INTRALAMINAR FRACTURE IN OFF-AXIS PLIES OF CFRP LAMINATES

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SUMMARY

Matrix cracking in $(0_2/\theta_4)_s$ CFRP laminates (with $\theta = 45^o$, 60^o, 75^o or 90^o) has been investigated in order to study crack initiation (from polished coupon edges) and crack propagation (from a machined-in defect) as a function of off-axis ply angle. The results indicate that the transverse normal stress appears to be the controlling stress for crack initiation and propagation, except for cracking in 45^o plies for which there appears to be a significant degree of interaction between the transverse and shear stress components. Data from multi-layer angle-ply laminates are consistent with the data from the $(0_2/\theta_4)_s$ laminates when effects due to ply thickness and neighbouring ply interactions are considered.

KEYWORDS: matrix cracking, off-axis plies, crack initiation, crack propagation

INTRODUCTION

Matrix ply cracking in off-axis plies is the most common damage to form when a laminate is loaded and is of considerable significance for the integrity of a composite structure. It is well-established now that traditional failure criteria, such as those due to Tsai-Hill and Tsai-Wu, are unable to deal satisfactorily with the complexities of matrix cracking, such as the dependence of the strain to first cracking on ply thickness. Much work has focussed on a failure criteria based on fracture mechanics which has been shown to predict cracking successfully in the 90^o ply of laminates of the type $(0_m/90_n)_s$ and $(\pm\theta_m/90_n)_s$ where there is no shear component to the 90^o ply stress state [1-5].

A more complex situation is presented by cracking in off-axis plies for other angles, where cracking occurs because of mixed mode loading. In work on unbalanced $(0/\theta/0)$ GFRP coupons [6], it was shown 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 [7]. 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^o to 45^o. The results in this paper extend the work to CFRP and to an investigation of the effects of ply thickness on crack initiation in off-axis plies.

EXPERIMENTAL METHODS

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 laminates were manufactured, providing both different off-axis ply angles and different off-axis ply thicknesses. The laminates were (a) four unbalanced laminates of the type $(0_2/\theta_4)_s$, where θ is 45°, 60°, 75° and 90°; (b) a $(0/90)_{4s}$ laminate, which also provides $(\pm45)_{4s}$ coupons; and (c) quasi-isotropic laminates with configurations $(0/90/\pm45)_s$, $(0_2/90_2/\pm45_2)_s$ and $(0_2/\pm60_2)_s$.

For the $(0/90)_{4s}$, $(0_2/\theta_4)_s$ and quasi-isotropic material, rectangular test coupons 250 mm long by 20 mm wide were cut from the original panels using a diamond wheel saw with water lubrication. The edges of all coupons were polished to a 1 μm finish using a Struers Pedemax-2 grinding polishing machine. Polishing the edges provides a consistent sample condition, while facilitating crack observation during testing. 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° plies. Twelve notches, six on each edge, were drilled in the $(0_2/\theta_4)$ coupons (see Fig. 1(a) and 1(b)). In addition, for the $(0_2/45_4)_s$ laminate, additional coupons were made where the notches in the central off-axis ply measured 10 mm in depth (Fig. 1(c)), with a total of six notches, three on each edge. In all cases, 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. Testing the $(\pm45)_{4s}$ coupons enabled the value of G_{12} and the shear stress/shear strain behaviour to be measured.

