

Project CPD2 - Report 8
LIFE ASSESSMENT AND PREDICTION

**Cyclic Fatigue of Continuous Unidirectional
Polymer Matrix Composites: An Interim Report**

W.R.Broughton and M.J.Lodeiro

August 1999

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**W R Broughton and M J Lodeiro
Centre for Materials Measurement & Technology
National Physical Laboratory
Teddington
Middlesex, TW11 0LW, UK**

ABSTRACT

This report provides an interim assessment of test methods developed within the Composites Performance and Design (CPD) Project "Life Assessment and Prediction" 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 to evaluate the suitability of the test methods for accelerating testing and for generating cyclic fatigue data. A comparative study has been carried out on narrow (i.e. 3 mm wide) and standard (i.e. 15 mm wide) unidirectional laminates to assess scaling effects. Strain rate and gauge-length effects on the measured tensile properties from fibre tow specimens have also been considered.

The principal conclusions that can be drawn from the results to-date 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) 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, and concludes with comments relating to future work.

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ISSN 1361 - 4061

National Physical Laboratory
Teddington, Middlesex, UK, TW11 0LW

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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 interim 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 (CPD2) “Life Assessment and Prediction” 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. A comparative study has been carried out on narrow (i.e. 3 mm wide) and standard (i.e. 15 mm wide) unidirectional laminates to assess scaling effects. Effects of strain rate and gauge-length on the tensile properties of composite rods have also been considered.

The report is divided into five sections including the introduction (Section 1). Section 2 describes the materials used to validate the test methods in this programme, 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 and gauge-length 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 for future work are given 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) to Hexcel Composites specifications. The laminates were also post-cured to the pre-preg suppliers specifications.

- (e) Autoclave compacted continuous unidirectional glass fibre-reinforced epoxy prepreg sheet (E-glass/Fibredux 913). Laminates were manufactured at NPL to Hexcel Composites specifications.
- (f) Autoclave compacted 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 weight mass then exposed to 600 °C in a furnace for at least an hour to remove all traces of resin. The fibre volume and weight fractions of unidirectional 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
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 in this section.

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.

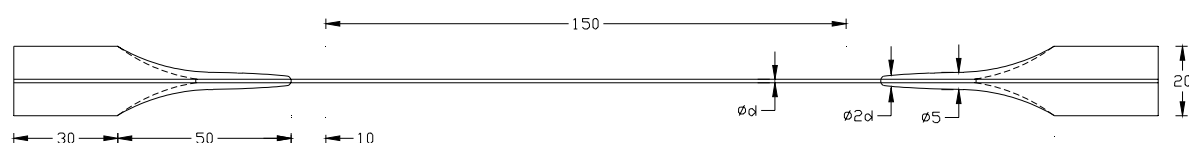


Figure 1 Fibre tow test specimen (mm).

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. The end tabs were cast in modified moulds, using BS ISO 9163 specifications as a guide, and cured at 80 °C for 20 minutes. **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.**

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 yields/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 2 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.

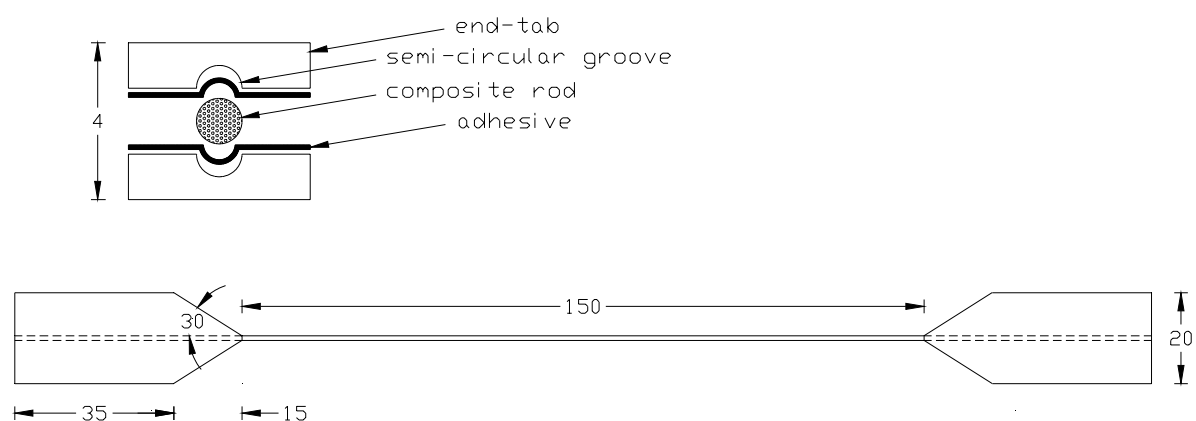


Figure 2 Composite rod specimen and end tab (mm).

