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LIFE ASSESSMENT AND PREDICTION

Fatigue Testing of Composite Laminates

W.R.Broughton and M.J.Lodeiro

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ABSTRACT

This report provides an assessment of test methods for characterising the fatigue performance of unidirectional and multidirectional laminates. The work was carried out within the “Composites Performance and Design Project - Life Assessment and Prediction (CPD2)”. The project is directed towards the development and validation of test methods and predictive methodologies that can be used for characterising the long-term properties and residual life/strength of polymer matrix composites. Constant amplitude tension-tension fatigue tests have been carried out on glass and carbon fibre-reinforced systems in order to evaluate the suitability of these techniques for generating cyclic fatigue data at accelerated rates. This report provides an assessment of test methods and the data generated for composite laminates under monotonic and cyclic loading conditions. The report considers both dumbbell and straight-sided coupon specimens for testing multidirectional laminates. A discussion of the effects of stress amplitude and methods of end tabbing has been included.

The principal conclusions that can be drawn from the results are: (i) standard test geometries in the international standards IS0527-4 and ISO 527-5 are suitable for assessing fatigue performance under tension-tension loading conditions; (ii) continuous aligned and cross-ply carbon fibre-reinforced laminates have excellent fatigue resistance at loads approaching the tensile strengths for these materials; (iii) normalised S-N curves for unidirectional and cross-ply glass fibre-reinforced laminates show an underlying similarity and can be “approximated” by a simple algebraic relationship, which is dependent on stress amplitude; (iv) waisting coupon specimens results in an improvement in fatigue performance for cross-ply glass fibre-reinforced laminates; and (v) progressive development of damage generally leads to a gradual reduction in laminate stiffness and strength of glass fibre-reinforced laminates. The notable exception is the stiffness of continuous axially aligned laminates, which remains constant for almost the entire life of the coupon specimen. The stiffness and strength of a cross-ply glass fibre-reinforced laminate close to its fatigue life plateaus to a value equivalent to that predicted for a laminate of equal thickness, but with no load-bearing contribution from the 90° plies (i.e. full ply discount). The report includes recommendations on preparation, testing and inspection of composite laminates.

The report was prepared as part of the research undertaken at NPL for the Department of Trade and Industry funded project on “Composites Performance and Design - Life Assessment and Prediction”.

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
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CONTENTS

1. INTRODUCTION

This report provides an assessment of test methods developed for characterising the fatigue properties of unidirectional and cross-ply laminates under tension-tension cyclic loading conditions. The research described forms part of the DTI funded project "Composites Performance and Design (CPD2) - Life Assessment and Prediction". This project is directed towards the development and validation of test methods and predictive models that can be used for characterising the behaviour of polymer matrix composites (PMCs) exposed to a combination of aggressive environments and applied loads (i.e. static and fatigue). Tests have been carried out on both glass and carbon fibre-reinforced systems in order to evaluate the suitability of specimens for generating cyclic fatigue data at accelerated rates. A study of the effects of stress amplitude, specimen geometry and methods of specimen end tabbing has been included.

The report is divided into five sections including the Introduction. Section 2 describes the materials used to validate the test methods in this programme, specimen geometry and specimen preparation. The fatigue results for unidirectional and cross-ply (i.e. 0°/90°) laminates are presented in Sections 3 and 4, respectively. Methods for measuring transverse cracking in cross-ply laminates are included in Section 4. Conclusions are given in Section 5. **Throughout this report, statements of particular importance or relevance are highlighted in bold type. Test data will generally be expressed as an average value ± one standard deviation.**

2. MATERIALS CHARACTERISATION

2.1 MATERIALS DESCRIPTION

The materials used to develop and validate the test methods in this programme are listed below:

(a) Continuous unidirectional glass fibre-reinforced epoxy prepreg sheet (E-glass/Fibredux F922).

(b) Continuous unidirectional carbon fibre-reinforced epoxy prepreg sheet (Tenax HTA/Fibredux F922).

(c) Continuous unidirectional glass fibre-reinforced epoxy prepreg sheet (E-glass/Fibredux 913).

(d) Continuous unidirectional carbon fibre-reinforced epoxy prepreg sheet (Torayca T300/Fibredux 924).

Unidirectional and cross-ply (0°/90°) laminates were autoclaved (including post cured) at the National Physical Laboratory (NPL) to Hexcel Composites specifications. All panels were visually inspected for evidence of damage or processing defects.

Several cross-ply configurations (i.e. $[0°/90°]_{4S}$, $[0°_2/90°_2]_S$, $[0°_2/90°_4]_S$, $[0°_2/90°_6]_S$ and $[0°_2/90°_8]_S$) have been included in the programme to assess the predictive methodology being developed within the CPD programme.

2.2 FIBRE CONTENT AND COMPOSITE DENSITY

Fibre volume fraction, $\mathbf{V_f}$, fibre weight fraction, $\mathbf{W_f}$, and composite density, ρ_c, were measured for all materials (Table 1). Composite density measurements were carried out using method A (zeroed pan immersion) specified in ISO 1183 [1]. Fibre volume and weight fraction measurements for the glass fibre-reinforced epoxy laminates were carried out according to the ISO 1172 standard [2], which uses a resin burn-off technique. In this technique, the composite is dried to constant mass and then subjected to 600 °C in a furnace for at least an hour to remove all traces of resin. The fibre volume and weight fractions of carbon fibre-reinforced epoxy panels were determined according to BS ISO 11667 [3]. Resin removal was achieved using concentrated sulphuric acid and hydrogen peroxide. This process was carried out using a Prolabo Microdigest 401 digester.

Table 1: Composite Density, Fibre Volume Fractions and Fibre Weight Fractions

Material	Composite Density (kg/m³)	Volume Fraction (%)	Weight Fraction (%)
Aligned GRP			
E-glass/F922	2,122 ± 53	65.41 ± 4.46	78.84 ± 3.01
E-glass/913	1,883 ± 39	50.95 ± 0.19	69.26 ± 0.26
Aligned CFRP			
HTA/F922	1,562 ± 17	58.64 ± 2.21	66.41 ± 1.79
T300/924	1,555 ± 10	61.49 ± 1.44	68.48 ± 1.24
Cross-Ply GRP			
E-glass/913 $[0°/90°]_{4S}$	1,957 ± 62	56.47 ± 0.41	72.16 ± 0.48
E-glass/F922 $[0°_2/90°_2]_S$	2,060 ± 6	60.73 ± 0.73	75.48 ± 0.62
E-glass/F922 $[0°_2/90°_4]_S$	2,042 ± 21	59.70 ± 1.08	74.61 ± 0.58
E-glass/F922 $[0°_2/90°_8]_S$	1,966 ± 4	53.32 ± 0.56	69.45 ± 0.49
Cross-Ply CFRP			
HTA/F922 $[0°_2/90°_2]_S$	1,543 ± 6	57.52 ± 1.96	65.90 ± 2.00
HTA/F922 $[0°_2/90°_4]_S$	1,548 ± 8	57.80 ± 0.86	65.94 ± 0.75
HTA/F922 $[0°_2/90°_6]_S$	1,537 ± 3	56.02 ± 2.34	64.47 ± 2.69

2.3 SPECIMEN GEOMETRY AND PREPARATION

This section describes the test methods and specimen geometries used for tensile testing of unidirectional and cross-ply laminates. Details of specimen preparation for each method are also covered in this section.

2.3.1 Unidirectional Laminates

Specimen preparation and testing of unidirectional laminates was carried out to BS EN ISO 527-5 [4] specifications. Specimens (Figure 1) were 250 mm in length, 15 mm wide and 1 mm (i.e. 8 plies) thick. The overall gauge-length (i.e. region between grips) was 150 mm. End tabs (50 mm long), manufactured from a plain woven glass fabric/epoxy laminate (1.6 mm thick) with the fibre axes of the fabric set at ±45° to the specimen axis, were adhesively bonded to the specimens. The tab angle was 90° (i.e. not tapered). An epoxy film adhesive with a cure temperature of 120 °C was used to bond the end tabs to the specimen. **A high elongation adhesive is recommended for bonding the end tabs to the specimen. The use of a film adhesive with carrier to bond the end tabs was found to reduce both preparation time and adhesive wastage. Specimen preparation was also relatively clean in comparison**

to paste adhesives. It is essential to dry the end tabs before bonding to remove moisture, which can compromise the adhesive bond.

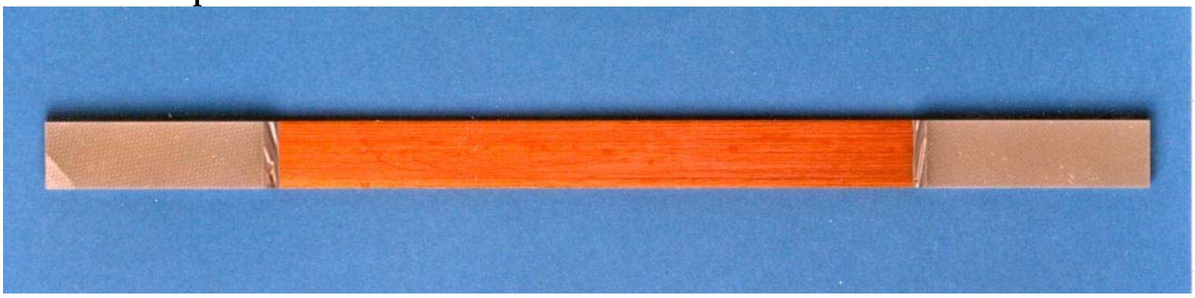

Figure 1: Continuous unidirectional glass fibre-reinforced laminate.

Continuous unidirectional laminated specimens were also produced with integrated (i.e. in-built) end tabs (Figure 2). The objective was to manufacture the entire specimen and end tabs in a single process from pre-preg sheet with the intention of avoiding debonding and splitting within the grip region under tension-tension cyclic fatigue. Specimen dimensions are identical to the previously mentioned test geometry. Tests were also carried out to assess the effect of end tab geometry on tensile properties of unidirectional laminates.

