MICROMECHANICS-BASED MODELING OF DAMAGE EVOLUTION IN VISCOELASTIC COMPOSITES

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ABSTRACT

Damage in composite laminates affects their overall viscoelastic response. Previous research has been focused on developing constitutive equations for these materials considering a fixed state of damage. A complete description, however, requires suitable damage evolution laws. This paper is focused on studying damage evolution in viscoelastic laminates using a computational micromechanics approach. We use cohesive finite elements to study nucleation and subsequent growth of a transverse crack between two existing cracks in the 90° layer of a linear viscoelastic cross-ply laminate. The effect of loading rate, thickness of 90° ply and initial crack density on the evolution of a new crack is investigated.

1 INTRODUCTION

Composite materials are prone to damage when they are subjected to quasi-static, fatigue or dynamic loads. Damage mechanisms observed in a multi-directional laminate depend on the laminate configuration. Damage in the form of intra-laminar cracking occurs first in the off-axis layers. These cracks quickly grow to span the entire layer thickness as well as laminate width. These cracks are more or less uniformly spaced. With applied cyclic loading, their number increases and then reaches a saturation level. This level has been termed as Characteristic Damage State (CDS). After reaching a saturation crack density, deterioration in the material occurs in the form of internal delaminations at the tips of these cracks. These delaminations grow with further cyclic loading. The final failure of the laminate occurs by fiber breakage in the 0° plies.

The effects of damage on the elastic behavior of laminated composite materials are extensively studied using micromechanics and continuum damage mechanics approaches. In many service conditions, composite materials are likely to be subjected to high temperature and moisture in addition to the usual mechanical loads. Such conditions induce time dependent viscoelastic response of the constituents and hence a coupling between damage and viscoelasticity. While damage in elastic composite materials is extensively studied, there is relatively little research in understanding damage in viscoelastic composite materials. Most work in this area is limited to particulate composites (cf. Schapery [1] and references therein). For laminated composite materials, Zocher et al. [2] and Kumar and Talreja [3] have applied micromechanics approach to obtain time variation of the overall effective properties at a fixed level of damage. Recently Kumar and Talreja [4] have proposed an internal variables-based continuum damage model for linear viscoelastic behavior of laminated composites for a fixed damage state. The constitutive relationships developed in that work must be supplemented with suitable damage evolution laws.

2 DAMAGE EVOLUTION IN VISCOELASTIC COMPOSITE MATERIALS

Studies on damage evolution in viscoelastically deforming laminated composites are scarce. Moore and Dillard [5] observed time-dependent evolution of matrix cracks in Kevlar/epoxy and graphite/epoxy cross-ply laminates at room temperature. They observed significant effects of loading rate on the crack density evolution. Raghavan and Meshii [6] conducted creep and quasi-static tests on AS4/3501-6 cross-ply laminates at room temperature. Again, a significant effect of strain rate on the nucleation and multiplication of transverse cracks was observed. Akshantala and Brinson [7] have reported a damage evolution model for linear viscoelastic cross-ply laminates. This model is based on extending Hashin's elastic analysis [8] of a cracked cross-ply laminate to the viscoelastic domain. Assuming maximum stress failure criterion, they studied instantaneous formation of a transverse crack midway between two existing cracks. They showed loading rate dependency on the crack formation. However, their assumption of instantaneous formation of a new crack between two existing cracks is not entirely correct. Even though a new crack is formed instantaneously between two existing transverse cracks in the elastic regime, it is not likely to be the case when the laminate is deforming viscoelastically. Depending on the viscoelastic properties and rate of applied loading, it may take certain time to nucleate a crack and to further propagate it to a full transverse crack spanning the entire width of the transverse layer. We shall study these aspects in the present work.

3 COMPUTATIONAL MICROMECHANICS MODEL

In this work we adopt a computational micromechanics approach to understand damage evolution in linear viscoelastic laminated composite materials. We restrict our study to 2-D configuration and consider growth of the crack in the thickness direction only as a simplified first analysis. A schematic of the configuration analyzed is shown in Fig. 1. This figure shows an edge view of a symmetric cross-ply laminate with two fully developed cracks in the 90° plies separated by a distance of *2L*. We are interested in studying nucleation and growth of a new crack in between these cracks. It is known from analytical micromechanics solution that maximum axial stress in the 90° plies occurs midway between the existing cracks. Thus a new transverse crack can nucleate and grow in a plane located here and lying parallel to the existing crack planes.

