

Good Practice Guide No. 115

Generation and assessment of fatigue data for fibre-reinforced plastics

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Good Practice Guide for the Generation and Assessment of Fatigue Data for Fibre-Reinforced Plastics

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ABSTRACT

This Guide provides best practice guidance for generating and assessing long-term cyclic fatigue data for fibre-reinforced plastics for material qualification and design purposes. It covers tension-tension, compression-compression and tension-compression fatigue testing and examines both in-plane and through-thickness characterisation. Guidance is given on the use of test methods, non-destructive evaluation and strain measurement techniques, and data analysis and interpretation. The guide is primarily concerned with continuous carbon and glass fibre-reinforced laminated materials.

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Good Practice Guide for the Generation and Assessment of Fatigue Data for Fibre-Reinforced Plastics

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Executive Summary

IN THIS CHAPTER

- Executive Summary

Fibre-reinforced plastics (FRPs) are increasingly being used in a wide range of applications where long-term service under dynamic fluctuating loads, often involving hostile environments, is required. A major concern is that under dynamic fluctuating loads, engineering structures can fail at stress levels much lower than the structure's short-term strength. As a consequence, there is growing demand for manufacturers to guarantee the life of their products, particularly where inspection can be difficult or failure catastrophic. Examples of such applications include aerospace structures, civil structures (e.g. bridges), offshore gas/oil platforms, marine vessels and wind turbines. Stringent product guarantees are also increasingly being demanded for engineering components in products such as cars and domestic appliances, where consumers often view extended lifetime warranties as a sign of product quality. Whilst the life expectancy of products in non-demanding applications have traditionally been predicted from past experience, the use of FRPs in long-term or safety critical applications requires a far better understanding of the failure mechanisms to enable reliable lifetime predictions.

Long-term durability is a serious issue, which can have health and safety, and economic implications. The repair or replacement of a deteriorated part can be labour and capital intensive, added to the economic costs and inconvenience of removal of a structure from service is an overwhelming incentive to develop reliable test methods and predictive models for assessing the performance of FRPs for use in safety critical applications. For large structural applications, such as aircraft, bridge and offshore construction, composite parts are very expensive and due to "parts integration" are often very large. Airlines are reluctant to hold spare parts because of the cost of purchase and storage space. These problems will escalate as seating capacity of aircraft increases. The demand for increased sustainability of materials, through the pressures of preservation of the environment and limited resources, is an added incentive to the provision of accurate and traceable metrology techniques, and methods of data analysis and interpretation.

This Measurement Good Practice Guide aims to provide guidance to technologists, laboratory and quality assurance personnel, and engineers generating and assessing long-term cyclic fatigue data for polymer matrix composite materials and joined systems for material qualification and design purposes. Guidance is provided on cyclic fatigue behaviour under tension-tension, compression-compression, tension-compression and shear loading conditions for in-plane and through-thickness material characterisation. Constant amplitude and variable amplitude (i.e. single- and multiple-step constant amplitude block loading) cyclic conditions are considered. The document covers test procedures, strain measurement and non-destructive evaluation (NDE) techniques for monitoring deformation and damage progression. Consideration is also given to the presence of notches, adhesive bonds and mechanical fasteners (i.e. bolts), and the effect of test frequency on stiffness and strength.

The information and advice presented in this document is based on underpinning research undertaken at the National Physical Laboratory as part of research programmes funded by the National Measurement Office of the United Kingdom's Department for Innovation Universities and Skills (formerly Department of Trade and Industry).

Introduction

1

IN THIS CHAPTER

- Background
- Scope

1.1 Background

With the increasing use of fibre-reinforced plastics (FRPs) in secondary and primary structural applications comes the requirement for improved design and predictive methodologies to maximise the benefits engendered by these highly versatile materials. Life prediction of a composite structure is a notoriously difficult task, especially if the structure contains mechanically fastened (i.e. bolted) and/or adhesively bonded joints [1-3]. The ability to accurately predict residual strength and stiffness, and remnant life under realistic service conditions is dependent on the availability of accurate and reliable test methods, and non-destructive evaluation (NDE) and strain measurement techniques for monitoring deformation and damage propagation.

Fatigue damage can be particularly harmful to the structural integrity of engineering structures, shortening the life expectancy of the structure by considerable margins, and is known to occur at relatively low stress levels, particularly in the presence of hostile environments. At present, there is insufficient information available as to the reliability of methodologies for predicting fatigue behaviour of composite materials and structures [3-5]. Design approaches used for composite materials are predominantly dependent on experimental data and analytical models [3-10] that are essentially empirical in nature, and often only applicable to specific materials, laminate stacking sequence and loading conditions. The deficiencies in lifetime prediction methodologies have resulted in conservatism in the design of composite structures (i.e. large in-built safety factors). The models are also limited to constant amplitude conditions. Realistically, the stress conditions experienced by engineering structures are far more complex involving varying applied stresses with time (i.e. variable amplitude or spectral loading conditions).

1.2 Scope

This Measurement Good Practice Guide is intended to give guidance to technologists, engineers and designers on fatigue testing of composite materials and joints for generating design data and for material qualification purposes. The document is primarily concerned with continuous carbon and glass fibre-reinforced laminated materials. Consideration is given to the effect of loading modes, rate effects (i.e. test frequency) on the long-term fatigue performance of composite materials and joined systems. Fracture toughness testing, which could justify a complete Guide in its own right, is not included in this document.

The intention of the Guide is to provide designers and users with sufficient information, which when coupled with their own expertise and a suitable accelerated test regime can be used to produce design data and enable screening of materials for qualification purposes. The document provides guidance on the use of test methods, NDE and strain measurement techniques that can be used to measure deformation and damage resulting from fatigue. If the intention is to generate design data, then the Guide should be used in conjunction with the appropriate structural design codes and standards. The Guide assumes some basic knowledge of the materials and mechanical engineering, and is not intended as a textbook or as a design protocol. There are a number of published works, which provide a comprehensive coverage of composites technology, testing, design and analysis [11-36]. Other NPL Measurement Good Practice Guides [37-41], provide advice on issues relating to the preparation and testing of plastics, adhesives and adhesive joints. The intention of the Guide is to complement these published works.

It is recommended that specialist advice be sought from manufacturers and suppliers on material selection, and the use of associated technologies and health and safety requirements. Expert advice should be obtained from the composite manufacturer or supplier on machining and surface treatment requirements for the use of these materials in joined systems, and the detailed requirements specified by the manufacturer should be completely satisfied. **Organisations that can provide specialist advice are listed at the back of the Guide along with relevant standards and publications.**

Principles of Cyclic Fatigue Loading

2

IN THIS CHAPTER

- Introduction
- Constant Amplitude and Frequency
- Variable Amplitude Spectral Loading

2.1 Introduction

This section provides guidance on cyclic fatigue loading of composite materials under constant single- and multiple-step or phase amplitude loading conditions. It is recognised that for the vast majority of engineering applications, variable amplitude and frequency loading (i.e. spectral loading) is more realistic of what happens in practice, and that analysis and life prediction for spectral loading is more complicated than constant amplitude and frequency regimes. A number of spectral loading histories characteristic to specific structures are available, such as TWIST (Transport WIng Standard) and FALSTAFF (Fighter Aircraft Loading STandard) developed to simulate the load sequence for aircraft transport and military aircraft, and WISPERX (WInd SPectrum Reference) a standardized European wind turbine fatigue load spectrum [42-43]. Control software packages exist that allows the user to input spectral loading waveforms (e.g. Instron Wavemaker). Certain composite materials will have a low stiffness, which may pose particular problems in relation to monitoring stiffness changes and strain control of testing.

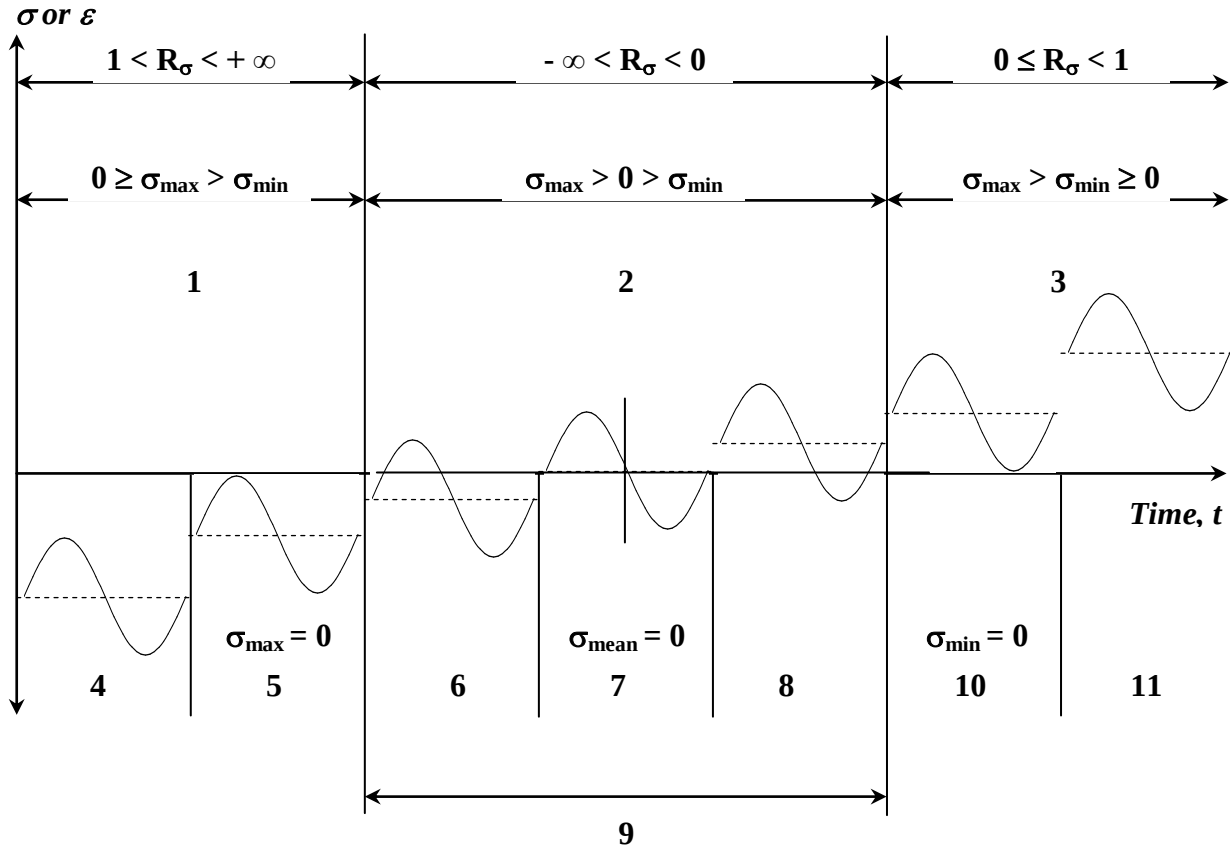
2.2 Constant Amplitude and Frequency

The principle of the method, as described in ISO 13003 [44], is that a continuously alternating mechanical load or displacement is applied at a constant frequency to the specimen under test until the specimen either fails or reaches a certain number of fatigue cycles (fatigue life). This load is applied in combination with a specified mean load (which may be zero) - see Figure 1 for the nomenclature for stress parameters for constant amplitude cyclic loading. By testing specimens at each of several percentage levels of the ultimate stress or strain, a plot of the stress/strain versus number of fatigue cycles can be constructed. This plot provides information on the fatigue life of the material or the number of fatigue cycles the material can sustain at a certain stress/strain level before failure occurs.

Tests may be carried out at constant stress (load), strain or displacement amplitude. The test method, specimen geometry, dimensions and calculations are the same as those used in the equivalent test mode under static (monotonic) loading conditions. The fatigue properties of adhesively bonded joints are a function of the joint geometry and adhesive, and therefore cannot be determined from the intrinsic properties of the adhesive. The fatigue performance of mechanically fastened joints is dependent on a number of factors, such as joint geometry, fastener type and array geometry, clamping force, washer type, etc. It is therefore necessary to conduct cyclic fatigue tests on representative joints to those used in service.

2.2.1 Fatigue regimes

The variety of fatigue regimes that exist, as shown in Figure 1, includes compression-compression (C-C), tension-compression (T-C) and tension-tension (T-T). The selection of the most appropriate fatigue regime to use is directly linked to the material application requirements and anticipated stress field. The fatigue data presented in this Guide relates to the fatigue performance of composite laminates subjected to sinusoidal cyclic waveforms (Figure 2), but it is noted that other types of waveform are commonly used (i.e. triangular, square, saw-tooth etc.) and that proprietary test machine control software allows the user to input bespoke waveforms. Prior research conducted at NPL [45] on a glass-fibre fabric/epoxy laminate showed that at longer fatigue lives there was no difference between the various cyclic waveforms.



1	Compression-compression region	Nomenclature of stress and strain parameters are given below:
2	Tension-compression region	Minimum stress or strain, $\sigma_{\min}$ or $\epsilon_{\min}$
3	Tension-tension region	Maximum stress or strain, $\sigma_{\max}$ or $\epsilon_{\max}$
4	Compression-compression cycle	Stress range, $\Delta\sigma = \sigma_{\max} - \sigma_{\min}$
5	Zero-compression alternating cycle	Strain range, $\Delta\epsilon = \epsilon_{\max} - \epsilon_{\min}$
6	Compression-dominated alternating cycle	Stress amplitude, $\sigma_{\text{amp}} = \Delta\sigma/2$
7	Fully reversed or fully alternating cycle	Strain amplitude, $\epsilon_{\text{amp}} = \Delta\epsilon/2$
8	Tension-dominated alternating cycle	Mean stress, $\sigma_{\text{mean}} = (\sigma_{\max} + \sigma_{\min})/2$
9	Alternating cycles	Mean strain, $\epsilon_{\text{mean}} = (\epsilon_{\max} + \epsilon_{\min})/2$
10	Zero-tension cycle	Stress Ratio $R = \sigma_{\min}/\sigma_{\max}$
11	Tension-tension cycle	

Figure 1: Examples of different fatigue loading cycle conditions and parameters

The stress or strain amplitude is dependent on the anticipated application stress/strain field and will be selected as a range of percentage levels of the measured static ultimate stress or strain (see Section 2.2.4).

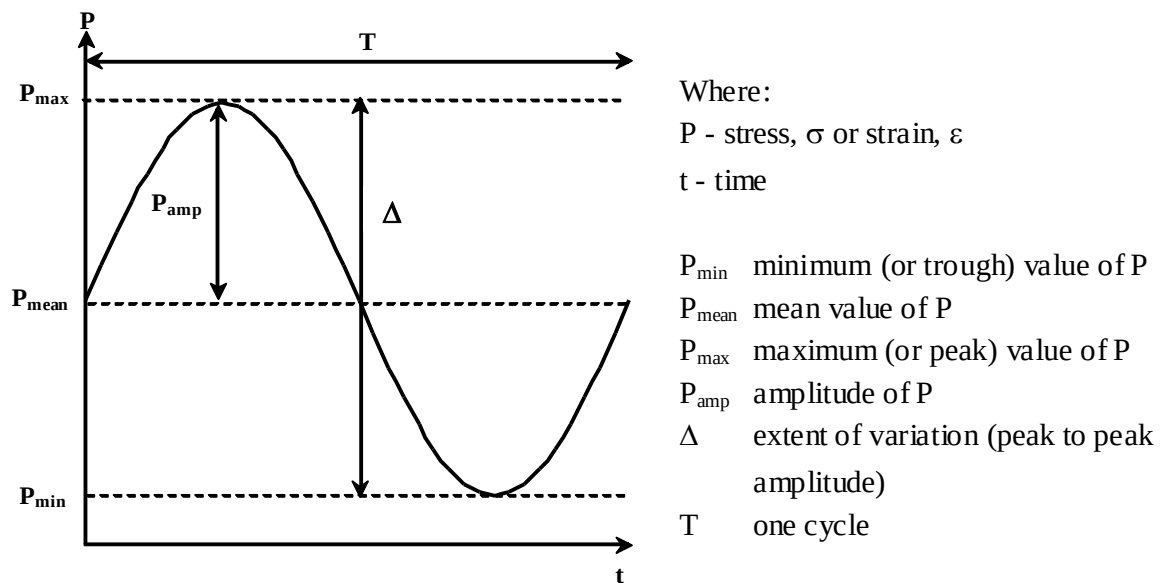


Figure 2: Schematic of sinusoidal waveform cycle

2.2.2 Test frequency

Fatigue data are normally obtained at the highest frequency possible in order to minimise the duration of tests. Restrictions on test frequency can arise from test equipment limitations (response time), time dependent processes and hysteretic or autogenous (self-generated) heating. Hysteretic heating, which increases with increasing load and frequency, can result in thermal softening of the polymer matrix, adversely affecting the fatigue performance of the material and causing erroneous stiffness and life expectancy measurements. The amount of heat generated in a material under fatigue loading will depend on a number of factors, including stress/strain amplitude, specimen displacement range (stroke), test frequency, lay-up, level of damage and the ability of the material or component to dissipate heat. It is recommended that even where prior knowledge of test frequency versus heat rise is known for a material, a thermocouple should be attached to the surface of initial test specimens to monitor the degree of hysteretic heating. Most test geometries result in non-uniform in-plane and through-thickness (T-T) temperature profiles, which requires the location of maximum temperature to be identified.

It is recommended that the temperature rise of the material surface be kept to a minimum. The solution is to either select a lower test frequency or stop the test when a fixed maximum temperature rise is reached and allow the specimen to cool to ambient before continuing the test. The acceptable level of temperature rise depends on the temperature dependence of the ultimate properties of the material, however a limiting value of 10 °C above ambient is recommended in ISO 13003 [44]. Stopping fatigue tests to allow the temperature to cool to ambient may prove unsatisfactory at high frequencies, as the surface temperature can quickly rise on test recommencement (5-10 minutes) to the same value it had prior to stoppage.

Alternatively, the test could be carried out in an environmental cabinet with a thermocouple attached to the specimen surface for monitoring and controlling the temperature of the test specimen, although the cooling rate may be too slow to be practical. Thermal imaging equipment can be used to monitor surface temperature, although the latter is beyond the budget of most industrial facilities. The temperature sensitivity/resolution is $\sim 1^\circ\text{C}$ for the two methods.

Tests should be carried out at each stress level to ensure the temperature rise is kept to less than 10°C , and if necessary the test frequency should be reduced to prevent over-heating. For temperature sensitive materials, it may be necessary to set a lower limit on the temperature rise. These comments do not apply to any rapid temperature rise associated with final failure. Reliable data can be obtained at high frequencies provided the stress levels are low. Test frequencies of the order of 10 to 30 Hz can result in substantial heating, particularly in the grip regions. The upper frequency limit will be dependent upon the thermal conductivity of the system, mode of loading and specimen size. Trials may be necessary to determine the upper frequency limit. It is unlikely that test frequencies of the order of 5 Hz (with the exception of low amplitude vibration), or higher will be experienced in service. Fatigue resistance decreases with a reduction in frequency; the decrease is attributable to creep deformation. At a test frequency of 5 Hz, 10^7 loading cycles is equivalent to 23 days testing. Increasing the test frequency to 25 Hz reduces the test duration to less than 5 days (see Table 1). Hysteretic heating will be discussed further in Sections 3, 4 and 5.

Table 1: Fatigue test duration versus frequency for fatigue lifetimes

Test frequency (Hz)	Number of days to complete 10^n fatigue cycles		
	10^6	10^7	10^8
1	11.6	116	1157
5	2.3	23	231
10	1.2	12	116
20	0.6	6	58

2.2.3 Determination of ultimate material properties

To determine the relative stress/strain levels to use in a fatigue test the ultimate properties (i.e. strength, strain to failure, etc.) should first be measured at a loading rate equivalent to fatigue testing conditions (i.e. test frequency). When undertaking measurements of ultimate properties it is important to recognize that stiffness and strength of polymeric materials are rate dependent. The fatigue test rate is defined as that resulting in failure in a time equivalent to $0.5 \times$ the cycle time. Mean values for ultimate properties should be determined from tests undertaken on at least 5 specimens.

2.2.4 Number of test specimens

For the determination of the lifetime diagram (e.g. S-N curve), five specimens should be tested at a minimum of four stress levels, or preferably five stress levels (80%, 70%, 55%, 40% and 25% of the fatigue rate ultimate strength). A minimum of five fatigue tests should be conducted at each stress level (unless otherwise specified). If a greater precision is required then the number of specimens tested should be increased (see ISO 2602 [46]). It is advisable to increase the number of tests per level when carrying out statistical analysis for generating design data.

2.2.5 Specimen preparation and test conditions

Specimen preparation, specimen geometry, loading arrangement and environmental test conditions should be the same as those employed for the monotonic tests. The applied conditions (i.e. peak load, strain and/or displacement data) when stabilized should be recorded throughout the duration of test.

2.2.6 Specimen dimensions

Specimen dimensions and geometric features (e.g. notches) need to be accurately measured, as small measurement errors can translate into large variations in strength, stiffness or fracture toughness, particularly if the calculation includes squares or cube terms of the measured parameter (see Table 2). The uncertainty in strength, stiffness or fracture toughness calculation is compounded where there is more than one term (i.e. width, thickness, crack length, etc), each with an associated uncertainty. Small errors in strength can translate into large (orders of magnitude) errors in fatigue life. In bonded structures, the bond-line thickness being very small tends to be the dimension where accuracy and precision of dimensional measurement are most critical. Measurement at different locations should be carried out to check the uniformity of bond-line thickness. Vernier calipers or a traveling microscope are recommended for measuring specimen width and bond length, and a micrometer and traveling microscope for measuring specimen and bond-line thickness. A traveling microscope should be used to measure crack length. Video extensometry can also be used for measuring bond and crack lengths.

Table 2: Associated uncertainty with measurement

Dimensional Error (%)	Linear Error (%)	Squared Error (%)	Cubed Error (%)
± 1	± 1	± 2	± 3
± 5	± 5	± 10	± 16
± 10	± 10	± 21	± 33

2.2.7 Analysis of fatigue data

In addition to recording the number of cycles to failure, the stiffness properties of specimens can be monitored throughout the test at each logged cycle. This is carried out to see whether changes in stiffness occur due to the growth of damage throughout the fatigue tests, and if there are changes in stiffness, where in relation to the failure cycle they occur. Other measurements can also be made during the test (e.g. specimen temperature, acoustic emission etc.). Cyclic fatigue data is generally presented in the form of a stress-cycle (**S-N**) diagram (i.e. a plot of the fatigue life (number of cycles to failure N_f) at various levels of maximum stress). For inter-comparative purposes, fatigue strength data are normalised with respect to the ultimate static strength P_{ULT} (or σ_{ULT}) of identically conditioned specimens measured at an equivalent loading rate to the test frequency. The uncertainty in life expectancy at any stress level is large (typically an order of magnitude). Figure 3 shows a typical normalised S-N curve for a notched glass fibre-reinforced plastic (GFRP) laminate (σ_{ULT} denotes the ultimate strength of the laminate measured at an equivalent displacement rate to the test frequency).

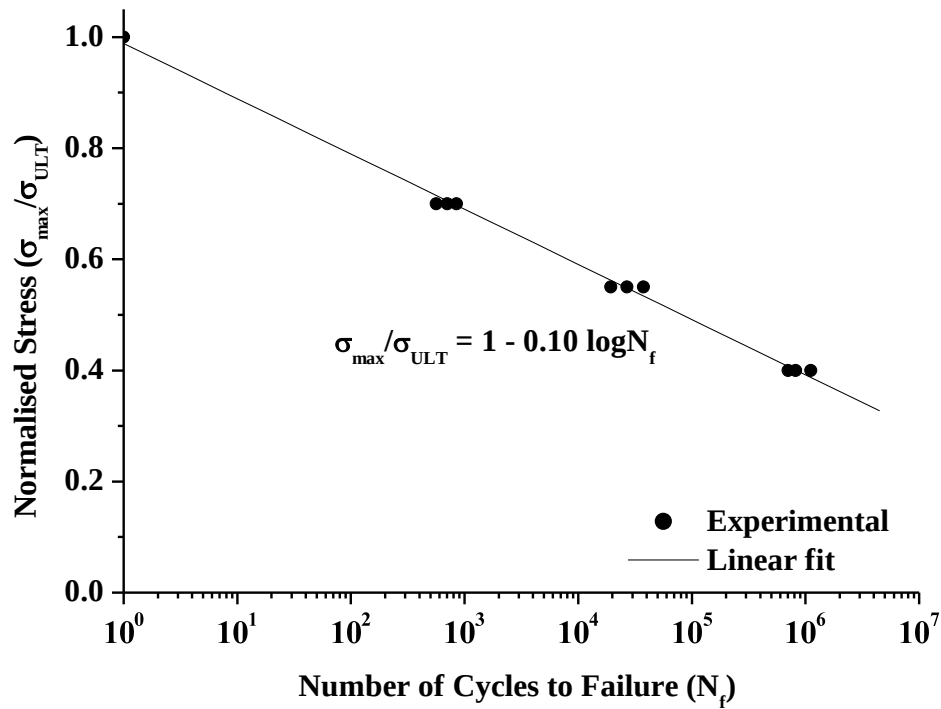


Figure 3: S-N curve for notched GFRP laminate ($R = 0.1$)

Specimen stiffness: The simplest way of calculating the modulus is to use the minimum and maximum stresses and corresponding strain levels derived from the recorded actuator positions. Whilst this method is relatively simple, the fact that actuator positions are used to calculate strains can lead to errors due to the compliance of the loading train. Using devices such as clip gauge extensometers, linear variable differential transformers (LVDTs) and strain gauges, can eliminate compliance errors but ensuring that these types of devices do not detach or de-bond from specimens during the fatigue test is crucial (see Section 3).

The stiffness (i.e. dynamic compliance) will often decrease with the onset of damage within the material (Figure 4). Ultimate failure is marked by a rapid reduction in stiffness and an increase in the loss or damping factor ($\tan \delta$). The loss factor $\tan \delta$ is the ratio between the storage modulus E' and the loss modulus E'' (i.e. $\tan \delta = E'/E''$) where δ is the phase angle between dynamic load/stress and the dynamic displacement/strain (see Figure 4) [38, 47]. The storage modulus is proportional to the maximum energy stored during a loading cycle and represents the stiffness of the material. The loss modulus is proportional to the energy dissipated (lost) during one loading cycle.

The stress σ and strain ε are given by the following relationships (see Figure 4):

$$\sigma = \sigma_0 \sin(\omega t + \delta); \quad \varepsilon = \varepsilon_0 \sin(\omega t) \quad (1)$$

where ω is the period of strain oscillation, t is time and δ is the phase angle in radians.

