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Arrest, deflection, penetration and reinitiation of cracks in brittle layers across adhesive interlayers

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Abstract

A layer structure consisting of two glass plates bonded with polymer-based adhesives and loaded at the upper surface with a line-wedge indenter is used to evaluate crack containment. Two adhesives are used, a low-modulus epoxy resin and a particle-filled composite. The adhesives arrest indentation-induced transverse cracks at the first interface. A substantially higher load is required to resume propagation beyond the second interface in the second glass layer. Delamination is not a principal failure mode. Nor is the operative mode of failure one of continuous crack penetration through the adhesive, but rather reinitiation of a secondary crack in the glass ahead of the arrested primary crack. A fracture mechanics analysis, in conjunction with finite element modeling, is presented to account for the essential elements of crack inhibition, and to identify critical material and layer thickness variables. It is confirmed that adhesives with lower modulus and higher thickness are most effective as crack arresters.
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1. Introduction

Polymer-based adhesives provide a simple means of joining adjacent brittle layers at room temperature, thereby avoiding the serious residual stresses from differentials in coefficient of thermal expansion that can accompany fusion-bonding processes. Adhesive bonds are relevant to functional structures such as car windshields and laminates [1–7]. They also offer a potential means for fabricating dental crowns, by joining porcelain veneers to core ceramics [8]. Goals for such adhesives include: (i) provide strong bonding to impede any transverse cracks formed within the brittle layers at the adhesive interface, without delamination; (ii) make the adhesive sufficiently compliant, so as to shield adjacent layers from applied loading [9]; and (iii) make the adhesive sufficiently stiff, to avoid flexure of the upper the layer and thus circumvent the incidence of secondary failure modes [6]. Clearly, the design of optimal layer structures of this kind involves some compromises in properties matching.

At issue here is the behavior of transverse cracks when they approach such an adhesive interlayer. Transverse cracks may initiate at one surface in tension or bending or, more frequently, in concentrated top-surface loading [6,10–12]. Once any such crack has traversed a single brittle layer and arrested at the first adhesive interface, various possibilities exist for further advance in overload: delaminate at the first or second interface (deflection) [13–15]; extend progressively through the adhesive into the adjacent brittle layer (penetration); or reinitiate ahead of the crack tip in the adjacent brittle layer (reinitiation) [9]. This raises a number of questions. What determines which of these modes prevails? What is the role of key material properties

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of the adhesive – modulus, toughness, strength, hardness – relative to the adjacent brittle layers? What is the role of adhesive thickness relative to that of the brittle layers?

Here we consider the fracture mechanics of an adhesively bonded model layer system fabricated specifically to address these questions [6,10]. Glass plates are joined with epoxy resin interlayers of specified thicknesses. An indenting wedge is loaded at the surface of the top glass layer to introduce and propagate a line crack through the system. Progress of the crack is monitored directly during indentation by side viewing. This test configuration has the advantage of being particularly simple, with highly stable cracks. It is also amenable to plane strain fracture mechanics, thus providing a theoretical basis for characterization of adhesive properties.

2. Fracture mechanics: penetration vs. reinitiation

2.1. General mechanics

Consider the test configuration in Fig. 1. A brittle plate (material 1) of thickness d, modulus E_1, toughness T_1 and strength S_1 is bonded with adhesive (material 2) of thickness h, modulus E_2 and toughness T_2 to a like brittle base plate (material 1) of thickness $\gg d$. A wedge indenter under line load $P_l = P/l$ along a specimen width l introduces a transverse plane crack of depth c within the upper plate, and drives this crack downward to the adhesive interface. The action of the indenter will generally induce a near-field contact plastic zone, responsible for nucleating the crack in the first place and augmenting the elastic driving force in the initial propagation stage [16].

Suppose that the crack reaches the first adhesive interface, and that the bonding is strong enough that delamination does not occur. There are two possibilities for subsequent growth: (i) the crack penetrates into the adhesive, ultimately reaching and entering the second brittle layer; and (ii) after arresting at the first interface or penetrating part way into the adhesive, the crack reinitiates in the second brittle layer ahead of the primary tip. These two modes may be expected to have different dependencies on material and geometrical (thickness) variables.

