Fatigue Damage Evolution in Unidirectional CFRP

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ABSTRACT

Cyclic tests were conducted on unidirectional carbon-epoxy composite specimens loaded at 45^o to the fibre axis, using a stress ratio R (minimum/maximum stress)of 0.1. Matrix damage was monitored through measuring strain changes in the direction perpendicular to the fibres and in the loading and transverse directions. Hysteresis loops were constructed for the loading, longitudinal, transverse and shear directions. Ratchetting of the loops indicated that cyclic creep in the matrix was dominant. A parameter based on cyclic creep allowed damage evolution to be described and fatigue life to be predicted.

INTRODUCTION

It has been observed that damage evolution in unidirectional composites occurs in two dominant stages involving an initial decreasing damage rate followed by an accelerating rate [1,2]. The first consists of homogeneous non-interactive cracking which is restricted to individual plies. Damage develops at a decreasing rate due to the exhaustion or saturation of new damage sites and the slow growth of existing ones. The transition from the first to the second occurs when the Characteristic Damage State (CDS) is established and the specimen exhibits a well-defined crack pattern in cross-ply laminates. The second stage is characterized by the localization of damage in zones of increasing crack interaction resulting in delamination and fibre fracture which may lead to an overall acceleration in damage evolution until 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.

When a unidirectionally reinforced component is loaded off-axially experimental observations have shown that matrix cracking occurs preferentially. Because the matrix is relatively weak in comparison to the fibres, it serves as the potential fracture path. Since there are many stress concentration sites in the matrix immediately next to the fibres, matrix damage is a process of multiple initiation and coalescence of microcracks. Therefore, shear plays an important role in the fatigue process. The microcracking stage which follows is occasionally not detected before failure occurs, presenting the so-called “sudden-death” behaviour.

Matrix cracks are constrained by the fibres and as a consequence the cracks are confined to a direction parallel to the fibres. Matrix cracking serves as the source of other damage, such as fibre breakage because of the stress concentrations at the crack tips. As matrix cracking is a process of crack initiation and propagation, it is usually regarded as progressive damage, as opposed to non progressive damage in the fibres. The intent of the present work is to define a parameter that expresses this progressive matrix damage evolution. In particular, this work is concerned with damage evolution in different material directions in a unidirectional off-axis carbon-epoxy composite.

EXPERIMENTAL PROCEDURE

Static and cyclic tests have been carried out on 45^o off-axis unidirectional HTA/6376 carbon fibre-reinforced epoxy composites. The composite properties (V_f=60%) are shown in Table 1.

Table 1 - Material properties for HTA/6376 composite [3]

Properties	Fibre Direction (0^o)	Matrix Direction (90^o)	Shear (±45^o)
Strength (MPa)	1670	60	70
Modulus (GPa)	136	8.75	5.5

Rectangular $[45]_8$ coupons were cut from 300 mm x 300 mm plates with a diamond blade saw and the edges were then polished, reducing surface flaws. The nominal coupon dimensions were 200 mm x 15 mm x 1mm. The specimens were instrumented with three-gauge rosettes (0/45/90). Each rosette was centrally located on the specimen surface with the gauges measuring strains in the loading (X), and transverse (Y) directions, as well as strains in the direction perpendicular (2) to the fibre direction.

Both static and cyclic tests were performed using a servo-hydraulic test rig with rigid grips and a 2.2 kN load cell. An MTS 406 controller coupled with external computer controls provided the load control. The static tests were loaded to failure. The cyclic tests were sinusoidally loaded with a stress ratio

($\sigma_{min}/\sigma_{max}$) of R=0.1 at a frequency of 10 Hz. The tests were periodically stopped and then cycled at 1 Hz for 10 cycles to acquire stress-strain data.

RESULTS AND DISCUSSION

Stress-Strain Measurements

The average static strength and strain to failure were 100 MPa and 0.69% respectively. These tests exhibited non-linear behaviour in the loading and transverse directions, whereas in the 1 and 2 directions, the stress-strain responses were linear for the majority of the tests.