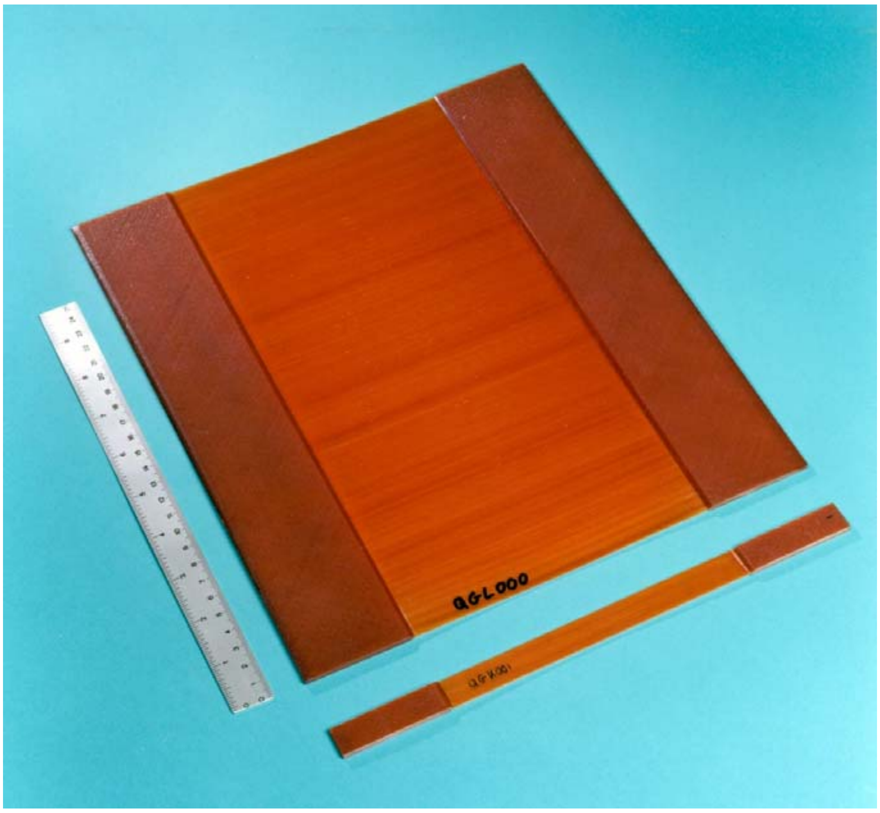

Figure 2: Unidirectional E-glass/913 laminate with in-built end tabs.

2.3.2 Cross-Ply Laminates

Two specimen configurations (straight-sided and dumbbell) were considered for tension-tension cyclic fatigue testing of cross-ply laminates.

Straight-Sided Specimens (Figure 3) were prepared and tested according to BS EN ISO 527-4 [5] specifications. Specimens were 250 mm in length, 25 mm wide and 2 mm (i.e. 16 plies) thick. The overall gauge-length (i.e. region between grips) was 150 mm. End tabbing was identical to that used for the unidirectional specimens with square end tabs.

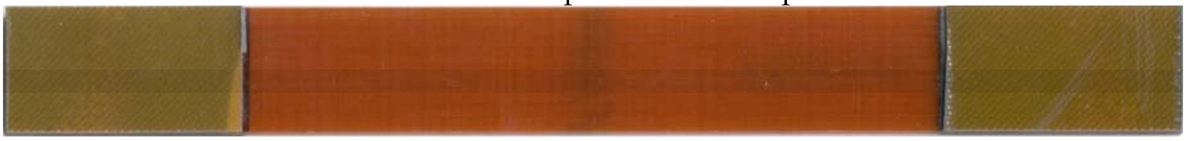

Figure 3: Straight-sided cross-ply specimen with bonded end tabs.

Dumbbell Specimens (Figure 4) were 250 mm in length and 2 mm (i.e. 16 plies) thick. Specimens had an overall gauge-length (i.e. region between grips) of 150 mm. The length and width of the straight portion of the gauge-section was 110 mm and 15 mm, respectively. The fillet radius at the intersection of the gauge-section and end tabs was 60 mm. The end tabs were 50 mm in length and 25 mm wide. End tabbing was identical to that used for the unidirectional and straight-sided cross-ply specimens. The specimens were surface ground to the final shape.

Figure 4: Dumbbell cross-ply specimen with bonded end tabs.

3. UNIDIRECTIONAL LAMINATES

Unidirectional continuous fibre-reinforced laminates are known to possess excellent fatigue resistance; particularly carbon fibre-reinforced systems. The results from tests conducted on unidirectional carbon fibre-reinforced systems support this statement. This section examines the fatigue performance of unidirectional laminates, presenting the results of fatigue tests on glass/epoxy and carbon/epoxy laminates that have been subjected to constant amplitude tension-tension cyclic fatigue loading. Stress-life (also known as the **S-N** response) and residual strength data are presented.

3.1 STRESS-LIFE RESPONSE

Constant amplitude (sinusoidal waveform) fatigue tests were carried out on the unidirectional coupon specimens in load control using an Instron servo-hydraulic test machine at a frequency of 5 Hz. The stress ratio **R** ($\sigma_{MIN}/\sigma_{MAX}$) was either equal to 0.1, 0.5 or 0.75. All tests were carried out under standard laboratory conditions (i.e. 23 °C and 50 % relative humidity (RH)). Instron MAX software was used to control the servo-hydraulic test machine and to collect the test data. In order to limit the duration of tests, the number of cycles was limited to a maximum number of 10^7 cycles (equivalent to 23 days). **Testing, particularly at high loads, was best carried out using fatigue rated servo-hydraulic (wedge-action) grips.**

Five duplicate tests (generally) were carried out at five stress levels (i.e. 80%, 70%, 55%, 40% and 25% UTS). Fatigue tests were carried out on both bonded and integral end tabbed specimens. A limited number of tests were carried out on the T300/924 carbon/epoxy system. The **S-N** curve and associated fatigue data for unidirectional E-glass/F922 and E-glass/913 laminates tested at **R** = 0.1 are shown in Figures 5 and 6. The fatigue strength data are normalised with respect to the ultimate tensile strength, σ_{UTS}, of identically conditioned specimens measured at an equivalent loading rate to the fatigue test. The fatigue data shown in Figure 6 includes results from fatigue tests performed on specimens with bonded and integrated tabs.

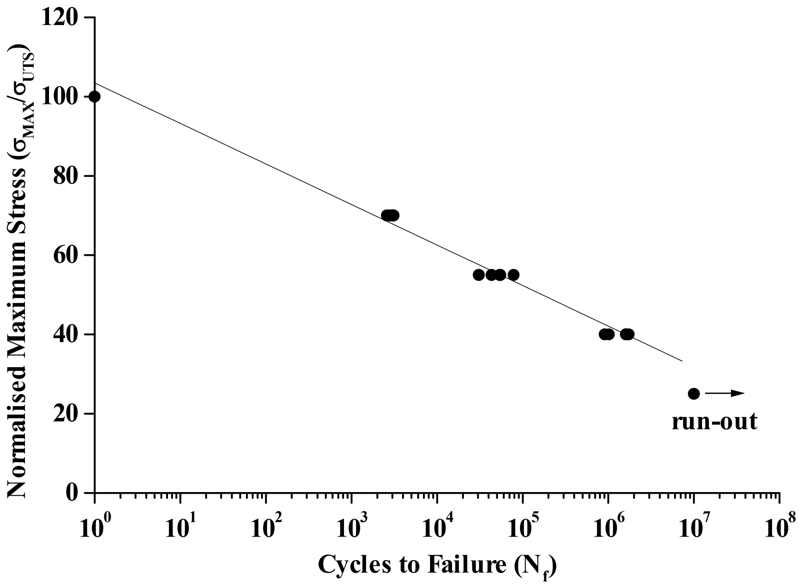

Figure 5: S-N curve for unidirectional E-glass/F922 (R = 0.1).

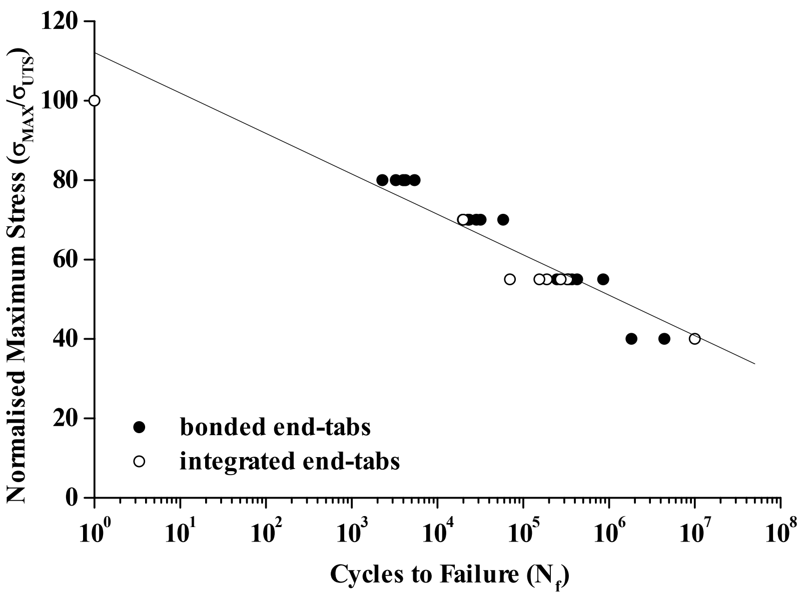

Figure 6: S-N curve for unidirectional E-glass/913 (R = 0.1).

The normalised **S-N** data can be represented by a linear relationship as follows [6]:

$$\sigma_{MAX} / \sigma_{UTS} = 1 - k \log_{10} N_f \quad \textbf{(1)}$$

σ_{MAX} is the maximum applied load, σ_{UTS} is the ultimate tensile strength, **k** (the slope) is the fractional loss in tensile strength per decade of cycles and $\mathbf{N_f}$ is the number of cycles to failure. The value of **k** is approximately 0.1 for the aligned materials. Increasing the mean load has a deleterious effect on the fatigue life.

Due to limits on time and equipment an upper fatigue limit of 10^7 cycles was chosen. The fatigue limit (i.e. 10^7 cycles) occurs at approximately 25% UTS. At this stress level, there was no detectable damage in the aligned glass fibre-reinforced laminates following 10^7 cycles. At higher applied stresses (i.e. 40% UTS or greater), specimens failed progressively with failure occurring invariably within the gauge-length, although frequently near the end tabs. Figures 7 and 8 show examples of failed specimens that have been loaded in monotonic tension and cyclic tension-tension, respectively.

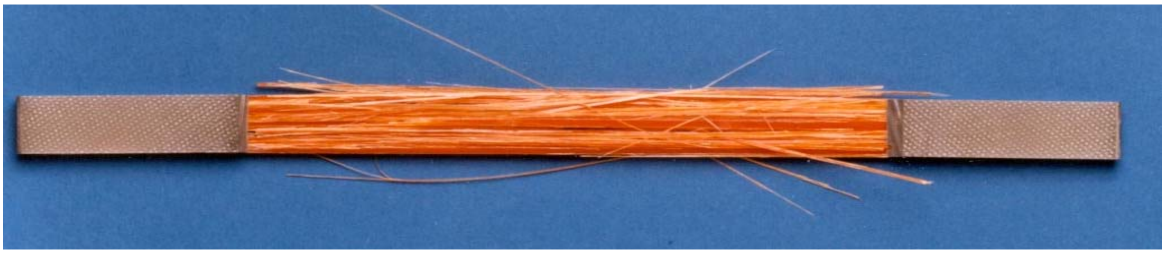

Figure 7: Typical tensile failure for unidirectional E-glass/913 laminate.

Figure 8: Typical tension-tension fatigue failure for unidirectional E-glass/913 laminate.

