, A. C. (1988). Engin. Fract. Mech. **29**: 557-584.
8. Rybicki, E. F. and M. F. Kanninen (1977). Engin. Fract. Mech. **9**: 931-938.
9. Tay, T.-E. (2003). Applied Mechanics Review **56**: 1-31.
10. Whitney, J. M. and R. J. Nuismer (1974). Journal of Composite Materials **8**: 253-265
11. Pipes, R. B., R. C. Wetherhold, et al. (1979). Journal of Composite Materials **12**: 1151-1155
12. Spearing, S. M., P. W. R. Beaumont, et al. (1992). Composites Science and Technology **1992**: 169-177.
13. de Borst, R. (2002). Engineering Fracture Mechanics **69**: 95-112.
14. Elices, M., G. V. Guinea, et al. (2002). Engineering Fracture Mechanics **69**: 137-163.
15. Wei, Y. and J. W. Hutchinson (1997). International Journal of Fracture **93**: 315-333.
16. Yang, Q. D. and M. D. Thouless (2001). International Journal of Fracture **110**: 175-187.
17. Needleman, A. (1987). Journal of Applied Mechanics **54**: 525-531.
18. Tvergaard, V. and J. W. Hutchinson (1996). Journal of the Mechanics and Physics of Solids: 789-800.
19. Xu, X.-P. and A. Needleman (1994). Journal of the Mechanics and Physics of Solids **42**: 1397-1434.
20. Needleman, A. and A. J. Rosakis (1999). Journal of the Mechanics and Physics of Solids **47**: 2411-2445.
21. Corigliano, A. (1993). International Journal of Solids and Structures **30**: 2779-2811.
22. Schellekens, J. C. J. and R. de Borst (1996). Key Engineering Materials **121-122**: 131-60.
23. Borg, R., L. Nilsson, et al. (2003). Composites Science and Technology **in press**.
24. Wisnom, M. R. and F.-K. Chang (2000). Composites Science and Technology **60**: 2849-2856.
25. Yang, Q. D. and B. N. Cox (2004). International Journal of Fracture, submitted, 2004.

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