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FATIGUE DAMAGE IN CARBON FIBRE EPOXY COMPOSITE UNDER VARIABLE LOADING CONDITIONS

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ABSTRACT

Cyclic tests were conducted on $[\pm 45]_{2S}$ angle ply carbon-epoxy specimens using stress ratios R (minimum/maximum stress) of 0.1 and -1.0. Damage was monitored by measuring progressive strain changes in the loading direction. The fatigue damage parameter was found to satisfactorily describe the evolution of damage throughout life. Two stages of damage evolution were identified. In Stage I, the fatigue damage parameter and the density of matrix microcracking rapidly increased to a level dependent upon the stress. This was followed by Stage II, a long period (90% life) of gradual increase in damage, involving crack coalescence, debonding and delamination.

On subjecting the specimens to variable amplitude loading tests, the total fatigue life was greater than that of the constant amplitude tests. Changes from low to high stress levels required more cycles to complete Stage I. For the high to low stress changes, the presence of large numbers of cracks and matrix debris within them resulted in closure, with a consequent increase in Stage II life.

INTRODUCTION

Damage evolution in unidirectional composites occurs in two dominant stages [1,2]. The first consists of homogeneous non-interactive cracking restricted to individual plies. Damage develops at an initially high but decreasing rate caused by exhaustion of damage sites which relax the internal stress created by the applied load. The transition from the first (I) to the second (II) stage occurs when a balance between crack density and applied load is established and the specimen exhibits 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 a steady state increase in the damage rate until just before fracture takes place. The amount of damage occurring during each stage depends upon the configuration of the composite and the imposed stress level.

Initially, cracking occurs preferentially in the relatively weak matrix. There are many stress concentration sites in the matrix immediately next to the fibres, resulting in matrix damage being a process of initial multiple initiation and coalescence of microcracks. Because of continual crack initiation and propagation, matrix cracking is regarded as progressive.

The intent of the present work is to consider and apply a parameter that expresses the progressive matrix damage evolution in a polymer matrix laminate. This parameter will be used to express the fatigue damage during variable amplitude loading tests.

EXPERIMENTAL PROCEDURE

The samples used in this work were prepared from HTA carbon fibre (58% V_f) pre-impregnated 6376 epoxy. Table I gives the mechanical properties of the fibre, matrix and composite.

Table I. Mechanical Properties of Fibre, Matrix and Composite

Mechanical Properties	Carbon Fibre HTA (12K)	Epoxy 6376	58% V_f HTA-epoxy $[\pm 45]_{2S}$
E-Modulus [GPa]	238	3.6	21.24 ±0.46
Tensile Strength [MPa]	3400	105	188.37 ±2.40
Compression Strength [MPa]	-	-	177.5 ±0.72
Density [g/cm^3]	1.78	1.31	1.58

Flat specimens were cut from pre-impregnated plates stacked in an angle-ply $[\pm 45]_{2s}$ configuration. Tests were carried out under cyclic stress control on a servo-hydraulic test rig using stress ratios (R=minimum/maximum stress) of 0.1 or -1.0. Strains were measured throughout the tests using gauges mounted on the specimens and calibrated ram displacements. These allowed damage evolution to be monitored by the fatigue modulus, defined as the slope of the line connecting the origin of the stress-strain hysteresis loop to the maximum stress for a given cycle, N. By substituting for stress and using Hooke's Law, this definition of damage, D_F, can be related to the initial elastic modulus, E_o, and the fatigue modulus E_N, after N cycles:

$$D_F = 1 - (E_N/E_o) \qquad (1)$$

The widths of the cyclic stress-strain loops were also measured. Decreases in modulus have been shown to correspond to increased crack density [4-7]. Application of modulus degradation is applied as an indicator of the uniform damage occurring in composites [8, 9]. In the present work, crack development was monitored by applying acetate replicas to the test specimen surface after a given number of cycles and then examining the replicas in a scanning electron microscope.

