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# MODELLING THE FRACTURE BEHAVIOUR OF ADHESIVELY-BONDED JOINTS AS A FUNCTION OF TEST RATE - A RATE DEPENDENT CZM IS REQUIRED TO PREDICT THE FULL RANGE OF BEHAVIOUR

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## Introduction

Adhesive bonding of lightweight, high-performance materials is regarded as a key enabling technology for the development of vehicles with increased crashworthiness, better fuel economy and reduced exhaust emissions. However, as automotive structures can be exposed to impact events during service, it is necessary to gain a sound understanding of the performance of adhesive joints under different rates of loading. Therefore, characterising the behaviour of adhesive joints as a function of loading rate is critical for assessing and predicting their performance and structural integrity over a wide range of conditions.

The present work investigates the rate-dependent behaviour of 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 [1-2]. The experiments were analysed analytically and numerically. The full details of the analysis strategy employing analytical approaches for different types of fracture are presented in [1]. The numerical modelling of the TDCB experiments was performed using the finite-volume based package ‘OpenFOAM’ [3].

## Experimental tests

A high-yield strength aluminium-alloy was used to manufacture the TDCB substrates. This ensured that the substrates remained within the elastic region throughout the tests, and so enabled valid linear-elastic fracture-mechanics (LEFM) test conditions. A structural-epoxy adhesive, ‘Betamate XD4600’ supplied by Dow Automotive Europe, was used for the current research.

The mode I adhesive fracture energy,  $G_{Ic}$ , was measured using TDCB test specimens, with the adhesive layer having a thickness of 0.4 mm. Slow-rate (i.e. quasi-static) tests up to crosshead rates of 0.1 m/s were undertaken using a displacement-controlled tensile-test machine. The crack length was determined visually using a travelling microscope with sufficient magnification to allow readings of  $\pm 0.5$  mm to be taken. The tests were carried out according to the ISO 25215 procedure [4]. For the crosshead rates between 0.1 m/s and 13.5 m/s, a high-rate servo-hydraulic

machine was used. The machine was fitted with a lost motion device (LMD), which allowed adequate ram acceleration prior to specimen loading. The LMD and other fixtures were manufactured from titanium and aluminium alloy, in order to reduce inertial effects during testing. The opening displacement at the loading points and the crack length were measured from the video sequence obtained using high-speed video camera. A high natural frequency and short rise-time piezo-electric load cell was attached immediately below the lower specimen arm for load measurements.

Different types of crack growth behaviour were observed over the range of test rates that were studied. *Type 1*: At relatively low loading rates up to about 0.1 m/s, the crack propagated in a stable, steady-state manner. *Type 2*: At somewhat higher rates, between about 0.1 m/s and 2.5 m/s, the crack propagated in an unstable, stick-slip fashion, observed in load traces by characteristic ‘saw-tooth’ shape. *Type 3*: At even higher rates of test from about 2.5 m/s to 6.0 m/s the unstable crack propagation behaviour was still observed but it was considered that dynamic effects were now important. *Type 4*: At test rates above about 6.0 m/s, crack propagation was relatively rapid but stable once again, despite the mounting dynamic effects that produced progressively more severe oscillations in the load versus time traces. It has to be noted that the crack propagated cohesively in the adhesive in all tests.

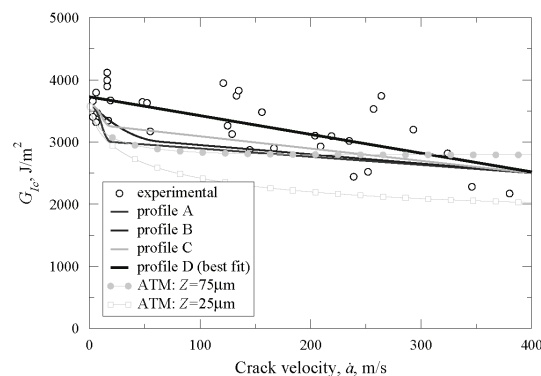


Figure 1. Adhesive fracture energy,  $G_{Ic}$ , as a function of average crack velocity with approximating profiles

The different types of fracture described above require different analysis strategies in order to determine the values of the adhesive fracture energy from the measured values such as load, displacement, crack history etc. These strategies are explained in detail in [1]. As a result, the fracture energy as a function of the crack velocity can be obtained, as plotted in Fig. 1, together with several curves approximating the obtained experimental data.

## Numerical modelling and predictions

In the numerical analysis, the adhesive was modelled as an elastic-plastic material using classical incremental J2 flow theory with von Mises plasticity, while the aluminium-alloy substrate was assumed to be linear-elastic throughout the analysis. Plane-strain conditions are assumed to dominate through the specimen thickness, and hence 2D calculations are performed. Due to two symmetries, only one quarter of the TDCB specimen is modelled. The numerical mesh used in the simulations is shown in Figure 2. The mesh consists of 14,380 cells with uniform rectangular cells in the adhesive region of  $0.5 \times 0.04$  mm.