The storage modulus E' and the loss modulus E'' are given by:

$$E' = \frac{\sigma_0}{\varepsilon_0} \sin \delta; \quad E'' = \frac{\sigma_0}{\varepsilon_0} \cos \delta \quad (2)$$

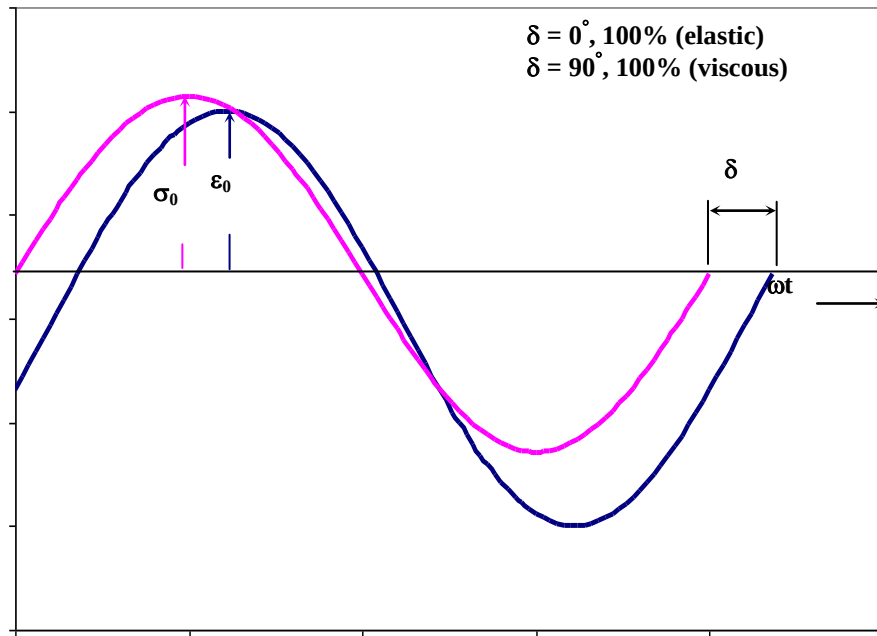


Figure 4: Out-of-phase stress-strain response for viscoelastic material, $\delta = 20^\circ$ [38]

For a purely elastic material, the mechanical energy stored during loading is returned completely when the specimen is unloaded. This generates load/displacement or stress/strain curves for the material, which are completely in phase with each other (i.e. $\delta = 0^\circ$), producing no hysteresis (see Figure 5). At the other extreme a purely viscous material (i.e. $\delta = 90^\circ$), which exhibits no elasticity only damping, results in all the energy being dissipated and the load/displacement or stress/strain curves being 90° out of phase with each other. Materials that fall between these two categories exhibit a phase lag (Figure 4) and are classified as viscoelastic.

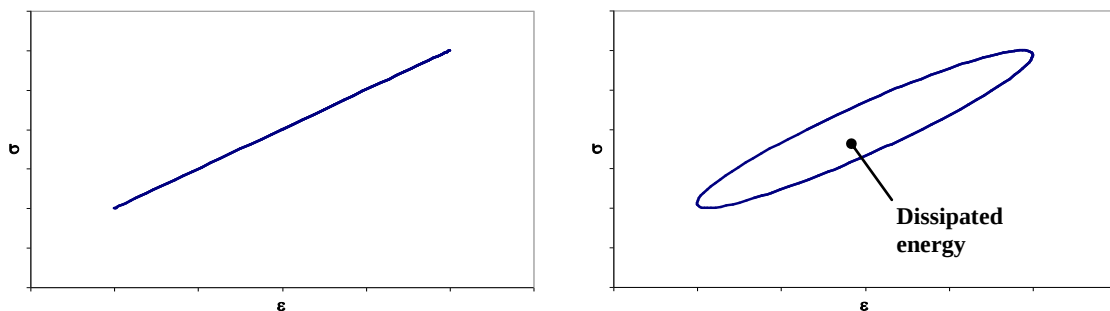


Figure 5: Hysteresis: (left) elastic and (right) viscoelastic response [38]

When viscoelastic materials are subjected to fatigue or cyclic motion, a proportion of the mechanical energy per cycle is converted to thermal energy (heat) with the rest of the energy being stored. A hysteresis loop develops whose area is equal to the dissipated energy per cycle (Figure 5). The stiffness and hysteresis can be derived mathematically – see [38].

Analysis of data generated from specimens that have been fatigued to failure should show that over time the stiffness of the material decreases towards failure with the energy loss of the material becoming greater as damage accumulates and friction causes material heating (Figure 6). As damage accumulates within the material, the slope of the hysteresis ellipse will decrease and the area within the ellipse will increase. For a considerable proportion of the fatigue life (50-60%), stiffness and hysteresis will remain fairly constant (see Figure 6). There will be a rapid change in stiffness and hysteresis within the last few hundred cycles. Although measurement of global stiffness is relatively straightforward using a LVDT, it is often difficult to obtain an accurate measurement of the hysteresis. Localised deformation measurements can be obtained using strain gauges bonded to the specimen surface. These gauges, if strategically located at critical stress regions, may indicate the onset of localised damage.

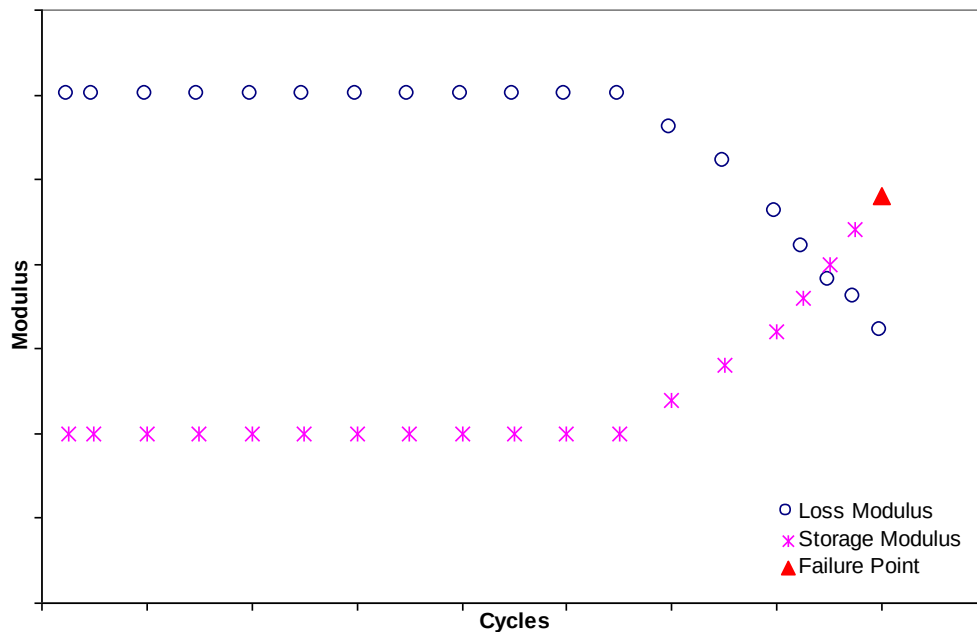


Figure 6: Storage and loss modulus changes [38]

Fatigue (endurance) limit is the maximum fluctuating stress a material can endure for an infinite number of cycles (Figure 7). Under constant amplitude loading conditions, most materials or structures seem to exhibit a plateau in the stress-cycle curve, which typically occurs at $N > 10^7$ cycles. The plateau level corresponds to the fatigue or endurance limit. Below this limit, the material or structure can in principle be cycled indefinitely without causing failure. Research conducted at NPL on unidirectional glass fibre-reinforced epoxy suggests that given sufficient time, fatigue failure will occur at stress levels less than 25% of the ultimate strength (i.e $N \approx 10^8$ cycles at 20% UTS).

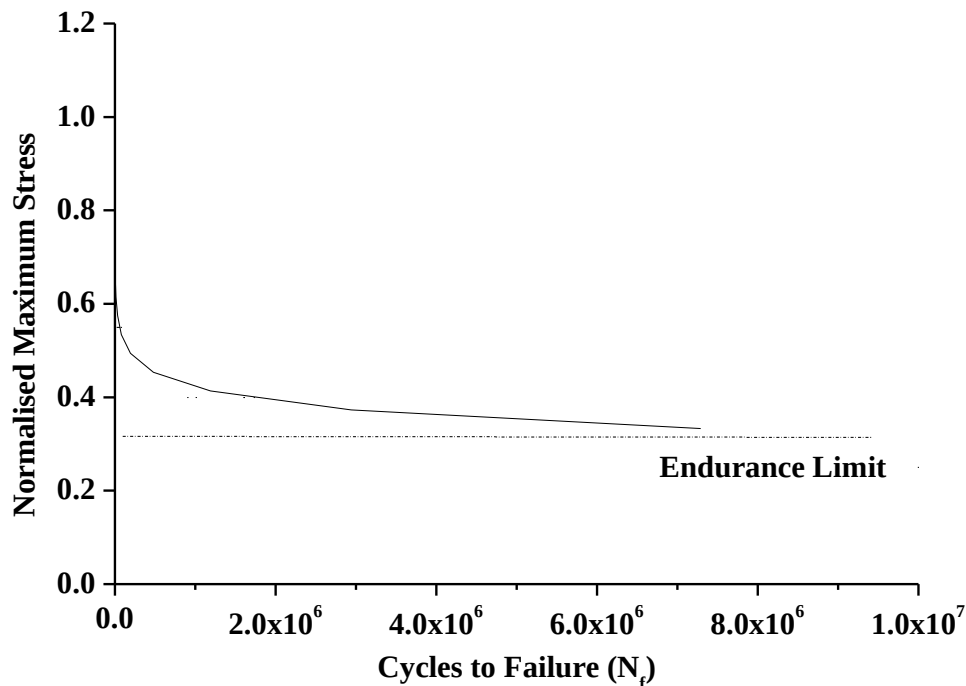


Figure 7: Schematic of S-N curve with fatigue endurance limit

2.3 Variable Amplitude Spectral Loading

An important aspect to fatigue design is ensuring that the load spectrum is representative of the stresses and strains actually experienced by the component during service. The distribution and number of stress cycles, and the order in which the loads are applied define the stress spectrum loading. For example, stress spectrum loading is used for testing spherical tanks for transporting liquid natural gas and for assessing fatigue performance of aircraft wings. Service load spectra can be estimated from typical operating conditions experienced by the component. This can be achieved by monitoring strain at critical regions of the component under service loads. For the purpose of life prediction, the spectrum loading is simplified.

A number of spectral loading histories characteristic to specific structures, such as TWIST and FALSTAFF, have been developed to simulate the load sequence for transport and military aircraft, and WISPERX a standardized European wind turbine fatigue load spectrum [42-43]. TWIST was designed to simulate the loading spectra for wing tension skins near the main landing gear attachment. The loading program allows for different types and levels of gust loadings. Metal airframes have traditionally been fatigue tested under spectrum loading conditions to a minimum of two lifetimes to ensure adequate fatigue life. A high structural reliability is generally guaranteed if the fatigue life of the structure is 2-4 times the lifetime of the structure. However, the high variability associated with fatigue life of composites means that the 2-4 lifetime fatigue criteria may not be sufficiently reliable, and hence the need to use larger life factors for fatigue design [8-10].

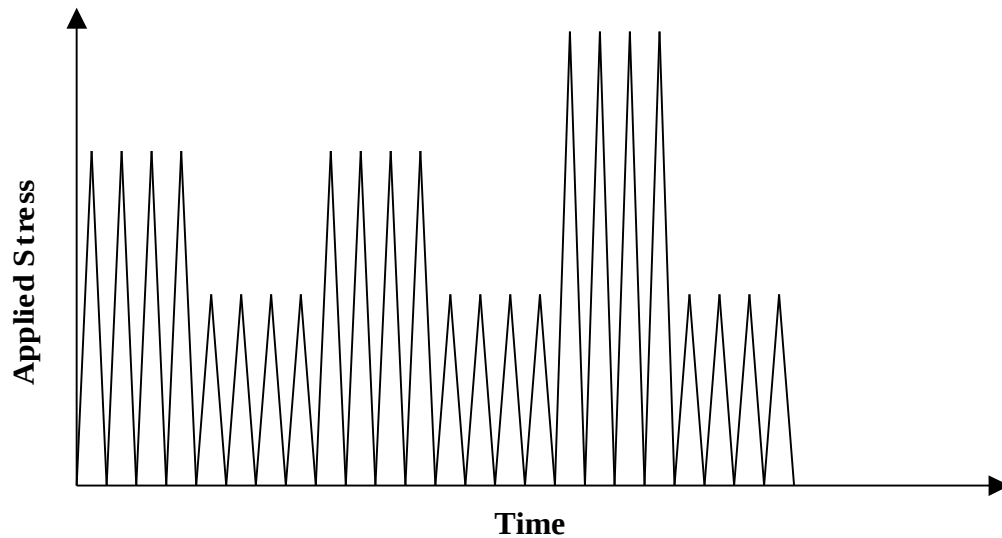


Figure 8: Blocking of constant amplitude cyclic stresses

An intermediate step between constant amplitude and spectral loading has been to apply a sequence of two or more constant amplitude blocks with different amplitudes (also known as multiple-step (or multiple-phase) block loading) that are repeated for a set number of cycles or to failure. In some cases, different frequencies and R ratios are included. Figure 8 shows a schematic of three-step blocking of constant amplitude cyclic stresses.

Fatigue Testing

3

IN THIS CHAPTER

- Introduction
- Mechanical Testing

3.1 Introduction

This section considers the affect of test parameters (i.e. test machine alignment, load train stiffness, methods of gripping, test machines, accuracy of load, and displacement and strain measurement techniques) on the accuracy and reliability of the long-term cyclic fatigue performance of composite materials and structures. Guidance is provided on the main factors that need to be controlled when carrying out mechanical testing.

3.2 Mechanical Testing

Residual strength, residual stiffness and fatigue life measured in fatigue tests form only part of the useful data that can be obtained. The different modes of failure that occur through fatigue should be recorded for each test. Optical microscopy or scanning electron microscopy may be required to analyse the fracture morphology, particularly if the cause of failure is not clearly evident from visual inspection. Standards often specify the failure modes (including location) that are acceptable for a particular material and loading condition. The effects of test environment need to be considered. The operator should ensure that the equipment used to load and monitor the specimen are unaffected by the test environment. It may be necessary to thermally insulate load cells and use molybdenum grease to ensure moving parts in test fixtures do not seize whilst testing. It is recommended that loading fixtures be fabricated from stainless steel to avoid environmental attack.

3.2.1 Test machine and specimen alignment

The majority of fatigue testing of high performance materials tends to be conducted using servo-controlled, hydraulically driven machines that can apply constant or varying waveforms. Although other types of test machines are available for this purpose (i.e. mechanically driven and pneumatic powered ram driven machines), servo-hydraulic machines are particularly suitable due to their rapid response time. Servo-hydraulic machines are designed for both uniaxial tensile and compressive testing and are capable of test frequencies of 50 Hz, or higher. As previously mentioned, the response time of load and strain transducers (or sensors), and associated instrumentation can become problematic at higher test frequencies, as can the issue of hysteretic heating (see Section 2.2.3). During fatigue tests the elements of the system are subject to acceleration and it may be necessary at high frequencies to correct the load cell calibration for dynamic inertial effects. In addition to the force applied to the specimen, the load cell experiences forces resulting from its own movement and the mass of the grips and fixtures attached. Attaching the load cell to the non-moving part of the test frame (i.e. not an actuator) can negate this effect. These additional forces are generally insignificant at the frequencies normally used (10 Hz, or less). Most commercial equipment is now supplied with in-built inertia compensation for load cells.

Commercial servo-hydraulic machines generally have desktop computers with software for both machine control and data processing. The basic control facilities enable the operator to select the test mode (i.e. tension, compression, flexure or shear), test frequency, waveform (e.g. sine, square, triangular or saw-tooth), mean condition and applied amplitude, or alternatively minimum and maximum values. These controllers also allow block and spectral loading programmes to be specified (see Section 2.2.9). Block loading may contain blocks with different frequency and minimum/maximum values.

Servo-hydraulic machines can operate in displacement, strain or load control (see [45]), and have load cells designed with high fatigue life and “over-load” protection. In displacement control, the in-built displacement transducer in the ram provides feedback on its position. Whereas, load control requires a specimen in the loading train in order to apply a displacement to the load cell to generate the load reading. As a consequence of specimen failure, there is a loss of the load signal and the test machine reverts to displacement control. Under load control the stiffness of the specimen forms part of the automatic electronic tuning of the gain control of the system to ensure the ram movement closely follows the control signal. Strain control relies on the use of strain gauges or other strain devices (i.e. contact extensometers or optic fibres) to provide feedback control of the test machine. However, strain control is notoriously difficult, as strain sensors can detach or fail with resultant loss of strain control. Under these circumstances the machine is designed to return control to the safer displacement mode. The number of cycles is measured directly or determined from the applied frequency and test duration. An accuracy of $\pm 2\%$ of the test frequency is normally required. Similar features to those described for tension-compression machines are available with torsion machines with the modes of operation being torsion, tension-torsion and compression-torsion.

The test machine should have high lateral rigidity and accurate alignment between the upper and lower gripping faces. The load train should be as short and as stiff as possible (i.e. no universal joints included). Small lateral (1 to 2 mm) or angular (1 to 2 degrees) offsets in the loading train can lead to additional stresses resulting in premature failure. It is worth noting that the slope of the load-displacement response can be similar for poor and well-aligned specimens and should not be used for checking alignment. Poor alignment of test specimens can result in low strength values and a significant reduction in fatigue life. It is recommended that the alignment of the test machine and the test specimen be checked at the centre of the gauge-length using a strain-gauged coupon. Alignment specimens can be in the form of a rectangular or circular bar. These specimens need to be accurately machined to ensure errors in parallelism are < 0.2 mm/m and in concentricity (lateral offset) of 0.03 mm [48]. Strain gauges are bonded to the surface of the alignment specimen in order to monitor alignment and bending strains. For tensile tests, the combined through-thickness and in-plane bending strains should be less than 3% of the average axial strain. For compression, the combination of these strains must be less than 10% of the axial strain. A positioning device should be used to ensure that the specimens are positioned in the grips in a repeatable manner. An alignment fixture can also be included in the loading train to minimise angular and lateral offset between the upper and lower machine grips or loading rods. The alignment cell is attached to the upper or lower crosshead of the test frame; whichever is the most convenient. Commercial alignment cells are available that allow lateral movement, tilt and rotation of the machine grip or loading rod.

3.2.2 Gripping specimens

Grips for holding test specimens to be loaded in tension should be attached to the test frame so that the major axis of the test specimen coincides with the direction of pull through the centreline of the gripping assembly. The centre line of the specimen should be aligned with the axis of the loading fixtures to avoid bending and asymmetric loading. It is important that when loading test specimens in the grips that no lateral or angular offset is introduced to the specimen. Avoid rotating the grips during the gripping operation. If one of the grips is articulated, this should be tightened first to prevent the specimen being subjected to large bending and twisting (torsion) loads during tightening.

Care should be taken to avoid axially stressing the specimen whilst the grips are being tightened. Any pre-stressing of the specimen should be kept to a minimum. Grips should be slowly tightened with any induced loads removed by progressively adjusting the crosshead position. The applied load on the specimen should be zero at the onset of testing. It may be necessary to use a device (i.e. metal spacer) during the test set-up to ensure good alignment and repeatable test results, as often the specimen width is less than the width of the mechanical grips.

Manual or servo-hydraulic grips can be used to hold specimens during testing. Wedge-action grips are recommended as the lateral force (i.e. pressure) applied to the test specimen in the gripping regions increases as the axial load applied to the specimen increases. Gripping pressure should be sufficient to prevent specimen slippage throughout the duration of the test, but not excessive to initiate failure of the specimen at the grips. Testing, particularly at high loads, is best carried out using fatigue rated servo-hydraulic (wedge-action) grips. For cyclic loading, it is essential that fretting in the gripped region be prevented to avoid the possibility of premature failure. Loading requirements for specific tests will be discussed in Section 5.

3.2.3 Strain and displacement measurement

This section considers the use of contact and non-contact techniques for measuring strain and displacement.

Contact extensometers are commonly used for measuring strain and displacement, and hence stiffness of the test specimen. It is recommended that two extensometers, attached to opposite faces of the specimen, be used to measure displacement (see Figure 9). Any bending of the specimen will be apparent from diverging displacement readings. It is also recommended that the individual transducer readings be recorded so that the quality of the test data can be checked. Errors due to minor bending are minimised by taking the average measurement of the two displacement transducers. To minimise inclusion of adherend deflection in the measurement of joint stiffness for bonded and mechanically fastened joints, the contact points should be as close to the bond layer or bolted section as possible [37, 41].

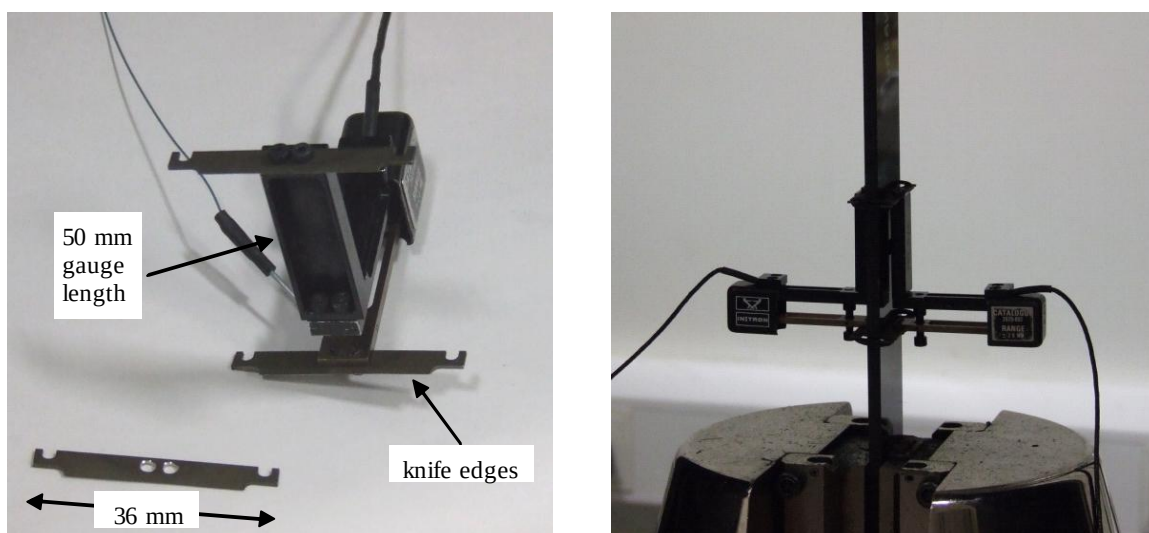


Figure 9: Extensometers used for measuring longitudinal tensile strain

Where specimens are flexible, it is advisable to support the weight of the extensometer because allowing the extensometer to hang unsupported from the specimen may cause bending and introduce contact stresses (or alternatively use a video extensometer). The contact forces should be sufficient to prevent slippage between the extensometer and the specimen, but not large enough to cut or nick the specimen surface causing the specimen to fail prematurely. Extensometers can be held in place using springs and/or rubber "O" rings stretched around the specimen. It may be necessary to remove extensometers attached to a specimen prior to failure in order to prevent the possibility of the extensometer sustaining damage during failure. Failure can be a violent event, releasing considerable energy, thereby damaging or even destroying the extensometer.

An extensometer should be capable of measuring the change in gauge-length with an accuracy of 1% of the applied displacement or better (i.e. equivalent to $\pm 0.5 \mu\text{m}$ for 10 % strain over a typical bond thickness of 0.5 mm). A gauge-length of 50 mm is typically used for uniaxial tensile tests (see ISO 527-1 [49]). Contact extensometers and the associated data acquisition system must have a sufficient response time to cope with the test frequency in cyclic fatigue testing. It is important that the extensometers are able to operate satisfactorily within the test environment (i.e. temperature and humidity), and that these devices are resistant to chemical attack when used in hostile environments. Precautions may need to be taken to insulate the leads to prevent moisture ingress.

Strain gauges: Electrical foil strain gauges are widely employed for monitoring mechanical (static and dynamic) and thermal induced strains. Strain gauges are routinely used for monitoring localised strains and for determining the onset and growth of localised damage in laminated and bonded structures. Strain gauges can be either directly bonded to the surface or embedded within the composite material and are generally limited to the measurement of strains less than 10%. Care should be taken to ensure that strain measurements derived from strain gauges are reliable, as strain gauges tend to locally stiffen the substrate, such that the strain is less than expected for a given load. Large strain gauges are preferable as alignment and handling is easier, and they average out local strain variations. Local strain variations can cause premature failure of the strain gauges. Correct alignment of strain gauges is important, as significant errors can be caused by careless application to the specimen. Errors of 15% can occur from a 2° misalignment. Biaxial rosettes are available for measuring longitudinal and lateral strains.

Strain gauges are prone to failure by disbonding, creep and fatigue, and thus are not particularly suited for long-term use over many years. Strain gauges have a limited fatigue life, although there are gauges that have been designed with long fatigue life. For cyclic loading, it is essential that the fatigue life of the strain gauges, over the operating strain levels, should be well in excess of the life expectancy of the test component. Hysteretic heating can also degrade the mechanical properties of the adhesive bond between strain gauge and the specimen. This can result in small errors in strain measurement, thus requiring correction of the data to account for the temperature rise. Measurements should also be carried out to determine the magnitude of creep within the strain gauge adhesive.

Thermal compensation will often be required to account for variations in temperature. Measurement electronics also tend to drift with time. Vibrating wire devices are available that are free from drift, however these devices are larger and much more expensive. The maximum operating temperature of conventional strain gauges is typically (350°C), which for most FRP applications is sufficient.

The adhesive used to bond strain gauges should be capable of withstanding the test environment for the complete duration of the test. Most adhesives are sensitive to moisture (and other chemicals), which can often preclude bonding prior to specimen conditioning. Moisture attack of an adhesive and strain gauges will occur from the top, edges and in the case of FRP materials through the substrate beneath the gauge. The situation is exacerbated at elevated temperatures. It is therefore important to ensure that the adhesive selected for bonding the strain gauge and associated electrical wiring is suitably encapsulated. Methods of encapsulating the gauge from environmental attack will often tend to slow rather than prevent moisture ingress. Strain gauge manufacturers can provide information on adhesive selection, surface preparation and procedures for protecting strain gauges, and providing advice on fatigue performance and strain limits of these devices.

Crosshead displacement provides an approximate measurement of strain, and hence stiffness can be obtained from measuring the crosshead displacement of the test frame. The strain is the ratio of crosshead displacement and the initial grip separation. Hence, any compliance or slippage within the loading train will produce errors in the strain measurement. The strain values obtained from crosshead measurements will differ from the actual strain in the central region of the specimen. Stiffness measurements directly obtained from the crosshead movement need to be corrected to take into account the stiffness of the loading train. This can be a difficult task as the specimen size and geometry, and the deformation behaviour of the specimen need to be taken into account. Given the small adhesive layer deflections that occur in bonded structures even at large deformations or loads owing to thin bond-lines, the accuracy of strains determined using crosshead displacements must also be considered suspect. Crosshead measurements should only be used for qualitative purposes.