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 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. The semi-circular groove, shown in Figure 2, was cut with a 1.5 mm thick diamond slitting wheel (water lubricated).

The test geometry shown in Figure 2 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. Preliminary trials were carried out on 3 mm diameter rods using bonded end tabs that were 1.25 mm thick and 50 mm long. The trials proved successful with tensile failure consistently occurring within the gauge-length.

2.3.3 Unidirectional Laminates

Specimen preparation of unidirectional laminates was carried out to BS EN ISO 527-5 [5] specifications. Specimens 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).

Narrow laminate strips, 3 mm wide and 2 mm (i.e. 16 plies) thick, were also tested. 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.

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 ten 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
Breaking Stress (N/Tex)	0.31 ± 0.04
Breaking Strain (%)	2.11 ± 0.14
Tensile Modulus (N/Tex)	18.3 ± 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.

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) and for different gauge-lengths (50, 125, and 200 mm). For the latter, the strain rate was held constant (2.5%/min). 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 and 5.

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
<u>Glass/Polyester</u>					
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
<u>Carbon/Vinylester</u>					
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
<u>Glass/Polyester</u>			
Tensile Modulus (GPa)	40.1 ± 0.9	41.6 ± 0.8	41.3 ± 0.8
Tensile Strength (MPa)	1032 ± 9	1083 ± 35	1058 ± 33
<u>Carbon/Vinylester</u>			
Tensile Modulus (GPa)	100 ± 6	112 ± 3	113 ± 1
Tensile Strength (MPa)	2229 ± 87	2058 ± 70	1990 ± 67

A number of observations can be made in relation to displacement rate and 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 3).
- $E_{11}(T)$ and $S_{11}(T)$ - independent of gauge-length.

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 4).

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. 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 smaller 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.

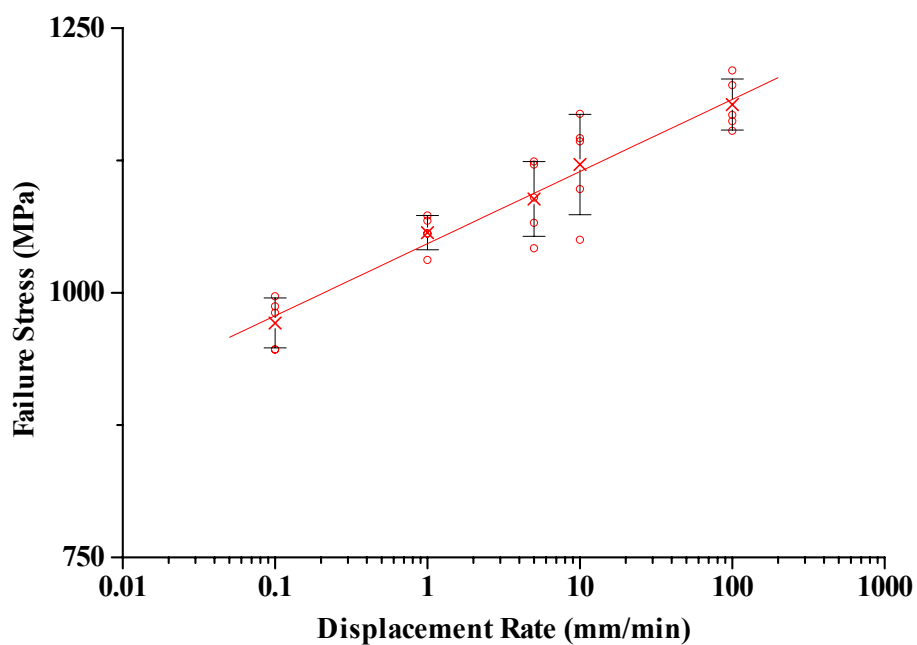


Figure 3 Tensile strength versus displacement rate for glass/polyester.

