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Characterising bonded joints with a thick and flexible adhesive layer. Part 2: Modelling and prediction of structural joint responses

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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. In this pair of papers, the mechanical behaviour of a rubbery adhesive and the bonded joints to be used in a lightweight automobile structure have been investigated, both experimentally and numerically. In this (part 2) paper, progressive damage FE modelling using cohesive elements is presented to predict the structural response of peel and lap shear specimens that were representative of the vehicle joints. The cohesive parameters that matched the load–displacement curves of the fracture testing presented in part 1 were determined and used, without modification in subsequent modelling of the representative joints. The numerical predictions of these joints correlated well with the measured experimental load–displacement and damage growth data. Based on the results, it has been demonstrated that the modelling approach presented is applicable to bonded joints with a highly compliant, thick adhesive layer.

1. Introduction

Bonded joints using flexible adhesives have attracted growing attention for more demanding applications such as automotive structural bonding due to their excellent impact resistance capabilities. Their high deformability allows sufficient load transfer through the joints under the local high deformation incurred during an impact event as well as providing energy absorption. Improved fatigue resistance is another advantage envisaged since more uniform stress distribution compared to that for rigid adhesives can be ensured. In order to further facilitate the application of such adhesives, it is expected that their unique mechanical behaviour be fully characterised and the structural response of representative bonded joints be quantitatively predicted.

Part 1 of the paper [1] has described the experimental programme which characterised the fracture behaviour and determined reliable fracture energies applicable to bonded joints using a rubbery polyurethane adhesive system with bondlines as thick as 3 mm. It was shown that, by designing the substrate geometry to provide sufficient flexibility, the frequently used double cantilever beam (DCB) method for mode I and single leg bending (SLB) for a mixed mode (mode mixity (G_{I}:G_{II}) of 4:3) generated consistent crack growth within the adhesive layer and provided reasonable and consistent fracture energies. However, as the mode II component becomes dominant, standard testing techniques such as end notch flexure (ENF), which rely on flexural strain energy of the substrates as the driving force for crack propagation, have been found to be impractical for such compliant adhesive layers. Instead, a cracked thick adherend shear test (TAST) type specimen in combination with FE analysis was used to obtain the mode II fracture energy.

Progressive damage modelling using cohesive elements has become increasingly popular as a tool to predict the structural response of bonded joints. It has been claimed that this method has great potential in that it is capable of predicting the whole mechanical response of structural bonded joints from damage initiation through to final failure [2]. A number of studies have been reported predicting joint behaviour under quasi-static loading. Yang et al. [3–5] has carried out a series of studies on predicting the mechanical behaviour of bonded joints with yielding in the substrates using FE models with cohesive elements. It has been demonstrated that the mode I and mode II cohesive parameters calibrated with a double cantilever beam joint and a torsion test of bonded butt joints, respectively, are applicable to other joint geometries without further modification. Crocombe and co-workers

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have extended this approach to predict the residual strength and service lifetime of joints degraded by moisture and fatigue loading [6–9]. In contrast to the above and other studies, all of which apply the model to bonded joints with conventional epoxy based adhesives, little has been reported on joints with a low modulus and thick adhesive layer. Loureiro [10] et al have modelled a T-Peel joint with a flexible but thin polyurethane adhesive layer using cohesive zone elements. It seems likely that progressive damage modelling of the joint bonded with a flexible and thick adhesive layer might be potentially challenging because the large deformations could lead to a greater risk of adverse mesh distortion and hence solution convergence difficulties.

Thus, this part 2 of the paper investigates the application of such modelling procedures to thicker and more flexible adhesive systems. Cohesive zone parameters were fitted using the experimentally measured load–displacement responses corresponding to the pure mode I and the mode II loading discussed in the partner paper. Using the fitted cohesive zone material models, progressive damage modelling of two joints representative of those used in the vehicle structure, was carried out. A peel joint and a lap shear joint were chosen by the manufacturer as representative joints as (i) they comprise the same, dissimilar substrate materials as used in the vehicle joints, (ii) are subjected to mixed mode loadings typically experienced by the vehicle in operation and (iii) use the same adhesive and (large) adhesive thickness that are used in the vehicle. The numerical predictions were compared with the experimental results and the validity of the predictions was assessed from both a quantitative and a qualitative point of view. It should be noted that in this work the authors have deliberately used the same thickness of adhesive in the tests to determine the key fracture parameters as the thickness in the structural joints being assessed. This is generally good practice but, due to the high ductility of the adhesive resulting in an extensive damage zone, the same fracture parameters may not be as applicable to structural joints with other thickness adhesive layers. This is an area that should be explored in future work.

