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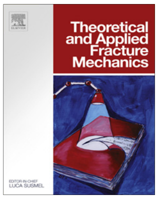

Improvement of adhesive strength at a bi-material interface by adjusting the interface angles at the free edge

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ABSTRACT

In the bonding of dissimilar materials, there is usually a stress singularity at the edge surface whose effects cause failure at the surface, resulting in a premature failure of the joint. In this work, the corresponding generalized stress intensity factor (GSIF) for an aluminum–epoxy joint is studied to determine the angles for which the stress singularity at the edge disappears. Experimental results are gathered for three different edge angles: a “concave” angle of 37° and a butt joint with 90°, both associated with interface stress singularities, and a “convex” angle of 143° that from theory is singularity free. It is demonstrated that the joint strength can be greatly improved by avoiding stress singularities through the selection of the proper edge angle, still preserving the external surfaces of the cylindrical samples. Testing with a larger diameter rod joint for the convex angle geometry shows the same nominal fracture strength, indicating that the measured strength is a material property independent of size when the stress singularity is absent.

1. Introduction

The adhesive bond strength between two dissimilar materials is often critical to the survival of a structure. As initial cracks grow, a poorly-designed joint can lead to premature failure. Designers may need to over-design joints, given the lack of reliable strength data. This constitutes a penalty, which has consequences for cost and weight considerations. Interestingly, theory suggests that significant improvements in overall strength can be obtained by developing a better understanding of the influence of the local interface geometry on stress singularities, which appear in linear elastic models with or without edge cracks.

One such attempt in that direction was developed by Wang and Xu [1], where local convex protuberances were introduced near the interface along the free edge. Quasistatic and dynamic physical experiments showed an increase in strength of approximately 20% for aluminum–PMMA joints with internal angles of 65–45°, respectively, for the two materials compared to the average butt joint strength for specimens having 90–90° internal angles. However, an alteration of the external surface of the joint may not be desirable or achievable in many cases. Meanwhile, Lauke was motivated to accurately quantify the adhesion strength between two polymers by creating an interface geometry with nearly uniform interfacial stress [2,3]. This led to finite element investigations of bonded cylindrical specimens with curved interfaces having angled approaches to the outer free surfaces. This computational work by Lauke provided the primary motivation for the present study. In particular, this paper examines the effect of changing the geometric parameters at the interface on the strength of the joint, while preserving the external surfaces of the cylindrical samples. In addition, the system is scaled up to confirm that the measured strength is independent of the sample size for the interface design with non-singular stresses.

2. Use of stress intensity factors (SIF) and generalized stress intensity factors (GSIF)

2.1. Theoretical and experimental background

For linear elastic fracture mechanics (LEFM), based upon the early work of Kolossoff [4], Muskhelishvili [5], Irwin [6] and others, one finds a characteristic $r^{-\beta}$ variation of stress with $\beta = 1/2$ and r representing the distance from the tip of a crack embedded within a single homogeneous elastic material. Williams [7] defined in detail the stress distribution in the vicinity of the crack tip in such non-smooth problems. Since stress tends to infinity as the crack tip is approached, a more suitable bounded measure is required to estimate whether or not the crack is likely to propagate. For this purpose, stress intensity factors (SIF) are introduced to quantify fracture behavior (e.g., Anderson [8]).

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For cracks along the interface between two dissimilar materials, the characteristic singular exponent β may become complex. In this case, the stress intensity factors associated with in-plane components of stress can be written in a complex form as follows [9,10]:

$$K = \lim_{r\to 0}[(2\pi)^{\mathrm{Re}(\beta)} r^{\beta}\{\sigma_{\theta\theta}(r,0,0) + i\,\sigma_{r\theta}(r,0,0)\}] \tag{1}$$

where $\sigma_{ij}(r,\theta,z)$ represent components of the stress tensor in cylindrical coordinates having an origin at the crack tip and oriented such that the crack surfaces emanate along the $r-z$ plane with $\theta = \pm\pi$. The singular exponent for the interface crack in Eq. (1) is $\beta = (1/2 - i\,\varepsilon)$ in which ε depends upon the elastic properties of the two materials. The real part of β remains one-half, but now the stress oscillates in proportion to $r^{i\varepsilon}$. This not only complicates the analysis, but also suggests an increased vulnerability associated with cracks on an interface compared to those which are embedded in monolithic bodies.

Other typical examples of non-smooth problems arising within the classical theory of elasticity include those involving sharp re-entrant corners and bi-material interfaces without cracks. Unlike elasticity solutions associated with cracks, which always exhibit stress singularities, solutions for these other two classes may or may not exhibit stress singularities, depending upon material properties and the local geometry. Williams [11] defined β for general isotropic elastic single-material wedges with enclosed angle α for various combinations of boundary conditions on the two faces of the wedge (i.e., free-free, fixed-free, fixed–fixed). Two decades later, Bogy [12,13] provided the definitive solutions for bonded isotropic elastic bi-material wedges having free-free outer edges.

