MODE I INTRALAMINAR FRACTURE TOUGHNESS OF 2D WOVEN CARBON FIBRE REINFORCED COMPOSITES: PRE-CRACK TIP RADIUS SENSITIVITY

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Abstract

The determination of intralaminar fracture toughness for carbon fibre composites has been the subject of several studies. However, pre-crack geometry has not been extensively investigated. Here we assess the sensitivity of the mode I intralaminar fracture toughness to pre-crack tip radius, numerically and experimentally. Two sets of five scaled Double Edge Notch Tension (DENT) specimens were made from the same 2D woven carbon fibre composite laminate, one with blunt notches and another with sharp pre-cracks, and tested using the size effect method. Experimental results depicted a higher fracture toughness for the sharp pre-crack specimens. A numerical investigation was then performed on the geometric correction factor used in the data reduction, to analyse whether the differing radii affect the stress intensity at the crack tip, which may explain the difference in experimental results. However, the correction factor for the two radii, which assumes a slit crack propagating from the initial pre-crack tip, converged to the ideal slit crack solution, before reaching peak load, for all specimen sizes tested. Further investigation is required to assess the difference in experimental fracture toughness values.

1. Introduction

The accurate prediction of composite structural failure may be significantly affected by the intralaminar fracture toughness values supplied to the numerical model [1]. Several experimental methods have been devised for measuring the quasi-static intralaminar mode I fracture toughness of fibre-reinforced composites [2-4], with the Compact Tension (CT) test being commonly used. One of its major drawbacks is the requirement to measure the crack length increments during the test. This is a subjective measurement, and can lead to large inaccuracies in the calculation of the fracture toughness [5]. Furthermore, the initiation fracture toughness of unidirectional Carbon Fibre Reinforced Polymers (CFRPs) was found to be sensitive to the notch tip radius [6]. Recent work by Catalanotti et al. on the determination of mode I intralaminar fracture toughness values for CFRPs was based on Bažant's method of relating the material's size effect law with the crack resistance curve (*R*-curve) [7,8]. This technique offers significant advantages over CT specimen testing. CT specimens are renowned to suffer from unwanted failure mechanisms that invalidate the test results, such as fibre buckling at the back-end, and bearing failure at the loading surfaces [9]. Typical size effect specimens (such as DENT) used for determining the mode I intralaminar fracture toughness, do not suffer from such undesirable failures. Furthermore, only the peak load is required from each tested specimen. No crack length increments are measured during these tests, so that the measured fracture toughness is less subjective than that obtained from CT specimens. The size effect observed in quasi-brittle materials such as CFRPs is also captured through this method, unlike other techniques. This permits the determination of a size-independent measurement of the fracture toughness [7,8]. It was reported that the size effect method's specimens could use both sharp and blunt pre-cracks to localise damage, under the assumption that a sharp crack will develop from the pre-crack, before the unstable propagation at critical load [7,10]. However, this geometric sensitivity has not been studied experimentally nor computationally/analytically. This work aims to investigate the pre-crack tip radius sensitivity of mode I intralaminar fracture toughness for a 2D woven CFRP composite.

2. Analytical and numerical modelling

An analytical model, proposed by Catalanotti et al. [7], was used to calculate the mode I intralaminar fracture toughness. This model requires the determination of a geometric correction factor κ, which was obtained using the Virtual Crack Closure Technique (VCCT) and the Finite Element Analysis (FEA) software package, Abaqus [11]. This κ was calculated for the entire range of the crack length to specimen width ratio, α, ranging from 0 (no crack) to 1 (a fully developed crack with no ligament). A polynomial fit of the VCCT results was obtained for κ, later used for generating the driving force curves of the different tested specimens:

$$\kappa = \sqrt{tan\frac{\pi\alpha}{2}} \sum_i Ķ_i \, \alpha^{i-1} \tag{1}$$

where $Ķ_i$ is the matrix of indices for a 6th order fitting function for κ in terms of α. This pre-crack geometry used in the VCCT assumed an infinitely thin slit crack, with no tip radius.

