A Mode I Fracture Behaviour Analysis of Adhesively Bonded Joints

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Abstract

The current work examines the fracture behaviour of adhesively bonded joints by conducting a series of low rate tapered double cantilever beam (TDCB) tests and simulating them numerically. Single part, nano-rubber toughened, structural epoxy adhesive was used throughout the current research. Particular emphasis is given to the effect of the bond thickness on the fracture surface appearance and the fracture toughness of the adhesive. The experiments are modelled numerically by employing a finite volume (FV) cohesive zone model (CZM). It is anticipated that numerical analysis, which employs a CZM and models the adhesive as an elastic-plastic material, should accurately partition the fracture (separation) energy from the energy dissipated in bulk plastic deformation of the adhesive layer. This would, in turn, help to resolve the issue of increasing G_{IC} as a function of the bond thickness, as predicted using the conventional linear elastic fracture mechanics (LEFM) approach. The work also introduces a novel experimental procedure for the direct measurement of traction separation curves in structural adhesives. For this purpose, circumferentially deep-notched tensile (CDNT) specimens were employed. The idea is that damage and separation processes will uniformly develop across and be confined within a highly constrained region of the notch ligament. During the experiment, the load is measured by the load cell and the separation by a clip-gauge extensometer. In parallel with these experiments, CZM parameters are calibrated numerically by fitting the experimental TDCB load-displacement and crack history results. Good agreement is obtained between the two experiments.

Introduction

Welding has been the primary method of joining sheet metal in the automotive industry for a large number of years. However, in the past decade, car manufacturers have been looking for alternative methods of joining metals. Adhesive bonding technology is becoming an alternative to spot welding because of the many benefits it has to offer to the automotive industry. It is important to understand the mechanism of fracture behaviour in an adhesive layer in order to improve the quality of bonded structures and structural integrity of the component. Bond thickness is one of the most significant parameters of an adhesive joint. Many studies have been carried out to investigate the mechanism of the bond thickness dependence of the adhesive fracture toughness. Bascom et al [1] found that the fracture energy in a rubber-modified epoxy resin adhesive is maximized when the diameter of the plastic zone ahead of the crack tip is equal to the bond thickness. Kinloch and Shaw [2] confirmed the bond-thickness effect on the fracture energy, G_{IC}, of adhesive joints, and proposed that the size of the damage zone played a role in enhancing G_{IC} of the adhesive joint. Yan et al [3] investigated the effects of substrate materials on the fracture behaviour of adhesive joints with different bond thicknesses. They also found that the fracture toughness initially increased and then decreased with increasing bond thickness. Generally it is found that as the bond thickness increases, the fracture energy increases, peaks and decreases. Fig. 1 below, illustrates this concept.

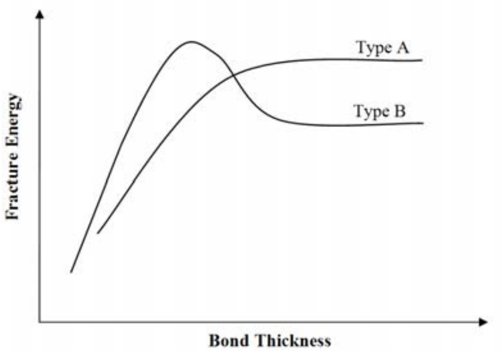


Figure 1: Two typical types of bond thickness effects on the fracture toughness of adhesive joints.

In the current work, a series of TDCB joints with increasing bond thickness are analysed at low loading rates. However, using the conventional LEFM approach, it is found that the fracture energy increases continuously with increasing bond thickness. Also, a significant change in the crack behaviour was observed when the bond thickness was increased above 1mm.

Materials

A single part, rubber toughened, hot cured structural epoxy adhesive (#3019-98) was supplied by Henkel Loctite Ireland and was used throughout the current work. The adhesive has a curing schedule of 180°C for 30 minutes. Tests were carried out using two different substrate materials. The first, Aluminium 2014, is a high yield strength alloy which is widely used in automotive applications. The second, Steel A366, is a cold rolled carbon steel of commercial quality. Uniaxial tensile tests were conducted to obtain the mechanical properties of both the substrate materials and the adhesive. Results of the tests conducted at the strain rate $0.00006s^{-1}$ are given in Table 1.