The fatigue data results were well represented by:

$$\sigma_{max} = 97.6 - 7.75 \log (N_f) \text{ MPa} \tag{1}$$

where σ_{max} is the maximum applied stress and N_f is the number of cycles to failure. This equation changed little when the static data were included. For example, when $N_f = 0.5$ (the maximum point of the first cycle equivalent to a tensile test) then $\sigma_{max} = 99.9$ MPa.

Cyclic stress-strain data provided by the rosette strain gauges allowed hysteresis loops in the X, Y and 2 directions to be constructed. In the 2-direction the strains were linear and stable during cycling. In the X-direction, the stress-strain relationships were slightly nonlinear and exhibited some cyclic creep with the loops shifting (ratchetting) to higher strains. However, the nonlinearity and creep become more pronounced for stress-strain data in the Y-direction. Although the maximum strains in the Y-direction were smaller than those in either the X or 2 directions, the creep strains were larger.

Damage Measurement

Damage mechanics provides an effective approach for assessing damage, D. It accounts for the damaged area, A_d, in terms of the original area, A_o:

$$D = A_d/A_o \tag{2}$$

Considering constant cyclic stress, this definition of damage can be expressed as a ratio of the initial dynamic modulus (E_o) and apparent dynamic modulus (E_N) after a given number of cycles N. The dynamic modulus is obtained from the slope of the line joining the minimum and maximum tips of the hysteresis loop.

$$D = 1 - E_N/E_o \qquad (3)$$

The results indicated that there was no apparent change in dynamic modulus in any direction. The shape and hystesis loops remained relatively constant throughout the life of each specimen. However, it was observed that the hysteresis loops displayed ratchetting owing to cyclic creep of the polymeric matrix. Creep strains, ε_{CN}, in both X and Y directions were evident. Those in the Y-direction were larger and were used for the damage measurements.

Damage was defined as the ratio of the cyclic creep strain, ε_{CN}, normalized by the maximum strain, $\varepsilon_{o\,max}$, determined from the original dynamic modulus.

$$D_c = \varepsilon_{CN}/\varepsilon_{o\,max} \qquad (4)$$

The general behaviour of matrix cracking may be illustrated by considering the fatigue results for pultruded glass-polyester rods [2] and $[0,90]_s$ glass-epoxy [4] and graphite-epoxy laminates [5]. During the first 10% life (N/N_f), the matrix crack density increased very quickly, thereafter slowly, approaching a stable and constant value followed by a gradual increase to failure. There was a direct relationship between this change in crack density and an accompanying decrease in stiffness which has been described by a damage variable [6].

The present work on off-axis carbon-epoxy displayed the same general behaviour when the creep damage parameter (equation 4) was considered. Two stages of damage accumulation were observed. The first was seen as an initially rapid, but decreasing cyclic creep rate until a saturation level was reached at 10% life. This level increased with stress. Once saturation had been attained, then the damage accumulated at a slower and linear rate to failure.

First Stage Damage

For the first stage, the relationship between crack density and apparent modulus (stiffness), used to measure damage, has been analyzed by several authors using different approaches, such as the self-consistent model [7], variation approach [8], shearlag model [4], and continuum damage mechanics [9]. Plumtree and Shen [6] considered damage using a two parameter Weibull model and expressed the longitudinal component of the damage tensor for a given number of cycles, N, as follows:

$$D_1 = D_1^{\,s} \{1\text{-}\exp[-N/\alpha]^{\beta}\} \qquad (5)$$

where D_1^s is the damage at saturation i.e. exhaustion of microcracking at the end of the first stage (~ 10% N/N_f). The scale factor, α, was found to be sensitive to cyclic stress whereas β was relatively constant. In the case of a $[0, 90]_s$ glass-epoxy laminate [6] and pultruded glass–polyester rod [2], the values of β were found to be 1.08 and 1.1 respectively.