3. Experimental testing and results

Composite laminates were manufactured in an autoclave, using a 5-Harness-Satin (5HS) woven prepreg with IM7 fibres. A $[0/90]_{2S}$ layup was used, with a final nominal cured thickness of 2.5mm. Five sizes of geometrically scaled DENT specimens were manufactured (Fig.1), with three to four specimens per size. Two sets of these geometrically scaled specimens were produced, one set with blunt 0.5mm radius notches machined with a 1mm milling bit, the other set having 0.15mm radius pre-cracks, sawed with a fine 0.3mm-thick razor blade, to the same length as the milled notches (see Fig.1). The specimens were tested using a tensile testing machine, under a displacement-controlled rate of 1mm/min. The peak loads were recorded. Using the aforementioned analytical model, a bilogarithmic size effect law was fitted through the nominal stresses obtained from the peak loads. Also, using the geometric correction factor from Eq.(1), the *R*-curve was derived for both sets of tested specimens. A 95% confidence interval was fitted to the size effect law based on the experimental data points, from which a subsequent confidence interval was generated for the *R*-curve. Fig.2 shows the *R*-curve (in black) for the blunt notch specimens, while Fig.3 depicts the same results for the sharp pre-crack specimens. The 95% confidence intervals for both *R*-curves are also represented in these figures (both in dashed black lines). The crack driving force curves for the different sized specimens are displayed in blue, tangent to the *R*-curves. The red curves represent the specimen sizes which were actually tested experimentally. The steady-state fracture toughness (R_{ss}) for the blunt notch specimens was found to be 86.7kJ/m^2, achieved after the full development of the FPZ, of length 0.6mm. This contrasted with the R_{ss} of the sharp pre-crack specimens, estimated at 113.7kJ/m^2, with an LFPZ of 1.48mm. The discrepancy in LFPZ values is not unexpected, due to the sensitive nature of its calculation, which is dependent on the derivative of the κ-α polynomial fit. However, a higher fracture toughness was not expected from the pre-crack specimens, since the stress intensity at the initial crack tip would be higher than that in a blunt notch.

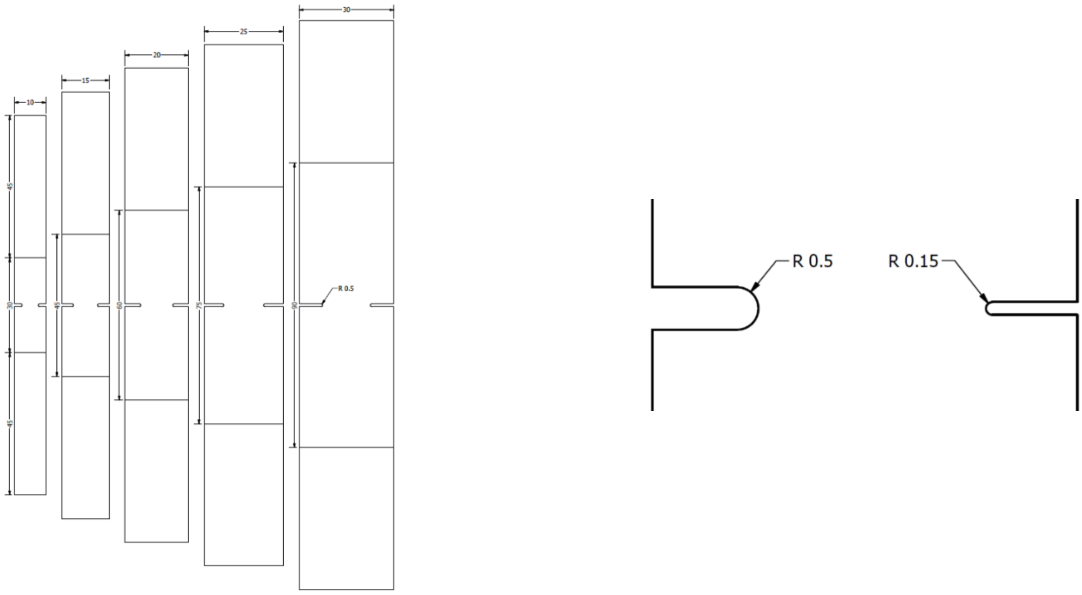

Figure 1 - Tested Specimen Sizes (Left); Tip radii for the milled notch and sawed pre-crack (Right).

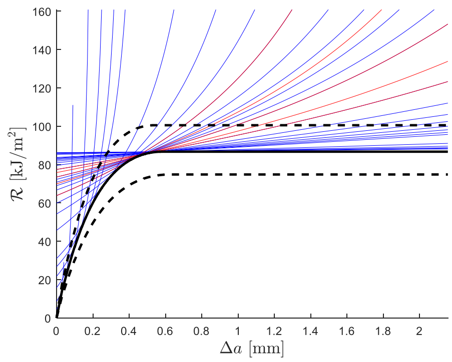

Figure 2 – Blunt notch *R*-curve with 95% confidence intervals and critical driving force curves for different sized specimens.

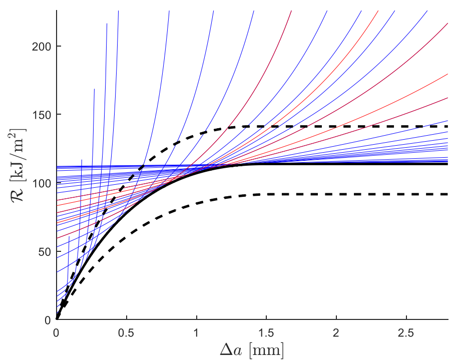

Figure 3 – Sharp pre-crack *R*-curve with 95% confidence intervals and critical driving force curves for different sized specimens.

