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FRACTURE LOAD PREDICTIONS FOR A TOUGHENED EPOXY ADHESIVE

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Introduction

Previously, an engineering approach was presented to predict the fracture loads in adhesive joints [1-4]. The approach is based on characterizing the strength of an adhesive system using a fracture envelope; i.e. the critical strain energy release rate as a function of the loading phase angle. The energy release rate for a particular joint is calculated using a closed-form expression for the *J*-integral in a cracked adhesive sandwich. The calculated energy release rate and phase angle for the joint are then compared to the critical strain energy release rate, G_c, at the corresponding phase angle, using the experimentally measured fracture envelope, and the fracture load extracted. This approach was shown to work well for relatively brittle adhesives with moderate strength. The objective of this work is to assess the performance of this technique with a much tougher and more visco-elastic adhesive.

To establish that joint strength can be predicted using the measured fracture envelope, $G_c(\psi)$, for a toughened epoxy adhesive, the fracture loads of two commonly used joints, the CLS (cracked-lap shear) and the SLS (single-lap shear), were measured and compared with predictions.

Measurement of Fracture Envelope

The load jig of ref. [3] provides a convenient way of measuring the critical strain energy release rate, G_c, as a function of the phase angle using a single DCB (double cantilever beam) specimen.

For the calculation of the phase angle and the critical energy release rate, G_c, two methods have been used, namely "Beam Theory" [3] and the "Beam on Elastic Foundation Model" [4]. In the beam theory approach, the presence of the adhesive is ignored, while the beam on elastic foundation model takes into account the existence of the adhesive and the additional compliance it imparts to the DCB. It was observed that for this adhesive system ignoring the adhesive underestimates G_c by 7%-15%, depending on the phase angle.

The DCB specimens were loaded under displacement control using a constant crosshead speed of 1.0-1.5 mm/min.

DCB specimens were fabricated from AA6061-T651 flat bars with the bondline thickness of 0.4 mm, which was controlled through placing spacing wires in the bondline. Prior to bonding, the substrates were pretreated using P2 etching process [5].

During the first several crack growth sequences, the measured critical energy release rate, G_c, increased with crack length, becoming almost constant after the crack propagated a certain distance. This subcritical crack propagation distance depended on the mode ratio and the bondline thickness, both of which affected the steady state damage zone size at the crack tip. The rising region of this R-curve is attributed to the development of such a damage zone as the crack grows. G_c at each phase angle was considered to be the average value over the "plateau" (steady state) region.

References 2 and 3 describe the procedure to measure the fracture envelope for two toughened, single-part epoxy adhesives. For these adhesives, it was appropriate to start and stop the cross-head displacement repeatedly until new cracking was observed in the damage zone ahead of the macro-crack at the critical load for the measured crack length. However, the adhesive used in this study, a single-part, heat-cured toughened epoxy, was found to be much tougher and more visco-elastic than those two adhesives, and therefore the crack growth was less abrupt, being more of a gradual tearing of the bondline. In the present case, relying solely on visual observation of the damage zone while manually starting and stopping the cross-head iteratively led to overloading the specimen and recording loads greater than the true critical load corresponding to G_c. In principle, this problem could be resolved by choosing a very small cross-head speed. However, a small crosshead speed would greatly increase the test duration, and due to the visco-elastic nature of the adhesive, creep crack growth might occur at loads below that corresponding to G_c. It was found that, for the present adhesive system, a better approach was to start and stop the loading repeatedly (each time at a constant crosshead speed of 1.0-1.5 mm/min) until a drop in load was observed. At this point, the bondline was viewed through the microscope to ensure that the macro-crack had propagated. If the macro-crack had

propagated, the load was recorded as the critical load for that crack length. Otherwise, this procedure would continue until the crack propagation was observed. After measuring the new macro-crack length, the DCB was unloaded partially and the same procedure was followed again beginning at the new crack length. Although this measurement procedure differs from that utilized in previous works [1-4], where the crack tip was considered at the furthest advanced micro-crack, it had a negligible effect on the plateau region of G_c, since the length of the damage zone was usually small compared to the overall crack length.