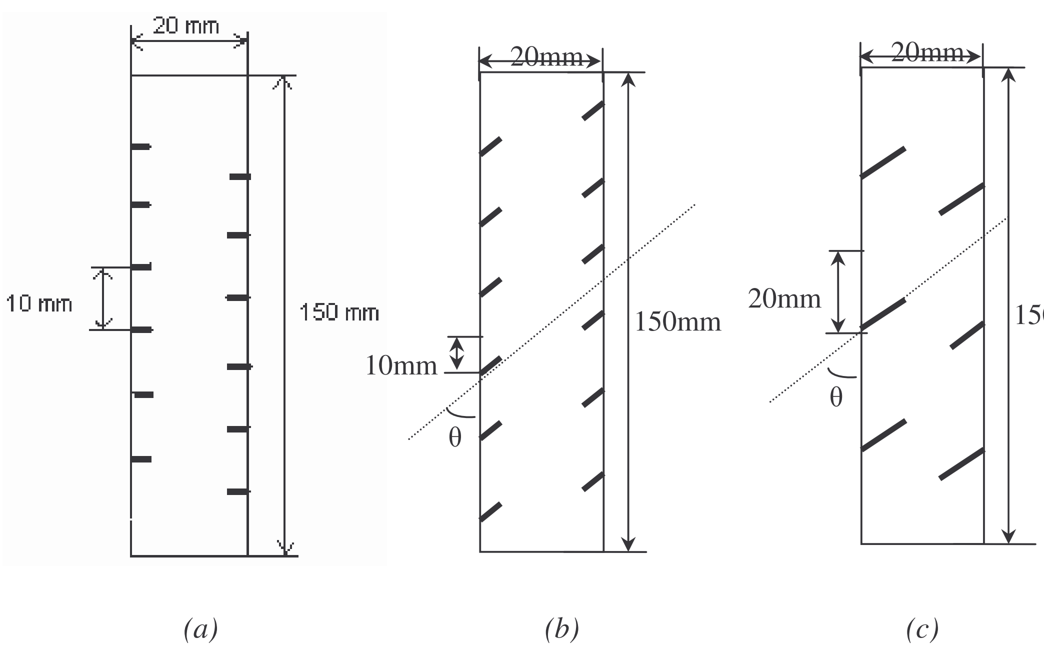

Fig. 1: Schematic of $(0_2/90_4)_s$ (a), $(0_2/45_4)_s$ with 3 mm notch depth (b) and $(0_2/45_4)_s$ with 10 mm notch depth (c) specimens, prior to testing

Aluminium alloy end-tabs were bonded to all the coupons to minimize damage to the coupons in the grips of the tensile testing machine during loading. For the unbalanced $(0_2/\theta_4)_s$ coupons, oblique end-tabs were used to minimise gripping constraints due to extension-shear coupling. Oblique end tabs have been used by others [8,9] when testing off-axis unidirectional composites. Modifying the Sun and Chung approach [8] to the case of an angle-ply laminate, the angle φ for the oblique end-tabs is given by

$$\varphi = \tan^{-1} - \frac{1}{\left(\frac{A_{16}^{-1}}{A_{11}^{-1}}\right)} \tag{1}$$

where A_{16}^{-1} and A_{11}^{-1} are components of the inverse laminate extensional stiffness matrix. Fig. 2 shows a comparison of the required oblique angle for the end-tabs as a function of off-axis angle θ for both unidirectional IM7/8552 and coupons with orientation $(0_2/\theta_4)_s$. It is clear that grip constraints are significant for both types of material for all angles of θ between 0^o and 90^o (the ply properties are shown in Table 1). For the tests carried out here, the oblique end-tab angle φ for off-axis angles of 45^o, 60^o, and 75^o are 62^o, 82^o and 89^o degrees, respectively.

Table 1: Ply properties and coefficients. of thermal expansion

	IM7/8552
$\mathbf{E_1}$	170.6 GPa
$\mathbf{E_2}$	9.1 GPa
$\mathbf{G_{12}}$	4.5 GPa
$\boldsymbol{\nu_{12}}$	0.31
$\boldsymbol{\alpha_1}$	0×10^{-6} K^{-1}
$\boldsymbol{\alpha_2}$	29×10^{-6} K^{-1}
$\boldsymbol{\Delta T}$	151.6 K

