

Cyclic Fatigue of Continuous Unidirectional Polymer Matrix Composites

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ABSTRACT

Test methods have been developed within the *Composites Performance and Design Project - Life Assessment and Prediction (CPD2)* for characterising the tensile properties of fibre bundles and impregnated strands under static and cyclic loading conditions. Tests have been carried out on both glass-fibre and carbon-fibre reinforced systems in order to evaluate the suitability of the test methods for accelerating testing and for generating cyclic fatigue data. This report provides an assessment of the test methods and the data generated using these techniques under static and cyclic loading conditions. Effects of strain rate, gauge-length and diameter on the tensile properties of composite rods have been included in the report along with the results from a comparative study carried out on narrow (i.e. 3 mm wide) and standard (i.e. 15 mm wide) unidirectional laminates to assess scaling effects.

The principal conclusions that can be drawn from the results are: (i) glass-fibre and carbon-fibre bundles, and continuous aligned carbon fibre-reinforced laminates have excellent fatigue resistance at loads approaching the tensile strengths for these materials; (ii) fatigue performance of small diameter glass fibre-reinforced rods and narrow unidirectional laminates is poor in comparison with the standard test specimen geometry; and (iii) the current standard for preparation and testing of composite rods requires revision to accommodate the determination of tensile strength. The report includes recommendations on preparation and testing of fibre bundles and composite rods.

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head of Centre for Materials Measurement and Technology.

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1. INTRODUCTION

This report provides an assessment of test methods developed for characterising the tensile properties of fibre bundles and impregnated strands under static and cyclic loading conditions. The research described in this report forms part of the DTI funded project *Composites Performance and Design - Life Assessment and Prediction (CPD2)*. This is directed towards the development and validation of test methods and predictive models that can be used for characterising polymer matrix composites (PMCs) exposed to combined aggressive environments and applied loads. Tests have been carried out on both glass-fibre and carbon-fibre reinforced systems to evaluate the suitability of the test methods for accelerating testing and for generating cyclic fatigue data. The programme examined the effects of varying strain rate, gauge-length and rod diameter on the measured tensile properties of composite rods. A comparative study was also carried out on narrow (3 mm wide) and standard (15 mm wide) unidirectional laminates to assess scaling effects.

The report is divided into five sections including the Introduction. Section 2 describes the materials used to validate the test methods in the programme, together with specimen geometry and specimen preparation. Tensile test results for fibre bundles and impregnated tows (i.e. composite rods) are presented in Section 3. Strain rate, gauge-length and diameter effects on tensile properties are also considered in this section. Section 4 considers the cyclic fatigue performance of fibre tows and composite rods. Conclusions and recommendations are presented in Section 5. **Throughout this report, statements of particular importance or relevance are highlighted in bold type.**

2. MATERIALS CHARACTERISATION

2.1 MATERIALS DESCRIPTION

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

- (a) E-glass (1,878 g/km or Tex) and Grafil 34-700 carbon (779 Tex) fibre tows supplied by RBJ.
- (b) Pultruded glass fibre-reinforced polyester rods (glass/polyester). The composite consisted of axially aligned E-glass fibres impregnated with Scott Bader Crystic 196 orthophthalic polyester. Rods of varying diameter, ranging from 1.5 mm to 5.0 mm, were obtained from RBJ. The rods were post cured for 3 hours at 80 °C.
- (c) Pultruded carbon fibre-reinforced vinylester (carbon/vinylester) rods. The composite consisted of axially aligned Grafil 34-700 carbon fibres impregnated with Norpol Dion 9100. Norpol Dion 9100 is a non-accelerated, Bisphenol-A epoxy based vinylester resin. Rods of varying diameter, ranging from 1.5 mm to 5.0 mm, were obtained from RBJ. The rods were post cured for 3 hours at 80 °C.
- (d) Autoclave compacted continuous unidirectional glass fibre-reinforced epoxy prepreg sheet (E-glass/Fibredux F922). Laminates were manufactured at the National Physical Laboratory (NPL). The laminates were autoclaved and post-cured to Hexcel Composites specifications.

- (e) Autoclaved continuous unidirectional glass fibre-reinforced epoxy prepreg sheet (E-glass/Fibredux 913). Laminates were manufactured at NPL to Hexcel Composites specifications.
- (f) Autoclaved continuous unidirectional carbon fibre-reinforced epoxy prepreg sheet (Torayca T300/Fibredux 924). Laminates were manufactured (including post curing) at NPL to Hexcel Composites specifications.

On delivery, all rods and panels were visually inspected for evidence of damage or processing defects.

2.2 FIBRE CONTENT AND COMPOSITE DENSITY

Fibre volume fraction, V_f , fibre weight fraction, 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 rods and 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, 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/epoxy panels and carbon/vinylester rods 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/m ³)	Volume Fraction (%)	Weight Fraction (%)
E-glass/polyester	1,862 ± 21	50.56 ± 1.10	69.50 ± 0.56
Carbon/vinylester	1,484 ± 2	50.68 ± 1.15	61.49 ± 1.34
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
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

2.3 SPECIMEN GEOMETRY AND PREPARATION

This section describes the test methods and specimen geometries used for testing fibre tows, composite rods and unidirectional laminates. Details of specimen preparation for each method are also covered.

2.3.1 Fibre Bundles

Tensile and cyclic fatigue (tension-tension) tests were carried out on unimpregnated E-glass and Grafil 34-700 carbon fibre tows using the specimen geometry shown in Figure 1.

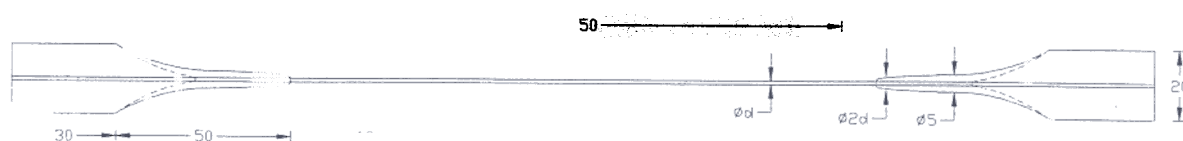


Figure 1 Schematic of fibre tow test specimen (mm).

Specimen preparation was carried out according to BS ISO 9163 [4]. A cold-curing epoxy system based on Araldite® LY 5052/hardener HY 5052 (Ciba Speciality Chemicals) was used to produce the end tabs. **It is important that the resin system has low viscosity to ensure full impregnation of the fibres within the tab region and good mechanical and dynamic properties.** Figure 2 shows a photograph of a fibre tow specimen.



