DESIGN AND EVALUATION OF A HIGH RATE MODE I TRANSLAMINAR FRACTURE TOUGHNESS TEST FOR COMPOSITE LAMINATES

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Abstract

The compact tension (CT) specimen has been investigated for the measurement of the high rate Mode I translaminar toughness of a carbon epoxy composite laminate with a layup of $[(90°/0°)_8 90°]_s$. Finite element analyses using LS-DYNA showed that when loaded at high rates (up to 12 m/s) the CT specimen achieved virtually pure Mode I fracture. In additional analyses a data-reduction strategy was developed in which strain (measured at a specific position on the specimen) and crack length measured during a test could be used to determine the toughness in high rate tests. In an experimental programme the average propagation toughness exhibited a small overall decrease with increasing test speed but, in view of the considerable scatter, further testing will be required to confirm the significance of this trend. Examination of the fracture surfaces using a scanning electron microscope indicated that the fracture characteristics are essentially unchanged with increasing test speed.

1 Introduction

The properties of high-performance, fibre-reinforced, polymer-matrix composites at high loading rates are not well understood and, in some cases, are simply unknown. However it is becoming increasingly important to understand the behaviour of composites at high rates so as to improve the simulation accuracy of, for example, aircraft accidents [1], bird strikes [2], motorsport impacts [3] and the performance of armour plating for tanks and personnel carriers [4]. Where the component failure process involves crack propagation, knowledge of how the fracture toughness varies with loading rate is particularly important. This paper describes the development of a test method for measuring the translaminar toughness of laminated cross-ply carbon fibre composites at high loading rates.

2 Background

Several test configurations, including the eccentrically loaded single-edge-notch tension specimen, the centre crack tension and the compact tension (CT) specimen, shown in Figure 1a, have been used to measure the Mode I translaminar fracture toughness of composite laminates at quasi-static (QS) test speeds. (For cross-ply laminates, from this measured laminate toughness it is possible to determine the toughness associated with mode I tensile fracture of the 0° plies in the laminate.) There have been no studies reported in the open literature on high rate (HR) translaminar fracture toughness of composites.

