Fatigue damage accumulation in CFRP

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Abstract

A cyclic bending study using a stress ratio of 0.1 was conducted on unidirectional 45°CFRP with a 60% nominal fibre volume fraction. This allowed the continuous matrix damage evolution to be followed without the influence of delamination. Damage was monitored by changes in the fatigue modulus, increase in crack density and amount of permanent bending. It was found that their effects were complementary and that, in general, damage evolved in the same way as that observed in unidirectional tension-tension cyclic tests. All three monitoring techniques showed that damage accumulation was cycle dependent. Damage may be divided into two main stages, with rapid growth at the onset of cycling to about 10-20% life (Stage I), after which the damage increases slowly, but steadily, to failure (Stage II).
Keywords: CFRP, polymer matrix composites, fatigue damage accumulation, cyclic bending, two stage damage.

1 Introduction

Fatigue damage in polymer matrix composites occurs in several forms including matrix cracking, fibre fracture and buckling, debonding at the matrix/fibre interface and delamination between plies. Initial cracking occurs preferentially in the relatively weak matrix. Since there are many stress concentration sites in the matrix adjacent to the fibres, matrix damage is a process of initiation and gradual coalescence. Because of continual crack initiation and propagation, matrix cracking is regarded as progressive damage, as opposed to non progressive damage of the fibres.

WIT Transactions on The Built Environment, Vol 97, © 2008 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/HPSM080291

It has been observed that fatigue damage caused by unidirectional cycling composites occurs in two dominant stages involving an initially high but decreasing damage rate followed by a slowly increasing rate [1,2]. The first consists of homogeneous non-interactive cracking restricted to individual plies. Damage develops at a high but decreasing rate due to the exhaustion of damage sites which relax the internal stress created by the applied load. The transition from the first to the second stage occurs when a balance between crack density and applied load is established (Characteristic Damage State). Generally, the specimen will exhibit a well-defined crack pattern. The second stage is characterized by the localization of damage in zones of increasing crack interaction by delamination and fibre fracture which lead to an overall steady state increase in damage until just before fracture takes place. The proportion and amount of damage occurring during each stage depends upon the configuration of the composite and the imposed stress level.

The intent of the current study is to show that the two stage model is applicable to cyclic bending of a unidirectional CFRP composite while concentrating on matrix damage accumulation by reducing the influence of other damage mechanisms.

2 Procedure

The composite studied was constructed of 60% volume fraction HTA carbon fibre reinforced with epoxy 6376. Specimens were machined from a unidirectional 8 ply plate at an angle of 45^o to the loading axis. Their size was approximately 90 mm long, 16 mm wide and 1 mm thick. The edges were sanded and polished with fine emery paper (600grit).

A servo-hydraulic test rig was used to conduct three-point bending fatigue tests. All the tests were performed at room temperature and a frequency of 4 Hz with a sinusoidal waveform and a stress ratio (R=minimum stress/maximum stress) of 0.1. Using a 22.2 kN load cell and a strain gauge mounted on the tensile surface of each specimen, the stress and strain data were recorded.

Some tests were stopped periodically to measure the amount of permanent bending and the corresponding number or cracks. For the crack counting procedure using an optical microscope, the tensile surface was examined at a magnification of 500x on polished areas of approximately 16000 μm^2. The fracture surfaces were examined in a JEOL scanning electron microscope.

3 Results

3.1 Static tests

The tensile strength and modulus of elasticity were determined using the same test rig and procedure as that for the fatigue tests. The average values of three tests were – Tensile Strength: 261.4 MPa and Modulus of Elasticity: 16.4 GPa.

3.2 Fatigue tests

The cyclic stress (σ) - life (N_F) curve for R=0.1 was determined and expressed by

$$\sigma = 270 - 31.25 \log N_F \qquad (1)$$

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

$$D_F = 1 - E_1^N / E_o \qquad (2)$$

where E_1^N is the fatigue modulus after N_1 cycles and E_o is the initial modulus measured during the first cycle. Figure 1 shows the development of the fatigue damage parameter for different stress levels. In general, the parameter is cycle dominant, rather than stress. The curves can be divided into two significant parts. The first 10-20% of life is defined by a rapid increase in damage. At the changeover to Stage II for 80-90% life the slope decreases, although the increase in damage parameter is still significant.