Linear Variable Differential Transformers (LVDTs) are recommended in preference to monitoring crosshead movement. These devices provide a direct measurement of the moving part and can be attached at any point on the structure as required. LVDTs tend to be used to monitor global rather than localised deformation. Accurate alignment is essential otherwise measurement errors will occur and the movement of the device can be restricted. It is important to ensure the device is capable of operating effectively in the test environment and that electrical wiring is suitably protected. There is a potential problem of friction, which arises from the movement of the core within the barrel, which is normally designed to have limited rotational freedom. Friction between the core and barrel can be significant resulting in “stick-slip” movement of the device.

Optical fibre based sensors can be used to monitor a wide range of parameters including strain, temperature, pressure, humidity, moisture ingress, in-situ cure kinetics, vibration, pH levels, chemical concentration and gamma radiation (see [50]). In addition, these devices can be used to monitor degradation processes and fracture. Most of the evaluation of these devices tends to be laboratory based under ideal conditions. As with other sensors, fibre optic devices can be located in obscure locations not readily accessible by conventional NDE methods. These devices are small with low weight and in many cases can be embedded into or bonded to the structure (to produce smart structures). Composite laminates are particularly suited to their use simply by the fibrous nature of the material, and the fact that these devices can be introduced during the manufacturing of composite components (see Figure 10). Bonding these devices to surfaces pose similar problems to those for strain gauges. Optical fibre diameters are large compared with carbon and glass fibres and can cause local distortion within composite structures. Optical techniques require sensors to remain fully bonded with the composite throughout the life of the component to ensure effective strain transfer.

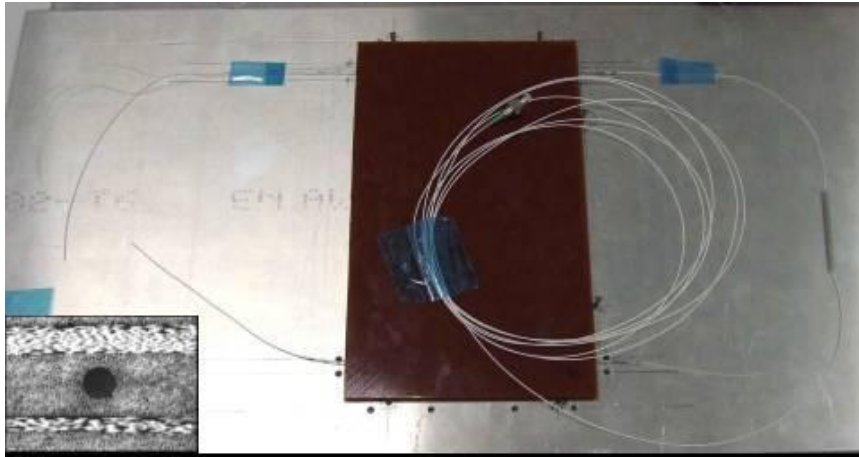


**Figure 10: GRP laminate with embedded optical fibres
(inset – micrograph of embedded fibre)**

Note: Optical fibre sensors can be multiplexed with a number of sensors attached along a single optical fibre [50-51].

One of the most promising fibre optic methods used is the Bragg grating strain sensor (also known as fibre Bragg grating (FBG)). These tiny gratings are ‘etched’ into the core of an optical fibre and the wavelength of ‘reflected’ light is measured to determine the local strain (Figure 11). In fact, the grating is based on a modulation of the inner core’s refractive index. Multiple gratings may be “written” on each fibre that, when embedded within structures, may serve as a fully distributed strain sensor. Advantages over conventional techniques include mechanical robustness when embedded, electromagnetic radiation immunity, large scale embedding capability to sense relevant stresses, large scale distributed sensing capability, inherent safety (no electrical connections), very large and mature telecommunications market that supports this application, and a large academic and industrial backing.

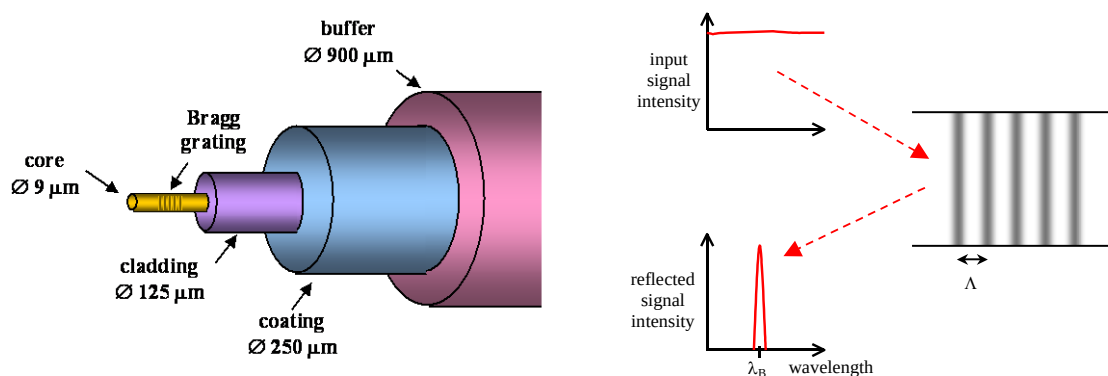


Figure 11: Optical fibre with Bragg grating with typical spectral response

The Bragg sensor is a segment (typically 3-15 mm long) of optical fibre with a longitudinal periodic modulation in the core refractive index, which acts as a narrowband reflection filter. The basic principle of operation is the measurement of changes in the wavelength of the reflected signal (i.e. centre or Bragg wavelength λ_B , when illuminated with a broadband light source) – see Figure 10. The Bragg wavelength is dependent on the effective refractive index of the core n_{eff} and the grating periodic spacing, Λ .

Strain sensitivities of the order of pico-strains and strain levels up to 10000 $\mu\epsilon$ are possible. FBG devices can be used to monitor transient strain signals of duration 100 ms, or less. These devices are purported to be able to measure temperatures ranging from -193 °C to 800 °C with a resolution of 0.05 °C. One of the major benefits of using FBG sensors according to a number of authors is the long-term stability of operation in hostile environments, although there is not sufficient data available to assess their long-term reliability, particularly under hot/humid and freeze/thaw conditions, and cyclic loading conditions. It is important that embedded sensors have minimal effect on the local microstructure and do not act as a path for moisture ingress. There are a number of technical issues to be resolved.

- Calibration and traceability of strain measurements, which is complicated by the interaction of mechanical and thermal induced strains. The addition of residual strains and cure shrinkage can further complicate data interpretation.
- Dependence of strain factor on stress state (differences observed between pure tension and bending loads).
- No standardised procedures for bonding or embedding FBG devices, which means wide variability in measurements compromising data reliability.
- Complexity of measurement due to the coupled response of the fibre optics to strain, temperature, and the electro-optics and electro-acoustic characteristics.

Non-contact or optical extensometers (e.g. video extensometers) avoid the problems of contact damage and use up to failure. There are no temperature or environmental restrictions as video extensometers can be located outside the test chamber (provided that the specimen can be imaged clearly). Standard systems measure the separation of marks in one direction, mimicking contact extensometers, but some systems provide capabilities for dot location measurements, which allows two-dimensional measurements and a limited strain mapping capability. Dot location provides versatility and, potentially, enables measurement for a wide variety of different specimen geometries using a single system.

The technique uses remote cameras and image analysis software to monitor the separation of high contrast marks or lines inscribed on the test specimen. The initial separation of the marks defines the gauge-length and the change in separation of the marks is recorded throughout the test. Gauge marks should not be made on the specimen in any way that may cause damage to the specimen. Accuracy tends to be low for small strain measurements. Developments in resolution, sensitivity and speed of digital imaging and data processing are leading to improved capabilities. One limitation of the technology is that, unless a dual camera system is used, measurement is normally only possible at one side of the specimen so that bending cannot be evaluated.

Digital image correlation (DIC) is a non-contact full-field strain measurement technique. The basic concept of DIC is to compare two images of a component before and after deformation. It uses computer image analysis to track the movement of blocks of applied speckle patterns on the surface of the specimen (see [52-53]). Displacements and strains are determined by correlating the position of pixel subsets or blocks in the original and deformed image, normally based upon contrast i.e. grey intensity levels. In order to identify if there is any movement between the two blocks there must be sufficient detail for it to be considered unique. It may be the case that the specimen or component already has a suitable level of surface features which can be imaged directly, but if not, some form of spray paint or coating or scratches on the surface can be used.

For best results a unique surface finish and a good distribution of intensity values must be obtained. This can be achieved by spraying the surfaces to be inspected with black, grey and white paint to produce a random specular pattern for the image correlation. The deformations of the specimens are then calculated by correlating the positions and displacements of pixel subsets or blocks in the original and deformed image to produce a deformation vector map. This is then processed further to produce a full-field strain map, shown schematically in Figure 12 (see [52]). Calculation of 3D deformations is possible if two or more cameras are used. Calibration of the image by using a calibration plate is straightforward.

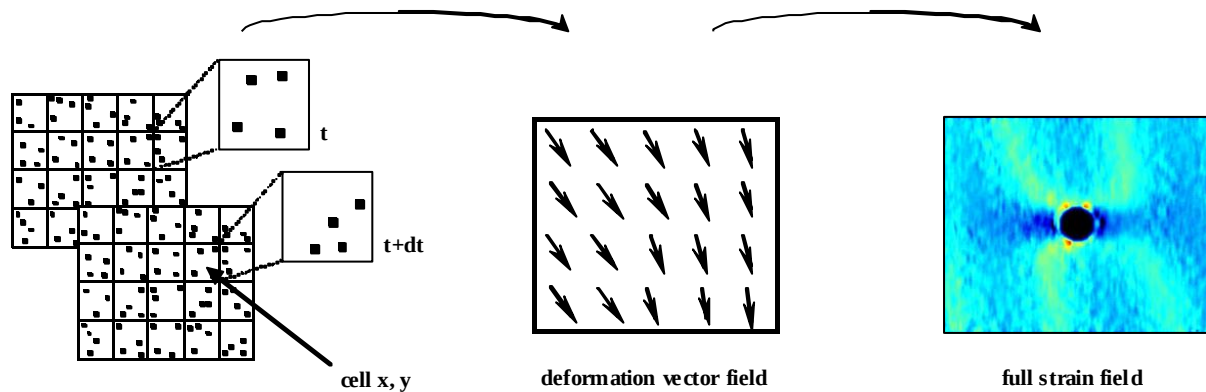


Figure 12: Principle of digital image correlation [52]

A key issue with DIC is the size of the interrogation window (i.e. the size of the pixel subset used for the correlation during data processing). The effect on accuracy of changing the size of the interrogation window on the calculated vectors and strain data can be seen in Table 3 and is illustrated in Figure 13. Although a small interrogation window size (e.g. 16×16) offers good spatial resolution, the strain resolution is poor. For a larger window size (e.g. 128×128) the spatial resolution is poor, but the error in the strain resolution is much lower. Careful consideration must be given to the size of this window as it has important implications on the spatial resolution and accuracy of the measurement. A compromise is needed between high spatial resolution (small interrogation window size) and high strain resolution and accuracy (large interrogation window) – see Table 3. Displacements can be resolved with sub-pixel accuracy to give an effective resolution of typically 0.01% strain. The decision on what size window to use depends on the particular application, expected strain field and data required.

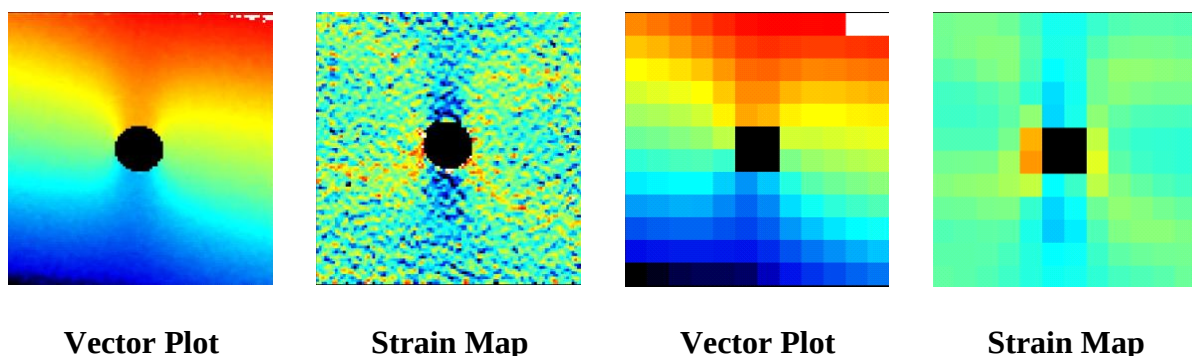
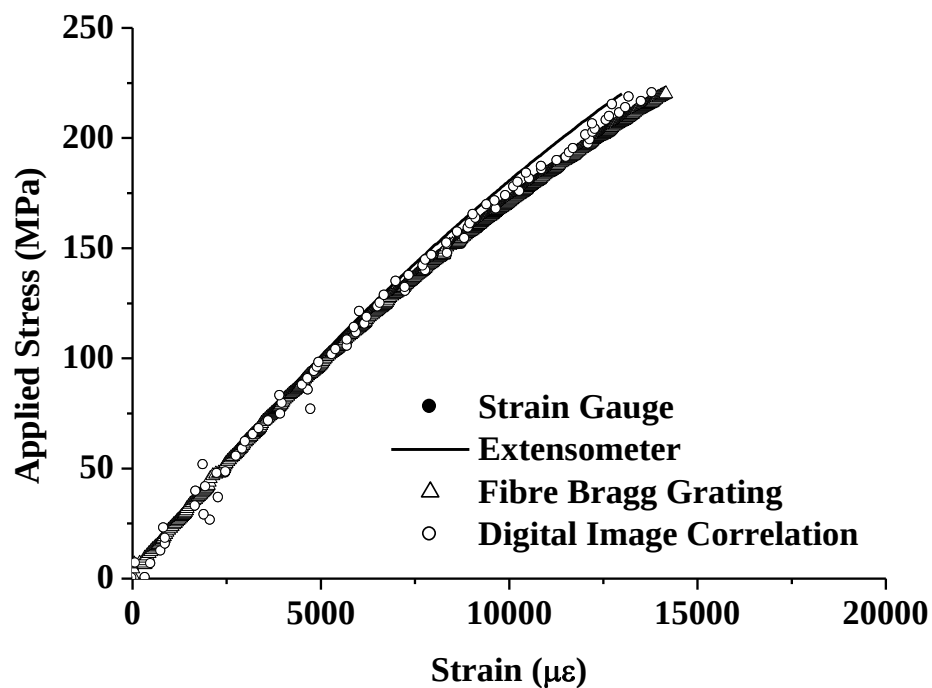


**Figure 13: Vector plots and strain maps
(calculated from a 16×16 (left) and 128×128 (right) interrogation window)**

Table 3: Estimated uncertainties and accuracies of strain measured using DIC [52]

Size of interrogation window in pixels	Accuracy of calculated vectors in pixels	Accuracy of calculated strain values
128 × 128	0.01 to 0.03	0.094%
64 × 64	0.02 to 0.05	0.3%
32 × 32	0.05 to 0.2	1.25%
16 × 16	0.1 to 0.3	5%

In principle, the strain measurements obtained using the different strain measurement techniques should be in good agreement as shown in Figure 14 for an open-hole tensile specimen subjected to quasi-static (monotonic) loading. The results can be expected to diverge with the onset of failure. Good correlation between stiffness values can also be expected for the different techniques under cyclic fatigue conditions.

**Figure 14: Comparison of strain measurements for four different techniques**

4

Loading Modes and Data Analysis

IN THIS CHAPTER

- Introduction
- Fibre Bundles and Composite Rods
- Polymers
- In-plane Tension
- In-plane Compression
- In-plane Shear
- Flexure
- Through-Thickness (T-T) Testing

4.1 Introduction

This section is concerned with loading modes and test specimen geometries used in assessing the fatigue performance of composites and their constituent materials. It examines specimen and test equipment requirements, methods of data analysis and interpretation, and factors associated with the various test methods and loading conditions that can influence fatigue performance.

4.2 Fibre Bundles and Composite Rods

4.2.1 Standards

Several test methods exist for measuring the tensile strength and longitudinal modulus of single fibre filaments and fibre tows or rovings (i.e. untwisted bundle of continuous parallel filaments). These methods are usually intended for yarns having a diameter less than 2 mm (typically 0.5 to 0.8 mm), or a linear density lower than 2,000 tex (g/km). Fibre tow methods include testing of both unimpregnated (i.e. loose or dry) and impregnated rovings (Figure 15). ISO 3341 [54] specifies a method for the determination of the tensile breaking force and failure strain of unimpregnated glass fibre rovings, whereas ISO 9163 [55] allows for both unimpregnated and impregnated fibre tows. ISO 11566, ISO 10618 and ASTM D 4018 [56-58] specify tensile test methods for carbon fibre tows.

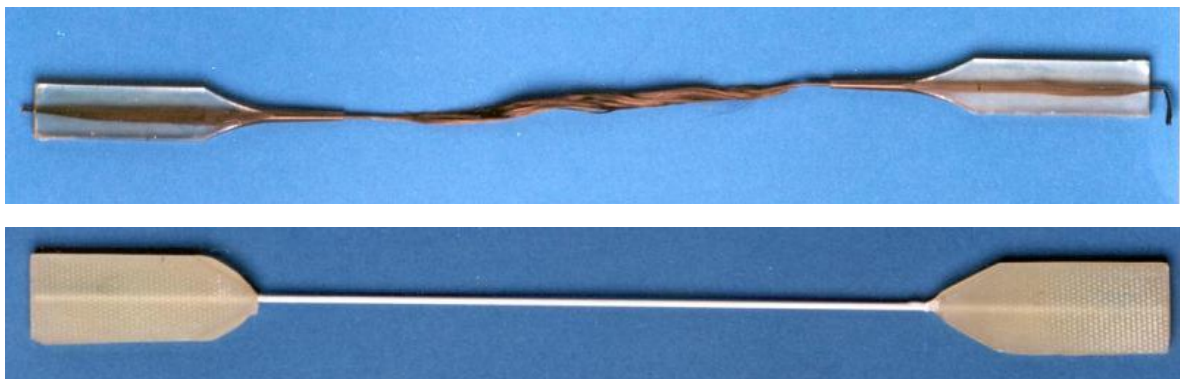


Figure 15: Carbon fibre tow (top) and GRP composite rod (bottom) specimens

4.2.2 Fibre bundles

Tensile cyclic fatigue (tension-tension) data for loose fibre bundles (tows) can be obtained using the specimen shown in Figure 15 (top). Specimen preparation is carried out according to ISO 9163. Typical specimen dimensions are shown in Figure 16. End tabs, although not mandatory, are recommended to avoid mechanical damage to the specimen ends and to ensure failure occurs within the gauge-length. For cyclic loading, the use of end tabs minimises the possibility of fretting/wear within the gripped region. ISO 9163 specifies a method for moulding end tabs. A cold curing epoxy system is recommended 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. Poor impregnation can result in non-uniform loading of the fibres within the fibre bundle resulting in low strength values with large uncertainties in static and fatigue strengths.

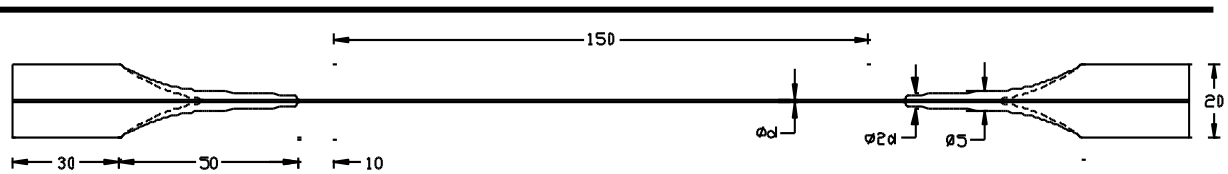


Figure 16: Fibre tow test specimen (mm)

The end tabs are cast in silicon moulds, which can be produced using a two-part, low-shrinkage, room-temperature curing silicon elastomer. Care needs to be taken to ensure that the mould is free of air bubbles (degassed) and the internal surfaces of the mould are smooth and free of defects. Moulds tend to split and break due to repeated handling and therefore need to be replaced on a regular basis (5 to 6 castings per mould). A schematic diagram showing the dimensions of the template used for producing the moulds is shown in Figure 17. The end tab length (110 mm) specified in ISO 9163 exceeds the grip length of most manual or hydraulic gripping systems, and hence, specimen tab lengths need to be be shortened to match the grip length of the test equipment (typically 50 mm).

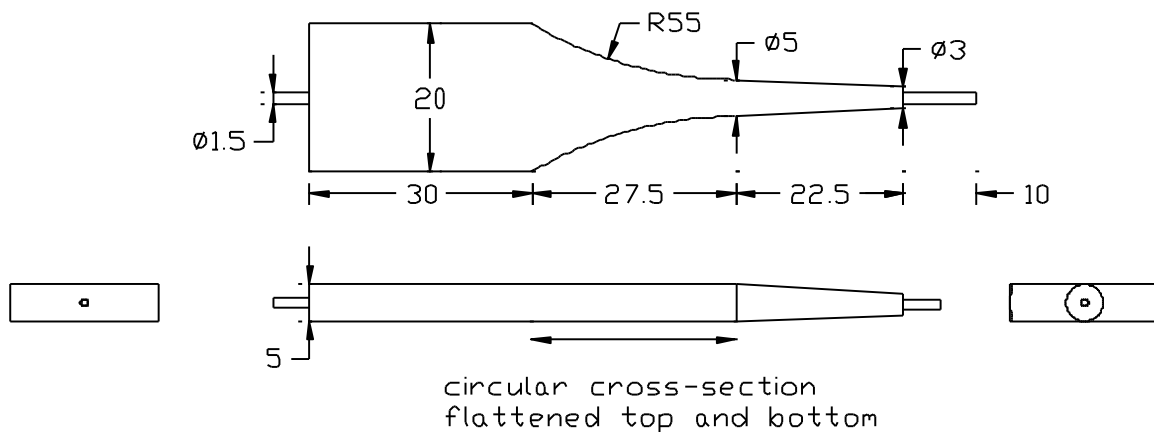


Figure 17: Schematic of moulding template used for producing end tabs (mm)

Initial strength and strength retention of fibres can be significantly reduced due to friction between fibres. An approach to protect conditioned or unconditioned glass fibres against abrasion is to impregnate the fibre tow with a rosin beeswax mixture. The effect of the protective coating on tow stiffness, although minimal, can be determined from comparative data obtained from unimpregnated material. Lubricating agents in the glass sizing formulation are introduced to protect fibres from abrasion.

Fibre bundle testing is relatively straightforward using low capacity mechanical or servo-hydraulic loading frames. Testing consists of loading the specimen to failure at a constant displacement rate (< 250 mm/min). The load and displacement are monitored during the test. Modulus and strain to failure are measured using an extensometer (mechanical or non-contact). It is important that the gripping system maintains good axial alignment throughout the duration of the test. Failure should occur within the specimen gauge-length otherwise the strength data are invalid. Glass-fibre and carbon-fibre tows exhibit excellent fatigue resistance under tension-tension cyclic loading. 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 is minimal. Provided the applied stress is smaller than the ultimate tensile strength and falls outside the scatter band (i.e. 2 standard deviations), then the lifetime of the fibre tow will exceed 10^7 cycles.

4.2.3 Composite rods

A resin-impregnated tow, when cured, produces a rigid specimen that is easier to handle and test than a loose bundle of fibres and also ensures uniform loading of the fibres in the bundle. The fibre tow is impregnated with resin and oven cured. It is important when feeding the fibre bundle through the resin bath that the speed and tension is sufficient to produce a uniformly impregnated test specimen. The resin must be capable of fulfilling that requirement. An automated strand preparation device equipped with a tension-regulating system (typically 0.2-20 N) is generally used. Specimen fabrication is fast and inexpensive, although considerable capital outlay is required to purchase fibre impregnation equipment. Specimens can be produced using a filament-winding machine. Carbon and glass fibre-reinforced rods can be pultruded in a range of resin systems (e.g. polyester, vinylester and epoxy). The minimum diameter size that can be pultruded is typically 1.5 to 2.0 mm.

The test geometry specified in ISO 9163 is unsatisfactory for measuring the tensile strength of composite rods with a diameter of 1.5 mm, or greater. The interface between the composite rod and epoxy resin end tabs will fail prematurely, resulting in pull-out of the composite rod rather than tensile failure within the gauge-length. Figure 18 shows a schematic diagram of a composite rod specimen with adhesively bonded composite end tabs that has been successfully employed in static and fatigue testing of glass/polyester and carbon/vinylester rods with a nominal diameter of 1.5 mm.

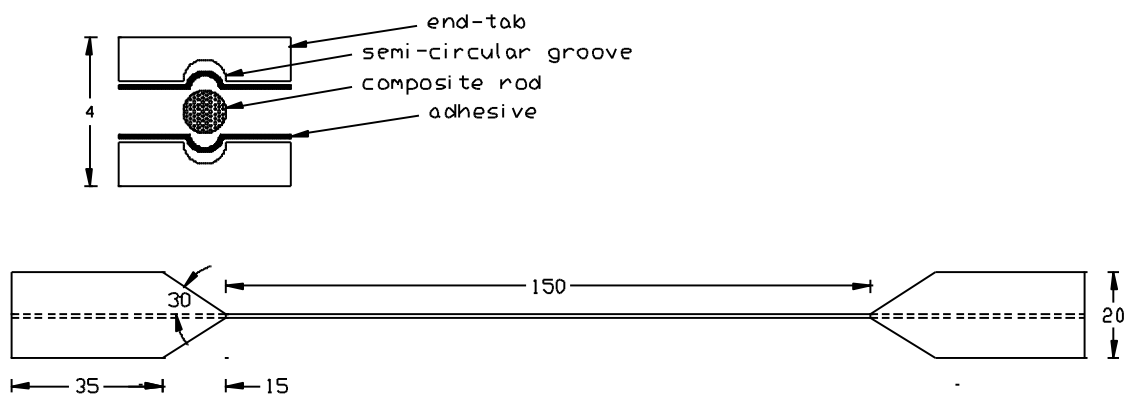


Figure 18: Composite rod specimen with bonded composite end tabs (mm)

End tabs are manufactured from 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 axes. 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 bond-line thickness. Specimen preparation is also cleaner in comparison with paste adhesives. The semi-circular groove to accommodate the specimen, shown in Figure 18, can be cut with a diamond-slitting wheel (water lubricated). The thickness of the wheel should match the rod diameter. It is essential to dry the end tabs before bonding to remove moisture, which can compromise the adhesive bond. The use of composite end tabs, described above, is limited to rods with diameters of 1.5 mm, or less. Cylindrical moulded end tabs made with a high shear strength epoxy adhesive paste that were 1.25 mm thick and 50 mm long proved satisfactory for testing rods up to ~ 3 mm in diameter. Tensile failure consistently occurs within the gauge-length. Figure 19 shows a composite rod specimen with moulded end tabs.



