MATRIX CRACKING IN CFRP LAMINATES

Felicity J Guild*+, Nadia Balhi*, Nikos Vrellos, Stephen L Ogin** and Paul A Smith****
***Department of Mechanical Engineering, University of Bristol, UK, **School of Engineering, University of Surrey, UK, +Now at: Department of Materials, Queen Mary, University of London, UK**

Keywords: *matrix cracking, finite element analysis, composite laminates*

Abstract

Matrix ply cracking is the most common damage to form when a laminate is loaded, and is of considerable significance for the integrity of a composite structure. The overall aim of the present work is to provide validated constitutive relations for crack accumulation in off-axis plies under mixed mode loading. The results presented in this paper include experimental investigations to describe the development of the cracking and the development of finite element-based models of cracked laminates. The effect of matrix cracking on the residual stiffness of various laminates is determined both experimentally and using finite element simulation. The ratio of modes in different angle ply laminates and the associated criteria for matrix crack initiation are explored.

1 Introduction

Matrix ply cracking is the most common damage to form when a laminate is loaded, and is of considerable significance for the integrity of a composite structure. In previous work on unbalanced [0/θ/0] GFRP coupons [1], we showed that the in-situ ply stresses at crack formation depend on whether there is a pre-existing defect present in the off-axis ply. When no defect was present, the ply stress state at crack formation was incompatible with currently proposed interactive failure criteria, both stress-based (e.g. Tsai-Hill) and fracture mechanics-based [2]. With a defect present, crack formation was governed by the mode 1 transverse tensile stress component for off-axis ply angles in the range 90^0 to 45^0. The results in this paper extend the work to CFRP. The experimental investigations have been complemented by finite element analysis. Analyses include both simulations of laminates containing matrix cracks as well as simulation of the actual process of crack growth.

2 Experimental

2.1 Materials

The material used in this work is IM7/8552 carbon fibre/epoxy resin. The laminates were made from unidirectional prepreg, 0.125 mm nominal thickness, autoclave moulded by QinetiQ, Farnborough. A number of different laminates were manufactured, providing both different off-axis ply angles and different off-axis ply thicknesses. The laminates used for the experimental results presented here were unbalanced $[0_2/\theta_8/0_2]$ lay-ups (where θ = 45°, 60°, 75°) and cross-ply laminates with different ply thicknesses in lay-ups $[0_2/90_8/0_2]$ and $[0/90]_{4s}$.

2.2 Mechanical Testing

Mechanical testing included quasi-static tests, to investigate crack initiation, propagation and multiplication, and fatigue tests to characterise the damage accumulation under cyclic loading. The quasi-static tests were carried out using 0.1% strain rate; the fatigue tests were carried out with a load ratio, R=0.1, at a frequency of 10 Hz.

For crack initiation experiments, coupons were tested with polished edges, whereas crack propagation experiments, which have been carried out only on the $[0_2/\theta_4]_s$ coupons, required the off-axis central plies to be notched. A 0.8 mm drill bit was used to drill holes, 3 mm deep, parallel to the direction of the fibres in the (off-axis) centre plies, without damaging the outer 0^0 plies. A total of twelve notches, six on each edge, were drilled for the $[0_2/\theta_4]_s$ laminates. The notches were drilled on alternating sides of the coupons in such a way that each crack would develop a distance of at least 10 mm apart from the neighbouring crack on the same edge. This distance was chosen so that the cracks would not interact with each other. The notch arrangement for the cross-ply samples is illustrated in Figure 1.

