Matrix Fatigue Damage Evolution in a Longitudinal CFRP Composite

A. Plumtree[1] and M. Ostgathe[2]
[1] Department of Mechanical Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada
[2]Department of Mechanical Engineering, University of Karlsruhe, D-76128 Karlsruhe, Germany

ABSTRACT

Three point bend tests were conducted on 45° off-axis 60% volume carbon fibre reinforced polymer composites under stress control (stress ratio, R=1) and frequency of 4Hz. This allowed a fundamental study to be carried out on the continuous damage accumulation in the matrix without the influence of delamination.

Permanent bending was observed at all stress levels and found to be cycle dependent, increasing with longer lives. Bending resulted from matrix debris collecting in cracks on the tensile side of the specimen and preventing them from closing. Bending occurred rapidly during the first (Stage I) 20% of life, then continued to develop at a slower rate over the remaining life (Stage II). This characteristic behaviour was followed by the development of transverse cracks which were monitored during the bending tests. The amount of cyclic bending was found to remain constant, whereas statically bent specimens relaxed completely indicating the absence of debris in the cracks.

Cyclic stress and strain data were recorded throughout each test, allowing the gradual decrease in material stiffness and corresponding increase in fatigue damage to be monitored. Damage increased with decrease in stress and increase in number of cycles to failure. The two stage process was again evident. A large amount of fatigue damage accumulated during the first 20% of life. Thereafter, the rate decreased. In addition to transverse cracking, damage accumulated owing to cyclic creep in the matrix as well as the formation and growth of longitudinal cracks.

1 INTRODUCTION

This work presents information on research with CFRP composites under three-point bending. Understanding material behaviour under these loading conditions is important for life estimation and component design.

Plumtree and Shi [1] investigated cyclic damage evolution in unidirectional 10° off-axis carbon fibre reinforced epoxy matrix composites under four-point bending with a stress ratio, R, of 0.1 and a frequency, f, of 1 Hz with a triangular waveform. They found that in short-life specimens less damage accumulated compared to long-life samples. In terms of crack accumulation they showed that for long-life specimens fibre cracks exceeded matrix cracks at approximately mid-life. After a large number of cycles, the matrix was no longer capable of transferring the load uniformly to the fibres.

2 PROCEDURE

The composite investigated was constructed of eight layers of 60% volume fraction HTA carbon fibre reinforced epoxy 6376. Specimens with a thickness of approximately 1mm were cut to a length of 90 mm and a width of 16 mm. To avoid notch effects and therefore stress concentrations, all the edges were successively polished with fine emery paper with a granulation of 240, 400 and 600.

Stress and strain data were recorded with a strain gauge mounted in the middle of the specimen on the tensile side. A servo-hydraulic test rig was used to perform static and fatigue tests. A 22.2 kN load cell was used to measure the applied force. The three-point bend tests were conducted under load control at room temperature under a frequency, f, of 4 Hz using a sinusoidal waveform with a stress ratio, R, of 0.1.

Some tests were stopped periodically to measure the amount of bending and the corresponding number or cracks. For the crack counting procedure, a polished area of approximately 16000 μm^2 on the tensile side of the sample was examined under a light microscope with a magnification of 500x. Fracture surfaces were examined using a JEOL JSM-6460 Scanning Electron Microscope.

3 RESULTS

The development of bending during cyclic testing was measured at frequent intervals and the testing procedure was stopped for several minutes for data acquisition. The bending process displayed two stages; a powerful increase in bending during the first 10-20% of life, followed by a much slower rate of bending over the remaining 90-80% life. In the first stage, about 60-70% of the total bending accrued. Consequently it was possible to predict the subsequent fatigue life with reasonable accuracy. Figure 1 shows the progression of bending in terms of normalised life, N/N_f.

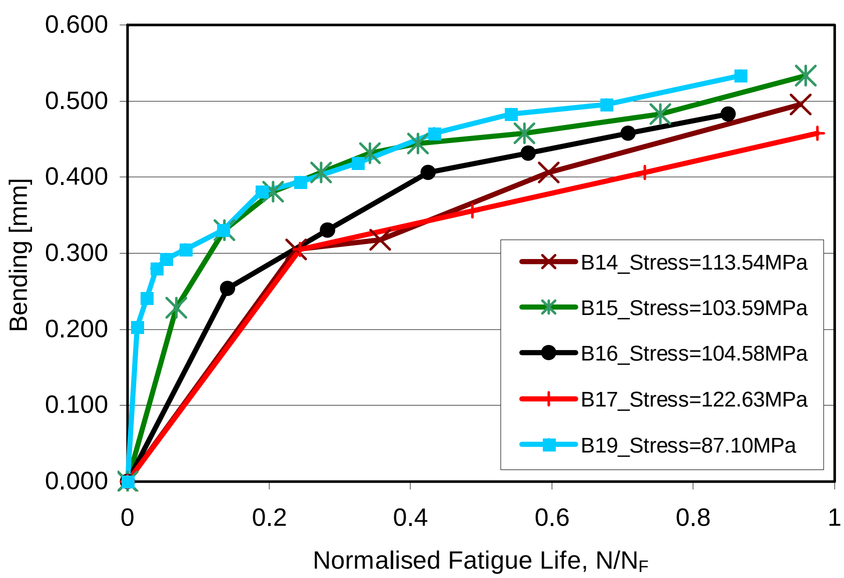

Figure 1: Development of the bending versus the normalised number of cycles-to-failure for different stress levels with R = 0.1 and f =4Hz