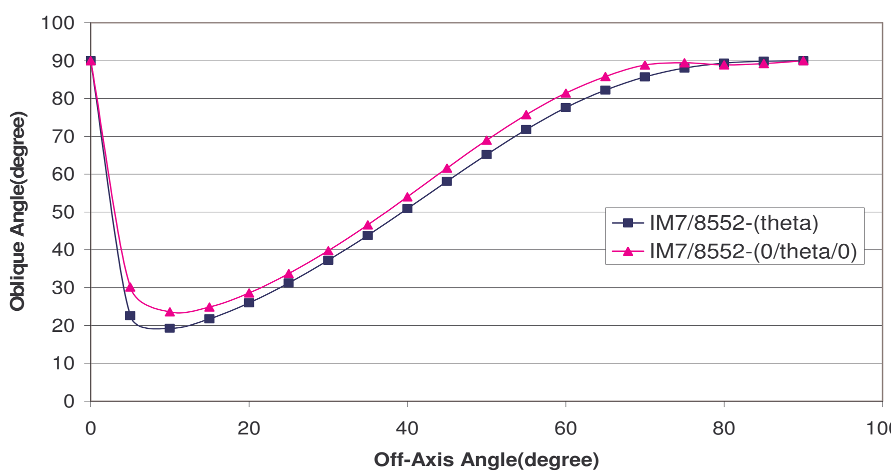

Fig. 2: Oblique end-tab angle φ as a function of ply off-axis angle θ for unidirectional laminates and unbalanced $(0_2/\theta_4)_s$ laminates.

All coupons were tested under quasi-static loading at a displacement rate of 0.5 mm per minute and the strains were measured using longitudinal and transverse strain gauges bonded to the specimen on either side, with cyanoacrylate glue, in the longitudinal and transverse directions. The tests were carried out to progressively higher strains as follows. Coupons were loaded to a strain level of about 0.6 %, the specimen was unloaded, and reloaded to a strain level of 0.7 %. The process was then repeated so that each reload took the specimen to a strain 0.1% higher than the previous strain. Some tests were taken to coupon failure, while others were stopped at a strain of 1.1 % or 1.2 %. A simple method was used to monitor the onset of matrix cracking, using a stethoscope placed on the surface of a coupon. When cracking was identified during an incremental step, the sample was taken out of the testing machine and optical microscopy of the coupon edge was used to confirm cracking, followed by examination using x-radiography. X-radiography was then used to monitor the crack accumulation over subsequent strain increments.

For the determination of the stresses at crack formation, it is necessary that the thermal stress state of the laminate prior to testing is well-characterised. This requires a knowledge of the temperature difference, ΔT, between the lock-on temperature of cure and room temperature, which can be found through measuring the radius of curvature, *R*, of an unbalanced 0/90 beams. The associated theory [10] gives the relation:

$$(a_t - a_l)(\Delta \mathrm{T}) = \frac{b}{12R}\left[\left(\frac{E_l}{E_t}\right) + 14 + \left(\frac{E_t}{E_l}\right)\right] \tag{2}$$

Here, α_l and α_t are the longitudinal and transverse thermal expansion coefficients, respectively, E_t and E_ℓ are the longitudinal and transverse ply moduli, and *b* is the thickness of both the 0^o and 90^o layers. Measurements on a $0_4/90_4$ beam led to a value of ΔT = 151.6 K.

ANALYSIS OF RESULTS

The experiments gave results for the stresses (strains) at which cracks first propagated from the notches in the notched coupons, and the stresses (strains) at which crack initiation and (instantaneous) propagation occurred in the unnotched coupons with polished edges. Laminated Plate Theory (LPT) was used to determine the corresponding stress states in the plies undergoing cracking. For the 90^o plies in cross-ply and multi-ply laminates, there is no shear stress component associated with the principal material directions and so the cracking occurs essentially under mode 1 loading, driven by the transverse normal stress σ_2. For other off-axis angles, the shear stress is non-zero and cracking occurs under mixed mode loading, under the action of the transverse normal stress σ_2, and the in-plane shear stress τ_{12}.

Various LPT calculations were carried out using the commercial LAP software. The results for the ply stress states at crack onset reported here were obtained incorporating the non-linear behaviour of the material in shear, which was deduced from the tensile tests on the $(\pm 45)_{4s}$ coupons, and the effect of the residual thermal stresses, which was determined from the analysis of the measurements on the unbalanced beam specimens.

RESULTS AND DISCUSSION

$(0_2/\theta_4)_s$ lay-ups

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, 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 which occurred by fracture of the fibres in the 0^o layers at a longitudinal strain of 1.1 % or greater. Fig. 3 shows the initial cracking strain in the unnotched $(0_2/\theta_4)_s$ lay-ups as a function of off-axis angle (upper trend line).

