DELAMINATION RESISTANCE OF THROUGH THICKNESS REINFORCED COMPOSITES

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Abstract
In this study the delamination resistance of arrays of Z-pins are measured in Mode I, Mode II and mixed Mode I/II loading scenarios, using standard fracture toughness test methodologies. Through experimental observations and measured results it is shown that the bridging behaviours predicted in previous single pin tests are analogous to the arrays of pins inside fracture toughness coupons. Although it is not feasible to measure the steady state delamination propagation in a through-thickness reinforced (TTR) region in all Mode mixities, a method is proposed to measure the apparent toughness of these TTR pins at pre-determined delamination lengths. This method provides useful, conservative results that could improve the design of composite components which contain TTR elements.

1. Introduction

In the absence of through thickness reinforcement, laminated composites are susceptible to delamination, in some cases leading to catastrophic failures for the structure. There have been many techniques developed over the years to reinforce laminated composites in the thickness direction include stitching, tufting and Z-pinning [1] termed as through thickness reinforcement (TTR). In particular, the process of Z-pinning involves insertion of small diameter pins, made from fibrous composites or metals, through the thickness of a laminated composite material. This reinforcement process is performed prior to final cure and results in a composite structure with increased resistance to delamination growth.

Measurement of the delamination resistance of laminated composite reinforced through the thickness is not a trivial task. Through the use of standard test methodologies, many issues arise with the addition of such reinforcements, such as excessive bending of the beam arms of a standard DCB/MMB coupon which may result in their rupture, transfer of large loads to the specimens through bonded hinges and crack growth monitoring etc. The most challenging aspect however is the data reduction techniques required to reliably analyse the apparent toughness of the through thickness reinforced regions. Previous characterisation of a single small diameter carbon composite pin inside a composite block yielded unique information about the behaviour of such TTR elements when loaded, over a wide range of loading scenarios [2]. The purpose of the work presented this paper was to investigate the behaviour of such pins in an array and characterise their resistance to delamination propagation at various Mode mixities using standard fracture toughness experimental methods.

2. Materials and manufacturing methods

Test specimens manufactured for this investigation where made using IM7/8552 prepreg (Hexcel, UK) stacked in a quasi-isotropic (QI) sequence to achieve a nominal thickness of 8mm. Full details of the stacking sequence and the effective properties are presented in Table 1. A 16μm PTFE release film was inserted at the mid-plane and an array of T300 carbon/BMI pins arranged with a 2% areal density inserted in to the uncured composite using the ultrasonically assisted Z-fiber (UAZ) insertion method. A total of 154 pins were inserted per sample (14 rows, 11 lines) totalling 22.75mm in length and covering the full width of each specimen. The position of the Z-pin array and the release film will be described in the next section.

Laminate type	Sequence	Effective Properties (IM7/8552)			
Quasi-isotropic (QI)	$([0, -45, 90, +45]_{4S})_s$	E_1	61.65GPa	G_{12}	23.37GPa
		E_2	61.65GPa	ν_{12}	0.32
		E_f (3 point bend)	55.21GPa		

Table 1. Stacking sequence and effective properties

3. Experimental methods

The experimental procedures followed for this investigation have been developed to measure the fracture toughness of a unidirectional (UD) fibre reinforced plastic (FRP) composite for a thickness range between 2-5mm. However, in order to propagate the delamination through the Z-pinned region, large loads are required which would result in large deflections of the specimen arms generating non-linearity in the measured data To overcome this, specimens were designed with a nominal thickness of 8 mm. The data reduction schemes which follow linear elastic fracture mechanics (LEFM) may not be sufficient to account for the large scale bridging of the interface of the thick 8 mm specimens tested. Nevertheless this investigation will generate useful data for help with the characterization of the Z-pin array reinforcements including their behavioural difference as compared to single pin experiments [2].

3.1. Mode I

For this investigation the ASTM-D5528 standard for DCB testing was followed [3] to generate Mode I delamination propagation. The specimens were manufactured such that the release film edge and the Z-pinned region were positioned at 50mm and 75mm ahead of the load line respectively. Using a calibrated Instron test machine with a 10 kN load cell, the load was applied to the specimen at a displacement rate of 4mm/min. The resulting values of Load, P, and displacement, δ, were recorded for every 1mm increment in crack length, a, until delamination grew past the Z-pinned region. Five replicates were tested for each configuration of the Z-pinned specimens. It is expected, that the propagating delamination from an unreinforced region into a reinforced region will generate an R-curve similar to Figure 2a. As can be seen there are three stages to the delamination state termed I to III. Stage I is the region in which delamination is propagating through the unreinforced composite interface. Stage II initiates when delamination reaches the start of the reinforced region, where the reinforcement bridging zone starts to develop resulting in an increase of apparent toughness. This continues until stage III, when the bridging zone is fully developed and steady state delamination propagation in the reinforced region is reached. The effective toughness of the reinforced region is then calculated as the average of the *G* values in stage III.