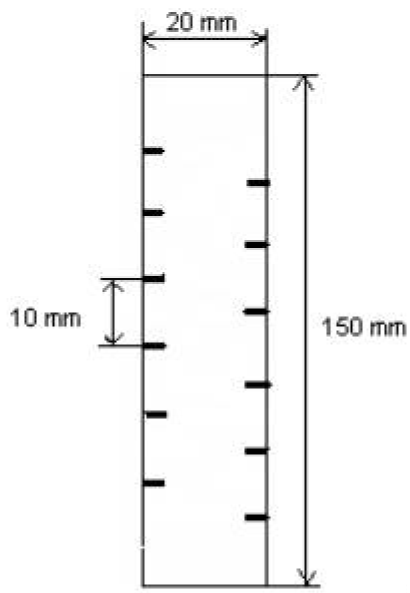

Fig. 1. Arrangement of Notches in Cross-ply Samples

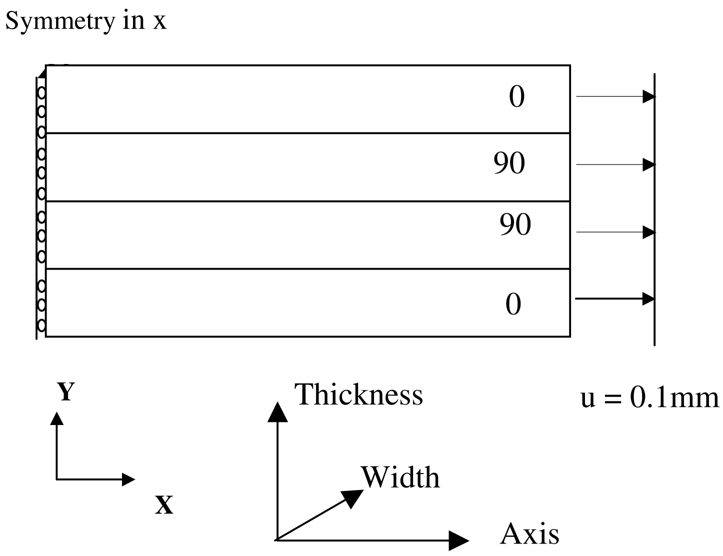

Fig. 2. Geometry and Boundary Conditions for Generalised Plane Strain Models

3 Finite Element Analysis

Matrix crack growth in CFRP laminates has been simulated using finite element analysis. The package used was ABAQUS Standard (Implicit code) version 6.4. For cross-ply laminates, the models could be drawn in two dimensions in the thickness-axial plane using generalised plane strain elements. For these 2-dimensional models, only crack growth across the whole width could be simulated. The geometry and boundary conditions for these meshes is shown in Figure 2. The generalised plane strain conditions are applied in the out-of-plane direction, i.e. the width direction; the conditions used are that the out-of-plane strain is equal throughout the mesh and no rotation is allowed. These are the required boundary conditions for the cross-ply laminates.

Angle-ply laminates require full 3-dimensional finite element models to simulate both mechanical properties and crack growth across the width. Generalised plane strain conditions cannot represent the in-plane shear coupling for these specimens.

Cracks were introduced by releasing nodes on the edge or plane opposite to the imposed deformation. The simulations for increasing crack density were carried out using symmetry condition on meshes with reduced length. Linear material properties were used, but geometric non-linearity was included in all the models.

Further three-dimensional finite element simulations were used to investigate the proportions of modes I and II for crack propagation in off-axis laminates. The method used is virtual crack closure; this is a method requiring two successive analyses and requires a fine mesh around the crack tip. The technique of sub-modelling was required for these analyses. Sub-modelling uses the results from a coarse mesh representing the whole structure to impose the correct boundary conditions on a detailed mesh of the region of interest.

The first analysis for the virtual crack growth method is carried out with the initial crack length, and the forces acting through nodes ahead of the crack are output. For the second analysis, these nodes are released and their displacements are found. The energy associated with that crack growth is calculated from half the product of the forces and associated displacements. These calculations can be carried out to find the total energy; alternatively the directional values can be calculated and thus the proportions of modes I and II can be found.

These simulations for growing cracks were carried out for isolated cracks; neither crack interaction nor thermal stresses were included in these simulations. The values of strain energy release rate were found to be dependent on the elements and meshes used; all results presented here have been obtained following mesh convergence studies.

4. Results

4.1 Experimental Results

The strains at which cracks first propagated from the notches in the notched coupons, and the strains at which crack initiation and (instantaneous) propagation occurred in the unnotched coupons with polished edges were carefully observed. For the unnotched coupons from the $[0_2/\theta_4]_s$ lay-ups with polished edges the crack formation was instantaneous with cracks propagating across the thickness and width of the off-axis ply in an unstable manner. The associated crack morphology was complex, suggesting considerable energy release during crack formation. In the $[0_2/90_4]_s$ specimens, first cracking was seen at an applied longitudinal strain of about 0.8 %. For lay-ups with the central plies oriented at other off-axis angles, it was found that the strain for first cracking increased with decreasing off-axis angle. For the $[0_2/45_4]_s$ lay-up there was no matrix cracking in the central layer prior to laminate failure by fracture of the fibres in the 0^o layers at an applied longitudinal strain of 1.1 % or greater. Figure 3 shows the initial cracking strain in the notched and unnotched $[0_2/\theta_4]_s$ lay-ups as a function of off-axis angle (upper trend line).