In the notched $(0_2/\theta_4)_s$ lay-ups, where the pre-existing defect spanned the thickness of the off-axis central layer, crack growth occurred rapidly in the specimens with high off-axis angles, i.e. as the strain was increased in steps of 0.1 %, cracks grew from the starter notches across the entire coupon width. There were also some cracks formed away from the notches. This is apparent in Fig. 4, which shows a series of x-radiographs for a $(0_2/75_4)_s$ specimen. For specimens from lay-ups with lower off-axis angles, there was evidence of more progressive crack growth, i.e. cracks that propagated from notches did not always extend across the full width of the coupon immediately, but grew with increasing strain. This aspect of the crack propagation behaviour can be seen in Fig. 5, which shows a series of x-radiographs for a $(0_2/45_4)_s$ specimen. There was no apparent difference in the behaviour of the $(0_2/45_4)_s$ specimens with the two different initial notch lengths (3 mm and 10 mm). Crack propagation occurred at similar strains in each case.

The data for the strains at which crack propagation first occurred in the various lay-ups are shown in Fig. 3. Overall (and in accordance with the results in [6] for GFRP coupons containing off-axis plies) the data show that crack propagation in coupons with notches occurred at lower strains than crack initiation in the unnotched coupons.

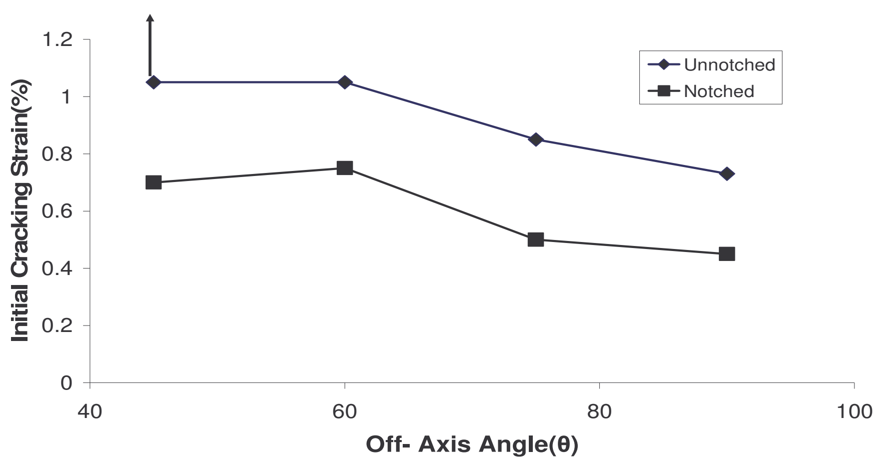

Fig. 3: Applied longitudinal strain for off-axis ply crack formation as a function of ply angle for unnotched (polished edges) and notched coupons from $(0_2/\theta_4)_s$ laminates

For both the unnotched and notched coupons, the crack density increases, as the strain is incremented. Fig. 6 and 7 show data for the elastic properties of the laminates as a function of the off-axis ply crack density. For any given lay-up the data from the unnotched and notched laminates fall within the same scatter band, which is as expected since the introduction of the notches has no significant effect on the initial values of Young's modulus and Poisson's ratio. The initial values for the different laminates are reasonably consistent with laminate theory predictions and the data show also that as the crack density increases there is a larger percentage reduction in Poisson's ratio than in Young's modulus; this result is consistent with previous work [11].