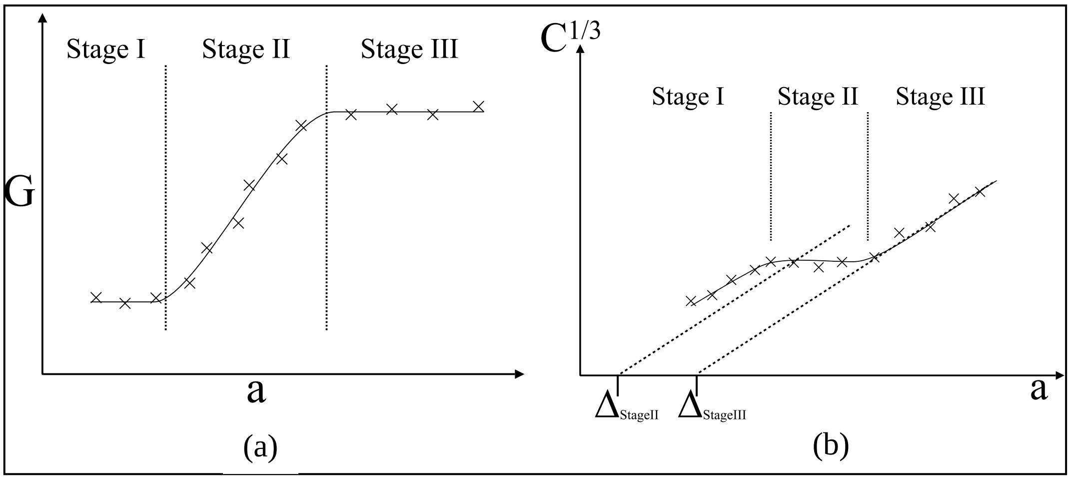


Figure 2. (a) Idealised R-curve of delamination propagation from a non-reinforced to a reinforced region (b) MBT crack correction factor calculation for specimens with discrete reinforcements

The basic modified beam theory (MBT) equation (1) was used to calculate the G_I values at each increment in crack length [3].

$$G_I = \frac{3}{2}\frac{P\delta}{b(a+\Delta)} \quad (1)$$

Where *b* is the specimen thickness and Δ is the crack length correction factor. However due to the inclusion of Z-pins the standard method of measuring Δ may not yield correct results as shown by Robinson and Das [4]. They proposed a simple technique to calculate Δ which reduces the error in the calculated G_I values. By applying MBT and treating the data points in the three stages separately, the crack length correction for stage III, $\Delta_{stageIII}$, can be evaluated from the intercept of the line of best fit of the stage III data points, with the crack length axis as shown in Figure 2b. Similarly, the crack length correction for stage II, $\Delta_{stageII}$, may be evaluated by the intercept of a line parallel to the line of best fit of the stage III data points, passing through a stage II data point.

3.2. Mixed Mode I/II

To generate Mixed Mode I/II delamination propagation for this investigation, the ASTM-D6671 standard for mixed Mode bending (MMB) testing of UD FRP composites [5] was followed. The MMB experiment is a combination of Mode I and Mode II tests, where a load is transferred to the specimen at four separate locations by means of a lever. The half span distance of the MMB, *L*, determines the location of each loading line and was set at 65mm. The lever length, *c*, which is the distance between the load application, *P*, and the location of the middle loading line, determines the mode mixity percentage. The mixed mode percentage is defined as the amount of Mode II component of strain energy release rate, G_{II}, to the total mixed mode strain energy release rate, $G_T=G_I+G_{II}$. The specimens were manufactured such that the release film edge and the Z-pinned region were positioned 30mm and 40mm ahead of the load line respectively. The lever length, *c*, was positioned at 101.1mm, 57.5mm and 41mm to achieve nominal mixed mode percentages of 25%, 47% and 69% respectively. Using a calibrated Instron test machine with a 10kN load cell, the load was applied to the specimen at a displacement rate of 0.5mm/min. The resulting values of Load, *P*, and displacement, δ, were recorded for every 1 mm increment in crack length, *a*, until delamination reached 60mm. Five replicates were tested for each configuration of the Z-pinned specimens. Similar to the DCB tests, the R-curve is expected to follow the shape shown Figure 2a.