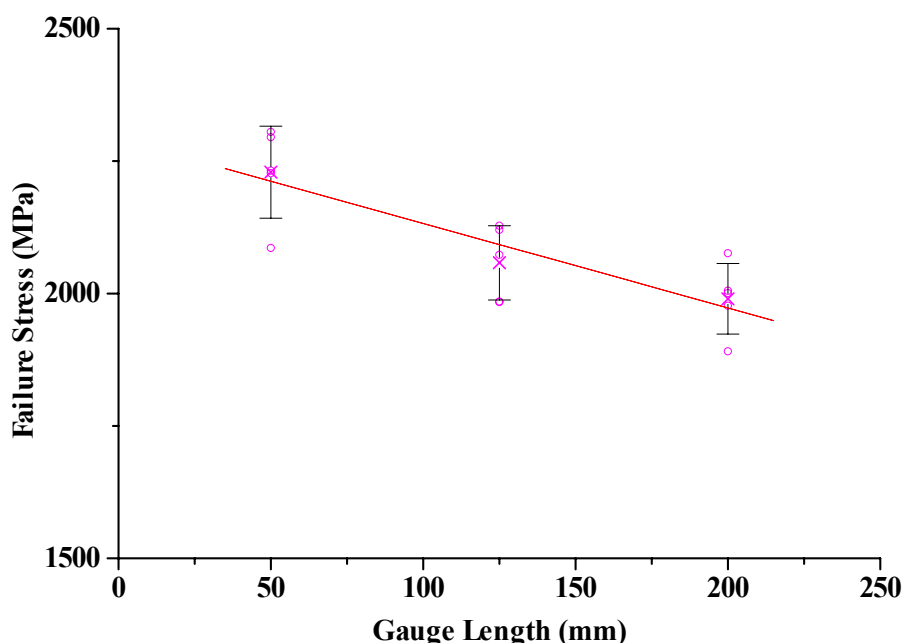


Figure 4 Tensile strength versus gauge-length for carbon/vinylester rods.

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 6. 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 6 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	37.9	1057 ± 16	1273
Carbon/Vinylester	109 ± 4	120	2083 ± 132	2344
E-glass/F922				
3 mm wide	45.9 ± 1.5	48.5	1168 ± 50	1622
15 mm wide	43.0 ± 0.9	48.5	1087 ± 29	1622
E-glass/913	41.1 ± 1.4	38.1	1215 ± 20	1281
T300/924	133 ± 2	140	1723 ± 89	2141

The F922 epoxy is a low viscosity, untoughened, epoxy system, which flows substantially during cure resulting in a composite with a high fibre content. Based on the rule of mixtures, tensile strength of E-glass/F922 is expected to be 1622 MPa, which is substantially higher than the measured strengths. This indicates that the strength potential for the composite has been compromised; possibly by weak interfacial bonding between fibre and matrix.

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 ($\sigma_{\min}/\sigma_{\max}$) ratio was equal to 0.1. All tests were carried out under standard laboratory conditions. 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, N , of cycles to failure) 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 (equivalent to 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 5. For inter-comparative purposes, fatigue strength data (Figure 5) 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.**

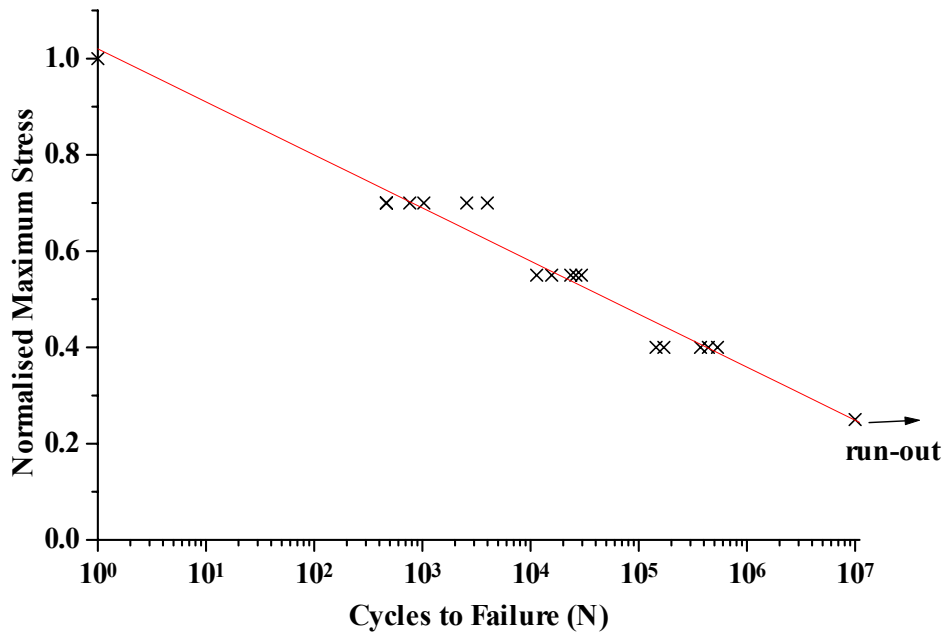


Figure 5 S-N curve for glass/polyester rods.

