FATIGUE OF NOTCHED (0,±45) CFRP WITH WOVEN AND NON-WOVEN ±45° LAYERS

S. M. Bishop* and J. Morton**

**Materials and Structures Department, Royal Aircraft Establishment, Farnborough, Hants, England*
***Aeronautics Department, Imperial College of Science and Technology, Price Consort Road, London, England*

ABSTRACT

An investigation was carried out on the fatigue performance of notched carbon fibre reinforced plastic laminates with (0,±45) lay-ups. The first laminates were made from unidirectional laminae while the second had woven fabric in place of each pair of ±45° plies. Damage at the notches was assessed using ultrasonic and microscopic techniques.

In zero-tension fatigue, the tensile strengths increased with increasing numbers of cycles and corresponded with an increase in stresss relieving fracture mechanisms at the notch tip; the increase was less for woven ±45° layers. In zero-compression fatigue the decrease in compressive strength with increasing numbers of cycles was greater for non-woven laminates. Failures occurred in non-woven specimens where no failures were observed in specimens with woven ±45° layers.

It was concluded that the fatigue performance of notched (0,±45°) CFRP with woven fabric ±45° layers is not significantly different to that of a similar non-woven laminate.

KEYWORDS

Fibre composites; laminates; fatigue damage; tensile and compressive loading; woven fabric; notch sensitivity; residual strength.

INTRODUCTION

The high specific strength and stiffness of carbon fibre reinforced epoxy resin laminates have led to substantial projected applications of the material in the primary structure of both civil and military aircraft (1-4). As with many materials, properties such as impact damage tolerance, notch sensitivity or fatigue damage tolerance impose significant limitations on the weight savings that can be obtained with composite materials. A lack of test data and service experience necessarily gives rise to over-conservative design and inefficient use of the material (5).

Early studies of the impact damage tolerance of carbon fibre composites (6) indicated that this could be a major limitation on design stress levels. Later investigations (7,8) have shown that appropriate selection of the laminate stacking sequence greatly increases the impact damage tolerance. Impact damage tolerance in composites can also depend upon the size and geometry of the component (9,10).

A recent study (11) of fatigue in conventional non-woven composites provides a summary of previous published results and much useful information for the designer. Broadly, the problem of fatigue in carbon fibre composites is not so severe as in light alloy. In most cases ensuring that the nominal strain does not exceed 0.4% seems sufficient to eliminate fatigue failure in plain specimens.

The presence of stress raisers such as notches or impact damage will, however, affect the fatigue performance. Fatigue studies on carbon fibre composite coupons containing holes have been performed by Sturgeon *et al.*(12). The effect of subsequent fatigue on impact damaged panels has been described by Aoki and Stellbrink (7) and Cantwell (13).

Woven carbon fibre fabric is an attractive material for use in aircraft structures because it offers considerable savings in laminate fabrication and superior draping characteristics which aid the moulding of curved panels. However it is not desirable to use woven material to carry primary loads because distortion of the fibres results in reductions in strength and stiffness (14). In recent work (14,15) it was found that mixed laminates with non-woven load bearing layers (0° layers) and woven ±45° layers had very similar static properties to conventional (0,±45) laminates where all the layers were non-woven. However damage in the form of shear cracking and delamination was contained by the weave with the result that significant improvements in the residual static tensile and compressive performance were obtained when such damage was present.

The present paper considers the important case of fatigue damage growth from a sharp notch in notch sensitive (0,±45) carbon fibre composites. Two similar materials were tested; the difference lying in the replacement of ±45° plies by suitably oriented woven fabric. Fatigue damage growth is estimated using ultrasonic C-scan and the damage mechanisms determined using microscopic sectioning. As no fatigue failures occurred residual tensile strengths were measured after various numbers of fatigue cycles. It was thought that the introduction of woven material in the ±45° layers might also affect the micro mechanisms of fatigue damage and, as a result, the fatigue performance in general and the residual strength in particular.