Figure 2 Fibre tow test specimen

The end tabs were cast in silicon moulds, using BS ISO 9163 specifications as a guide, and cured at 80 °C for 20 minutes. The silicon moulds were produced using a two-part, low-shrinkage, room-temperature curing silicon elastomer. **Care was taken to ensure that the mould was free of air bubbles (degassed) and the internal surfaces of the mould were smooth and free of defects.** Moulds tend to split and break due to constant handling and therefore need to be replaced on a regular basis (5-6 castings per mould). A schematic diagram showing the dimensions of the template used for producing the moulds is presented in Figure 3.

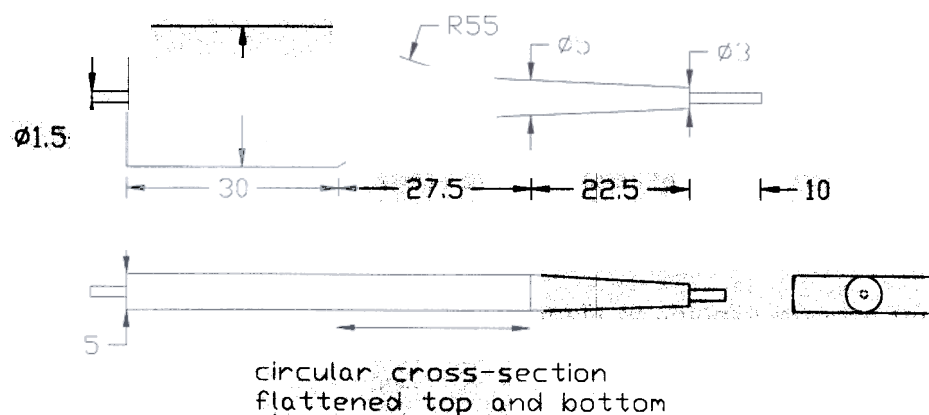


Figure 3 Schematic of moulding template used for producing end tabs (mm).

2.3.2 Composite Rods

The test geometry specified in BS ISO 9163 proved unsatisfactory for measuring the tensile strength of composite rods with diameters of 1.5 mm or greater. It was found that the interface between the composite rod and epoxy resin end tabs yielded/failed prematurely; resulting in pull-out of the composite rod rather than tensile failure within the gauge-length. As a result, a new method was developed for producing end tabs for the composite rods. Figure 4 shows a schematic of the composite rod specimen and end tab used for testing glass/polyester and carbon/vinylester pultruded rods with a nominal diameter of 1.5 mm.

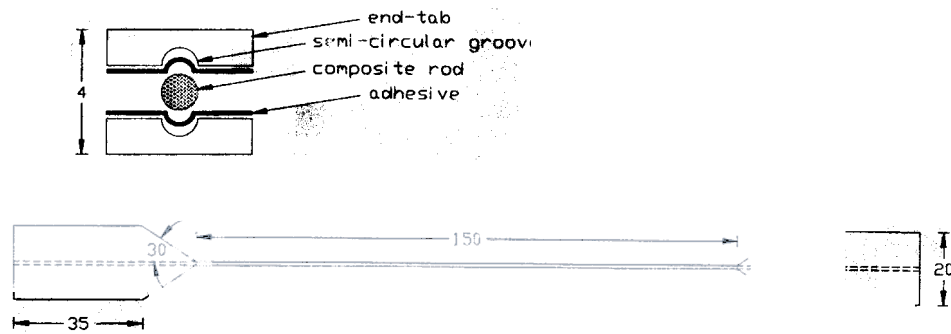


Figure 4 Schematic of composite rod specimen and end tab (mm).

The end tabs were manufactured from a plain woven glass fabric reinforced epoxy laminate (1.6 mm thick) with the fibre axes of the fabric set at $\pm 45^\circ$ to the specimen axis. A high elongation adhesive was used to bond 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. The carrier ensured good contact and constant bondline thickness, reducing adhesive loss. Specimen preparation was also relatively clean in comparison to paste adhesives. The semi-circular groove, shown in Figure 4, was cut with a 1.5 mm thick diamond slitting wheel (water lubricated). It is essential that the end tabs are dried before bonding to remove moisture, which can compromise the adhesive bond.

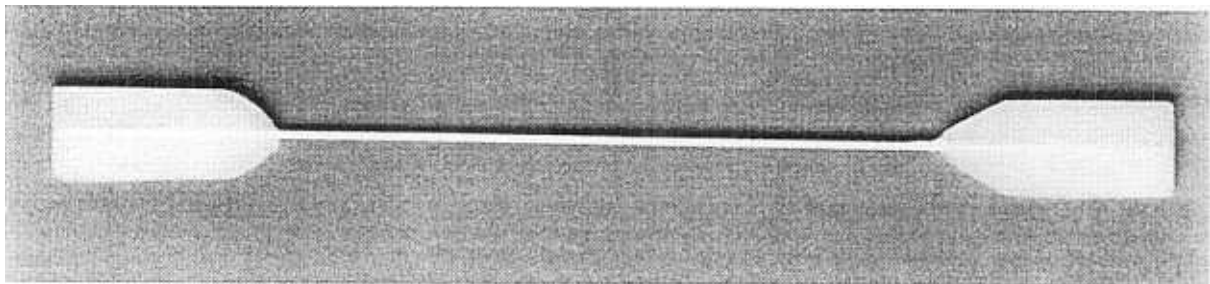


Figure 5 Composite rod specimen with bonded end tabs.

The test geometry shown in Figure 5 is limited to rods with diameters of 1.5 mm or less. Testing of larger diameter rods required cylindrical moulded end tabs made with a high shear strength adhesive paste (Figure 6). Tests were carried out on composite rods with diameters ranging from 1.5 to 4.5 mm using moulded end tabs that were 1.25 mm thick and 50 mm long. This procedure proved successful for testing rods up to approximately 3 mm in diameter with tensile failure consistently occurring within the gauge-length. Larger diameter rod specimens tended to crush in the grips. This may be remedied by using thicker moulded end tabs and/or by adjusting the V-notch angle on the jaw face of the grips to ensure the points of contact are equidistant around the circumference.

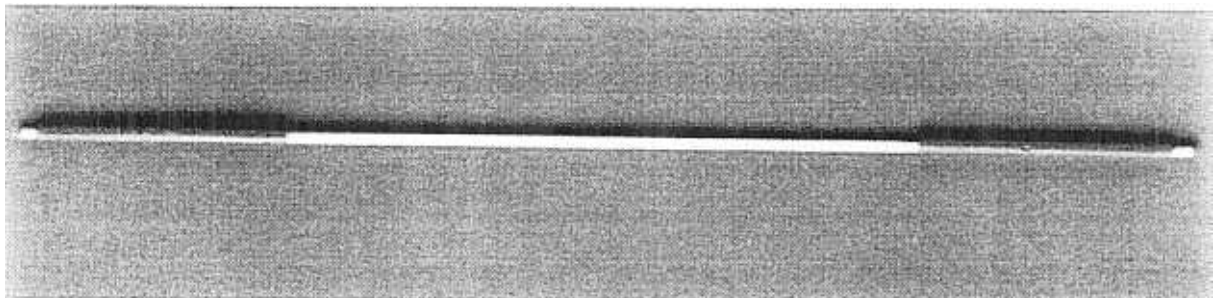


Figure 6 Composite rod specimen with moulded end tabs.

