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FATIGUE DAMAGE IN ADVANCED POLYMER MATRIX COMPOSITES

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ABSTRACT

Advanced polymer matrix composites such as carbon fibre reinforced composites (CFRP) offer many advantages over more traditional materials such as metals. However, due to a lack of understanding of the materials behaviour, especially under in-service conditions such as fatigue, these materials are not being used to their full capability. This work investigates the fatigue response and damage mechanisms of a carbon fibre reinforced polymer with a quasi-isotropic lay-up, $[(\pm 45^\circ, 90^\circ, 0^\circ)_2]_s$. Fatigue tests have been carried out at R ratios of +0.1 (tensile) and +10 (compressive) using thermography to identify damage. Results show that delamination is the major damage mechanism and that the main delamination occurs at a different interface for the different loading conditions. The interfaces highlighted in the fatigue tests are being investigated using a modified mixed-mode bend test.

KEYWORDS

Composite, Fatigue, Delamination.

INTRODUCTION

Advances have been made in the design, manufacture and application of composite materials. Much of this progress has been made in the field of Fibre-Reinforced-Plastics (FRP). FRP often have greater strength to weight and stiffness to weight ratios than traditional materials such as metals, which makes them ideal for use in many applications especially in the aerospace sector. However, there remain many unanswered questions regarding the behaviour of these materials especially under in-service conditions such as fatigue. There is an increasingly urgent need to gain an better understanding of how FRPs behave under fatigue load cases. Until recently the strains used in the design of aircraft structures have been so low (approximately 0.4%, but with a safety factor of 50% the expected peak is around 0.27%) that fatigue has not been considered an issue(1) and static properties have been used in design. This is now changing as designers want to use composite materials to their full capability and therefore design strains are increasing to such a level that fatigue is now a real problem, particularly under compressive loading. To fully understand the fatigue of a material it is necessary to gain an understanding of how damage initiates and accumulates, and how this damage will affect the materials properties.

The complexity of composite microstructures means that the wide range of fatigue damage mechanisms are often diffuse throughout the laminate. Another major factor that restricts the understanding of damage initiation during fatigue testing of laminates is the scatter found in fatigue lives. This impedes the effectiveness of carrying out interrupted tests with destructive evaluation, since at a given number of cycles it is impossible to say what percentage of life has passed. There is the possibility of using thermography to overcome this problem and this is investigated here. The work carried out here identifies delaminations as the major damage mechanism. These need further investigation and hence work has begun to investigate the relationship between mixed-mode loading and delamination growth rates using a mixed-mode bending rig.

EXPERIMENTAL

The material used in the program was a composite system containing high strength continuous 919HF carbon fibres in HTA epoxy resin matrix. Cytec Fiberite supplied this in zero-bleed pre-preg form with a nominal fibre content of 55-wt%.

A single stacking sequence was used for all static and fatigue tests. This was a 16-ply laminate with the lay-up $[(\pm 45^\circ, 90^\circ, 0^\circ)_2]_s$. This lay-up is a quasi-isotropic lay-up and it gives approximately uniform properties in the plane of the laminate. The composite panels were laid up by hand. The composites were then autoclaved following the manufacture's specifications. The cured plates were then C-scanned to check for any defects. Any faulty areas were avoided when preparing specimens. The panels were cut into specimens with final dimensions 250 mm or 200 mm long by 20 mm wide, unwaisted. This left a gauge length of either 150 mm or 100 mm for tensile and compressive fatigue tests respectively. The final thickness of the specimens was nominally 2 mm without end tabs and 6 mm with end tabs.

The MMB specimens have a balanced lay-up with a 0/45° interface at the centre. A PTFE film was used as a starter crack and edge inserts are also used to try and prevent fibre bridging. The specimens were then prepared in the same way as the fatigue specimens.

Static tests were conducted using a 100 kN screw machine at a loading rate of 1 to 2 mm per minute to bring failure within 90 seconds. Fatigue tests have been completed using an Instron servo hydraulic machine. Tests have been completed at R ratios 0.1 and 10. These represent a tension-tension and a compression-compression loading case respectively. All fatigue tests have been completed at a rate of 10 Hz. As has already been stated, thermography was used in the fatigue tests at $R = 0.1$ to investigate damage initiation and growth.

To investigate delaminations in more detail mixed-mode bend tests have been carried out using the modified MMB rig designed by Crews *et al*(2). A schematic diagram is shown in figure 1. Currently only static results are available.