EXPERIMENTAL PROGRAMME

Specimen preparation

Panels were made from preimpregnated unidirectional warp sheet and five shaft satin woven cloth. The pre-preg consisted of high tensile strength carbon fibres in epoxy resin. The panels were fabricated with the lay-up:

$$[\ 0/+45/-45/0_2/-45/+45/0\ ]_s$$

That is, a sixteen ply (0,±45) composite. The first laminates were made up of non-woven unidirectional laminae. The second laminates were produced with each pair of ±45° plies replaced by a layer of woven fabric arranged with the fibres at ±45°; this consisted of mixed woven and unidirectional layers. Both types of laminate had a nominal fibre volume fraction of approximately 60% but the introduction of the woven fabric in the mixed laminate caused a slight decrease in fibre volume fraction indicated by the panel thicknesses which were 2.07mm and 2.25mm for the non-woven and mixed woven laminates respectively.

Preliminary zero-tension fatigue tests and zero-compression fatigue tests were carried out on newly moulded laminates which were essentially 'dry' whereas the subsequent zero-tension fatigue tests were carried out on laminates which had been stored at a relative humidity of 65% and had a moisture content of approximately 1% by weight.

Coupons measuring 50mm x 250mm x thickness were cut from the moulded panels. A 10mm slot was cut in the centre of each coupon. This was performed by first drilling a 1mm starter hole and opening up the slot with a jeweller's saw. The resulting sharp notch was about 0.22mm (9thou) wide with a tip radius of about 0.1mm. Aluminium end tabs (50mm x 50mm) were then cemented to the coupons.

Mechanical testing

Before loading specimens were ultrasonically C-scanned to determine the degree of damage introduced in the notching procedure and to provide a datum for the assessment of subsequent fatigue damage. Six specimens from each laminate type were loaded to fatigue in tension and the resulting strengths used to select the load range in the subsequent fatigue programme.

Initially zero-tension fatigue tests were carried out with a maximum load corresponding to 80% of that which produced failure in the monotonic tests and a minimum load of 50N. The fatigue test frequency was 20Hz. Since no fatigue failure occurred before 2 x 10^6 cycles with this load the maximum load was then increased to 90% of the monotonic failure load. Once again fatigue failure did not occur within 2 x 10^6. The programme then consisted of subjecting the notched specimens to varying numbers of fatigue cycles, at the higher load range. The fatigue damage was determined using the C-scan and microscopic examination of specimen sections taken in the region of the notch tip.

The C-scans integrate the effects of delamination damage through the coupon thickness so that it is not possible to determine the exact location of the damage. Microscopic sectioning was performed to overcome this limitation and the examine other forms of fatigue damage which are not readily detected using the ultrasonic technique. The specimens were then loaded in tension until failure and the residual notched strengths determined.

The investigation continued with a study of the performance of the laminates under compressive loading with notched specimens supported in an anti-buckling jig. Fatigue tests were performed with a minimum load corresponding to 80% of that producing compressive failure in the monotonic test. The non-woven laminate failed in fatigue after about 10^5 cycles. No fatigue failures were observed at this load level in coupons with woven ±45° layers. The damage development was assessed as described above and the residual compressive strength determined.

EXPERIMENTAL OBSERVATIONS

Notched tensile tests specimens

The mean failure loads were similar for both (0°±45°) laminates with values of 29.2kN (±0.8kN) and 30.4kN (±1.4kN) for the non-woven and mixed materials respectively. The failure modes were, however, quite different. Fig. 1 shows the final fracture paths in typical coupons.

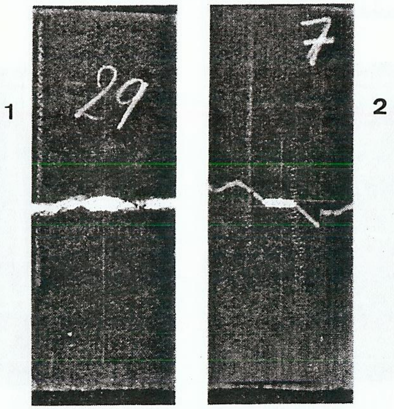

Fig. 1. Typical fractures in notched tensile tests for (0,±45) CFRP laminates with 1) woven ±45° layers and 2) non-woven ±45° layers.

In the non-woven material fracture of the 0° plies follows direction of ±45° to the loading axis; the direction of propagation being defined by the adjacent 45° ply. The fracture surface does not lie in the plane of the initial notch. The mixed material, however, fractures approximately in the plane of the notch and perpendicular to the loading axis. The woven lamina does not allow the failure path in the 0° fibres to depart, substantially, from the crack plane.