Figure 19: Composite rod specimen with moulded end tabs

Larger diameter rod specimens tend to crush in the grips. This may be remedied by using thicker moulded end tabs and/or by adjusting the V-notch angle of the jaw face of the grips to ensure the points of contact are equidistant around the circumference. Problems may be encountered under cyclic loading conditions (e.g. possible fretting or wear of end tabs). GFRP rods tend to fail in a non-progressive (i.e. catastrophic) manner within the gauge-length, although failure frequently occurs near the end tabs. Non-progressive failure occurs due to insufficient material being available to accommodate local stress concentrations induced through fibre fracture. Figure 20 shows an example of a failed GFRP rod with fibre breakage and longitudinal splitting. The fatigue performance of CFRP rods is far superior to that for an equivalent GFRP composite. It should be noted that 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.



Figure 20: Typical cyclic fatigue failure for glass/polyester rod specimen

4.3 Polymers

4.3.1 Specimen Preparation

Bulk resin specimens can be cast or machined to the required shape for measuring tensile, compression and shear properties (i.e. modulus, Poisson's ratio, yield/ultimate strengths and strain-to-failure). Many liquid resins can be cast into bulk specimens without the need for machining. It is possible to generate stress-strain curves for all three modes of loading using bulk polymer test specimens. Although resin specimens are relatively straightforward to test, there are a number of problems associated with casting or machining bulk specimens. Recommended procedures for the preparation of bulk resin specimens are given in Parts 1 and 2 of ISO 15166 [59-60]. Porosity, in the form of entrapped air and volatiles, is a common cause of premature failure (i.e. voids act as stress concentrators). In many cases it is virtually impossible to produce void free specimens, particularly for materials with a high viscosity. Water also permeates faster through porous materials. For resins cured at elevated temperatures, differences in the effective thermal mass of the polymer in bulk and composite specimens may result in differences in the thermal histories of the resin. The cure schedules used for producing test specimens should replicate the thermal history experienced during cure by the matrix in the laminate. Exothermic reactions can also occur when casting bulk resin specimens, resulting in material degradation through overheating. The problem is exacerbated with increasing thickness. To minimise the deleterious effect of surface scratches that may cause premature failure, the edges and faces of the specimen are carefully polished to remove any surface defects.

4.3.2 Tension

Tensile specimens typically consist of a waisted section with parallel sides (dumbbell) to facilitate strain measurements and to ensure failure occurs within the gauge-section away from the gripped ends. ISO 527-2 [49], which specifies test methods for determining the tensile properties of plastics and FRPs, includes several dumbbell specimen configurations. The test geometries specified in ISO 527-2 are suitable for fatigue testing. No end tabs are required. Testing and data reduction are relatively straightforward. The tensile stress is simply the applied load divided by the cross-sectional area (CSA) of the specimen gauge-section (i.e. $\sigma = P/A$). Contact (e.g. strain gauges, extensometers) and non-contact (e.g. video and laser scanning extensometry) techniques can be used to measure strain. Modulus is determined over the strain range 0.05% to 0.25% (provided this region on the stress-strain curve is linear). It is important when using contact extensometers to support the weight of the devices and to ensure that extensometer knife-edges do not cut into the specimen.

4.3.3 Compression

Compression properties of polymers can be obtained by loading small rectangular specimens between two parallel, hardened stainless steel platens in accordance with ISO 604 [61]. The recommended specimen length is 50 mm and 10 mm for modulus and strength measurement, respectively. Both specimen types are 10 mm wide and have a thickness of 4 mm. The compressive strength is simply the applied load at failure divided by the CSA of the gauge-section (i.e. $\sigma = P/A$). It is important that the two faces in contact with the top and bottom compression platens are flat and parallel to prevent buckling, which can result in premature failure. Contact surfaces are also lightly oiled to reduce friction effects. Provided the specimen does not bend and/or buckle under compressive loads the data analysis is relatively straightforward. Extensometers or strain gauges are used to measure longitudinal and lateral strains/displacements. For maximum accuracy, strain needs to be measured on the two opposing faces of rectangular specimens. Although the test geometry is used for determining Young's modulus, small displacement measurements tend to be inaccurate and difficult to repeat. Failure can be expected to initiate at the specimen ends of thermoset resins due to stress concentrations, however thermoplastics tend to undergo shear failure. ISO 604 is incompatible with fatigue testing.

4.3.4 Shear

V-notched beam (ASTM D 5379 [62]) and torsion rod (ASTM D 1043 [63]) shear tests can be used to provide shear property data for polymers under both static and fatigue conditions. The first method employs a double edge-notched, flat rectangular specimen (76 mm × 20 mm × 5 mm) – see Figure 21. Two 90° angle notches with a notch root radius of 1.3 mm are machined at the specimen mid-length of each longitudinal edge with faces oriented at ±45° to the longitudinal axis, to a depth of 20% of the specimen width (i.e. 4 mm). The average shear stress is the applied load divided by the cross-sectional area between the notches. Shear strain is measured using biaxial strain gauges (1 or 2 mm gauge-length) aligned ±45° to the longitudinal axis bonded to both faces of the specimen. Shear modulus is determined from the average response of the back-to-back biaxial rosettes. To minimise potential effects of out-of-plane movement or twisting of the specimen, it is recommended that the strain data used for determining shear modulus be the average of the indicated strains from each side of the specimen. A special test fixture is required (Figure 21).

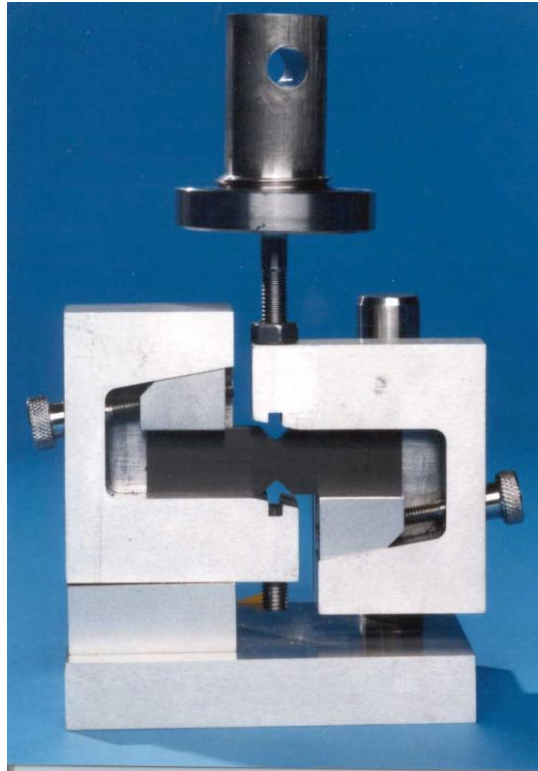


Figure 21: V-notched beam shear method

A technique that can be used to measure both shear and tensile properties of polymers is the circular rod specimen, which can be loaded in torsion to provide shear data and in tension to provide tensile data. Specimens may be moulded or machined directly from rods. The ends of the gauge-section are filleted to minimise stress concentrations present at these locations. The high degree of machining required exposes this specimen geometry to a high risk of machine-induced damage. This is compounded by difficulties in producing castings free of voids and residual stresses, thus placing considerable limitations on the materials that can be evaluated using the torsion method. Tests are performed with one end of the specimen fixed and a rotational load applied to the opposite end (using either a rotary motor or via a lever). Surface shear strain is measured using either strain gauges or contact extensometers. Strain gauges are adhesively bonded to the specimen surface at the centre of the gauge-section. The gauges are oriented at $\pm 45^\circ$ to the longitudinal axis of the specimen. An additional axially aligned strain gauge is recommended to monitor longitudinal strain. Tensile or compressive axial strains must not be present throughout the test duration. The shear modulus is determined from the linear region of the stress-strain curve. A torsion test machine is also required, a facility not available to most laboratories.

The main concern is that the shear stress distribution along and through the specimen under torsion loading is non-uniform. The shear distribution is high on the external surface and lower in the centre. The advantages of the test geometry is that combined shear and tensile, and shear and compressive loading can be applied, and tests can be carried out under cyclic loading conditions. The failure mode in torsion as with the V-notched beam is dependent on the ductility of the polymer (i.e. brittle materials tend to fail in tension whilst ductile materials undergo shear yielding).

4.4 In-Plane Tension

4.4.1 Specimen preparation and test geometry

ISO 527-4 and 5 [64-65] provide tensile testing specifications for determining the ultimate tensile properties of multidirectional and continuous aligned (longitudinal (0°) and transverse (90°)) laminates, respectively (see Figure 22). ISO 527 (Parts 4 and 5) specifies methods and specimen geometries for determining the tensile properties for continuous aligned, random mat, woven fabric and multidirectional laminates. ISO 527-4 allows for 10 mm thick isotropic and orthotropic laminates. Specimens are typically 250 mm in length with a 150 mm gauge-length. The width of longitudinal and transverse unidirectional laminates is 15 mm and 25 mm, and thickness 1 mm and 2 mm, respectively. The width of multidirectional laminates is 25 mm and thickness 2 mm. The ends of the specimen are reinforced with adhesively bonded end tabs made from a glass-fibre reinforced cross-ply or fabric laminate with the fibre axes of the fabric set at $\pm 45^\circ$ to the specimen axis, with a 90° tab angle (i.e. not tapered). A toughened epoxy (i.e. high strain to failure) adhesive should be used to bond the end tabs. For ease of manufacture, and lower specimen preparation time and costs, it is recommended that the end tabs should be bonded to the panel rather than to individual specimens. It is possible to manufacture the laminate with in-built (integrated) end tabs (Figure 23), but the advantages are minimal as the short-and long-term properties are similar to those obtained using adhesively bonded end tabs (see Figure 24). Polishing specimen edges, and thus removing cracks can significantly increase fatigue life.



Figure 22: Longitudinal (top) and transverse (bottom) tensile specimens



Figure 23: Unidirectional E-glass/epoxy laminate with bonded end tabs

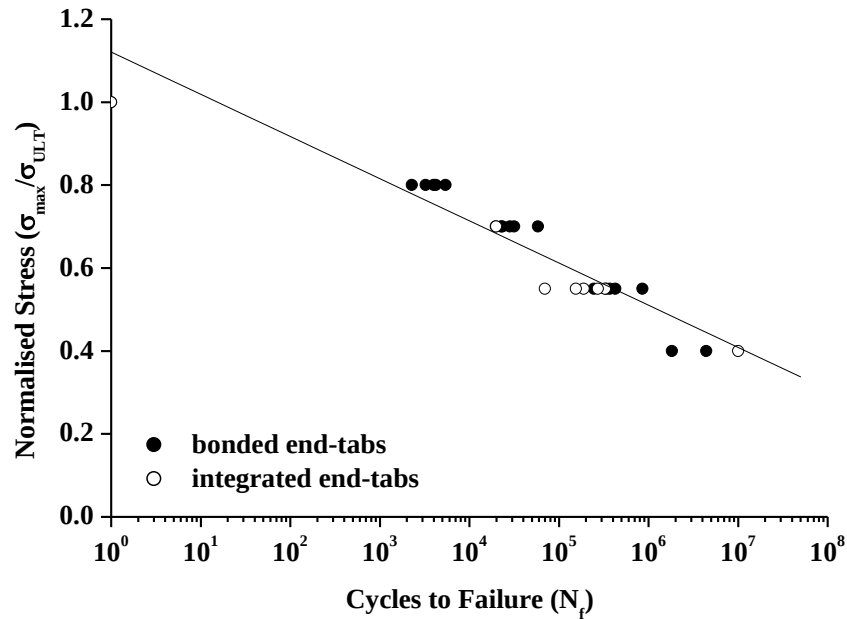


Figure 24: S-N curves for unidirectional GFRP with bonded and integrated end tabs

4.4.2 Unidirectional laminates

Unidirectional CFRP laminates possess excellent longitudinal tensile fatigue resistance in comparison with metals and GFRPs. The normalised S-N curves are relatively flat for unidirectional CFRP, but in the case of unidirectional GFRP there is a marked decrease in fatigue strength with loading cycles as shown in Figure 24. Increasing R reduces the gradient of the S-N curve (see Figures 25 and 26).

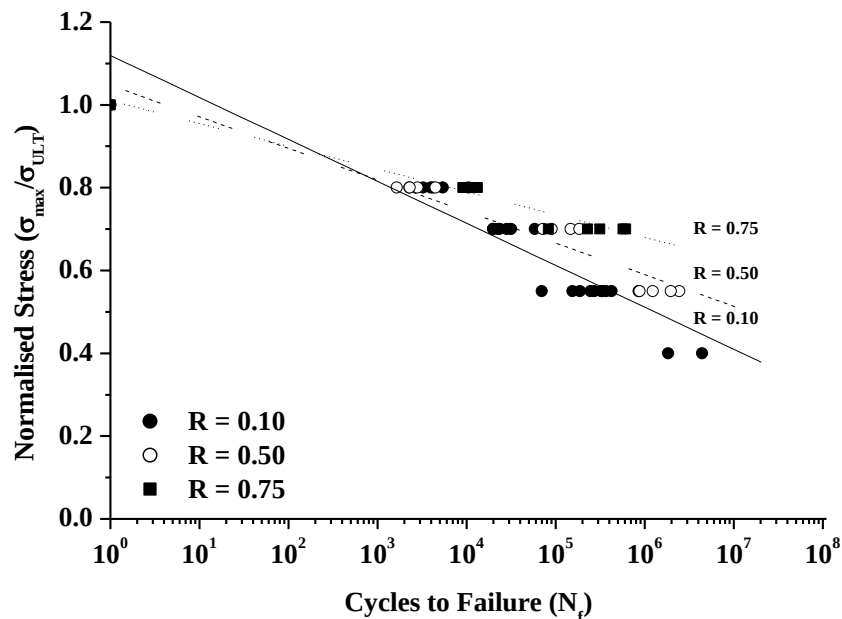


Figure 25: Typical stress/life curves for unidirectional GFRP at different R ratios

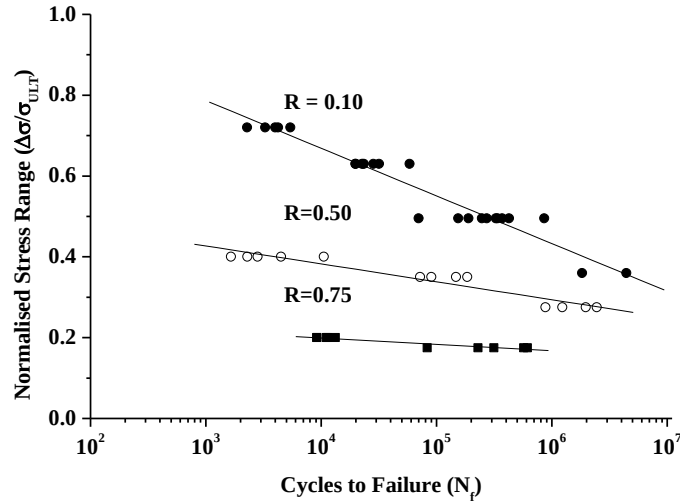


Figure 26: Normalised stress range versus fatigue life curves for unidirectional GFRP

The **S-N** data can be represented by the following numerical expression:

$$\frac{\sigma_{\max}}{\sigma_{\text{ULT}}} = 1 - k \log_{10} N_f \quad (3)$$

where $\sigma_{\max}$ is the maximum applied stress, σ_{ULT} is the ultimate tensile strength in the loading direction, k is the gradient of the slope (fractional loss in strength per decade of cycles) and N_f is the number of loading cycles to failure. The value of k is ~ 0.1 for the aligned GFRP laminates at $R = 0.1$.

The following phenomenological relationship proposed by Kawai [66] provides a reasonable estimate of the fatigue life of the notched quasi-isotropic laminate subjected to the constant amplitude tension-tension loading conditions ($0.1 \leq R \leq 0.5$):

$$\Sigma^* = \frac{(1-R) \left(\frac{\sigma_{\max}}{\sigma_{\text{ULT}}} \right)}{2 - (1+R) \left(\frac{\sigma_{\max}}{\sigma_{\text{ULT}}} \right)} = \left(\frac{1}{2N_f} \right)^{\frac{1}{n^*}} \quad (4)$$

Σ^* is interpreted as a modified non-effective stress (or modified theoretical fatigue stress ratio) and n^* is an experimentally derived material constant obtained from fatigue tests carried out at the different stress ratios. The estimated value of n^* was 8.4 for E-glass/913.

The phenomenological fatigue model, described by Equation 4, was developed to predict the fatigue behaviour of unidirectional FRPs under constant amplitude stress cycling with non-negative mean stresses. It assumes that the failure mechanisms (damage modes), sequence of damage modes and extent of sub-critical damage associated with each damage mode are the same (self-similar), independent of the loading conditions. Evidence suggests that the mode and extent of damage is dependent on the amplitude and mean values of the applied loading conditions.

Failure (damage accumulation) is progressive with localised regions of damage occurring within the laminate. Damage modes include: fibre breakage, interfacial debonding (longitudinal splitting), matrix cracking and interfacial shear failure. Longitudinal splitting is the primary damage growth mechanism with regions, typically 0.5 to 1 mm wide, gradually extending along the full length of the specimen with increasing loading cycles. Splitting along the fibres affects the ability to redistribute load, initiating further damage until ultimate failure occurs (see Figures 27 and 28). Damage accumulation may occur slowly (i.e. wear-out) as observed at low applied stresses or catastrophically (sudden-death) as observed at high stresses (i.e. near the ultimate tensile strength of the laminate). Fibre breakage is the predominant failure mode at the higher stress levels. Whilst at lower stresses, damage is in the form of debonding (longitudinal splitting) with successive fibre breakage. The failure modes for dynamic and monotonic tests differ considerably in that the latter involves considerably more fibre breakage (see Figure 29).



Figure 27: Fibre debonding and matrix cracking in fatigued unidirectional GFRP (damage indicated by narrow, whitened areas along gauge-length)



Figure 28: Longitudinal splitting in fatigued unidirectional GFRP



Figure 29: Typical tensile failure for monotonically loaded unidirectional GFRP

Due to limits on time and equipment, an upper fatigue limit of 10^7 cycles will often be selected. Failure occurs invariably within the gauge-length, although frequently near the end tabs. The fatigue performance of thin rods and narrow rectangular specimens is poor in comparison with the standard test geometry. Consequently, the results from these geometries cannot be scaled upwards. The lower fatigue performance can be attributed to insufficient material surrounding the damaged region to accommodate local stress concentrations induced through fibre fracture.

Damage formation will weaken the material and lower its stiffness. Figure 30 shows a typical normalised residual fatigue stiffness E/E_0 versus loading cycles N curve for unidirectional GFRP. E_0 denotes the undamaged (initial tangent) modulus of the laminate and E is the secant modulus, corresponding to the maximum cyclic stress and strain levels, measured at selected intervals in the fatigue life. Figure 31 shows a typical plot of residual strength as a function of loading cycles for a unidirectional GFRP laminate. The stiffness and strength values have been normalised with respect to those values obtained under monotonic loading at an equivalent rate to the test frequency. It can be seen that the accumulation of damage results in a gradual reduction in residual strength, which tends to asymptotically approach a value of $\sim 70\%$ UTS.

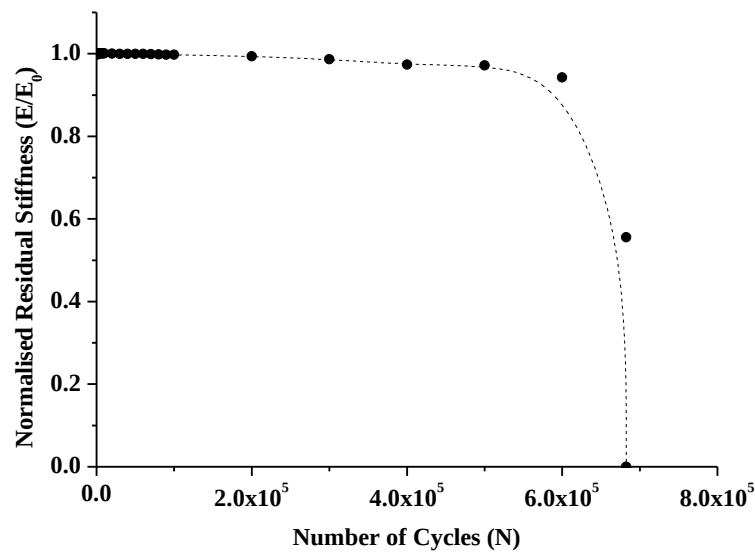


Figure 30: Normalised residual fatigue stiffness curve for unidirectional GFRP

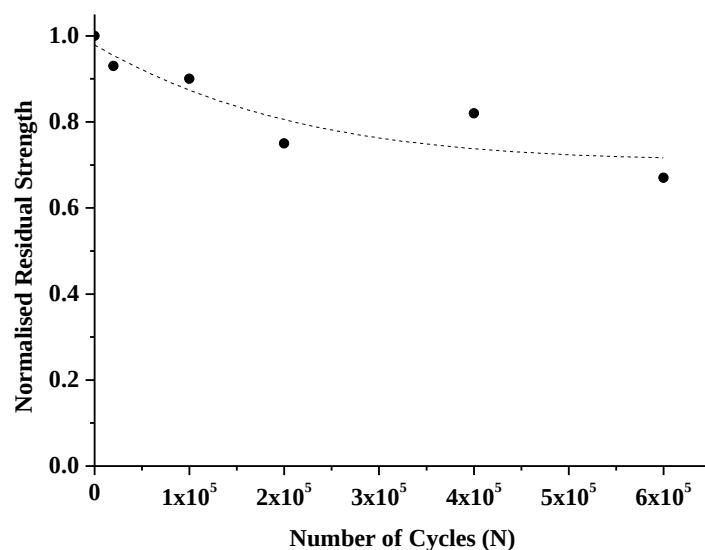


Figure 31: Normalised residual fatigue strength curve for unidirectional GFRP

4.4.3 Multidirectional laminates

Often failure will occur near the end tabs in straight-sided specimens due to the stress concentrations present in these regions. An alternative approach for testing multidirectional laminates is to use a waisted (dumbbell) test specimen, similar to that shown in (Figure 32), to promote failure within the gauge-section. Using waisted (or dumbbell) specimens also eliminates the tendency for the end tabs to debond, which can occur at high loads and/or high cycles. Figure 33 shows typical failures for straight-sided and dumbbell specimens. The test geometry shown in Figure 33 has an overall gauge-length (i.e. region between grips) of 150 mm. The length and width of the straight portion of the gauge-section are 110 mm and 15 mm, respectively. The fillet radius at the intersection of the gauge-section and end tabs is 60 mm. The end tabs are 50 mm in length and 25 mm wide. End tabbing is identical to that used for other laminated specimens. Fatigue performance improves using the dumbbell specimen (see Figure 34) as failure invariably occurs within the gauge-section and not at the end tabs.



Figure 32: Dumbbell cross-ply specimen with bonded end tabs

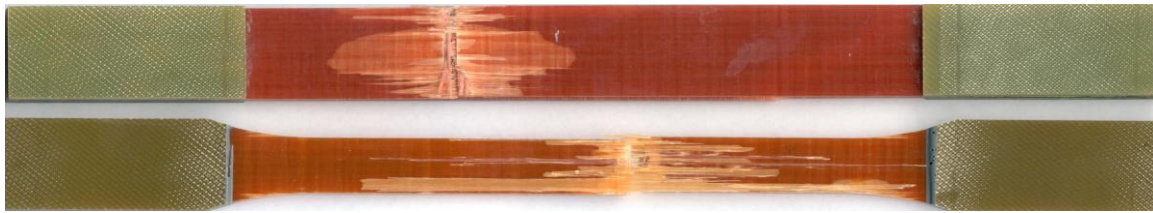


Figure 33: Typical failures for straight-sided and dumbbell specimens

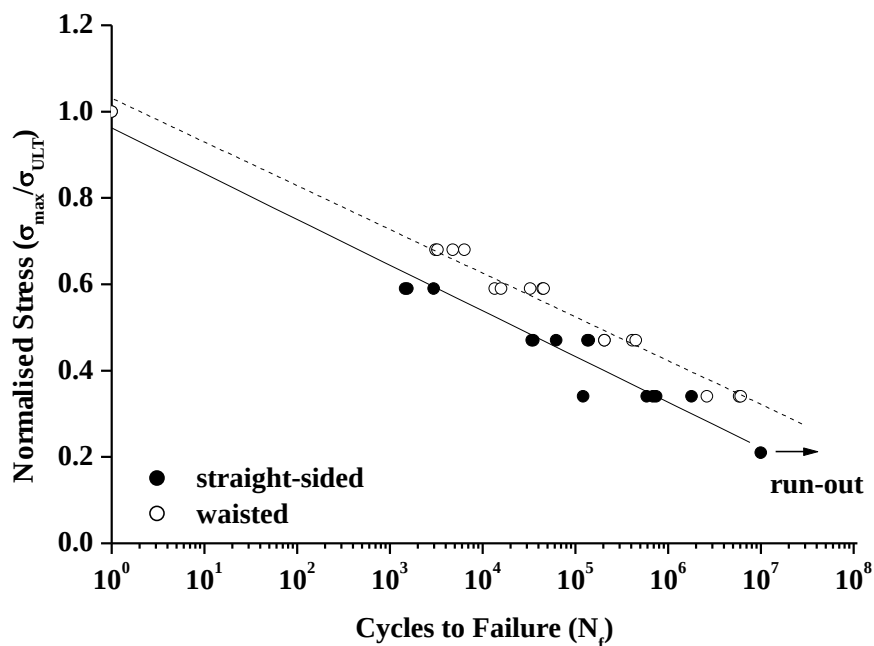


Figure 34: Fatigue performance for waisted and straight-sided specimens

Cross-ply (0°/90°) laminates: CFRP cross-ply laminates have excellent fatigue resistance in comparison with GFRP equivalents (i.e. slope **k** is less for CFRP). The fatigue life $N_f > 4 \times 10^6$ cycles at loads approaching 90% UTS for $[0/90]_{4S}$ T300/924 and 70% UTS for $[0_2/90_2]_S$. End tabs are prone to debond during testing, and hence prevention of end tab debonding is essential for ensuring reliable fatigue data.