RESULTS AND DISCUSSION

CONSTANT AMPLITUDE

Constant amplitude tests were conducted in order to establish the basic stress-life data for the stress ratios R = 0.1 and R = -1.0. The fatigue results are given in the following equations:

$$R = 0.1,\ \sigma_F = 209.7 - 17.5 \log (N_F)\ \text{MPa} \quad (2)$$

$$R = -1.0,\ \sigma_F = 164.9 - 19.1 \log (N_F)\ \text{MPa} \quad (3)$$

where σ_F is the maximum applied stress and N_F is the number of cycles to failure.

The overall damage is represented by a two stage model, shown in Figure 1 for R= 0.1. Although the composite sustained more cracking at the higher stresses, the two stage model applies for all stress levels. Initially a rapid increase in matrix cracks occurred for approximately the first 10% life (Stage I), followed by crack coalescence and delamination that accumulated at a slower rate (Stage II), equilibrium being established between the applied load and crack density. The number, size, and distribution of the cracks were measured. Figure 1 gives the crack data for the R= 0.1 test, showing the matrix damage accumulation throughout the two stages.

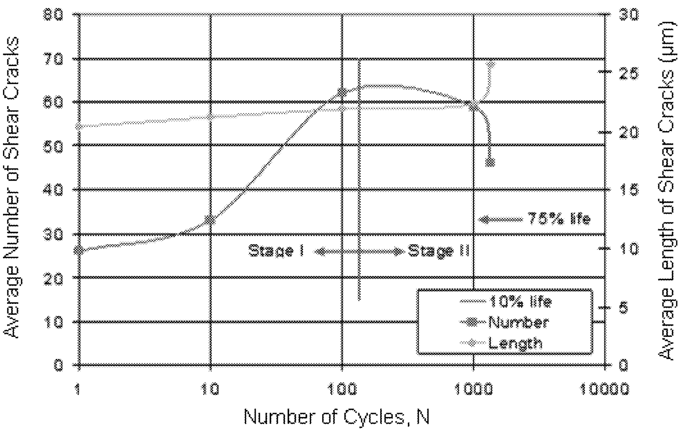

Figure 1. Variation of number and length of cracks with increasing cycles, R = 0.1.

Figure 2 shows the fatigue modulus plots for the R = -1.0 tests carried out at the maximum stresses of 65 and 110 MPa. Fatigue modulus plots for the R = 0.1 for tests conducted at maximum stresses of 115 and 155 MPa showed the same trends. Damage increased with maximum stress and for a given stress level, damage evolved in two distinct stages: rapidly for the first 10% life (Stage I), then slowly (Stage II) for the remainder of life.

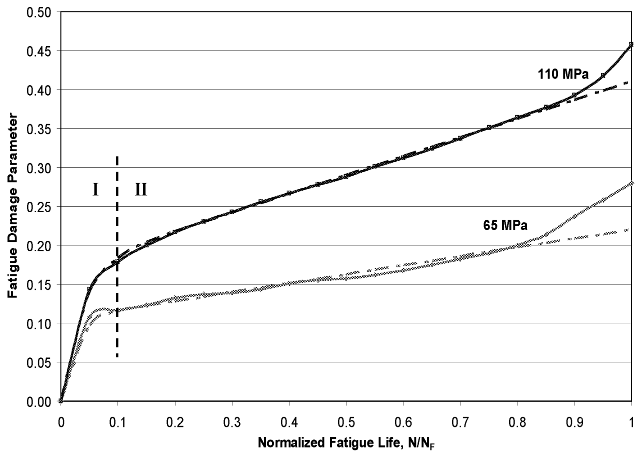

Figure 2. Fatigue damage evolution, R = -1.0.