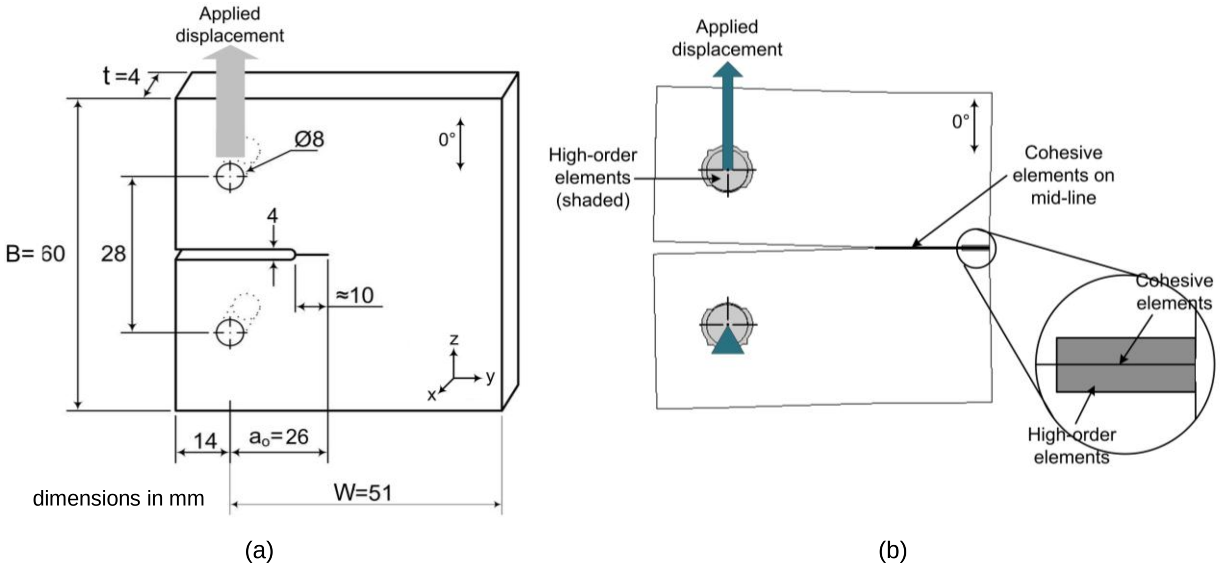


Figure 1 a) Compact Tension (CT) specimen [5] b) Details of FE model

Performing fracture toughness tests at high loading rates can pose a number of difficulties. Often the data recorded from the load cell are complex, affected by vibration effects in the specimen and in the loading fixture, so that it is difficult to readily relate the load cell data (commonly used in data reduction strategies for quasi static tests) to the stress state at the rapidly advancing crack tip. The crack tip stress state itself may also be significantly influenced by vibration effects. An additional problem for Mode I fracture specimens is caused by inertia effects which can lead to asymmetry of deformation and therefore a mixed-mode fracture rather than the intended pure mode I. The design of a test method for measuring the HR Mode I translaminar toughness of a composite laminate must therefore address these issues. In the work described in this paper finite element (FE) analysis has been used to investigate a suitable specimen configuration, to identify useful data measurements that can be made during the test and to develop a successful data reduction strategy using this data. The paper also describes a programme of experiments in which the proposed test method was applied to a carbon fibre composite and presents the results.

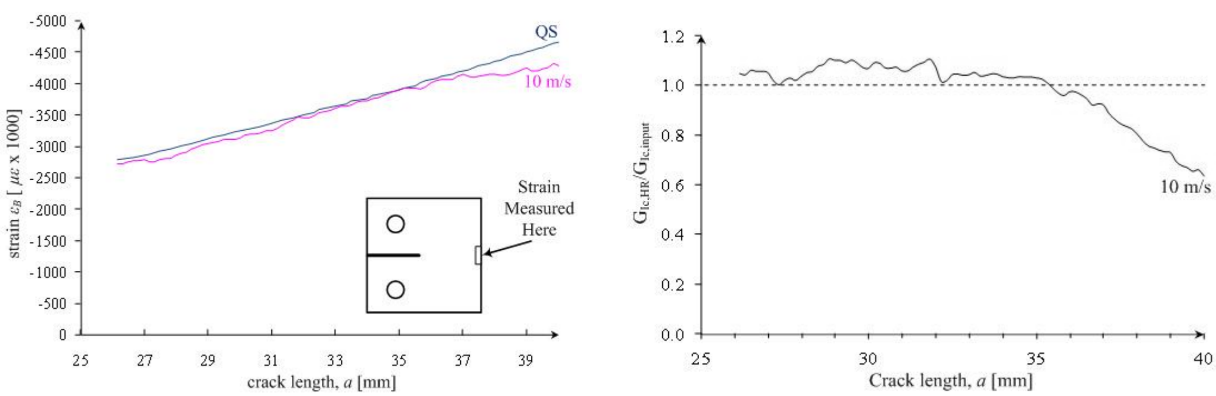
3 Design of the high rate test method

3.1 FE investigation of the HR CT test

Given the proven effectiveness of the CT specimen configuration for measuring translaminar toughness at quasi-static rates [5], this specimen was chosen as the focus of the FE investigation. The analyses were performed for a IM7 8552 carbon-fibre epoxy composite with a layup of $[(90°,0°)_8,90°]_s$. (This was a layup which had previously been successfully used to measure the quasi–static translaminar toughness of this material. [7]) A full set of material properties used in the analyses for this laminate, for the titanium used for the loading pins and for the cohesive elements used to model the laminate fracture behaviour are given in [6]. The specimen was modelled using 8-node solid elements with a single element through the thickness. Reduced integration elements were used throughout except, as shown in

Figure 1b, for a small region at the rear of the specimen (next to the cohesive element region) and around the loading pins, as well as the loading pins themselves, where fully-integrated, 8-node solid elements were necessary to suppress hour-glassing problems. The displacement was applied to the specimen at the centre-point of each end of the top loading pin by means of an applied velocity in the z-direction. The load points were constrained so that they were free to move in the z-direction only and free to rotate about any axis. The centre-point of each end of the lower pin was constrained in the x-, y- and z-directions but was free to rotate. A surface-to-surface contact with a penalty stiffness based algorithm was implemented between the pins and the specimen. The model was tested at a range of velocities from QS to 20 m/s. To reduce run times the QS models were run at 0.1 m/s with a combination of mass scaling and damping but at higher displacement rates no mass-scaling or damping were implemented as these would affect the dynamic behaviour of the specimen.