The sequence of damage development and failure modes observed for the cross-ply laminates under fatigue tensile loading was as follows:

- Longitudinal splitting at the fillet radii (applicable only to dumbbell specimens).
- Formation of matrix cracks parallel to the fibres in the 90° plies (i.e. transverse cracking) - see Figure 35;
- Transverse crack density increases with loading cycles forming a regular array of matrix cracks;
- Formation of edge and local delaminations (see Figure 36); and
- Fibre-breakage and longitudinal splitting in the primary or load-bearing (i.e. 0°) plies.
- Final fracture was catastrophic and sudden, resulting in specimen separation.



Figure 35: Transverse cracking of a cross-ply E-glass/F922 laminate



Figure 36: Transverse cracks along an edge of a cross-ply laminate

In the case of translucent materials, such as glass/polyester and some glass/epoxy systems, transverse cracks can be directly observed by illuminating the back of the specimen with a light source (Figure 35). This transmission technique, however, cannot be applied to opaque materials, such as CFRP and many GFRP composites. Penetrant enhanced X-radiography, optical microscopy and edge replication are the most commonly used techniques for locating and sizing transverse cracks. An alternative method consists of smoothing the longitudinal edges of the coupon specimen with silicon carbide paper (1200 grade), wiping the surfaces with acetone and then coating the surfaces with a film using a white paint marker. Specimens need to be left for several hours to dry. The transmission technique is a more reliable method for transverse crack density measurements, and hence its preferred use for translucent GFRP laminates (see Figure 37).

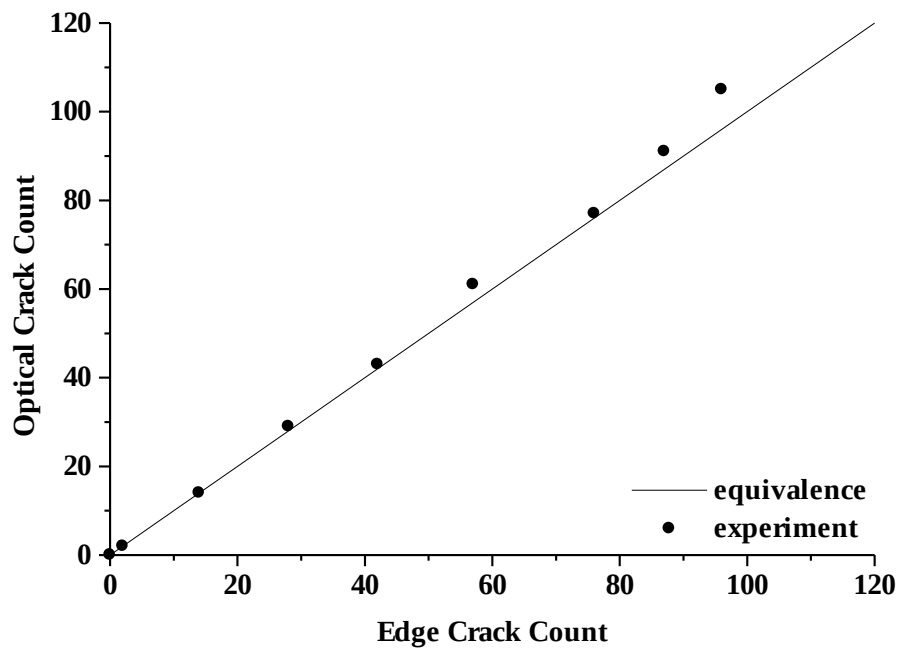


Figure 37: Optical crack versus edge crack counts for $[0_2/90_2]_s$ GFRP laminate

Measurement of transverse cracks usually requires periodical interruption of the test. It is not possible to monitor crack formation using the above-mentioned techniques whilst the specimen is subject to dynamic loading. The specimen is often unloaded and removed from the test machine for each measurement, which adds to the time and costs required to complete a test, and may also damage the specimen. Removing the specimen may induce artefacts in the results due to alignment problems in re-gripping the specimen. Overloading the specimen is also a possibility in the initial cycles on recommencing the test. The solvents used in edge replication may lead to premature cracking of the matrix. Similarly, the use of penetrants to enhance X-radiographic images whilst monitoring damage progression will shorten the fatigue life (by a factor of 2, or greater).

Pulse thermography, back scattering ultrasonics and acoustic emission (AE) are frequently used to monitor transverse crack formation (see also Section 5). It is often difficult to resolve two or more closely spaced cracks using either PT or back scattering ultrasonics. In both cases, the test specimen needs to be removed from the machine to be scanned. In contrast, AE, can be used for in-situ monitoring of damage without the need to interrupt the test. The effects of wave propagation, such as attenuation, dispersion and multiple modes of propagation need to be considered. Attenuation and dispersion can significantly alter the amplitude of AE signals even for short propagation distances. In addition, noise sources due to fretting of the sample within the grips and movement of the loading train can make interpretation difficult. It is important to identify noise sources and adjust the threshold setting and location of AE sensors accordingly. The reliability of the technique deteriorates with increasing thickness of the internal 90° plies (see Figure 38). Bifurcation of transverse cracks, which occur frequently in thicker laminates, are difficult to identify using acoustic emission.

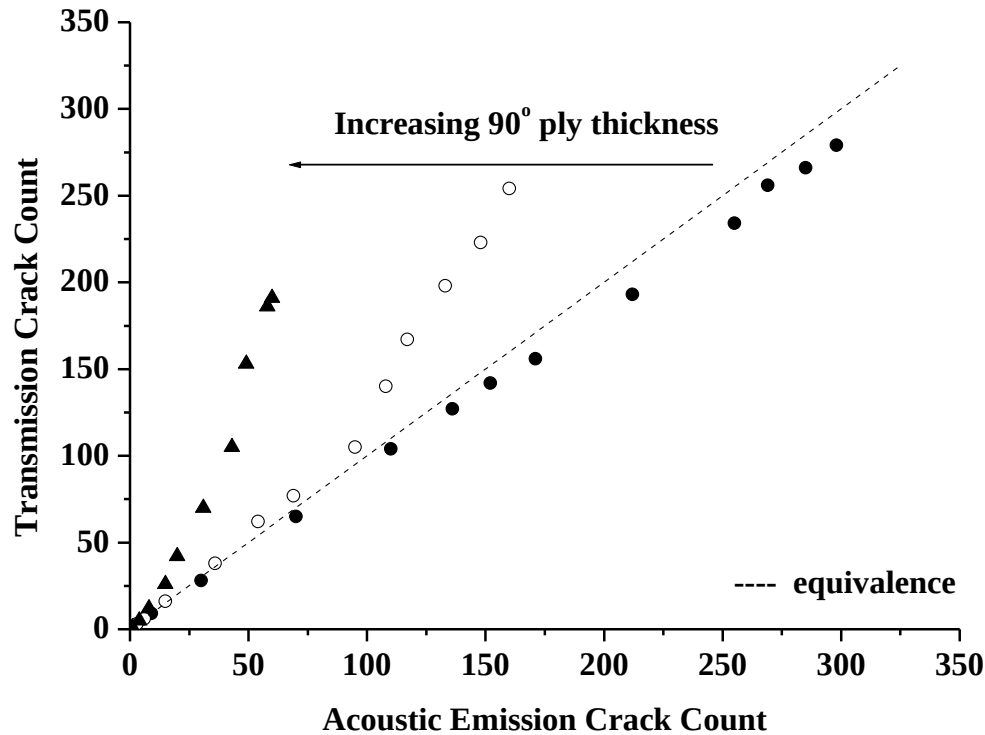


Figure 38: Edge crack versus optical crack counts for cross-ply GFRP laminates ($[0_2/90_2]_s$, $[0_2/90_4]_s$ and $[0_2/90_8]_s$)

The appearance of transverse cracks in the 90° plies of cross-ply laminates is usually the first visible indication of damage in cross-ply laminates (see Figure 35). Transverse cracking will often cause adverse affects, such as stiffness, Poisson's ratio and strength reduction (Figures 39 to 42). Poisson's ratio is particularly sensitive to transverse cracking, with the reduction in elastic properties appearing to be directly related to the transverse crack density.

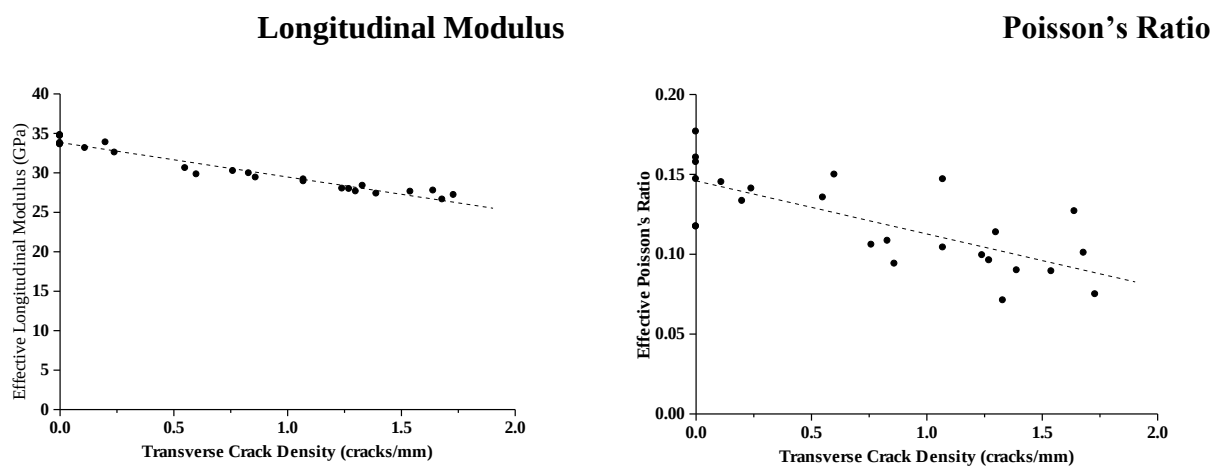


Figure 39: Axial stiffness and Poisson's ratio reduction for $[0_2/90_2]_s$ GFRP laminate

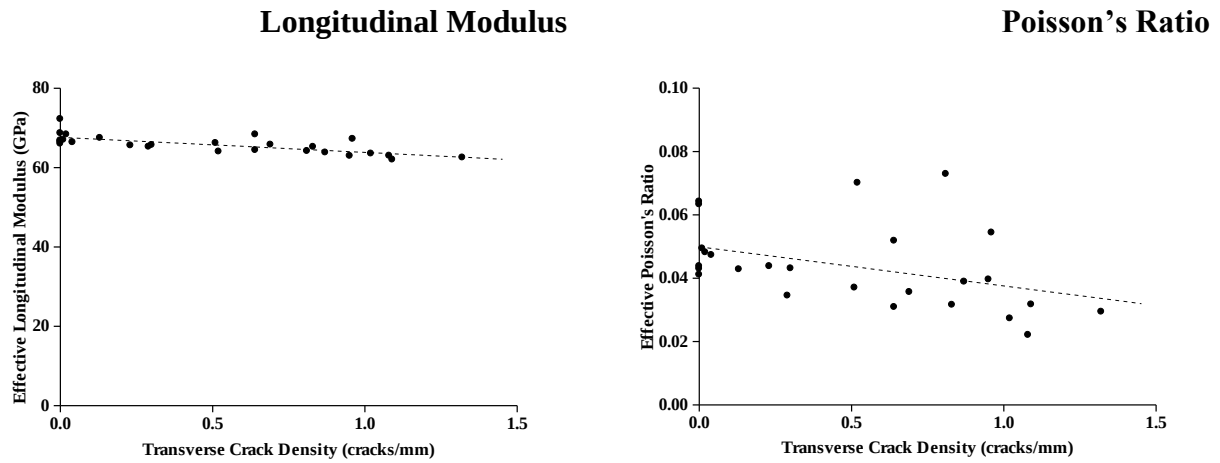


Figure 40: Axial stiffness and Poisson's ratio reduction for $[0_2/90_2]_s$ CFRP laminate

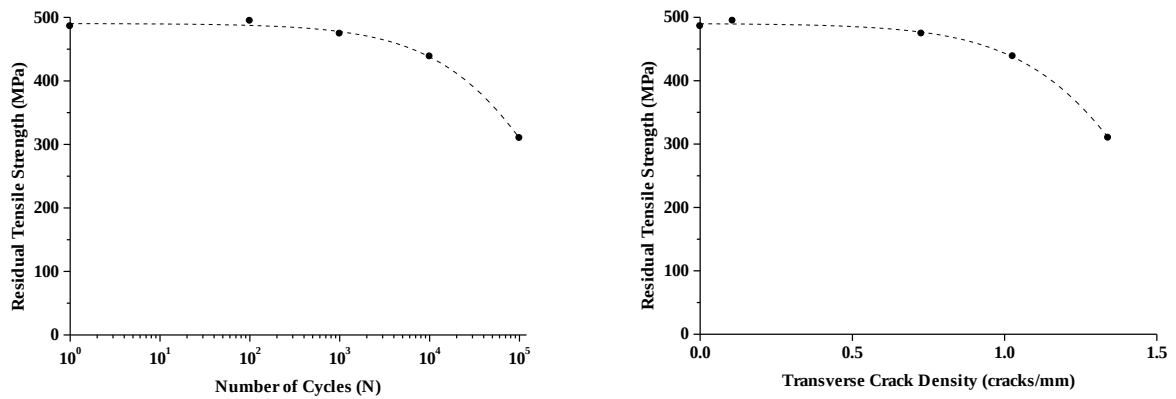


Figure 41: Strength reduction for $[0_2/90_2]_s$ GFRP laminate ($\sigma_{\max}/\sigma_{ULT} = 0.4$)

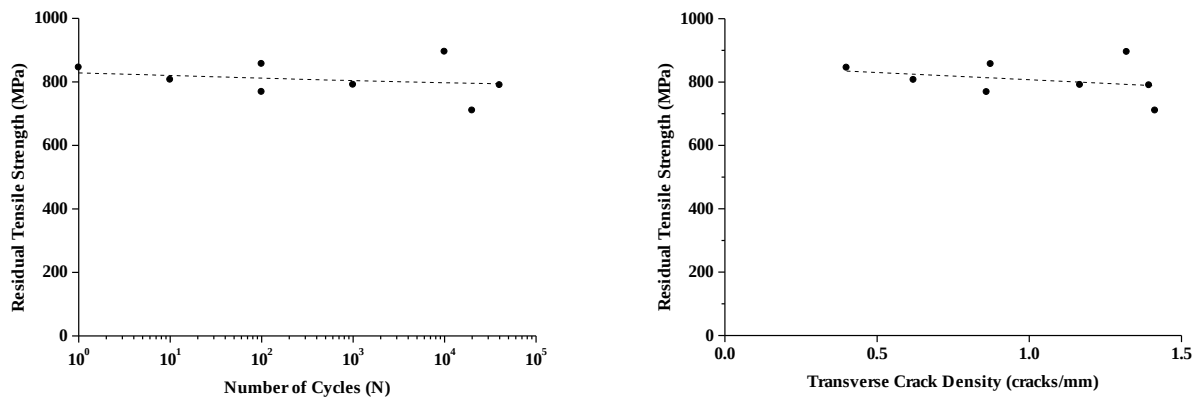


Figure 42: Strength reduction for $[0_2/90_2]_s$ CFRP laminate ($\sigma_{\max}/\sigma_{UTS} = 0.8$)

The above issues of specimen preparation, mechanical testing and data analysis apply to most multidirectional laminates. An additional failure mode in the form of delaminations, which are constrained to grow between individual plies (i.e. planar), will also be encountered in multidirectional laminates (see Figure 33). Delaminations are probably the most life-limiting defects that occur in layered or laminated structures and are readily detectable using ultrasonic C-scan. Crack initiation and growth usually occurs under mixed-mode conditions, a combination of Mode I (crack-opening), Mode II (forward-shear) and Mode III (scissor-shear or tear). Growth tends to be rapid (i.e. unstable). Delaminations tend to occur between plies of different orientations rather than between plies of identical orientation. Heating effects are more pronounced in laminates that contain $\pm 45^\circ$ plies where heating arises from cyclic shear stresses (i.e. scissoring or rotation of fibres).

4.4.4 Effect of stress concentrations

Stress concentrations, such as cut-outs, drilled holes and waisted sections, are frequently encountered in composite structures. Evidence from S-N data suggests that there is no degradation due to the notch or hole in the fatigue properties, other than the initial decrease in the ultimate strength [45]. The centre-notched (or open-hole) specimen with a width-to-hole diameter ratio of 6:1 (see Figure 43) is routinely used for determining the effect of a hole on the tensile strength of thermoset and thermoplastic FRPs – see [38]. The static method used under fatigue loading in this guide is ASTM D 5766 [67]. There are several similar versions of the open-hole tension (OHT) test including EN6035 [68] and AITM 1.007 [69].

The OHT test method does not require a special loading jig as the load is introduced via mechanical wedge action grips. The grips must be fatigue rated to prevent relaxation of the gripping pressure under fatigue loading. Ideally hydraulic wedge action grips should be used to grip the ends of the specimen. Although, end tabs are normally not required to grip the notched specimens as failure tends to occur around the central hole. A lateral grip pressure of 150-200 bars is applied to the specimens. Care should be taken if higher grip pressures are used to ensure that damage to specimens, which can lead to premature failure, is avoided. For long-term tests (i.e. low-stress), it may be necessary to use end tabs as fretting can occur within the grip region. The OHT specimen is loaded in tension and the maximum load sustained by the specimen is used to determine the open-hole (notched) strength based on the gross specimen cross sectional area. A gross tensile stress concentration factor is calculated from the ratio of the unnotched tensile strength divided by the open-hole (notched) strength.

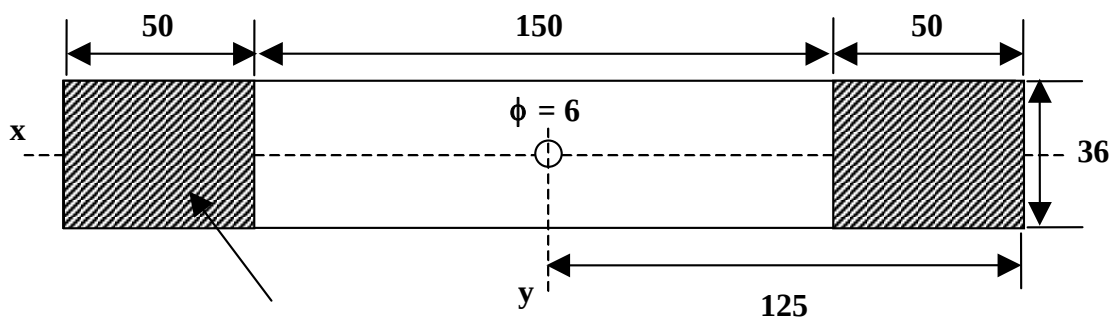


Figure 43: Open-hole (notched) tension specimen (units: mm)

The specimen stiffness according to ASTM D 5766 is not required to be measured, however it is recommended that the longitudinal tensile strain and stiffness be monitored throughout the duration of the fatigue test. Longitudinal stiffness changes indicate damage accumulation. Clip gauge extensometers, attached to the front and back faces of the specimen, with a gauge-length of 50 mm and full scale deflection of ± 2.5 mm are generally recommended for measuring deformation in the specimen gauge-section. The test geometry shown in Figure 43 is only suitable for tension-tension loading conditions. Fatigue test parameters are similar to those employed for unnotched specimens. Figure 44 shows a GFRP OHT specimen with a single extensometer and thermocouple attached to the specimen, and typical damage formation that occurs around the central hole.



Figure 44: OHT test set-up showing damage around the hole

Damage accumulation, which occurs mainly around the perimeter of the hole and along free edges of the specimen, weakens the material and lowers the stiffness. The effects of damage formation on strain distributions and longitudinal stiffness due to cyclic loading can be monitored using DIC (see Figure 45). Damage initiates early in the fatigue life and tends to be concentrated around the hole for most of the fatigue life with rapid delamination growth at failure (last few cycles).

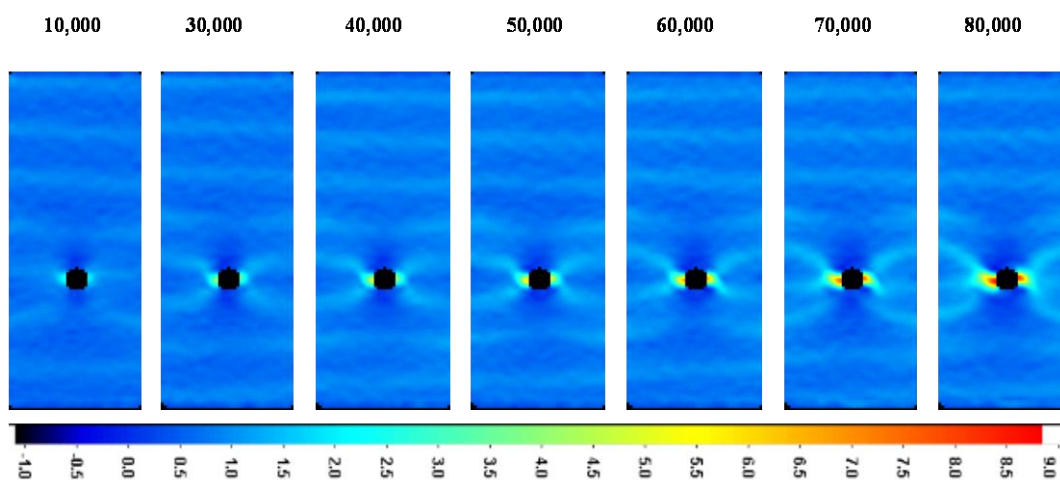


Figure 45: ϵ_{xx} strain distribution versus loading cycles for GFRP OHT (measured at a static stress following cyclic loading)

The DIC images shown in Figure 45 indicate damage growth increases around the hole with increasing number of loading cycles, and as a consequence the localized ϵ_{xx} strain increases significantly (Figure 46). The maximum value of ϵ_{xx} strain at the perimeter of the hole tends to increase linearly with loading cycles, as shown in Figure 47. The values have been averaged to account for non-symmetric damage around the hole. In comparison, global strain (and consequently stiffness) is less sensitive to damage growth (i.e. damage effects tend to be localized, either around the hole perimeter or along the free edges). The stress concentration around the hole as measured using DIC is generally in close agreement with predictive analysis (i.e. finite element analysis and analytical solution).

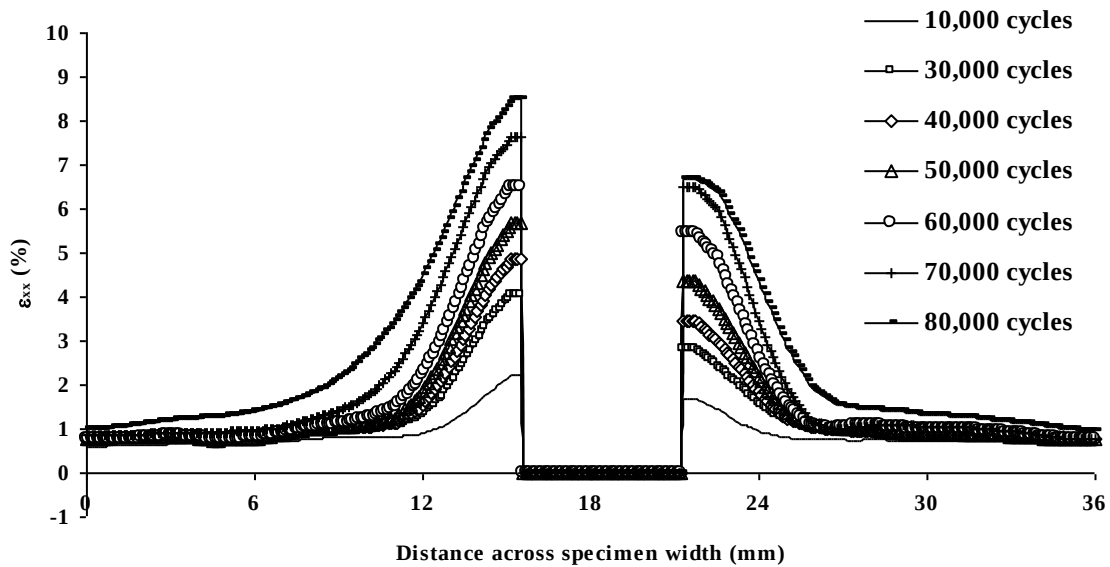


Figure 46: ϵ_{xx} strain across the specimen mid-length versus loading cycles (measured at a static stress following cyclic loading)

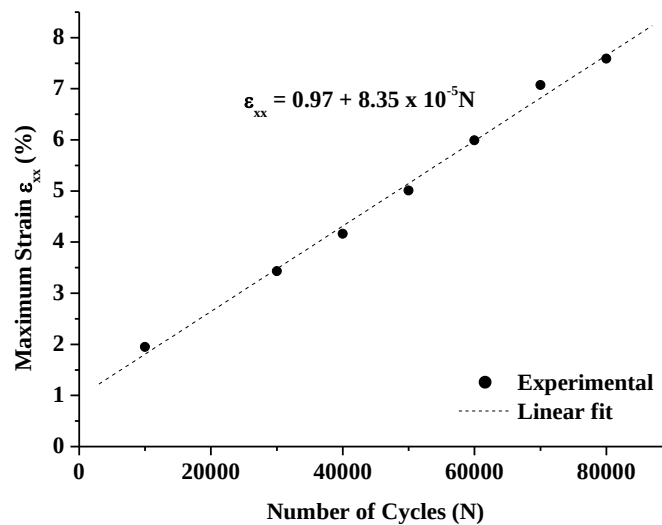


Figure 47: Maximum ϵ_{xx} strain at hole perimeter versus loading cycles (measured at a static stress following cyclic loading)

As previously mentioned, hysteretic heating which increases with increasing load and frequency, can adversely affect the fatigue performance of the composite. Particular concern should be paid where the temperature approaches the glass transition temperature of the material. Reliable data can be obtained at frequencies upto 5 Hz provided the stress levels are low. Test frequencies of the order of 5 Hz (or greater) can result in substantial heating, particularly in the grip regions.

Table 4 shows typical values of maximum surface temperature measured for a notched quasi-isotropic GFRP laminate at different loading conditions. Trials may be necessary to determine the upper frequency limit. Temperature can be monitored using a thermocouple attached to the specimen. Thermal imaging equipment can also be used to monitor surface temperature. The temperature resolution is 1 °C for the two methods.