VARIABLE AMPLITUDE

For the variable amplitude tests, the specimens were divided into two main groups, each having a unique test sequence. One group (H-L) was first subjected to a high stress and then a low stress whereas the other group (L-H) was started at an initially low stress level and then changed to a high stress. In both cases, the fatigue lives and corresponding scatter bands were significantly different. The initial stress level was applied for a predetermined number of cycles (N_1) based on the percentage of expected fatigue life (N_1/N_{F1}) at that stress level. Upon completion of N_1 cycles, the stress level was changed and the test continued at the new maximum stress level for a pre-determined number of cycles (N_2) - the proportion of life being expressed as a ratio (N_2/N_{F2}) - until failure occurred or the number of cycles exceeded one million, at which point the test was stopped.

The effects of the maximum stress level and stress ratio were determined. The former was investigated using a constant stress ratio of R = -1.0, changing the maximum stress from high (H) to low (L) and vice versa. A second group of tests was carried out by varying R between -1.0 and 0.1.

CONSTANT STRESS RATIO

Constant stress ratio tests were conducted under complete reversed loading with a stress ratio of R = -1.0 using an anti-buckling guide. The maximum stresses chosen were 110 MPa for the high (H) stress and 65 MPa for the low (L) stress levels. The difference in the mean fatigue lives at each stress level was more than one decade with very little overlap. Figure 3 gives the representative data depicting the progression of the fatigue damage parameter for two H-L and two L-H tests. Good reproducibility is apparent.

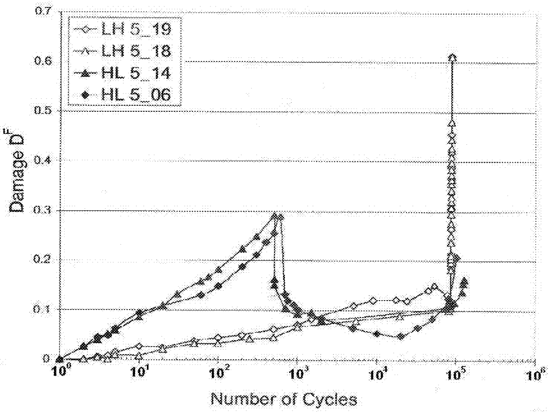

Figure 3. Fatigue damage parameter changes during amplitude change test, R = -1.0.

The normalized fatigue life data for the variable amplitude tests are shown in Figure 4. In all cases, the accumulated life fractions exceeded unity. It is apparent that the test sequence (L or H first) had no significant effect.

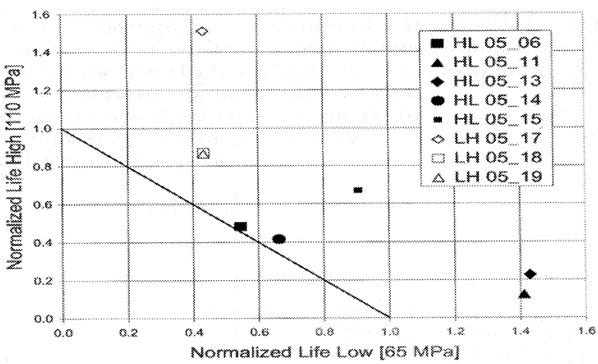

Figure 4. Accumulated normalized life fractions, R = -1.0.

H-L TEST SEQUENCE

The damage evolution for test 05-14 shown in Figure 3 is representative of all the H-L tests. In this case, during the high (H) frequency sequence of cycles, the damage parameter increased to D = 0.3 after 511 cycles (0.41 N/N_F) at 106 MPa, as in the constant amplitude test. On changing to the lower maximum stress of 64 MPa, the damage parameter decreased significantly to D = 0.1 and continued to decrease, reaching a minimum of D = 0.05 after 15,000 cycles. It then increased to D = 0.15 at failure after 131,816 cycles. The constant amplitude life for σ_{max}= 64 MPa was 198,444 cycles (Equation 3). Hence the L life fraction for specimen 05-14 was 0.66, resulting in a total life fraction of 1.07 and is shown in Figure 4 above.

