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Failure response of fiber-epoxy unidirectional laminate under transverse tensile/compressive loading using finite-volume micromechanics

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ABSTRACT

The transverse damage initiation and extension of a unidirectional laminated composite under transverse tensile/compressive loading are evaluated by means of Representative Volume Element (RVE) presented in this paper based on an advanced homogenization model called finite-volume direct averaging micromechanics (FVDAM) theory. Fiber, fiber-matrix interface and matrix phases are considered within the RVE in determining fiber-matrix interface debonding and matrix cracking. The simulated fracture patterns are shown to be in good agreement with experimental observations.

1. Introduction

Transverse failure is one of the most important failure patterns in composites. Composite laminates that are subjected to complex loading usually show transverse cracking as the first observable phenomenon which often causes the first deviation from linear behavior. In many applications such as pressure vessels and pipes the transverse cracking is not allowed to occur in the composite structure.

The transverse failure behavior of undirectional fiber-epoxy systems is characterized by a combination of fiber debonding and epoxy cracking, many authors have investigated the influence of the matrix and interface properties on the mechanical behavior of composites through experimental [1–4] or numerical methods [5]. Among these researchers, Vaughan, McCarthy, Liu and Qi et al. [6–9] pointed out that both the matrix properties and interface properties affect the failure characteristics of composites. Hobbiebrunken [3] Canal [10] and Gamstedt [1]et al. presented experimental evidence of matrix failure and/or interface failure using in situ SEM experiments. The effect of local fiber array irregularities on microscopic interfacial normal stress states for transversely loaded unidirectional composites has been examined by Hojo [11]. Transverse fracture is often the first failure mechanism that occurs early in the loading stage of composite structures and the transverse fracture strain is often much smaller than that of neat resin [12]. A transverse crack under tensile/compressive loading, what we call first-ply failure, sometimes causes considerable damage and leaks, and can trigger fatal delamination. So a number of experimental methods [13–15] and numerical simulations [16–26]of transverse failure of unidirectional composites have been studied to reveal the failure behavior.

While the above-mentioned authors have proved the important influence of matrix and interfacial debonding on the transverse damage behavior of a unidirectional laminated composite, the damage initiation and evolution process and the interactions of different damage mechanisms based on the semi-analytical model have not been revealed. In order to simulate composite failures microscopically, a high-fidelity microscopic model with individual fibers, matrix and fiber-matrix interface should be employed. The finite-volume direct averaging micromechanics (FVDAM) theory developed by Bansal, Khatam and Pindera [27,28] is a promising choice, and the recent generalization of the finite-volume theory for plane elastic problems on rectangular domains proposed by Cavalcante and Pindera [29–32] offered several advantages with respect to the original version. There are two primary failure patterns when the unidirectional composite laminate is subjected to

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transverse loading (tensile/compressive loading), one is the fiber-matrix interface debonding and the other is matrix failure. Therefore in this paper, the maximum-stress criterion component-based for matrix damage and interface failure criterion under local normal and tangential stress conditions are implemented, while fiber failure is disregarded. Herein, a semi-analytical FVDAM-based damage model with random arrays of fibers [33]which accounts for the interface damage is presented and employed to predict transverse failure of unidirectional laminates.

2. Computational model

This work establishes a new virtual experiment using a progressive damage model on which a new finite volume method called FVDAM is used to test the transverse behavior of fiber-reinforced composites. The transverse stress–strain relationship and failure mode pattern under uniaxial tension or compression are obtained by progressive damage analysis method. And then the failure pattern is compared with that obtained in an actual experiment. Finally the influence of the interphase strength on the stress–strain curve is analyzed with this virtual experiment.

2.1. Finite-volume direct averaging micromechanics(FVDAM)

FVDAM is a 0th order homogenization theory based on unit cell discretization into N_β columns and N_γ rows of rectangular subvolume. The displacement field in the each (β, γ) subvolume is given by the same two-scale expansion $u_i^{(q)}(x,y) = \bar{\varepsilon}_{ij}x_j + u_i'^{(q)}(y)$ based on macroscopic and fluctuating components, the fluctuating components are approximated by the second-order, Legendre-type polynomial expansion in the local coordinates

$$u_i'^{(\beta,\gamma)} = W_{i(00)}^{(\beta,\gamma)} + \bar{y}_2^{(\beta)} W_{i(10)}^{(\beta,\gamma)} + \bar{y}_3^{(\gamma)} W_{i(01)}^{(\beta,\gamma)} + \frac{1}{2}\left(3\bar{y}_2^{(\beta)2} - \frac{h_\beta^2}{4}\right) W_{i(20)}^{(\beta,\gamma)} + \frac{1}{2}\left(3\bar{y}_3^{(\gamma)2} - \frac{l_\gamma^2}{4}\right) W_{i(02)}^{(\beta,\gamma)} \tag{1}$$