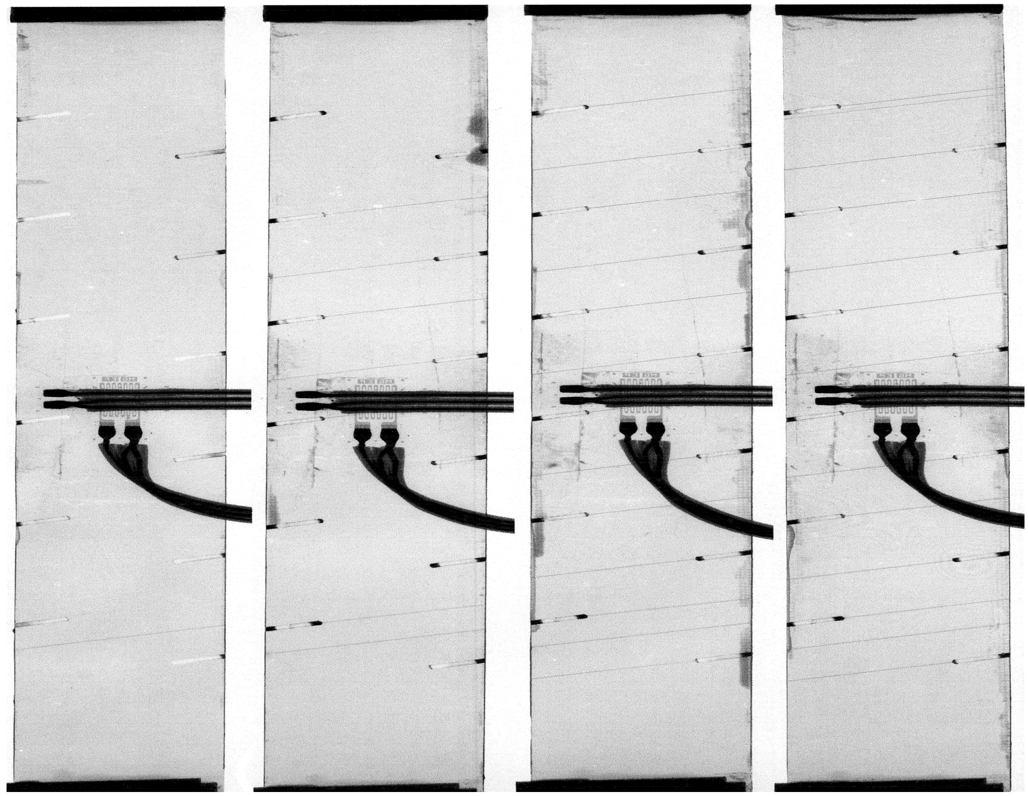

Fig. 4: Dye-penetrant enhanced x-radiographs of a notched $(0_2/75_4)_s$ coupon showing crack development with increasing applied longitudinal strain

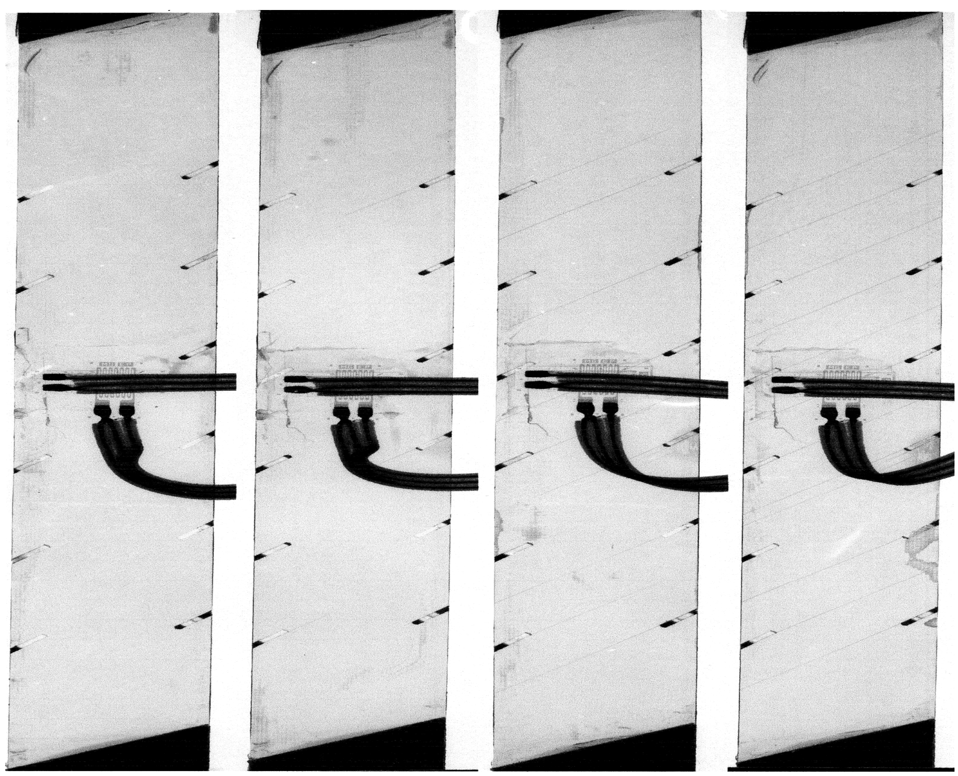

Fig. 5: Dye-penetrant enhanced x-radiographs of a notched $(0_2/45_4)_s$ coupon showing incremental crack growth with increasing applied longitudinal strain