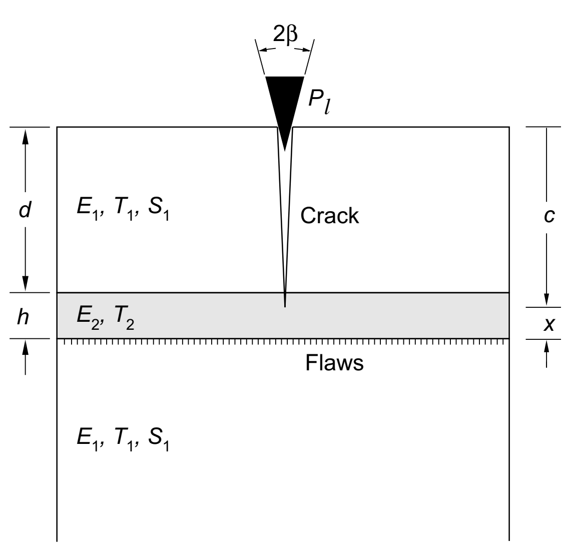

Fig. 1. Schematic of line force crack configuration in a layer system consisting of two brittle plates bonded by a polymer-based adhesive. The crack can propagate into the lower brittle layer either by continuous penetration or reinitiation from a surface flaw ahead of an arrested primary crack tip.

2.2. Crack penetration

Crack penetration might be expected to be the principal mode for adhesives that are relatively stiff, hard and brittle. Begin with a simple relation for a thick monolithic brittle specimen of material 1, and then modify to allow for presence of an intervening adhesive material 2. Assuming the principal driving force to come from the horizontal component of the applied line force, the stress intensity factor for such a crack may be written [16–18] as

$$K_0 = \alpha P_l/[(\pi c)^{1/2} \tan \beta'] = \chi_e P_l/c^{1/2} \quad (1)$$

where $\beta' = \beta + \arctan \mu$ is an effective indentation wedge half-angle, with β the true wedge half-angle and μ a friction coefficient, and α and $\chi_e = \alpha/\pi^{1/2}\tan \beta'$ dimensionless constants. This relation ignores any influence from the vertical line force component on the crack growth, but any such contribution may be subsumed into α and χ_e in Eq. (1). For a layer system with an adhesive interlayer we may write

$$K = \phi K_0 \quad (2)$$

where $\Phi = \Phi(c/d, h/d, E_2/E_1, \nu_2/\nu_1)$ is a dimensionless function defining the influence of the interlayer, with E Young's modulus and ν Poisson's ratio. (Note the limiting case $\Phi = 1$ for a brittle monolith, $E_1 = E_2$ and $\nu_2 = \nu_1$). The function Φ for any given ratio E_2/E_1 can be evaluated by two-dimensional finite element modeling (FEM) by emplacing cracks of length c in structures with and without adhesive interlayers (Fig. 1) using the Irwin crack-opening displacement relation [19] to compute relative stress intensity factors at any given load Pl and crack size c [20]. A supplementary benefit of FEM analysis is to confirm that stress components in our system remain within the elastic limit, a necessary condition for validity of the fracture mechanics formalism.

Results of FEM calculations of the function Φ as a function of relative crack size c/d are shown in Fig. 2 for a set of experimental conditions to be described in the next section, using ANSYS software (Version 6.0, ANSYS Inc., Cannonsburg, PA). The FEM system comprises upper and lower glass plates with an interlayer adhesive of relative modulus $E_2/E_1 = 0.22$ or 0.040 and relative thickness $h/d = 0.05$. Lateral dimensions for the system are 80d, large enough to eliminate any boundary effects. Values of material parameters inserted into the FEM code are listed in Table 1. Forces are applied at the crack mouth with an indenter of rectangular cross-section (i.e. $\beta = 45°$). The