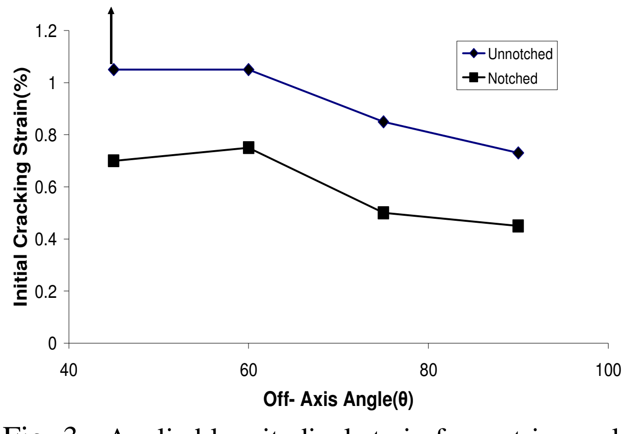

Fig. 3. Applied longitudinal strain for matrix crack formation as a function of ply angle.

Further tests were carried out using careful strain gauge measurements. The longitudinal and transverse strains with increasing crack density were measured for increasing crack density, leading to values of longitudinal stiffness and major Poisson's ratio. The results for the $[0_2/75_4]_s$ coupons are shown (as the crosses) in Figures 4 and 5. These results are presented as normalized values with respect to the uncracked property. The Poisson's ratio results are far more scattered; this is not surprising since the measured values of transverse strain are very small. Reasonable agreement is found between results from separate tests for both stiffness and Poisson's ratio. As expected, the values of both stiffness and Poisson's ratio reduce with increasing crack density, but the size of the decrease is far higher for the values of Poisson's ratio.

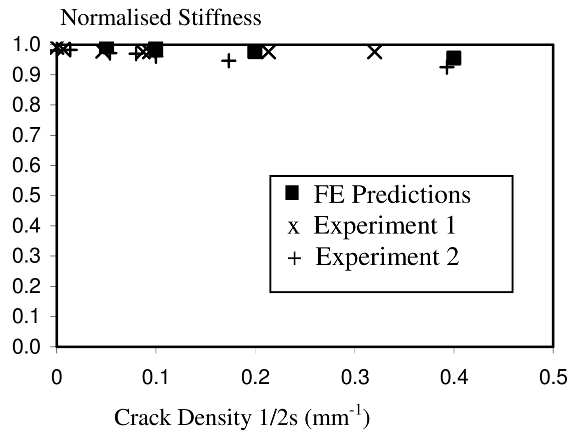

Fig. 4. Variation of Normalised Longitudinal Stiffness with Crack Density for $[0_2/75_4]_s$ coupons

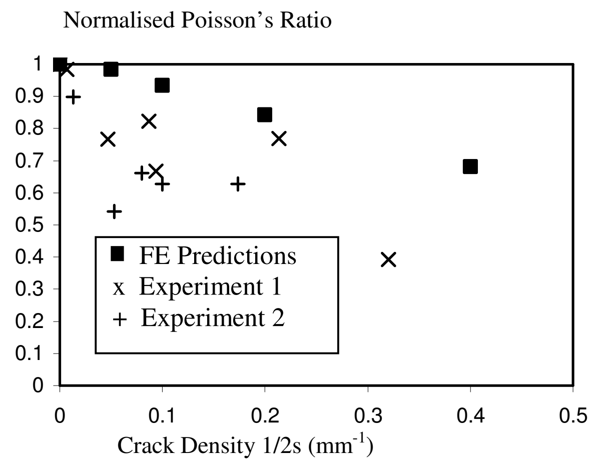

Fig. 5. Variation of Normalised Poisson's Ratio with Crack Density for $[0_2/75_4]_s$ coupons

4.2 Finite Element Results

Finite element simulations were carried out for different values of crack density, and predicted values of residual longitudinal stiffness and values of major Poisson's ratio were extracted. The results are shown by the filled squares in Figures 4 and 5. The trends are in good general agreement with the experimental results. Far higher property changes are predicted for values of Poisson's ratio than Young's modulus, consistent with previous studies of cross-ply CFRP [3]. The predicted change for crack density of 0.4 mm^{-1} is less than 5% for longitudinal stiffness and almost 40% for Poisson's ratio.

Finite element simulations of crack growth were carried out using the experimentally measured values of strain shown in Figure 3. The values used were from the notched specimens since these simulations were for the propagation of cracks. The process of single crack growth in the $[0_2/45_4]_s$ laminates has been examined in detail. The geometry of the crack growth simulated is shown in Figure 6. The through-thickness symmetry is used to halve the size of the analysed region. It is assumed that the crack has spanned the entire thickness of the off-axis layer. It should be noted that the total width, w, is larger than the width of the coupon since the cracks are growing at 45° with respect to the coupon axis, following the fibre direction in the off-axis layer.

