# INTRALAMINAR FATIGUE CRACK INITIATION AND GROWTH IN OFF-AXIS PLIES OF COMPOSITE LAMINATES

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## ABSTRACT

Matrix crack development has been studied in unbalanced $(0_2/\theta_4)_s$ GFRP and CFRP laminates with off-axis angle $\theta$ in the range 45° to 90°, and containing initial defects in the off-axis ply. In all laminates cracks grew at a roughly constant rate across the coupon width and the growth rate increased with increasing cyclic stress. When the crack growth rate data are plotted against the corresponding mode I stress intensity factor, the data are reasonably consistent suggesting that the magnitude of the transverse normal stress is the main parameter controlling the fatigue crack growth rate of matrix cracks in off-axis plies of CFRP and GFRP, for all ply angles.

## 1. INTRODUCTION

Matrix crack initiation and growth in off-axis plies of a composite laminate is a complex problem as a consequence of mixed mode loading. Previous work on unbalanced $(0/\theta/0)$ GFRP and CFRP coupons [1-3] 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. In GFRP [1], 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 [4-7]. With a defect machined into the off-axis plies without damaging the outer 0° plies, crack development was governed by the mode 1 transverse tensile stress component for off-axis ply angles in the range 90° to 45°. CFRP laminates [2] showed some similarity with GFRP in that the stress required for propagation of defects was lower than the stress to initiate failure in laminates with polished edges. Interestingly, there was a significant reduction in the transverse tensile stress component required for crack propagation in the (0/45/0) laminate compared to laminates with higher off-axis angles. It seems possible that this is associated with a greater level of material non-linearity under combined tension/shear loading in this relatively tough CFRP system (*i.e.* compared to the GFRP).

In this paper, the growth of individual cracks in these material systems is described for fatigue loading. To do this, the fatigue behaviour of a range of laminates, with pre-existing defects in the off-axis plies is examined. Data are presented relating to the initiation and propagation of matrix cracks from these defects. The propagation data are presented as Paris type plots, based on a simple theoretical expression for the Mode 1 stress intensity factor associated with intra-laminar matrix crack growth.

## 2. EXPERIMENTAL METHODS

The materials used in this work were $(0/\theta/0)$ GFRP and CFRP laminates. The GFRP system was manufactured in-house using a frame winding technique, while the IM7/8552 carbon fibre/epoxy laminates were made from unidirectional pre-preg, 0.125 mm nominal thickness, autoclave moulded by QinetiQ, Farnborough.

A number of laminate configurations have been tested, both balanced and unbalanced, providing a range of off-axis ply angles and off-axis ply thicknesses. In this paper, the results are restricted to unbalanced laminates of type $(0_2/\theta_4)_s$, where $\theta$ is 45°, 60°, 75° and 90° for the CFRP pre-preg system and 45 °, 54 °, 75 ° and 90 ° for the GFRP frame-wound system. 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 (as shown schematically in Figure 1), without damaging the outer 0° plies.

For the tension-tension fatigue tests, an Instron 1341 servo hydraulic fatigue machine was used, employing a sinusoidal waveform with an R-ratio of 0.1 and a frequency of 10 Hz. Crack length as a function of cycle number has been monitored using X-radiography for the CFRP laminates while for the transparent GFRP laminates, cracks could be monitored simply via transmitted light. Peak stress levels in the range 50 – 75% of the initial (quasi-static) cracking stress have been used for each of the lay-ups tested. For the analysis of the ply stress state of the coupons the thermal strains are required, and the necessary thermo-elastic parameters have been determined using unbalanced 0/90 beams, enabling $\Delta T$ to be calculated [8].

