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A simple cohesive zone model that generates a mode-mixity dependent toughness

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ABSTRACT

A simple, mode-mixity dependent toughness cohesive zone model (MDG_c CZM) is described. This phenomenological cohesive zone model has two elements. Mode I energy dissipation is defined by a traction–separation relationship that depends only on normal separation. Mode II (III) dissipation is generated by shear yielding and slip in the cohesive surface elements that lie in front of the region where mode I separation (softening) occurs. The nature of predictions made by analyses that use the MDG_c CZM is illustrated by considering the classic problem of an elastic layer loaded by rigid grips. This geometry, which models a thin adhesive bond with a long interfacial edge crack, is similar to that which has been used to measure the dependence of interfacial toughness on crack-tip mode-mixity. The calculated effective toughness vs. applied mode-mixity relationships all display a strong dependence on applied mode-mixity with the effective toughness increasing rapidly with the magnitude of the mode-mixity. The calculated relationships also show a pronounced asymmetry with respect to the applied mode-mixity. This dependence is similar to that observed experimentally, and calculated results for a glass/epoxy interface are in good agreement with published data that was generated using a test specimen of the same type as analyzed here.

1. Introduction

It is now firmly established that the measured apparent interfacial toughness of many polymer solid interfaces increases with increasing crack-tip mode-mixity (Cao and Evans, 1989; Wang and Suo, 1990; Liechti and Chai, 1992; Swadener and Liechti, 1998; Mello and Liechti, 2006). On the other hand, the earliest cohesive zone models were formulated in terms of a traction potential (Tvergaard and Hutchinson, 1993; Xu and Needleman, 1994). These useful and still widely used formulations generate a mode-mixity independent work of separation. The extension of such models to include a mode-mixity dependent toughness has proved difficult (Hui et al., 2011; Park and Paulino, 2011). A polynomial-based potential formulation that is defined in terms of four fracture parameters in each fracture mode does replicate a mode-dependent toughness; however, determining all eight fracture parameters is a challenging task (Park and Paulino, 2011). In an alternate approach, a nonpotential-based method that defines mode I and mode II response independently and links these traction–separation relationships via a mixed-mode failure condition has been used to successfully model the mode-mixity dependent failure of adhesive joints (Yang and Thouless, 2001).

The present effort is aimed at developing a simple, mode-dependent interfacial toughness cohesive zone model. This work was motivated by the recent development of a continuum mechanics-based Adhesion/Atomistic Friction (Ad/AF) surface interaction model (Reedy, 2013; Reedy and Cox, 2013). That model was intended for solid materials interacting through van der Waals dispersion forces. It models adhesive interactions between surfaces as well as the atomistic friction that opposes the tangential motion of atomistically smooth surfaces as they slide relative to each other (e.g., as measured by scanning probe-based friction force microscopy). This surface interaction model was implemented within the framework of a contact algorithm for use in explicit dynamics finite element calculations. This type of implementation allowed large relative motion of opposing surfaces and also permitted surfaces to jump in and out of adhesive contact. In the broadest sense, this model combines a traction–separation relationship for normal separation with a model for shear dissipation as generated by tangential slip. Interestingly, fracture simulations using the Ad/AF model showed that the calculated effective toughness displayed a significant dependence on the applied mode-mixity. This

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prompted the current effort to implement a conceptually similar CZM, but now within a cohesive surface element framework for implicit quasistatic finite element calculations.

In its current incarnation, the model parameters of what will be referred to as the mode-mixity dependent toughness cohesive zone model (MDG_c CZM) are interpreted somewhat differently from those used to define the Ad/AF model (where model parameters referenced adhesion and atomistic friction). Roughly speaking, the MDG_c CZM incorporates all sources of crack-tip dissipation where: (1) mode I dissipation is defined by a traction–separation relationship that depends only on normal separation, and (2) mode II (III) dissipation is generated by interfacial shear yielding and slip in the cohesive surface elements that lie in front of the region where mode I softening occurs. The amount of shear dissipation is not defined by a traction–separation relationship; the length of the slip zone is determined by the level of interfacial shear in front of the mode I cohesive zone. The MDG_c CZM should be considered to be a simple, phenomenological model that produces a mode-dependent toughness similar to that observed in interfacial fracture tests. Its interpretation in terms of a mode I separation process (e.g., at the tip of a blunted crack) coupled with additional dissipation due to shear yielding is meant to be suggestive and there is no expectation that this model provides a detailed description of the local crack-tip yielding. The intent is for the MDG_c CZM to be used in analyses where the bulk materials are modeled as linear elastic with all material dissipation incorporated into the MDG_c CZM. Note that the current effort differs from other work that aims to perform a more detailed analysis that includes the large-strain plastic deformation in the bulk materials and resolves the local, nanometer-scale deformations (Swadener and Liechti, 1998).