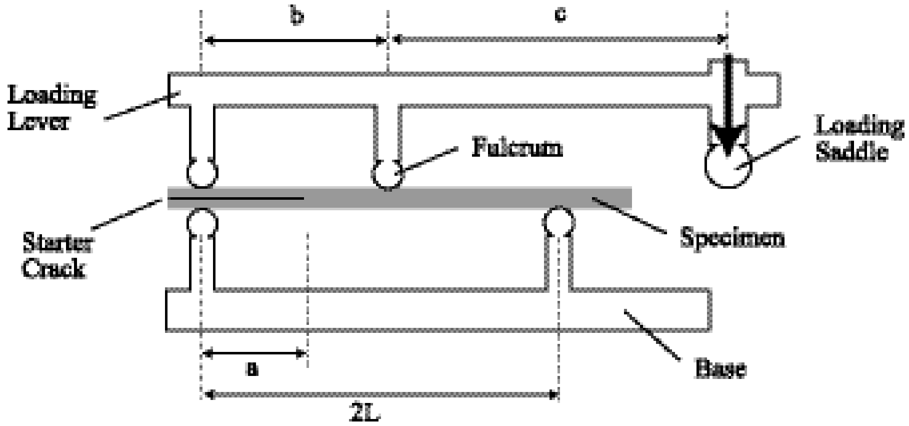

Figure 1. A Schematic of the Modified Mixed-Mode Bend Test Apparatus.

RESULTS AND DISCUSSION

Static Results

Two series of 5 tests were performed on 919HF/HTA to obtain values for the materials tensile and compressive strengths. The results are shown in Table 1. It can be seen that there is relatively little scatter in the results. The standard deviation of the mean tensile strength is 0.04 and of the compressive 0.03, which are approximately 5% of the mean value in both cases. The compressive strength is approximately 20% weaker than the tensile strength but that is to be expected.

TABLE 1. STATIC TEST RESULTS FOR 919HF/HTA

Test	Tensile Failure Stress (GPa)	Compressive Failure Stress (GPa)
1	0.760	0.545
2	0.762	0.608
3	0.710	0.592
4	0.750	0.620
5	0.679	0.587
Average (mean)	0.732	0.590
Standard Deviation (%mean)	5.46	5.08

Fatigue Results

Tensile fatigue tests

A series of tests were carried out at 90% and 80% of the laminates mean tensile strength and all were taken to failure. The fatigue lives for each test are given in Table 2.

The scatter in the results of 90% is significant; the standard deviation of the mean is 2682, which is 68% of the mean. It is not unusual to find this amount of scatter in fatigue results at higher stress levels due to the two elements which contribute to the scatter, i.e. the tensile scatter and the fatigue scatter. The scatter in the results at 80% is significantly lower than that for the tests conducted with a peak stress at 90%. The standard deviation is 31,472, which is 44% of the mean life. This reduction in the fatigue scatter agrees with the hypothesis of Barnard et al.(3) that as the peak stress is reduced the amount of static scatter as a proportion of the applied stress decreases and therefore scatter in the fatigue results will also decrease.

Alongside recording the cycles to failure for each specimen tested, a series of thermographic images were also taken. The change in temperature picked up by the camera has two causes 1) hysteresis heating and 2) local heating caused by friction induced by damage in the laminate such as crack faces shearing over each other. Figure 2 shows a typical thermographic image taken during a test and a schematic of the specimens "hot spots", where there is assumed to be the highest occurrence of damage.

TABLE 2.
FATIGUE LIVES AT, (A) 90% AND (B) 80% OF THE TENSILE FAILURE STRENGTH.

Test	Cycles to Failure
1	6600
2	1900
3	600
4	5700
5	5800
Average (mean)	3920

(A)

Test	Cycles to Failure
1	113,820
2	43,000
3	96,800
4	60,500
5	47,000
Average (mean)	72,224

(B)

All of the laminates in this series of tests showed varying degrees of delamination. These delaminations were visible with the naked eye at the outer 0/90° interface and were present from a very early stage of the laminates life. The images showed the progressive initiation and propagation of delaminations. However, the outer 0/90° interface had completely delaminated along the length and breadth of the specimen by approximately 50% of laminate life in all cases. The image in figure 2 is taken after the outer layer has fully delaminated and formed a sub-laminate. However, hot spots are still visible. This suggests that as there is a continued increase in temperature in the hot spot regions and that the early initiation of delamination in the outer 0/90° interface has induced some further damage mechanisms in this area such as delamination of the inner 0/90° interface or fibre fracture. This must be the case, as the laminates failed through the area of the hottest point in all cases and the delaminations alone were not enough to cause final failure or it would have occurred when complete delamination occurred. It is important to note here that all of the tests in the two series of experiments were conducted at an R ratio of +0.1, i.e. tensile-tensile fatigue. In this case the delaminations will not cause the final failure of the laminate. However, once fatigue moves into the compressive regime, the delaminations buckle and this may cause final failure of the laminate.

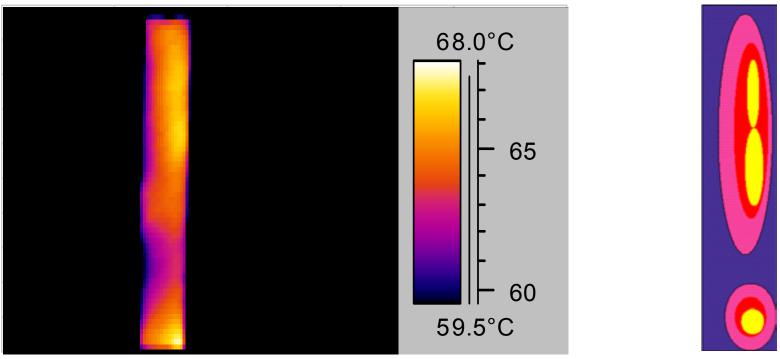

Figure 2. A Typical Thermographic Image Taken During a Fatigue Test and a Schematic of the Composite "Hot Spots" During Testing.