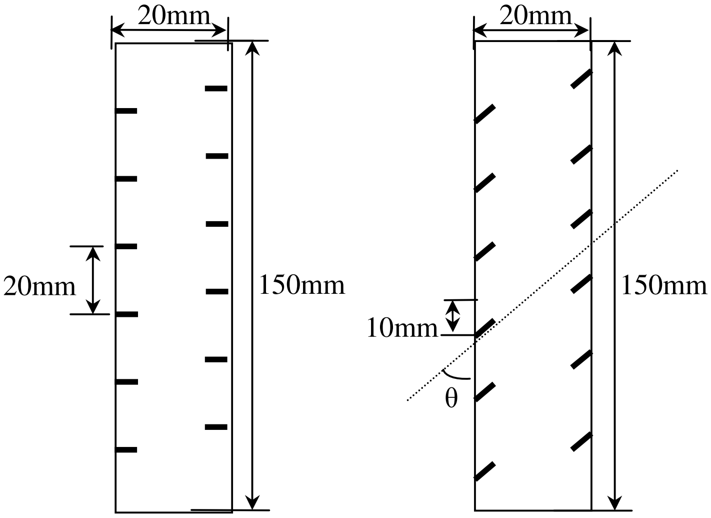


Figure 1. Schematic of (a) $(0_2/90_4)_s$ and (b) $(0_2/45_4)_s$ laminates with 3 mm notches prior to testing

## 3. RESULTS AND DISCUSSION

### 3.1 Observations of crack growth in the laminates under cyclic loading

Figure 2 shows crack development from the notches for the $(0_2/\theta_4)_s$ CFRP laminates where θ = 90°, 75°, 60° and 45°. For the plies at an angle of 90°, 75° and 60°, the cracks initiated from the centre of the drilled-in notch, but in the 45° plies, cracks consistently grew from one side of the notch, forming an obtuse angle with the laminate edge.