The normalised S-N curve (Figure 5) can be approximated by a straight line fit as follows [6]:

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

where **k** is the slope. The fatigue limit (i.e. 10⁷ cycles) occurs at approximately 25% UTS. At this stress level, there was no detectable damage in the glass/polyester rods following 10⁷ 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 6 shows a typical failed specimen with fibre breakage and longitudinal splitting.

The results to-date indicate that the **carbon/vinylester rods possess excellent fatigue resistance**. For $\sigma_{MAX} \leq 0.55 \sigma_{UTS}$, the fatigue limit exceeded 10⁷ 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 10⁶ cycles.

Figure 6 Typical failed glass/polyester rod specimen.

4.2.2 Residual Tensile Strength

Residual strength measurements were also carried out on glass/polyester rods (Figure 7). 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. Residual strength data is to be compared with predictive modelling.

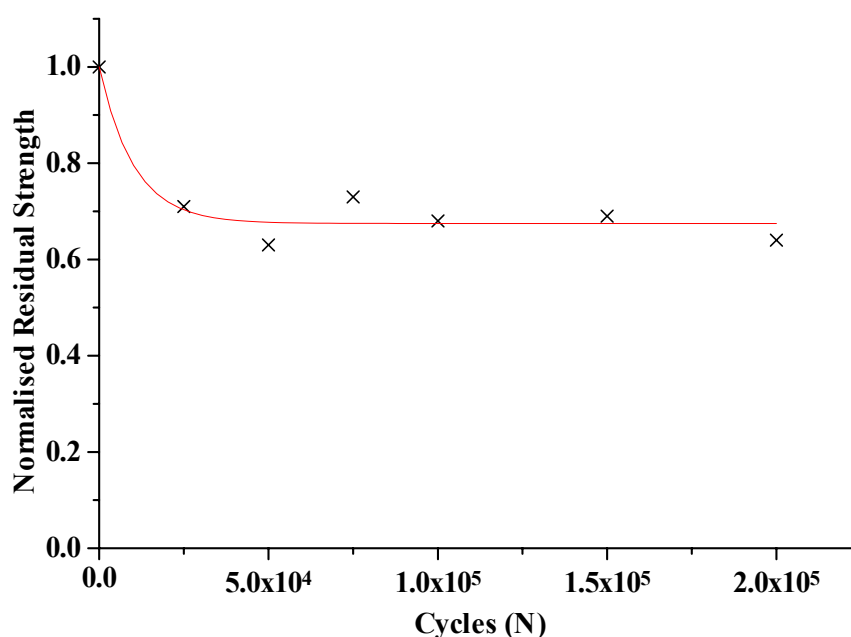


Figure 7 Residual strength versus cycles for glass/polyester rods.

The results in Figure 7 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

4.3.1 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 8 and 9. As previously, 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 8 clearly shows a scaling effect and that the 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, have proved unsuccessful as the F922 epoxy resin is difficult to handle.

The S-N data for the E-glass/913 laminate (Figure 9) 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). A typical failed specimen with longitudinal splitting is shown in Figure 10. Differences between the brittle F922 and the tougher 913 system were only marginal.

