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Analysis of the metal adhesively bonded double cantilever beam specimen

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ABSTRACT

The double cantilever beam specimen is currently standardized for measuring the mode I fracture energy of adhesive joints. In addition, it has been increasingly employed to evaluate the adhesive traction-separation law by the direct method, which involves crack tip separation measurements. The three-dimensional finite element analyses here conducted showed that significant anticlastic deformations of the metal adherends compromise the accuracy of the direct method in the elastic domain. It was also seen that the adherend plane stress and adhesive uni-axial strain hypotheses are adequate for the typical specimen geometries. Finally, the new elastic crack length correction derived from a beam model can be used to predict accurately the initial specimen compliance, to obtain conservative fracture energy values and to gain additional insight into the adhesive fracture behaviour.

1. Introduction

Owing to several advantageous characteristics and to the progress in adhesive formulations, adhesive joints are increasingly used in a wide variety of structural applications [1]. However, despite the vast research conducted, design of adhesive joints still faces considerable challenges right from the stress analysis stage [2–4]. Singularities at the adherend/adhesive interface and steep stress gradients are common in most joint configurations, posing difficulties to continuum mechanics based design approaches. Fracture mechanics is thus considered better suited for predicting joint strength if failure is actually dictated by the crack propagation stage. This failure mode is favoured by the preferential use of tough adhesives and by the frequent adoption of joint geometrical features that reduce stress gradients [1]. Moreover, one of the main limitations of traditional fracture mechanics, i.e. the need to assume a pre-existing crack, can be overcome by cohesive zone modelling (CZM) [5,6]. Considerable research has already been conducted on CZM of common structural adhesive lap-joints e.g. [7–11]. The basis of all formulations is the so-called traction-separation σ_c–δ_c law. Most of the traction-separation laws used for pure mode I loadings include an initial hardening stage until a cohesive strength is attained [12]. The final softening stage ends when the energy dissipated is equal to the mode I fracture energy.

Adhesive fracture energies have thus become particularly important properties for joint design. The majority of the experimental work has focussed on mode I fracture [13,14], for which the double cantilever beam (DCB) (Fig. 1) and the tapered double cantilever beam (TDCB) are currently standardized [15,16]. Data analyses are often carried out within linear elastic fracture mechanics (LEFM), meaning that the mode I fracture energy is actually the adhesive mode I strain energy release rate G_{IC}. However, fracture of tough adhesive may involve plastic zones around the crack tip that are too large for LEFM applicability. Therefore, the mode I fracture energy has also been designated as J_{IC} and measured with J-integral based data reduction schemes [17–20]. This is supported by the observed dependence of the fracture energy on the bondline thickness, which can be correlated with the height of the adhesive plastic zone [17–20]. Accordingly, Pardoen et al. [18] proposed to view the perceived fracture energy as the sum of an intrinsic work of fracture with the energy of adhesive layer elastic–plastic deformations, only the former being a true material property.

In spite of the above questions regarding the meaningfulness of the mode I fracture energy, the DCB specimen has been increasingly used to evaluate the traction-separation law of the adhesive [17–25]. The method employed, often designated as “direct”, requires measuring J_I and δ_c until “crack initiation” i.e. the instant at which the initial crack actually starts to propagate. The derivative of the J_I –δ_c curve yields the σ_c–δ_c law [17–25]. Obviously, this approach demands:

- A representative “sharp” pre-crack created in the specimen e.g. by inserting thin release films and/or razor blades.
- Accurate measurements of the small δ_c that have been facilitated by the performance of recent optical methods [20–25].

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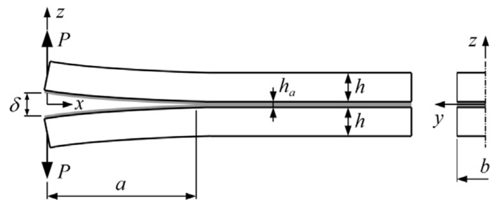

Fig. 1. The DCB specimen for adhesive joints.

- Accurate methods to compute J_I, which may in turn require measurements of load-point crack-tip rotations [19,20,25], or simply application of beam theory based data reduction schemes [21–24] similar to those used for delamination of composites [16,26,27].

Furthermore, in order to validate traction-separation law measurements, experimental load–displacement curves have been compared with predictions of two-dimensional (2D) CZM [21–24]. It is thus clear that characterization of the mode I fracture of adhesive joints has reached a high level of sophistication in both experimental techniques and analysis methods.

However, little attention has been paid to considerable three-dimensional (3D) effects already reported [21,28–32]. In fact, Han and Siegmund [21] detected significant differences between the edge separations predicted by 3D CZM and those obtained from 2D plane strain CZM. This can be explained by the anticlastic deformations resulting from Poisson effects associated with the longitudinal bending of the adherends [29,30]. This causes non-uniform width-wise distribution of G_I [30–32] that promote premature crack initiation at the centre of the specimen and end-up causing thumbnail-shaped crack fronts [28,32]. This phenomenon does not compromise steady-state propagation G_{IC} measurements on laminated composites [33,34], as demonstrated in the 3D FEA of [35] which simulated the curved delamination propagation with CZM. However, the transition of the straight pre-crack to the thumbnail-shaped one creates additional difficulties in measuring the initiation G_{IC} value [36]. As for evaluating the mode I traction-separation law in composites, the very small separations and the low initiation G_{IC} restrict the direct method to the characterization of the fibre bridging phenomenon [37,38] that has no parallel in adhesive fracture.