Table 4: Maximum surface temperature (°C) for GFRP OHT fatigue specimens (5 Hz unless otherwise specified)

Test Condition (% UTS)	Initial	Final	Ultimate Failure
<u>R = 0.1</u>			
40	33	46	87
55	46	78	104
55 (1 Hz)	30	34	41
70	23	65	68
<u>R = 0.5</u>			
40	25	26	33

The temperature rise (Figure 48) can potentially be used as a damage parameter to determine remnant stiffness and fatigue life. Figure 49 shows a plot of the normalised residual fatigue stiffness E/E_0 as a function of surface temperature T in which the relationship between E/E_0 and T is essentially linear over most of the fatigue life (see Equation 5).

$$\frac{E}{E_0} \approx 1 - AT \quad (5)$$

A is an experimentally derived constant dependent on the cyclic loading conditions (i.e. maximum applied stress and R ratio). The internal temperature can be expected to be higher than the temperature measured on the specimen surface.

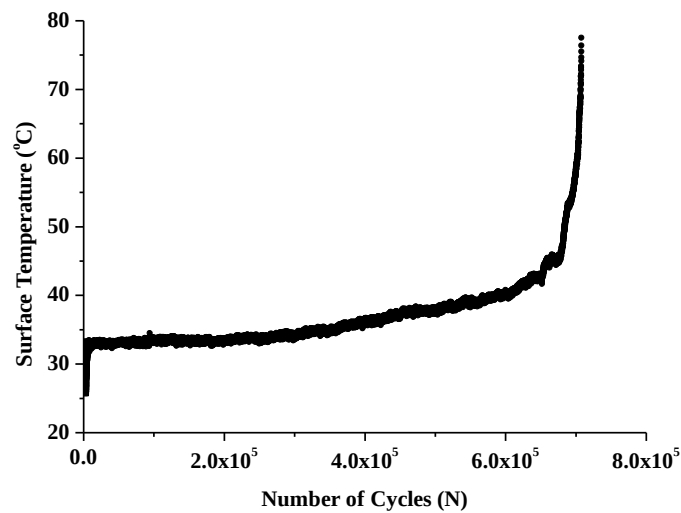


Figure 48: Surface temperature at hole-perimeter for GFRP OHT specimen

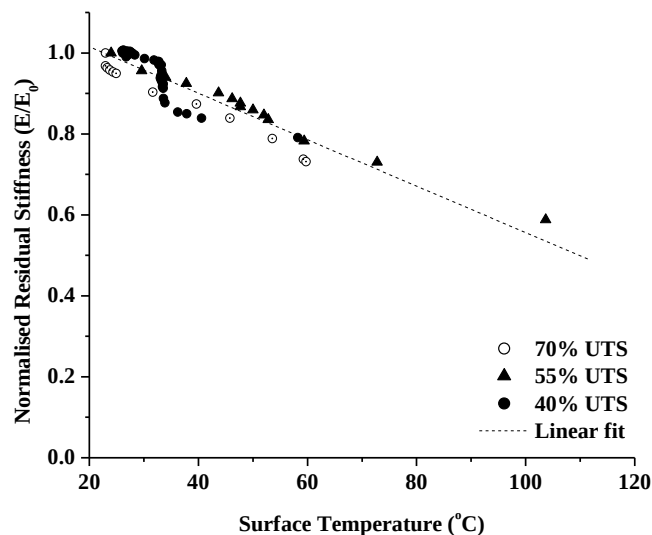


Figure 49: Normalised residual fatigue stiffness versus surface temperature (notched quasi-isotropic GFRP laminate at 40%, 55% and 70% UTS at $R = 0.1$)

4.5 In-Plane Compression

4.5.1 Specimen preparation and test geometry

In-plane compression specimens are far smaller than their tensile equivalents (see [26,70]). Unidirectional specimens (longitudinal and transverse) are typically 110 mm in length and 10 mm wide with a 10 mm gauge-length. The short gauge-length is designed to prevent buckling occurring before the maximum load is reached (i.e. self-stable). The required thickness is 2 mm for continuous aligned materials and between 2 and 10 mm for multidirectional laminates and random fibre reinforcements.

Wider specimens (typically 36 mm wide) with a longer gauge-length (typically 25 mm) are frequently used for characterising these latter materials. Specimens are end tabbed to prevent failure at the loaded ends of the specimen, although for random fibre formats this is not always necessary. The compression standard ISO 14126 [71] requires strain gauges on both specimen faces and for the strain difference between opposing gauge readings to be less than 10%. If the strain differential exceeds this limit then the test should be terminated.

4.5.2 Mechanical testing

The ISO standard allows for end, shear or combined loading. It is important when using any of the acceptable test fixtures specified in the standard (i.e. Celanese, IITRI, and end-loading blocks) to ensure good axial alignment. Hydraulic grips in aligned test machines are also acceptable (Figure 50). In all cases, the gauge-length is unsupported. The end-loading fixture shown in Figure 51 can accommodate a broad range of specimen thicknesses, making it more suitable for thick section compression testing than the IITRI or Celanese rigs, which require specifically made wedges to adapt to each different thickness. A four-pillar die set is used with the end-loading fixture to maintain uniform compression loading.

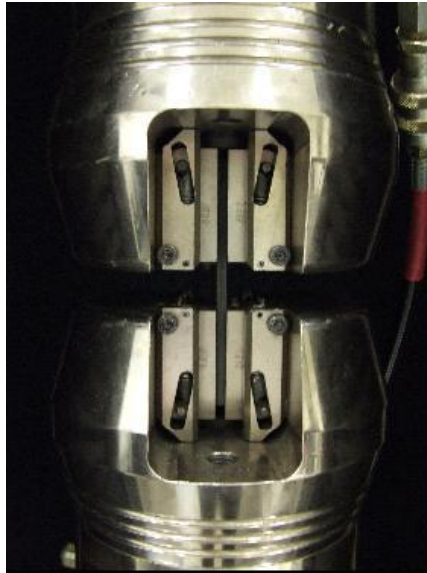


Figure 50: Compression specimen gripped in hydraulic wedge action grips

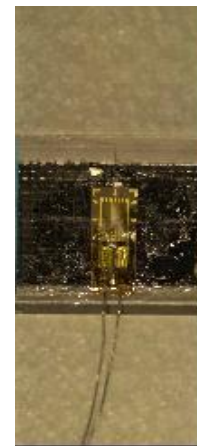


Figure 51: End-loading compression fixture with specimen

The end-loading and servo-hydraulic gripping methods shown in Figures 50 and 51 can be employed for compression-compression cyclic loading. Tension-compression testing can only be conducted using hydraulic grips. It is important that for the end-loading fixture that friction between the guide pillars and bushes is minimal. It is recommended that molybdenum grease be used on moving parts for tests conducted at sub-zero temperatures. Trials should also be conducted to ensure that the movement of the loading fixture is smooth (i.e. frictionless) when conducting fatigue tests.

An alignment fixture is recommended when using hydraulic grips to ensure good, reproducible specimen alignment. The use of clip gauge extensometers to measure specimen deflection/strain is not practical for compression-compression fatigue. If accurate measurement of the strain is required then specially designed extensometers of appropriate size or strain gauges positioned away from the hole would be needed. It needs to be emphasised that strain data obtained from actuator measurements should not be used for analysis in tests where specimens are gripped using wedge action grips as slippage of specimens can occur which drastically increases the compliance of the loading train. The fatigue performance of strain gauges also needs to be established prior to testing.

4.5.3 Open-hole compression (OHC)

The open-hole compression (OHC) test (ISO/WD 12817 [72]) is a well-established static method for determining the effect of a hole on the compressive strength of thermoset and thermoplastic FRPs. The specimen geometry and dimensions are shown in Figure 52. The test specimen consists of a strip of rectangular cross-section with a plain hole centrally located. End-tabs are shown in Figure 52, but as for the OHT specimens these are not normally required. The specimen is loaded in compression and the maximum load sustained is used to determine the open-hole (notched) strength based on the gross specimen cross sectional area. A gross compression stress concentration factor is calculated from the ratio of the unnotched compression strength divided by the open-hole (notched) strength. Measurement of stiffness is not a requirement for the test. Stiffness, if required, is measured in a similar manner to that employed for compression tests in general (see Section 4.5.2).

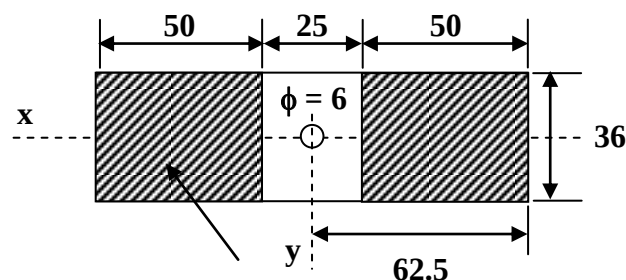


Figure 52: Open-hole (notched) compression specimen (units: mm)

The OHC specimen is suitable for both compression-compression and tension-compression testing. An end-loading fixture (see Figure 53) is used for compression-compression and hydraulic grips for tension-compression. Fatigue performance is better under compression-compression than under tension-tension (i.e. slope **k** is smaller). The performance under combined loading (tension-compression) is less favourable than either tension-tension or compression-compression.

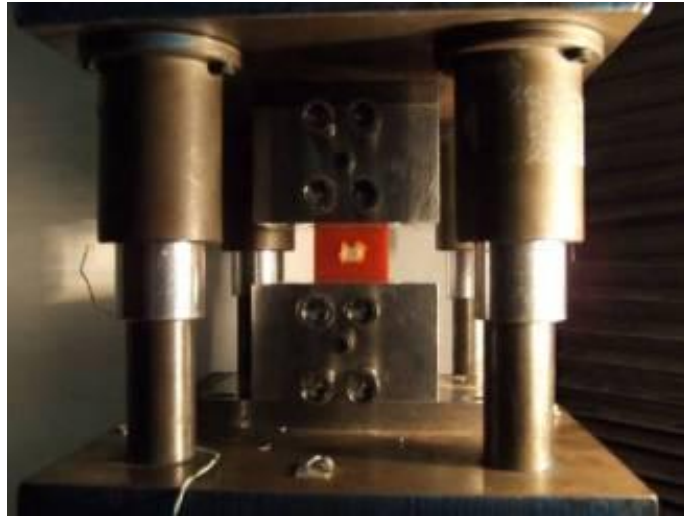


Figure 53: Open-hole compression-compression loading arrangement

The increase in surface temperature due to hysteretic heating tends to be lower than equivalent OHT test. The combination of a shorter gauge-length and a large thermal mass (i.e. end-loading test fixture) results in a higher rate of heat dissipation compared with the longer OHT specimen. The presence of the notch increases the maximum surface temperature experienced by the specimen (see Table 5).

**Table 5: Maximum surface temperature for GFRP OHC fatigue specimens
(tests conducted at 5 Hz and $R = 10$)**

Test Condition (% UTS)	Temperature at Ultimate Failure (°C)
60	41
65	54
70	59
70 (unnotched)	45

Typical damage observed for compression-compression loaded CFRP and GFRP OHC specimens are shown in Figures 54 and 55). The GFRP underwent shear failure. DIC images of quasi-isotropic GFRP OHC specimens subjected to compression-compression and tension-compression loading modes are shown in Figure 56.

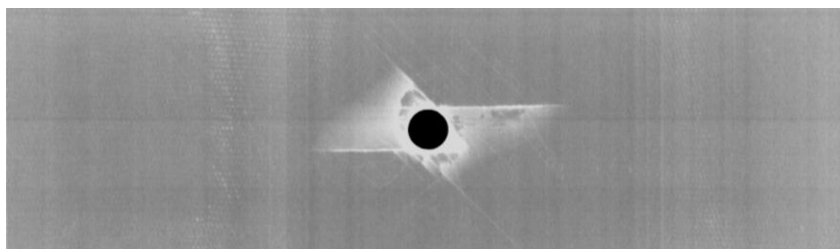


Figure 54: X-radiography image of a fatigued quasi-isotropic CFRP OHC specimen

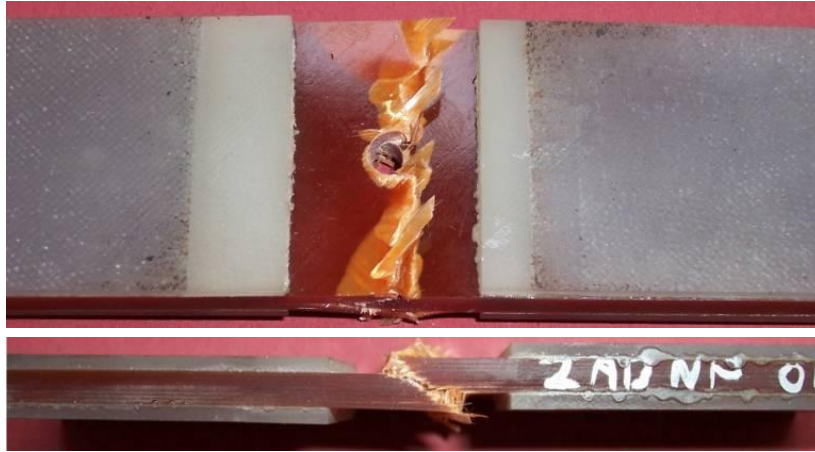


Figure 55: Fatigue failure of quasi-isotropic GFRP OHC specimen

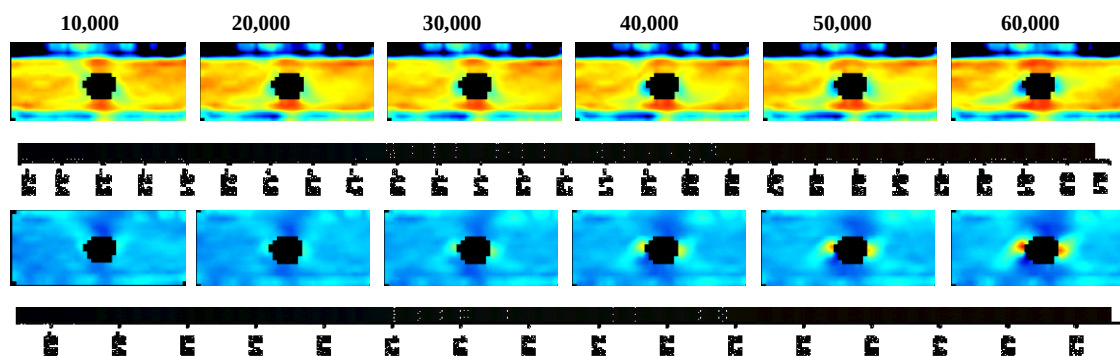


Figure 56: ε_{xx} strain distribution vs. loading cycles for GFRP OHC compression-compression (top) and tension-compression of fully reversed (bottom) measured at a static stress following cyclic loading

4.6 In-Plane Shear

Shear methods, such as uniaxial tension of a balanced symmetric $\pm 45^\circ$ laminate (ISO 14129 [73] and ASTM D 3518 [74]) and the V-notched beam (ASTM D 5379) shear test, can be used to characterise continuously aligned and woven fabric composites. 10° off-axis, two-rail and three-rail shear, and torsion of thin-walled tube test geometries are also used to a lesser degree – see [26]. The V-notched beam method can be used to measure shear modulus and shear strength in all of the three shear planes (1-2, 1-3 and 2-3) – see also Section 4.3.4. The $\pm 45^\circ$ tension test (Figure 57) can be used to determine in-plane shear properties of continuous aligned fibre-reinforced systems [26]. The test geometry and loading configuration is similar to that employed for tensile loading of the multidirectional laminates (250 mm x 25 mm x 2 mm). It is recommended that for materials constructed with layers (plies) thicker than 0.125 mm, the laminate should consist of 16 layers (i.e. $[\pm 45]_{4s}$).

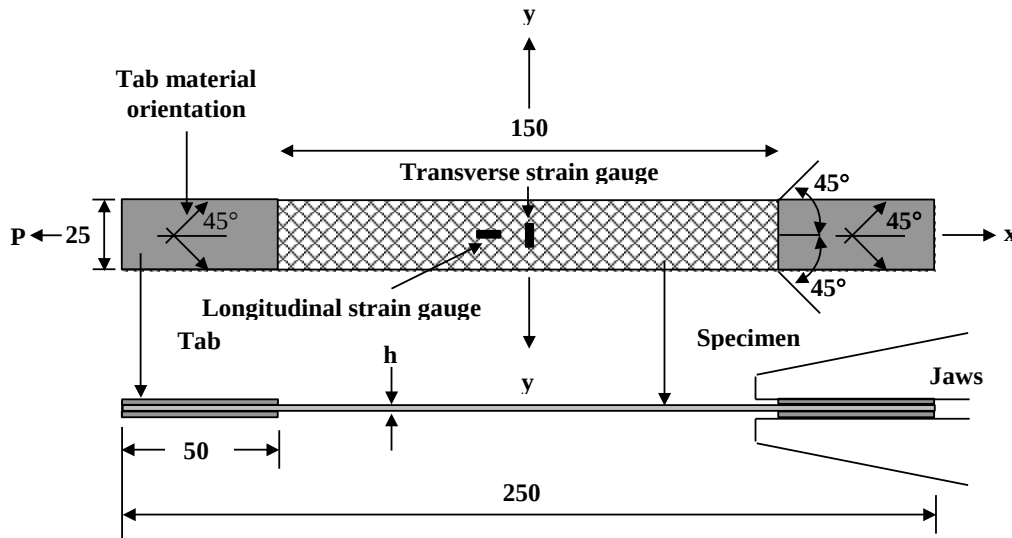


Figure 57: Schematic of the $\pm 45^\circ$ tension specimen (units: mm)

The average shear stress is the applied load divided by twice the cross-sectional area. The test is terminated at or before 5% shear strain, thus shortening the test duration, which can be excessive for tough matrix systems. The applied stress at failure or 5% strain equates to shear strength. The 5% shear strain limit also minimises fibre rotation (scissoring) and internal heating effects generated due to friction. Longitudinal and transverse strains, which can be measured using either strain gauges or extensometers, are required for determining the shear modulus. Scissoring or rotation of $\pm 45^\circ$ plies will cause hysteretic heating of the specimen, which will adversely affect the fatigue performance.

4.7 Flexure

Flexure tests, which are routinely employed throughout the plastics and composites industry for quality assurance and material selection purposes, are not suitable for generating engineering data as the tests are structural. Specimen preparation and testing is relatively straightforward (see ISO 14125 [75]), fast and economic with data reduction posing no particular problems. Testing is carried out using a special loading fixture, which is attached to the loading frame. Commercial fixtures are available at a moderate cost.

Displacement is measured directly from the crosshead or by using a LVDT. ISO 14125 includes three-point and four-point bending configurations. Advantages of using a four-point bending arrangement is that the bending moment between the central loading points is uniform and the loads applied to the inner loading points are halved (i.e. stress concentrations reduced). As four-point loading provides a more uniform stress field, it is the preferred method for determining longitudinal and transverse flexural properties of fibre-reinforced laminates. Continuous unidirectional glass and carbon fibre-reinforced laminates are typically 2 mm thick. An outer to inner span ratio of 3:1 is employed in four-point bending. The longitudinal and transverse specimens are 100 mm and 60 mm in length, respectively. The width for both specimens is 15 mm. Flexure tests have been readily adapted to fatigue, creep and environmental testing. ISO 13003 specifies a method for flexural fatigue of composites by constant-amplitude loading.

There are a number of issues relating to fatigue in flexure that need to be considered. The most significant are the compression stress concentration at the centre loading roller and fretting wear at the outer support points. Wear at the support points is particularly important when displacement control is used, as the reference points of displacement on the tensile face of the specimen are lost. Care needs to be taken to minimise friction at the loading rollers. Thin polypropylene shims (0.2 mm thick) may be required below the loading points to reduce the detrimental effect of stress concentrations at these points. It is also necessary to introduce backing rollers on the reverse of the flexure specimen if through-zero testing is intended.

4.8 Through-Thickness (T-T) Testing

4.8.1 Through-thickness tension

There are two contrasting methods and several associated geometries, which can be employed in the measurement of T-T tension (i.e. direct and indirect tensile loading) and compression [26, 76-79]. The direct method introduces tensile load to parallel sided (square cross-section) or waisted short block specimens via adhesively bonded metallic (reusable) loading bars (see Figure 58) – see also ASTM D 7291 [80]. The ASTM standard specifies tensile specimens in the shape of either a straight-sided cylindrical disk or a reduced gauge-section cylindrical “spool” (cotton reel shaped). The bonded assembly is loaded under tension loading by a force, applied normal to the plane of the composite laminate until failure of the laminate occurs. The indirect method aims to induce T-T tension, in significantly curved specimens by the application of bending moments. Indirect methods (e.g. C-section) tend to produce mixed-mode failure and not T-T tension.

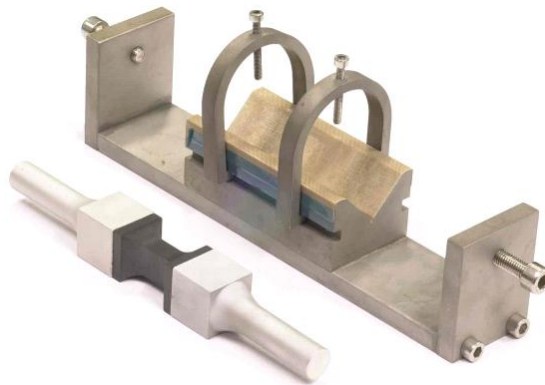


Figure 58: RARDE T-T tension specimen with bonding fixture

Short parallel-sided blocks (~40 mm high (laminate thickness) and 15 mm square) can be used to measure T-T elastic properties, however these are unsuitable for measuring the T-T tensile strength. Biaxial strain gauges (2 or 3 mm gauge-length) are bonded onto the mid-line of each of the four sides of the specimen to measure axial and transverse strains. This enables average strains to be calculated, thus accounting for bending due to small deviations in specimen or load alignment. Strength results are particularly sensitive to system alignment and load eccentricity. All faces must be flat and parallel (to within ± 0.1 mm). A special bonding fixture (Figure 58) is recommended to ensure good alignment and to maintain pressure on the bonding surfaces during cure.

Elliptical, or circular waisted block specimens, such as those specified in ASTM D 7291 and the NPL draft procedure [81] can be used to determine T-T tensile strength. The reduction in cross-sectional area promotes failure at the specimen mid-thickness with failure occurring in a plane normal to the applied load. The tensile strength is simply the applied load at failure divided by the cross-sectional area at the specimen mid-section. Using specimens with large circular radius or elliptical fillet reduces the stress concentration in the vicinity of the fillet root. Thinner material can be tested provided the laminate thickness is greater than 20 mm and linear dimensions of the specimen are scaled in proportion to the standard geometry. The inclusion of a rectangular gauge-section (e.g. RARDE specimen (Figure 59) [80]) enables both strength and elastic properties to be obtained using the same specimen. Equation 3 applies to T-T tensile **S-N** data. Strength values are only valid if failure occurs in the gauge-section of the specimen, and not at the bond-line. The test geometry is suitable for characterising tensile fatigue (see [79]). However, small misalignments during testing will result in large uncertainties in fatigue life. T-T tensile strength and fatigue life is also sensitive to defects (e.g. voids).

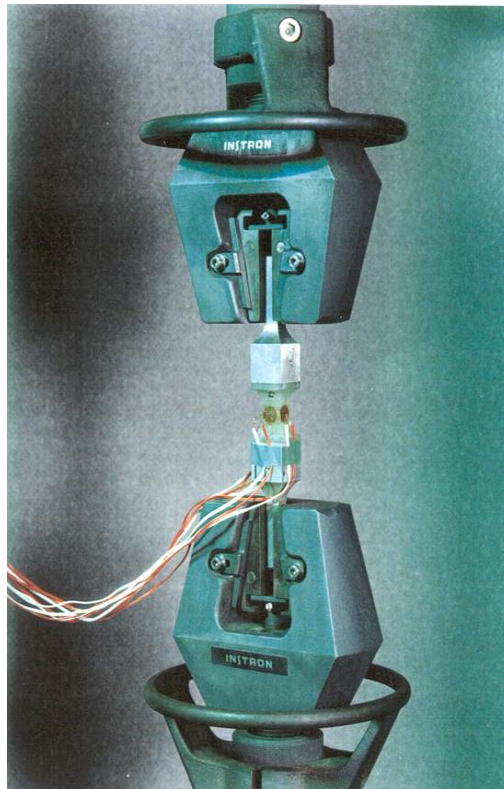


Figure 59: Tensile loading of RARDE T-T specimen (courtesy of QinetiQ)

4.8.2 Though-thickness compression

The direct tensile specimen geometries described previously can also be used to determine T-T compression properties [78-79]. Specimens are loaded in compression between flat, parallel, hardened stainless steel platens with recesses to reduce lateral movement of the specimen. A four-pillar die set is used to maintain uniform compression loading (Figure 60). Shear is the predominant cause of failure in all cases, independent of material microstructure, loading configuration or specimen size [82].

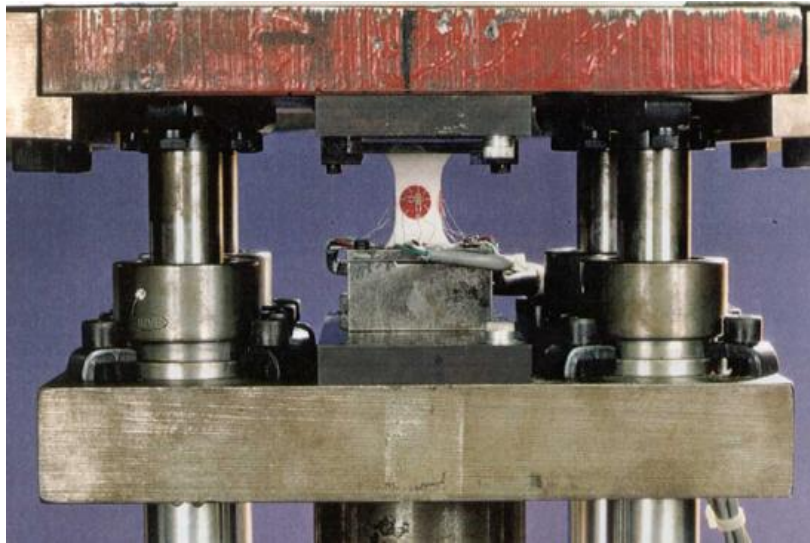


Figure 60: Compression loading of RARDE T-T specimen (courtesy of QinetiQ)

Fatigue tests are normally carried out at the highest frequency possible in order to minimise test duration. Restrictions on test frequency can arise due to test equipment limitations, (response time), time-dependent processes and hysteretic heating. Test frequencies of the order of 1-5 Hz can result in a substantial increase in the surface temperature ($> 250\text{ }^{\circ}\text{C}$) and a short fatigue life (Figure 61).