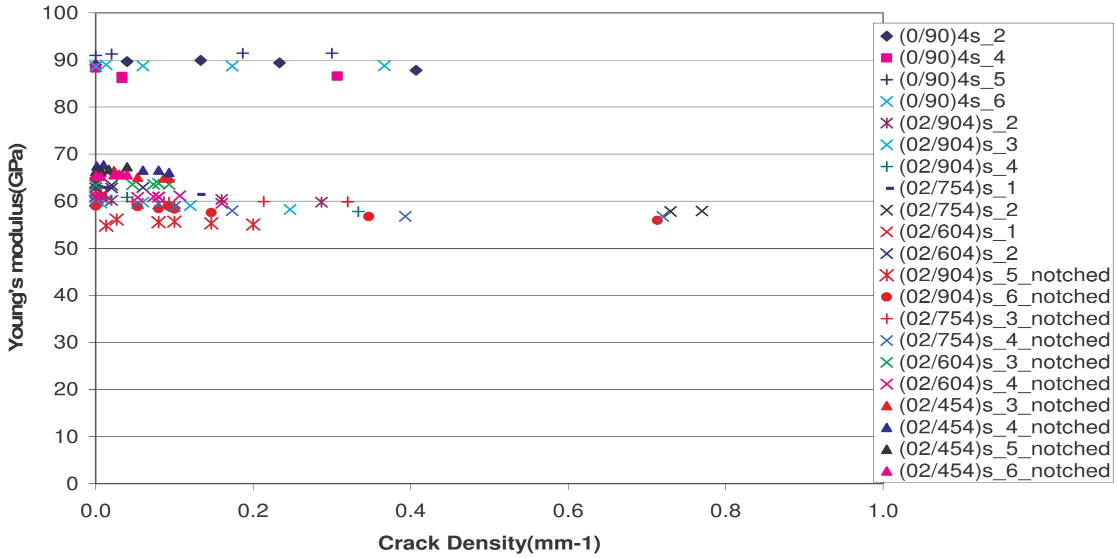

Fig. 6: Young's modulus as a function of off-axis ply crack density for the range of $(0_2/\theta_4)_s$ specimens tested

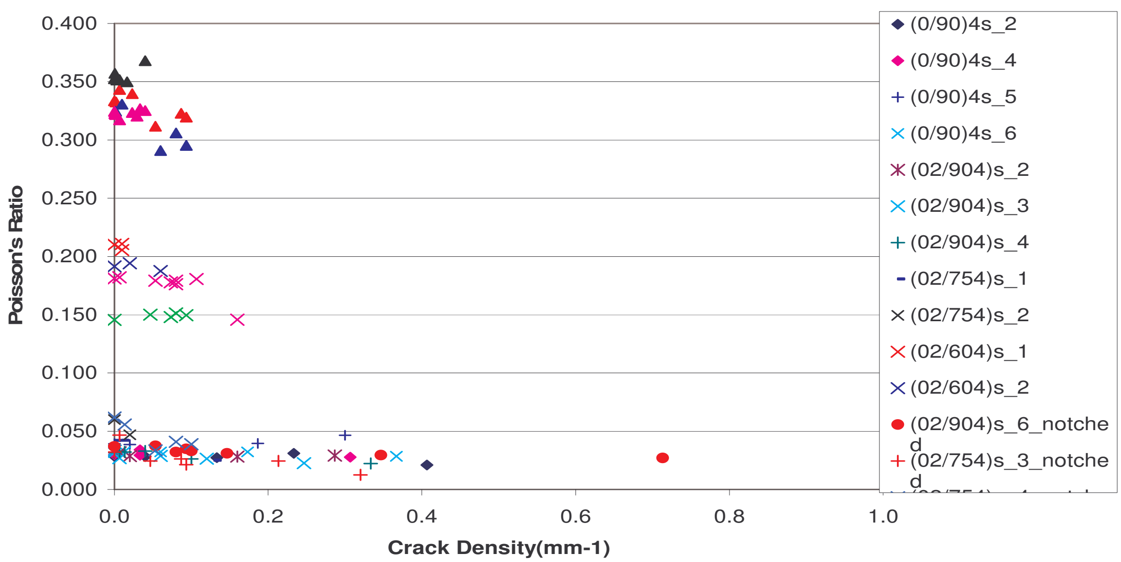

Fig. 7: Poisson's ratio s a function of off-axis ply crack density, for the range of $(0_2/\theta_4)_s$ specimens tested