3.3. Mode II

To generate Mode II delamination propagation, the end loaded split (ELS) test procedure was chosen, based on the guidelines provided by the European Structural Integrity Society (ESIS-TC4 01-04-02) [6]. The specimen had a thickness, *h*, of 8mm and width of 20mm. The release film edge and the Z-pinned region were positioned 65mm and 90mm ahead of the hinged load line respectively. Prior to testing, a natural Mode II crack was generated by clamping the specimen 5mm ahead of the embedded pre-crack film and loading until the crack propagated to 70mm.
To prevent unstable delamination during the initial part of the test, the specimens were clamped such that the ratio of crack length, *a*, over span length, *L*, satisfied the parameter $0.55 < \frac{a}{L}$. The specimen was clamped at a span length, *L*=125mm, with the initial crack length, *a*= 70mm, giving an *a/L* ratio of 0.56. Using a calibrated Instron test machine with a 10kN load cell, the load was applied to the specimen at a displacement rate of 2mm/min. The resulting values of Load, *P*, and displacement, δ, were recorded for every 1 mm increment in crack length, *a*, until delamination reached the clamped end. Five replicates were tested for each configuration of the Z-pinned specimens. Similar to the DCB and MMB tests the R-curve was expected to follow the profile shown Figure 2a.

4. Results

Representative load vs. displacement curves are given in Figure 3. The R-curve of the Z-pinned DCB test specimens are shown in Figure 4. The delamination in the QI specimens grew past the end of the Z-pinned region just as the bridged length was nearing the fully developed stage. The transitions between the three stages of the delamination propagation are labeled on the plot.

