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Determination of the first ply failure load for a cross ply laminate subjected to uniaxial tension through computational micromechanics

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ABSTRACT

A method for determining the in situ strength of fiber-reinforced laminas for three types of transverse loading including compression, tension and shear is presented. In the framework of this method, an analysis of local stresses that are responsible for the coalescence of matrix cracks is carried out by using a multi-fiber unit cell model and finite element method. The random distribution of fibers, fiber–matrix decohesion and matrix plastic deformations are taken into account in the micromechanical simulations. The present study also shows that the nonlinear hardening behavior of matrix reflects more realistically the influence of plastic deformations on the in situ transverse strength of lamina than the perfectly plastic behavior of matrix. The prediction of the in situ transverse strength is verified against the experimental data for a cross ply laminate subjected to uniaxial tension.

1. Introduction

When a fiber-reinforced polymer–matrix composite lamina is subjected to transverse loading, it fails due to matrix cracking. The physics of matrix cracking at the microscopic level is related to the appearance of fiber/matrix debonding, small cracks and plastic deformation within the matrix (Gonzalez and LLorca, 2007; Hobbiebrunken et al., 2006). For an isolated lamina, the initiation of the first matrix cracks indicates fracture of the lamina. This process happens differently when the lamina is embedded in a laminate. Since other laminas in a laminate retard the propagation of the matrix cracks, the stiffness of cracked lamina does not drop suddenly but declines gradually with increasing load. In this case, the strains to failure are larger than those of an isolated lamina. Calculation of the laminate stiffness reduction due to matrix cracking can be made by using progressive damage analysis at various scales (from the scale of the fiber to scale of the structure). Typically, matrix cracking is studied at the ply scale by using a unit cell which is a representative of the whole laminate. In each lamina, a measure of damage is the crack density which grows until the lamina is saturated with cracks. A number of mesoscale models for cross-ply laminates have been proposed in the literature in order to predict the degradation of the stiffness due to matrix cracking (see for example, Nairn, 1989; McCartney, 1998; Barbero and Cortes, 2010; Lubineau, 2010). This paper presents an alternative approach for matrix cracking based on a unit cell of a single lamina. In this case, a measure of damage is plastic deformation of the matrix which leads to matrix cracking

The reduction of lamina stiffness due to matrix cracking can be determined at the fiber scale by using computational micromechanics. Most of the literature on this subject, such as papers by Llorca and co-workers (2007, 2008), Vaughan and McCarthy (2011a,b) focuses on the study of the influence of matrix and interface properties on the macroscopic response of lamina. In these papers, the authors have proved the utility of unit cell models with random fiber arrangement in determining the transverse strength of isolated laminas. However, they have provided no prediction of the critical damage threshold in polymer matrices. Further development of this approach is to be found in papers by Melro et al. (2013), Yang et al. (2012), who have applied more complex constitutive laws of the matrices to trace the damage evolution in isolated laminas up to final failure. Although these studies have substantially contributed to our understanding of the failure behavior of unidirectional laminas under transverse loading, the constraining effects of other laminas have been less recognized. Modeling of matrix cracking initiation and evolution in cross ply composite laminates subjected to in-plane shear through multi-fiber unit cells has recently been presented by Totry et al. (2009), Ng et al. (2010), Soni et al. (2014). In these papers, the authors found the in-plane shear stress–strain response of laminates by averaging the shear responses of plies. Although they have successfully established methodology for modeling of cross ply composite

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laminates, they have not considered the coalescence of matrix cracks that corresponds to the first ply failure.

The main objective of this paper is to present a simple procedure based on the use of the unit cell with random fiber arrangement and the finite element method to predict the load at which the first lamina embedded in a laminate fails. For this purpose, an analysis of the hoop stresses that are responsible for the coalescence of the matrix cracks is carried out in the present paper. To find the in situ strength of lamina, the criterion of maximum hoop stress in matrix is used locally for the most loaded fiber. The first ply failure load predicted from proposed method is verified against the experimental data for a cross ply laminate subjected to uniaxial tension.

Another objective of this paper is to assess whether, and to what extent, the transverse failure behavior of lamina is sensitive to the hardening of matrix due to plastic deformation. Most of the numerical simulations on the mechanical behavior of composite laminas under transverse loading are based on an assumption that polymer matrices can be represented by an elastic-perfectly plastic solid following the one of the pressure-sensitive yield criterions. Although this simple model of plasticity is able to reproduce the localization of damage along a narrow fracture path, it leads to the overestimation of the plastic deformation because, in reality, a polymer matrix hardens and its ductility decreases. An alternative approach is to consider in situ properties of the matrix that are back-calculated from experimental data of the lamina. The role of the in situ properties of matrix in modeling the matrix cracking failure mode remains unexplored and therefore is also undertaken in this paper.