2.3.3 Unidirectional Laminates

Comparative tests were carried out on narrow (i.e. 3 mm wide) and standard (i.e. 15 mm wide) unidirectional laminates to determine the suitability of using narrow width specimens for accelerated test purposes. Specimen preparation of unidirectional laminates was carried out to BS EN ISO 527-5 [5] specifications. Standard specimens (Figure 7) 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 $\pm 45^\circ$ 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. The narrow laminate strips were 3 mm wide and 2 mm (i.e. 16 plies) thick. Apart from the differences in width and thickness, all other aspects of specimen geometry and preparation were the same as that for the standard test specimen.

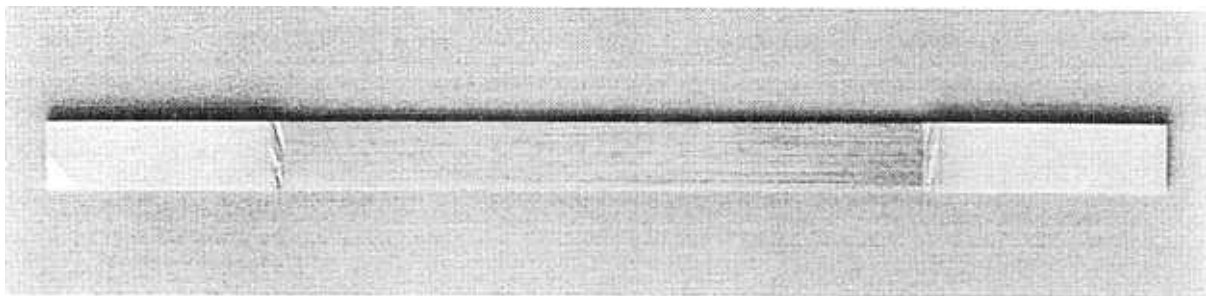


Figure 7 Continuous unidirectional glass fibre-reinforced laminate.

3. TENSILE TESTS

This section presents and discusses the results from static (or monotonic) tension tests conducted on E-glass and Graphil 34-700 fibre tows, and glass/polyester and carbon/vinylester rods.

3.1 FIBRE BUNDLES

The tensile stress at break of E-glass and Grafil 34-700 carbon fibre tows was determined using BS ISO 9163. Specimens were loaded to failure at a displacement rate of 2 mm/min under standard laboratory conditions (i.e. 23°C , 50% RH). Tests were conducted on 10 specimens per material. Displacement was determined directly from the cross-head movement. The tensile results are shown in Tables 2 and 3.

Table 2 Tensile Results for E-Glass Fibre Tows

Property	Measured Value
<u>Breaking Stress (N/Tex)</u>	
Batch 1	0.31 ± 0.04
Batch 2	0.38 ± 0.02
<u>Breaking Strain (%)</u>	
Batch 1	2.11 ± 0.14
Batch 2	3.01 ± 0.07
<u>Tensile Modulus (N/Tex)</u>	
Batch 1	18.3 ± 0.5
Batch 2	18.9 ± 0.5

Table 3 Tensile Results for Grafil 34-700 Carbon Fibre Tows

Property	Measured Value
Breaking Stress (N/Tex)	0.86 ± 0.05
Breaking Strain (%)	1.40 ± 0.05
Tensile Modulus (N/Tex)	71.1 ± 2.7

The uncertainty in the tensile breaking stress and strain measurements for the carbon fibre tows was noticeably less than for the E-glass fibre tows. This is to be expected as glass fibres are more susceptible to damage induced through handling and moisture degradation. Two batches of glass fibre tows selected from different sections (widely separated) on the same reel were found to have significantly different values of breaking stress and breaking strain (see Table 2). Figure 8 shows that the cumulative distribution of failure events for tests conducted on the glass and carbon fibres is essentially linear.

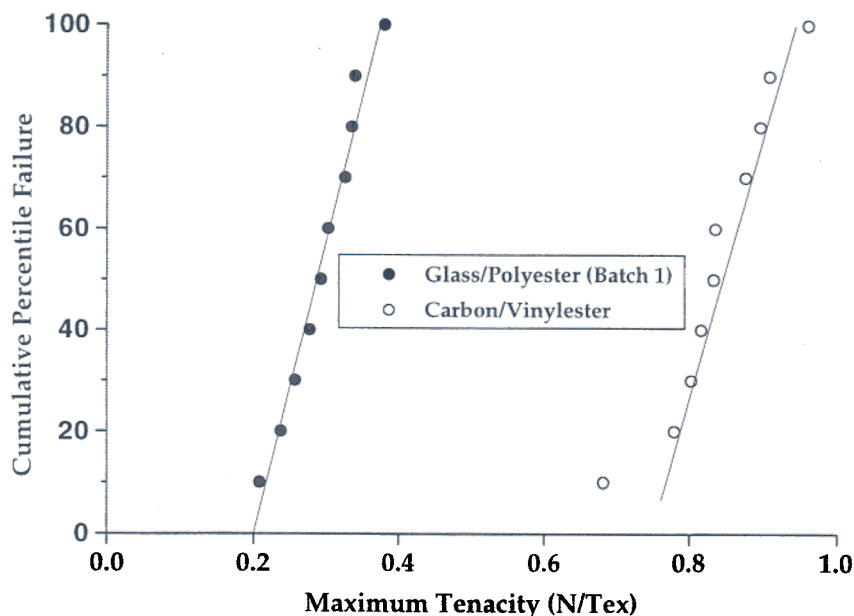


Figure 8 Cumulative distribution of failure events.

3.2 COMPOSITE RODS

The tensile properties of glass/polyester and carbon/vinylester rods were determined for a range of:

- Displacement rates (0.1, 1, 5, 10 and 100 mm/min);
- Gauge-lengths (50, 125, and 200 mm) - strain rate was held constant (2.5%/min);
- Rod diameters (1.5, 2.0, 2.5, 3.0, 4.0 and 5.0 mm).

Testing was conducted according to BS ISO 9163 specifications with five specimens tested per condition. Specimens were loaded to failure under standard laboratory conditions. Displacement was determined directly from the cross-head movement. The tensile modulus, $E_{11}(T)$, and tensile strength, $S_{11}(T)$, results are shown in Tables 4 to 6.