To study the evolution of this crack, we embed cohesive surfaces in this plane. These cohesive surfaces are modeled using 2D cohesive finite elements with the traction-displacement law as given by Xu and Needleman [9]. This law is derived from a potential Φ , which for 2D problems is given by

$$\Phi(\Delta_n,\Delta_t)=\Gamma_o\left[1-\left(1+\frac{\Delta_n}{\delta_{cr}}\right)\exp\left(-\frac{\Delta_n}{\delta_{cr}}\right)\exp\left(-\frac{\Delta_t^2}{\delta_{cr}^2}\right)\right]. \tag{1}$$

In this equation, the fracture energy per unit area Γ_o and the critical opening displacement δ_{cr} (corresponding to the maximum traction) are assumed to be same in both normal and tangential directions. The fracture energy is related to the maximum stress and the critical opening displacement through $\Gamma_o = e\sigma_{\max}\delta_{cr}$. Normal and tangential tractions are obtained from this potential by differentiating it with respect to the opening displacements Δ_n and Δ_t, respectively. These tractions are used to calculate the element tangent stiffness matrix.

A two dimensional, four noded cohesive finite element is developed and implemented as a user element (UEL) in the ABAQUS finite element analysis program (Abaqus, Inc. [10]). The details of the finite element formulation are described in Kumar [11]. An implicit integration formulation is used for the analysis which involves incremental-iterative solution of the nonlinear equations using full Newton-Raphson algorithm. A number of single element simulations were conducted to verify the element formulation. The element was also verified for a quasi-static crack growth in an elastic double cantilever beam specimen similar to that used by Rahulkumar et al. [12].

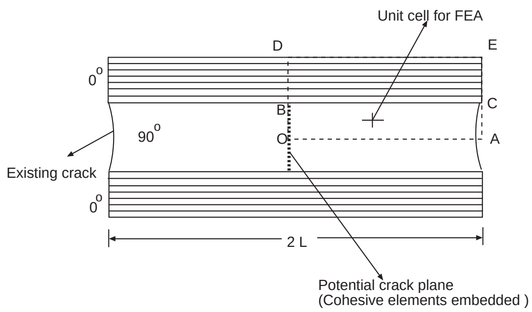

Fig. 1: Analysis configuration

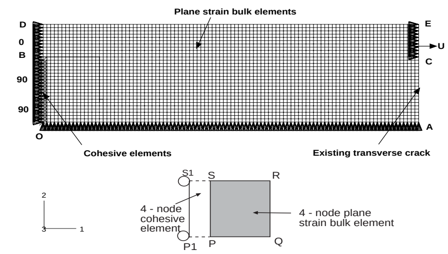

Fig. 2: Typical finite element mesh

A typical finite element mesh used in the analysis is shown in Fig. 2. Note that only a quarter of the unit cell (shown in Fig. 1) is considered for the finite element simulation due to the symmetry. In Fig. 2, *OACB* represents 90° layers and *BCED* represents 0° layer. *OA* is the laminate mid-plane and hence a plane of symmetry. Plane *OD* is also a plane of symmetry. *AC* is the traction free surface representing the existing crack. Length *OA* depends on the initial crack density. Cohesive elements are embedded only in the 90° plies, i.e., along the plane *OB*. The laminate is loaded by applying displacement u on the plane *CE*. We consider an IM7/8320 material system. The fibers are assumed to be transversely isotropic and elastic, whereas the matrix is taken as isotropic and linear viscoelastic. The relaxation modulus of the matrix is taken from Zocher et al. [2]. The material properties are listed in Table 1. Orthotropic lamina properties are derived from fiber and matrix properties using a viscoelastic extension of Composite Cylinder Assemblage (CCA) model. These properties are then used to describe the constitutive behavior of the bulk elements in the finite element mesh via a user material model (UMAT) (see Kumar and Talreja [4] and Kumar [11] for the details). The bulk elements considered in the analysis are four node continuum plane strain elements.