	Young's Modulus [GPa]	UTS [MPa]
Aluminium 2014	*72.4*	*430*
Steel A366	*190*	*320*
Henkel #3019-98	*1.9*	*36.7*

Table 1: Room temperature tensile properties at a strain rate of $0.00006s^{-1}$.

Tapered Double Cantilever Beam Tests

The TDCB configuration is used to measure the mode I adhesive fracture energy G_{IC}, and also to calibrate the CZM for the adhesives. Tests were carried out using two different TDCB setups: *(i)* Steel substrates of width 25mm (ASTM D3433 [4]) and *(ii)* 10mm wide aluminium 2014 substrates following the BS2001:7991 testing protocol [5]. It was important that the substrates remained within the elastic region throughout the test. Tests were performed at a constant crosshead speed of 0.5mm/min. The specimen geometry for both configurations is illustrated in Fig. 2. The profile of the arms is machined such that the compliance increases linearly with the crack length and hence the derivative of the compliance with crack length, and therefore G_{IC}, remain constant i.e. the geometry constant $m = 2mm^{-1}$.

Surface pre-treatment of a substrate prior to adhesive bonding is usually necessary in order to attain maximum bond strength. All substrates therefore, were pre-treated as follows:

- Degrease with Acetone,
- Grit blast using 180/220 mesh alumina grit at 5 bar,
- Chromic-acid etch at 68°C for 30min (*Aluminium substrates only*),
- Rinse with distilled water.

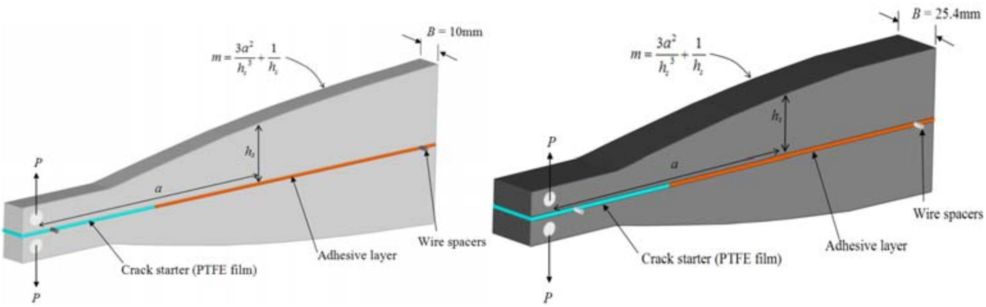


Figure 2: Illustration of the TDCB test specimens *(a)* 10mm wide aluminium substrate joint *(b)* 25.4mm wide steel substrate joint.

Excess adhesive was applied to each beam and allowed to squeeze out as the two adherents were pressed together. The extruded adhesive was removed from the side of the beams prior to curing. The bond thickness was set using stainless steel wire spacers. A 12 μm thick film of polytetrafluoroethylene (PTFE) was inserted at one end to act as a crack starter as specified in the protocol. The specimens were placed in a jig that would maintain alignment, and a slight compressive load was applied. For each batch of joints manufactured, a thermocouple lead was inserted in to the bond-line of one joint to monitor the temperature during cure. The samples were cured at 180°C for 30min. The tests were carried out using a screw driven tensile testing machine (Hounsfield H50KS) and records of the load and the displacement at different increments of the crack length were obtained. At least three repeats for each joint system were tested.

TDCB Results

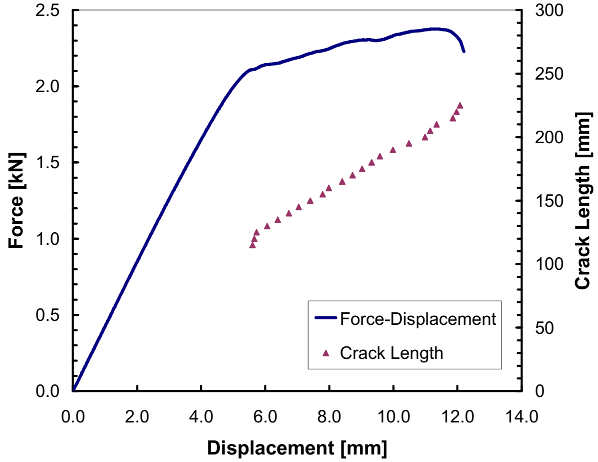
Steady state crack growth behaviour was observed in all tests. Fig. 3*(a)* gives a plot of load-displacement and crack length-displacement for a 10mm wide aluminium TDCB with a bond thickness of 1.8mm. The average fracture energy was calculated using the Corrected Beam Theory approach:

$$G_{CBT} = \frac{4P^2 m}{Eb^2}\left(1 + 0.43\left(\frac{3}{ma}\right)^{1/3}\right). \quad \text{(Eq. 1)}$$

where, P is the mean load during crack propagation, m Geometry factor, E Young's Modulus of substrate, b width of the beam, and a crack length. Calculated fracture toughness as a function of the bond thickness is presented in Fig. 3*(b)*.