Table 4 Effect of Displacement Rate on Tensile Strength and Tensile Modulus

Material	Displacement Rate (mm/min)				
	0.1	1.0	5.0	10.0	100
Glass/Polyester					
Tensile Modulus (GPa)	37.5 ± 1.2	40.4 ± 1.5	38.1 ± 3.6	42.2 ± 0.8	40.6 ± 1.1
Tensile Strength (MPa)	972 ± 24	1057 ± 16	1089 ± 35	1121 ± 47	1179 ± 24
Carbon/Vinylester					
Tensile Modulus (GPa)	103 ± 9	109 ± 4	104 ± 3	108 ± 3	109 ± 3
Tensile Strength (MPa)	2093 ± 81	2083 ± 132	2018 ± 50	2189 ± 75	2154 ± 26

Table 5 Effect of Gauge-Length on Tensile Strength and Tensile Modulus

Materials	Gauge-Length (mm)		
	50	125	200
Glass/Polyester			
Tensile Modulus (GPa)	40.1 ± 0.9	41.6 ± 0.8	41.3 ± 0.8
Tensile Strength (MPa)	1032 ± 9	1083 ± 35	1058 ± 33
Carbon/Vinylester			
Tensile Modulus (GPa)	100 ± 6	112 ± 3	113 ± 1
Tensile Strength (MPa)	2229 ± 87	2058 ± 70	1990 ± 67

**Table 6 Effect of Rod Diameter on Tensile Strength
(*Failure Mode - Crushing)**

Materials	Rod Diameter (mm)					
	1.5	2.0	2.5	3.0	4.0	5.0
Glass/Polyester						
Tensile Strength (MPa)	1037 ± 28	897 ± 28	925 ± 19	965 ± 18	$726 \pm 25^*$	$633 \pm 38^*$
Carbon/Vinylester						
Tensile Strength (MPa)	1904 ± 61	2059 ± 32	1498 ± 71	$1682 \pm 40^*$	$1253 \pm 59^*$	$814 \pm 20^*$

A number of observations can be made in relation to displacement rate/gauge-length effects on the tensile properties of the two composite materials.

Glass/Polyester

- $E_{11}(T)$ - increases (marginal) with displacement rate.
- $S_{11}(T)$ - increases (10%) with displacement rate (see Figure 9).
- $E_{11}(T)$ and $S_{11}(T)$ - independent of gauge-length.
- $S_{11}(T)$ - independent of rod diameter (1.5 to 3.0 mm).

Carbon/Vinylester

- $E_{11}(T)$ and $S_{11}(T)$ - independent of displacement rate.
- $E_{11}(T)$ - increases (marginal) with gauge-length.
- $S_{11}(T)$ - decreases (10%) with gauge-length (see Figure 10).

Tensile properties of glass fibre-reinforced composites are rate sensitive; as demonstrated by increases in both the tensile modulus and tensile strength for the glass/polyester rods (Table 4). These two properties were virtually unaffected by changes in gauge-length. In contrast, **the tensile properties of carbon fibre-reinforced composites are insensitive to changes in strain rate;** as demonstrated by the carbon/vinylester results. **Increasing the gauge-length of the carbon/vinylester rods resulted in a reduction in failure stress.** This length dependence can be explained in statistical terms. Increasing the length of the composite rod increases the probability that a defect of critical size will occur within the gauge-length; thus longer specimens have lower strengths. Although this effect was not observed for the glass/polyester, the results do not necessarily preclude this effect. It may be that other mechanisms (e.g. stress corrosion) have a far greater influence on the tensile strength of the glass fibre-reinforced system.

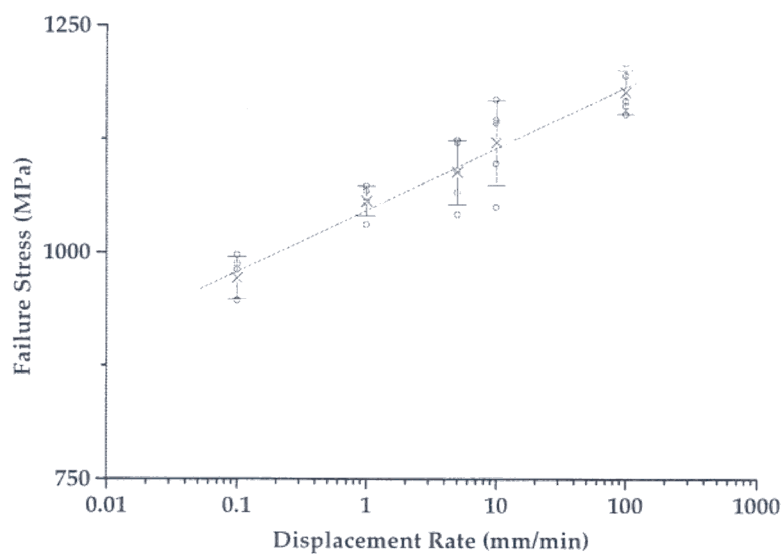


Figure 9 Tensile strength versus displacement rate for glass/polyester.

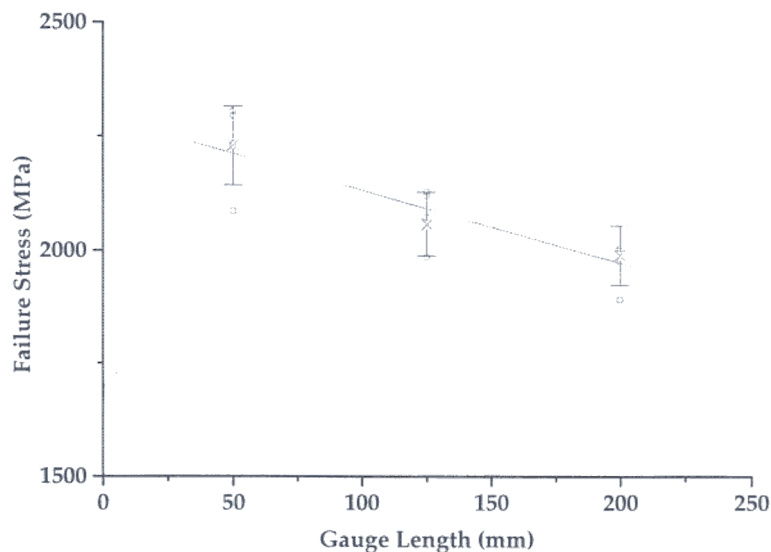


Figure 10 Tensile strength versus gauge-length for carbon/vinylester rods.

Figure 11 shows a typical failed glass/polyester specimen (1.5 mm diameter rod with composite end tabs) with fibre breakage and longitudinal splitting. This mode of failure only occurred in those specimens with a rod diameter of approximately 2.5 mm, or less. Post-failure inspection of specimens with larger diameters revealed localised crushing in the grip region, hence the lower strengths recorded for the larger diameter specimens (see also Section 2.3.2).

