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Comparison of cohesive zone model and linear elastic fracture mechanics for a mode I crack near a compliant/stiff interface

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ABSTRACT

Cohesive zone model has been widely applied to simulate crack growth along interfaces, but its application to crack growth perpendicularly across the interface is rare. In this paper, the cohesive zone model is applied to a crack perpendicularly approaching a compliant/stiff interface in a layered material model. One aim is to understand the differences between the cohesive zone model and linear elastic fracture mechanics in simulating mode I crack growth near a compliant/stiff interface. Another aim is to understand the effects of elastic modulus mismatch and cohesive strength of the stiff layer on the crack behavior near the interface. To simulate crack growth approaching an interface, the cohesive zone model which incorporates both the energy criterion and the strength criterion is an effective method.

1. Introduction

For a crack that propagates perpendicularly towards an elastically mismatched interface, before the crack tip reaches the interface or after the crack tip has passed through the interface, the crack growth criterion can be cast as: $J_{tip} = G_{Ic}$, where J_{tip} is the J-integral at the crack tip, and G_{Ic} the critical strain energy release rate of the local material where the crack tip is located [1].[1] The energy-based criterion becomes ineffective when the crack tip touches an elastically mismatched interface, where J_{tip} becomes path-dependent. In fact, LEFM becomes ineffective even before the crack tip reaches the interface. LEFM predicts that a crack penetrates the interface at either zero or infinite value of the applied load, depending on the relative stiffness of the bonded materials [2–4]. This implies that a crack cannot extend to a compliant/stiff interface, independent of the material toughness and strength, which is obviously incorrect. Cracks may cross a compliant/stiff interface if the tensile strength of the material ahead of the interface is low enough. In such a case, a secondary crack may initiate ahead of the interface before the primary crack reaches the interface. Hence, if only the energy criterion is applied, the behavior of a crack near a compliant/stiff interface may be incorrectly predicted.

Why does LEFM sometimes fail to predict correctly the behavior of a crack approaching an elastically mismatched interface? One reason is that no LEFM parameter can describe the crack driving force when the crack tip touches the interface. Another more important reason is that the failure of the material ahead of the interface is not taken into account in LEFM,

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[1] It should be pointed out that the J-integral and the energy release rate are not limited to linear elastic fracture mechanics (LEFM) even though they are used in this context in this paper.

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Nomenclature

a	crack length
a_p	fracture process zone length
E	Young's modulus
G_{Ic}	critical energy release rate
h	$h = h_1 + h_2$, where h_1 and h_2 are the interlayer thickness and the surface layer thickness, respectively
J_{tip}	J-integral at the crack tip
K_{Ic}	critical stress intensity factor
M	initial stiffness of traction–separation curve
T_0	cohesive strength
δ	separation distance between cohesive surfaces
δ_0	separation distance corresponding to the cohesive strength
δ_f	separation distance value at which the cohesive traction drops to zero
ε_{appl}	average of the y-direction applied strain
$\varepsilon_{appl}^{crit}$	critical applied strain
Γ	separation energy
ν	Poisson's ratio
σ_u	tensile strength

because LEFM assumes that the failure occurs only at the crack tip. Before the crack tip has entered the crack-free material ahead of the interface, the energy criterion is not suitable for predicting local failure. For the material ahead of the interface, a strength criterion $\sigma = \sigma_u$ may be more suitable to serve as a local failure criterion, where σ and σ_u are local stress and tensile strength, respectively [5]. Therefore, to correctly predict the behavior of a crack approaching an interface, both the energy and strength criteria are needed. Since the cohesive zone model incorporates both toughness and strength parameters [6], in theory, it can be applied to a crack that approaches an interface. The cohesive zone model treats each potential crack path as two internal surfaces connected by cohesive tractions, and uses a traction–separation curve to describe the separation process between the two surfaces. The separation energy (i.e., the area under the traction–separation curve) and the cohesive strength (the peak traction on the traction–separation curve) represent the local toughness and local strength, respectively. The cohesive zone model not only can be applied to the local fracture process zone ahead of a crack tip to replace the energy criterion, but can also be applied to crack-free materials to replace the strength criterion.

The cohesive zone model has been widely applied to simulate crack propagation. In simulating crack propagation along interfaces, the cohesive zone model has become a popular method. However, its applications to crack propagation perpendicularly towards interfaces are not very much studied. Finite element (FE) models with a cohesive zone were applied to simulate fatigue crack growth [7] and dynamic crack growth [8,9] across a plastically mismatched bi-material interface, assuming no elastic mismatch existed. Theoretical analyses were performed for a crack crossing a bi-material interface, assuming the cohesive traction is constant within the cohesive zone [4,10]. The cohesive zone model was also applied to analyze the competition between crack deflection and crack penetration at the interface [2,6], where the penetrating crack tip had already passed the interface.

In this paper, a cohesive zone model is applied to analyze a crack that perpendicularly approaches a compliant/stiff interface in a layered elastic material model, assuming that the crack direction is from a lower modulus layer to a higher modulus layer. One aim of this study is to describe how the cohesive zone model is used to simulate crack growth near an elastically mismatched interface. Another aim is to understand the effects of Young's modulus mismatch and cohesive strength of the stiff layer on the crack behavior when the crack is approaching a compliant/stiff interface.

2. Models

2.1. Problem description

A crack perpendicularly approaching a compliant/stiff interface is shown in Fig. 1, where one fracture process zone is adjacent to the crack tip and another fracture process zone is just ahead of the interface. The fracture process zone lengths in materials 1 and 2 are represented by a_{p1} and a_{p2}, respectively. The distance between the crack tip and the interface is $(h–a)$. One requirement for using LEFM is that the fracture process zone adjacent to the crack tip must be smaller than any characteristic dimension in the model. For a crack approaching an interface, the smallest characteristic dimension is the distance between the crack tip and the interface. With $(h–a) \to 0$, the condition $a_{p1} < (h–a)$ cannot be satisfied if a_{p1} is not zero. In LEFM, both a_{p1} and a_{p2} are assumed to be zero, and LEFM predicts that the crack cannot reach the compliant/stiff interface, since the crack driving force tends to zero for $(h–a) \to 0$.

A requirement in fracture mechanics is that an initial crack must preexist, which means that fracture mechanics cannot simulate the initiation of a new crack in the crack-free material ahead of the interface. As the cohesive zone model not only