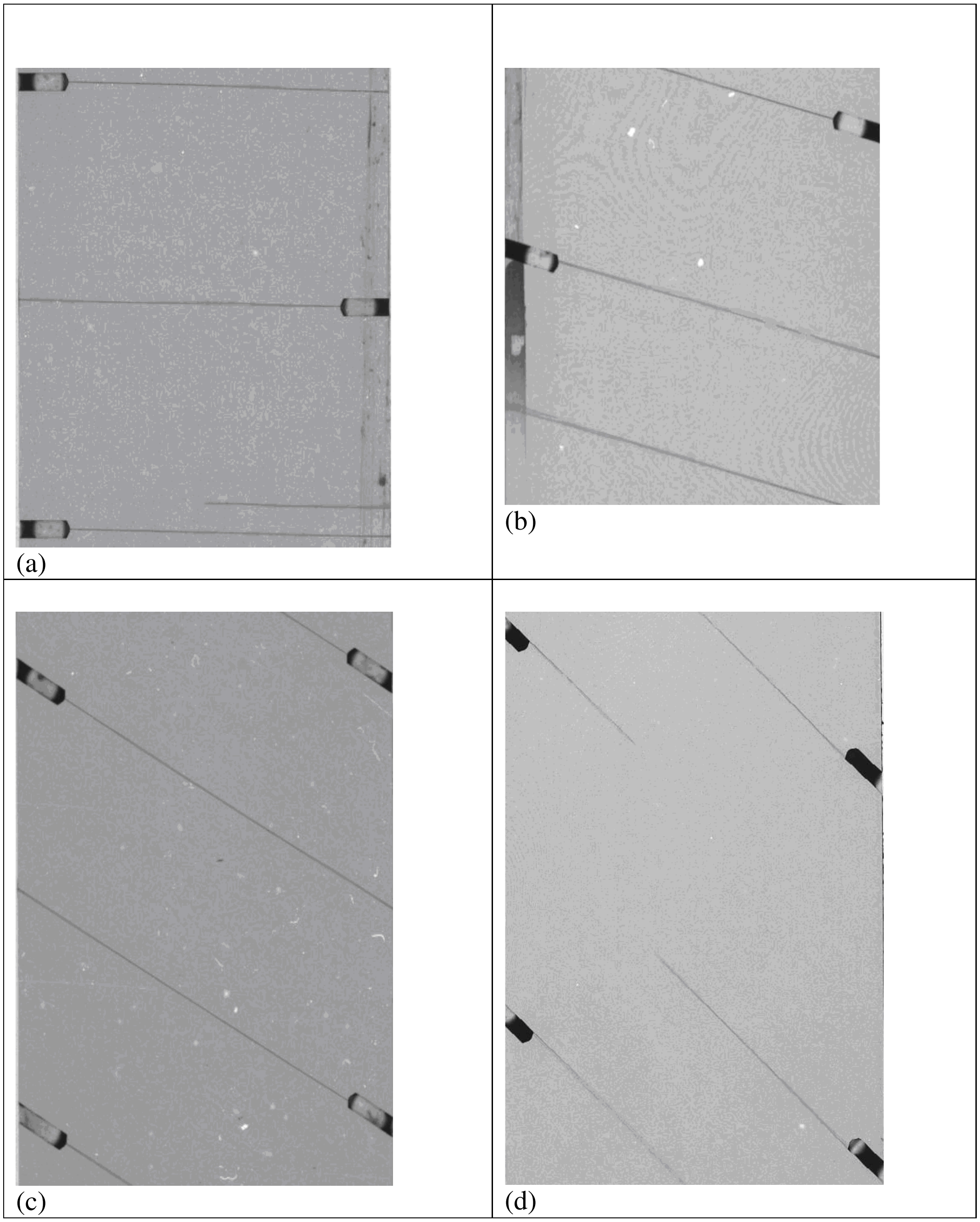

(a)
(b)
(c)
(d)

Figure 2. Crack development in in the off-axis ply of the $(0_2/\theta_4)_s$ laminates, where $\theta$ is (a) $90^{o}$, (b) $75^{o}$, (c) $60^{o}$ and (d) $45^{o}$.

Crack lengths were measured by interrupting the fatigue tests and using the X-ray dye-penetrant technique to monitor crack growth. Figure 3 shows crack length against cycle number for cracks at each angle. Some cracks grew so quickly across the width of the coupons, between x-ray scans, that the crack was not observed having grown part-way across the coupon; in these cases, the cracks are shown as dotted lines in the plots of crack length against number of cycles. For the results shown in Figure 3, the peak cyclic transverse normal stress, $\sigma_t$, for the $\theta$-ply has been calculated, included thermal stresses, and these correspond to (a) 63 MPa, (b) 62.5 MPa, (c) 60.2 MPa and (d) 43.4 MPa. For each off-axis ply angle, a further two stress levels were also tested.