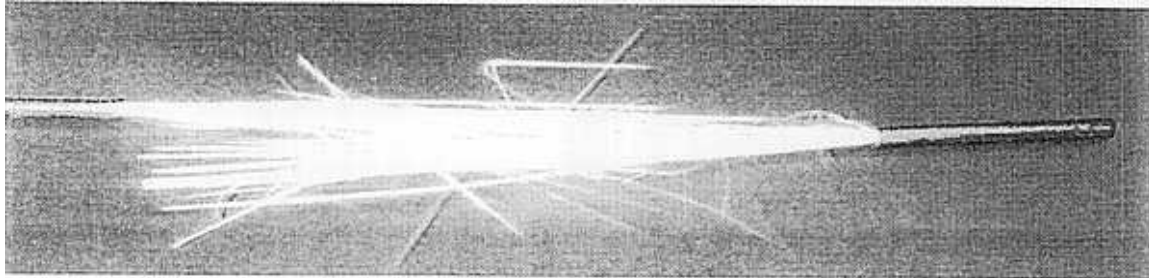


Figure 11 An example of a failed glass/polyester rod specimen (1.5 mm diameter).

3.3 PREDICTIVE ANALYSIS

A comparison between measured (1 mm/min, 150 mm gauge-length) and predicted tensile modulus and tensile strength for the five aligned composite materials is shown in Table 7. The two sets of results, with the exception of the tensile strength for E-glass/F922, are in reasonable agreement. A clip-on extensometer was used to measure longitudinal strain for the unidirectional laminates, which were tested according to BS EN ISO 527-5. Predicted values were determined using CoDA (Composite Design and Analysis) preliminary design software developed by NPL.

Table 7 Measured and Predicted Tensile Properties for Unidirectional Composites

Material	Tensile Modulus (GPa)		Tensile Strength (MPa)	
	Measured	Predicted	Measured	Predicted
Glass/Polyester	40.4 ± 1.5	36.4	1057 ± 16	1170
Carbon/Vinylester	109 ± 4	120	2083 ± 132	2344
<u>E-glass/F922</u>				
3 mm wide	45.9 ± 1.5	46.1	1168 ± 50	1481
15 mm wide	43.0 ± 0.9	46.1	1087 ± 29	1481
E-glass/913	41.1 ± 1.4	36.6	1215 ± 20	1178
HTA/F922	126 ± 5	141	1684 ± 132	2107
T300/924	133 ± 2	140	1723 ± 89	2141

The rule of mixtures approach generally proved satisfactory for predicting the tensile modulus and tensile strength for both the glass/polyester and carbon/vinylester rod materials. There was also good agreement between predicted and measured tensile modulus for the aligned glass/epoxy and carbon/epoxy laminates. The rule of mixtures approach, however, tended to overestimate the tensile strength of these materials. The difference between predicted and measured values, with the exception of E-glass/913 (see Table 7), was typically 25%. The tensile data for the narrow and standard specimen widths were in reasonable agreement. Figure 12 shows an example of a failed unidirectional E-glass/F922 laminate (standard geometry).

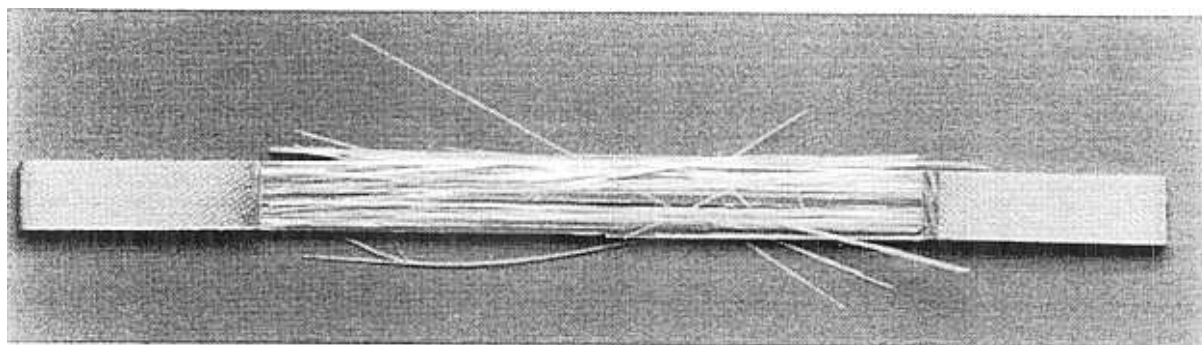


Figure 12 An example of a failed unidirectional E-glass/F922 laminate (standard geometry).

4. CYCLIC FATIGUE

Fibre tows, composite rods and unidirectional laminates were subjected to tension-tension cyclic fatigue loading. Constant amplitude (sinusoidal waveform) fatigue tests were carried out 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 equal to 0.1. All tests were carried out under standard laboratory conditions (i.e. 23 °C, 50% RH). Instron MAX software was used to control the servo-hydraulic test machine and to collect the test data. This section presents the results of tensile fatigue tests, examining the fatigue life (i.e. applied stress, S , against number of cycles to failure, N , and residual strength). In order to limit the duration of tests, the number of cycles was limited to a maximum number of 10^7 cycles (~23 days). Testing, particularly at high loads, was best carried out using fatigue rated servo-hydraulic (wedge-action) grips.

4.1 FIBRE BUNDLES

Unimpregnated glass-fibre and carbon-fibre tows exhibit excellent fatigue resistance. Fibre tow specimens can maintain applied stress levels approaching the ultimate tensile strength (UTS) of the fibre bundle for at least 10^7 cycles. Accumulated damage in the form of broken fibres was observed to be minimal. Provided the applied stress is smaller than the UTS and falls outside the scatter band (i.e. 2 standard deviations), then the lifetime of the fibre tow will exceed 10^7 cycles.

4.2 COMPOSITE RODS

4.2.1 S-N Response

Five duplicate tests (generally) were carried out at five stress levels (i.e. 80%, 70%, 55%, 40% and 25% UTS) on glass/polyester rods. Similar tests were carried out on carbon/vinylester rods, although the number of tests conducted was limited. The S-N curve and associated fatigue data for the glass/polyester rods are shown in Figure 13. For inter-comparative purposes, fatigue strength data (Figure 13) are normalised with respect to the ultimate tensile strength, σ_{UTS} , of identically conditioned specimens measured at the fatigue test loading rate. **The scatter associated with fatigue testing is generally large.**