Laminate Analysis

Results from the Laminated Plate Theory analysis of the $(0_2/\theta_4)_s$ laminates are shown in Fig. 8 as a. plot of transverse normal stress against the corresponding ply shear stress at off-axis ply crack formation in notched and unnotched $(0_2/\theta_4)_s$ CFRP coupons. The results show that for both the unnotched and notched specimens the transverse normal stress σ_2 value corresponding to initial cracking is similar for the $(0_2/90_4)_s$, $(0_2/75_4)_s$ and $(0_2/60_4)_s$ samples, with the notched values some 20 MPa lower than the unnotched values. Interestingly, the behaviour of the $(0_2/45_4)_s$ laminates is somewhat different, in that for crack propagation from notches in these laminates there appears to be a significantly reduced value of σ_2, implying that there is an interaction between the transverse normal and shear stress components which promotes crack propagation. It is not possible to comment upon whether there may be a similar effect in the unnotched $(0_2/45_4)_s$ coupons, since laminate failure occurred before any off-axis ply cracking was seen in these laminates.

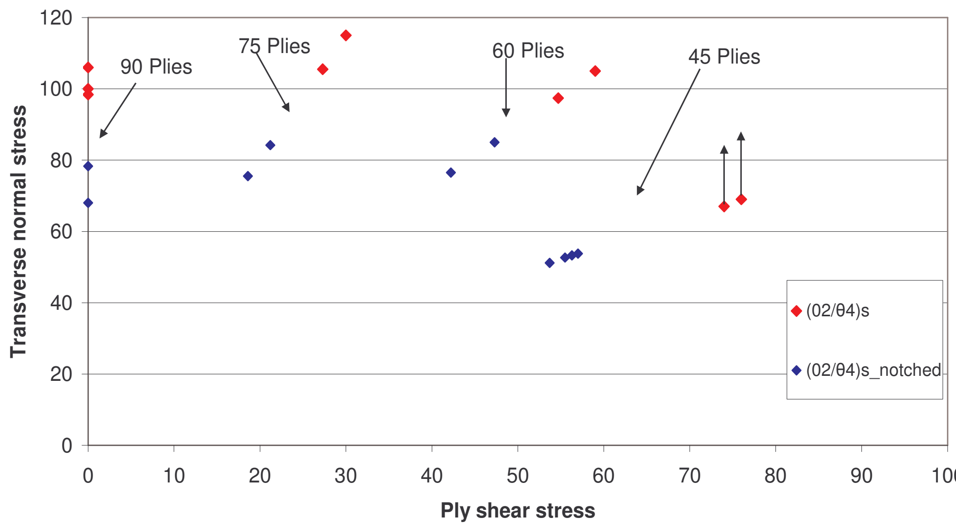

Fig. 8: Plot of transverse normal stress as a function of the corresponding ply shear stress at off-axis ply crack formation in notched and unnotched $(0_2/\theta_4)_s$ CFRP specimen. [Values based on non-linear laminate analysis including thermal stresses]

In previous work on GFRP laminates [6], the transverse normal stress value for crack propagation was similar for a range of (0/θ/0) type laminates, with $\theta = 45^o$, 54^o, 75^o and 90^o. The reason for the slight difference in behaviour for the 45^o off-axis angle is not clear.

Data from other laminates

Test data were also obtained relating to matrix crack development in a number of other lay-ups: $(0/90)_{4s}$, $(0/90/+45/-45)_s$, $(0_2/90_2/+45_2/-45_2)_s$ and $(0_2/+60_2/-60_2)_s$. Unnotched coupons (with polished edges) from each of these lay-ups were tested. The stresses at which cracks formed in the various layers were determined and then laminate theory was used to determine the *in situ* ply stress state at crack formation. The resulting stress state data can be compared with the corresponding data from the unnotched $(0_2/90_4)_s$, $(0_2/60_4)_s$ and $(0_2/45_4)_s$ coupon data in Fig. 9. These data show that there are effects due to ply thickness and laminate lay-up.