Compressive Fatigue Tests.

A series of compressive fatigue results have been completed at an R ratio of +10 at 10 Hz. The results are given in Table 3. The scatter in both sets of compression data is approximately 40% of the mean. This is a large number and as opposed to the tensile case the scatter had not decreased with decreasing peak load. It should also be noted that the peak loads are considerably lower in compression to produce comparable fatigue lives. This shows that compression-compression fatigue is much more damaging than tension-tension fatigue.

TABLE 3.
FATIGUE LIVES AT, (A) 70% AND (B) 60% OF THE COMPRESSIVE FAILURE STRENGTH.

Test	Cycles to Failure
1	4711
2	7064
3	12045
4	3658
5	6274
Average (mean)	6750

(A)

Test	Cycles to Failure
1	31,255
2	63,978
3	71,503
4	93,855
5	41,261
Average (mean)	60,370

(B)

Unfortuanatly, thermography could not be used during compression-compression fatigue tests due to the presence of antibuckling guides. However, post failure examination showed that the primary delamination occurred on the inner 0/+45° interface. This is different to the primary delamination interface in the tension tests and led to further investigations.

Mixed-Mode Bending (MMB) Tests.

To investigate the different delamination interfaces being highlighted in the fatigue tests a series of work has begun to investigate delamination growth rates using MMB tests. This work is at a very early stage. Initial tests have begun to investigate the 0/+45° interface at a mixed-mode ratio of 50% M_I and 50% M_{II}. A typical graph is shown in figure 3. This graph shows the load–displacement response to be almost linear up to a maximum load where it is assumed that the delamination begins to grow. In this case the fracture was sudden and grew quickly. This is a typical response where mode II is dominant(2). The average maximum load was 0.254 kN. The overall strain energy release rate, G_t, for this test is 408.2 J m^{-2}. This was calculated using Eqns. 1 and 2(4), where the total G is the sum of the strain energy release rate due to mode I and mode II loading.

$$G_I = \frac{3P^2\left(a+\chi_I h\right)^2}{\omega_s \omega_c h^3 E_{11}}\left[\left(1-\frac{c+b}{2L}\right)-\frac{c}{b}\right]^2 \tag{1}$$

$$G_{II} = \frac{9P^2\left(a+\chi_{II} h\right)^2}{4\omega_s \omega_c h^3 E_{11}}\left[\left(1-\frac{c+b}{2L}\right)+\frac{c}{b}\right]^2 \tag{2}$$

Where E_{11} is the axial stiffness, a the crack length, ω_c the width of the composite fracture surface, ω_s the specimen width, h is the half thickness of the specimen and χ_I and χ_{II} are the mode I and mode II end rotation correction factors. Tests will now continue investigating a range of mode I / II ratios and a range of interfaces.

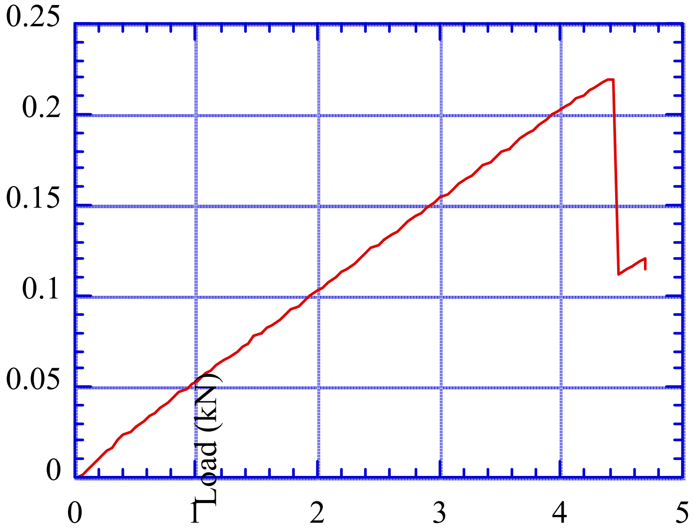

Figure 3. Graph of Displacement Against Load for Static MMB Test at 50% Mode I.

CONCLUSIONS

- The fatigue response of a quasi-isotropic CFRP has been investigated at two R ratios.
- Compression fatigue is more damaging than tensile fatigue.
- The tests completed identify delamination as the primary damage mechanism.
- Delaminations occurred at different interfaces for the different loading conditions. These were the -45°/90° interface in the tension-tension fatigue tests and the 0/+45° interface for the compression-compression fatigue tests. The reasons for this trend to delaminate along a particular interface is now being investigated using MMB tests

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