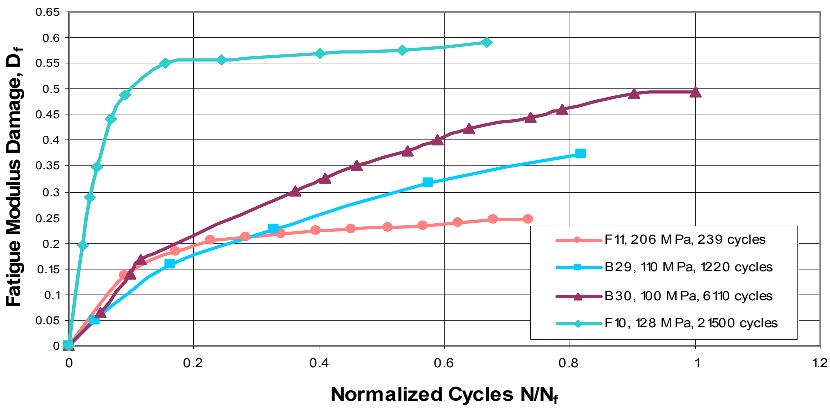

Figure 1: Fatigue damage parameter for a $[45]_8$ HTA/6376 composite under three-point cyclic bending at a frequency of 4 Hz and R= 0.1.

3.3 Crack density

Crack density measurements were determined by monitoring the number of cracks on the tensile surface of the specimens. Crack density is a bulk material characteristic since the final fracture site was not observed in the areas viewed under microscope. Figure 2 shows the evolution of the number of cracks with increasing normalized cycles for a typical three-point bending specimen. It can be seen that the initial number of cracks increased quickly with increasing number of cycles, and that the rate of increase dropped dramatically after about 20% life. Cracks accumulated in a consistent manner during this second stage - slowly at the lower stresses, hence lower growth rates. However, during the first stage the crack distribution was established, which determined the location of the incipient fatal crack.

For four-point cyclic bending, the number of cracks also increased in those specimens experiencing higher stress levels, as shown in Table 1 [3]. The same trends have been observed in unidirectional cyclic tension samples, R=0.1[4,5].

Crack accumulation, shown in Figure 2 can be represented by the two stage model related to the development damage [2]. An initial rapid increase in matrix cracking takes place for the first 20% life (Stage I), followed by slower accumulation (Stage II) due to crack coalescence and fibre fracture [4]. Stage I cracking also corresponds to the initial rapid increase in the fatigue damage parameter, which is greater for longer lives. As the initial crack density slows significantly, a Characteristic Damage State is reached signifying the end of Stage I. This indicates a balance having been established between the applied load and crack density. Thereafter, the number of cracks and their lengths increase slowly over the remainder of life (Stage II) which is reflected by a gradual increase in the fatigue damage parameter.

Examination of the fracture surfaces under the scanning electron microscope showed such characteristic features as matrix hackles (A) and broken fibres (B), as seen in Figure 3. More significantly, the specimens displayed debris (C) and smooth fibres with no matrix material adhering to them (D). This was more evident after large numbers of cycles, indicating that the fibre/matrix interface had broken down, forming debris consisting of matrix particles [6].

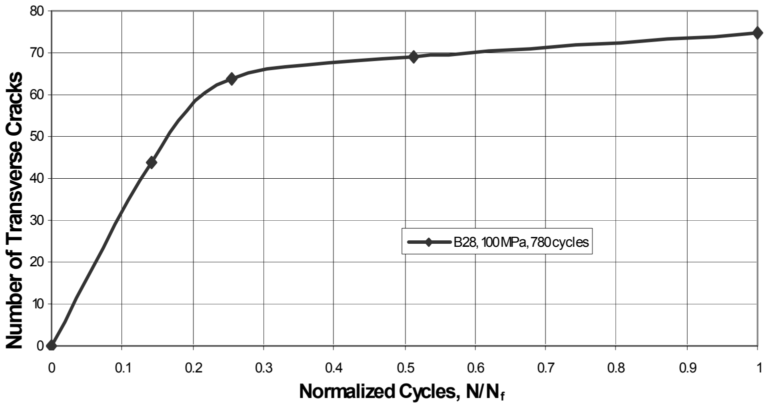

Figure 2: Development of transverse cracks in 16,000 μm^2 on the tensile side of 45^o CFRP specimen tested in 3-pt cyclic bending, R=0.1.

Table 1: Crack densities: 10^o CFRP 4-pt cyclic bending, R = 0.1 [3].