To check that the measured G_c was independent of the adherend width, two specimens were made, one with a 25.4 mm (1") wide bar and the other with a 19 mm (3/4") bar. When tested at a phase angle, ψ=16°, the G_c values for the two specimens were found to be within 1% of each other, and it was thus decided that all specimens would be constructed from 19 mm wide bars.

Another possible concern was the effect that the cross-head speed of the displacement controlled actuator would have on the fracture behavior of the adhesive (i.e. the possible strain rate sensitivity of the adhesive). To investigate this, G_c values at ψ=16° were measured at cross-head speeds of 0.5, 1.5, and 5 mm/min giving values of 4121±124 J/m^2, 3797±128 J/m^2 and 3921±105 J/m^2, respectively. The effect of cross-head speed was considered to be insignificant, given the scatter between different specimen batches and the fact that the cross-head speed was changed by ten times.

To determine the fracture envelope, mixed mode DCB fracture tests were conducted at seven different phase angles. The measured fracture envelope with standard deviation bars, using the beam on elastic foundation model, is shown in Figure 1.

Quasi-Static Fracture Tests

Eight SLS and six CLS joints of varying overlap and arm lengths were made from 25.4×19.05 mm (1"×3/4") AA 7075-T65 flat bars. Three different initial conditions at the overlap ends were considered: a small adhesive fillet, a large adhesive fillet and a precracked condition. To form the small adhesive fillet, the excess adhesive was removed from the overlap end before curing, while in the large adhesive fillet case, this excess adhesive was not removed. The precrack was formed by inserting an aluminum foil before bonding the specimen. For SLS and CLS joints precracks were 10 mm and 3 mm long, respectively.

All specimens were loaded to ultimate fracture on a servo-hydraulic load frame with a displacement controlled actuator under constant cross-head speed. Two CCD cameras were used to monitor crack growth as the specimens were loaded. One camera was focused on the overlap end (the longer arm in the SLS joints) in order to determine the crack initiation load, while the other camera was focused on the middle of the overlap length, to monitor the crack propagation behavior.

All fractures, except for one of the CLS joints, were cohesive within the adhesive.

Single-Lap Shear Joints (SLS)

It was observed, as expected, that the crack started to propagate at a lower load than that required for ultimate fracture. The subcritical crack propagated for several centimeters before the critical load was attained and final fast fracture occurred. The crack initiation loads for four SLS specimens were measured, and found to range from 50% to 90% of the ultimate failure load. Since crack initiation occurred well below the critical load during damage zone development in the bondline, the ultimate fracture load did not depend on the initial condition of the end of joint overlap (fillet or precrack), which is consistent with results for an adhesive referenced in [6].

From the DCB fracture tests that were performed during the measurement of the fracture envelope, it was observed that the length of the rising part of the G_c vs. crack length graph (i.e. the R curve) was dependent on the phase angle. This length increased with increasing phase angle, and was quite reproducible at each phase angle. Phase angles that are achieved by changing the geometry of the SLS joints are in the relatively narrow range of 45º to 55º. It was noted that the crack propagation associated with the rising part of the R-curve for phase angles between 45º and 55º was between 4 and 6 cm for DCB specimens. From the fracture surfaces of the SLS joints, it was observed that there were two different failure loci for slow and fast fracture, consistent with observations by Aydin et al. [7]. For the eight SLS specimens in total that were tested, the change in the failure surface occurred at an average of 6±1 cm from point of crack initiation and was due to the onset of the catastrophic final fracture of the specimen.

Since the subcritical crack growth changed the final geometry of the SLS joint considerably, the final geometry before the critical load was used in the calculation of G and ψ. A sensitivity analysis showed that the failure load prediction was relatively insensitive to the amount of subcritical crack propagation. Therefore, choosing this length based on the rising part of the DCB fracture tests for the calculated phase angle, can yield reasonably good predictions for the final fracture load.