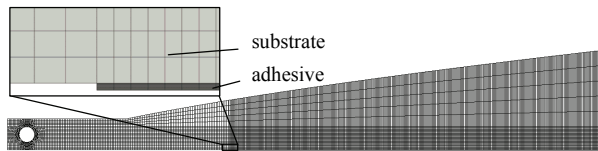


Figure 2. Finite volume mesh of the TDCB specimen

Mechanical properties for substrate used in simulations are: Young's modulus,  $E_s = 72.4$  GPa, the mass density,  $\rho_s = 2700$  kg/m<sup>3</sup>, and the Poisson's ratio,  $\nu_s = 0.33$ ; all assumed to be rate independent. On the other hand, the adhesive mechanical properties were found to be rate dependent [2,5]. Hence, the values are set according to particular test rate (see [6] for more details).

Regarding fracture modelling, only mode I fractures were simulated by applying the Dugdale cohesive-zone model (CZM) along a prospective crack path in the mid-plane of the adhesive. The cohesive strength,  $\sigma_{CZ}$ , was assumed to be equal to the value of the UTS of the adhesive at the corresponding strain-rate, whereas fracture energy  $G_{Ic}$  was taken as constant throughout a simulation or as a function of the crack speed.

Simulations with constant fracture energy assumption showed capable to predict successfully only Type 1 and 4 fracture tests, whereas the same assumption did not succeed in simulating Type 2 and 3 fractures (see Fig. 3 where three different constant values of  $G_{Ic}$  were employed). In other words, simulations using CZM with a  $G_{Ic}$  value held constant, corresponding to a particular test rate and hence fixed to a corresponding average crack velocity, could not predict the stick-slip fracture behaviour.

In order to overcome this problem, it was decided to use a rate-dependent  $G_{Ic}$ . A number of relationships were fitted to the  $G_{Ic}$  versus crack velocity data and a selected

number of the attempts are shown in Fig.1. 'Profile D' corresponds to the linear fit through the data points, as shown in Figure 5. 'Profiles A to C' assume an initial rapid decrease of  $G_{Ic}$ , with 'Profile C' having the highest decrease and 'Profile B' the lowest, followed by a less steep decrease. The profiles named 'ATM' are obtained from an adiabatic thermal-heating model (ATM) with the values of the thickness of the heat-affected zone being 25 or 75  $\mu$ m (see [1-2] for more details). The simulations, using the different profiles, are compared to the experimental results in each case, both in terms of loads and crack histories, and the main findings are given below.

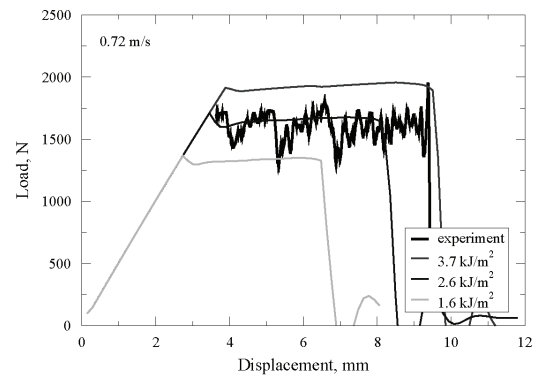


Figure 3. Using a rate-independent  $G_{Ic}$ : 'Type 2' @ 0.72 m/s,  $E_a = 4.7$  GPa,  $\sigma_y = 54.7$  MPa,  $\sigma_{CZ} = 88.7$  MPa.

At a test rate of  $3.33 \times 10^{-6}$  m/s stable crack ('Type 1') was observed and both the load and the crack-length traces are predicted very well using any profile. This is due to the fact that for all the profiles (i) the variation in the predicted crack velocity, and hence  $G_{Ic}$ , was very small at low loading rates, and (ii) all the profiles possess a very similar value of  $G_{Ic}$  at low crack velocities. This can be easily observed in Fig.4 where the variation in the crack speed and corresponding  $G_{Ic}$  for the predictions with the 'Profiles A, ATM  $Z = 75 \mu$ m and D' are shown (more or less the same crack speed for all profiles).