Specimen	Strain x10^{-3}	Stress (MPa)	Cycles to Failure	Total Cracks /mm^2	Matrix Cracks/mm^2
L1	7.29	66	1986	1007	903
L2	5.75	52	534718	4132	1558

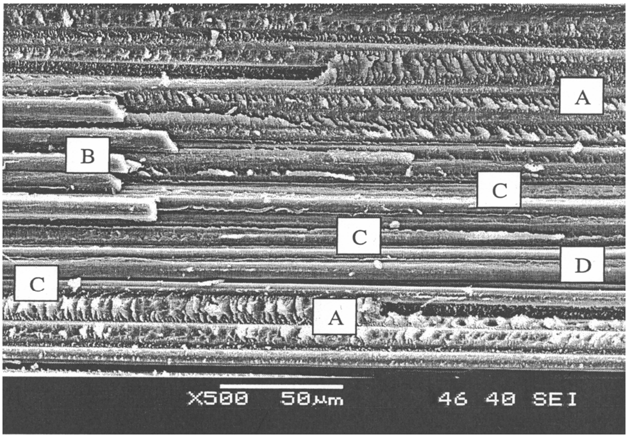

Figure 3: Fracture surface: A hackles, B broken fibres, C debris, D smooth fibres.

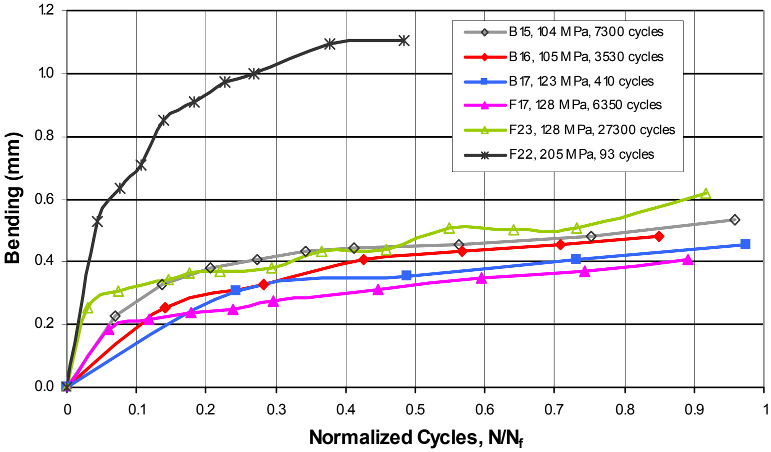

Figure 4: Permanent bending in 45^o CFRP tested in cyclic 3-pt bending at R=0.1. Normalized cycles abscissa.

3.4 Bending

Permanent bending is the curvature of the specimen, resulting from cracking and visco-elastic effects. Companion specimens tested to the same stress level in monotonic bending showed immediate relaxation upon unloading, whereas bending was permanent for fatigue specimens [7]. Figure 4 shows the bending of specimens cycled at different stress levels. Permanent deflection displayed a two-stage response. The majority of permanent bending took place within the first 10-20% of life (Stage I) and the rate of deflection then dropped significantly (Stage II). Larger deflections occurred at higher cyclic stress levels.

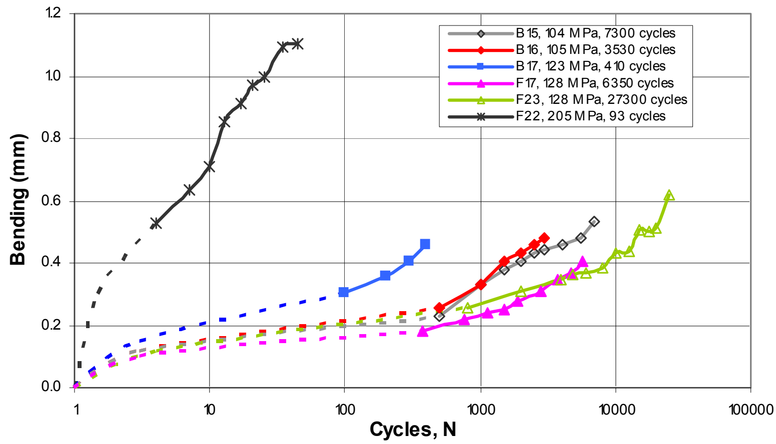

Figure 5: Permanent bending in 45^{o} CFRP tested in cyclic 3-pt bending at R=0.1. Logarithmic cycles abscissa.