The measured and predicted ultimate fracture loads for the tested SLS joints are compared in Table 1 based on 6 cm subcritical crack propagation. Very good agreement was observed between the measured and predicted critical loads for all SLS joints with different crack initial conditions (maximum error less than 7%).

Cracked-Lap Shear Joints (CLS)

The practical phase angle for a CLS specimen is around 50º. Following a similar approach as for SLS specimens, the CLS joint geometries were modified by the length of the subcritical crack, in this case 5±1 cm from the point of crack initiation. This length agreed well with the length of crack propagation during the rising part of the DCB R-curve at a phase angle of 50º. It was also consis-

tent with the appearance of the fracture surface of the debonded CLS specimens.

The measured and predicted fracture loads for CLS joints are given in Table 2, which shows an average error of less than 8%. It is observed that predicted values underestimate the experimental measurements, except in one case in which the fracture surface was a combination of cohesive and interfacial failure.

Conclusions

A previously established analytical approach for predicting the fracture loads in common tensile fracture specimens (CLS and SLS) was tested for a toughened epoxy adhesive. It was found that, due to the high toughness and visco-elastic nature of the adhesive, some changes in the experimental procedure of fracture envelope measurement were necessary. It was also found that the toughening of the adhesive (rising part of the R-curve in G_c vs. crack length) should also be considered in the calculation of ψ and G. No effect of overlap initial condition on the final fracture load was observed. Good agreement was observed between the predicted and experimental fracture loads.

Acknowledgements

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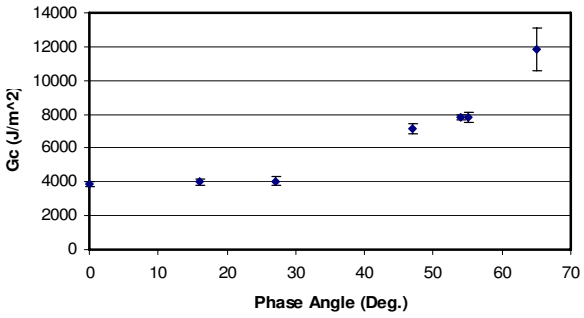

Figure 1. Fracture envelope using beam-on-elastic foundation model, average G_c (±1 SD)

Table 1. Comparison of predicted and measured failure loads for aluminum SLS joints.

Initial Condition	P_{Exp} (kN)	P_{Pred} (kN)	Error % $(P_{Exp} - P_{Pred})/ P_{Exp}$	Cross-head Speed (mm/min)
Small fillet	38.4	41.0	-6.6	1.23
Small fillet	39.7	39.6	0.2	0.60
Precracked	45.3	47.6	-5.8	0.66
Large fillet	43.8	44.6	-1.9	0.60
Small fillet	45.7	44.6	2.4	0.20
Large fillet	50.6	49.8	1.6	0.20
Small fillet	35.6	34.4	3.4	0.25
Large fillet	38.5	38.2	0.8	0.25

Table 2. Predicted and experimental measurement of fracture loads for aluminum CLS specimens

Initial Condition	$P_{Initial}$ (kN)	P_{Exp} (kN)	P_{Pred} (kN)	Error % $(P_{Exp} - P_{Pred}) / P_{Exp}$	Cross-head Speed (mm/min)
Precracked	46.5	66.0	61.3 ± 3.9	-7 ± 6	1.00
Large fillet	41.0	65.0	61.1 ± 2.8	-6 ± 4	0.34
Small fillet	47.8	65.9	74.5 ± 3.7	13 ± 5	1.50
Precracked	42.0	64.2	63.8 ± 3.3	-1 ± 5	1.00
Large fillet	53.4	65.2	56.6 ± 2.7	-13 ± 4	1.00
Precracked	40.7	71.3	68.9 ± 3.9	-3 ± 4	1.50

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