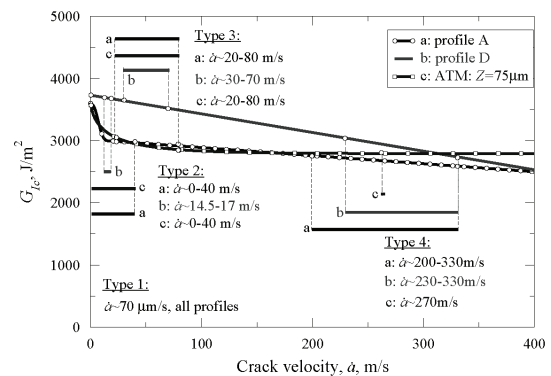


Figure 4. Predicted variations of crack velocity with  $G_{Ic}$  for the various fracture types

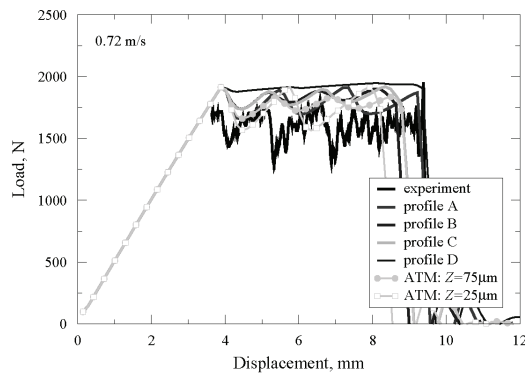


Figure 5. Using a rate-dependent  $G_{Ic}$ : 'Type 2' @0.72 m/s,  $E_a = 4.7$  GPa,  $\sigma_y = 54.7$  MPa,  $\sigma_{CZ} = 88.7$  MPa.

At a test rate of 0.72 m/s slow-rate unstable stick-slip fracture was seen, i.e. 'Type 2' behaviour (see Fig. 5). It is clear that 'Profile D' (i.e. a linear fit) does not predict these stick-slip fractures at all well. However, profiles with a relatively steep initial decrease in  $G_{Ic}$  with crack speed (such as 'Profiles A, ATM  $Z = 25 \mu\text{m}$  and ATM  $Z = 75 \mu\text{m}$ ') gave more pronounced stick-slip behaviour than the profiles with less steep initial decreases (such as 'Profiles B, C and D'). Indeed, 'Profiles A and ATM  $Z = 75 \mu\text{m}$ ' gave reasonable predictions of the stick-slip fracture behaviour, while 'Profile ATM  $Z = 25 \mu\text{m}$ ', which is a lower-bound fit to the  $G_{Ic}$  versus crack velocity data (see Fig.1), does not capture the number of oscillations in the load traces. In fact, as can be seen from Fig.4, only those profiles with significant drop in fracture energy in the range of crack speeds covered during simulation will successfully simulate stick-slip behaviour.

At a test rate of 2.5 m/s, high-rate unstable fracture was seen, i.e. 'Type 3' behaviour. The load versus displacement curve for this test rate is of a highly oscillatory nature, which in the first instance may appear as the stick-slip characteristic saw-tooth shape, with a relatively large number of oscillations. Apart from the 'Profile ATM  $Z = 25 \mu\text{m}$ ', the predictions from all other profiles are in reasonably good agreement with each other and resemble the experimental data well. This is in the line with the observation from Fig.4 that  $G_{Ic}$  does not change much in the range of crack speeds predicted by numerical simulations.

At test rates of 9.6 m/s and 13.5 m/s, the stable crack growth was again observed, i.e. 'Type 4' crack behaviour in both cases. As for the 'Type 1' and 'Type 3' fracture behaviour, all the profiles predict the experimental load and crack length traces in a similar fashion. The crack velocity varies from 200 to 330 m/s when using 'Profile A' and from 230 to 330 m/s when using 'Profile D' (see Fig.5), but the variations in  $G_{Ic}$  between the three profiles are similar and hence the similarity in predicted load and crack length traces. Whilst the predicted crack length versus displacement traces closely resemble the experimentally recorded traces, the agreement between the predictions and measurements of the load versus displacement

curves gets progressively worse with increasing test rate. This is expected as uncertainties, particularly in the load history measurements, increase with increasing test rate due to more pronounced dynamic effects of the entire machine-specimen system which obscures the 'true' load trace.

## Conclusions

This paper presents an investigation how fracture energy, as a CZM parameter, used to describe fracture process, affects the behaviour of TDCB bonded joints subjected to a range of test rates. It was found that for the stable fracture behaviour, i.e. 'Type 1' and 'Type 4', predictions were very accurate using all the 'profiles' which were selected to describe the relationship between  $G_{Ic}$  and the average crack velocity. In fact, similar results can be obtained using both constant and rate-dependent fracture energy values. However, for the unstable, stick-slip fracture behaviour, i.e. 'Type 2' and 'Type 3', the experimentally-measured load and crack-length traces were only successfully predicted using 'Profile A' and 'Profile ATM  $Z = 75 \mu\text{m}$ '. The main characteristics of both of these profiles are (i) a rapid drop in the value of  $G_{Ic}$  at low crack velocities, followed by (ii) a steady decrease in  $G_{Ic}$ . 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 is largely due to the system dynamic effects superimposed on the 'true' load versus displacement trace, which the current FVM/CZM procedure fails to capture.

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