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Fiber-size effects on the onset of fiber–matrix debonding under transverse tension: A comparison between cohesive zone and finite fracture mechanics models

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ABSTRACT

The problem of fiber–matrix debonding due to transverse loading is revisited. Predictions of the critical load for the debond onset obtained by a Cohesive Zone Model combined with contact mechanics and by a Finite Fracture Mechanics model based on a coupled stress and energy criterion are compared. Both models predict a strong nonlinear dependence of the critical load on the fiber size. A good agreement between the predictions provided by these models is found for large and medium fiber radii. However, different scaling laws for small fiber radii are noticed. A discussion of the asymptotic trends for very small and very large fiber radii is presented. Limitations of both models are also discussed. For very small fibers, it is shown that matrix plasticity can prevail over fiber–matrix debonding, leading to an upper bound for the critical load. When fiber–matrix debonding prevails over plasticity for large enough fibers, the predictions provided by the two models are still in fair good agreement.

1. Introduction

The study of the micromechanical fiber–matrix behavior has demonstrated to be very useful for explaining some macroscopic phenomena in Fiber Reinforced Composites (FRCs). A few examples are: the effect of the reinforcement size on the superplastic deformation properties observed in fiber reinforced metal matrix composites [6,51], the macroscopic effect of the interface properties [50], the features of failure under transverse tension [28,39,42] and compression [12,13] and the influence of a transverse compression on the failure under dominant transverse tension [29,30,38] in FRC laminates.

In particular, the plane strain problem of a long cylindrical inclusion (sometimes referred to as inhomogeneity) surrounded by a matrix has been studied since 1930s when Goodier [18] deduced the elastic solution of the problem of an elastic circular inclusion perfectly bonded to an elastic matrix subjected to transverse tension. The problem of partial debonding at the fiber–matrix interface under a rather general transverse load was solved, assuming the open model of interface cracks, in Toya's [44] seminal work in 1970s. Toya's solution provided analytical expressions for displacements, stresses and the Energy Release Rate (ERR). Later, analytical solutions were presented considering the interface as a continuous distribution of linear springs for a circular inclusion in [17,26] and for an elliptical inclusion in [47].

Many numerical studies have been carried out with the aim of understanding the micromechanical behavior of the fiber–matrix system using different techniques. Boundary Element Method (BEM) codes with contact were used in [12,37,39,46] to analyze the growth of a partial debond at the interface and its subsequent kink towards the matrix. Several Cohesive Zone

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Nomenclature (alphabetic order)

Principal symbols

a	fiber radius (m)
a_0	$G_{1c}E^*/\sigma_c^2$ = interface characteristic length (m)
E_f	Young's modulus of the fiber (Pa)
E_m	Young's modulus of the matrix (Pa)
$E^* = 2/\left(\frac{1-\nu_f^2}{E_f}+\frac{1-\nu_m^2}{E_m}\right)$	harmonic mean of effective elastic moduli (Pa)
g_N	relative normal (opening) displacement (m) (CZM)
g_T	relative tangential (sliding) displacement (m) (CZM)
G_{1c}	interface fracture toughness in mode I (J/m^2)
G_{2c}	interface fracture toughness in mode II (J/m^2)
l_{Nc}	critical relative opening displacement (m) (CZM)
l_{Tc}	critical relative sliding displacement (m) (CZM)
v	volumetric fiber content (%)
$\alpha = \frac{E_f(1-\nu_m^2)-E_m(1-\nu_f^2)}{E_f(1-\nu_m^2)+E_m(1-\nu_f^2)}$	first Dundurs bimaterial parameter (–)
$\beta = \frac{1}{2}\frac{E_f(1-\nu_m-2\nu_m^2)-E_m(1-\nu_f-2\nu_f^2)}{E_f(1-\nu_m^2)+E_m(1-\nu_f^2)}$	second Dundurs bimaterial parameter (–)
$\gamma = \frac{1}{\sigma_c}\sqrt{\frac{G_{1c}E^*}{a}}$	fiber–matrix interface brittleness number (–)
θ	polar angle denoting a point at the fiber–matrix interface (rad)
ε_1	averaged (homogenized) transverse strain (–)
λ	dimensionless effective relative displacement (–) (CZM)
μ	τ_c/σ_c (–)
ν_f	Poisson's ratio of the fiber (–)
ν_m	Poisson's ratio of the matrix (–)
σ	normal interface traction (Pa)
σ_1	averaged (homogenized) transverse stress (Pa)
σ_c	maximum normal interface traction (interface tensile-strength) (Pa)
σ_{1c}	critical averaged transverse stress for the onset of fiber–matrix debonding (Pa)
σ_y	matrix yield strength (Pa)
τ	tangential interface traction (Pa)
τ_c	maximum tangential interface traction (interface shear-strength) (Pa)
ψ	effective displacement-based fracture-mode-mixity angle (rad)
ψ_σ	stress-based fracture-mode-mixity angle (rad)

Principal abbreviations

BEM	Boundary Element Method
CZM	Cohesive Zone Model
ERR	Energy Release Rate
FEM	Finite Element Method
FFM	Finite Fracture Mechanics
FRC	Fiber Reinforced Composites

Models (CZM) were implemented in Finite Element Method (FEM) codes to model the fiber–matrix interface in [6,10,26,31,49] and BEM codes, see e.g. [20,42], in order to study the onset and growth of a debond at the fiber–matrix interface. Moreover, the interaction between close fibers has also been examined by analytical [54], semianalytical [22,23] and computational [1,27] techniques. Recently, a coupled stress and energy criterion [24] in the framework of Finite Fracture Mechanics (FFM) [11,40,43] was applied to predict crack initiation at the fiber–matrix interface in [28,29]. Some experimental work was also carried out [53].

An effect of the inclusion size for a fixed volumetric reinforcement content on the macroscopic properties of composites has been observed in experiments. For instance, the superplastic behavior of metal–matrix composites [51] and the tensile strength [9,16,25] are found to be dependent on the inclusion size. This size effect has been explained using different CZM laws for describing the fiber–matrix interface in [6,30,42], and FFM in [28,29]. In view of this background, the aim of the present work is to provide a better understanding of the mechanisms leading to this size effect by analyzing and comparing the predictions of two different models. The first is a CZM for the fiber–matrix interface based on the Tvergaard law [45] implemented in a FEM code in [6]. The numerical tests carried out in [6] have shown a strong fiber-size effect on the transverse tension leading to an unstable decohesion at the fiber–matrix interface. In the second model, a coupled stress and