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Characterising bonded joints with a thick and flexible adhesive layer—Part 1: Fracture testing and behaviour

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ABSTRACT

Adhesively bonded structural joints have increasingly found applications in automotive primary structures, joining dissimilar lighter-weight materials. Low-modulus rubbery adhesives are attracting rising interest as an alternative to conventional rigid structural adhesives due to benefits such as the excellent impact resistance they provide. This paper is the first of two parts that investigate, both experimentally and numerically, the mechanical behaviour of a rubbery adhesive and the bonded joints to be used in a lightweight automobile structure. This part 1 paper characterises the fracture behaviour of the flexible adhesive layer with thick bondlines and presents a way to reliably determine the fracture mechanics parameters under a range of loading modes. Assessment of the various fracture tests indicated that DCB and SLB should provide mode I and mixed mode fracture energies but that the conventional ENF for mode II would not be practical for such compliant adhesive layers. Instead a cracked thick adherend shear specimen was developed and used. Reliable fracture energies were obtained from these specimens and a mixed mode fracture criterion developed for application in the part 2 paper.

1. Introduction

Adhesive bonding has been widely used in engineered products to join individual parts into a structural component. Bonding provides a number of benefits such as an ability to join dissimilar materials and a more uniform stress distribution in the joint, and has often replaced traditional welding or mechanical fastening techniques [1]. More recently, it has been increasingly used in demanding structural applications including aircraft, automobiles, and construction. The automotive industry, in particular, is paying considerable attention to using adhesive bonding to join primary structural components [2]. This trend has been driven by the extensive use of lightweight materials such as aluminium or fibre reinforced polymers (FRP) in combination with conventional steel in a quest to improve fuel consumption. As assembling such dissimilar materials by spot welding is generally difficult or impractical, adhesive bonding provides an attractive alternative.

Low modulus rubbery adhesives with high ductility have attracted rising interest for structural bonding in the automotive industry [3]. They are based on different types of polymers, including polyurethanes, acrylics, and their blends with epoxies, typically exhibiting a modulus as low as a few MPa as well as failure strain of over 100% [4]. A major advantage in their application has been claimed to be excellent impact resistance. Their high deformability allows sufficient load transfer through the joints as well as providing energy absorption during an impact event. Their damping capability can more effectively reduce noise or vibration compared with rigid structural adhesives. Also, a more uniform stress distribution is expected than that for rigid adhesives, which could lead to greater fatigue resistance.

Since these flexible rubbery adhesives for structural bonding application have a rather short track record [3] limited literature on their mechanical behaviour have been found. Basic ideas about their behaviour can be obtained through the work extensively conducted in the past on traditional rubbers such as natural rubbers or the cross-linked styrene–butadiene rubber (SBR) and bonded joints using those rubbers [5].

The limited literature available has reported a wide range of mechanical responses of bonded joints with polyurethane based adhesives similar to the adhesive studied in this work. These include quasi-static, fatigue and impact loading on lap shear or peel joints at various temperatures or strain rates [3,6–8]. However, a considerable difference in properties can be expected because different adhesives were used, and because the bond thickness in those studies was much thinner than in the current application (3 mm). In other studies that attempted to measure fracture energies, difficulty in applying standard test geometries

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has been reported, presumably due to the high deformation capability of those adhesives [9–11].

The primary objective of the current research is to investigate the application of experimental and modelling procedures used successfully for thinner more rigid adhesives to thicker and more flexible adhesive systems. This has been undertaken first by characterising fracture behaviour and determining fracture energies for three different loading modes, pure mode I, mode II, and a mixed mode. Then, the structural response of bonded joints representative of those used in the vehicle structure were tested and modelled using progressive damage modelling with cohesive zone material damage models using the fracture testing results. Part 1 of the paper focuses on the fracture testing and analysis and part 2 of the paper discusses the validity of numerical prediction. The fracture parameters used in this paper are only strictly applicable when linear elastic fracture mechanics (LEFM) prevail, ie when the non-linear response is localised to the crack tip. It is anticipated that this is unlikely to be the case with these low modulus high thickness adhesive layers. Thus it is important to include the process zone in any modelling work and this has been done in part 2 of this paper. In this work the same adhesive thickness and modelling approach has been used in the fracture mechanics specimens and structural joints. The applicability of the fracture parameters to structural joints with other thicknesses has not been included in this work but is an area that could be considered further.