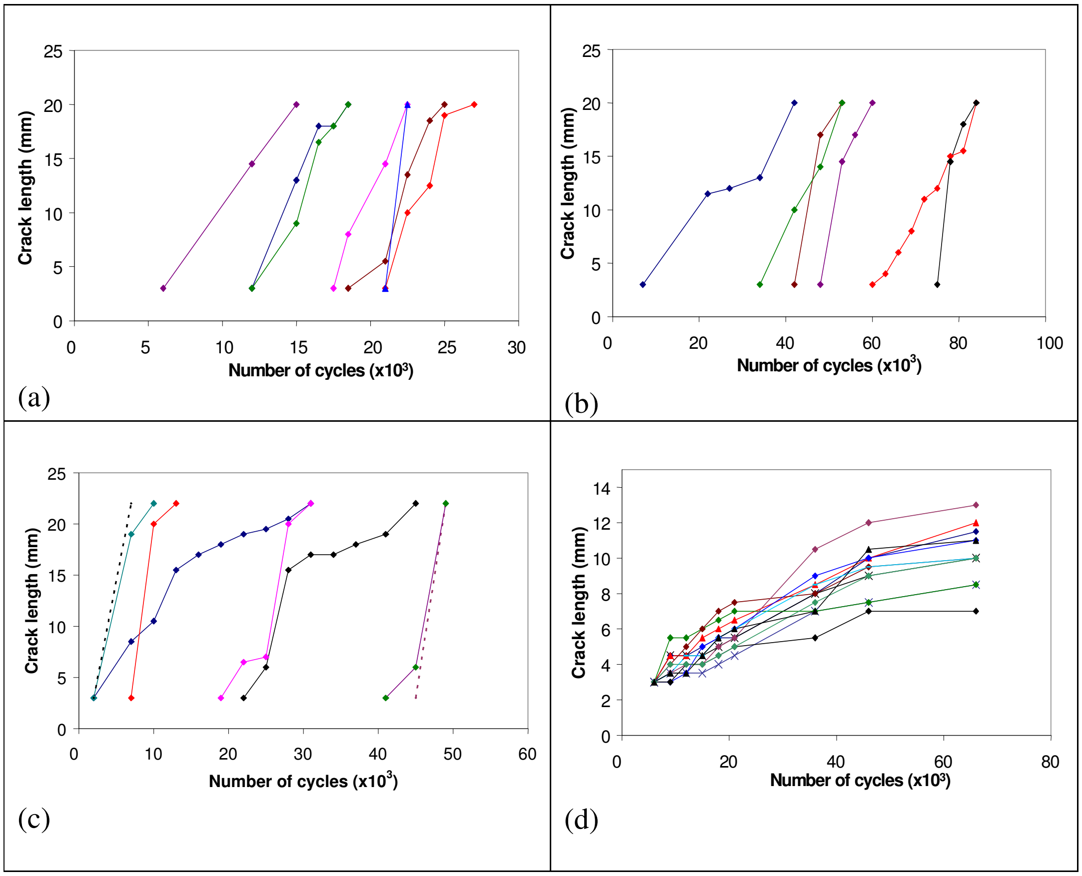
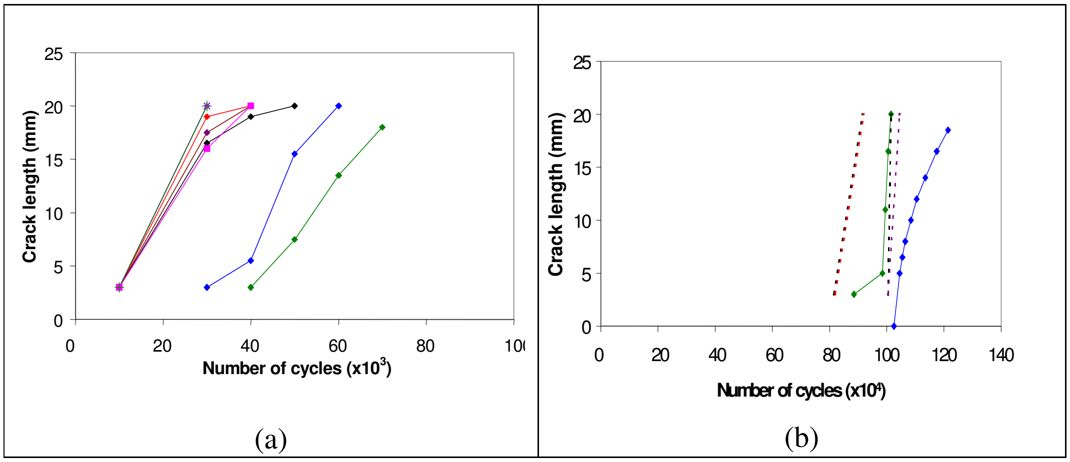


Figure 3. Typical plots of crack length against number of cycles in the off-axis ply of the $(0_2/\theta_4)_s$ CFRP laminates, where $\theta$ is (a) 90°, (b) 75°, (c) 60° and (d) 45°.

It is interesting to note the different crack behaviour of the laminates shown in Figure 3. When $\theta$ = 90°, 75° and 60°, cracks initiate from notches after different numbers of cycles, but then grow at a roughly constant rate across the specimens. The behaviour of the 45° plies is different in that the cracks initiated at the same time from the notches and then propagated at a remarkably uniform rate across the specimen.