Table 1. Amount of Bending Related to Maximum Stress and Life

Specimen No.	Maximum Stress	Number of Cycles to Failure N_F	Amount of Bending [mm]
B14	113.54	840	0.495
B15	103.59	7300	0.533
B16	104.58	3530	0.483
B17	122.63	410	0.457
B19	87.10	36910	0.533

The amount of bending was dependent on the number of load cycles, hence the stress level. The longer the life, more bending was observed, as shown in Table 1.

When cyclic loading was interrupted at any given stress level the amount of bending remained constant over time. For comparison, static tests loaded to the same stress level and then unloaded, relaxed completely.

Data from the strain gauges allowed changes in stiffness to be recorded. The decrease of the material stiffness with cycles can be expressed in terms of accumulating fatigue damage, D_F , given by:

$$D_F = 1 - E_F^N / E_o \tag{1}$$

where E_F^N is the fatigue modulus after N cycles and E_o is the original modulus measured during the first cycle.

Figure 2 shows the fatigue damage curve for two different stress levels; first a maximum stress of 100 MPa with a lifetime of 6110 cycles and secondly a maximum stress level of 110 MPa with 1220 cycles to failure. Both curves can be divided into two significant parts. The first 10-20% of life is defined by a rapid increase in damage. This initial increase is the result of the formation of new cracks. At the changeover to stage II (90-80% life) the slope decreases, although the increase in the damage is still significant.

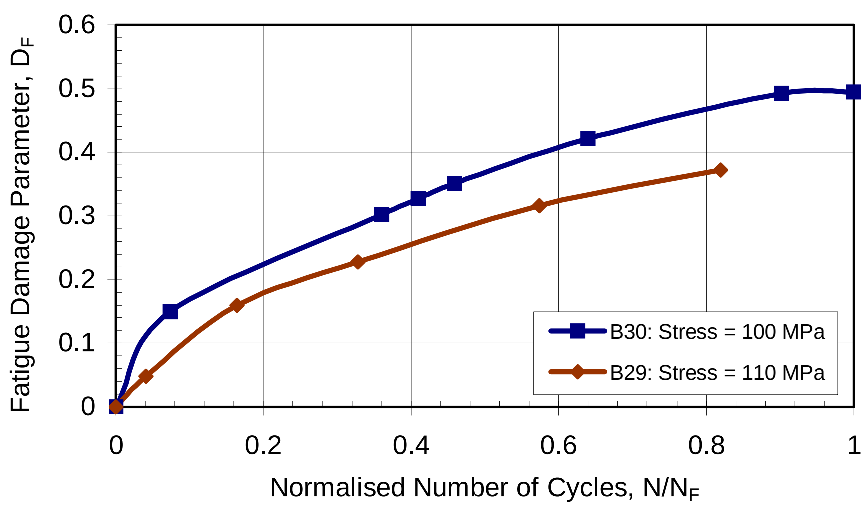

Figure 2: Fatigue Damage Parameter for a $[45]_8$ HTA/6376 composite under cyclic loading at a frequency, f, of 4 Hz and a stress ratio, R, of 0.1 for three-point bend tests

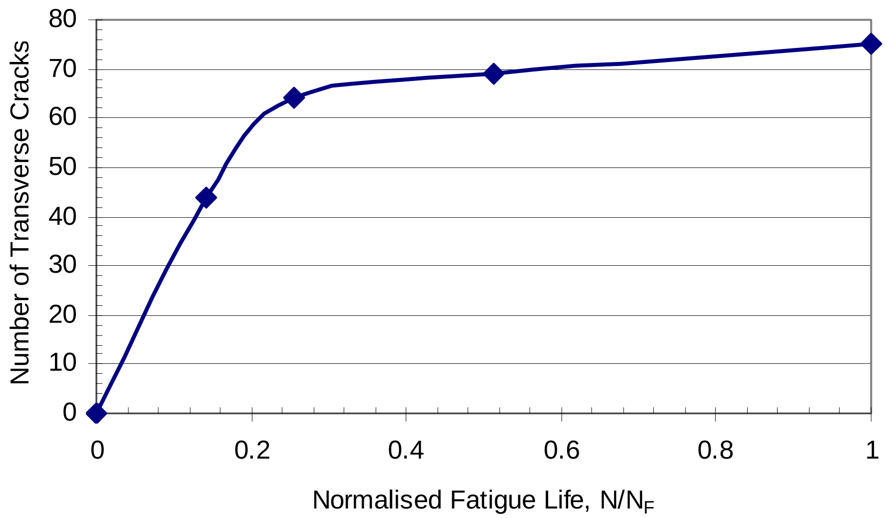

Figure 3: Development of transverse cracks versus the normalised number of cycles to failure in a 16000 μm^2 area for a $[45]_8$ HTA/6376 composite; σ_{max} = 100 MPa, R = 0.1, f = 4 Hz, N_f = 780 cycles