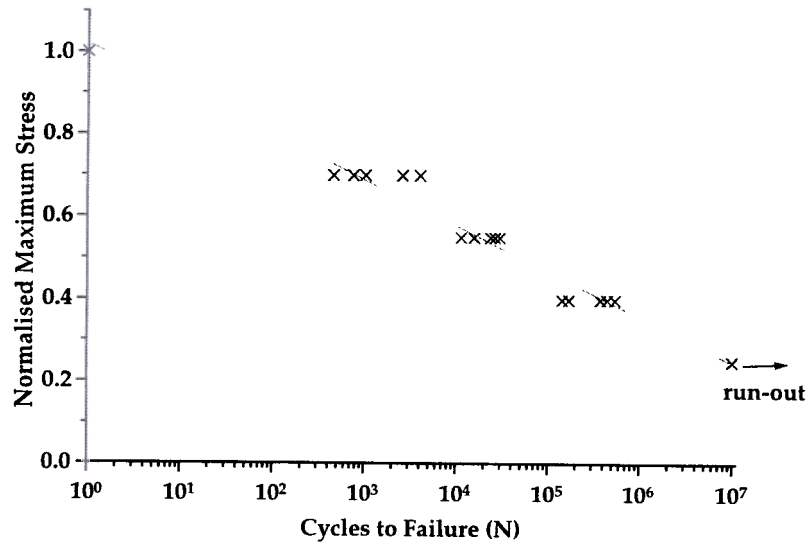


Figure 13 Normalised S-N curve for glass/polyester rods.

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

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

where σ_{MAX} is the maximum applied load, σ_{UTS} is the ultimate tensile strength and k (the slope) is the fractional loss in tensile strength per decade of cycles. The fatigue limit (i.e. 10^7 cycles) occurs at approximately 25% UTS. At this stress level, there was no detectable damage in the glass/polyester rods following 10^7 cycles. At higher applied stresses (i.e. 40% UTS or greater), specimens failed catastrophically with failure occurring invariably within the gauge-length, although frequently near the end tabs. Non-progressive failure occurs due to insufficient material being available to accommodate local stress concentrations induced through fibre fracture. Figure 14 shows an example of a failed specimen with fibre breakage and longitudinal splitting. This failure mode was observed for both static and cyclic fatigue loading.

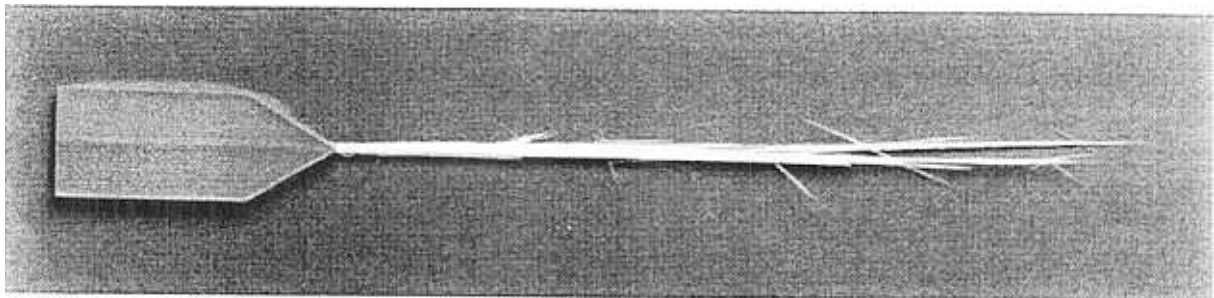


Figure 14 An example of a cyclic fatigue failure for glass/polyester rod specimen.

The results indicate that the carbon/vinylester rods possess excellent fatigue resistance. For $\sigma_{\text{MAX}} \leq 0.55 \sigma_{\text{UTS}}$, the fatigue limit exceeded 10^7 cycles. Technical difficulties associated with the presence of high stress concentrations near the end tabs prevented the successful completion of tests at applied stress levels equal to or higher than 70% UTS. Tests conducted at 70% UTS indicate a minimum fatigue life of 10^6 cycles.

Residual Tensile Strength

Residual strength measurements were also carried out on glass/polyester rods (Figure 15). These specimens were subjected to continuous cyclic loading at an applied stress level of 40% UTS. This applied stress level enabled sufficient time to monitor stiffness and strength changes with number of cycles. Residual strength was determined by discontinuing cyclic loading and carrying out a quasi-static test to failure on the damaged material. Tests were conducted at selected cycle intervals. The results are normalised with respect to the UTS of the composite.

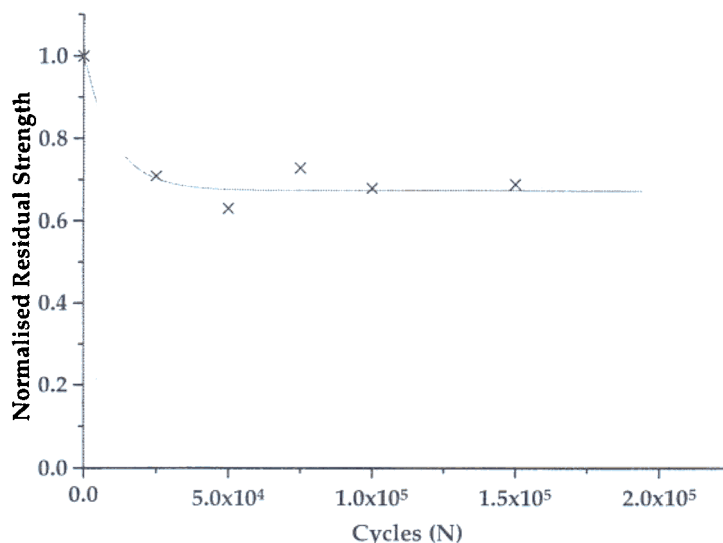


Figure 15 Residual strength versus cycles for glass/polyester rods.

The results in Figure 15 show residual strength decreasing rapidly within the first 25,000 cycles and then remaining constant at 70% UTS for the remaining lifetime. This reduction in strength was not accompanied by any marked change in the longitudinal modulus. **For all intents and purposes, $E_{11}(T)$ remains constant over the entire lifetime of the unidirectional composite.** Although degradation of residual strength and elastic modulus may occur near the fatigue limit, it was not possible to measure changes in these properties.

4.3 UNIDIRECTIONAL LAMINATES

S-N Response

Unidirectional continuous fibre-reinforced laminates are known to possess excellent fatigue resistance; particularly carbon fibre-reinforced systems. The results from tests conducted on unidirectional E-glass/F922, E-glass/913 (standard geometry only) and T300/924, support this statement. Again, five duplicate tests (generally) were carried out at five stress levels (i.e. 80%, 70%, 55%, 40% and 25% UTS). A limited number of tests were carried out on the T300/924 carbon/epoxy system. The S-N curves and associated fatigue data for the unidirectional glass fibre-reinforced laminates are shown in Figures 16 and 17. Again, fatigue strength data are normalised with respect to the ultimate tensile strength, σ_{UTS} , of identically conditioned specimens measured at the fatigue test loading rate. In all cases, the results could be represented by a normalised fatigue life equation (i.e. Equation (1)).