The HR FE analyses showed that the inertia effects in the specimen did not significantly alter the symmetry of the stress state and so the fracture was almost totally Mode I-dominated. The results also showed that no other failure modes occurred in the specimen until the crack tip had reached a position close to the back edge of the specimen [6]. The FE analyses confirmed that, due to the oscillations observed in the applied load data, it is not possible to use load data to determine the fracture toughness of the CT specimen loaded at high rate. The FE investigation therefore focussed on whether strain measurements on the test specimen could be used to infer the applied load associated with crack propagation. Figure 2a shows the *z*-direction compressive strain, ε_B at the back edge of the CT specimen plotted against the crack length for both QS loading and HR loading at 10 m/s. From this figure it can be concluded that the effect of inertia and of stress waves within the specimen is very small – contributing to an average 0.91 % decrease in strain from the QS to the 10 m/s model from initiation, a = 26 mm, to a = 36 mm. (For a > 36 mm the dynamic nature of the stresses in the HR tests causes the relationship between the strain at the back edge and the stresses surrounding the crack tip to significantly depart from that observed in the quasi-static test.) The other reason for the similarity of the HR and QS curves of Figure 2a is, of course, because the same translaminar toughness has been used in the FE models for the two test speeds. If in reality the toughness and/or the stiffness parameters are rate dependent then the experimentally observed ε_B versus a curves will not be the same for the HR and QS tests.



(a) (b)

Figure 2. a) Strain at the back edge of CT specimen for QS and 10 m/s b) $G_{hr}/G_{ic,input}$ versus a for 10 m

3.2 HR data reduction technique

It is proposed to use the experimental QS ε_B, *a* and applied load data to enable the HR toughness to be determined from the experimental HR ε_B and *a* data. Using the QS model data the ratio, *k(a)* is determined as

$$k(a) = P_c(a) / \varepsilon_{B,QS}(a) \tag{1}$$

in which P_c is the critical applied load and $\varepsilon_{B,QS}$ is the z-direction strain, measured close to the back edge of the specimen (both values being associated with crack growth at crack length *a*). The *k* versus *a* curve for all of the QS specimens is then plotted and the best fit 2nd order polynomial, $\bar{k}(a)$, is determined. An equivalent load, $\bar{P}_{HR}(a)$, can then be determined from the experimentally observed strain, $\varepsilon_{B,HR}$, associated with propagation at crack length *a*:

$$\bar{P}_{HR}(a) = \bar{k}(a) \cdot \varepsilon_{B,HR}(a) \tag{2}$$

(This is the load which would need to be applied in a QS test to cause crack propagation if the laminate exhibited the same toughness as the encountered in the HR test.) The value of HR fracture toughness can then be determined by using the compliance calibration method:

$$G = \frac{P^2}{2t} \frac{dC}{da} \tag{3}$$

where *C* is the compliance of the specimen and *t* the thickness of the specimen in the x-direction. Substituting $\bar{P}_{HR}(a)$ for P from Equation 2 gives:

$$G_{Ic,HR} = \frac{\bar{k}^2(a) \cdot \varepsilon_{B,HR}^2(a)}{2t} \cdot \frac{dC}{da} \tag{4}$$

where $G_{Ic,HR}$ is the HR Mode I translaminar fracture toughness of the specimen, $\bar{k}(a)$ is the polynomial fit to k(a) calculated using Equation 1, $\varepsilon_{B,HR}$ is the strain measured at the back surface of the specimen associated with propagation at crack length *a* in the HR experiment. Assuming no rate dependence of the stiffness properties then dC/da can be determined from the QS test data. Figure 2b shows the ratio of $G_{Ic,HR} / G_{Ic,Input}$ in which $G_{Ic,HR}$ was calculated using Equation 4 with the FE predictions for $\varepsilon_{B,HR}$ for the specimen loaded at 10 m/s and for dC/da of the QS test, and $G_{Ic,Input}$ is the value assigned to the cohesive elements. If the data reduction process was perfect then this ratio would be equal to unity. It can be seen that the percentage error in the results is small and the toughness given by Equation 4 shows an average increase of 5 % above the input value for crack lengths between 26 mm and 36 mm. (This is as expected from Figure 2a.) Given this inaccuracy of the data reduction technique, if in experimental testing the average HR value is measured to be significantly different from 5 % higher than the QS value then the result could indicate that the G_{Ic} is rate dependent (subject to examination of the scatter of the two data sets).