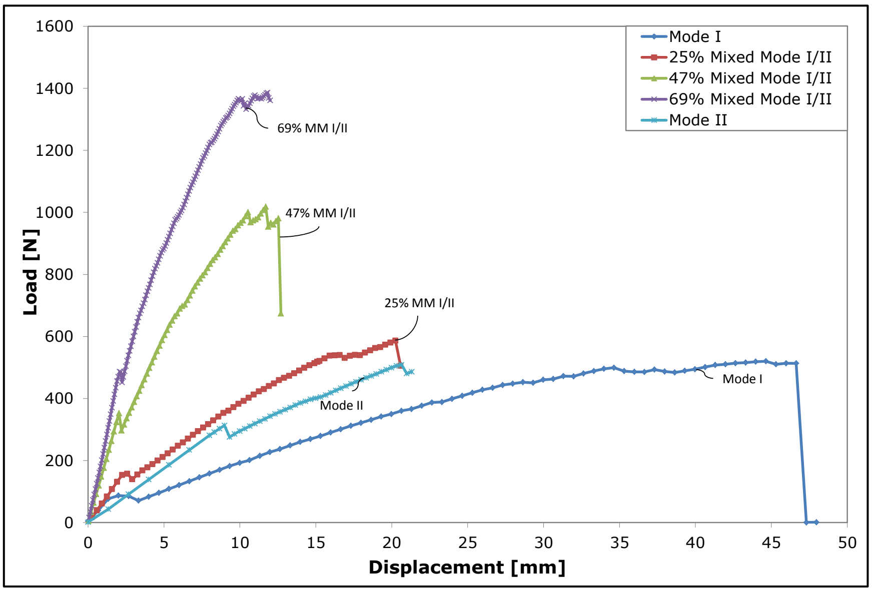


Figure 3. Representative Load vs. Displacement plots from each test

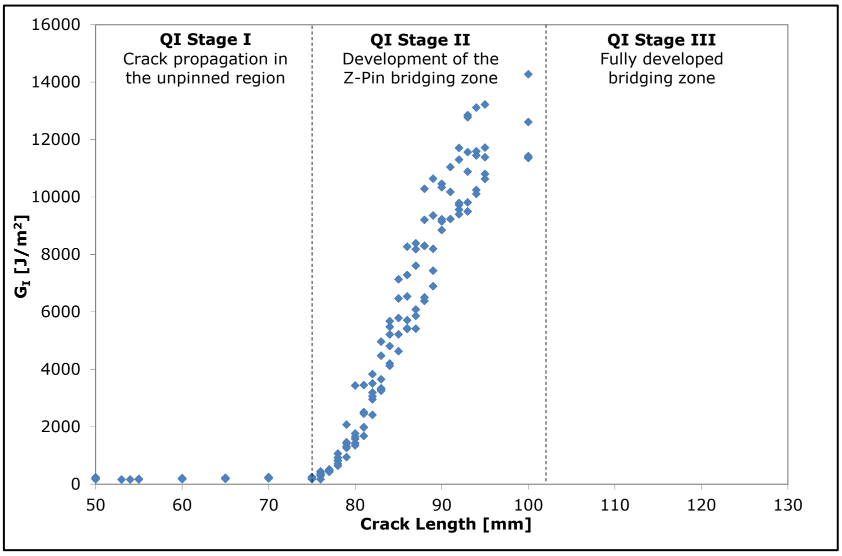


Figure 4. Mode I R-curve of Z-pinned QI DCB specimens

The calculation of the total delamination resistance for the MMB test is a function of the flexural modulus, E_{1f} of the composite material. This value may be taken from manufacturer's data but more ideally measured through a standard 3 point bending test. For the MMB test procedure the value of E_{1f} for each specimen is calculated from the material properties and corrected through a calibration process carried out at each mixed Mode ratio. The averaged calculated value, E_{1f}, of the MMB test specimens at each mixed Mode ratio are shown in Figure 5. Also shown on the plots are the axial modulus, E_1, and the flexural modulus, E_{1f}, calculated from 3 point bend tests. As can be seen, the calculated flexural modulus from the test procedures differs significantly at a Mixed-mode ratio of 0.25, which resulted in calculation of an excessively high total critical fracture toughness, G_{TC}. This behaviour has also been reported previously by other researchers [7,8]. The calculated E_{1f} value from the 0.25 Mixed-mode ratio tests was considered to be incorrect and was replaced with the averaged E_{1f} values from the 0.47 and 0.69 Mixed-mode ratio tests in the calculation of G_{TC}.

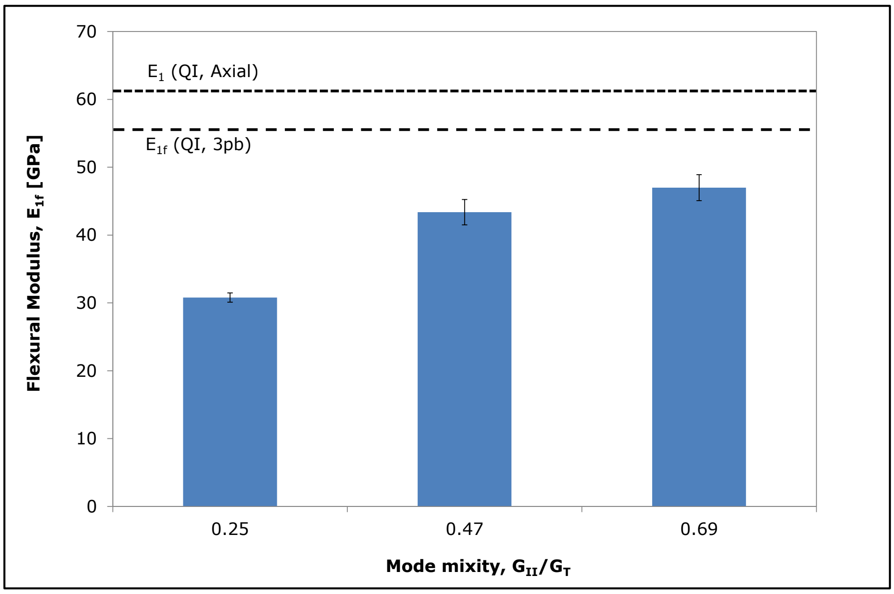


Figure 5. Calculated flexural modulus of IM7/8552 specimen using MMB test procedure

The R-curve of the Z-pinned QI MMB test specimens is shown in Figure 6. The QI exhibits little change in resistance between 0.25 and 0.47 but a slight drop is seen at 0.69 Mixed-mode ratio. For all tests the bridging development remained in the stage II region (Figure 2a) thus no steady state delamination was achieved. The Mode II R-curve for the QI Z-pinned ELS specimens is shown in Figure 7. Similar to the MMB tests the bridging development remains in stage II for the entire length of the Z-pinned region.