2. Determination of cohesive zone parameters

2.1. The FE models

2.1.1. Mode I

Two dimensional FE modelling with cohesive elements using the FE code ABAQUS was performed to calibrate the mode I cohesive parameters. Since it was known the adhesive shows a fairly linear relationship in a shear (in the thick adherend shear test, TAST), with no extended stress plateau, a triangular rather than trapezoidal traction–separation law was selected for use in the FE modelling, see Fig. 1. The only unknown parameter was the maximum traction in mode I, σ_{max}, since the fracture energy was obtained from the testing detailed in part 1 of the paper [1]. The DCB test data for the specimens with 6 mm thick substrates showed relatively consistent crack growth in the adhesive layer and hence was selected for the calibration modelling because it exhibited the same failure mode as shown in the representative peel joint test, described in Section 3 of this paper. The model geometry is shown in Fig. 2 along with the boundary conditions. The loading blocks on the FE model were subjected to a displacement cycle up to 18 mm, down to 0 mm, and then up again to 60 mm. This corresponded to the pre-cracking, unloading and the re-loading in the experimental tests. Horizontal movement of the loading points was constrained. Instead of modelling the adhesive as a single layer of cohesive elements as is often

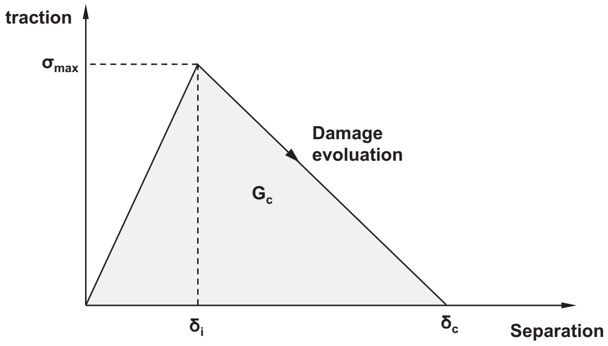

Fig. 1. A triangular traction–separation law.

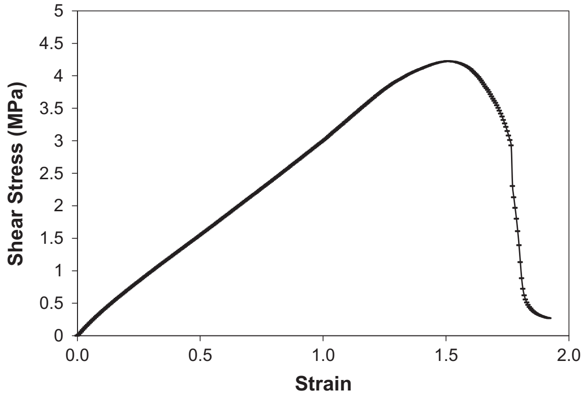

Fig. 3. A typical shear stress–strain response of the adhesive obtained from a TAST specimen.

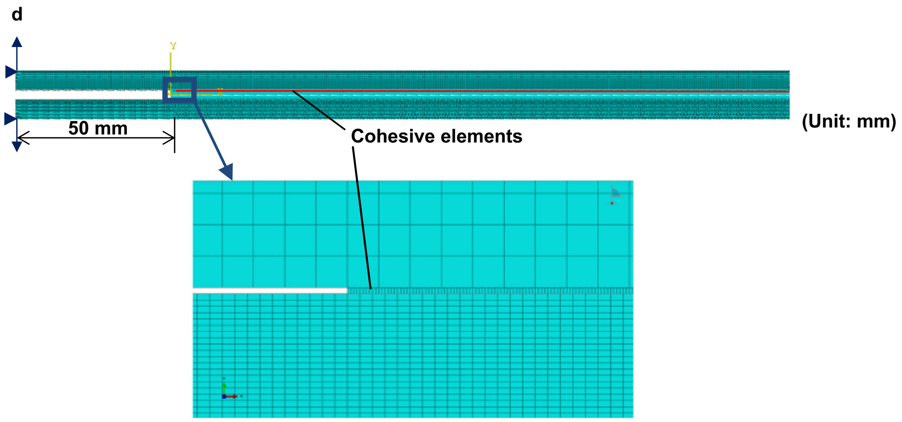

Fig. 2. FE model geometry of the DCB specimen.