4. Discussion on pre-crack tip radius sensitivity

A representative specimen's pre-crack geometry was investigated using an analytical model combined with FEM. VCCT and contour integral analyses were performed in Abaqus for three different pre-crack tip radii: i) a slit crack (no radius), used for the previously described polynomial fitting; ii) a sharp pre-crack (radius 0.15mm); iii) a blunt notch (radius 0.5mm).

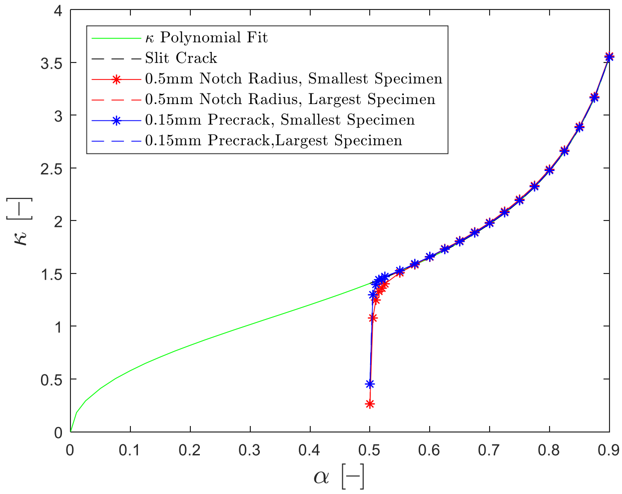

Figure 4 - κ analysis for various pre-crack geometries.

The contour integral, analysed using Abaqus' inbuilt function, was shown to match the energy release rate computed from the VCCT. This integral was then used to obtain the value of κ at α_0, equal to 0.5 for the tested specimens. The VCCT analysis provided the κ values for all the propagated pre-cracks at the larger α values. Here, it was assumed that a slit crack would propagate from the tips of all the different pre-crack radii. The variation in κ for the different tip radii, at α_0 and just after initial propagation, can be observed in Fig.4. The slit crack, which is an idealisation of the pre-crack geometry to a null radius, was used to derive κ from VCCT, together with its polynomial fit, already described in section 2. For the sawed pre-crack of radius of 0.15mm, the κ values can be seen to converge to within 95% of those for the ideal slit crack after initial propagation, before α=0.51, for both the smallest (2w=10mm) and largest (2w=30mm) of the tested specimens (see Fig.4). For the blunt notch of radius 0.5mm, the size of the notch produces a more noticeable effect on the correction factor. While the largest specimen still converges to within 95% of the slit crack at α=0.51, the smallest specimen requires further propagation to α=0.52 for convergence, since the milled notch produces a larger geometric effect. However, α=0.51 and α=0.52 for the largest and smallest specimens would equal a propagation of the initial notch by 0.3mm and 0.2mm respectively, from α_0=0.5. These initial propagations are the minimum Δa for κ convergence. In order to assume that the slit crack VCCT model used in the κ polynomial fitting is representative of the notch tip radius, the unstable crack propagation at peak load for the blunt notch specimens, must occur after an initial propagation Δa which is larger than these minimum Δa for convergence. As can be seen from the critical driving force curves in Fig.2, the peak load for the tested blunt notch specimens occurs for Δa between 0.4mm and 0.5mm. These values are larger than the minimum Δa for κ to converge to the slit crack correction. Thus, the different fracture toughness values observed experimentally cannot be explained from this geometric correction factor analysis. Several other reasons could explain this discrepancy. One possibility is that the assumption that a blunt notch will develop into a slit crack during propagation might not be valid for woven CFRP composites.

5. Conclusions

In this study, a pre-crack geometric sensitivity study has been performed on the calculated fracture toughness of 2D woven CFRP, with DENT specimens tested using the size effect method. The mode I intralaminar fracture toughness value obtained from the specimens with sharp pre-cracks was found to be higher than that from the blunt pre-crack specimens. An analysis of the geometric stress correction factor was then performed for the different radii used on the smallest and largest specimens. This factor was shown to converge after very slight propagation of a slit crack from the original pre-crack tip, before the critical failure at peak load. Thus, it is not possible to attribute the difference in fracture toughness observed experimentally from the blunt and sharp pre-crack specimens to the geometric correction factor used in the data reduction. It is concluded that the assumption that a slit crack will propagate from an initially blunt notch might be invalid for a woven CFRP composite.

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