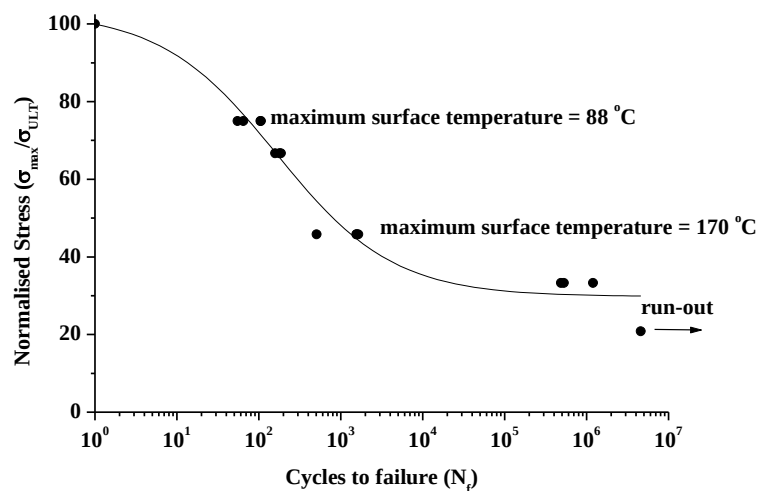


Figure 61: S-N compressive fatigue data for a woven GFRP laminate

4.8.3 Though-thickness shear

The V-notched beam test is suitable for measuring interlaminar shear properties under both static and fatigue loading conditions. It is important to ensure that friction between the guide pillars and bushes on the test fixture is minimal (see Figure 21). Friction between the two components will alter the fatigue response, as the load is not fully transferred to the specimen. The change in stiffness with loading cycles due to damage formation (notch root cracks and shear cracking in the specimen mid-section) for a woven GFRP laminate is shown in Figure 62 – see also Figure 63.

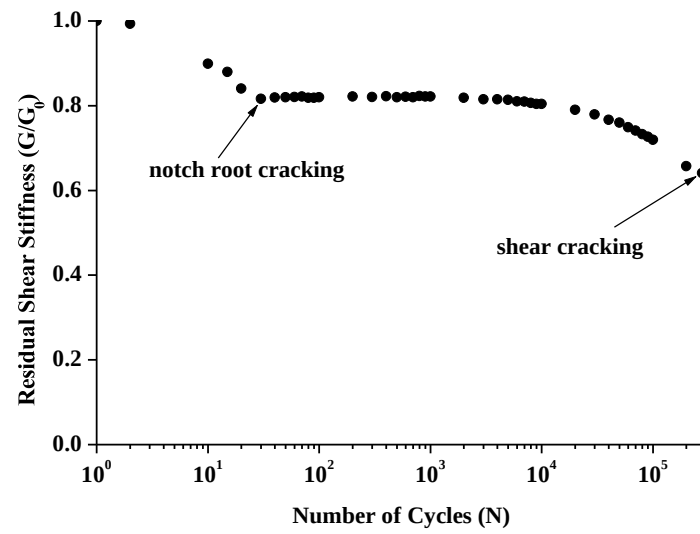


Figure 62: Normalised residual shear stiffness plot for a woven GFRP laminate

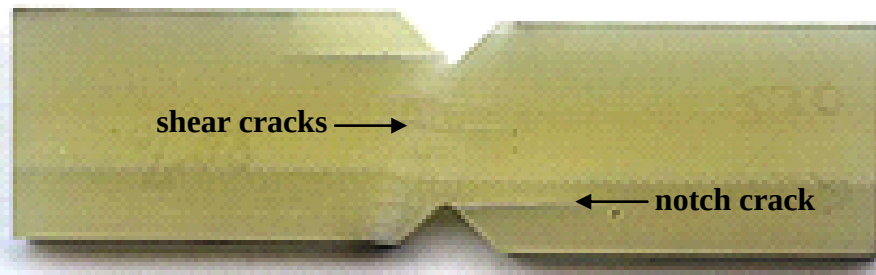


Figure 63: Failed woven glass/epoxy interlaminar specimen

Methods for Damage Assessment

5

IN THIS CHAPTER

- Introduction
- Optical Inspection
- Ultrasonic and Acoustic Techniques
- X-radiography
- Pulse Thermography
- Impact Excitation

5.1 Introduction

This section provides guidance on non-destructive evaluation (NDE) techniques that can be used for detecting and monitoring damage, and measuring the effects of damage growth via changes in mechanical properties [38, 83]. Consideration is given to the effect of material and geometric factors, test parameters and suitability for industrial applications (i.e. production and service inspection). Sensitivity, resolution, ease of use and cost are also covered.

5.2 Optical Inspection

Although the number of NDE techniques available is very large, the most universally applied approach to damage evaluation is still visual inspection. A preliminary visual inspection can often reveal the location, type and cause of damage. The unaided eye is frequently unable to detect micro-cracks until the cracks have become relatively large and diffuse, by which time the component is no longer functional (i.e. loss of stiffness or strength) and in the case of load bearing structures critically dangerous or unstable. In order to aid visual inspection of surface and sub-surface fractures use is made of dyes and penetrants. The dye penetrant method consists of painting the surface of the material to be tested with a low viscosity dye, which is then attracted to microscopic surface fractures through capillary action. The excess dye is removed and fractures that otherwise might have not been detected optically become visible. Visual inspection is suitable for detecting the presence of voids and solid inclusions (e.g. release film). Delaminations and thin debonds are difficult to detect because the presence of these defects has minimal effect on the absorption characteristics of polymeric materials. The use of penetrant fluids, whilst enhancing the imaging process, can adversely affect the short-term properties and fatigue performance of FRPs. Penetrants should not be used to assist damage monitoring in those tests where the test data is to be used for design or quality assurance purposes. Small tensile loads or the use of a vacuum pump can be used to promote fluid penetration.

A number of optical microscopy techniques are available for producing visible images of structures or details too small to be visible by the human eye, using an optical microscope (or other magnification tool). Microscopy either involves diffraction, reflection, or refraction of radiation incident upon the subject of study and the subsequent collection of this scattered radiation in order to build up an image of the surface being inspected. This process may be carried out by wide field irradiation of the sample (e.g. standard light microscopy) or by scanning of a fine beam over the sample (e.g. confocal laser scanning microscopy). The maximum resolution is $\sim 0.2 \mu\text{m}$ on very idealised objects, but normally the resolution is limited to $0.5 \mu\text{m}$. At the highest magnifications (where the maximum resolution is possible) the depth of focus is of the order of $1 \mu\text{m}$. Contrast enhancement can be achieved through staining different structures with selected dyes (see above).

5.3 Ultrasonic and Acoustic Techniques

Acoustic and ultrasonic techniques are frequently used to detect, measure and characterise a wide range of manufacturing and in-service defects in FRP structures. The techniques are divided roughly in to two groups; those that make use of the sound naturally produced by the specimen as it deforms or fractures, and those, which inject sound waves into the material using a coupled transducer.

5.3.1 Acoustic emission

Acoustic emission (AE) monitoring involves detection of sound waves (usually inaudible to the human ear) made by a structure under load. The technique, which can be used for monitoring the "state of health" of a structure, involves attaching one or more ultrasonic microphones to the object and analysing the sounds using computer based instrumentation. AE may arise from friction (including bearing wear), crack growth and material changes such as corrosion. Microscopic events can be detected if sufficient energy is released and source location is also possible using multiple sensors. It can be used to monitor damage initiation and growth during fatigue testing (see Section 4.4.3). The technique relies on the operator having sufficient experience to be able to identify particular defect types from the AE data.

5.3.2 Ultrasonic C-scan

Ultrasonic inspection is routinely used within the aerospace/defence industry for quality assurance purposes and for in-service inspection of aircraft. It uses high frequency sound energy to interrogate for surface and subsurface discontinuities or flaws. The sound energy is introduced and propagates through the material in the form of waves. The sound waves propagate through the material with attendant loss of energy (attenuation) and are reflected at interfaces. The reflected wave signal is transformed into an electrical signal, which is displayed and then analysed to determine the location, size and orientation of discontinuities or flaws (e.g. cracks or disbonds), and variations in material density. Ultrasonic signals are scattered or reflected from any interface that separates regions of differing acoustic impedance. The reflective signal at the interface becomes smaller as the differences in density between the two medium decreases. Discontinuities or flaws, such as cracks, shrinkage cavities, voids, inclusions and porosity are detectable using ultrasonic inspection. Thickness and elastic properties can also be measured using ultrasonic techniques.

Ultrasonic inspection is particularly suited to the detection of planar type defects (e.g. delaminations) normal to the incident beam. Planar defects as small as 0.3 mm in size can be detected and accurately located using ultrasonic techniques. Planar resolution is limited by the ultrasonic transducer diameter. Although a 0.3 mm spatial resolution is possible with many of the high resolution imaging systems, technical expertise is required to obtain this degree of accuracy. Discontinuities that are present immediately beneath the top surface are difficult to detect. This region is called the "dead zone" and is typically 0.1 to 0.25 mm thick. The maximum inspection depth for FRPs is typically 40-50 mm. Discontinuous reinforced systems tend to be difficult to inspect due to attenuation of the ultrasonic signal as a result of dispersion due to the fillers. Visco-elastic effects in the polymer also contribute to attenuation along with porosity, and damage or defects within the composite.

Ultrasound is non-hazardous to both operators and nearby personnel, and has no effect on equipment and materials in the vicinity of testing. Large-scale and small-scale (portable) inspection systems are commercially available. Considerable knowledge and experience is required to operate equipment and interpret data. Components that have rough surfaces, complex shape (i.e. curved surfaces), or are very small or thin are difficult to inspect. Couplants, such as water may be required for effective transfer of ultrasonic wave energy between transducers and the inspected part. Reference materials are also needed for calibration purposes [84-87].

A large range of ultrasonic transducers is available with operating frequencies between 0.5 to 75 MHz, and higher. Improved spatial resolution is achieved by using high frequency transducers. It is possible to ascertain fibre orientations for individual plies in laminated composite structures. Higher frequency signals, however, are more sensitive to surface anomalies and surface roughness and are subject to high signal attenuation (i.e. signal-to-noise ratio decreases with increasing frequency). Ultrasonic transducer beam diameters range from 6 to 25 mm, with the most commonly used being 10 mm. Increased spatial resolution can be achieved by the introduction of a small circular aperture (known as a collimator) in front of a parallel transducer (i.e. unfocused), although at the expense of a loss in beam power. The introduction of a collimator also improves near-surface resolution and increases penetration depth for use in inspecting thick honeycomb structures.

Of the many ultrasonic methods that exist, three predominate in their use for inspection purposes [88]:

- Pulse-echo
- Single through-transmission
- Double through-transmission

Pulse-Echo Method: In this inspection mode, a single transmitter-receiver transducer scans along the material surface capturing signals that have been reflected from the back surface, or from discontinuities (interfaces or defects) in the material. Regions free of discontinuities return echoes from only the near and back surfaces. Additional echoes are produced due to the presence of discontinuities within the region being interrogated. In the presence of a defect, the incident pulse is almost totally reflected at the interface with little or no ultrasonic signal transmitted to the material below the defect. The arrival time of these echoes provides information as to the through-thickness location of the associated defect. This method of operation can be carried out in an immersion tank with deionised water as the ultrasonic couplant or by using a contact transducer (see Figure 64). For the contact mode, water is replaced by gel, oil or grease couplant.

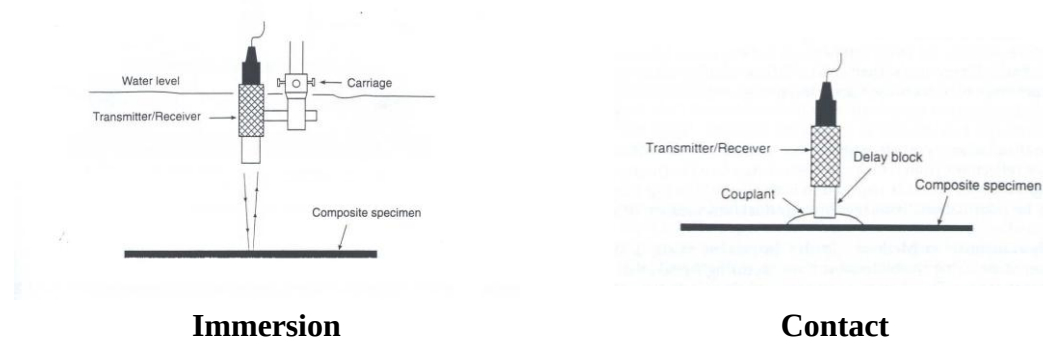


Figure 64: Pulse-echo method

In some circumstances exposure to water may be detrimental to the product (e.g. water absorption). Water may also enter the structure (e.g. honeycomb structures) and act as a block to ultrasonic signals, thus inhibiting the detection of flaws. One solution is to employ a contact probe. This requires considerable pressure to maintain good coupling between the ultrasonic transducer and the specimen surface.

Alternatively, air-coupling ultrasonic inspection could be used. For these systems, acoustic power output from the transmitter and sensitivity of the receiver have been maximised to partially overcome the inherent signal losses in air. Air-coupling systems, however, are less sensitive than immersion ultrasonic methods.

A strong reflection from the back surface means the specimen can be readily inspected from one side. This is particularly advantageous where access, as often the case, is limited to one side of a structure or component, hence the propensity of users to operate systems in the pulse-echo mode in preference to through-transmission. The pulse-echo mode is most sensitive to planar defects aligned normal to the interrogating beam. Pulse-echo is used for measuring amplitude attenuation and material thickness (time-of-flight). Measuring the amplitude of reflected signals by this method is preferred when inspecting thin or varying thickness structures.

Single Through-Transmission Method: This method of inspection involves two ultrasonic transducers (i.e. transmitter and receiver) facing directly opposite each other and separated by the specimen (Figure 65). The principle of operation is the measurement of the transmission of ultrasound through the material. To avoid spurious multiple reflections a short pulse is generally used. The transmitted pulse is received, amplified and displayed on an oscilloscope as well as the amplitude being measured and recorded. Discontinuities are detected by comparing the ultrasonic signal transmitted through the test specimen with the intensity transmitted through a reference standard made of the same material. Water couplant is generally used to transmit ultrasound from the transmitter to the specimen and from the specimen to the receiver. This can be accomplished either by fully immersing the specimen and transducers in a water bath (i.e. immersion method), by water jets (squirters) or by a water film. Defects will either block or attenuate the transmitted ultrasonic signal, thus a reduction in the signal amplitude or a total loss of signal usually occurs in regions containing internal flaws.

This method is more suitable for large components (where water jets or squirters are used instead of a water bath), honeycomb structures and thick sections where multiple reflections occur due to the presence of numerous interfaces (composite laminates), often prevent the use of other methods. Single through-transmission is often superior to pulse-echo for detecting near-surface discontinuities, the reflections from which can often emerge from the front-surface signal. The main disadvantages are that access is required to both sides of the test material and the method provides no information about through-thickness location of defects.

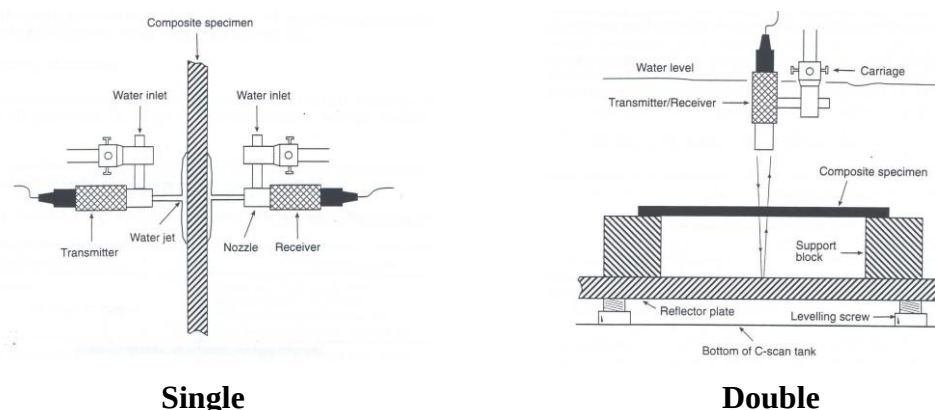


Figure 65: Through-transmission method

Double Through-Transmission Method: In this inspection mode, a single transmitter-receiver transducer scans along the material surface capturing signals that have propagated through the specimen twice (Figure 65). The specimen is supported above a flat glass or metal reflector plate and the inspection area, transducer and reflector plate are fully immersed in water. A short ultrasonic pulse passes through the specimen, normal to the surface, is reflected by the reflector plate and travels back through the specimen again to the transducer. The reflected signal is captured, amplified and displayed on an oscilloscope and the amplitude is measured and recorded.

Using the double-through transmission approach enhances the detection of near-surface flaws by directly monitoring the amplitude of the back-surface reflection rather than monitoring intermediate signals between the front and back reflections. The presence of a near-surface discontinuity will result in a reflected signal, and thus a reduction in energy of the transmitted pulse that propagates to the reflector and back. This effectively reduces the amplitude of the reflection.

Display Modes

There are four main formats for displaying ultrasonic data: A, B, C and D-scans.

A-Scan: This format provides quantitative information concerning signal amplitudes and time-of-flight data obtained at a single point on the surface of the specimen. The amplitude of the received signal, and its position relative to the signals corresponding to the upper and lower surfaces of the target, indicates the degree of severity and location of the damage or defect. The A-scan display is used to analyse the type, size and relative depth of discontinuities.

B-Scan: This format provides a quantitative display of time-of-flight data obtained along a line of the test specimen. The B-scan is essentially a linear collection of A-scans and can be considered as equivalent to taking a through-thickness slice of the specimen. B-scan displays show the relative depths of discontinuities and are used mainly to determine size (length in one direction), location (both planar position and depth) and, to a limited degree the geometry and orientation of damage or defects.

C-scan: This format provides a two-dimensional scanning pattern of ultrasonic attenuation, with threshold discrimination in the form of either a grey scale or a range of colours. For this type of presentation the transducer is scanned, in a plane that is essentially parallel to the specimen surface, in a rectilinear raster pattern. The C-scan format can also be used to display time-of-flight data.

D-scan, Time-of-Flight Scan or Depth Scan: This is essentially a C-scan format where a two-dimensional map of time-of-flight data is recorded rather than amplitude data.

5.4 X-radiography

Radiography uses localised differences in attenuation under X-ray illumination to provide a cross-sectional picture of the density of a material system. Traditionally images have been recorded on film although increasingly, digital or real-time recording systems are used. The method is well suited to volumetric defects and to complex components, which might be difficult to inspect by other methods.

The method is not popular because of health and safety implications. Increasingly portable low intensity systems are available, such as those used in the offshore industry, which reduce the associated hazards, however, previous studies have found that the technique is not really suitable for real-time, on-line measurements.

To improve definition and contrast, penetrants may be used which are opaque to X-rays. A commonly used penetrant which is relatively non-toxic and reasonably radio-opaque is zinc iodide. Other possible penetrants are halogenated hydrocarbons such as tetrabromoethane, diiodobutane and trichloroethylene although these are volatile and have health and safety implications. A drawback of the X-ray technique is that if penetrants are to be used, then the material under inspection must contain a degree of surface damage in order for penetration of the chemical into the damaged areas. Small tensile loads or the use of a vacuum pump can be used to promote fluid penetration. Specimens are soaked in dye penetrant for periods up to 24 hrs. Excess penetrant should be wiped from the specimen surfaces prior to inspection. As previously mentioned, the use of penetrant fluids can enhance the imaging process, however, these fluids can adversely affect the short-term properties and fatigue performance of polymeric materials. Figure 66 shows typical X-radiograph images obtained for CFRP OHC specimens that have been subjected to cyclic loading for 10^4 , 10^5 , 5×10^5 and 10^6 cycles. The inspection settings used were; a voltage of 35 kV, tube current of 3 mA and an integration time of 300 ms.

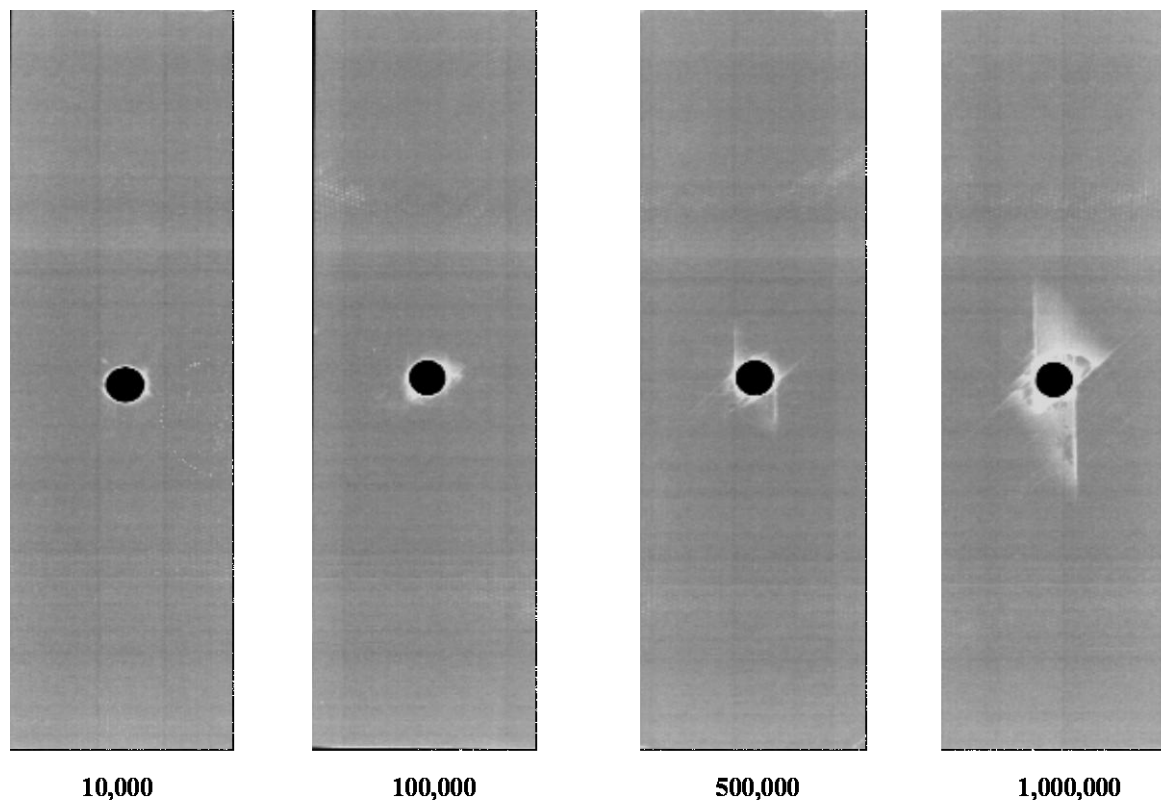


Figure 66: X-radiography images of CFRP OHC specimens

5.5 Pulse Thermography

Pulse thermography is a NDE technique that examines the thermal response (to heating or cooling) of a material or structure to determine the presence of subsurface defects and/or material properties of the target. When a material is momentarily exposed to a heat source, for example a halogen flash lamp, heat conducts into the material and is also reflected as infrared radiation. The presence of a sub-surface defect or damage reduces the amount of heat conducted through the material and therefore increases the level of infrared radiation in the location of the defect. By monitoring the level of infrared radiation emitted by the material using a thermal camera, the presence and size of damage can be determined. The principle of the technique is shown schematically in Figure 67. For poor thermal conductors such as composite materials (e.g. CFRP, GRP), the time-scales over which defects appear after application of the heat pulse are generally several seconds, or even a few minutes. For good conductors, such as metals, the timescales are often much shorter, typically a second or less. In general, the timescales for single-sided (reflective) thermography are less than those for double-sided (transmission) thermography. Heat diffuses sideways as well as through the specimen, and as a result the worst spatial resolution of the technique will be of the same order as the specimen thickness. Defects at different depths will have different resolutions however, and the resolution will be optimum when the defect is close to the surface being scanned.

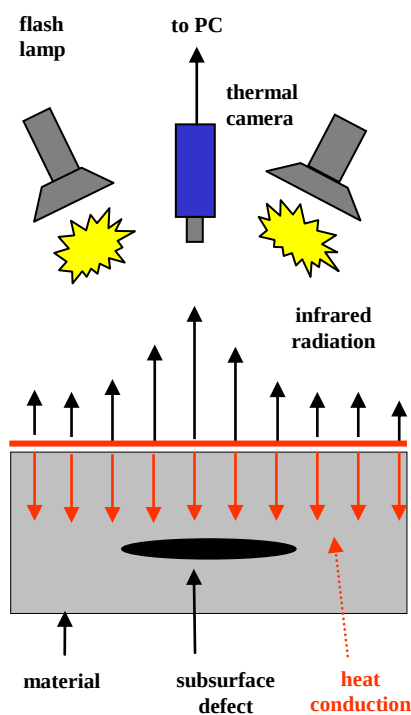


Figure 67: Principle of pulse thermography for damage monitoring

One of the key advantages of pulse thermography for damage detection compared to other techniques (ultrasonic C-scan and X-radiography) is that the inspection can be performed without the need to remove the specimen from the loading fixture. After various numbers of fatigue cycles have been completed, tests are stopped and the specimen under test is held briefly under load and interrogated before the fatigue test is resumed. Figure 68 shows typical results obtained using pulse thermography for fatigued GFRP OHT specimens.

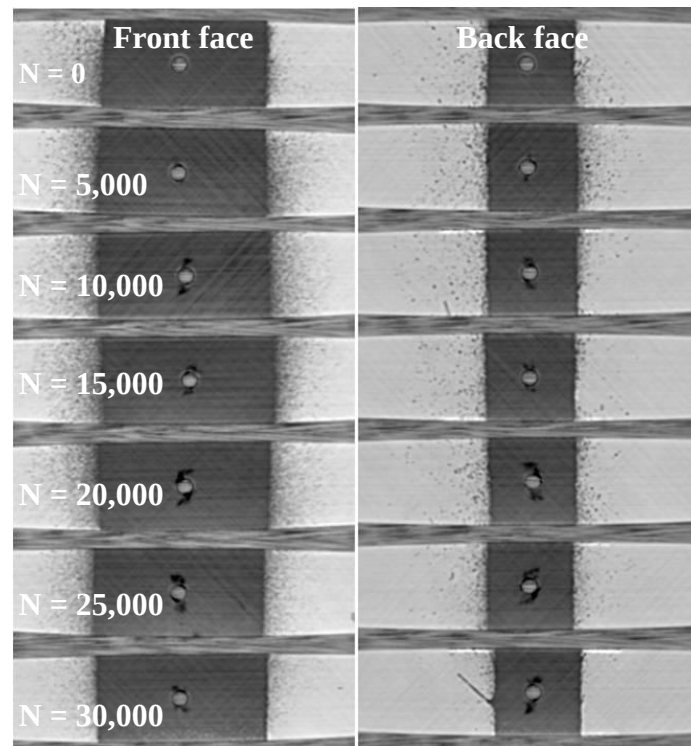


Figure 68: Pulse thermography images showing fatigue damage in OHT specimens

The duration of the thermal recording is typically 30 seconds with most of the contrast exhibited in the first 5 seconds; following the midway point, the temperature simply continues to dissipate yielding little additional information. Penetration depths for FRPs are typically 1-2 mm.