The unknown coefficients are determined by satisfying the equilibrium equations locally in a surface-average sense, and then imposing continuity of surface-averaged displacements and tractions in conjunction with periodic boundary conditions. This leads to the global system of equations for the unknown surface-averaged displacements

$$\mathbf{K}\widehat{\mathbf{U}}' = \mathbf{C}\bar{\varepsilon} \tag{2}$$

Solution of Eq. (2) produces the (β, γ) subvolume localization relations in the homogenized Hooke's law for the unidirectional laminate.

2.2. Generation and discretization of RVE

A square representative volume element (RVE), which contains a random and homogeneous dispersion of circular fibers embedded in the polymeric matrix, is selected to predict failure behavior of the unidirectional laminate under transverse loading, in which the fiber and matrix are represented by an elastic solid, fiber/matrix elastic decohesive behavior is introduced by means of interface model whose behavior is controlled by a crack model provided by Tang [33]. Fibers intersecting the RVE edges are split into an appropriate number of parts and copied to the opposite sides of the square RVE to create a periodic microstructure. New fibers were added until the desired volume fraction of 60% was reached. An example of the fiber distribution an RVE with 23 fibers is shown in Fig. 1.

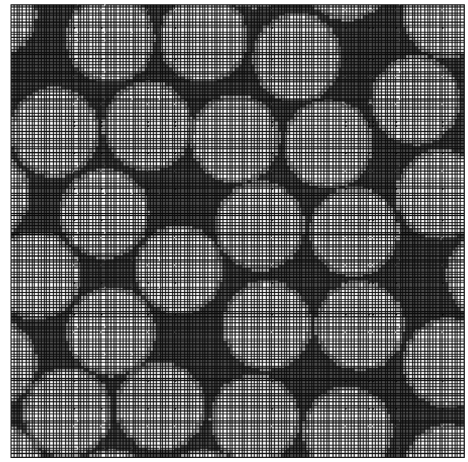

Fig. 1. Fiber distribution and mesh discretization (150 × 150) of a representative volume element of the composite with 23 fibers.

2.3. The matrix damage and interfacial debonding model

2.3.1. Failure theory used at the matrix phase

The employed failure theory is outlined herein, which is applied at the matrix constituent level. In the sequel, X_C, X_T and X_S are the compressive, tensile and shear strengths.

$$\begin{cases} X_C < \sigma_{11} < X_T \\ X_C < \sigma_{22} < X_T \\ X_C < \sigma_{33} < X_T \end{cases}, \begin{cases} |\sigma_{23}| < X_S \\ |\sigma_{13}| < X_S \\ |\sigma_{12}| < X_S \end{cases} \tag{3}$$

2.3.2. Fiber–matrix interface failure criterion

The following condition is employed to determine whether the fiber–matrix interface has been damaged

$$\left(\frac{\langle t_n \rangle}{Y_n}\right)^2 + \left(\frac{t_t}{Y_t}\right)^2 = 1 \tag{4}$$

where angular bracket ⟨⟩ stand for the Macaulay brackets, which return the argument if positive and zero otherwise, so that there will be no damage at the interface when the interface is under compression. t_n and t_t indicate interfacial tractions in normal and tangential directions, respectively, while Y_n and Y_t represent the maximum allowable values of interfacial tractions in those two directions, respectively.

2.3.3. Stress components of interface

The stresses utilized in the fiber/matrix failure criterion are obtained from the lamination theory analysis in the global coordinate system, but the stresses applied in the interface failure criterion are expressed in the local coordinate system with the origin at the center of the fiber, as shown in Fig. 2. The normal interfacial tractions T_n and the tangential interfacial tractions T_t are comprised of the global stress vector components (T_2^I, T_3^I), see Eq. (5) and Eq. (6).

$$T_n = T_2^I \sin(\theta) + T_3^I \cos(\theta) \tag{5}$$

$$T_t = T_2^I \cos(\theta) + T_3^I \sin(\theta) \tag{6}$$