Fatigue behaviour

There were no fatigue failures when the coupons were loaded in tension - even when peak loads were as great as 90% of the static notched failure loads. The ultrasonic C-scans in Fig. 2(a,b,c) however, show a steady build up of fatigue damage as the number of fatigue cycles increases. This damage was initiated at the notch tip and extended parallel to the 0° fibres and between the 45° directions. There was no extensive damage growth in the plane of the notch. In preliminary tests, C-scans carried out on newly moulded laminates after high numbers of fatigue cycles showed that the fatigue damage zone in the non-woven laminates was much more extensive than that laminate containing woven layers (see Fig. 2a). However the results presented in Fig. 2(b,c) obtained subsequently on laminates which had been stored at a relative humidity of 65% before testing showed similar areas of delamination for woven and non-woven ±45° layers. Differences in the extent of delamination in notched specimens subjected to various moist environments have been recorded by Bishop (16). One explanation of this is that moisture reduces the residual internal stresses by a process of swelling, in turn the interlaminar stresses at the notch tip are reduced and the extent of delamination decreased.

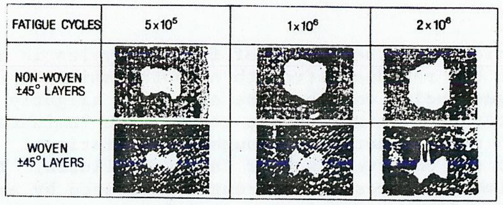

Fig. 2(a)
Fatigue damage at notches in (0,±45) dry CFRP laminates with non-woven or woven ±45° layers.

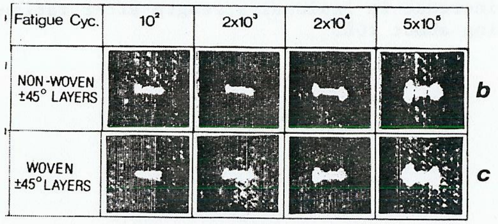

Fig. 2(b,c)
C-scans of wet (0,-45) CFRP laminates with b) non-woven ±45° layers and c) woven ±45° layers after various numbers of fatigue cycles.

Microscopic examination in the subsequent tests showed thatin the non-woven material delamination occurred between the +45° and -45° plies; that is at the greatest change of ply orientation. On a macroscopic scale, these planes do not exist in the laminate with woven ±45° layers. However the coarse nature of the weave does result in local areas of high orientation mismatch. Perhaps the most dramatic result in the microscopic examination of the fatigued specimens was the traverse or matrix cracks observed in both the ±45° and woven plies after as few as 2,000 fatigue cycles - see Figs. 3 and 4. These cracks are not picked up with the C-scan inspection. After traversing the ply they are then initiators of delamination at the interface with the load-bearing 0° plies.

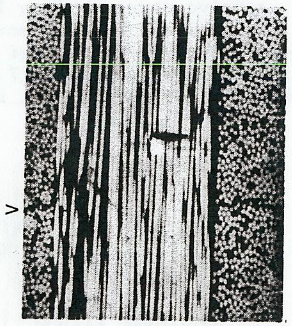

Fig. 3. Matrix cracking in a non-woven laminate after 20,000 cycles.

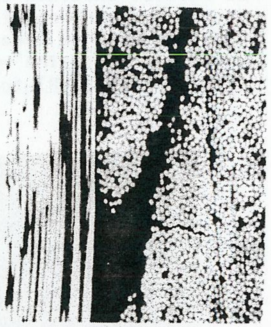

Fig. 4. Matrix cracking in a mixed laminate after 2,000 cycles. The cracking is initiated at a fibre cross-over in the weave.

Residual strength

The residual strength variation with the number of fatigue cycles is shown in Fig. 5. It can be seen that the residual strength of both laminates increases with increased tensile fatigue cycles and that the effect is slightly greater in the non-woven. Effectively the fatigue damage renders the laminates less sensitive to sharp defects; the laminates are toughened by fatigue! This behaviour is consistent with the observed lack of fatigue failures. In the most severely fatigued specimens the residual strength increased by as much as 44%. In the fatigue of carbon fibre composites containing a circular notch Dorey (17) also records an increase in residual strength after fatigue; the quoted level of increase being about 10%.