Visual inspection of fatigue damage before and after failure reveals that longitudinal or axial splitting is the primary damage growth mechanism. Longitudinal splitting and fibre breakage invariably occur at the specimen edges (see Figures 9 and 10). Figure 9 clearly shows regions of fatigue damage (i.e. fibre breakage, interfacial debonding and matrix cracking). Narrow, whitened regions along the specimen gauge-length indicate the presence of damage. These regions, typically 0.5 to 1 mm wide, eventually develop into longitudinal cracks that extend the full length of the specimen. Splitting along the fibres affects the ability of the composite to redistribute load, thus initiating further fibre breaks (and associated damage) until ultimate failure occurs. There were indications that longitudinal splits initiated within the grip regions, which is unavoidable with the current test geometry.

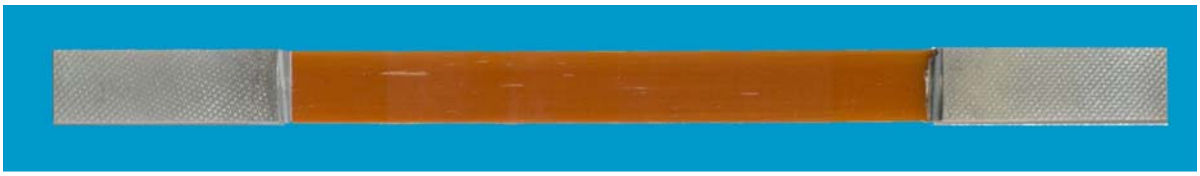

Figure 9: Fibre debonding and matrix cracking in unidirectional E-glass/913 (narrow, whitened areas along gauge-length indicate damage).

Figure 10: Edge damage in unidirectional E-glass/913.

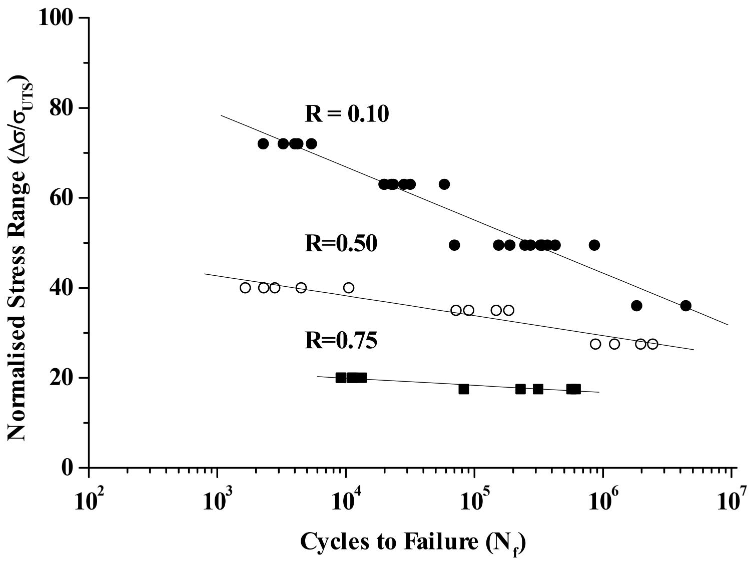

Figure 11: Load-life data to failure for unidirectional E-glass/913.

Unidirectional E-glass/913 laminates were subjected to cyclic tension-tension fatigue at three different stress ratios (**R** = 0.1, 0.5 and 0.75). The load-life data to failure for the three stress ratios are shown in Figure 11 where $\Delta\sigma = (\sigma_{MAX} - \sigma_{MIN})/2$ is the normalised stress amplitude or range. The **S-N** data in Figure 11 clearly shows that the stress ratio has a significant effect on the fatigue life of unidirectional laminates. Increasing either the amplitude or mean value of the sinusoidal load reduces fatigue life. To achieve a given life, a lower stress range is required as the mean stress level is increased.

The normalised **S-N** data (i.e. normalised maximum stress σ_{MAX} versus N_f) for all three stress ratios can be approximated by Equation (1) with the fractional loss in tensile strength per decade of cycles, **k**, decreasing as **R** increases (Figure 12). The relation between **k** and **R** can be approximated by the following linear relationship:

$$k = 0.11 - 0.07R \qquad \textbf{(2)}$$

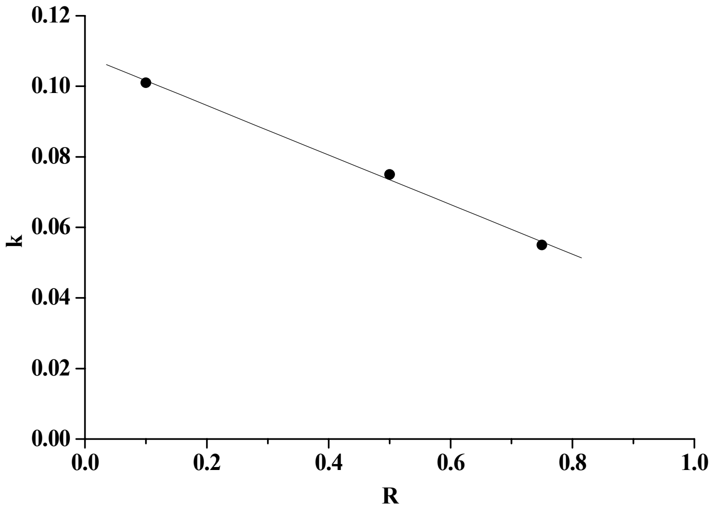

Figure 12: Plot of k as a function of R for unidirectional E-glass/913.

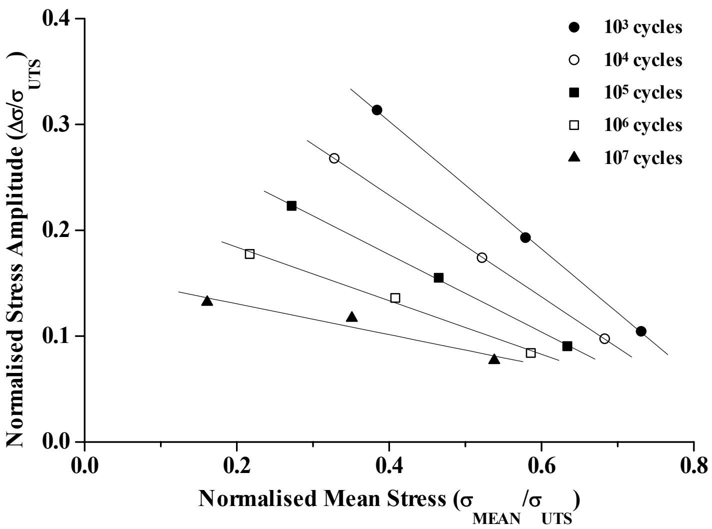

Figure 13: Stress amplitude-life plots for different mean stress values for E-glass/913.

Mean stress effects in fatigue can be represented in terms of constant-life diagrams, as shown in Figure 13. Different combinations of normalised stress amplitude, $\Delta\sigma/\sigma_{UTS}$ (where $\Delta\sigma = (\sigma_{MAX} - \sigma_{MIN})/2$), and the normalised mean stress, $\sigma_{MEAN}/\sigma_{UTS}$ (where $\sigma_{MEAN} = (\sigma_{MAX} + \sigma_{MIN})/2$), are plotted to give constant fatigue life curves (or Goodman type curves [7]) for fatigue lives ranging from 10^3 to 10^7 cycles. In principle, the curves should converge to the static strength of the composite on the mean stress axis (i.e. when the mean load is increased to the static strength then no amplitude is required to cause failure).

A number of attempts have been made to empirically model stress-life behaviour of composites. Harris and co-workers [8-9] have developed a constant life-model (see box below) which, according to the authors, agrees well with experimental data for tension-tension, compression-compression and tension-compression fatigue. The model is based on a substantial experimental database including results for different **R** ratios, constant and variable amplitude loading, materials (i.e. aramid, carbon and glass fibre-reinforced systems) and lay-ups, etc [10]. The model is claimed to account for both undamaged and damaged composite materials. Bell-shaped constant life diagrams are used to display the data.

Constant-Life Model

$$a = f(1-m)^{u}(c+m)^{v} \qquad \textbf{(3)}$$

$$\text{where: } a = \frac{\Delta\sigma}{\sigma_{UTS}};\quad m = \frac{\sigma_{MEAN}}{\sigma_{UTS}};\quad c = \frac{\sigma_{UCS}}{\sigma_{UTS}}$$

The parameter **c** is the normalised compression strength (i.e. ratio of compressive strength, σ_{UCS}, to tensile strength, σ_{UTS}), **m** is the normalised mean stress component ($\sigma_{MEAN}/\sigma_{UTS}$) and **a** is the normalised stress amplitude ($\Delta\sigma/\sigma_{UTS}$). The parameters **f** (stress function), **u** and **v** in Equation (3) are linear functions of **log** $\mathbf{N_f}$ ($\mathbf{N_f}$ is the cycles to failure). This approach will be investigated in a future report on predictive models for characterising long-term behaviour of PMCs exposed to aggressive environments and cyclic fatigue loading conditions.
Difficulties were encountered in long duration tests (i.e. **N** > 10^6 cycles) due to debonding of end tabs from the specimens. Frictional effects in these regions were often exacerbated by an additional heating effect from the servo-hydraulic system (i.e. actuator and grips). Differences between the brittle epoxy F922 and the tougher epoxy 913, and between adhesively bonded and integrated end tabs were only marginal. Finite element analysis indicates that the inclusion of an inverted taper on the end tabs would significantly reduce stress concentrations in the vicinity of the end tabs. The strength data obtained from unidirectional specimens with square end tabs were identical to the strength values obtained using specimens with end tabs that had an internal 45° taper. **Careful consideration should be given to adhesive selection for bonding end tabs. It is important to minimise the possibility of debonding between the end tabs and the specimen, which can result in a shorter specimen fatigue life. This is particularly relevant to testing of carbon fibre-reinforced composite laminates, which have high fatigue resistance at loads approaching the ultimate tensile strength of the material.**

The continuous aligned glass fibre-reinforced laminates show far greater sensitivity to fatigue than the continuous aligned T300/924 carbon/epoxy. **For $\sigma_{MAX} \leq 0.70\ \sigma_{UTS}$, the fatigue limit for T300/924 exceeded 10^7 cycles**. Technical problems associated with end effects and end tabbing prevented the successful completion of tests at applied stress levels of 80% UTS or higher. Tests conducted at 80% UTS indicate a minimum fatigue life of 4 x 10^5 cycles. **The greater sensitivity of the glass fibre-reinforced laminates to cyclic fatigue is due to the lower stiffness of glass fibres, thus resulting in higher strains within the matrix.**

3.2 RESIDUAL TENSILE PROPERTIES

Residual strength and stiffness measurements were carried out on 3 mm and 15 mm wide unidirectional E-glass/F922 coupon specimens. The specimens were subjected to constant amplitude cyclic loading. The stress ratio **R** was equal to 0.1 and the normalised maximum stress ($\sigma_{MAX}/\sigma_{UTS}$) was 0.4. Tests were conducted at selected intervals appropriate to the lifetime of the test specimens.

