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Effect of incident angle on crack propagation at interfaces

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ABSTRACT

The effect of incident angle on crack deflection versus penetration has not been widely studied using a combined stress-and-energy criterion. This work does so by using a cohesive-zone method and dimensionless parameters. Results show deflection becomes more likely as angle decreases with greatest sensitivity to angular change at large angles. Deflection becomes increasingly strength-ratio dependent at small angles due to a shared crack-tip stress field. As fracture length scale decreases, deflection becomes more likely. Normalized toughness is shown to have a small effect on results. Significant is the insight provided on propagation behavior and the simplification in the use of a stress-and-energy criterion.

1. Introduction

The load carrying ability of a composite is significantly affected by the manner in which a crack propagates when encountering an interface between constituent materials. Propagation occurring by deflection (i.e. growth along the interface) tends to blunt the crack tip and increase macroscopic toughness. Propagation occurring by penetration (i.e. growth across the interface) tends to the opposite. Whether deflection or penetration occurs depends on a number of factors such as the material properties of the constituent materials and interfaces. Strong, tough constituent materials will tend to promote deflection and strong, tough interfaces will tend to promote penetration. Also of significance is the crack geometry, particularly the incident angle between the crack and the interface. Small angles promote deflection and large angles promote penetration. An application of the dependence on both material properties and incident angle of deflection versus penetration behavior is the indentation interface fracture (IIF) test which is used to measure the relative toughness of a bonded interface [1]. Despite the significance of incident angle, much of the research on penetration versus deflection behavior has not included its effect.

A large body of literature exists related to crack propagation by deflection versus propagation and criteria for predicting transition from one to the other. The earliest published work, written over 50 years ago, is that of Cook and Gordon [2]. They used a simple stress-based criterion to predict if deflection would occur. Subsequently, others pursued more sophisticated stress-based approaches to determine transition criteria [3]. Also a number of others have used energy-based, or LEFM, approaches [4–7]. Some of this work included a discussion of the effect of incident angle [8]. However, more recently it has been shown that a combined stress-and-energy-based approach is necessary, particularly regarding the transition between deflection and penetration [9–11]. It has been shown that the energy-based approach is a special case of the more general combined stress-and-energy-based solution [12]. The stress-and-energy-based approach has been used to explore the effect of incident angle for a high-strength, low-toughness material system [13]. For this material system it was found that the propagation by deflection versus penetration was a strong function of incident angle. However a study using the

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Nomenclature

δ	CTOD (crack-tip opening displacement)
δ_n	normal CTOD
δ_{n1}	normal CTOD corresponding to the end of the traction-law elastic region
δ_{n2}	normal CTOD corresponding to the end of the traction-law constant-stress region
δ_{n3}	normal CTOD corresponding to fracture
δ_s	shear CTOD
δ_{s1}	shear CTOD corresponding to the end of the traction-law elastic region
δ_{s2}	shear CTOD corresponding to the end of the traction-law constant-stress region
δ_{s3}	shear CTOD corresponding to fracture
E	Young's modulus
$\overline{E}$	plane strain Young's modulus
ϕ	incident angle of crack
G_I	mode one energy release rate
G_{II}	mode two energy release rate
Γ	toughness
Γ_I	mode one toughness
Γ_{II}	mode two toughness
Γ_i	toughness of interface
Γ_{iI}	mode one toughness of interface
Γ_{iII}	mode two toughness of interface
Γ_m	toughness of material
K_I	mode one stress intensity factor of initial crack
L_c	characteristic length
LEFM	linear elastic fracture mechanics
ν	Poisson's ratio
θ	angular position measured counterclockwise from the positive x-axis
r	radial distance from crack tip
R	crack length (radius of circular model)
σ	normal stress
$\hat{\sigma}$	cohesive normal strength
$\hat{\sigma}_i$	cohesive normal strength of interface
$\hat{\sigma}_m$	cohesive normal strength of material
σ_y	yield strength
τ	shear stress
$\hat{\tau}$	cohesive shear strength
$\hat{\tau}_i$	cohesive shear strength of interface
u_x	x-direction displacement
u_y	y-direction displacement

combined stress-and-energy-based approach and spanning a wider range of material systems to explore the effect of incident angle on crack propagation by deflection versus penetration does not currently exist in the literature.

This paper presents work using the cohesive-zone approach of Parmigiani and Thouless [9]. The study of the effect of incident angle on the transition between propagation by deflection and penetration is extended in several significant aspects: results are given for incident angles of zero to ninety degrees in terms of dimensionless groups, key results are compared to LEFM special-case solutions, and insight is provided on why data trends occur. Also the effect of an additional dimensionless group, not explicitly considered in prior work, is explored.

2. Methods

2.1. Cohesive zone model

The cohesive zone approach used in this paper is based on the work by Thouless [14–16]. It consists of two separate trapezoidal traction laws joined by a failure criterion. One traction law, illustrated in Fig. 1a, gives crack-tip normal stress as a function of the normal displacement in the crack-tip process zone. The maximum stress given by this traction law, denoted by $\hat{\sigma}$, is the cohesive normal strength. The maximum normal displacement given by this traction law, denoted by δ_{n3}, is the critical normal displacement corresponding to fracture for pure mode I loading. Similarly, a second traction law, illustrated in Fig. 1b, gives crack-tip shear stress as a function of the shear displacement in the crack-tip process zone. The maximum stress ($\hat{\tau}$) is the cohesive shear strength and the maximum displacement (δ_{s3}) is the critical shear