During the initial high (H) stress cycles, a large number of well distributed matrix cracks formed in response to the stress level. A relationship developed between the matrix crack density and maximum cyclic stress, and on changing to the lower (L) stress more cracks were present than were required to maintain the reduced stress level. Consequently, the local stress intensity decreased with an accompanying decrease in crack opening displacement. Also, additional closure resulted from matrix debris becoming trapped in the cracks. The effective intensity factor range was reduced, delaying failure and resulting in an increased life.

L-H TEST SEQUENCE

The development of damage in specimens 05-18 and 05-19 is shown in Figures 3 and 5. Initial damage for the L sequence developed in the same manner as that for the constant amplitude stress tests. For specimen 05-18 the accrued damage D was 0.10 after 85,960 cycles (0.43 N_F). On changing to a maximum stress of 108 MPa the damage rapidly increased. For clarity, damage evolution for the high stress sequence of both specimens 05-18 and 05-19 is given in Figure 5 using linear coordinates, indicating the manner in which the damage parameter increased. Initially damage increased to a value of about 0.25, then linearly to 0.45 and finally rising to 0.6 at failure after 846 cycles for specimen 05-18. It is interesting to note that this reflected the general damage behaviour of a constant amplitude test, as illustrated in Figure 2.

However, the amount of damage at the end of the L sequence remained within Stage I for the H stress level test. In order to maintain continuity, the damage at the low stress level must increase to that at the higher stress level. Consequently, more matrix cracks formed in order to achieve and maintain the Stage II level for the H stress. Accordingly, this occurred, accounting for the immediate rapid increase in damage. The initial damage (D = 0.15) at the start of this high stress sequence corresponded to only 0.04 N/N_F, indicating that nearly a full fatigue life (96%) remained at this high stress level. Consequently the total life summation exceeded unity, as seen in Figure 4.

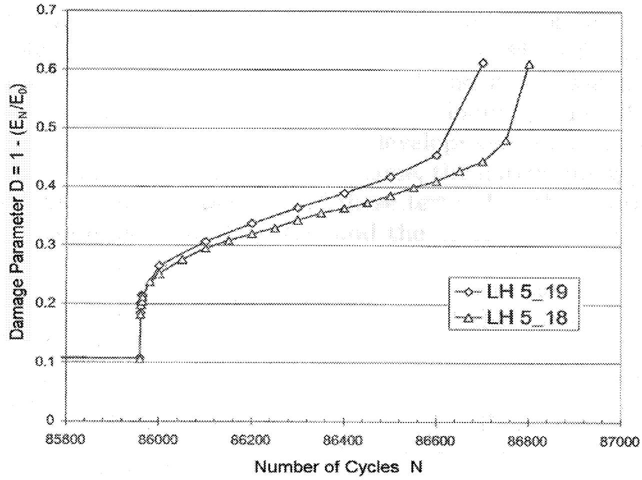

Figure 5. Evolution high (H) stress cyclic damage following low (L) stress cycling.

CHANGE OF STRESS RATIO

The test conditions for the tests with different stress ratios of R = -1.0 and R = 0.1 were chosen to give the same expected lives. Although the stress range was greater for the fully reversed tests, R= 0.1 was chosen as the high (H) stress, based on the higher maximum tensile and crack opening stress per cycle. The corresponding maximum stresses for the expected lives of 50,000 cycles were 124 MPa for R = 0.1 and 74 MPa for R = -1.0. Hence, after 25,000 cycles at R = 0.1 (H) the stress ratio was changed to R = 1.0 (L) for the H-L tests. The reverse was the case for the L-H tests. Table II below gives the results of these tests. In each case the total fatigue life exceeded the linear summation of the constant amplitude tests, as in the case of the previous variable amplitude tests at R = - 1.0.