Table 1: Fiber and Matrix Properties

- Fiber (Transversely Isotropic, Volume fraction = 0.6)

  $E_L = 256.76$ GPa

  $E_T = 25.51$ GPa

  $\nu_{LT} = 0.289$

  $\nu_{TT} = 0.380$

  $G_{LT} = 22.06$ GPa

  $G_{TT} = 9.25$ GPa

- Matrix (Isotropic, Linearly viscoelastic)

$$\tilde{E}_m = \frac{6.8947 \text{ X } 10^3}{880 + 19.780\,\Gamma(1.33) s^{-0.33}} \quad \text{GPa}$$

  $\nu_m = 0.3$

The parameters used in the cohesive law are chosen as $\gamma_o = 22$ J/m^2 and $\sigma_{\max} = 12.65$ MPa. The critical opening displacement δ_{cr} is obtained as $0.64\ \mu m$. These parameters are of an order of magnitude expected to be typical for a transverse ply. However, they are not true material properties. These parameters must be adjusted by comparing the simulation results with experimental data. However, due to the lack of suitable experimental data, this is not done in the present study. Our aim is to merely evaluate the suitability of the cohesive modeling approach by observing the trends in the simulation results. Crack growth is based on the criterion that a point fails when the normal opening displacement Δ_n is greater than or equal to five times the critical opening displacement δ_{cr}, i.e., when $\Delta_n \geq 5\delta_{cr}$. Similar criterion has been adopted by other researchers in conjunction with crack growth in elastic materials.

As shown in Fig. 2, a uniform mesh is used for the analysis. Ten elements are used per ply thickness. The number of elements along the length (axis - 1) depends on the initial crack density and the aspect ratio of the elements. The connection between a bulk element and a cohesive element is shown schematically in Fig. 2. Face *PS* of the cohesive element is connected to the bulk element, whereas face P_1S_1 is supported on "rollers" as required by the symmetry condition. The symmetry condition also requires the *v*-displacement of the nodes forming the two cohesive surfaces to be same. This is applied as a constraint condition. In the initial undeformed state, nodes forming the two faces of the cohesive element have same coordinates. Under the action of applied loading, the bulk elements deform in a time-dependent fashion. This causes the two faces of the cohesive elements to separate in a time-dependent manner as well.

4 RESULTS AND DISCUSSION

Nucleation of a transverse crack and its growth in the ply thickness direction is considered for cross-ply laminates deforming in a linear viscoelastic manner. Effects of initial crack spacing (or initial crack density), ply constraint and applied strain rate are considered. Fig. 3 shows the plot of normalized crack length (normalized with respect to 90° plies thickness) with time for a $[0/90_2]_S$ cross-ply laminate with an initial crack density of 0.4/mm and loaded with different applied strain rates. It is seen that applied strain rate has an effect on the nucleation time of a crack. However, the rate of crack growth is same for all three cases as the curves can be superimposed by lateral translation. This is a manifestation of the linear viscoelasticity. Time required to nucleate and grow a crack is higher for the laminate loaded at a lower strain rate, as expected.

The stiff 0° plies constrain the deformation behavior and damage evolution in the 90° plies. The constraint effect can be studied by varying the structural stiffness ratio of the two plies. This can be done by varying the thickness of the 90° plies while keeping the thickness of the 0° plies constant. In the present research, we analyzed three configurations, viz., $[0/90]_S$, $[0/90_2]_S$ and $[0/90_3]_S$ laminates. The thickness of the 90° plies is smallest in the first case, and hence it is the most constrained configuration. The $[0/90_3]_S$ laminate is the least constrained configuration. Keeping the material properties, initial crack density (at 0.4/mm) and loading strain rate (1E-3 /sec.) same for the three cases, evolution of a new crack is observed. Fig. 4 shows the variation of normalized crack length with time. It is observed that the constraint effect is quite significant on both nucleation and subsequent growth of a crack. The nucleation is significantly delayed in the most constrained case. Further, in such laminates, the final failure (i.e., failure of the 0° plies) may occur even before the crack develops fully.

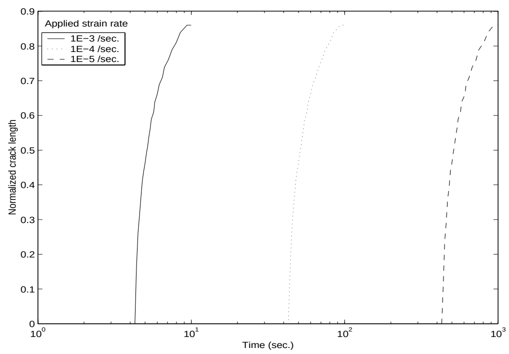

Figure 3: Effects of Loading Strain Rate on the Nucleation and Growth of a Crack in $[0/90_2]_S$ Laminate with Initial Crack Density of 0.4/mm

