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# Tear resistance of a square-wave joint: Experiment versus cohesive zone model

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ABSTRACT

The load versus displacement response of a double-cantilever beam (DCB) adhesive joint is measured for two interface geometries: a planar interface and a non-planar "square-wave" interface. Joints with a square-wave interface are stronger and tougher than planar joints of equal adhesive layer thickness provided the square-wave amplitude is sufficiently large. Computed tomography (CT) imaging is used to examine the failure morphology of DCB specimens with planar interfaces, and optical fractography is used to observe the failure mechanisms for DCB specimens with square-wave joints of fixed wavelength and selected amplitude; in all cases, the failure mode is similar to those of tensile, square-wave, butt joints. The finite element method is used to predict the cracking response of the DCB adhesive joint. To do so, the adhesive layer is idealised as a plane of cohesive elements with a normal traction versus separation response, as measured independently from square-wave butt joint specimens. Satisfactory agreement exists between the predicted and observed DCB response for all interface geometries, provided the reduction in DCB bending stiffness, arising as a consequence of the square-wave interface geometry, is taken into account.

## 1. Introduction

Commonly, adhesive joints are stronger and tougher under shear loading (such as a lap joint) configuration, than under tensile loading (such as a butt joint). This suggests that a strategy for increasing the peel strength and peel toughness of a joint is to inter-digitate the two substrates, and thereby exploit the high strength and toughness associated with a lap-joint configuration, see for example Maloney and Fleck [18].

The present study builds on the promising studies on micro-patterned adhesive joints by Matsuzaki and co-workers [20,28,12,36,29] and on the work of Kim et al. [15]. These studies make use of an in-mold surface modification method whereby a corrugated molding tool is pressed against a low-viscosity matrix during curing of a composite, and the patterns are transferred by demolding at low temperature. The wavelength and amplitude of the pattern is typically on the order of 10 μm, and an elevation in the butt joint strength, macroscopic mode I toughness of a double cantilever beam (DCB) specimen, and macroscopic mode II toughness of an end-notch flexure (ENF) specimen increase with the amplitude of the pattern (typically by a factor of 50% in strength and 100% in toughness). More recently, Cordisco et al. [6] investigated sinusoidal DCBs of amplitude $A$ and wavelength $\lambda$ with $A/\lambda$ in the range 1/4 to 1/2; they found that the peak load increased with $A/\lambda$ and concluded that patterned adhesive joints can be substantially tougher than joints with no pattern. Maloney and Fleck [18] conducted tensile tests on butt joints of square-wave configuration, and observed that the measured tensile strength and energy absorption increase with amplitude $A$.

Suzuki et al. [28,29] have modelled the mode I response of a DCB specimen with a micro-patterned joint by placing cohesive zones along the profiled interface of the joint and also within the adhesive. An elastic-brittle analysis sufficed, with no dissipation in the adhesive layer, as the epoxy adhesive was of low toughness. The present study explores a different class of adhesive (elastomeric rather than untoughened epoxy), and on a different length scale of patterning (millimetre scale rather than micron scale).

Crack advance within a joint is commonly modelled by a cohesive zone approach, with the traction versus displacement response of the cohesive zone sensitive to the thickness of the adhesive layer [11,27,34]. Cohesive zone modelling (CZM) has become a popular tool for predicting the fracture response of adhesive joints [17,30–32]. The CZM approach can capture the linear-elastic fracture mechanics (LEFM) limit whereby the zone of inelasticity is much less than that of leading structural dimensions such as crack length or ligament size. It can also capture large-scale bridging where LEFM fails, see for example Elices et al. [8], Yang and Cox [33] and Alfano et al. [2].

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Commonly, the traction versus separation ($T$-$\delta$) response of the “cohesive zone” is defined by two parameters such as the cohesive strength and work of separation, or cohesive strength and critical separation [1,3,4]. Cohesive zones have been used to model crack initiation [21], but they are more commonly used to model the growth of a crack [8]. We note that the CZM represents both the process zone ahead of the crack and the bridging zone in the wake of the crack, and the CZM length can vary from nanometres to millimetres [25,27,38].

There is scope for choosing the appropriate level of sophistication in a cohesive zone model, depending upon the research question to be addressed. For example, the role of mode mix on the fracture strength and toughness can be analysed by suitable modification to the traction versus separation law across the cohesive zone, see for example Yang and Thouless [35]. The role of plastic yielding in the adherends has been addressed by Ferracin et al. [9] for the wedge-peel test and by Georgiou et al. [10] for the peel test, with the deformation and fracture response of the adhesive idealised by a cohesive zone. This pragmatic approach requires a calibration of the bondline toughness as a function of the thickness of the adhesive layer. In contrast, Pardoen et al. [22] model explicitly plastic deformation within both the adherends and the adhesive, but idealise the fracture process zone by a cohesive zone law; in this manner, the role of constraint effects and thickness of adhesive layer can be modelled. However, the details of the crack tip failure mechanism are not interrogated explicitly by this approach; to do so would require a detailed constitutive model for microvoid growth or crazing within the fracture process zone, along with a representative material length scale in order to predict the macroscopic toughness. Nevertheless, the use of a cohesive zone embedded within an elasto-plastic adhesive layer and outer elasto-plastic adherends is a useful predictive tool, and has been validated for the peel test by Martiny et al. [19], and for the tapered double cantilever beam by Cooper et al. [5]. Recently, the importance of rate effects in the failure of rubber-toughened epoxies has been highlighted by Karac et al. [16] by making use of a crack velocity dependent cohesive zone law to predict the load versus displacement response of a tapered double cantilever beam.