2. Mode I fracture

2.1. Experimental methods

Details of the double cantilever beams tested are shown in Fig. 1. The substrates were short glass fibre reinforced composite (either 6 or 12 mm thick) and the polyurethane adhesive had a thickness of 3 mm. The material and thickness of the substrates were determined by performing a preliminary FE analysis to establish that the substrate would not fail before crack growth was likely to occur. Two steel blocks were bonded on the end of the substrates to receive the loading pins. A notch was introduced in the middle of the bond thickness by inserting a razor blade when curing the adhesive. The tip of the notch was located 50 mm from the centre of the load pins. To facilitate the detection of the crack growth, a thin layer of typewriter correction fluid was applied to the adhesive on both sides. The specimen was placed in an Instron universal testing frame using clevis fixtures and load pins. Initially, the notch was slightly extended by loading the specimen to create a sufficiently sharp pre-crack. As soon as a few millimetres of extension was observed, the specimen was unloaded. The specimen was loaded again at a constant cross-head rate of 1 mm/min and the crack movement was monitored with a high resolution camera connected to a PC display until it had propagated about 60 mm. Testing was carried out on five and two specimens with 12 and 6 mm thick substrates respectively.

The technique used for determining the fracture energy is the compliance based beam method (CBBM) [12]. Whilst simple beam theory assumes that the substrate is fully built-in at the crack tip, in reality, root rotation occurs due to the deformation of the adhesive layer as well as significant softening of the adhesive caused by a damage process around the crack tip. Both give rise to enhanced compliance making the joints behave as if the crack is further advanced than it actually is. CBBM aims to adjust the observed crack length (a) to the effective crack length, a_e ($=a+\Delta$). The correction (Δ) is determined by solving the equation for compliance based on the beam theory expressed as

$$C = \frac{8a_e^3}{EBh^3} + \frac{12a_e}{5BhG} \tag{1}$$

where E, B, h, and G denote the Young's modulus, the width, the thickness, and the shear modulus of the substrate, respectively. The second term accounts for shear deformation but was ignored in the present work as it has a negligible effect compared with the first term for the geometry considered here. G_{IC} can then be determined from

$$G_{IC} = \frac{12P^2a_e^2}{EB^2h^3} \tag{2}$$

where P is the load corresponding to the effective crack length. A flexural modulus value of 11.4 GPa measured by a 3-point bending of the substrate was used to provide the substrate Young's modulus E.

2.2. Results and discussion

Initial testing was undertaken on the 12 mm substrate DCBs. During the initial loading that produced the small extension (1–2 mm) of the notch, remarkable non-linearity in the load–displacement curve was observed, resulting in a large increase in the compliance. This is shown in Fig. 2 for a typical specimen. No visible damage in the substrates or the adhesive was observed. The effective pre-crack length calculated by the CBBM from the compliance from the linear portion of the loading curve is 79 mm. Subtracting the pre-crack length of 50 mm from the effective crack length gives the correction Δ, associated with the root rotation of the substrate, of 29 mm. This is in good agreement with a crack correction value of 28 mm derived from a closed form Eqn. (3) found elsewhere [9]

$$\Delta = h(1/6)^{1/4}\left(1 + \frac{h_a}{h}\frac{E}{E_a}\right)^{1/4} \tag{3}$$

where the subscript, a, denotes the adhesive. Likewise, Δ determined for the unloading curve was 41 mm. This increase in effective crack length (12 mm) is likely to be due to the damage

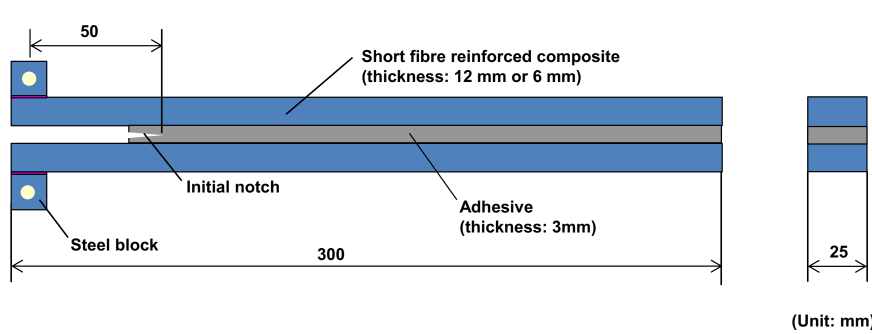

Fig. 1. DCB specimen geometry.