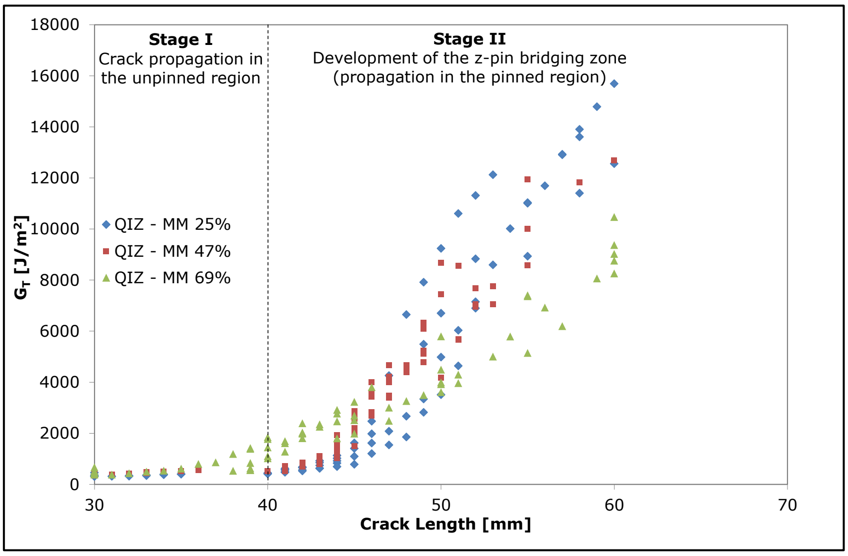


Figure 6. R-curve of Z-pinned QI MMB specimens at 0.25, 0.47 and 0.69 mixed Mode ratio

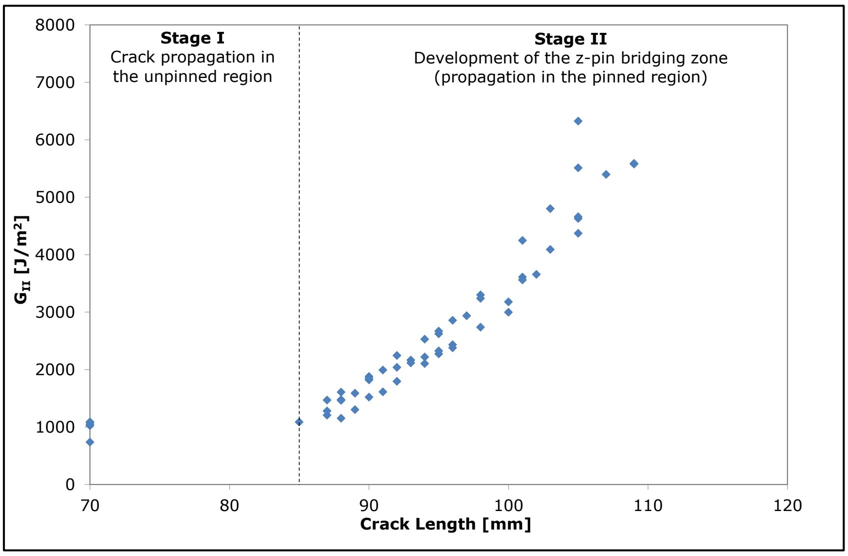


Figure 7. Mode II R-curve of Z-pinned ELS specimens

5. Apparent fracture toughness

Due to the shortcomings of the current test fixtures to effectively measure the delamination resistance with a fully developed bridging zone of the Z-pinned region, the different mode mixity tests could not be directly compared to each other. An approach was therefore adopted which compares the apparent delamination fracture toughness values at predetermined positions within the reinforced region. Values of apparent fracture toughness of all the specimens were collated at delamination positions of 9mm and 19mm into the Z-pinned region, as shown in Figure 8.