2. Mode-mixity dependent toughness cohesive zone model (MDG_c CZM)

The MDG_c CZM has two elements. The plane strain version of this model is discussed first. Normal separation is defined by a mode I only version of what is now commonly referred to as a cohesive zone model (Barenblatt, 1962; Needleman, 1987; Tvergaard and Hutchinson, 1992). The associated traction–separation (T–U) relationship defines how normal traction σ depends on normal interfacial separation δ_n (Fig. 1a). This relationship holds when $\delta_n \geqslant 0$, otherwise normal interpenetration is penalized by applying a prescribed multiple of the initial loading stiffness $k = \sigma^*/(\lambda_1\delta_{nc})$. The two key parameters defining this T–U relationship are the interfacial strength σ^* and the intrinsic mode I work of separation/unit area of interface Γ. This study uses a trapezoidal T–U relationship where λ_1, λ_2 and the requirement that the traction vanishes when δ_n equals δ_{nc} define its shape. The trapezoidal T–U relationship was chosen for its simplicity and other forms could be used if there were a compelling reason to do so. The initial loading is defined by λ_1, while final stress decay is defined by λ_2, (with typical values of 0.1 and 0.9, respectively). For a trapezoidal T–U relationship, Γ, which equals the area under the T–U curve, has a value of $\Gamma = ½\sigma^*\delta_{nc}[1 + \lambda_2 - \lambda_1]$. If unloading occurs prior to final separation, elastic unloading is assumed with an unloading stiffness equal to the initial T–U loading stiffness k.

The second element of the MDG_c CZM defines perfectly plastic shear yielding (Fig. 1b). The yield strength is τ^* and plastic slip is associated with the tangential displacement jump δ_t. The initial loading stiffness k was chosen to be the same as used for normal separation. Here it is assumed that shear yielding only occurs prior to mode I softening (i.e., when $\delta_n < \lambda_1\delta_{nc}$). Accordingly, shear stress is set to zero once $\delta_n > \lambda_1\delta_{nc}$. The intent of this model is to model interfacial crack growth where failure is associated with normal separation in the presence of interfacial shear. When there is interfacial compression, the interface can slip, but there is no limit to the extent of slip (i.e., shear cracking under interfacial compression is not modeled).

In this study, the initial stiffness k of the T–U model was chosen so that it was roughly equal to (or slightly greater than) the stiffness of adjoining elements, E_u/Δ, where E_u is the uniaxial strain modulus of the more compliant of the two adjoining bulk materials and Δ is the characteristic length of interfacial elements. This stiffness is not meant to model interface compliance. Rather, this stiffness can be thought of as a penalty that ties the adjoining interfacial materials together so as to prevent normal separation (i.e., the interface is intact when $\delta_n \leqslant \lambda_1\delta_{nc}$ and begins to separate when $\delta_n > \lambda_1\delta_{nc}$). With this interpretation, shear yielding occurs only in the region where the interface is intact and has not begun to separate (i.e., when $\delta_n < \lambda_1\delta_{nc}$). As the cohesive zone develops and its length increases, interfacial shear is released whenever a previously intact portion of the interface begins to separate. It was anticipated that an abrupt reduction in interfacial shear might prove troublesome for the solver in these implicit quasistatic finite element calculations. Therefore, a capability for controlling the rapidity with which the shear is released was implemented by introducing a shear unloading stiffness k_u (controlled by λ_3, see Fig. 1b). Although this capability is potentially useful, it was not essential for the analyses reported herein. Finally, recall that the initial loading stiffness in shear was chosen to be the same as used for normal separation (Fig. 1b). As with normal separation, this initial stiffness can be thought of as a penalty that ties the adjoining interfacial materials together. Here it prevents relative tangential motion prior to plastic-slip.

The plane strain version of the MDG_c CZM can generalize to 3-D by including anti-plane mode III slip δ_u in addition to the in-plane mode II slip δ_t by defining an effective shear stress τ_e and an effective slip rate $\dot{\delta}_e$ where

$$\tau_e = \left(\tau_t^2 + \tau_u^2\right)^{1/2} \quad \text{and} \quad \dot{\delta}_e = \left(\dot{\delta}_t^2 + \dot{\delta}_u^2\right)^{1/2}. \tag{1}$$

$$\text{When } |\tau_e| < \tau^* \qquad \dot{\tau}_t = k\dot{\delta}_t \text{ and } \dot{\tau}_u = k\dot{\delta}_u. \tag{2}$$

$$\text{When } |\tau_e| = \tau^* \qquad \tau_t = \frac{\dot{\delta}_t}{\dot{\delta}_e}\tau^* \text{ and } \tau_u = \frac{\dot{\delta}_u}{\dot{\delta}_e}\tau^*. \tag{3}$$

Sandia National Laboratories' Sierra/SM implicit quasistatics finite element code was used to perform the analysis (Thomas, 2011). This code implements cohesive surface elements (CSEs) within the context of large displacements where the CSE reference plane is defined by the average position of its upper and lower nodes. In the calculations reported herein, the maximum slip δ_s (see Fig. 1b) is generally < Δ. This generates a maximum dissipation due to plastic slip of $\sim\tau^*\Delta$. For the model parameters used in this study, this enabled a substantial increase in effective toughness (∼a factor of 20).

3. Application of MDG_c CZ model to an interfacial crack growth problem

The nature of predictions made by analyses that use the MDG_c CZM is illustrated by considering the classic plane strain problem of crack growth along the interface of a thin elastic layer that is loaded by rigid grips (Fig. 2). This geometry, which models a thin adhesive bond with a long interfacial edge crack, is similar to that which has been used to measure the dependence of interfacial toughness on crack-tip mode-mixity (Swadener and Liechti, 1998). The model geometry was chosen so as to closely approximate an infinitely long layer with a semi-infinite interfacial crack.

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