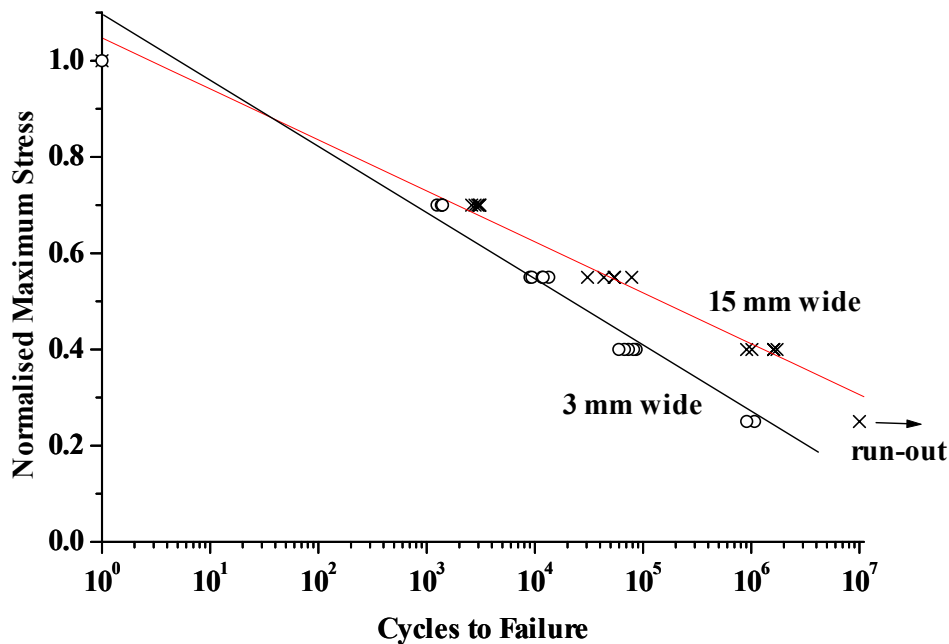


Figure 8 S-N curves for 3 mm and 15 mm wide unidirectional E-glass/F922 laminates.

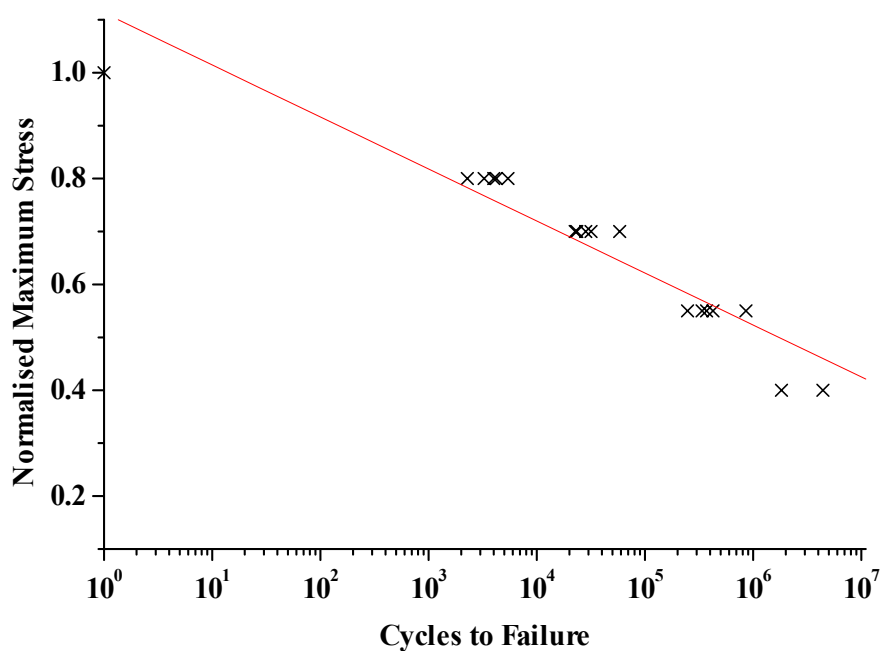


Figure 9 S-N curves for unidirectional E-glass/913.

Figure 10 Typical 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. 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.

Consideration is being given to producing a specimen with integrated (i.e. in-built) end tabs. The objective is 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 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