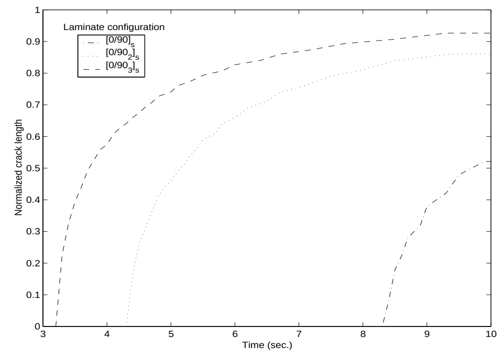

Figure 4: Effects of Ply Constraint on the Nucleation and Growth of a Crack (Initial Crack Density of 0.4/mm; Loading Strain Rate is 1E-3 /sec.)

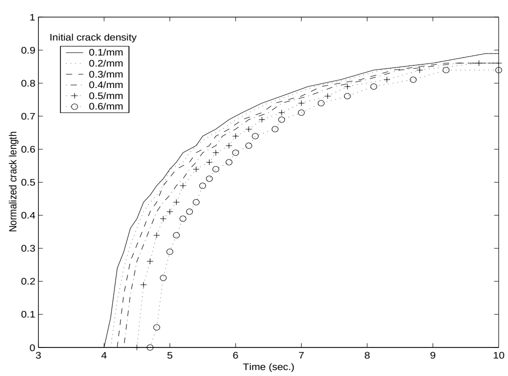

Figure 5: Effects of Initial Crack Density on the Nucleation and Growth of a New Crack in a $[0/90_2]_S$ Laminate Loaded at a Strain Rate of 1E-3 /sec.

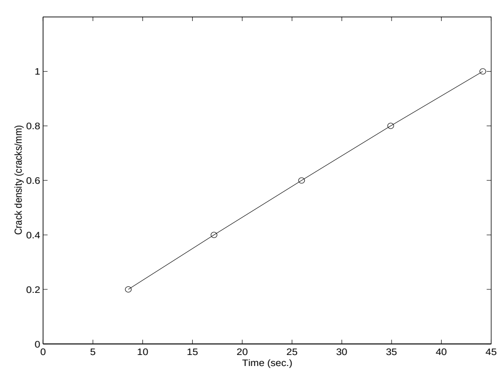

Figure 6: Crack Density Evolution in $[0/90_2]_S$ Laminate Loaded at a Strain rate of 1E-3 /sec.

Finally we consider the effects of initial crack spacing (initial crack density) on nucleation and growth of a new crack. We consider a fixed laminate configuration, $[0/90_2]_S$, and a fixed loading strain rate of 1E-3 /sec. By considering different lengths *2L* of the unit cell (Fig. 1), the initial crack density can be varied. The formation of a crack is then examined using the finite element analysis procedure. Fig. 5 shows the crack length as a function of time for different initial crack spacing. It is observed that when the initial crack spacing is smaller (i.e. higher initial crack density), nucleation of a new crack is delayed. This is because as the crack density increases, the axial stress in the 90° plies midway between the two cracks reduces. Hence more stress needs to be applied to form a new crack. This is in agreement with what has been observed for elastic laminates. From Fig. 5, the time required to form a "full" crack (taken here as 85% of 90° plies thickness) can be obtained for each crack density. This would then correspond to the time required to double the crack density. A plot showing the evolution of crack density is shown in Fig. 6. It is implicitly assumed here that a new crack forms only after the previous one has grown fully.

5 CONCLUSIONS

A computational micromechanics approach employing cohesive finite element is used to study damage evolution in linear viscoelastic composite laminates. Time dependent nucleation and growth of a transverse crack in between two existing cracks is studied. Effects of loading strain-rate, ply constraints and initial crack density (spacing) are studied. It is observed that these parameters have a significant effect on the nucleation time for a crack. They also affect the subsequent growth of the crack. The results show that cohesive finite element modeling approach is suitable for clarifying damage mechanisms and to study the effects of material and damage parameters on damage evolution in laminated composite materials. However, for realistic cases, a rate-dependent cohesive law must be adopted. Parametric studies using such a formulation must be used in conjunction with experiments to develop reliable phenomenological damage evolution laws. This study is underway and the results from it will be presented in the future.

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