4 Experimental investigation

An experimental programme was conducted to measure the high rate translaminar toughness of an IM7 8552 carbon-fibre epoxy composite laminate with a layup of $[(90°,0°)_8,90°]_s$ (i.e. the same material which was used in the FE analyses of section 3).

4.1 Specimen preparation and test procedure

The laminate was cured according to the pre-preg manufacturer's instructions and specimens of the geometry shown in Figure 1a were cut from the laminate. The crack tip for each specimen was prepared in three steps:

- (i) a notch, approximately 4 mm wide, with a total length of approximately 30 mm was cut with a circular saw fitted with a diamond-coated cutting disc;
- (ii) a thin crack for next 10 mm was obtained using a 0.2 mm thick razor saw;
- (iii) the crack tip was further sharpened using a sawing action with a 0.1 mm thick razor blade.

In the zone surrounding the mid-line, the front surface of each specimen was painted white with a water-based spray paint and a scale was marked to monitor the crack growth. On the back surface a strain gauge was bonded at the centre of the back edge (Figure 2a).

The QS CT tests were performed with an Instron 4505 machine fitted with a 10 kN load cell. A total of eight specimens were loaded at 0.5 mm/min. Load, applied displacement, crack opening displacement (measured using an LVDT), strain at the back edge of the specimen and crack length were recorded during the test.

HR tests were carried out using a servo-hydraulic Instron machine at cross-head velocities from 0.2 m/s to over 12 m/s. The aim was to test at least four specimens for a given cross-head speed. The typical setup for the HR tests is shown in Figure 3.

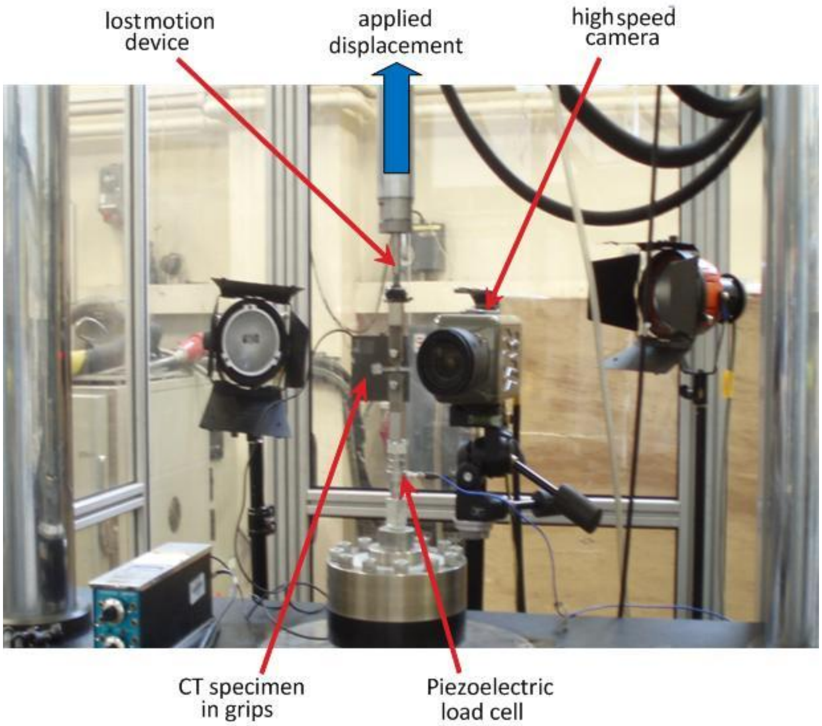


Figure 3. High rate test setup for the CT specimen

Displacement was measured using an LVDT mounted at the top of the machine. Between the ram and the specimen a lost-motion device (LMD) was used to ensure that the ram has undergone adequate acceleration prior to specimen loading. During the test displacement, load, strain and high speed video were recorded. Load was measured using a high natural frequency, short rise time, piezo-electric, 44.5 kN capacity load cell. Strain was measured at the same position as in the QS tests; at the centre of the back edge of one of the specimen faces. A Phantom 7.1 high-speed digital camera (with a Nikon macro zoom lens with a focal length of 24 – 85 mm and an f-stop of 2.8) was used to monitor the crack length on the specimen during the test.

