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An experimental assessment of methods to predict crack deflection at an interface

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ABSTRACT

Several criteria have been proposed to predict whether a crack will penetrate through, or deflect along, an interface between two linear elastic materials. Moreover, the different criteria predict different crack penetration/deflection behavior creating uncertainty about which method to choose. To help remove some of this uncertainty, the present study presents experimental results on the quasi-static penetration/deflection behavior of cracks incident to interfaces in polymethyl methacrylate (PMMA) with various incident angles. Interfaces were created by bonding PMMA sheets using two different solvents. By varying the incident angles of the cracks on the interfaces, the transition angle for the transition from crack penetration to deflection was determined to be $\phi_{tran} \approx 80°$ for the stronger and tougher interfaces and $\phi_{tran} \approx 85°$ for the weaker and less tough interfaces. Using an energy-based criterion based solely on the toughness ratio, much lower transition angles ($\phi_{tran} = 47°$ and 57°) were predicted for the interfaces than were experimentally observed. In contrast, using a cohesive zone method (CZM) approach that incorporates both the strength and toughness ratios gave predicted transition angles much closer to those experimentally observed for both the stronger ($\phi_{tran} = 73°$) and weaker ($\phi_{tran} = 80°$) interfaces. Finally, an approach that only considers the normal strength ratio was examined and poor agreement was found between predictions and experiments for 90° indent angle samples. Overall, it was found that the CZM approach makes predictions of the crack penetration/deflection behavior that were closest to the experimental results of this study.

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1. Introduction

One of the most important questions regarding the fracture behavior of composites and laminated materials is whether a crack will deflect along, or penetrate though, an interface. In the case of a fiber reinforced composite there are numerous interfaces between the matrix and the fibers. When a crack propagates through the matrix and fibers without deflecting, the overall strength and toughness of the composite is not improved much compared to the matrix material since little additional energy dissipates through this kind of penetration cracking process. On the contrary, if a crack deflects around the fibers, this creates more crack surface area, fiber bridging toughening, more energy dissipation, and a stronger, tougher composite. The same benefit of interfacial crack deflection occurs for toughened ceramics [1–4], laminated materials [5,6],

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Nomenclature

CZM	cohesive zone method
LEFM	linear elastic fracture mechanics
δ_1	crack tip opening displacement corresponding to the end of elastic region of the traction-law
δ_2	crack tip opening displacement corresponding to the end of plastic region of the traction-law
δ_3	crack tip opening displacement corresponding to the end of the traction-law or fracture
$\hat{\sigma}$	cohesive normal strength
$\hat{\sigma}_i$	adhesive strength of interface
$\hat{\sigma}_m$	cohesive strength of material
$\hat{\tau}$	shear strength
ν	Poisson's ratio
E	Young's modulus
E'	Young's modulus for plane strain
ϕ	incident angle
ϕ_{tran}	incident angle at transition
G_I	Mode I energy release rate
G_{II}	Mode II energy release rate
G_I^p	energy release rate of penetration
G^d	energy release rate of deflection along interface
Γ_I	Mode I toughness
Γ_{II}	Mode II toughness
Γ^i	toughness of interface
Γ_I^m	Mode I toughness of material
K_I^p	Mode I stress intensity factor of penetration
K_I^d	Mode I stress intensity factor of deflection
K_{II}^d	Mode II stress intensity factor of deflection

polycrystalline or multi-phase materials [7–9], and natural composites (e.g., wood, bone, nacre, teeth, etc.) [10–13]. Predicting if a crack penetrates through an interface, or deflects along it, is an important consideration in composite material design and analysis.

The earliest approach to predict crack penetration versus deflection is from Cook et al. [14] and is based on strength. They considered a high-aspect-ratio elliptically-shaped crack tip incident to a fiber at an angle of 90° in a material system where the elastic properties of the matrix and fiber are the same. Using results for the stress field near a crack tip as determined by Inglis [15], they determined that the tensile stress acting along the axis of the fiber (contributing to propagation by penetration) was five times greater than the tensile stress acting across the interface (contributing to propagation by deflection). Based on this analysis they hypothesized that the transition between penetration and deflection occurs when the fiber strength is five times the interface strength. Gupta et al. [16] extended this work to develop an improved strength based crack penetration versus deflection criterion for bi-material systems. They used stress fields around a crack tip derived in earlier work [17,18] for a crack 90° incident to an interface. The ratios of maximum tensile stress across the interface and along the interface were used to predict penetration versus deflection behavior. It was found from their analysis that for a homogeneous system the transition between penetration and deflection occurs at a material-to-interface strength ratio of approximately 3.5.

Another approach for determining crack penetration versus deflection at interfaces is based on fracture energy and uses linear elastic fracture mechanics (LEFM). Many researchers have used this energy approach to predict penetration vs. deflection behavior [19–22]. In general, this approach consists of considering two distinct geometry types, one consisting of an infinitesimal kink extending from the crack tip in the penetrating direction and a second consisting of infinitesimal kinks extending from the crack tip in the deflecting direction(s). The energy release rate corresponding to each kink is then calculated. A comparison of kink energy release rates and the material and interface toughness is used to determine when the transition between penetration and deflection occurs. The work of He and Hutchinson [19] using this approach is particularly well known, and it has often been employed by other researchers to interpret experimental results [13,23,24]. Their work predicts that for an elastically homogeneous material system with a crack incident to an interface at 90°, the transition occurs when the material has a toughness approximately four times that of the interface.

The most recent work in predicting penetration-versus-deflection behavior uses a combined strength-and-energy approach. This approach uses the cohesive zone method (CZM) originally and independently proposed by Barenblatt and Dugdale [25,26]. This approach considers the strength and toughness of both the material and the interface and was first applied to the penetration-versus-deflection problem by Parmigiani and Thouless [27]. They showed that a general solution must necessarily include strength, toughness, and material elastic properties thus precluding a strength-only or toughness-only criterion except in special cases. A key feature of this approach is the ability to model propagation by penetration and by

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