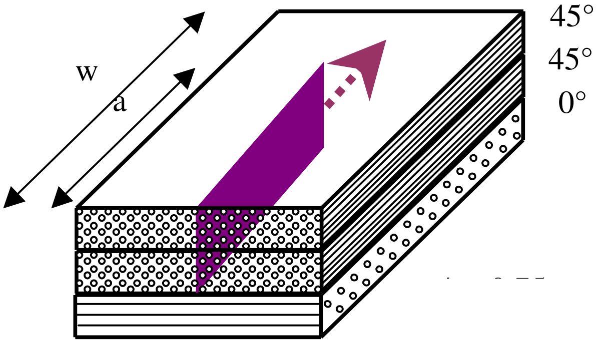

Fig. 6. Geometry of analysed Crack Growth

Results for crack growth with the crack extending half way across the width are shown in Figure 7. The virtual crack growth method has been used to assess the mode mixity of the crack growth. The results in Figure 7 show that the Mode I and Mode II components of the energy release rate are nearly equal. The variability across the laminate thickness indicates the displacement dependence of the strain energy values; as expected, the contribution from the ply nearest the 0° ply is smaller than the contribution from the centre ply. This arises from the constraint on the displacement imposed by the 0° ply.

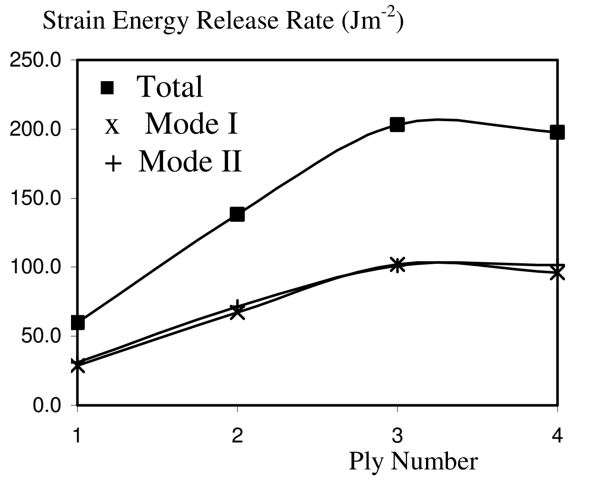

Fig. 7. Variation of Strain Energy Release Rate for $[0_2/45_4]_s$ crack growth half-way across the width

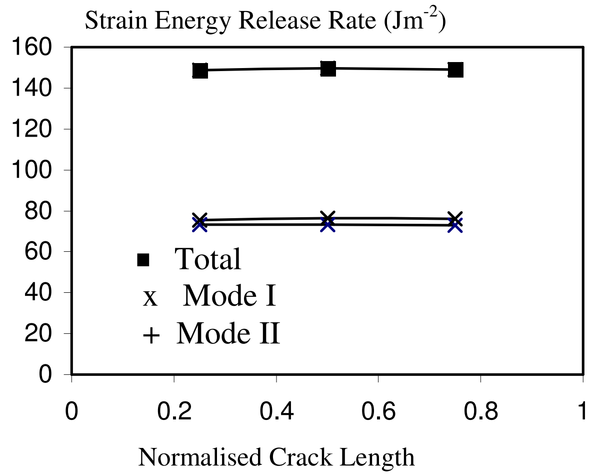

Fig. 8. Variation of Strain Energy Release Rate for $[0_2/45_4]_s$ crack growth across the width

The variation of the values of strain energy release rate as the crack grows across the width is shown in Figure 8. The total value remains constant as the crack grows across the width; the proportions of Modes I and II remain almost the same. These predictions correlate with the experimental observations regarding the non-catastrophic crack growth across the width for these laminates.

5. Concluding Remarks

Finite element simulations of matrix crack growth in off-axis laminates have been successfully undertaken. The predictions show good agreement with experimental results. The measurements of residual properties clearly demonstrate that measurement of transverse strain may be a more sensitive method to monitor crack development.

The strain energy release rate associated with matrix cracking has been found and the importance of mode mixity has been demonstrated. The combination of experimental results and finite element simulations will lead to the provision of validated constitutive relations for crack accumulation in off-axis plies under mixed mode loading.

6. References

[1] Crocker L.E., Ogin S.L., Smith P.A. and Hill P.S., "Intra-laminar fracture in angle-ply laminates", *Composites part A*, Vol. 28A, 1997, pp. 839-846.

[2] Shahid, I. and Chang, F-K. "An accumulative damage model for tensile and shear failures of laminated composite plates", *Journal of Composite Materials,* Vol. 29, 1995, pp. 926-981

[3] Smith P.A. and Wood J.R. "Poisson's Ratio as a Damage Parameter in the Static Tensile Loading of Simple Crossply Laminates". *Composites Science and Technology* Vol. 38, No. 1, pp 85-93, 2006.

Acknowledgements

This project was jointly funded by the Engineering and Physical Sciences Research Council, UK, and the Defence Science Technology Laboratory, UK.