Therefore, it seemed useful to investigate the 3D effects on the evaluation of the adhesive traction-separation law and on the 2D beam theory based data analysis methods commonly employed. The analyses described below considered the most desirable cohesive fracture mode [1] i.e. it was assumed that the starter crack was generated and subsequently propagated within the adhesive layer.

2. Three-dimensional finite element analyses

As seen above, relatively few 3D FEA have been reported on the metal adhesively bonded DCB specimen. The present models were constructed with second-order 20-node reduced integration elements (C3D20R) of the ABAQUS® code. The material and loading $y=0$ and $z=0$ symmetry planes (Fig. 1) allowed the modelling of a quarter-specimen. Mesh refinement studies showed that accurate results could already be obtained by modelling the adhesive half-layer with a single layer of finite elements and the adherend by two layers of finite elements. The elements around the crack tip were 0.25 mm long and 0.83 mm wide. Loading consisted of applying a vertical displacement $\delta/2$ (Fig. 1) to the adherend mid-thickness end node set, on which length-wise displacements were prevented. In view of the objectives of this work and the results that were actually obtained, the analyses adopted linear elastic behaviour for both adherends and adhesive. The virtual crack closure technique (VCCT) [39] was employed to compute G_I along the straight crack front. The present analyses considered typical steel and aluminium (Al) adherend properties and geometries i.e. Young's modulus $E=210$ and 70 GPa, Poisson ratio $\nu=0.3$ and thickness h from 7 to 13 mm (Fig. 1). For the adhesive $E_a=1.8$ GPa and $\nu_a=0.35$ were used with bondline thickness h_a from 0.1 to 0.7 mm. Crack lengths a were varied between 40 and 130 mm, while the width was always $b=25$ mm.

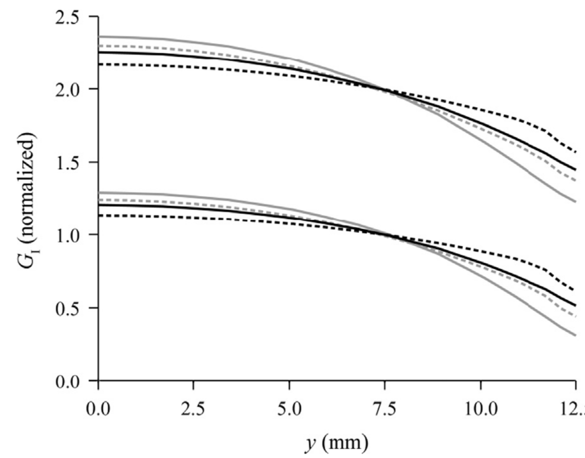

Fig. 2. Distributions of G_I along half-width of steel adhesively bonded DCB specimens with dimensions (mm) $h=7$ (grey lines) and 13 (black lines), $h_a=0.1$ (continuous lines) and 0.7 (dashed lines), $a=40$ and 130 (vertically offset by one unit). G_I values were normalized by the width-wise average.

Fig. 2 depicts the clearly non-uniform width-wise distribution of G_I for steel adhesively bonded DCB specimens as a result of considerable adherend anticlastic deformations. Distributions for Al adherend specimens were similar but slightly more non-uniform. In fact, it can be seen that the degree of non-uniformity increases for decreasing adherend bending stiffness, especially by lowering the adherend thickness and, to less extent, by increasing the crack length. Thicker bondlines in turn reduce the effect of adherend anticlastic deformations on adhesive through-thickness strains ε_z (Fig. 1) and thus the non-uniformity of G_I. Nonetheless, it seems clear that the non-uniformity is always significant enough to compromise the accuracy of traction-separation law evaluation by the direct method. Let us consider the most recent approach, based on optical measurements of crack tip separations at a specimen edge, applied to the most favourable case of Fig. 2, which corresponds to a stiff $h=13$ mm adherend with a small $a=40$ mm initial crack. The edge G_I is about 60% of the width-wise average value that would be measured by a beam theory or J-integral based analysis method. For the linear elastic adhesive behaviour adopted, G_I correlates with δ_c^2, and thus δ_c measured at the edge would be about 80% of the width-wise average δ_c. Therefore, the direct method would not provide an accurate linear elastic part of the traction-separation law.

Naturally, it can be argued that the linear elastic range is only a small portion of the traction-separation law and that subsequent plastic deformations and damage could reduce the width-wise non-uniformity of energy dissipation through load redistribution. However, such phenomena do not prevent anticlastic deformations of the stiff adherends, which end-up causing the thumbnail-shaped crack fronts observed in [28]. Therefore, evolution from the straight pre-crack to the thumbnail-shaped propagating crack will still bring about additional errors in traction-separation law measurements. Evidently, the true magnitude of such errors will have to be evaluated with 3D CZM.