Crack evolution was examined during fatigue testing and viewed periodically under a light microscope at a magnification of 500x. The dominant damage mechanisms were transverse cracks perpendicular to the fibres in matrix rich regions and longitudinal cracks parallel to the fibres at the fibre/matrix interface which lead to eventual failure. The initial transverse cracks were monitored and the same two stage characteristic properties that accounted for the decrease of in stiffness and for the evolution of the bending were observed. This can be seen in Figure 3 where the number of transverse cracks is plotted against the normalised fatigue life.

In the first 20% of life the formation of the transverse cracks increased very rapidly, then the growth decelerated and began to saturate. It appears that the transverse cracks were responsible for the large decrease in stiffness for the first 20% of life and for the development of bending over the whole life. The difference in the fatigue damage curve compared to the transverse crack evolution after the first 20% of life is due to fibre breakage, longitudinal crack formation and coalescence, which become prominent in this second stage.

Examination of fracture surfaces under the Scanning Electron Microscope showed polymer matrix characteristic features such as matrix hackles (A) and broken fibres (B). Most importantly, the fatigue specimens showed debris (C) and smooth fibres with no matrix material adhering (D), as seen in Figure 4. It is suggested that during cycling, the fibre/matrix interface breaks down forming debris consisting of matrix material particles. The reason for permanent bending in the cycled specimens can be accounted for the accumulation of this debris in the cracks. During cycling, the matrix particles collect in the open cracks on the tensile side. On unloading, the cracks cannot close completely. Cyclic crack opening

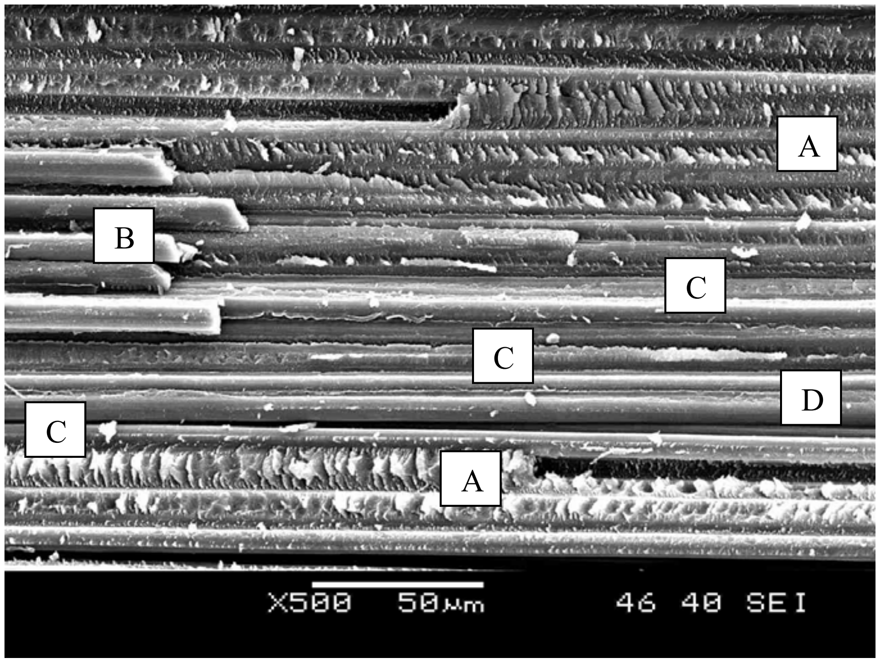

Figure 4. Fracture surface of specimen B26, σ_{max}=100 MPa, N_f = 3930

displacement is thereby reduced. Consequently the crack driving force and the effective cyclic stress is reduced, extending the life of the specimen.

Statically loaded specimens had little or no opportunity to form debris due to lack of back and forth motion between fibre and matrix material. Hence, no debris was formed and available to cause crack closure on the tensile side of the sample.

The effects of debris have been examined by Ewart and Suresh [2] as well as Wilson and Case [3] in cyclic compression/tension tests on ceramics. They observed the occurrence and accumulation of debris particles between crack faces, which led to crack closure. They concluded that crack closure reduced crack growth since previous test results had shown higher crack propagation rates when the debris was periodically removed.

4 REFERENCES

[1] Plumtree, A., and Shi, L., Fatigue Damage Evolution in Off-Axis Unidirectional CFRP, International Journal of Fatigue, Vol. 24, pp. 155-159, 2002.

[2] Ewart, L., and Suresh, S. Crack Propagation in Ceramics under Cyclic Loads, Journal of Materials Science, vol. 22, pp. 1173-1192, 1987.

[3] Wilson, B., and Case, E., Low Cycle Mechanical and Thermal Fatigue of Ceramics and Ceramic Composites with Consideration of Debris Accumulation Effects. Proceedings of the American Society for Composites, pp. 931-940, 1994.