Figure 5 shows the same data as Figure 4, but with logarithmic number of cycles as the abscissa. Now the curves resemble creep behaviour. The secondary creep rate increased with increase in stress. However, the amount of permanent bending is a combination is of local and general bulk deflection. In the case of the higher stress level, the larger deflection indicated a higher degree of viscoelasticity and poorer distribution of cracks, with a large number confined to a small region directly beneath the point of loading. In this case the small bend signified a large amount of bending over a confined region.

4 Discussion

The results show that, as with unidirectional cycling, cyclic bending damage evolution can be divided into two main stages. Rapid growth occurs at the onset of loading (Stage I) and a levelling off occurs after about 10-20% life (Stage II). The transition from Stage I to Stage II indicates a change in damage mechanism. During Stage II, the three monitoring methods show a more gradual increase in the amount of damage. However, the effect of the fatal crack was not seen. It is estimated that the fatal crack only becomes evident after approximately 90-99% life [6].

During the first 20% life, the number of transverse cracks increased very rapidly, but the initiation rate decelerated. It appears that the transverse cracks were responsible for the large decrease in stiffness over the first 20% life and partly for the development of permanent bending over the whole life. After the first 20% life, other fracture mechanisms such as fibre/matrix crack formation, coalescence and fibre breakage become prominent in this second stage.

The changes in crack density were reflected by similar changes in the fatigue modulus. This involves a strain shift in the hysteresis loop as well as a tilt. In the present work the fatigue modulus was dominated by the former, indicating that cyclic creep or ratchetting increased with cycles. Similar behaviour has been observed in non-crimped glass-epoxy composites [8] where fatigue modulus and crack density showed the same behaviour. A large amount of damage in the form of cracks developed during the first cycle. The number of shear cracks increased quickly in the first 20% life (Stage I), then more slowly to failure (Stage II). As in the present case, crack density was cycle, not stress, dependent.

Permanent bending is the consequence of several damage mechanisms such as viscoelastic behaviour, non homogeneous deformation and debris inclusion in cracks. The first two increase with stress and the last with cycles. Viscoelastic behaviour of the polymer matrix leads to greater deformation and permanent bending at the higher stresses, as observed. Also, these high stresses result in a poor distribution of cracks. Such concentrated damage causes a small bend radius to form, producing a large deflection. Consequently, assessing damage by the amount of permanent bending reveals a poor general crack distribution along the specimen which causes early failure. Permanent bending in the cycled specimens can also be attributed to the accumulation of matrix debris in the cracks. During cycling, the matrix particles collect in the open cracks on the tensile side. On unloading, these cracks cannot close completely resulting in permanent bending.

Statically loaded specimens have shown no permanent bending [7] indicating that no debris had formed to keep the crack open on the tensile side of the sample because of lack of relative motion between the fibres and matrix.

Petermann [6] showed that more debris formed after large numbers of cycles, indicating that erosion was operating at the fibre-matrix interface. The effects of debris have been examined by Ewart and Suresh [9], and Wilson and Case [10] in cyclic compression/tension tests on ceramics. They observed the occurrence and accumulation of debris between crack faces, which reduced the crack opening displacement. They concluded that this reduced the crack growth since previous test results had shown higher crack propagation rates when the debris was periodically removed.

5 Conclusions

In a unidirectional 45^{o} CFRP composite tested under cyclic bending, damage evolution was found to be a two stage process, similar to that observed under unidirectional tension-tension. A large amount of damage accumulated in Stage I. The transition from Stage I to Stage II, where the damage accumulated slowly, occurred after 10-20% life. Three methods were employed with each monitoring different aspects of damage. However, all three showed the same general behaviour.

Specifically:

1. The amount of cracking was cycle dominant. The number of transverse matrix cracks increased with increasing number of cycles and decreasing stress level. In long life specimens the damage was well distributed.

2. The fatigue damage modulus was also cycle dependent. This was dominated by cyclic creep that increased with cycles.
3. The amount of permanent bending increased with cyclic stress. It is suggested that within those specimens experiencing high stresses, the damage distribution was highly localized, resulting in a small bend radius and large deflection.
4. The fatigue life can be assessed using each of the monitoring methods by determining the transition from Stages I to II, knowing that there is 80-90% life remaining. All the assessment methods monitored different characteristics of damage accumulation within the composite, although the fatigue modulus parameter had the benefit of in-situ measurements.

Acknowledgements

The authors acknowledge the Natural Sciences and Engineering Council of Canada for financial assistance. They would like to thank Martin Ostgathe and Ahmad El-Sayed for technical assistance and Marlene Dolson for typing the manuscript.

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