In both configurations, a mode I cohesive fracture was observed in each test up to a bond thickness of approximately 1mm. When the bond-line thickness was increased above 1mm, a significant change in the crack behaviour was observed (see Fig. 4). After initiating as a predominantly mode I crack, a slanted fracture gradually developed along the specimen. It is believed that this behaviour is a result of plastic deformation of the adhesive. Due to shear lips appearing on the stress free sides of the specimen, a local mode III loading was introduced forcing the fracture to change from plane cohesive mode I to slant mixed mode I and III fracture. In the region where the slant fracture meets the substrate, the crack is forced to propagate along the interface between the adhesive and the substrate. In some cases, as a result of fast propagating crack in the last third of the specimen length, plastic deformation and occurrence of shear lips were reduced and fracture 'switched back' to a cohesive mode I fracture in the adhesive. This is similar to the slant fracture of AL2024-T3 loaded under remote Mode I conditions, observed in the work of Mahgoub et al [6].

(a)



(b)

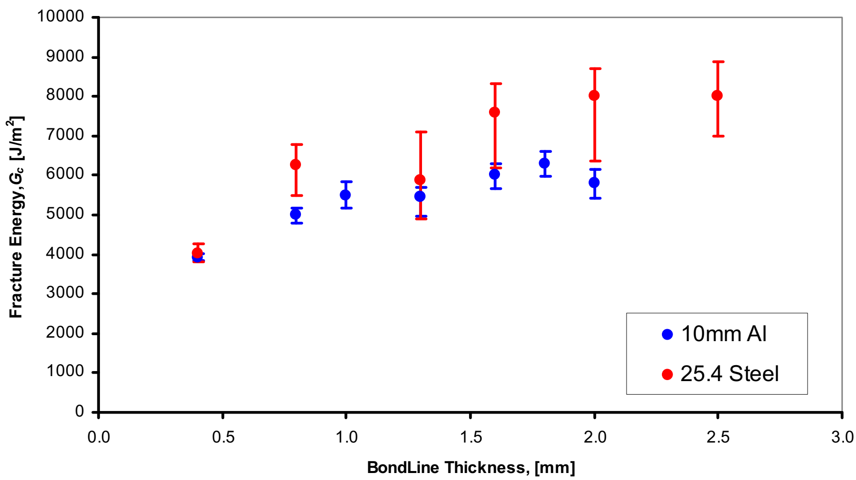


Figure 3: Henkel #3019-98 adhesive *(a)* Force-displacement and crack length history for TDCB with 1.8mm bond thickness tested at 0.5mm/min (10mm wide specimen). *(b)* Adhesive fracture energy, G_{IC}, versus bond thickness for 10mm wide aluminium and 25.4mm wide steel specimens.

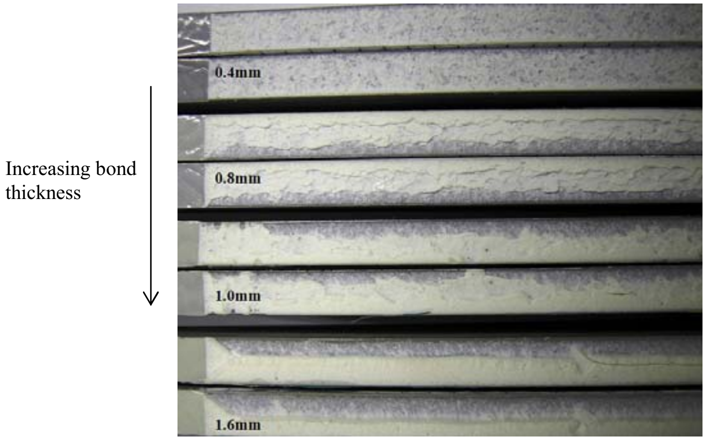


Figure 4: The development of slant fracture in the 10mm aluminium specimens with a bond thickness ranging from 0.4mm – 1.6mm.