### 1.1. Determination of the cohesive zone law

The central task of implementing a cohesive zone model is a determination of the traction versus separation ($T$-$\delta$) law, or “cohesive law”, to define the response of cohesive elements [23,24,27]. Most methods assume a simple shape for the traction-separation law and attempt to match the results of a finite element simulation to experimental measurements by varying the parameters of the cohesive law such as the peak traction or energy dissipation. When adequate agreement is achieved between simulation and experiment, it is assumed that the correct cohesive parameters have been deduced [35].

There exist two main methods for measuring a Mode I cohesive law directly from experimental results. The first makes use of the measured $J$-integral for a crack in a double-cantilever beam specimen, and a simultaneous measurement of the crack tip opening displacement (and crack tip opening angle). The traction exerted by the cohesive layer is the derivative of the $J$-integral with respect to the crack tip opening displacement. This method has been used by several researchers to derive empirically-based cohesive laws [26,27,38,7] and generally provides accurate predictions of the response of a cracked specimen.

The second method is more straightforward, but there are only limited studies to explore its validity. The Mode I cohesive law is assumed to equal the $T$-$\delta$ response of a tensile specimen so-chosen to represent a thin ligament ahead of the crack. Ivankovic et al. [14] pursued this strategy to model the response of cracked three-point-bend polyethylene specimens with mixed success. They extended their model by including rate-dependence in the cohesive law and thereby achieved satisfactory predictions. They recognized the shortcomings of this approach and proposed the development of a physical material model which could describe the local fracture process by a $T$-$\delta$ response which depends on rate, constraint and temperature.

### 1.2. Scope of the present study

In this study, the load versus displacement response of a double-cantilever beam (DCB) specimen with a square-wave interface geometry is explored as a function of square-wave amplitude. The observed failure mechanisms of square-wave DCB specimens are compared to those observed for tensile butt joints with square-wave interfaces as presented in a previous study [18].

A finite element model is used to predict the response of double-cantilever beams with either a planar interface or a square-wave interface. The adhesive layer is represented by cohesive elements with a traction versus separation response as specified by the measured tensile response of a butt joint specimen with the same micro-architecture (planar or square-wave). The accuracy of the finite element model is evaluated by comparing the predicted load versus displacement response to the measurements. Additionally, the accuracy of a $J$-integral method for predicting the load versus displacement response of DCB joints with planar interfaces is confirmed in the appendix.

## 2. Materials and methods

### 2.1. Experimental methods

The adhesive joints comprised a two-part, room-temperature and moisture-curing silyl-modified polymer (SMP) adhesive[1] sandwiched between aluminium alloy 6082-T651 substrates. The adhesive contains filler particles on a scale of 10 µm to control its viscosity in an un-cured state. The double-cantilever beam (DCB) joint is characterised by arms of height $H = 25.4$ mm, beam lengths l and L of 25.4 mm and 228.6 mm, respectively, and a starter crack of length $a_o = 30$ mm, see Fig. 1(a). The square-wave interface geometry was presented in a previous study [18]. It is characterised by five parameters as defined in Fig. 1(b). The amplitude $A$ ranges from 0 mm (corresponding to a planar interface) to 20 mm, while the magnitude of wavelength $\lambda$, adhesive thickness parameters $t$ and $s$, and depth (into page) $B$ are fixed at $\lambda = 28$ mm, $t = s = 1.1$ mm, and $B = 12.8$ mm. The pattern wavelength and layer thickness were chosen within the practical range for the manufacturing and test methods adopted. Suitably-shaped substrates were water-jet cut to within a dimensional tolerance of 0.1 mm.

#### 2.1.1. Specimen preparation

Roughening of the substrates was accomplished by manual polishing using 60 grit emery paper; the surfaces were then cleaned and degreased by wiping with acetone. The adhesive was applied in accordance with the manufacturer’s recommendations. A manual applicator gun was used with a static-mixing nozzle. A quantity of adhesive was initially discarded to ensure that both components were flowing freely and to remove any bubbles which may have accumulated in the component tubes. The adhesive layer thickness $t$ was adjusted by shims prior to infiltration of the gap by the adhesive. All specimens were cured in ambient air for one week at room temperature, and G-clamps were used to prevent relative movement of the substrates. A starter crack was generated in all specimens by making use of fresh razor blades: the razor blade was broached to a depth of 5mm, to give an initial crack length of 30mm. Additionally, the uniaxial response of the SMP adhesive was measured by casting a dogbone specimen from the adhesive, of gauge length 20 mm and square cross-section 6.5 mm × 6.5 mm.

[1] Sabatack Fast, produced by SABA Dinxperlo BV, Industriestraat 3, 7091 DC Dinxperlo, Netherlands.