Figure 4 shows crack growth data for the $(0_2/\theta_4)_s$ laminate, with $\theta$ = 75°, for peak transverse normal stresses in the fatigue cycle of (a) 57.5 MPa and (b) 55 MPa. The peak transverse normal stress of 57.5 MPa produced an average crack growth rate of about $4 \times 10^{-4}$ mm/cycle and for the peak stress of 55 MPa MPa, the crack growth rate was about $0.7 \times 10^{-4}$ mm/cycle.

The major difference between the GFRP and CFRP results with regard to crack propagation is that crack growth was much more uniform in GFRP [9]. For example, Figure 5 shows the crack length/number of cycles plot for such a crack.



(a) (b)

Figure 4. Fatigue crack growth in the $(0_2/\theta_4)_s$ CFRP laminates, where $\theta = 75^o$, for peak transverse normal stresses (including thermal stresses) of (a) 57.5 MPa, and (b) 55 MPa,

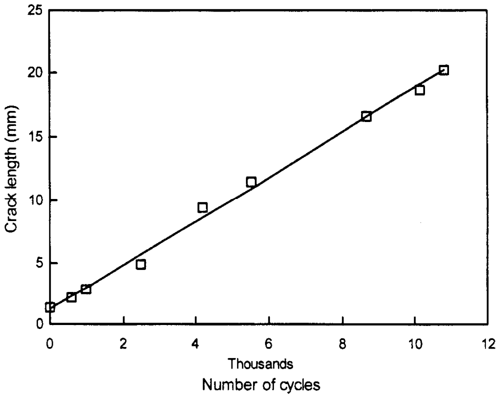


Figure 5. Plot of crack length against number of cycles for a single crack growing in the $75^o$ ply of a (0/75/0) GFRP coupon under fatigue loading.

### 3.2 Analysis of crack growth using the Paris relation

In earlier work [4,10], it was suggested that the fatigue growth of matrix cracks could be described by an expression of the form

$$\frac{da}{dN} = AK_{\max}{}^{m} \qquad (1)$$

where an approximate expression for the stress intensity factor, *K*, is given by

$$K = \sigma_t \sqrt{(2d)} \qquad (2)$$

In equation (2), *2d* is the off-axis ply thickness and $\sigma_t$ is the stress in the ply driving the fatigue crack growth of the matrix crack (this approximate expression for the stress intensity factor is very similar to an expression derived in [11] using finite-element modelling). Identifying $\sigma_t$ as the transverse normal stress, and ignoring any shear interactions, then Figure 6 shows the result of plotting the crack growth rate against the maximum value of the stress intensity factor (where $K$ is defined by Eqtn. 2) for the CFRP off-axis coupons. The value of the mode I fracture toughness, derived from compact tension tests on unidirectional coupons of the same material, has also been added to the plot. There is a good correlation using this expression for $K$ for the 90°, 75° and 60° coupon data. For the 45° data, although the slope of the d$a$/d$N$ vs $K_{max}$ plot is approximately the same, the data are shifted to lower $K_{max}$ values