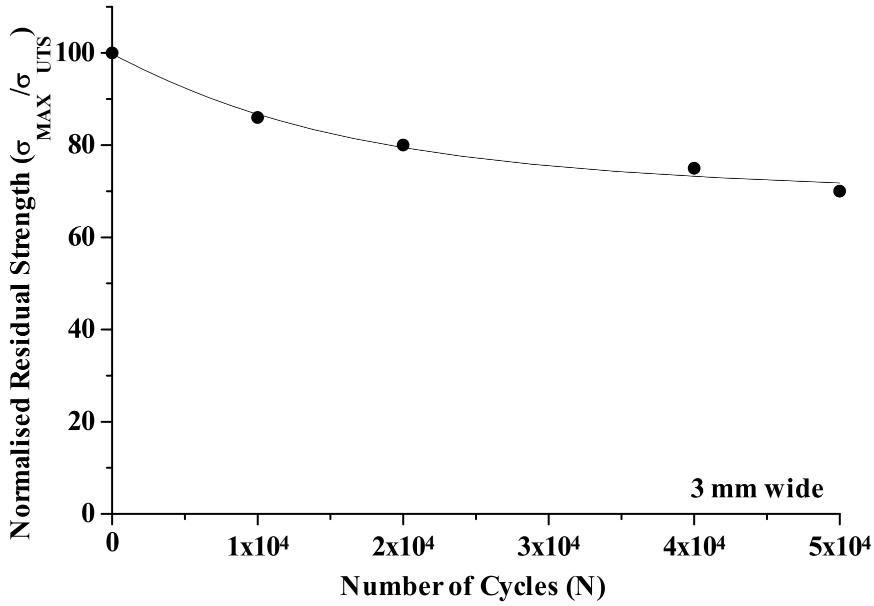

Figure 14: Residual strength versus cycles for 3 mm wide unidirectional E-glass/F922. (line added as a visual aid to show trends)

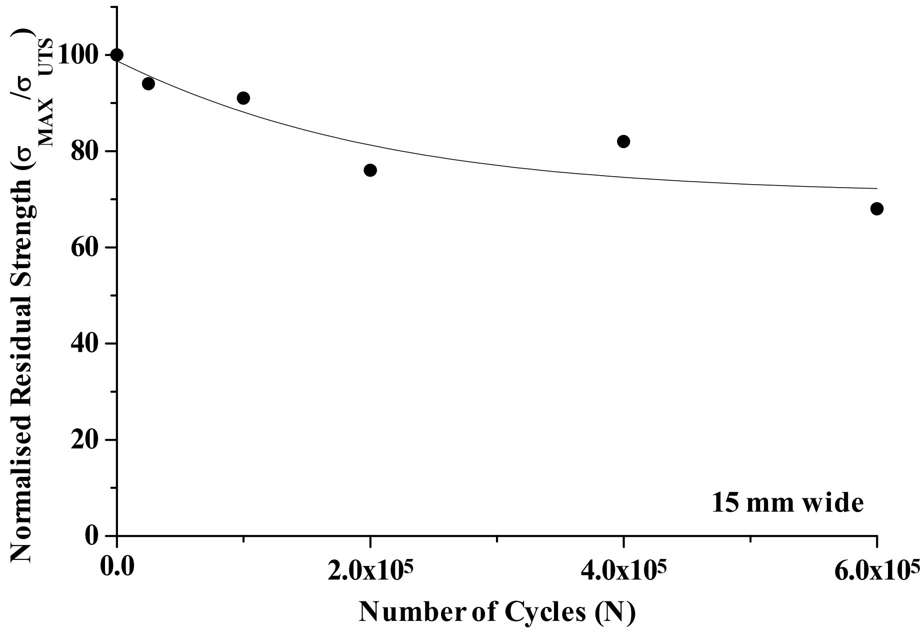

Figure 15: Residual strength versus cycles for standard width unidirectional E-glass/F922. (line added as a visual aid to show trends)

Normalised residual strength results, shown in Figures 14 and 15, indicate that there is a reduction in residual strength with loading cycles. The reduction in residual strength in both cases was similar to that observed for aligned glass/polyester rods (see [6]). There was no discernible change in longitudinal (or axial) modulus with loading cycles. The residual strength at $\mathbf{N_f}$ was approximately 70% UTS for both the 3 mm and 15 mm wide coupon specimens. Residual strength results (Figure 14) provide further evidence that the long-term performance of narrow strips is poor in comparison with the standard 15 mm wide specimens (see NPL report CMMT(A) 251 [11]). It is suspected that this because there is insufficient material to enable stress redistribution around regions of damage, which can extend 0.5 to 1.0 mm across the specimen width.

4. CROSS-PLY LAMINATES

This section presents the results from fatigue tests that were conducted on cross-ply glass/epoxy and carbon/epoxy laminates under standard laboratory conditions (i.e. 23 °C and 50% relative humidity (RH)). Tests were carried out on $[0/90]_{4S}$ E-glass/913 and T300/924, and $[0_2/90_2]_S$ E-glass/F922 and HTA/F22 laminates. The cross-ply specimens were subjected to constant amplitude tension-tension cyclic fatigue loading. As previously mentioned, two specimen configurations (i.e. straight-sided and dumbbell) were considered for cyclic fatigue testing of cross-ply laminates (see Section 2.3.2). It was expected that end failures that can occur in straight-sided specimens at high loads and/or high cycles would be eliminated for the dumbbell geometry, thus increasing the specimen fatigue life. This section examines the stress-life response, residual properties (i.e. stiffness and strength) and progressive transverse cracking of the cross-ply laminates. It also includes a description and results obtained from optical and acoustic emission techniques used for determining transverse crack density.

4.1 TENSILE PROPERTIES

This section presents the tensile test data (see Table 2) obtained for cross-ply glass/epoxy and carbon/epoxy laminates. Test conditions, data collection (i.e. strain and load measurements) and data analysis were identical to those employed for tension tests conducted on the unidirectional laminate specimens. The lay-ups tested and specimen geometry for each material are shown below:

(i) $[0/90]_{4S}$ E-glass/913 – straight-sided and dumbbell
(ii) $[0/90]_{4S}$ T300/924 – straight-sided and dumbbell
(iii) $[0_2/90_2]_S$ E-glass/F922 and HTA/F922 – straight-sided

Table 2: Measured Tensile Properties for Cross-Ply Laminates

Material	Tensile Modulus (GPa)	Poisson's Ratio	Tensile Strength (MPa)
E-glass/913			
Straight-sided	28.0 ± 1.3	0.154 ± 0.008	545 ± 8
Dumbbell	27.2 ± 1.0	0.152 ± 0.001	502 ± 19
E-glass/F922			
Straight-sided	29.4 ± 1.0	0.159 ± 0.010	486 ± 31
T300/924			
Straight-sided	67.1 ± 1.8	0.055 ± 0.008	736 ± 70
Dumbbell	70.8 ± 1.8	0.055 ± 0.007	661 ± 10
HTA/F922			
Straight-sided	64.4 ± 1.3	0.042 ± 0.001	814 ± 42

It is apparent from the tensile data, presented in Table 2 that the ultimate tensile strength measured for the straight-sided specimens was approximately 10% higher than that measured using the dumbbell specimens. The elastic properties remain unaffected. Failure in the dumbbell specimens invariably occurred in the vicinity of the fillet radii; a region of high tensile stress concentration. A larger fillet radius would probably improve the tensile strength results obtained using this specimen type.

4.2 STRESS-LIFE RESPONSE

Constant amplitude (sinusoidal waveform) fatigue tests were carried out on the two test specimen types (i.e. straight-sided and dumbbell) in load control using an Instron servo-hydraulic test machine at a frequency of 5 Hz. The stress ratio **R** was equal to 0.1. Test conditions were identical to those employed for the unidirectional materials. Five duplicate tests were generally carried out at six stress levels (i.e. 90%, 80%, 70%, 55%, 40% and 25% UTS). The lay-ups and materials tested using the two specimen types are shown below:

(iv) $[0/90]_{4S}$ E-glass/913 – straight-sided and dumbbell specimens
(v) $[0/90]_{4S}$ T300/924 – straight-sided specimens only
(vi) $[0_2/90_2]_S$ E-glass/F922 and HTA/F922 – straight-sided specimens only

Full **S-N** curves have been generated for both straight-sided and dumbbell $[0/90]_{4S}$ E-glass/913 specimens. The **S-N** curves and associated fatigue data for the two specimen types are shown in Figure 16. The fatigue strength data have been normalised with respect to the ultimate tensile strength, σ_{UTS}, of identically conditioned specimens measured at an equivalent loading rate to the fatigue test.

The **S-N** data for the $[0/90]_{4S}$ E-glass/913, as shown in Figure 16, can be represented by a normalised fatigue life equation (i.e. Equation (1)). The value of **k** (the fractional loss in tensile strength per decade of cycles) is approximately 0.1 for both the straight-sided and dumbbell E-glass/913 specimens. As previously mentioned, the value of **k** for unidirectional E-glass/913 and E-glass/F922 glass/epoxy laminates was also 0.1.

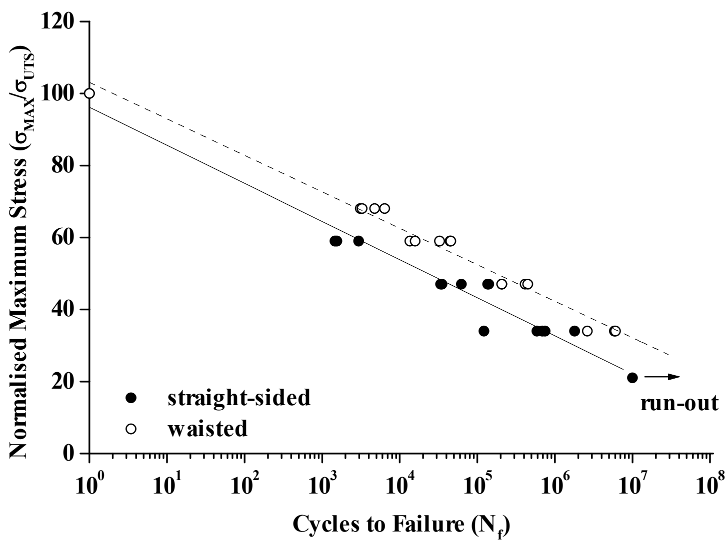

Figure 16: S-N curves for straight-sided and dumbbell cross-ply E-glass/913 specimens.

The results presented in Figure 16 clearly show an improvement in fatigue performance when the specimen was waisted. This was possibly due to stress relief at the fillet radii as a result of longitudinal splitting (see Figure 17). **Using dumbbell specimens also eliminates the tendency for the end tabs to debond, which can occur at high loads and/or high cycles.**

Figure 17: Typical failures for the straight-sided and dumbbell specimen types.