For the unidirectional 45° carbon-epoxy composite, first stage saturation was stress dependent and the corresponding damage level was expressed by:

$$D_1^s = A\,\sigma_{max} + B \tag{6}$$

where $A = 4.41 \times 10^{-3}$ and $B = -0.147$. This describes the amount of damage required to reach saturation and expresses a particular amount of damage for a given stress level. On the other hand, D_1 in equation 5 describes the manner in which damage increases with increasing cycles throughout the whole of the first stage.

Second Stage Damage

Since damage evolution over the second stage involves the coalescence of microcracks and development of macrocracks, the growth rate should be expressed by the Paris equation. However, there is no clear definition of crack length and the crack tip stress intensity factor for the multi-damage mechanisms which take place. Plumtree and Shen [6] replaced crack length with its counterpart in damage mechanics to provide a descriptive parameter for damage in the form

$$D = 1 - (1-[N/N_f]^{\gamma}) \tag{7}$$

where the exponent is regarded as a constant [10].

Equation (7) may be modified by introducing coefficient D_2 to account for failure occurring when the total damage $D_T<1$, since the critical value of D_T at fracture has been found to vary from 0.2 to 0.8. A critical value of 0.3 is generally accepted for long fibre composites [2]. For the off-axis unidirectional carbon-epoxy composite presently under consideration, D_T, ranged from 0.19 to 0.28. The second stage of damage may then be written:

$$D = D_2\,[1-(1-N/N_f)^{\gamma}] \tag{8}$$

Plumtree and Shen [6] postulated that γ should be stress dependent. However, based on experimental data, a less rigorous approach proved to be satisfactory by assuming γ to be constant, as suggested by Lemaitre and Plumtree [10]. Stage 2 damage behaviour has been found to be well described for pultruded glass-polyester and $[0.90]_{2s}$ glass-epoxy composites when $\gamma = 0.22$ [6]. For the 45^o off-axis unidirectional carbon-epoxy composite under investigation, second stage damage evolution was linear, hence γ=1. Cyclic creep damage evolution for stage 2 is therefore simply expressed by:

$$D = C(N/N_f) \tag{9}$$

where the constant C = 0.0865.

Total Damage

Damage evolution throughout the cyclic life of the material, covering stage 1 and 2 damage, may be expressed by combining equations 5 and 8 to give

$$D_T = D_1^s \{1-\exp[-(N/\alpha)^\beta]\} + D_2[1-(1-N/N_f)^\gamma] \tag{10}$$

This equation has successfully predicted cyclic damage evolution in pultruded glass-polyester rods [2], $[0.90]_{2s}$ glass-epoxy laminates [11] and elastomers [12]. Considering the present unidirectional 45^o carbon-epoxy composite, combination of equations 6 and 9 also gives the total damage accumulated. Hence for N=1:

$$D = A\,\sigma_{max} + B + C \tag{11}$$

On substituting the experimental values for A, B, C, then,

$$D_T = 4.41 \times 10^{-3}\,\sigma_{max} - 0.0605 \tag{12}$$

This shows that the total damage varied from 0.19 to 0.28 for the range of experimental σ_{max} values used in the present work.
When correlating D_T with N_f, the following equation became apparent:

$$D_T = 0.372 - 3.25 \times 10^{-2} \log N_f \tag{13}$$

indicating that damage at fracture in a tensile specimen would be 0.37.

Substituting equation 12 into equation 13 allows the relationship between σ_{max} and N_f to be expressed by:

$$\sigma_{max} = 98.2 - 7.37 (\log N_f) \text{ MPa} \tag{14}$$

This equation is in very good agreement with the experimental data, expressed by equation 1. Hence, the simpler two stage model can be applied to satisfactorily describe cyclic damage evolution and predict failure in the off-axis unidirectional composite.

CONCLUSIONS

The accumulation of matrix damage in a unidirectional off-axis carbon-epoxy composite can be described by a simple two stage model. Initially cyclic creep damage increases rapidly, changing into steady-state damage accumulation for the remaining life. The changeover to the second stage occurs by 10% of life. The cyclic creep damage parameter is capable of describing damage evolution throughout life for all values of stress and may be applied to predict fatigue life.

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