2. Micromechanical models

Numerical simulations using a concept of the unit cell with random fiber arrangement are a current trend of work in computational micromechanics. The benefit of the use of such unit cells is that the effect of fiber array irregularities on transverse responses of composite can be accurately taken into account. In this paper, the unit cell models of randomly distributed fiber composite are generated using Wongsto and Li's algorithm (Wongsto and Li, 2005). Analyses were made on models that contained 39 fibers. The data required for the simulation study were taken from the world wide failure exercise WWFE (Soden et al., 1998) for an example case of E-glass/MY750/HY917/DY063 lamina with the fiber volume content of 60%. The properties of this material and its constituents are listed in Table 1. Two-dimensional finite element meshes that mainly consisted of plane strain elements with four nodes (PLANE182) were constructed by using ANSYS finite element code. To ensure accurate displacement and stress field representation within each unit cell, sufficiently dense meshes comprising of approximately 45,000 elements were used. A cohesive layer consisted of contact elements with four nodes (CONTA172, TARGE169) was introduced between the fibers and the matrix to reproduce the fiber–matrix debonding. Each fiber/matrix interface contained 100 contact elements equally spaced around the circumference. Previous works by Vaughan and McCarthy (2011a,b) have shown that this finite element topology gives converged solutions.

Table 1
Mechanical properties of the unidirectional lamina and its constituents.

E-glass fiber		MY750 epoxy matrix				lamina				
E_f [GPa]	ν_f	E_m [GPa]	ν_m	k [MPa]	μ	ε_{2T} [%]	ε_{2C} [%]	σ_{2T} [MPa]	σ_{2C} [MPa]	V_f [%]
74	0.2	4	0.35	43.35	0.1	0.246	1.2	40	145	60

Fiber–matrix interface

k_n [GPa/m]	k_t [GPa/m]	G_n^c [J/m^2]	G_t^c [J/m^2]	σ_n^c [MPa]	τ_t^c [MPa]
0.1×10^9	0.1×10^9	15	30	30	60

2.1. Numerical homogenization technique

In this paper, the effect of the matrix ductility has been studied for the selected lamina subjected to three types of transverse loading including compression, tension and shear. For each loading type, periodic boundary conditions were imposed on the unit cell to reflect the repeatability of the microstructure and to ensure the compatibility of the displacement fields. By the assumption of periodicity, each displacement field u_i may be decomposed in a part associated with the applied strain ε_{ij} and a periodic one u_i^p (Suquet, 1987)

$$u_i(x_1, x_2) = \varepsilon_{ij} x_j + u_i^p(x_1, x_2) \tag{1}$$

These relations are implemented at each periodic pair of nodes to link the displacements of the top and the bottom boundaries and the displacements of the right and left boundaries of the unit cell. Because of a huge number of nodes at the opposite boundary edges, a Ansys APDL macro has been used to generate automatically all required constraint conditions (1). The normal σ_2 and shear τ_{23} stresses corresponding to the applied strains ε_2 and $2\varepsilon_{23}$ were computed from the resultant normal and tangential forces acting on the edges divided by the actual cross-section.

2.2. Constitutive equations of matrix and interface

Although the extension of plastic strain zones in polymer matrices is inhibited by the nearest fibers, they can exhibit considerable plastic deformation between the fibers (Fiedler et al., 2001; Hobbiebrunken et al., 2007). This is because when the probability of finding defects (e.g., voids, microcracks) is low, the glassy polymers like epoxy can deform plastically. It is well known that the presence of defects induces a triaxial stress state which reduces locally the ductility of material. Thus, when the size scale is decreased, the failure behavior of epoxy changes from brittle to ductile. The epoxy matrix is therefore modeled within the framework of the finite deformations as a elasto-plastic solid which hardens isotropically. It is widely accepted, nowadays, that the deformation of polymeric materials is highly sensitive to the hydrostatic pressure and plastic flow of these materials can exhibit plastic dilatancy. To address this requirement, the Drucker–Prager plasticity model (Drucker and Prager, 1952), which incorporates the linear dependence on the hydrostatic stress, is used. In terms of the first invariant of stress I_1 and the second invariant of the deviatoric part of stress J_2, the yield function is given as

$$\mathrm{f} = (\mu I_1/3) + \mathrm{sqrt}(J_2) - k, \tag{2}$$

where μ is the pressure sensitivity factor, k is the flow stress of the material under pure shear. Experiments showed that the pressure-sensitivity factor μ ranges from 0.10 to 0.25 for polymers (Kinloch and Young, 1983; Quinson et al., 1997). Note, that if $\mu = 0$, Eq. (2) reduces to the von Mises yield function. The Drucker–Prager plasticity model with $\mu = 0.1$ and $k = 43.30$ MPa was used to study the role of the matrix ductility in the matrix cracking failure mode. An associative flow rule is used to compute the direction of plastic flow. More details regarding the flow rule may be found in Ansys theory manual (Ansys, 2012).

For the fiber/matrix interface failure, the cohesive zone model is employed, in which the constitutive equations of the interface relate the normal σ_n and tangential τ_t cohesive tractions to the