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A cohesive zone model incorporating a Coulomb friction law for fiber-reinforced composites

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A B S T R A C T

A cohesive zone model (CZM) combining interfacial debonding, frictional sliding, and coupling between decohesion and friction is developed. The proposed interface model forms by incorporating a Coulomb friction law into the bilinear traction-separation law, and only one additional parameter is introduced compared to the traditional CZM. To verify this model, microbond test is carried out using an in-house developed tester. The interface model has been implemented into a commercial software package ABAQUS as a user-defined element. An axisymmetric finite element model with geometry and boundary conditions identical to the physical test has been used to simulate interfacial debonding and frictional sliding. The parameters for the interface model are determined by comparing the results of experiment and simulation. Once the parameters have been obtained for one test, the interface model can be used without further modification to predict the results of other experiments. The present interface model gives excellent quantitative predictions for the results of microbond test. Moreover, dimensional analysis has been adopted to study the relationship between the interfacial behavior and various parameters including the interfacial properties and the geometry of the structure. Dimensional considerations introduce a characteristic length, and the interfacial shear strength (IFSS) monotonically increases with the ratio of the characteristic length to the embedded length and is asymptotic to a horizontal line.

1. Introduction

Interface plays a critical role in stress transfer between fiber and matrix and thus influences the mechanical performance of fiber-reinforced composites. A fundamental understanding of the interfacial behavior is necessary to design composites with high performance. In both pull-out and push-out tests, interfacial progressive debonding and the ensuing frictional sliding are observed in ploymeric matrix composites, metallic matrix composites, and ceramic matrix composites [1,2]. Interfacial friction is closely related to thermal residual stress and the roughness of the contact surface. When the composites are cooled after processing from a stress-free temperature, the thermal residual stress arises due to the difference in the coefficients of thermal expansion of the constituents. To comprehensively describe the interfacial behavior, it's essential to consider the interfacial debonding, frictional sliding, and coupling between them.

One of the most popular approaches to address fracture issues, cohesive zone model, proposed by Barenblatt and Dugdale, has proved useful in analyzing interface crack problems [3–5]. In most of the cohesive zone models, the constitutive relations (i.e., the traction-separation relations) for the interfaces behave as follows, with increasing the interfacial separation, the traction across the interface reaches a maximum, decreases, and eventually vanishes so that complete decohesion occurs. Polynomial, exponential, trapezoidal, linear, and bilinear traction-separation relations have been proposed to describe fracture and failure behavior in kinds of material systems [4,5]. Tvergaard and Hutchinson [6] have used a mode-independent cohesive zone model to study interfacial fracture of bi-material systems. Yang and Thouless [7] have extended this cohesive zone model by incorporating a mode-dependent failure criterion. Su et al. [8] have developed an elastic-plastic cohesive zone model which accounts for both reversible elastic and irreversible inelastic separation-sliding deformations. Xu and Lu [9] have extended the elastic-plastic cohesive zone model by considering the finite deformation to account for nonlinear

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traction-separation relation. Tvergaard [10] has introduced a cohesive zone model combining interfacial decohesion and friction to analyze the failure of a whisker-reinforced metal matrix composite. Snozzi and Molinari [11] have coupled a contact algorithm to the cohesive approach to account for mixed mode loading with frictional contact capability. Xu et al. [12] have proposed a cohesive zone model which accounts for interfacial debonding, frictional sliding, and the effect of the residual stress to analyze fiber push-out problems in metal matrix composites. Other approaches and models which combine interfacial decohesion and friction have been applied to fiber pull-out or push-out tests and structure engineering [13,14] (e.g., reinforced concrete and masonry walls). However, few interface models focus on all the geometrically nonlinear, damage evolution, frictional behavior, and coupling between decohesion and friction due to the complex failure mechanism at the interface. Therefore, we propose to develop a simple and powerful cohesive zone model which comprehensively accounts for the interfacial behavior and forms by incorporating a simple Coulomb friction law.

One of the most popular micromechanical experimental methods, microbond test (also called microdroplet test), developed by Miller et al. [15], has been widely used to characterize the interfacial properties. This experimental method has been applied to several fiber-matrix systems, such as glass-epoxy, glass-polypropylene, carbon-epoxy, continuous carbon nanotube (CNT)-epoxy, and flax-epoxy [1,2,16,17]. Gao et al. [18] have studied the effect of fiber sizing and surface texture on the strength and energy absorbing capacity of fiber-reinforced composites using the microbond test. Tamrakar et al. [19] have modified the microbond test and designed an experimental setup for high rate test utilizing a modified version of a tensile Hopkinson bar. Thomason and Yang [1] have studied the dependence of the interfacial properties on the temperature using TMA-microbond apparatus which allows for the operation of microbond test in the temperature controlled environment.