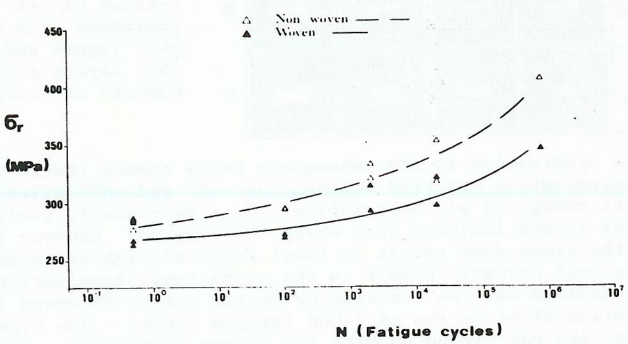

Fig. 5. Residual tensile strength of notched (0,±45) CFRP after varying numbers of tensile fatigue cycles.

Compressive loading

The results indicate that the notched compressive strength is a little greater than the notched tensile strength. There is, however, rather more scatter in the results as usually observed in the compression testing of composite materials (18). The mean failure loads in compression were 32.7 kN (±2.6kN) and 34.2kN (±1.3kN) for the non-woven and mixed woven laminates respectively.

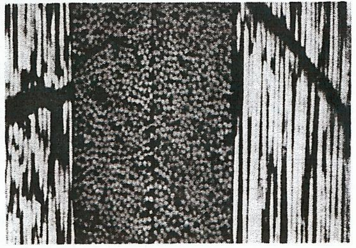

Fig.6. Fibre fractures in 0° plies in a non-woven (0,±45) CFRP laminate after 20,000 cycles of compressive fatigue loading.

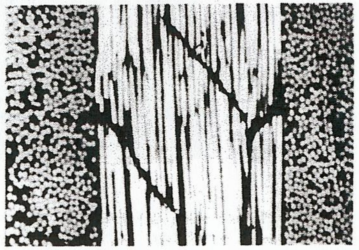

Fig.7. Fibre fractures in 0° plies in a (0,±45) CFRP laminate with woven ±45° layers after 2,000 cycles of compressive fatigue loading.

Fatigue damage in compression was characterised by failure of the load-bearing 0° fibres after relatively few cycles. These fibre fractures appear to be initiated at the outer 0° plies, in a brush-like manner, perpendicular to the loading direction. Adjacent ±45° plies suffer matrix cracking and inner 0° plies are sheared at about 45° to the loading direction. Such damage is illustrated in Figs. 6 & 7. The mixed laminates show local delamination in the woven layers, initiated at resin-rich areas associated with fibre cross-over, after 20,000 fatigue cycles - see Fig. 8. Delamination damage was not apparent in the non-woven laminate until near the end of the specimen life when damage is extensive - see Fig. 9.

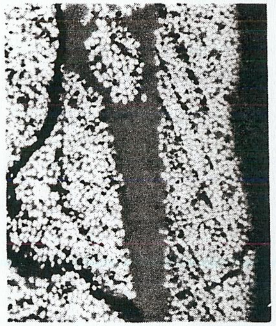

Fig. 8. Delamination and matrix cracking in a (0,±45) CFRP laminate with woven ±45° layers after 20,000 cycles of compressive fatigue loading.

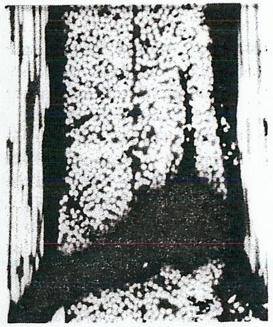

Fig. 9. Extensive damage in a non-woven CFRP laminate after 10^5 compressive fatigue cycles.

The variation of the residual compressive strength with number of fatigue cycles is shown in Fig. 10. Initially the non-woven laminate showed a slightly greater compressive strength than that of the mixed laminate with woven ±45° layers. However, after more than about 5 x 10^4 cycles, fatigue failures often occurred in the non-woven laminate where none occured in the mixed woven laminate and the mixed laminate had the superior residual compressive strength.

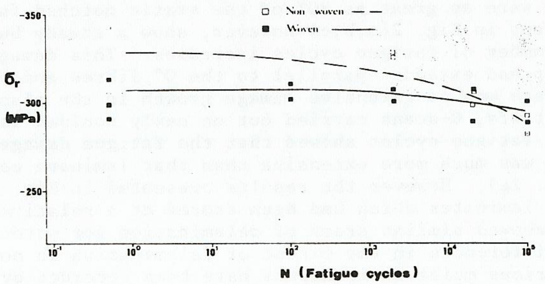

Fig. 10. Variation of residual compressive strength of notched (0,±(45) CFRP with a number of compressive fatigue cycles.