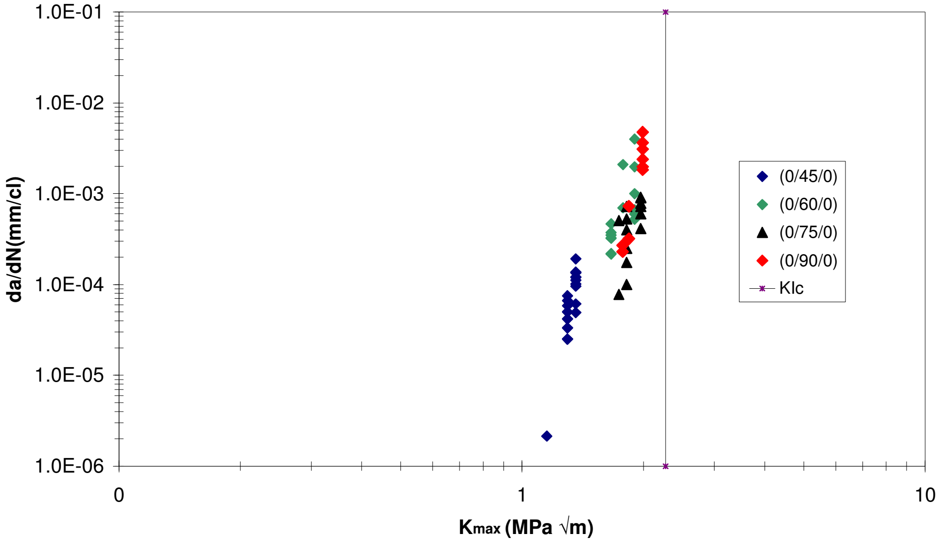


Figure 6. Plot of crack growth rate, d$a$/d$N$, against the maximum value of the stress intensity factor, $K_{max}$, for the CFRP coupon data.

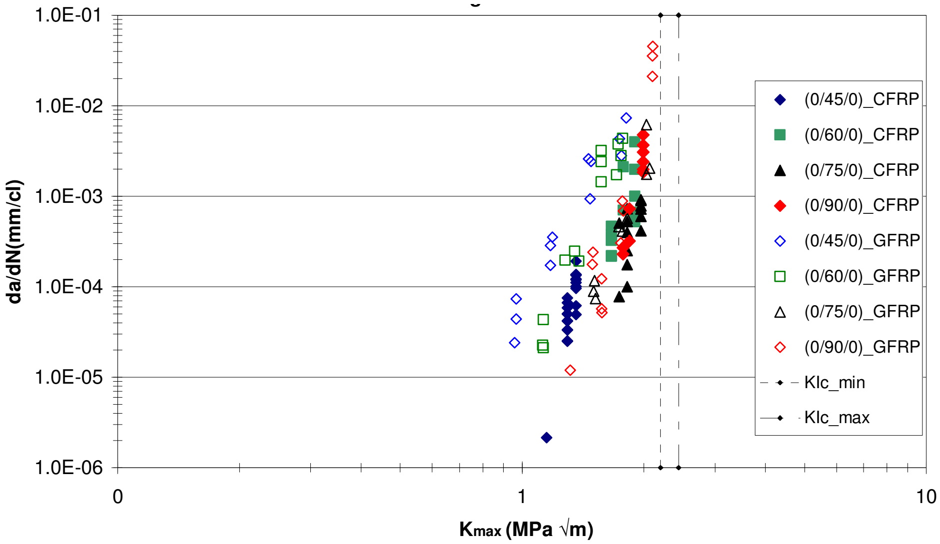


Figure 7. Plot of crack growth rate, d$a$/d$N$, against the maximum value of the stress intensity factor, $K_{max}$, for both the CFRP and GFRP coupon data.

Figure 7 shows the combined data from the CFRP and GFRP data plotted in the same way. The agreement between the CFRP and GFRP data suggests that the ply stress driving matrix crack growth in fatigue is the transverse normal stress within the ply.

## 4. CONCLUDING REMARKS

The fatigue crack growth rates of individual matrix cracks have been monitored under cyclic loading in CFRP and GFRP coupons for a range of off-axis angles in ($0/\theta/0$) laminates. For the CFRP laminates, the fatigue crack behaviour of the cracks for the 90°, 75° and 60° plies differed qualitatively from the behaviour of the 45° plies. For the former angles, (i) the fatigue cracks initiated from the centre of the machined notches and (ii) the cracks did not initiate after the same number of cycles but over a range of many hundreds, or thousands, of cycles. By contrast, all the 45° cracks initiated on the obtuse side of the machined notches, and all the cracks began to grow at the same time, from the beginning of the test. For the GFRP specimens, the cracks tended to grow at a more constant rate than the CFRP cracks, for all angles. The propagation behaviour of both the CFRP and GFRP cracks has been quantified using a Paris-type relation with an approximate expression for the stress intensity factor. Although the data is reasonably well represented by this approach, it is not possible at present to draw any conclusions regarding the relative importance of peak stress (as opposed to stress range) or, indeed, the effect of mode mixity.

## ACKNOWLEDGEMENTS

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