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# MODELLING THE FRACTURE BEHAVIOUR OF ADHESIVELY-BONDED JOINTS AS A FUNCTION OF TEST RATE

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## Introduction

The present work investigates the rate-dependent behaviour of structural adhesive joints under mode I loading conditions. A series of fracture tests were conducted using tapered double-cantilever beam (TDCB) specimens at various loading rates [1] to determine the adhesive fracture energy,  $G_{Ic}$ . A high-velocity video camera was used to monitor the fracture events, i.e. to record the crack-length history, while a piezo-electric load-cell positioned closely to a lower arm of the specimen recorded the variation in load as a function of time. The experiments were analysed analytically and numerically. The full details of the analysis strategy employing analytical approaches for the different types of fracture behaviour that were observed are presented in [1,2].

The numerical modelling of the TDCB experiments was performed using the finite-volume method (FVM) based upon the package 'OpenFOAM' [3]. The cohesive-zone model (CZM) employed was a Dugdale-shaped traction-separation law, and was applied as a traction boundary condition along a prospective crack plane. This type of CZM has been previously found to fit well the experimentally measured load versus displacement data [4-6]. The initial region of the traction-separation law was taken as rigid. Two parameters, the adhesive fracture energy  $G_{Ic}$ , and the maximum traction, i.e. the cohesive strength,  $\sigma_{CZ}$ , are then sufficient to define the traction versus separation law. For the form of  $G_{Ic}$  for the rate-dependent CZM, the value of  $G_{Ic}$  as a function of crack velocity was obtained by fitting an appropriate curve through the  $G_{Ic}$  versus crack velocity data reported in [1].

## Experimental

Structural adhesive joints were manufactured using aluminium-alloy substrates. The joints were bonded with a rubber-toughened, automotive paste adhesive, i.e. Dow Automotive, CH, XD4600. The aluminium-alloy substrates were bonded to form TDCB test specimens [1,2].

Joints were loaded in mode I (the tensile opening mode) at rates from 1 mm/min up to 15 m/s using a high-rate testing machine, and the loci of joint failure were always visually observed to be via a cohesive fracture in the adhesive layer.

The test methodology incorporated a high-speed video camera which was used to record the deformation of the test specimens, as well as the crack length and crack velocity during the high-rate tests.

## Results and Conclusions

The present paper presents a combined experimental, analytical and numerical-modelling study of the mode I fracture behaviour of tapered double-cantilever beam (TDCB) bonded joints subjected to a range of test rates between  $3.33 \times 10^{-6}$  m/s and 13.5 m/s. All the tests failed via the crack propagating cohesively along the centre of the adhesive layer.

Different types of fracture behaviour were observed depending on the test rate: 'Type 1' slow-rate, stable crack growth at test rates below 0.1 m/s; 'Type 2' slow-rate, unstable stick-slip fracture at test rates between 0.1 m/s and 2.5 m/s; 'Type 3' high-rate, unstable stick-slip fracture at test rates between 2.5 m/s and 6 m/s; and 'Type 4' high-rate, stable crack growth at test rates above 6 m/s. The experiments were analysed analytically, via linear-elastic fracture mechanics methods [1] and numerically [6]. In the analytical study, different approaches were required for the different fracture types. 'Type 1' and 'Type 2' fracture behaviour were analysed using a quasi-static approach: with the measured crack propagation loads being used for 'Type 1' and the measured load at crack initiation being used for 'Type 2'. Dynamically-corrected analyses, based on the crack length instead of the load, were employed to determine  $G_{Ic}$  values for 'Type 3' and 'Type 4' fracture behaviour. Again, crack initiation data were used for the unstable 'Type 3' fractures, while crack propagation data were employed for the stable 'Type 4' fractures.

Numerical simulations were conducted using the FVM based package ‘OpenFOAM’, with an embedded CZM based upon a Dugdale shape. The CZM employed either (i) a rate-independent, or (ii) a rate-dependent value of  $G_{Ic}$ . The uniaxial-tensile properties and the adhesive fracture energy,  $G_{Ic}$ , for the adhesive were measured and calibrated at the appropriate strain-rates. In the CZM, the maximum traction (i.e. the cohesive strength,  $\sigma_{CZ}$ ) was assumed to be equal to the value of the ultimate tensile strength (UTS) of the adhesive at the strain-rate corresponding to the test rate of interest. When a rate-independent value for  $G_{Ic}$  was used in the CZM, then a constant value of  $G_{Ic}$  was selected which corresponded to the measured average crack velocity for the crack growing through the adhesive layer of the TDCB joint. When a rate-dependent value of  $G_{Ic}$  was employed in the CZM, then various forms for the  $G_{Ic}$  versus average crack velocity ‘profiles’ were assumed in the numerical simulations. These were obtained from (i) assuming the best-fit experimentally, (ii) trial and error assumptions, and (iii) an adiabatic thermal-heating model (ATM), which has been previously proposed [1].

Two-dimensional plane-stress, elastic-plastic, fully-implicit transient analyses were performed and numerical predictions of the load versus displacement and crack length versus displacement traces were compared against the experimentally-measured traces.

It was found that for stable fracture behaviour, i.e. ‘Type 1’ and ‘Type 4’, the load and crack-length traces were predicted very accurately using all the ‘profiles’ which were selected to describe the relationship between  $G_{Ic}$  and the average crack velocity. Indeed, it was also found that a rate-independent (i.e. constant) value of  $G_{Ic}$  for the CZM gave good predictions of the experimentally-measured load and crack-length traces when stable fracture behaviour was observed: i.e. ‘Type 1’ and ‘Type 4’ crack growth.

However, for the unstable, stick-slip fracture behaviour, i.e. ‘Type 2’ and ‘Type 3’ crack growth, then the experimentally-measured load and crack-length traces were only successfully predicted using two forms of the ‘profile’ relationships between  $G_{Ic}$  and the average crack velocity. The main characteristics of both of these ‘profiles’ were (i) a rapid drop in the value of  $G_{Ic}$  at low crack velocities of between  $\approx 0$  and 60 m/s (i.e. from about 3.5 kJ/m<sup>2</sup> at  $\approx 0$  m/s to about 3.0 kJ/m<sup>2</sup> at 20 m/s), followed by (ii) a steady decrease in  $G_{Ic}$  to about 2.5 kJ/m<sup>2</sup> at about 400 m/s. It was of interest to note that one of these successful profiles was based on the adiabatic thermal-heating model, referred to above.

Nevertheless, the numerical simulation of the ‘Type 3’ fracture did suggest that the large number of minor oscillations observed in the load versus displacement trace were largely due to the system dynamic effects superimposed on the ‘true’ load versus displacement trace, which the current FVM/CZM theoretical procedure fails to capture [6].

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