DISCUSSION

Tensile fatigue performance

The fatigue damage, under tensile loading, occurs first in the form of shear cracking in the ±45° plies in both non-woven and mixed woven laminates. This cracking propagates through the ply until it reaches a change in fibre orientation at which a change in crack direction occurs. In both laminates delamination occurs around the notch. In the non-woven laminates the fibres, themselves, in the ±45° layers act as stress raisers for shear cracking. In the mixed laminates the weave pattern offers further stress raisers in resin-rich areas for resin cracking - see Fig. 4.

Delamination tends to uncouple the load carrying 0° fibres from the ±45° plies. The composite in the region of the notch is then, locally less notch sensitive (15). The residual strength is then expected to be greater after fatigue. Results from the non-woven laminate indicate an increase in residual strength of about 44% after 10^6 cycles. The increase in residual strength of the mixed laminate is about 30% after the same number of cycles. The difference is off-set to some extent by the effective lower volume fraction of fibres due to the woven fabric layers. However, the slower rate of improvement in the mixed laminate may also be due in part to the constraint imposed by the weave on rotational deformation of the ±45° layers, which will result in less interlaminar shear stress between the 0° and 45° layers and thus less delamination.

Fatigue of the notched laminates changed the fracture mode in the non-woven laminate. Fig. 11 shows that the fracture becomes similar to that in the mixed laminate in that delamination occurs between load bearing 0° layers and 45° layers removing the stress concentration effects of the 0° layers of 45° shear cracking (15).

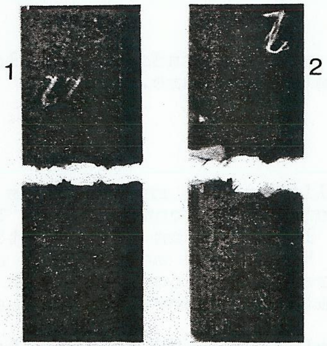

Fig. 11. Typical fractures in residual strength tests for (0,±45) CFRP laminates with 1) woven ±45° layers and 2) non-woven ±45° layers.

The fatigue damage induced under zero-compression loading was markedly different from that in zero-tension fatigue. Fracture of the 0° fibres was extensive within 2,000 cycles when the peak compression load was 80% of the compression failure load. The observation that the cracks in the 0° layers are extensive before complete matrix cracking occurs suggests that the mechanism of fatigue damage under compression loading consists of first developing fibre failures in the 0°, load bearing plies. This is probably due to fibre buckling - there is limited evidence in Fig. 7 suggesting a transfer length of about 40 fibre diameters. The ±45° plies and the undamaged material offer some support against macro buckling. Matrix fatigue cracking then occurs in the same way as in tension but with the fibre fractures providing further stress raisers which determine the location of the matrix cracks. After large numbers of fatigue cycles delamination damage becomes extensive. The residual compressive strengths are a substantial fraction of the initial notched compressive strengths until delamination causes a significant decrease in the laminate flexural stiffness. The lack of extensive planes of delamination in the mixed laminate with woven ±45° layers may account for the superior fatigue and residual notched strength performance after a large number of fatigue cycles. At the moment the extent of the fibre cracking is still to be determined. Also the effect of the cracks in the 0° layers is expected to be more apparent if the residual notched tensile strength is meaured. It may be that the most significant fatigue damage occurs under the compressive part of any fatigue history but the following tensile cycles could lead to overall failure. Conversely, delamination produced in tension fatigue could lead to buckling failure in compression. Since delamination growth is less with woven ±45° layers, buckling failure is less likely.

CONCLUSIONS

Fatigue of notched (0,±45) CFRP does not require additional design factors under a tensile load regime. Both the conventional laminates made from unidirectional non-woven material and those containing woven fabric in place of ±45° plies become less notch sensitive as a result of tensile fatigue. The effect is more apparent in the non-woven laminate where the growth of delamination during fatigue is greater.

Under compressive loading, fatigue leads to fibre fracture in the 0° plies and fatigue failure in non-woven specimens after 10^5 cycles. The residual notched compressive strengths were greater in the laminate with woven ±45° layers after about 5×10^4 cycles.

The replacement of the ±45° plies with a suitably oriented woven fabric offers manufacturing advantages. The performance of such laminates is not significantly different to that of a similar non-woven laminate and, in the case of compressive fatigue, woven ±45° layers may offer superior properties.

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