In this latter case, bi-material interfaces without cracks may provide geometric constraints sufficient to produce $r^{-\beta}$ stress singularities with $\mathrm{Re}(\beta) < 1/2$. Here r represents the distance from the point at the intersection of the bi-material interface and a free surface. Although the direct connection to energy release rates no longer applies, Eq. (1) can still be used to extract a finite measure related to strength, which may be labeled the generalized stress intensity factor (GSIF). In some of these cases, the maximum value of β is zero. This implies bounded stresses, improved strength and size-independent behavior. In the other cases, the characteristic exponent β has a positive real part that is less than one-half and a corresponding GSIF may be calculated. The fundamental question is whether this GSIF correlates with failure. While no supporting theory presently exists, there is some physical evidence suggesting that this is the case.

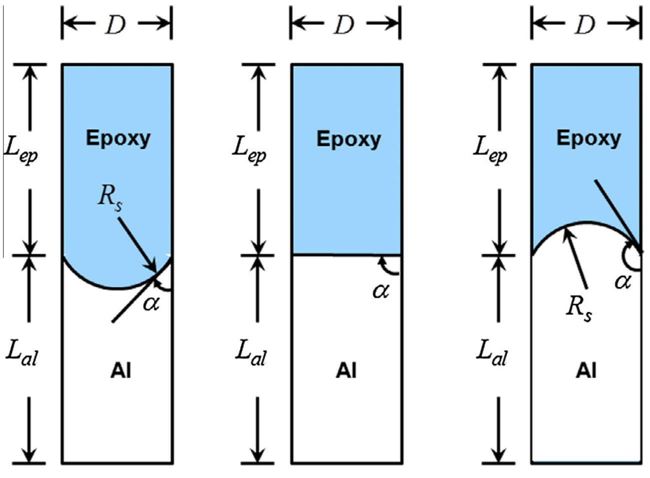
In a series of physical and computational experiments, Reedy and Guess [14–17] explored the behavior of epoxy–metal butt-jointed cylindrical specimens pulled in tension. They found that nominal tensile strength $\sigma_{\max}$ was dependent upon the thickness h of the epoxy layer with thinner layers providing enhanced strength. Most interestingly, their strength data scaled in close accordance with the singularity exponent β determined for the adjoining materials with $\sigma_{max} \propto h^{-\beta}$, thus exhibiting power law behavior. This implies that the GSIF in (1) could provide a suitable measure of strength, given a critical value K_{cr} for a specific β. Furthermore, Reedy and Guess conducted finite element analysis to estimate the GSIF in fully bonded models, which produced the expected scaling for stress and K. In addition, LEFM finite element analysis was performed by Reedy [18] to examine scaling of the SIF for models with small interfacial edge cracks. Remarkably, the SIF also scaled as h^{β}, suggesting that both GSIF and SIF approaches could be used to estimate strength. More recently, Dargush and Hadjesfandiari [19,20] studied this same butt joint problem using traction-weighted boundary element methods and confirmed the common scaling of GSIF and SIF approaches. Campillo-Funollet et al. [21] also found such consistent scaling of GSIF and SIF measures for the tensile strength of a dental adhesive butt joint. Other notable work on this generalized fracture approach includes research by Dunn et al. [22–24] and Carpinteri [25,26].

2.2. Computation of the singularity exponent

The transcendental eigenproblem defined in Bogy [13] for bi-material interfaces is solved numerically for the eigenvalues β associated with internal angles α_1 and α_2 of the two materials. The interface geometry here is defined such that $\alpha_1 + \alpha_2 = 180°$. For convenience, let the angle $\alpha_1 = \alpha$ and thus $\alpha_2 = 180° - \alpha$. Solutions are obtained for α from 15° to 165° at half-degree intervals. At each value of α, many randomly selected initial guesses are attempted within an iterative process to locate all of the relevant solution branches. Special attention is focused on finding eigenvalues β corresponding to singular stress solutions of the form $\sigma \propto h^{-\beta}$ with $\mathrm{Re}(\beta) > 0$.

3. Materials and specimen fabrication

The aluminum was used in rod form and was of type 6061-T6. The epoxy was Epon 815 (Momentive Specialty Chemicals, Columbus, OH). A cylindrical mold was fabricated of RTV 1000 silicone rubber (Eager Polymers, Chicago, IL) by curing the rubber around the rod and inside a plastic form. The aluminum was cleaned with ethyl alcohol before all machining processes. The rod was cut to approximately 100 mm length and one end was then machined on a lathe to produce the proper end shape (concave, flat, or convex). The cut surface was then cleaned with alcohol. This was the entire preparation for the 12.7 mm DIA rod; for the 25.4 mm rod, a hole was drilled through for later insertion of a pin during mechanical testing. The rod was inserted into a rubber mold. The epoxy was mixed in the ratio 100 parts epoxy to 20 parts triethylenetetramine (TETA) by weight, stirred for 2 min and degassed in vacuum for 2 min to eliminate bubbles. The epoxy was then poured into the rubber mold to coat the aluminum surface and fill the mold. The length of epoxy in the mold was approximately 100 mm. The epoxy cure time was a minimum of 48 h. The aluminum rod and bonded epoxy were then pushed out of the mold. To avoid mechanically gripping the epoxy, high-strength Hysol EA 9309 NA epoxy (Henkel Corp, Bay Point CA) was placed on the end of the epoxy rod and an aluminum coupling with a pin was bonded to this surface. The resulting fixture is thus self-aligning and free to rotate. See Fig. 1 for the definitions of the sample geometries.



(a) Concave (b) Butt (flat) (c) Convex

Fig. 1. Sample geometries.