Figure 16 clearly shows differences between the two sets of data and that the cyclic fatigue results from the 3 mm wide E-glass/F922 strips cannot be scaled upwards. The fatigue limit at 25% UTS is at least an order of magnitude higher for the standard test geometry. Efforts were made to minimise the possibility of machine induced damage at the specimen edges affecting the strength results; particularly for the narrow strips. Although the narrow specimens were cut oversized and then polished to the final width, damage generally initiated at the edges. Attempts to pultrude 2mm diameter rods of E-glass/F922, thus avoiding edge damage due to machining proved unsuccessful as the F922 epoxy resin is difficult to process.

The S-N data for the E-glass/913 laminate (Figure 17) can also be characterised by a straight line given by Equation (1). 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 was often exacerbated by an additional heating effect from the servo-hydraulic system (i.e. actuator and grips). Differences between the brittle F922 and the tougher 913 system were only marginal.

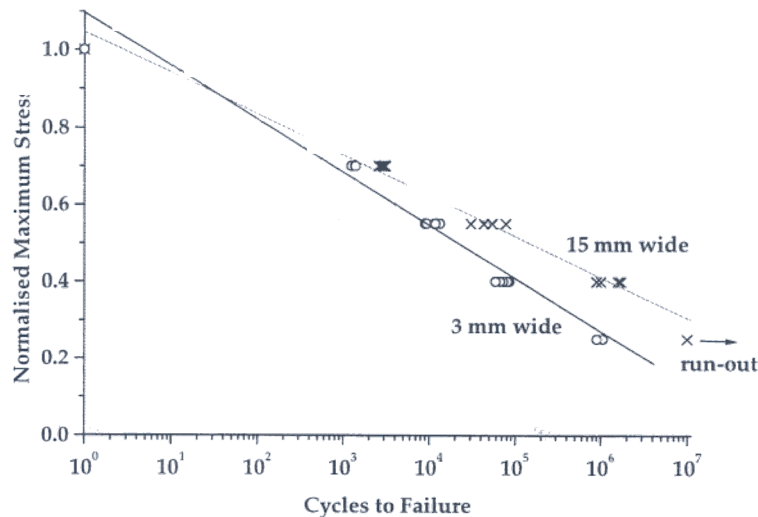


Figure 16 S-N curves for 3 mm and 15 mm wide unidirectional E-glass/F922 laminates.

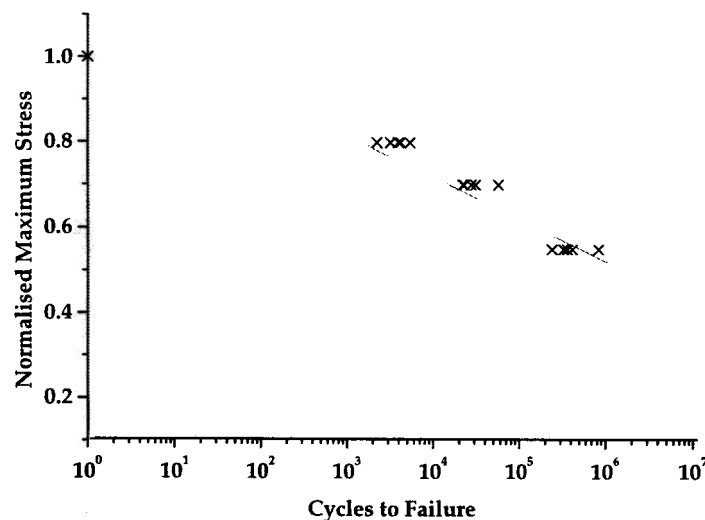


Figure 17 S-N curves for unidirectional E-glass/913.

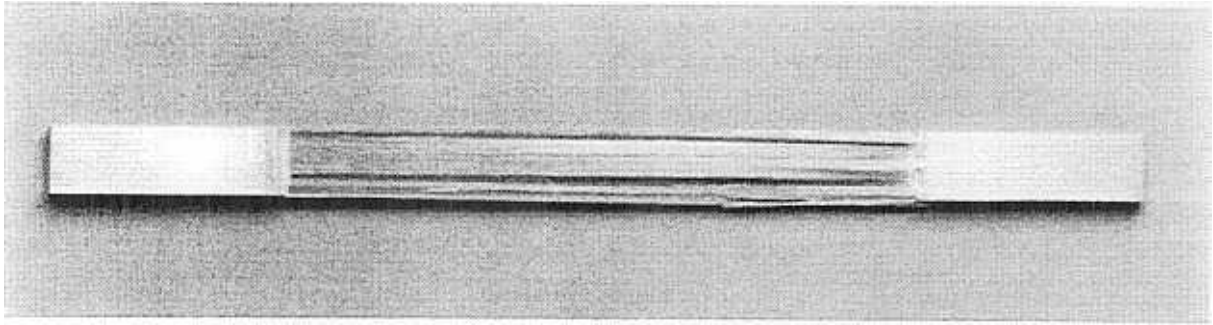


Figure 18 An example of a cyclic fatigue failure for unidirectional E-glass/913 laminate

The process of failure was progressive with regions of damage in the form of fibre breakage, interfacial debonding, matrix cracking and interfacial shear failure. Longitudinal splitting was the primary damage growth mechanism observed for the unidirectional glass fibre-reinforced epoxy systems (Figure 18). These regions, typically 0.5 to 1 mm wide, gradually extended along 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 these longitudinal splits initiated within the grip regions, which is unavoidable with the current test geometry.

Unidirectional laminated specimens were also produced with integrated (i.e. in-built) end tabs (Figure 19). 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. The fatigue results and failure mode for this test geometry were similar to those obtained using adhesively bonded tabs.