Figure 17 shows fatigue failures for the two specimen types tested at low stress levels. At higher stress levels, failure tends to occur at the end tabs for straight-sided specimens and at the fillet radius for dumbbell specimens. The sequence of damage development and failure modes observed for the cross-ply laminates under fatigue tensile loading was as follows:

(i) Longitudinal splitting at the fillet radii (applicable only to dumbbell specimens).
(ii) Formation of matrix cracks parallel to the fibres in the 90° plies (i.e. transverse cracking);
(iii) Transverse crack density increases with loading cycles forming a regular array of matrix cracks;
(iv) Formation of edge and local delaminations (Figure 16); and
(v) Fibre-breakage and longitudinal splitting in the primary or load-bearing (i.e. 0°) plies.
(vi) Final fracture was catastrophic and sudden, resulting in specimen separation

As previously mentioned, tests were carried out at six stress levels (i.e. 90%, 80%, 70%, 55%, 40% and 25% UTS). In this case, ultimate tensile strength (UTS) corresponded to the tensile strength measured at a displacement rate of 2 mm/min. It was therefore necessary to normalise the applied stress values after testing using the ultimate tensile strength as measured at the equivalent displacement rate experienced in the fatigue test. Figure 18 shows that the corrected **S-N** data for the $[0_2/90_2]_S$ E-glass/F922 can be represented by the normalised fatigue life equation (i.e. Equation (1)). The value of **k** (the fractional loss in tensile strength per decade of cycles) is 0.13 for the cross-ply E-glass/F922 laminate.

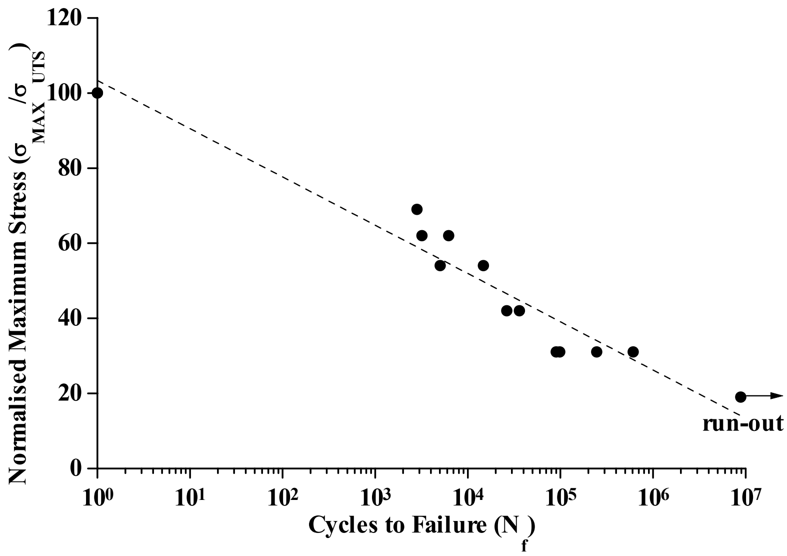

Figure 18: S-N curve for $[0_2/90_2]_S$ E-glass/F922.

A limited number of fatigue tests were conducted on straight-sided specimens fabricated from $[0/90]_{4S}$ T300/924 and $[0_2/90_2]_S$ HTA/F922 (see Figure 19). **Both carbon/epoxy**

materials showed excellent fatigue resistance (N_f > 4 x 10^6 cycles) at loads approaching 90% UTS and 70 UTS, respectively. End tabs were prone to debond during testing, and hence prevention of end tab debonding is essential for ensuring reliable fatigue data.

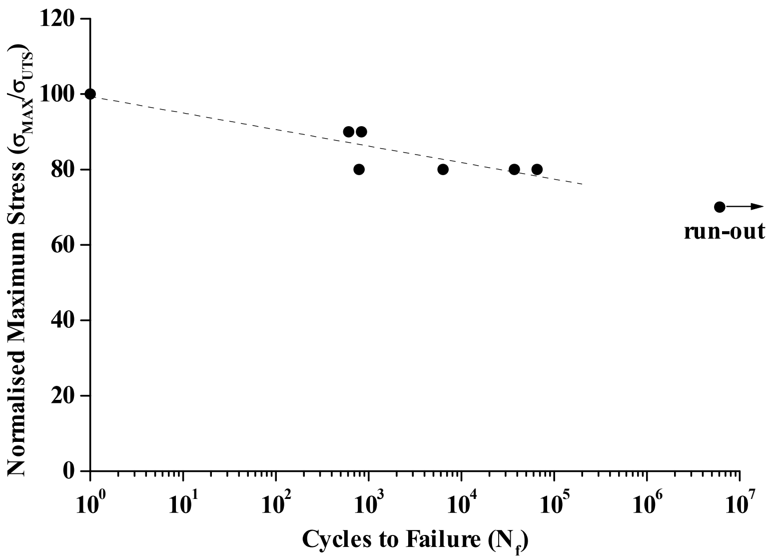

Figure 19: S-N curve for $[0_2/90_2]_S$ HTA/F922.

The **S-N** data for the $[0_2/90_2]_S$ HTA/F922 (Figure 18), unlike the equivalent E-glass/F922 laminate, can be represented by the normalised fatigue life equation (i.e. Equation (1)). The value of **k** (the fractional loss in tensile strength per decade of cycles) is 0.044 for the cross-ply HTA/F922 laminate.

4.3 PROGRESSIVE TRANSVERSE CRACKING

The appearance of transverse cracks in the 90° plies is usually the first visible indication of damage in cross-ply laminates (see Figure 20). Transverse cracking will often cause adverse affects, such as stiffness and strength reduction. An experimental study was carried out to investigate progressive transverse cracking in the 90° plies of cross-ply E-glass/F922 and HTA/F922 laminates resulting from monotonic tensile and tension-tension fatigue loading conditions. This section presents the results of a study in which the transverse crack density was measured as a function of applied stress under monotonic loading conditions. Optical techniques and acoustic emission (AE) were used to monitor transverse crack formation. Section 4.4 will examine the reduction of longitudinal modulus and Poisson's ratio with transverse cracking induced through tension-tension fatigue.

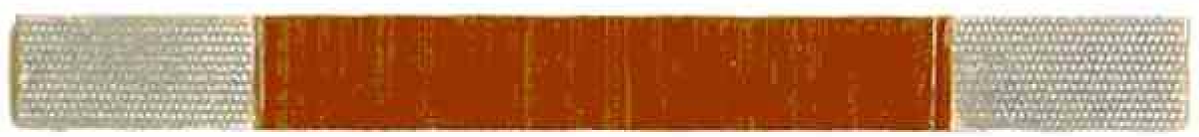

Figure 20: Transverse cracking of a cross-ply E-glass/F922 laminate.

Laminates were cracked using a step-wise monotonic mechanical loading technique. This method consisted of loading specimens to a specific stress level and then unloading, at which time the resultant crack density and elastic property data were measured. The specimen was then reloaded to a higher stress level and the process was repeated until the applied stress approached the ultimate tensile strength of the material. It was not possible to monitor crack formation optically during constant monotonic loading of the specimens.

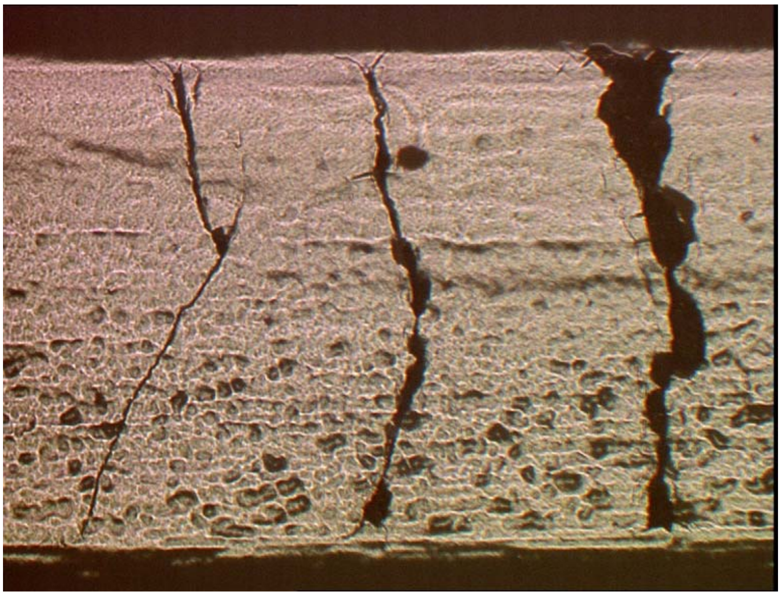

Figure 21: Magnified image of transverse cracks along an edge of a cross-ply laminate.

In the case of the glass/epoxy specimens, transverse cracks can be directly observed by illuminating the back of the specimen with a light source (Figure 20). This transmission technique, however, cannot be applied to carbon/epoxy and therefore an alternative approach was adopted. This consisted of smoothing the longitudinal edges of the coupon specimen with 1200 grade silicon carbide paper, wiping the surfaces with acetone and then coating the surfaces with a film using an Edding white paint marker. Specimens were left for several hours to dry. The marker pen produces a thick brittle layer that clearly shows crack formation in the cross-ply laminates (see Figure 21). A Vickers optical microscope (x 50 magnification) was used to count the transverse cracks (see Figure 21). This technique, however, was not entirely satisfactory. A test conducted on a $[0_2/90_2]_S$ glass/epoxy laminate showed that the number of cracks detected along the specimen edge was slightly less than the number of transverse cracks detected by the transmission technique (see Figure 22). **The transmission technique is a more reliable method for transverse crack density measurements, and hence its preferred use for glass/epoxy laminates.**

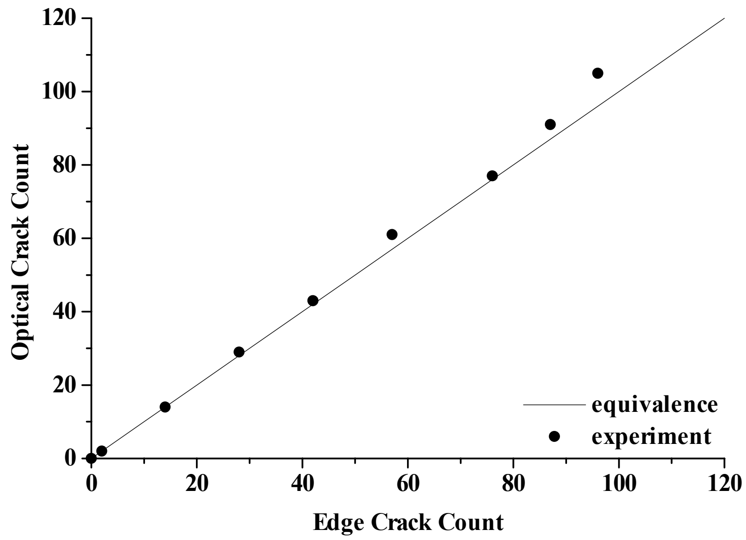

Figure 22: Comparison of edge crack and optical crack counts for $[0_2/90_2]_S$ E-glass/F922.