Numerical modelling

Numerical modelling of the 10mm wide TDCB tests was performed in OpenFOAM (version 1.3) [7] using the Finite Volume (FV) method. The CZM was defined using a two-parameter Dugdale model, with the parameters being the adhesive fracture energy G_{IC}, and the maximum cohesive stress, σ_{max}. The adhesive fracture energy was set to the lowest value calculated from the TDCB experiments (obtained from 0.4mm bond thickness), whereas σ_{max} was estimated from the corresponding stress strain curves. Numerical analysis of the tests was conducted by increasing the bond thickness while keeping the adhesive fracture energy constant. In the analysis, the substrate was represented as a linear elastic material using Hooke's law while the adhesive was represented using a conventional incremental plasticity model with the von Mises yield criterion and the Prandtl-Reuss associated flow rule. A 2D illustration of the mesh used is shown in Fig. 5.

Experimental and numerical analysis results (load vs. displacement and crack-length vs. displacement), obtained for the 0.4mm bond thickness case, are compared in Fig. 6. Good agreement between both sets of data is observed. The current numerical model with a predefined crack plane can accurately predict the behaviour of the adhesive when a low bond gap thickness is employed i.e. when a single, mode I crack propagates cohesively through the adhesive layer. However, when the bond gap thickness is increased above 1mm, a more complex crack path is formed and the numerical analysis, which is essentially 2D with a prescribed straight mode I crack, failed to reproduce experimental results.

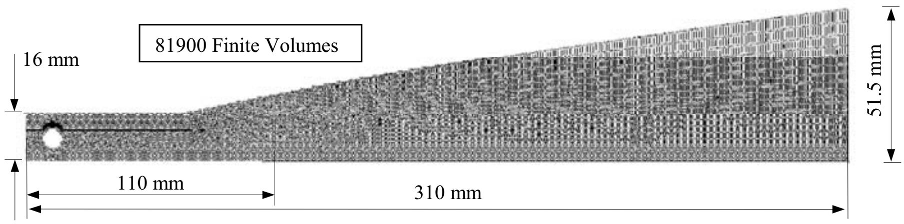


Figure 5: FV representation of the TDCB geometry.

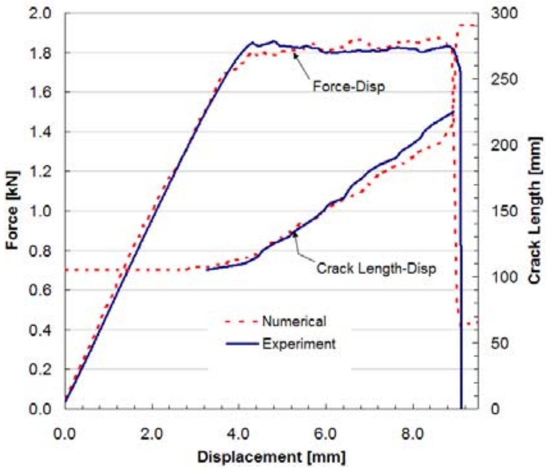


Figure 6: Experimental and numerical analysis results for Henkel #3019-98 adhesive with a 0.4mm bond thickness.

Circumferentially Deep Notch Tensile Tests

CDNT experimental work was carried out in parallel with the TDCB tests. The idea is that damage and separation processes will uniformly develop across and be confined within a highly constrained region of the notch ligament. During the experiment, the load is measured by the load cell and the separation by a clip-gauge extensometer. The traction is obtained by dividing the measured load with the original cross sectional area of the adhesive joint. The results from the TDCB tests are used to verify CDNT results.

CDNT specimens (see Fig. 7) were manufactured by applying adhesive between two aluminium substrates to form a joint. The specimen is then mounted in a curing jig to ensure alignment during the cure process. The critical parameter in the CDNT is the geometry of the notch, i.e. the radius of curvature and therefore the sharpness of the notch. If the notch is too sharp the crack propagation may take place, and if the notch is too blunt localised plastic deformation may develop at the notch. Both processes will make the test invalid. In order to form the notch, two methods were investigated. First, a PTFE film of 12.7 μm thickness was inserted between the two substrates. The PTFE film had a circular hole to control the diameter of the notch, and a pair of stainless steel wires was used to control the bond line thickness. Tests were conducted at room temperature using a computer-controlled electro-mechanical Hounsfield H50KS tensile test machine at a test rate of 0.05 mm/min.