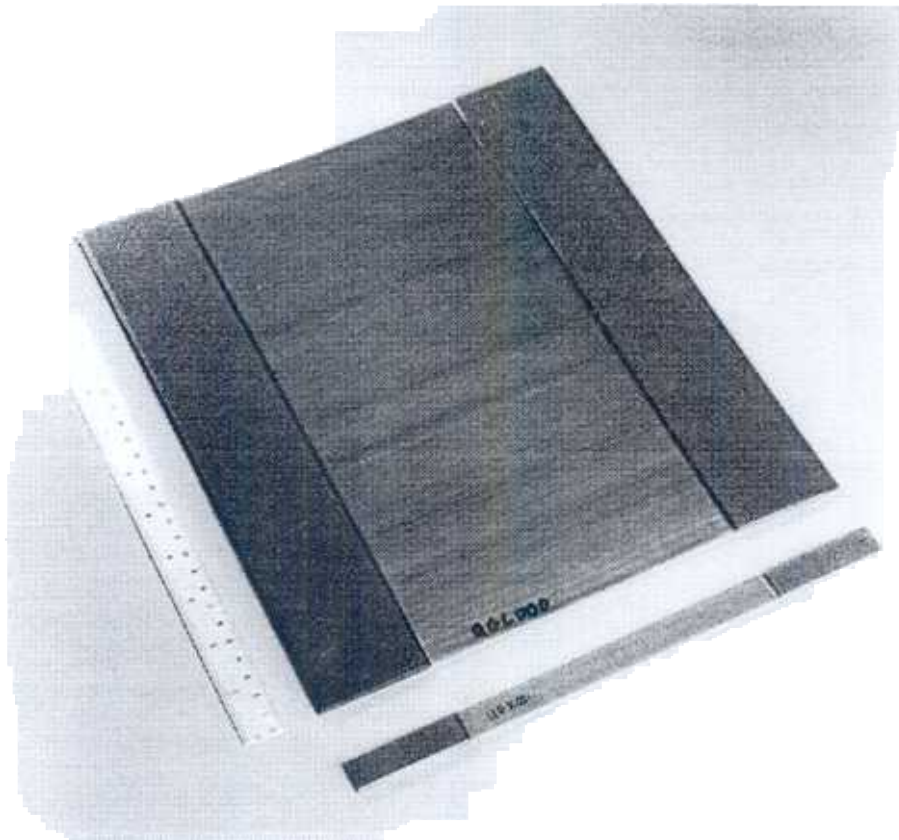


Figure 19 Unidirectional E-glass/913 laminate with in-built end tabs.

The glass fibre-reinforced laminates show far greater sensitivity to fatigue than the continuous aligned T300/924 carbon/epoxy. For $\sigma_{\text{MAX}} \leq 0.70 \sigma_{\text{UTS}}$, 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 4×10^5 cycles. The greater sensitivity of the glass fibre-reinforced laminates is due to the lower stiffness of glass fibres, thus resulting in higher strains within the matrix.

4.3.2 Residual Tensile Strength

Residual strength was determined as a function of applied cycles for the 3 mm and 15 mm wide E-glass/F922 laminates. These specimens were subjected to continuous cyclic loading at an applied stress level of 40% UTS. Tests were conducted at selected cycle intervals appropriate to the lifetime of each specimen type. Normalised residual strength results, shown in Figure 20, indicate that there is an early reduction in residual strength which tends to level off at approximately 70% UTS. As with the glass/polyester rods this reduction is not accompanied by any discernible change in longitudinal modulus. The stiffness and strength tends to remain constant throughout the remaining lifetime of the composite. Further tests are to be conducted on unidirectional and multidirectional laminates at other stress levels.

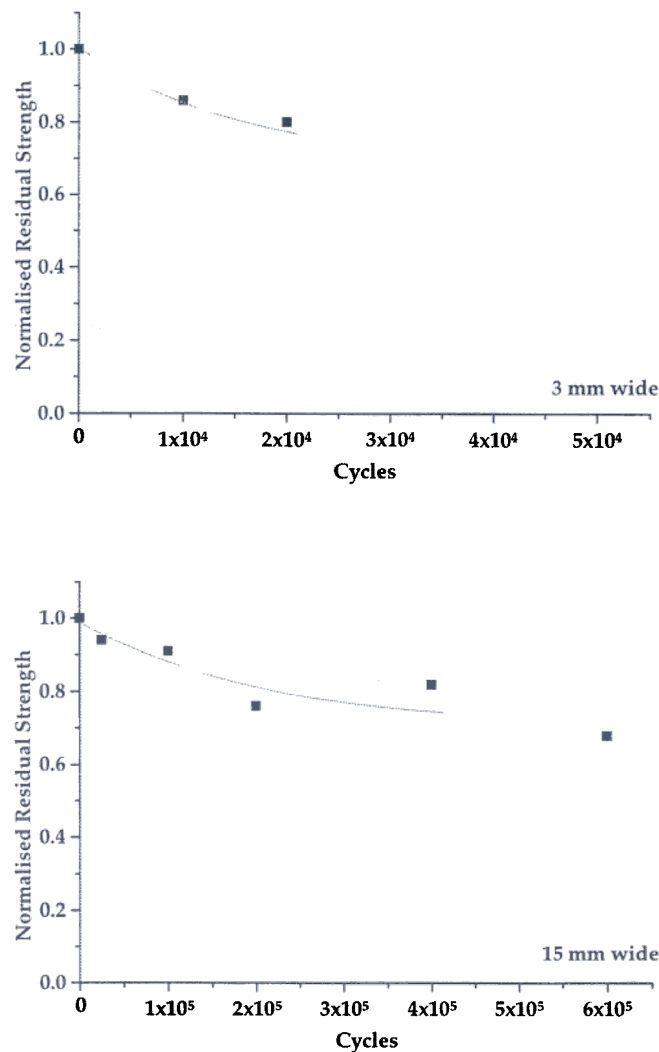


Figure 20 Residual strength versus cycles for E-glass/F922 laminates.

5. CONCLUSIONS

The achievements of this programme and principal conclusions drawn from this work are summarised below:

Test methods have been developed for measuring the tensile properties of fibre tows and composite rods (≤ 3 mm diameter).

Tensile strength of glass/polyester increases with strain rate.

Tensile strength of carbon/vinylester decreases with gauge-length.

Variation of rod diameter had only a marginal effect on tensile strength results. Differences can be attributed to difficulties in pultruding and testing large diameter rods.

Glass-fibre and carbon-fibre bundles, and continuous aligned carbon fibre-reinforced composites have excellent fatigue resistance.

Fatigue performance of small diameter glass fibre-reinforced rods and narrow unidirectional laminates is poor in comparison with the standard test geometry.

Linear regression data analysis of the S-N data indicates that for continuous aligned glass/epoxy and glass/polyester laminates, the normalised fatigue life can be generalised using Equation (1) with the value of k approximately equal to 0.1 [6]:

$$\sigma_{\text{MAX}} / \sigma_{\text{UTS}} = 1 - 0.1 \log_{10} N \quad (2)$$

The above equation can be used to characterise the S-N data with reasonable engineering accuracy.

Residual strength asymptotically approaches a value of 70% UTS for the unidirectional laminates fatigued at 40% UTS and remains constant for the remaining life of the laminate. Longitudinal elastic modulus remains unaltered throughout the fatigue lifetime. Further tests are to be conducted on unidirectional and multidirectional laminates at other stress levels.

Current standard (Part 10 of ISO 3597 [7]) for preparation and testing of composite rods requires revision to accommodate the determination of tensile strength.

Future work on laminates will consider:

Fatigue behaviour of multidirectional laminates - evaluating methods for determining and predicting cumulative damage (e.g. residual strength, stiffness loss and transverse matrix cracking).

Revising ISO 3597-10 to accommodate the determination of tensile strength of composite rods.

R ratios greater than 0.1 and frequency below 1 Hz to determine if there is a cross-over point between static and cyclic fatigue behaviour.

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