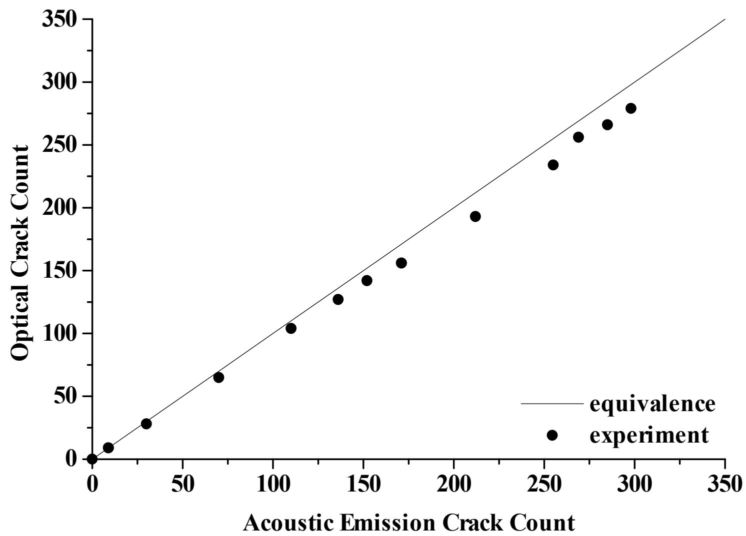

Figure 23: Comparison of optical and AE crack count data for $[0_2/90_2]_S$ E-glass/F922.

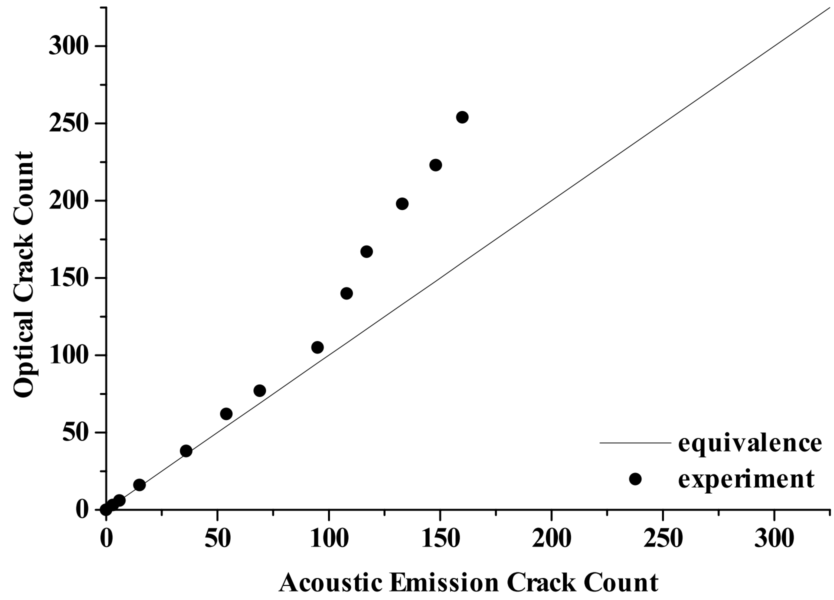

Figure 24: Comparison of optical and AE crack count data for $[0_2/90_4]_S$ E-glass/F922.

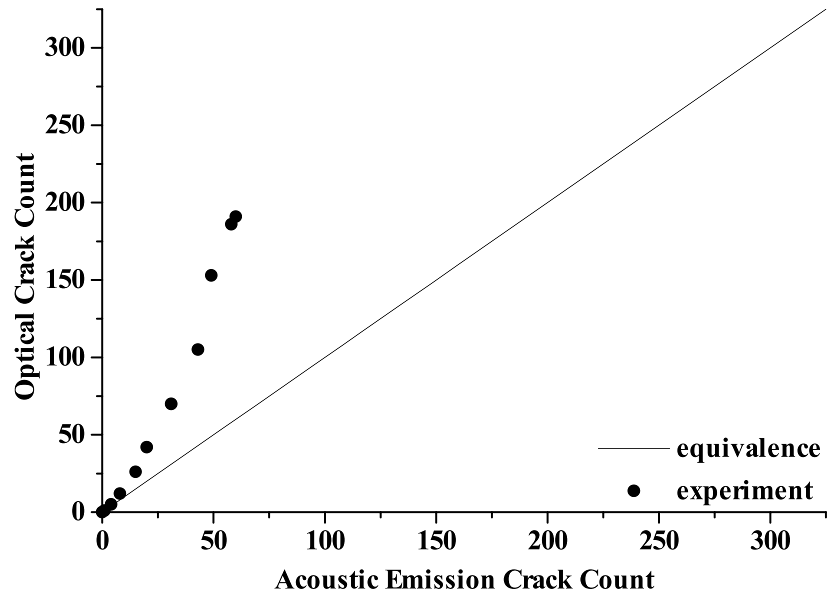

Figure 25: Comparison of optical and AE crack count data for $[0_2/90_8]_S$ E-glass/F922.

A MISTRAS AE system (Physical Acoustics Corporation) was also used to monitor the damage progression in the glass/epoxy during testing. **As it was not possible to differentiate between causes of AE events with increasing damage, the technique proved of limited use in detecting transverse cracking.** The results shown in Figures 23 to 25 clearly indicate that the reliability of the technique deteriorates with increasing thickness of the internal 90° plies. **Bifurcation of transverse cracks, which occurred frequently in the thicker laminates, could not be identified using acoustic emission.**

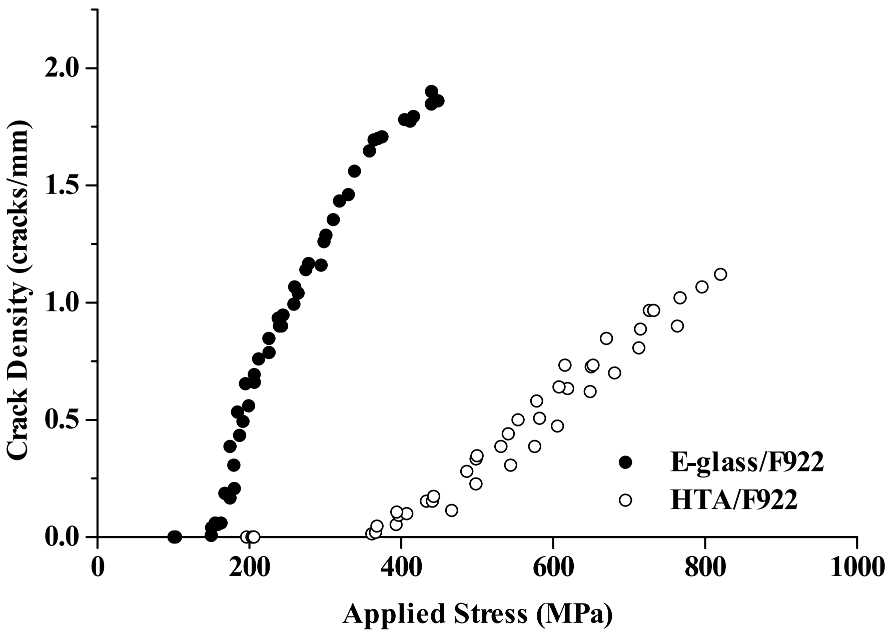

Figure 26: Comparison of crack density data for $[0_2/90_2]_S$ E-glass/F922 and HTA/F922.

Figure 26 shows crack density measurements for both $[0_2/90_2]_S$ E-glass/F922 and HTA/F922 laminates when subjected to monotonic tensile loading. Increasing the stiffness of the fibre reinforcement (i.e. substituting E-glass fibres with HTA carbon fibres whilst maintaining the same-lay-up and fibre content) resulted in an increase in the first ply failure (FPF) stress, and a reduction in the rate of transverse cracking and the maximum crack density. The maximum crack density values obtained prior to the onset of longitudinal splitting in the outer 0° plies for E-glass/F922 and HTA/F922 laminates were 1.90 and 1.22, respectively. There was no indication that crack saturation had occurred in either cross-ply laminate.

4.4 STIFFNESS DEGRADATION

4.4.1 $[0_2/90_2]_S$ E-glass/F922 and HTA/F922

This section compares elastic properties of $[0_2/90_2]_S$ E-glass/F922 and HTA/F922 laminates under tension-tension fatigue with monotonic tensile data and predictive analysis. Specimens were subjected to one of six stress levels (i.e. 90%, 80%, 70%, 55%, 40% and 25% UTS) and the effects of progressive transverse cracking on the longitudinal (or axial) stiffness and Poisson's ratio were monitored as a function loading cycles, **N**, and/or transverse crack density. The value of **R** was equal to 0.1. Transverse crack and elastic property measurements were carried out on a number of $[0_2/90_2]_S$ E-glass/F922 and HTA/F922 laminates at suitable intervals (e.g. **N** = 1, 10, 100, 1000, 10,000 cycles, etc.) during fatigue testing.

A number of observations, shown below, were made in relation to the fatigue tests performed on the $[0_2/90_2]_S$ E-glass/F922 and HTA/F922 laminates (see Figures 27 and 28).

- **Elastic properties were sensitive to crack formation, particularly Poisson's ratio with the reduction in elastic properties appearing to be directly related to the transverse crack density.**

- Transverse cracking had a greater effect on the elastic properties of cross-ply glass/epoxy laminates. The combined effect of increased damage (see Figure 26) and the larger contribution made by 90° plies to the overall laminate stiffness for these materials, compared with equivalent carbon/epoxy laminates, results in a more severe reduction in stiffness for glass/epoxy.

- **Rate of transverse cracking and stiffness loss decreases as the amplitude of applied stress is reduced.**

- **Although Poisson's ratio is highly sensitive to the presence of transverse cracks, the large uncertainty associated with the test data makes it difficult to use this parameter for monitoring the level of degradation (see Figures 27 and 28).** Poisson's ratio values are based on very small transverse strain measurements, and hence small fluctuations translate into large errors.