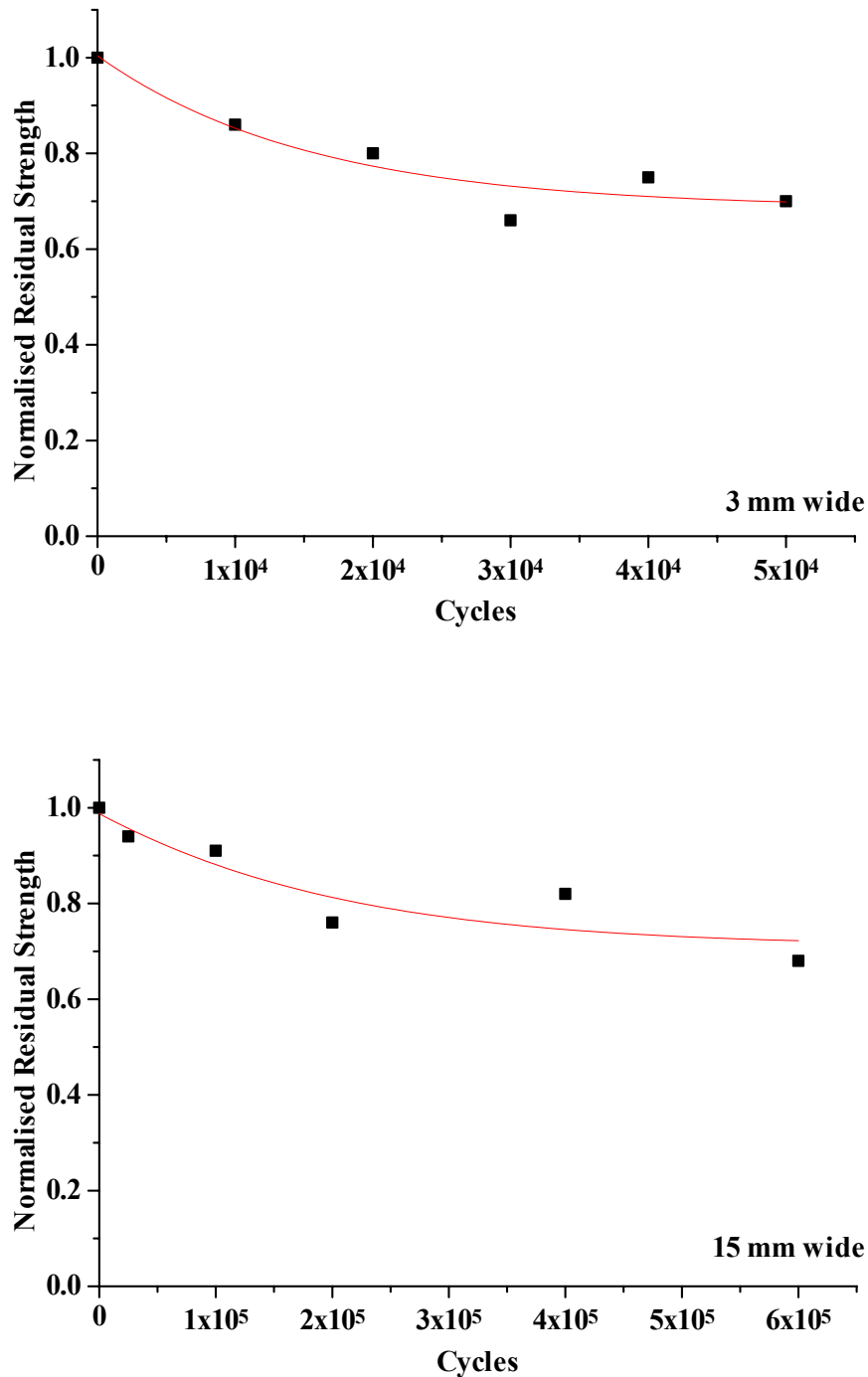


Figure 11 Residual strength versus cycles for E-glass/F922 laminates.

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 11, 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.

5. CONCLUSIONS

A number of key points that have arisen from this work are summarised below:

- Tensile strength of glass/polyester increases with strain rate.
- Tensile strength of carbon/vinylester decreases with gauge-length.
- 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 equal to 0.1 [6]:

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

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 tested at 40% UTS and remains constant for the remaining life of the laminate. Longitudinal elastic modulus remains unaltered throughout the fatigue lifetime. Further tests 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 will consider:

- Fatigue behaviour of multidirectional laminates - evaluating methods for determining and predicting cumulative damage (e.g. stiffness loss and transverse matrix cracking).
- Development of a tensile specimen with integrated (in-built) end tabs to improve on the fatigue performance of the standard test geometry.
- 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.
- Scaling effects (i.e. variations in rod diameter) for glass/polyester and carbon/vinylester.
- Fatigue performance of bulk resins (i.e. Fibredux F922 epoxy, Scott Bader crystic 916 polyester and Norpol Dion 9100 vinylester).

ACKNOWLEDGEMENTS

This work forms part of the programme "Composites Performance and Design" funded by the Engineering Industries Directorate of the UK Department of Trade and Industry, as part of its support of the technological competitiveness of UK industry. The authors would like to express their gratitude to all members of the Industrial Advisory Group (IAG) and to colleagues at the National Physical Laboratory, particularly to Mr R Shaw and Mr G Nunn whose contributions have made this work possible.

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