Table II. Test Results with Different Stress Ratios

Samples	Sequence	R = 0.1 σ_{max} MPa	R= -1.0 σ_{max} MPa	N_1 Cycles	N_1/N_{1F}	N_2 cycles	N_2/N_{2F}	N_i/N_{iF} Total
13-02	H-L	126.7	74.1	25000	0.45	48599	0.83	1.28
13-03	H-L	126.0	74.0	25000	0.41	86452	1.46	1.87
13-04	H-L	128.4	73.2	25000	0.57	107888	1.65	2.12
13-05	H-L	124.9	76.0	25000	0.36	74761	1.61	2.00
13-06	L-H	130.6	76.0	25000	0.55	126280	3.81	4.36
13-07	L-H	127.8	77.3	25000	0.65	62044	1.30	1.95
13-08	L-H	128.2	76.2	25000	0.57	48302	1.06	1.63
13-09	L-H	126.9	75.7	25000	0.53	46014	0.85	1.38

H-L TEST SEQUENCE

Figure 6 follows the development of the fatigue damage parameter for H-L test specimen 13-03, which is representative for this series of tests. After 25,000 cycles (0.41 N_F) at R = 0.1, the damage parameter reached a level of D = 0.22. Changing the stress ratio to R = -1.0 resulted in an immediate and significant decrease in the fatigue damage parameter to D = 0.1. It continued to decrease to a minimum of D = 0.055 after 20,000 cycles before increasing slightly to D = 0.075 at failure. The decrease in the fatigue damage parameter corresponded to the change in maximum stress from 126MPa to 74MPa. Further cycling resulted in a continuous shift of the balanced tension-compression hysteresis loop towards the origin, decreasing ε_{max} and the fatigue damage parameter accordingly.

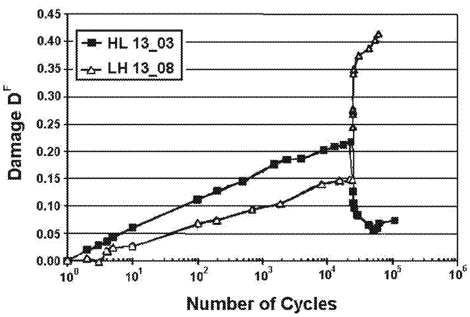

Figure 6. Fatigue damage parameter plot for changing stress ratios: H (R = 0.1), L (R = -1.0)

Changing the stress ratio from R = 0.1 (H) to R = -1.0 (L) decreased the maximum stress. Buckling was not apparent. The lower maximum tensile stress for the second block of cycles resulted in crack stress intensities and opening displacements that were low, since a large number of matrix cracks had formed in the previous H block. Fewer cracks would have formed in a constant amplitude test at this lower stress level. The overall effect caused by the smaller crack opening would require more cycles for to them to propagate, extending the fatigue life.

L - H TEST SEQUENCE

Figure 6 shows a typical L-H sequence, depicted by specimen 13-08. Initially, damage increased to D = 0.15 after 25,000 cycles (0.55 N/N_F). This was comparable for half life under constant stress. Changing to R = 0.1, the fatigue damage parameter increased significantly. Although the maximum tensile stress increased, ε_{max} increased more and continued to increase to failure at D = 0.4.

The results in Table II of all four L - H tests show that the remaining life for the H sequence approached or exceeded unity, resulting in high total life summations (1.38 - 4.36). It would appear that the amount of matrix damage which developed during the first block was insufficient to attain the balance between crack density and the maximum stress for the second block, and a new transition from Stage I to Stage II was established- requiring more stress cycles, thereby increasing life, as in the case of the stress change tests at R= - 1.0.

CONCLUSIONS

Variable amplitude tests on $[\pm 45]_{2S}$ angle-ply carbon fibre reinforced epoxy specimens resulted in lifetimes greater than unity, when compared to constant amplitude stress tests.

Changing from low to high stress levels required additional cycles to increase the matrix crack density in order to balance the internal stress created by the previously higher applied stresses. This delayed the transition from the first to second stage damage, resulting in longer lives.

For the high to low stress level changes, the accompanying stress relaxation in specimens containing large numbers of matrix cracks resulted in a reduced crack opening displacement. A lower stress intensity and accumulation of debris in the cracks accounted for the increased life.

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