Near-tip dual-length scale mechanics of mode I cracking in laminate brittle matrix composites

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Abstract. This paper presents the results of a numerical study on the near-tip mechanics of mode I cracking in brittle matrix composite laminates. A finite element model is developed within the context of two competing characteristic lengths present in the composite, i.e., the microstructural length such as the layer thickness and the macro-length such as the crack length, uncracked ligament size, etc. The crack surfaces are assumed to be traction free and perpendicular to the reinforcing layers. Conditions leading to macroscopic homogeneous orthotropic mechanical behavior are also assumed. Thus, the near-tip numerical studies are carried out within a small-scale heterogeneous zone which surrounds the crack tip and is dominated at its outer boundary by the displacements associated with a mode I crack in a homogeneous orthotropic medium. The model is used to calculate the stresses and stress intensities in the vicinity of the crack tip which develop due to the alternating fiber/matrix heterogeneous composite microstructure. Parameter studies elucidating the effects of the two competing composite characteristic lengths on the evolution and structure of the near-tip heterogeneous stress fields are carried out. The results indicate that when the characteristic microstructural length is relatively large compared to the macroscopic length, the singular heterogeneous stress fields may deviate substantially from the assumed homogenized orthotropic fields. The study can be used to determine the necessary conditions under which homogenization applies in obtaining an accurate description of the stresses in the vicinity of the crack tip in a laminated composite.

1. Introduction

A significant amount of research has been conducted aimed at gaining better understanding of the fracture mechanics of Brittle Matrix Composites (BMCs). Some of the earlier work [1–3] concentrated on the development of models which could be used to predict the first matrix cracking stress under mode I loading conditions. These models addressed primarily fiber reinforced systems and were developed utilizing the mechanics of a fundamental fiber/matrix unit cell subjected to remote tension. More recently the problems of stability of fiber failure [4–6], fiber debonding [7–8] and delamination in composite laminates [9, 10] have been addressed.

For mode I problems in which the crack propagates in a direction which is perpendicular to the fiber reinforcement, various techniques have been used to solve for the stress intensity factor driving the matrix crack. For example, in accordance with the 'unit cell' models the onset of crack growth is assessed with the aid of a $K_{\text{ortho}}$-dominated local zone, the extent of which is controlled by the composite microstructure, such as the fiber or the composite cylinder diameter for fiber reinforced composites, or the layer thickness in composite laminates shown in Fig. 1a. In other methods, the microstructure of the composite is smeared out and the material is modeled as homogeneous anisotropic consistent with Fig. 1b. To predict matrix cracking it is assumed that the local matrix stress intensity factor $K_{\text{tip}}^m$ (the stress intensity factor which exists when the crack tip is in the matrix) is related to the orthotropic $K_{\text{ortho}}$
through the relation $K_{\text{tip}}^{\text{ ortho }} = K_{\text{ ortho }} E_m / E_c$, where $E_m$ and $E_c$ represent the elastic moduli of the matrix and the composite respectively. This relation, which follows from the assumption that the rule of mixtures applies for stress intensity factors, implies that the stress and strain fields in the vicinity of the crack tip are dominated by $K_{\text{ ortho }}$ regardless of the details of the microstructure. Such an approach may be warranted for composite systems wherein the microstructural characteristic length is sufficiently smaller than its dual macroscopic characteristic length obtained from the finite specimen geometry. As discussed elsewhere [11], although such conditions may apply to fiber reinforced systems, it is very likely that they may be violated in composite laminate systems in which case a more thorough study of the near tip mechanics is warranted.

The present study addresses the near-tip mechanics of mode I cracking in brittle matrix composite laminates within the context of two competing characteristic lengths: the microstructural length $\ell$ and the macro-length $L$. The term ‘dual length scale mechanics’ arises from the competition between these lengths to characterize the near-tip singular stress field in the composite. As such, in this paper emphasis is placed on the mechanics governing the elastic singular stress...