- **Transverse crack density at failure (i.e. $N = N_f$) for tension-tension fatigue is similar in magnitude to that observed close to failure for monotonic tension tests (Table 3). The elastic properties at failure were also in close agreement for the two loading modes.**

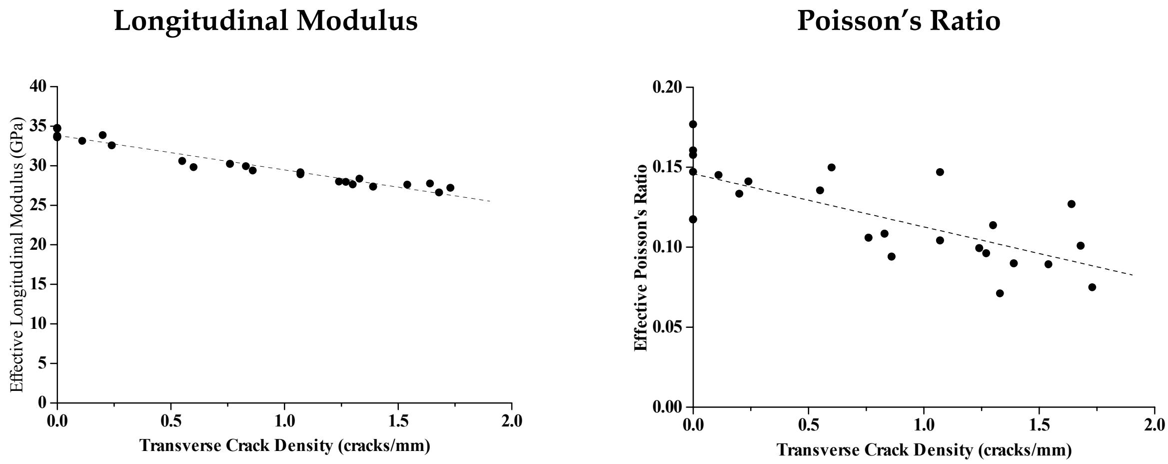

Figure 27: Axial stiffness and Poisson's ratio reduction in $[0_2/90_2]_S$ E-glass/F922 laminate. (lines added as a visual aid to show trends)

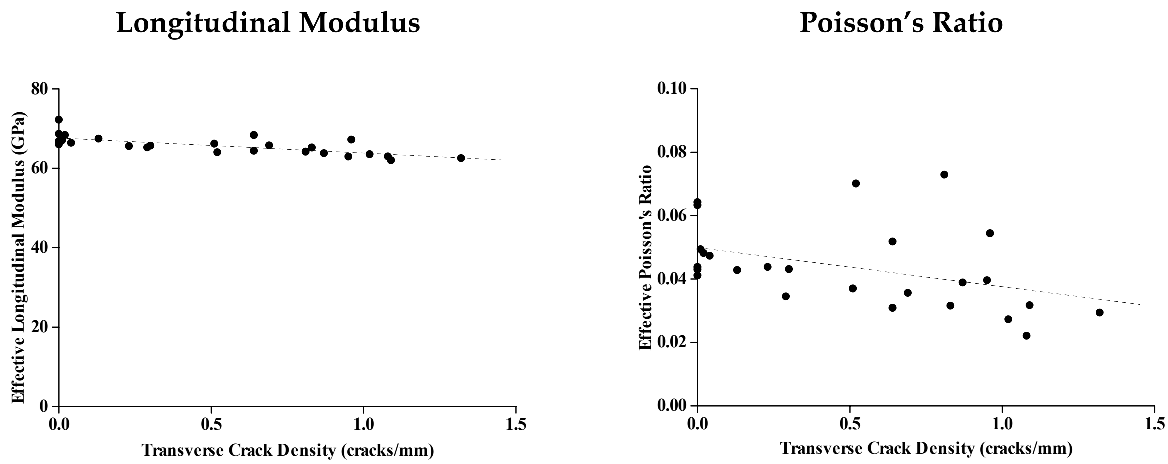

Figure 28: Axial stiffness and Poisson's ratio reduction in $[0_2/90_2]_S$ HTA/F922 laminate. (lines added as a visual aid to show trends)

Table 3 compares measured and predicted initial (undamaged) and final values of longitudinal stiffness and Poisson's ratio for $[0_2/90_2]_S$ E-glass/F922 and HTA/F922 laminates. Predicted values were determined using CoDA (Composite Design and Analysis) preliminary design software developed by NPL. It should be noted that the final values in Table 3 denote elastic properties of the laminate close to failure (i.e. $\sigma_{APP} \approx \sigma_{UTS}$ or $N \approx N_f$, depending on loading mode). Large variations in fatigue life (a factor of 10) made it difficult to measure the transverse crack density and elastic properties near the end of life ($N \approx N_f$). The differences between initial values of longitudinal stiffness and Poisson's ratio for monotonic and fatigue loading modes can be attributed to variations in material properties between panels. The tensile and fatigue specimens were taken from separate panels.

Table 3: Elastic Properties of $[0_2/90_2]_S$ E-glass/F222 and HTA/F922 Laminates

Material/Mode	Longitudinal Modulus (GPa)		Poisson's Ratio	
	Initial	Final	Initial	Final
E-glass/F922				
Monotonic	29.4	23.5	0.159	0.084
Fatigue	34.0	27.7	0.146	0.087
Predicted	28.6	22.1	0.162	0.084
HTA/F922				
Monotonic	64.4	60.7	0.042	0.040
Cyclic fatigue	68.1	64.5	0.051	0.038
Predicted	70.2	66.3	0.040	0.019

The preliminary design analysis used in CoDA to predict the elastic properties of the cross-ply laminates can be considered in most cases to be satisfactory. The large uncertainty associated with Poisson's ratio measurements makes it difficult to compare predictive values with experimental results, particularly for the damaged material. The predictive analysis assumes that a transverse ply fully saturated with matrix cracks is unable to contribute to the load-bearing capacity of the cross-ply laminate (i.e. full ply discount).

Note. Transverse crack measurement and stiffness loss data will be compared with predictive modelling in future reports (see also [12]). Indications are that predictions from the plain strain model developed by Dr L N McCartney at NPL are generally in good agreement with the experimental data. Reports on predictive modelling will be available in the near future.

4.4.2 $[0/90]_{4S}$ E-glass/913

Tension-tension fatigue tests carried out on $[0/90]_{4S}$ E-glass/913 specimens also resulted in stiffness degradation. The effect of cyclic loading on the longitudinal tensile modulus, E_{xx}, can be seen in Figure 29. Crosshead displacement and longitudinal strain were monitored throughout the entire duration of the fatigue test. A contact extensometer was also used in a number of tests to measure longitudinal strain with loading cycles. The stiffness measurements for the two techniques (i.e. cross-head displacement and extensometer) produced similar results. The effective modulus determined from the crosshead was always slightly lower than that measured directly from the specimen with the contact extensometer. Differences were due to the loading train compliance, which when taken into account should result in almost identical values to the contact technique. The results shown in Figure 29 were obtained using a contact extensometer. **Care should be taken to avoid possible extensometer damage as a result of fatigue loading or final failure. It is also important that extensometer knife-edges do not nick or cut the specimen edges as the damage may reduce fatigue life.**

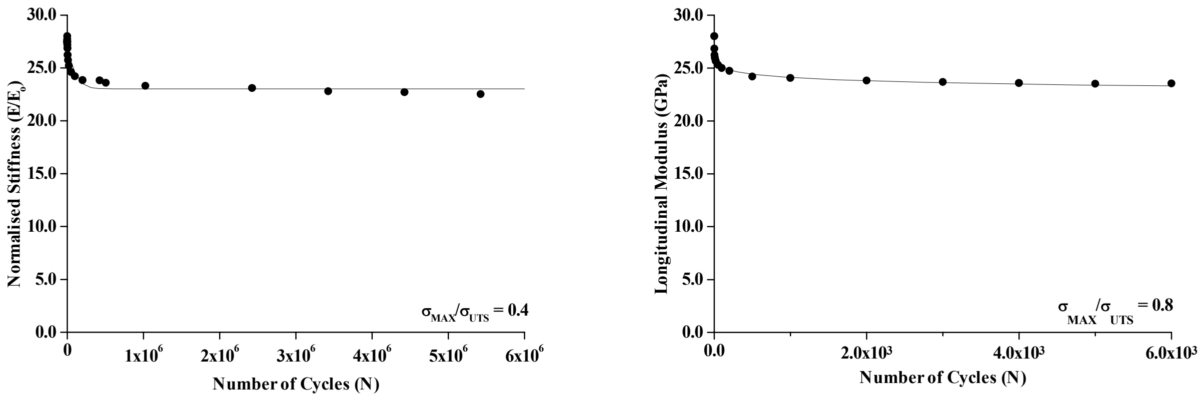

Figure 29: Reduction in stiffness versus cycles for cross-ply E-glass/913 laminates.

Increasing either the amplitude (see Figure 29) or mean value of the sinusoidal load results in an increase in the fractional loss in stiffness per decade of cycles. In all cases, the effective modulus at failure was approximately 0.8$\mathbf{E}_{xxo}$. This value is equivalent to that predicted for a laminate of equal thickness, but with no load-bearing contribution from the 90° plies (i.e. full ply discount). The modulus reduction is mainly the result of ply failures and, to a far lesser degree, ply delaminations.

4.5 STRENGTH DEGRADATION

This section examines the consequences of constant amplitude tension-tension fatigue on the strength of $[0_2/90_2]_S$ E-glass/F922 and HTA/F922, and $[0/90]_{4S}$ E-glass/913 laminates.

4.5.1 $[0_2/90_2]_S$ E-glass/F922 and HTA/F922

Straight-sided coupon specimens fabricated from $[0_2/90_2]_S$ E-glass/F922 and HTA/F922 were subjected to constant amplitude cyclic loading for selected number of cycles and then tested to failure. The value of **R** was equal to 0.1 and the normalised maximum stress, $\sigma_{MAX}/\sigma_{UTS}$, was 0.4 and 0.8 for the E-glass/F922 and HTA/F922, respectively. Tests were conducted at selected intervals appropriate to the lifetime of the test specimen. Residual strength results are shown in Figures 30 and 31.

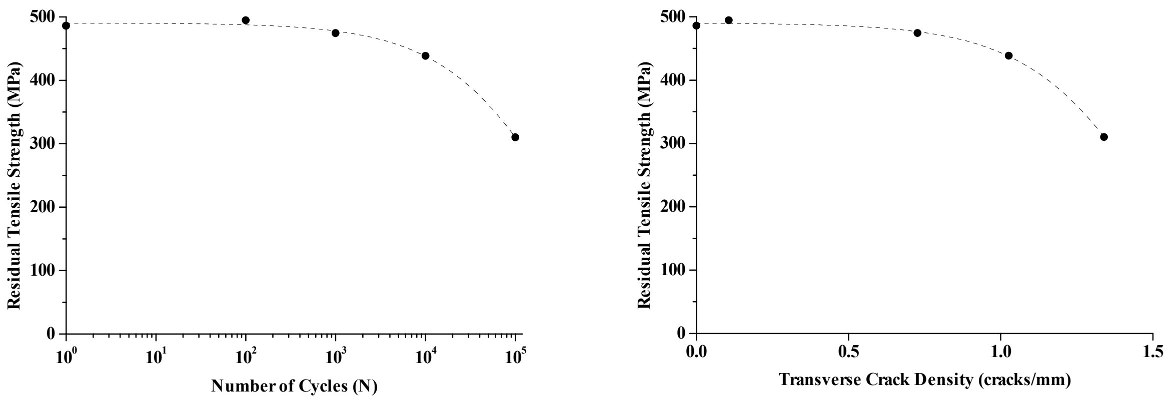

Figure 30: Strength reduction in $[0_2/90_2]_S$ E-glass/F922 laminate ($\sigma_{MAX}/\sigma_{UTS}$ = 0.4).
(lines added as a visual aid to show trends)