4.2 Data processing and Results

Spurious noise was detected in the displacement versus time data and a noise of the same frequency was also observed in the strain gauge data. A filter was therefore applied to these data sets. The parameters of the filter were optimised to ensure the filtered displacement data gave a linear variation with time (as a constant velocity was applied by the test machine) and that the slope of this line matched that of the best-fit straight line for the unfiltered displacement data.. Both the filtered and unfiltered data was used in the calculation of G_{Ic} using equation 4. (The compliance C was determined from the experimental quasi static tests and a third order polynomial was fitted to this data to enable dC/da to be determined.) The crack length data was determined from the HSV frames using an edge filter to improve identification of the crack tip.

Figure 4 shows the ratio of load/strain measured at the back of the specimen, P_c/ε_B, versus crack length for the translaminar QS CT tests, including the output calculated from the LS-Dyna model. (Note that specimens 1-1 and 1-4 had no strain measured during the tests.) It is this ratio, P_c/ε_B from the QS experiments which is used in the HR data reduction strategy to determine the equivalent load, $\overline{P}_{HR}(a)$, from the experimentally observed strain and crack lengths in the HR experiments.

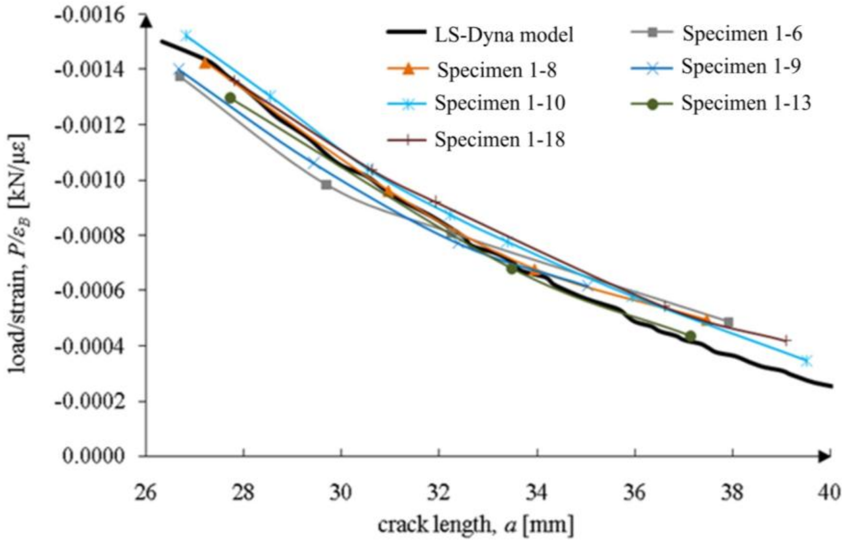
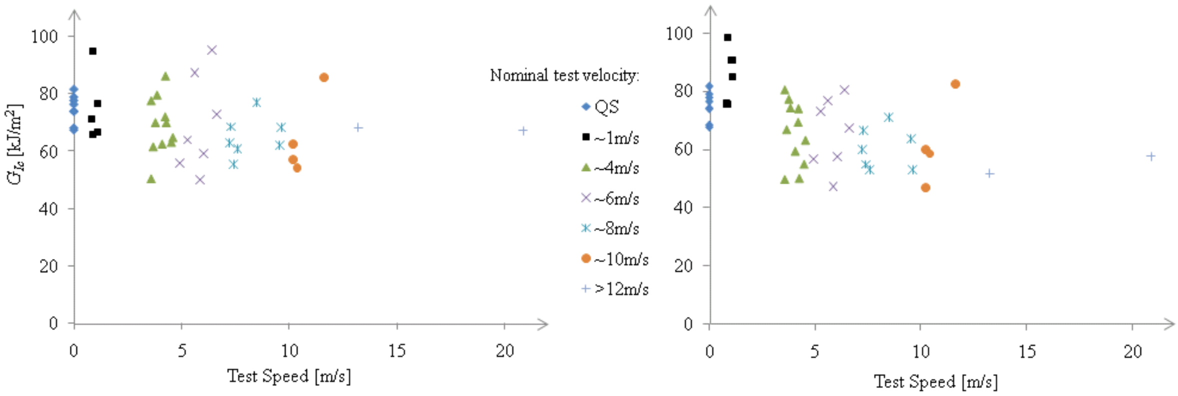