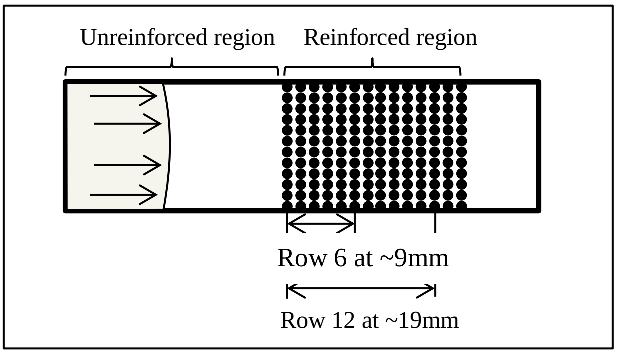
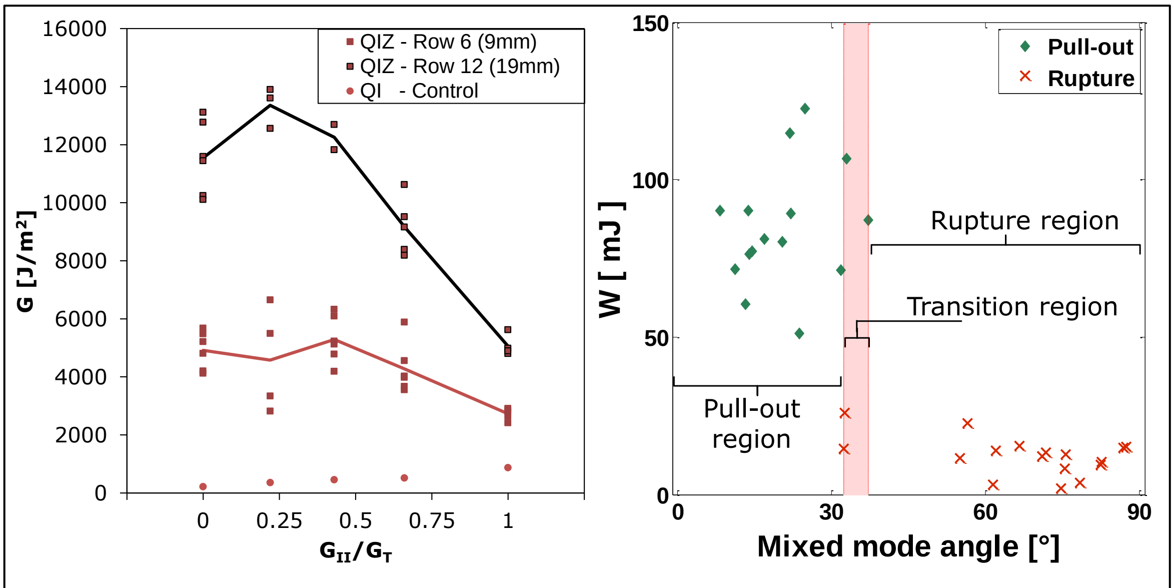


Figure 8. Delamination positions lengths at which apparent fracture toughness were measured

Presented in Figure 9 (a) is the apparent toughness of the Z-pin reinforcement at each mixed Mode ratio measured when the delamination has propagated to 9mm and 19mm into the reinforced region. At 9mm into the array, the Z-pins generate an average apparent toughness of 5kJ/m^2 from Mode I to 67% mixed Mode ratio, before reducing to 3kJ/m^2 in Mode II. When measured at 19mm into the array, there is an increase in resistance across all Mode ratios, more significantly from Mode I to 47% Mixed- mode ratio with highest of 13kJ/m^2 at 22% mixed Mode ratio. At 67% mixed Mode ratio the increase in apparent toughness is on average 9kJ/m2 with Mode II increase only reaching 5.6kJ/m2.



(a) (b)

Figure 9. (a) Effective delamination resistance of the Z-pinned QI composites at 9 mm and 19 mm into the Z-pin array, (b) Absorbed energy vs. mixed Mode angle for failure/pull-out of single carbon pins inside QI laminates

Figure 9 (b) presents the result of experiments carried out by characterising single pin behaviour when loaded from Mode I to Mode II regimes [2], showing the absorbed energy of the pin when bridging an artificially delaminated interface. The overall profile of Figure 9(a) follows closely those in Figure 9(b). With an initial increase in Mode II component from pure Mode I loading, the energy contributions from the bridging forces increase due to frictional increases of the pins during pull-out. With further increase in Mode II, the frictional enhancements acting on the pins will overcome its ability to pull out and the pins end up failing through a mixture of tension and bending. In the higher Mixed-mode loading regimes, the pins' contribution to the bridging forces is at its lowest.

6. Conclusions

In this investigation the delamination resistance of carbon Z-pin arrays has been characterized under a variety of mixed Mode ratios. Specimens of 8 mm nominal thickness were designed so as to overcome non-linearity that arises due large beam arm curvatures during the tests. Steady state delamination through the Z-pinned region was not reached for any of the tests. The Z-pins generated large scale bridging of the specimen interfaces and significantly increased the delamination resistance of the composites. For pure Mode II tests the increases in delamination resistance were not as significant relative to lower Mixed-mode ratios. The bridging zones were observed to increase with increasing Mode II mixities. However, to achieve a steady state propagation of delamination in the pinned region and to measure a fully developed bridging zone, longer Z-pin regions and specimen dimensions are required as well as longer span lengths for mixed Mode and Mode II tests.

7. Acknowledgements

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8. References

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