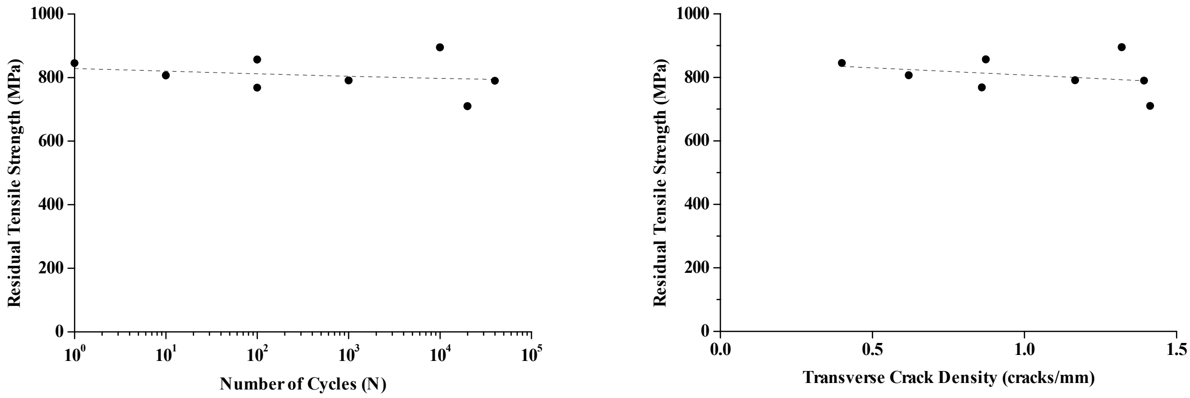

Figure 31: Strength reduction in $[0_2/90_2]_S$ HTA/F922 laminate ($\sigma_{MAX}/\sigma_{UTS}$ = 0.8). (lines added as a visual aid to show trends)

The results shown in Figures 30 and 31 indicate that there is a reduction in residual strength during fatigue life caused by transverse cracking in the 90° plies and possible fibre fracture in the 0° plies. In the case of cross-ply HTA/F922 composite, the strength reduction during the fatigue life is constant and gradual. The same trend was not observed for the cross-ply E-glass/F922 system. The rate of strength reduction for this composite was initially rapid, decreasing with increasing loading cycles. The relative reduction in residual strength was also far larger for the glass/epoxy laminate. Direct comparisons of strength reduction for the two materials can only be made at relatively high stress levels (i.e. $\sigma_{MAX}/\sigma_{UTS} \geq 0.7$) due to the fact that the carbon/epoxy system has excellent fatigue resistance.

Damage progression in cross-ply glass/epoxy laminates may be considered to have three distinctive stages:

Stage I is characterised by an initial rapid loss in axial stiffness and strength caused by transverse cracking in the 90° plies and possible fibre fracture in the 0° plies.

Stage II a long period of gradual stiffness and strength reduction through additional transverse cracking, crack coupling along ply interfaces and internal delaminations.

Stage III is characterised by a rapid reduction in axial stiffness and strength resulting from an increase in damage (i.e. delaminations and fibre breakage) growth rates. It is worth noting that changes in material properties at the end of fatigue life were too difficult to monitor. Final fracture was rapid and catastrophic, occurring within 1or 2 loading cycles.

4.5.2 $[0/90]_{4S}$ E-glass/913

Testing involved the use of dumbbell coupon specimens, which were subjected to constant amplitude cyclic loading for selected numbers of cycles and then tested to failure. As previously, the value of **R** was equal to 0.1. The normalised maximum stress, $\sigma_{MAX}/\sigma_{UTS}$, was 0.55. Tests were conducted at selected intervals appropriate to the lifetime of the test specimen. Residual strength results, shown in Figure 32, indicate that there is a reduction in residual strength with loading cycles. The residual strength at $\mathbf{N_f}$ was approximately 80% of the ultimate tensile strength, σ_{UTS}, of the cross-ply laminate. This reduction in tensile strength was identical to that observed for the stiffness measurements; this is to be expected if full ply discount theory applies.

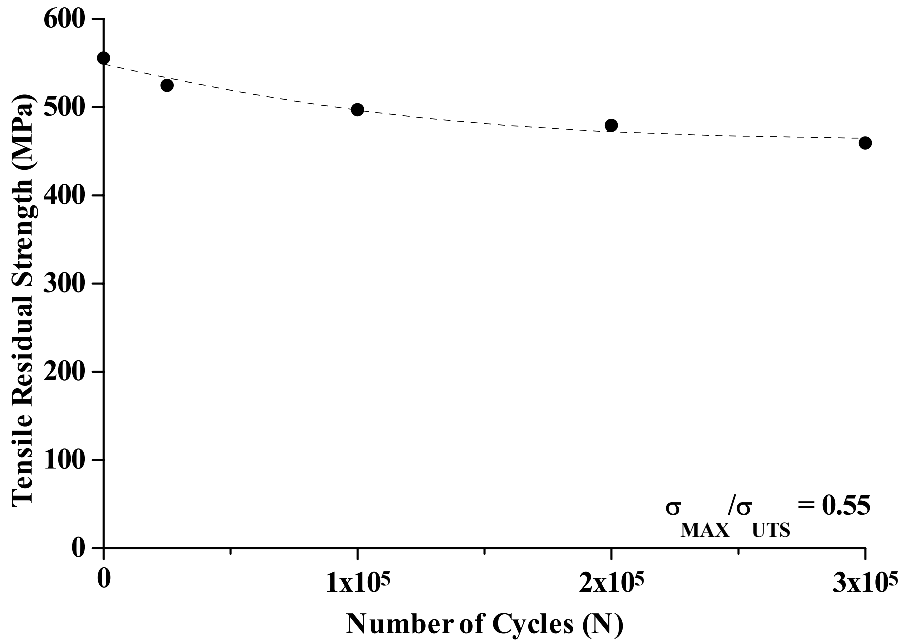

Figure 32: Strength reduction during fatigue cycling for $[0/90]_{4S}$ E-glass/913. (line added as a visual aid to show trends)

5. DISCUSSION AND CONCLUSIONS

The principal conclusions that can be drawn from the study of fatigue performance of unidirectional and cross-ply glass/epoxy and carbon/epoxy laminates are summarised below.

Tensile Test Methods/Standards

- Test geometries as specified in the international standards ISO 527-4 and ISO 527-5 are suitable for assessing the performance under constant amplitude tension-tension fatigue loading conditions.

- Tensile strength values obtained for unidirectional glass/epoxy and carbon/epoxy laminates were unaffected by end tab geometry (i.e. square ended tabs (as specified in ISO 527-5), integrated (i.e. in-built) end tabs and end tabs with an inverted taper).

- Waisting the cross-ply laminates (i.e. dumbbell specimens) improved fatigue performance and prevented the problem of end tabs debonding at high loads and/or high cycles, which can result in lower fatigue life. However, the ultimate tensile strength measured for the straight-sided specimens was approximately 10% higher than that measured using the dumbbell specimens. Elastic properties were unaffected by specimen geometry. Failure in the dumbbell specimens invariably occurred in the vicinity of the fillet radii; a region of high tensile stress concentration. A larger fillet radius (i.e. greater than 60 mm) would probably improve the tensile strength results, and also the fatigue performance.

Progressive Transverse Cracking in Cross-Ply Laminates

- The transmission optical technique proved the most reliable method for monitoring progressive transverse cracking in cross-ply glass/epoxy. The number of transverse cracks observed using the edge crack measurement technique was 5-10% less than that observed using the transmission technique. X-ray diffraction techniques may prove more suitable for measuring transverse cracks in carbon/epoxy laminates.

- Acoustic emission (AE) proved unsatisfactory for counting transverse cracks, particularly for glass/epoxy laminates. In most cases, it proved impossible to identify the cause of the AE events. Limited success was achieved with $[0_2/90_2]_S$ glass/epoxy laminate.

- Elastic properties (particularly Poisson's ratio) and residual strength of cross-ply laminates were sensitive to progressive transverse cracking with the reduction in elastic properties appearing to be directly related to the transverse crack density. The large uncertainty associated with Poisson's ratio measurements make it difficult to accurately monitor progressive damage using this parameter.

Fatigue Performance of Unidirectional Laminates

- Continuous aligned carbon fibre-reinforced composites have excellent fatigue resistance under constant amplitude tension-tension loading conditions.

- Fatigue performance of narrow unidirectional laminates is poor in comparison with the standard test geometry.

- The normalised fatigue life (**S-N** data) of unidirectional glass fibre-reinforced laminates can be generalised by the following relationship:

$$\sigma_{MAX} / \sigma_{UTS} = 1 - k \log_{10} N_f$$

  where $\boldsymbol{\sigma_{MAX}}$ is the maximum applied load, $\boldsymbol{\sigma_{UTS}}$ is the ultimate tensile strength, **k** (the slope) is the fractional loss in tensile strength per decade of cycles and $\mathbf{N_f}$ is the number of cycles to failure. The value of **k**, which is dependent on the stress ratio **R**, is approximately 0.1 for a stress ratio **R** = 0.1. The above equation can be used to characterise the **S-N** data with reasonable accuracy.

- Increasing either the amplitude or mean value of the sinusoidal load reduces fatigue life. For aligned E-glass/913, the relationship between **k** and **R** can be approximated by the following equation:

$$k = 0.11 - 0.07R$$

- The residual strength at $\mathbf{N_f}$ was approximately 70% of the ultimate tensile strength, $\boldsymbol{\sigma_{UTS}}$, for the unidirectional glass/epoxy laminates fatigued at 40% UTS. Effective longitudinal modulus remains unaltered throughout the fatigue lifetime.

Fatigue Performance of Cross-Ply Laminates

- Cross-ply carbon fibre-reinforced composites have excellent fatigue resistance under constant amplitude tension-tension loading conditions.

- Rate of transverse cracking and stiffness loss in cross-ply laminates decreases as the amplitude of applied stress is reduced.

- The normalised fatigue life (**S-N** data) of $[0/90]_{4S}$ E-glass/913, and $[0_2/90_2]_S$ E-glass/F922 and HTA/F922 laminates can be generalised by the following relationship:

  $$\sigma_{MAX} / \sigma_{UTS} = 1 - k \log_{10} N_f$$

  For a stress ratio **R** = 0.1, the value of **k** is approximately 0.10, 0.13 and 0.044 for E-glass/913, E-glass/F922 and HTA/F922 laminates, respectively.

- Transverse cracking had a greater effect on the elastic properties of cross-ply glass/epoxy laminates. The combined effect of increased damage (see Figure 26) and the larger contribution made by 90° plies to the overall laminate stiffness for these materials, compared with equivalent carbon/epoxy laminates, results in a more severe reduction in stiffness for glass/epoxy.

- Transverse crack density at failure (i.e. $N = N_f$) for tension-tension fatigue of cross-ply glass/epoxy and carbon/epoxy laminates is similar in magnitude to that observed close to failure for monotonic tension tests. The elastic properties at failure are also in close agreement for the two loading modes.

- The preliminary design analysis used in CoDA to predict the elastic properties of the cross-ply laminates can be considered in most cases to be satisfactory. The large uncertainty associated with Poisson's ratio measurements prevented a reliable comparison between predicted values and experimental results, particularly for the damaged material. The predictive analysis assumes that a transverse ply fully saturated with matrix cracks is unable to contribute to the load-bearing capacity of the cross-ply laminate (i.e. full ply discount). Ply discount theory, which proved successful in predicting laminate stiffness prior to both FPF and ultimate failure, can also be used to "approximate" the tensile strength at the end of fatigue life.

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