Figure 4. P/ε_B versus a for the QS translaminar CT tests, also showing the FE LS-DYNA model data for G_{Ic} = 72.4 kJ/m^2

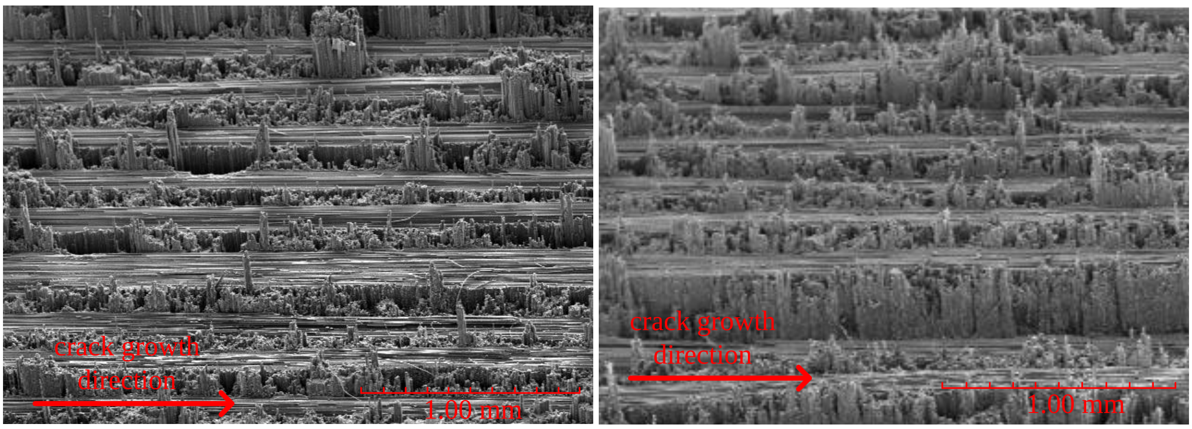
Figures 5a and b show the effect of test speed on the value of G_{Ic} determined using Equation 4 for the unfiltered and filtered results. Both sets of data suggest a possible decrease in mean G_{Ic} with test speed over the entire range of test speeds. For the filtered data this possible decrease in mean G_{Ic} with test speed is more pronounced. This is the case even if the results for the highest test speed are discounted as few measurements were taken at this speed. In both the filtered and unfiltered results, however, the scatter at each test speed is large and so it is not possible to conclude with certainty that there is any change in translaminar G_{Ic} with test speed.



(a) (b)

Figure 5. Effect of test speed on the translaminar G_{Ic} - average results for each specimen a) unfiltered, b) filtered

Comparing the SEM images of the translaminar specimen crack surfaces, Figures 6a and b for quasi static tests and HR tests at 10 m/s respectively, it can be seen that there are no significant differences in the fracture surface at each test speed. The amount and size of fibre pull-out was found to be very similar for all test speeds which is consistent with G_{Ic} varying very little with increasing test speed.



(a) (b)

Figure 6. SEM images of a) QS and b) 10 m/s CT fracture surfaces.

5. Conclusion

FE analyses showed that the CT specimen can be used to measure Mode I translaminar fracture toughness at high test speeds. A data reduction technique using strain measured at the back edge of the specimen was applied to FE-generated data and the calculated toughness was in good agreement with the input value. A test programme was conducted to measure translaminar G_{Ic} of a carbon-epoxy composite laminate for a range of test speeds from quasi static to a few tests over 12 m/s. The results showed that there may be a small decrease in G_{Ic} with test speed. Data which had been filtered to remove spurious noise indicated a more pronounced decrease than the unfiltered data. In both cases there was considerable scatter in the results and so further testing will be required to establish if this trend is significant.

Acknowledgements

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