Looking first at the 90^o ply data, there are results for plies based on one, two and eight layers of CFRP and the results are as expected – the *in situ* transverse tensile strength increases with decreasing ply thickness (in principle such behaviour could be explained using a fracture mechanics-based model for matrix cracking).

For the 60^o ply data, first cracking of the four-layer 60^o central ply in the $(0_2/+60_2/-60_2)_s$ lay-up occurs at the same stress as first cracking of the eight layer 60^o ply in the $(0_2/60_4)_s$ lay-up. This is as expected when transverse layers in a laminate are "thick"; cracking of the two layer

60° plies in the $(0_2/+60_2/-60_2)_s$ lay-up also occurs at the same stress, possibly because the cracks in the central layer provide initiation sites for cracks in the other off-axis layers.

Finally, for the 45° ply data, we note that cracks form in the four-layer 45° central ply of the $(0_2/90_2/+45_2/-45_2)_s$ lay-up under a combined stress state, which suggests an interaction between transverse tension and shear. These central layer cracks may again promote crack initiation in neighbouring two-layer thick 45° plies.

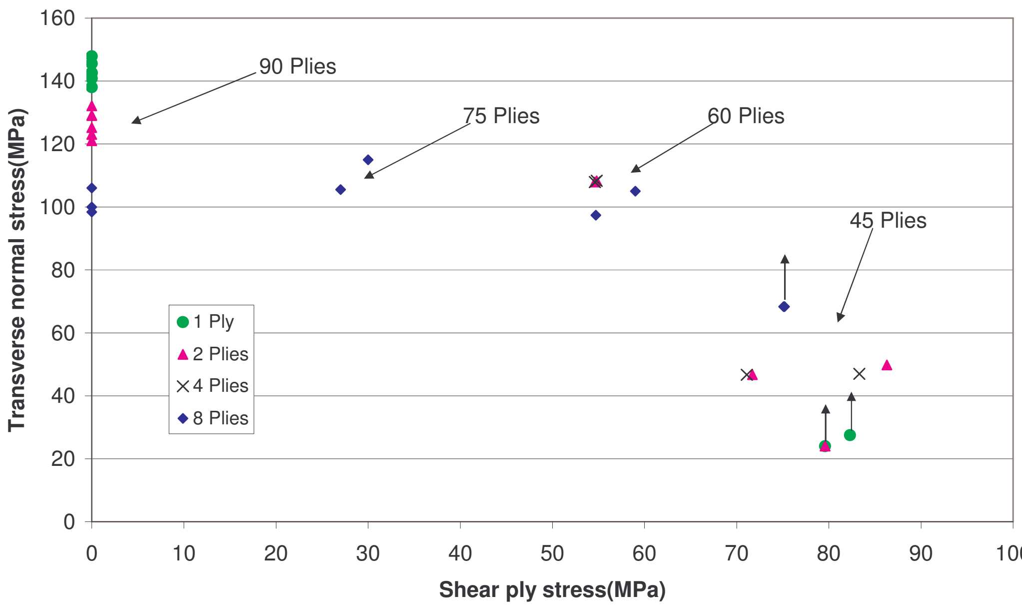

Fig. 9: Plot of transverse normal stress as a function of the corresponding ply shear stress at off-axis ply crack formation in unnotched $(0_2/\theta_4)_s$ CFRP specimens. [Values based on non-linear laminate analysis including thermal stresses]

CONCLUDING REMARKS

Crack initiation and propagation in the off-axis plies of a range of CFRP laminates have been studied. Careful introduction of notches into the central off-axis plies of $(0_2/\theta_4)_s$ laminates has facilitated separation of the initiation and propagation stages of matrix crack formation. The results for $(0_2/\theta_4)_s$ laminates show that for the off-axis angles investigated (i.e. 45°, 60°, 75° or 90^0), the applied strain for crack propagation in notched coupons was lower than for crack initiation in coupons with polished edges. Laminate theory has been used to examine the ply stress states at crack onset. It is shown that the transverse normal stress component appears to be the main controlling parameter, although there appears to be a significant shear interaction for cracking of off-axis plies at 45°. Data from a range of other multi-layer angle-ply laminates show consistent behaviour with the data from the $(0_2/\theta_4)_s$ laminates, when the effects of ply thickness and neighbouring ply interactions are considered.

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