Accurate traction separation curves were obtained for one particular level of constraint as shown in Fig. 8, i.e. 10mm diameter ligament, but this approach has not yet produced adequate results for other ligament sizes. It was difficult to control the position of the ligament and geometry of the notch using the PTFE film and hence the idea of the PTFE-coated steel washer is currently being introduced. This will allow a more accurate control of the notch geometry and give more reproducible results at various rates and constraints.

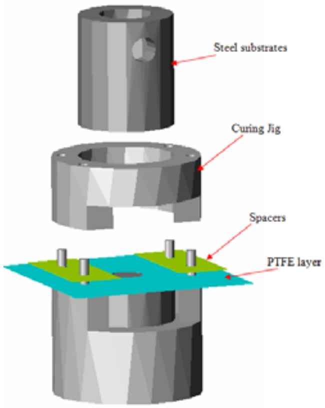


Figure 7: CDNT test specimen and curing jig.

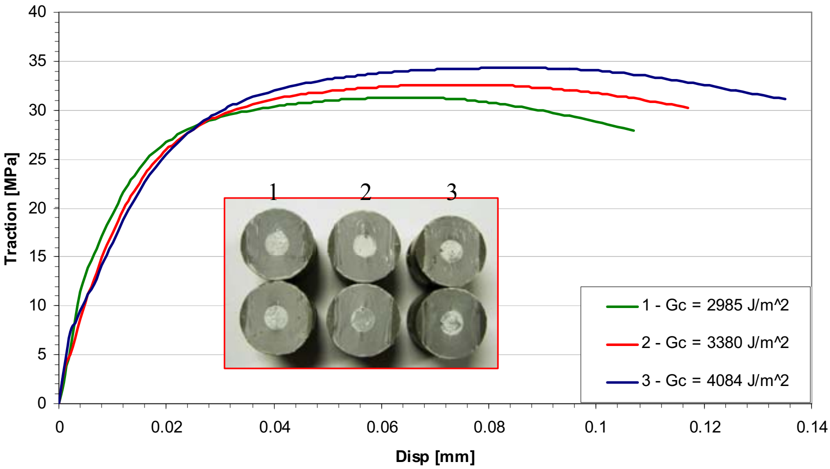


Figure 8: Traction-Separation curves and corresponding fracture surfaces obtained from the CDNT test. Adhesive ligament diameter = 10mm. G_C is determined by calculating the area beneath each curve.

Conclusions and Future Work

The TDCB experimental results show a strong dependence of the adhesive fracture toughness on the bond thickness when analysed using the conventional LEFM approach. However, the suitability of LEFM for the tests with larger bond thickness is questionable due to extensive plastic deformation of the adhesive and complex fracture behaviour. The use of CZM and elastic-plastic analysis of the adhesive should accurately partition the fracture or separation energy from the energy dissipated in bulk plastic deformation of the adhesive layer. This, along with the arbitrary crack propagation model and full 3D analysis, will result in an accurate relationship between the fracture toughness and the bond thickness and will lead towards better understanding of the fracture process of the adhesives under consideration.

Increasing the width of the substrates/bond resulted in predominantly plane strain conditions at the crack tip. This resulted in a reduction of the extent of plasticity occurring at the crack tip when compared to the 10mm specimens.

A novel Circumferentially Deep Notched Tensile (CDNT) test for characterising adhesive behaviour and classifying various grades of adhesives under different loading conditions was developed. The test is designed for the direct measurement of the cohesive properties or traction-separation laws of the adhesives at various rates, constraints and temperatures. It was successfully applied to the Henkel #3019-98, single part, rubber toughened, structural epoxy adhesive for a particular level of constraint. CDNT results were found to agree well with CZM results obtained from numerical calibrations of TDCB fracture experiments. The test is currently being further developed. Also, the idea of testing notched bulk adhesive specimens under tensile loading is being investigated. This design would be similar to the work carried out by Ting et al [8] where a circumferential deep notch tensile specimen was used for measuring traction-separation curves in polyethylene.

Work is currently being carried out to replace the existing finite volume model with one which incorporates arbitrary crack propagation. It is expected that this will predict the increasing load with bond gap thickness as observed in experiments.

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