The intention of this paper is to propose a cohesive zone model combining interfacial debonding, frictional sliding and coupling between decohesion and friction. Microbond test is carried out using an in-house developed tester. We implement the proposed interface model into the commercial software package ABAQUS as a user-defined element. An axisymmetric finite element model with geometry and boundary conditions identical to the physical test is used to simulate the interfacial behavior. The predictive capability of this interface model is evaluated by comparing the results of experiment and simulation. Dimensional analysis is performed to investigate the effects of the interfacial properties and the geometry of structure on the interfacial behavior.

2. Interface model

The mechanical response of the interface is described through a constitutive relation that gives the dependence of the traction on the separation. In general, the traction and the separation have both normal and shear components. For normal component, bilinear traction-separation law is adopted (Fig. 1a) [20]. For shear component, the mechanical response is characterized by three stages (i.e., I, II, and III in Fig. 1b). In stage I, the shear traction τ increases linearly with the shear separation δ. The interface keeps intact and no damage occurs. When δ reaches a certain shear separation δ_0 which corresponds to the maximum shear traction τ_{max} in the bilinear traction-separation law, initial debonding takes place. In stage II, because the thermal residual stress results in compressive normal stress, interfacial friction occurs and contributes to τ. As debonding progresses, damage accumulates and frictional traction τ'' increases until complete decohesion occurs. A

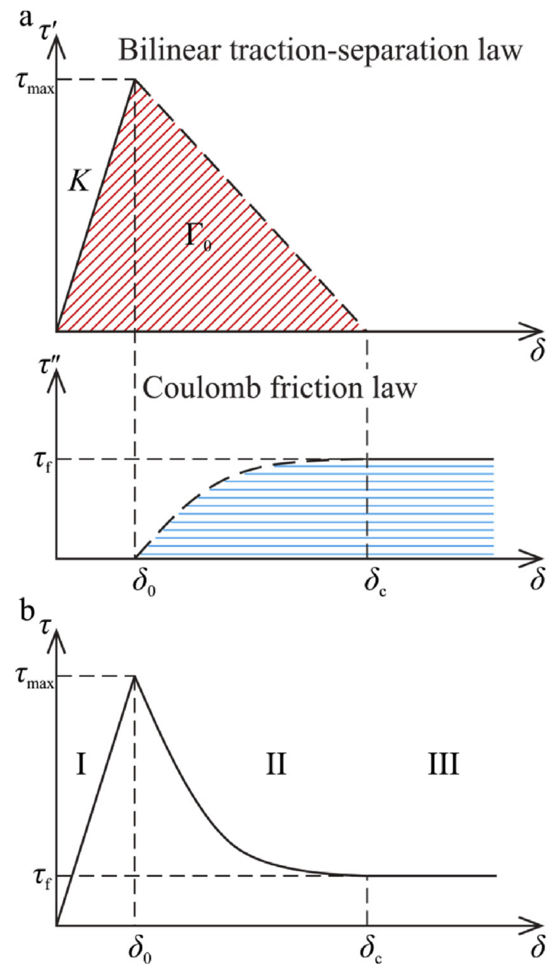

Fig. 1. (a) The Bilinear traction-separation law and the Coulomb friction law; (b) the proposed interface model.

simple Coulomb friction law (Fig. 1a)

$$\tau'' = \tau_f \left(1 - \left(1 - \frac{\delta - \delta_0}{\delta_c - \delta_0}\right)^n\right) \tag{1}$$

is adopted to give the dependence of τ'' on δ [11]. τ_f, the maximum fractional traction (i.e., the frictional traction in the pure frictional stage), is determined by the thermal residual stress and the roughness of the contact surface at the interface. The exponent n is set to 4 in this work [11]. In stage III, pure frictional sliding occurs with δ larger than the critical shear separation δ_c. Due to complete decohesion, the shear traction τ is completely determined by τ'' which reaches a plateau of τ_f in the pure frictional stage.

Consequently, by combining the bilinear traction separation law and the Coulomb friction law, the constitutive relation for shear component (Fig. 1b) is given as

$$\tau = \begin{cases} K\delta & \text{for} \quad D = 0 \\ (1-D)K\delta + \tau_f\left(1 - \left((1-D)\frac{\delta}{\delta_0}\right)^n\right) & \text{for} \quad 0 < D < 1 \\ \tau_f & \text{for} \quad D = 1 \end{cases} \tag{2}$$

where K is interfacial stiffness in stage I and equal to τ_{max}/δ_0. The interfacial damage variable D which represents the overall damage