5.6 Impact Excitation

The impact excitation method (see Figure 69), described in greater detail in NPL Measurement Good Practice Guide No 101 [38], is a technique that can be used to measure the elastic properties of materials by exciting various of modes of vibration (i.e. out-of-plane flexural, in-plane flexural, torsional and longitudinal).

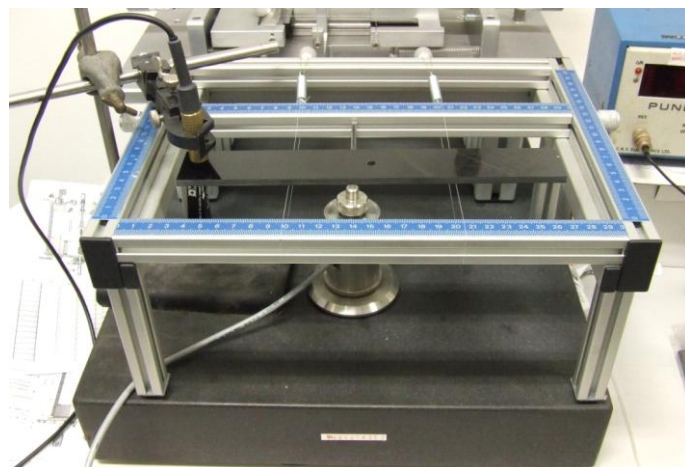


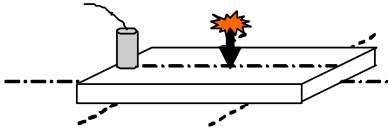
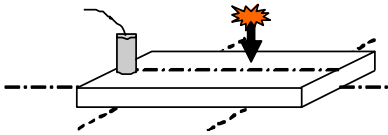
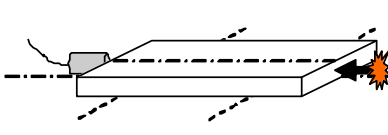
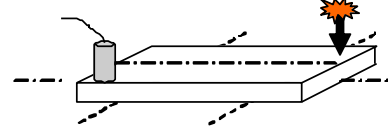
Figure 69: Impact excitation equipment with OHT specimen supported on wires

Every object has a frequency or set of frequencies at which they naturally vibrate when struck. The characteristic vibration frequencies of a beam test-piece with uniform cross-section (round, square or rectangular) can be determined by either continuously driving the vibration and sweeping the frequency to detect resonances or by striking it causing ‘ringing’ and then de-convoluting the recorded sound spectrum. The second method is often referred to as the impact excitation method. Analytical solutions exist that can be used to relate the resonant frequencies to elastic moduli.

The flexural vibration frequencies of a prismatic beam are governed primarily by the Young’s modulus E of the test specimen in the longitudinal direction of the beam (essentially independent of any material anisotropy). The torsional vibration frequencies for an isotropic material are governed primarily by the shear modulus G of the test-piece. If the material is anisotropic it is best if the principal axes of the test panel are parallel to the axes of anisotropy. The vibrations are governed by a mix of shear stiffness in the principal planes of the test piece containing the longitudinal direction.

The impact excitation equipment shown in Figure 69 basically consists of an aluminium frame across which nylon support wires are stretched. The nylon wires can be moved along graduated scales in order to match up with the nodal positions at which minimum vibration occurs. The ideal impact mechanism is a single strike with a hard ball. This can be achieved by gluing a ball bearing or a ceramic grinding bead (4-6 mm in diameter) onto the end of a flexible plastic strip like a cable-tie. Vibrations of the struck object are detected using a piezo-sensor placed close to the surface of the specimen at a position corresponding to an anti-node (i.e. position of maximum vibration). The positions of impact and vibration detection for the various excitation modes are shown schematically in Table 6. When comparing specimens with varying degrees of damage it is important that the specimen dimensions are approximately the same to enable assessment of relative changes in stiffness due to cumulative damage.

Table 6: Impact excitation modes and elastic moduli measured

Impact mode	Schematic of impact and vibration detection locations	Elastic modulus measured
Flexural - centre strike		Flexural, E_f
Flexural - off-centre strike		Flexural, E_f
Longitudinal end strike		Axial, E_{xx}
Flexural and torsion - end strike		Shear, G_{xy} Flexural, E_f

Two main issues to consider are:

- Test panels should be prepared with accurate geometry and dimensions. In this study specimen geometries and dimensions have been proportioned as per the relevant test standard. When one considers that the principal factor in flexural measurements is usually the thickness, which appears in the relevant equations for calculation of modulus as the third power, it is clear why accurate specimen dimensioning is so important.
- To ensure that the anticipated vibration frequencies of the test panels are within the capability of the measurement system. The user can obtain a good idea of the expected frequencies by performing a modal analysis using finite element analysis (FEA) for the test component/structure under consideration.

Figure 70 shows elastic moduli for CFRP OHT specimens that have been subjected to tension-tension fatigue ($R = 0.1$ and 80% UTS). It can be seen that flexural, longitudinal and shear modulus decrease with increasing fatigue life (i.e. cumulative damage). The damping factor is probably more sensitive to fatigue induced damage than elastic moduli, although the uncertainty associated with these measurements is greater.

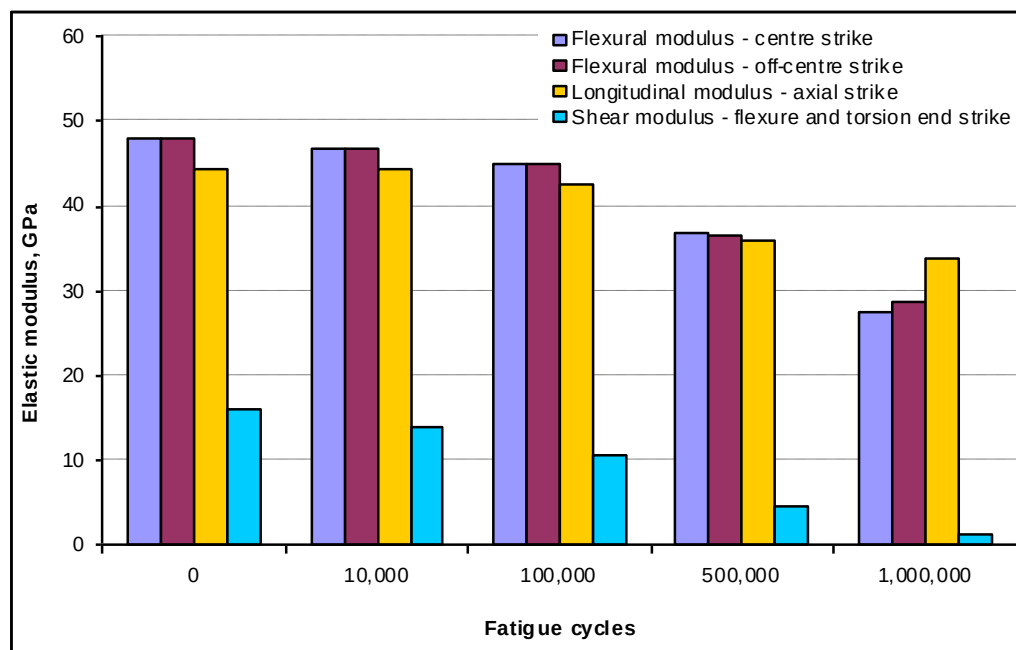


Figure 70: Elastic moduli for 80% UTS OHT fatigue specimens

Data Analysis and Fatigue Design

6

IN THIS CHAPTER

- Introduction
- Data Analysis and Presentation
- Precision Data
- Design Considerations
- Assessment of Fatigue Data

6.1 Introduction

This section is concerned with data analysis and presentation, and guidance on the assessment and use of fatigue data in the design of FRP structures. It covers topics, such as statistical analysis and precision data, and failure behaviour and criteria.

6.2 Data Analysis and Presentation

Fatigue data is generally presented in graphical form (see Chapters 2 to 4) with the y-axis representing applied loads (stresses) or strains (i.e. **S**) and the x-scale representing the number of cycles (i.e. **N**). This method of representation leads to the **S-N** or Wöhler curve [45]. For rate dependent materials, the ultimate strength data if plotted on the same curve should be obtained at a loading rate equivalent to the fatigue test frequency. The ultimate strength data point is normally plotted at 0.5 cycles. The results are often normalised with respect to the ultimate strength in order to compare fatigue performance. The y-scale is a decimal scale and the x-axis is generally a logarithmic scale. It is recommended that throughout the fatigue life of the test component that the applied load and global stiffness, and where appropriate the local strains around safety critical features are monitored. Contact or non-contact strain measurement techniques can be used for monitoring local and global deformation (or strain). NDE techniques can also provide key information as to damage formation and progression, and should be considered when establishing a test procedure.

6.2.1 Curve fitting

Fatigue data can be fitted using standard curve fitting procedures, such as linear least square regression to show the trend of the data. Curve fitting is the process of constructing a curve, or mathematical function, that has the best fit to a series of data points. In the least squares method, the unknown parameters are estimated by minimizing the sum of the squared deviations between the data (observed value) and the model. Often it is a means of comparing the effects of test variables on material response. It is convenient to represent normalised **S-N** data by a linear relationship (i.e. Equation 3). However, a pronounced S-shape can result from test artefacts, such as autogenous heating. Extrapolating an S-shaped curve can lead to the erroneous conclusion that a fatigue limit has been reached, whereas by correcting for heating effects (i.e. temperature increase) will show that the fatigue limit has not been reached [45].

6.2.2 Statistical analysis of results

Statistical analysis will often be applied to the measured fatigue data at each level of stress considered. However, this method is imprecise in the vicinity of the fatigue endurance limit, because for identical stress levels the lifetimes can have a large spread. In order to use statistical analysis, a large number of tests need to be carried out at a number of well-defined stress levels. It is also worth noting that fatigue tests can involve considerable lengths of time, particularly at low stress levels (referred to as high cycles) as shown in Table 1 in Section 2.2.2, and as a consequence increasing the precision of the fatigue data can add substantially to test programme costs and time.

6.3 Precision Data

There is an increasing requirement, particularly for load critical structures, to supply the precision of measured data where precision is defined as ‘the closeness of agreement between mutually independent test results obtained under stipulated conditions’. Composite materials can exhibit considerable variability in strength (i.e. $\pm 10\%$, or more) from batch to batch. Because of this variability, one should not indiscriminately pool data over batches. Pooling batches involves the implicit assumption that this source of variability is negligible, and in the event that this is not the case, the values, which result from pooling, can be optimistic [89]. Other sources of variability relate to testing by different operators, on different machines at different times [45]. Uncertainties associated with the accuracy of the measurement of specimen dimensions and load can also contribute to variability of test data. These factors will contribute to the overall variability in fatigue life.

The precision of a test method is normally determined through experimental validation and is reported as repeatability (i.e. within site variations) and reproducibility (between site variations) – see ISO 5725 [45, 90].

Repeatability – r refers to tests performed under conditions that are as constant as possible, with the tests performed during a short interval of time in one laboratory by one operator using the same equipment.

Reproducibility – R refers to tests performed in widely varying conditions, in different laboratories with different operators and different equipment. Thus the value of repeatability, r , and the value of reproducibility, R , are the values below which the absolute difference between two single test results may be expected to lie within a probability of 95%, under repeatability and reproducibility conditions respectively.

The level of precision required of the data is specific to the application of the material (see [91]). It is recommended that the strength at a specific environmental condition and test frequency will be determined from the results of 10 or 30 individual specimens (i.e. 1 or 3 batches of material, 2 panels per batch, 5 specimens per panel). The results shall be given as mean and standard deviation values calculated for 10 or 30 specimens per test condition (i.e. 1 or 3 batches, respectively) and after normalisation (where applicable) with respect to fibre volume fraction. A batch is defined as a quantity of material formed during the same process and having identical characteristics throughout (NB. For prepregs, laminae and laminates, material made from one batch of fibre and one batch of resin).

For calculation of design allowable values, such as A- and B- basis values, individual test results for all specimens shall be listed separately for subsequent data analysis [89-90].

A-basis value: A statistically based material property; a 95% lower confidence bound on the first percentile of a specified population of measurements. Also a 95% lower tolerance bound for the upper 99% of a specified population.

B-basis value: A statistically based material property; a 95% lower confidence bound on the tenth percentile of a specified population of measurements. Also a 95% lower tolerance bound for the upper 90% of a specified population.

6.4 Design Considerations

It is important when designing and constructing engineering structures that not only should the structure not fail through fatigue loading, but also its stiffness and load bearing capability should remain unaffected during the entire service life, and preferably longer. In the case of containment vessels or pipes, fluid retention may also be a governing factor as to the serviceability limit. The designer/engineer needs to demonstrate that no detrimental damage growth occurs under operational fatigue loading. Factors, such as loading conditions, service environment, criticality of component/structure, presence of stress concentrators arising from geometric features and construction method, consequence of failure, ease of access for inspection and frequency of inspection, and fatigue failure criteria need to be considered [24]. Loading conditions include the maximum, mean and minimum values of the fluctuating normal and shear stresses in a stress cycle. Aggressive environmental conditions will lower the fatigue strength of the material. The fundamental fatigue requirements for structures are generally specific to industrial requirements (e.g. Building Regulations or Building Codes).

Safety factors used in the design of composite structures must take into account the uncertainties associated with [24]:

- Composite manufacture
- Changes in material properties during service life

These include:

- Uncertainties concerning the assumed stress distribution in the structure, particularly complex structures under combined loading conditions
- Uncertainties in the magnitude and direction of loads applied to the structure
- Effects of workmanship
- Changes in matrix properties, and in some cases fibre properties (e.g. moisture ingress - property degradation)
- Changes at the interface affecting fibre-matrix interfacial bonding

The safety factors presented in Table 7 are for FRP laminates.

Table 7: Recommended values for partial safety factors for fatigue strength [24]

Inspection Conditions	Fail Safe Components	Non fail safe Components
Periodic inspection, good access	1.5	2.0
Periodic inspection, poor access	2.0	2.5
No inspection/maintenance	2.5	3.0

In designing a joint, the partial safety factor γ_m by which the composite properties should be divided to give design values is shown below (refer to [24] for descriptions and values of the partial safety factors for different design situations):

$$\gamma_m = \gamma_{m,1} \gamma_{m,2} \gamma_{m,3} \gamma_{m,4} \gamma_{m,5} \quad (6)$$

Fatigue strengths should be determined on the basis of tests conducted on specimens of the same material and the conditions of the test should represent the loading conditions and the environmental conditions of the component being designed. Due consideration should be given to test frequency as many FRPs are rate sensitive. The affects of geometric features on fatigue strength should be a design consideration as the presence of stress concentrators that occur at connections, re-entrant corners and points of discontinuity (e.g. tapers) can significantly reduce fatigue resistance. It is recommended in the absence of reliable fatigue models that fatigue data is generated on a representative component or structure rather than simply relying on fatigue data generated on coupon specimens. The test programme should be designed to simulate in-service loading and environmental conditions.

6.4.1 Fatigue design approaches

As previously mentioned, unidirectional CFRP composites are relatively insensitive to tension-tension fatigue when loaded in the fibre direction. In comparison, a GFRP laminate is far more sensitive to fatigue than composites reinforced with higher modulus fibres. In comparison with higher modulus fibre systems, the strain levels are high with respect to the failure strain of the matrix, thus facilitating the fatigue process and resulting in lower fatigue life. This reduction in fatigue performance is also observed for multidirectional GFRP laminates. The fatigue resistance of CFRP laminates are considerably superior to equivalent GFRP laminates.

The fatigue behaviour of FRP composites is notoriously difficult to predict owing to the limited test data available and the complexity of the interactions that can occur between the various stress conditions and failure modes involved. Numerous failure models [93] have been postulated, but most of these tend to apply to specific materials, test geometries and test conditions (see phenomenological fatigue model, described by Equation 4 in Section 4.4.2). The assumption that there is a clearly defined fatigue (stress or strain) limit for FRPs below which the fatigue life of the structure may be considered infinite needs to be treated with considerable caution. There is no evidence to indicate a fatigue limit of 10^6 cycles (or 10^7) cycles as often used when qualifying FRP composites. The progressive nature and catastrophic consequences of fatigue damage requires a failure criterion with a damage indicator that is clearly defined and can be accurately measured (e.g. stiffness loss).

Three approaches to designing composite structures for cyclic fatigue loading are shown below:

- Stress-life approach (i.e. stress-cycle (**S-N**) curves of typical joints and assemblies)
- Strain-based approach to fatigue life
- Fracture mechanics

Stress-Life Approach is an empirical method, which uses stress-cycle (**S-N**) curves to determine the fatigue or endurance limit (i.e. maximum fluctuating stress a material can endure for an infinite number of cycles without causing failure) of a material or structure. This approach is the most widely used of the above-mentioned techniques. Under constant amplitude loading conditions, most materials or structures exhibit a plateau in the stress-cycle curve, which typically occurs at $N > 10^6$ cycles. The plateau level corresponds to the fatigue or endurance limit. Below this limit, the material or structure can be cycled indefinitely without causing failure.

In most engineering applications, designers aim to ensure that no fatigue cracks develop during the service life of the component; the S-N approach works well in these cases. The performance of the joint depends on the joint geometry and the range of stresses that occur in the regions of peak stress (i.e. stress concentrations near bolt holes and ends of adhesive joints). The mean stress level and stress amplitude of the imposed fatigue cycle are known to play an important role in influencing the fatigue behaviour of engineered structures. Ideally, the range of stresses should be kept below the “endurance limit”. The stress levels should be sufficiently low for fatigue not to be a problem.

The performance of joined assemblies depends on the geometry of the structure and the range of stresses that occur in the regions of peak stress (i.e. stress concentrations near bolt holes and ends of adhesive joints). The mean stress level and stress amplitude of the imposed fatigue cycle are known to play an important role in influencing the fatigue behaviour of engineered structures. Ideally, the range of stresses should be kept below the “endurance limit”. The stress levels should be sufficiently low for fatigue not to be a problem.

The relationship given by Equation 3 has been found to describe the normalised S-N curves for many GFRP laminates. The introduction of holes (or notches), or exposure to elevated temperatures or hot/wet conditions will invariably lower the short-term strength (intercept) of the material, whilst k the gradient of the slope (fractional loss in strength per decade of cycles) of the normalised S-N curve remains relatively constant.

Constant-life diagrams are often used to represent the effects of mean stress and stress amplitude on fatigue performance of FRPs. Different combinations of normalised stress amplitude, $\Delta\sigma/\sigma_{ULT}$, and the normalised mean stress, $\sigma_{mean}/\sigma_{ULT}$, are plotted to give constant fatigue life curves. Figure 71 shows normalised stress-amplitude plots for different mean stress values that were obtained for tension-tension fatigue of a unidirectional GFRP composite material (E-glass/913 epoxy). The results in Figure 71 have been normalised with respect to the ultimate tensile strength, σ_{UTS} , of the material. 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).

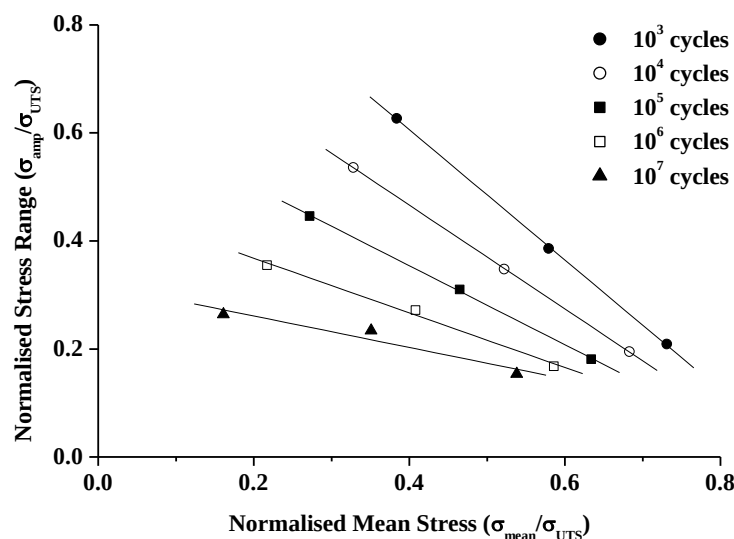


Figure 71: Stress amplitude-life plots for different mean stress values for E-glass/913

A number of models have been suggested for determining stress amplitude-life plots of polymeric materials including the Goodman relation given below [92]:

$$\sigma_{\text{amp}} = \sigma_{\text{FS}} \left(1 - \frac{\sigma_{\text{mean}}}{\sigma_{\text{ULT}}} \right) \quad (7)$$

where σ_{amp} is the stress amplitude (for a non-zero mean stress), σ_{FS} is the fatigue strength (for a fixed life), σ_{mean} is the mean stress and σ_{ULT} is the ultimate strength of the material. The Goodman relation is known to match experimental data for brittle metals.

Fatigue strength of typical details: In this approach, the designer selects a standard detail (e.g. joint) that is expected to behave similarly to the new design and uses the fatigue strength that has been established for the standard detail. This approach is straightforward and usually very successful. Hence, it has widespread use for designing joined metallic structures. However, the approach should only be considered for preliminary design purposes. Confirmation tests of assemblies representative of the actual structure need to be carried out to finalise the design. For this approach to be used, a large (and reliable) database is required for the standard detail in order to determine design stress cycles for a given stress level, or vice-versa. The database needs to include the effects of different stress ratios on fatigue life and allow for out-of-plane deformation of the joint. FEA is used to determine the stress and strain distribution in the structure. The problem arises when the new detail does not match any standard details or new materials are involved, then fatigue strength becomes very uncertain. Designers/engineers need to conduct verification tests on any final design of a fatigue-critical structure.

Strain-based approach assumes the material undergoes unconstrained deformation. In fact, engineering structures experience a certain degree of structural constraint, particularly in regions of high stress concentrations. In these situations, it is therefore more appropriate to assume strain-controlled conditions when modelling fatigue behaviour [92]. Strain-controlled fatigue is commonly used as a basis for structural design in components where cyclic fatigue crack initiation is of concern near stress concentrations.

The following strain-life model forms the basis of a widely used approach by industry for predicting the fatigue life of engineering alloys [92]:

$$\frac{\Delta \epsilon}{2} = \frac{\sigma'_f}{E N_f} (2 N_f)^b + \epsilon'_f (2 N_f)^c \quad (8)$$

where $\Delta \epsilon/2$ is the strain amplitude, ϵ'_f is the fatigue ductility coefficient (approximately equal to the true fracture strain ϵ_f in monotonic tension), σ'_f is the corresponding stress, E is the Young's modulus, and b and c are constants. The model accounts for both elastic and plastic strain.

Fracture mechanics: A major consideration in the design of composites structures is the possibility of crack (i.e. delamination) growth within the laminate. Crack propagation can be catastrophic when the strain-energy release-rate, G , or the stress intensity factor, K , of the laminate has been exceeded. Delaminations are probably the most life-limiting defects that occur in laminated structures, and may arise during processing or subsequent service.

Common structural features, such as drilled holes, machined corners, thickness changes or ends of joined assemblies generate T-T stress concentrations, which may initiate delamination under static or cyclic fatigue loading. Ultimate failure occurs when the remaining structure cannot withstand the applied maximum (or peak) stress.

The general approach is to relate the rate of crack growth, da/dN , to the applied strain-energy release rate G or the stress intensity factor K . This approach assumes a pre-existent crack and uses FEA to determine the stress state in the vicinity of the crack tip. It is worth noting that good progress has been made in applying fracture mechanics to predicting crack growth and failure of FRP structures for single-mode loading configurations, although the relevance and potential usage to actual composite structures is still regarded by a considerable proportion of the engineering community with some scepticism. From an engineering perspective, prediction of crack growth rate is considered less important than determining the crack initiation stress or energy. A considerable amount of effort has been expended in attempting to predict crack initiation and the rate of crack growth in composite materials and structures subjected to mode I (tension), mode II (shear), mode III (tear) and mixed-mode I/II static and cyclic loading conditions. The preferred approach has been to use the strain energy release rate; as stress intensity based analysis depends on accurately modelling the plastic zone that develops ahead of the crack tip. The input data requirements are far less demanding and easier to generate than those required for stress-based analysis.

The fracture mechanics approach is best suited to predicting failure subsequent to fracture propagation along a parallel crack path. However, failure is often catastrophic with no visible evidence of crack growth prior to the onset of failure. In these cases, failure is controlled primarily by the initial size of defects or flaws present in regions of high stress gradients (e.g. adhesive fillets). It has been suggested that failure occurs when the maximum stress/strain exceeds a critical stress/strain value over a certain distance, or when the stress acting over a certain volume exceeds a critical value. The critical distance or volume, which is generally defined using FEA and experimental data, is a function of the specimen geometry and size, and the defect spectrum contained within the specimen. Weibull statistical analysis has been used to model the sensitivity of both distance and volume failure criteria to changes in local geometry and singularity strength. An overview of fracture mechanics theory is presented in [32] and Design, Preparation and Testing Module of the Adhesive Design Toolkit (<http://www.adhesivetoolkit.com>).

Variable amplitude spectrum loading: An important aspect to fatigue design is ensuring that the load spectrum is representative of the stresses and strains actually experienced by the component during service. The distribution and number of stress cycles, and the order in which the loads are applied define the stress spectrum loading. Stress spectrum loading is used for testing spherical tanks for transporting liquid natural gas and for assessing fatigue performance of aircraft wings and wind turbines. Service load spectra can be estimated from typical operating conditions experienced by the component. This can be achieved by monitoring strain at critical regions of the component under service loads. For the purpose of life prediction, the spectrum loading is simplified. Metal airframes have traditionally been fatigue tested under spectrum loading conditions to a minimum of two lifetimes to ensure adequate fatigue life. A high structural reliability is generally guaranteed if the fatigue life of the structure is 2-4 times the lifetime of the structure. However, the high variability associated with fatigue life of composites means that the 2-4 lifetime fatigue criteria may not be sufficiently reliable, and hence the need to use larger life factors for fatigue design.

Palmgren-Miner cumulative damage rule: The most common tool for estimating the fatigue life of a structure under spectrum loading conditions is Palmgren-Miner (or linear damage accumulation) rule. This rule estimates fatigue life by the following expression (see also Figure 72) [94]:

$$D = \sum_{i=1}^m D_i = \sum_{i=1}^m \frac{n_i}{N_i} \quad (9)$$

D denotes the fatigue damage of the material, **m** is the number of load blocks, **n_i** and **N_i** are the number of applied loading cycles and the total number of cycles to failure at the *i*-th load level, obtained from constant amplitude tests. Fatigue failure occurs when the fatigue damage **D** equals or exceeds unity (i.e. **D** ≥ 1).

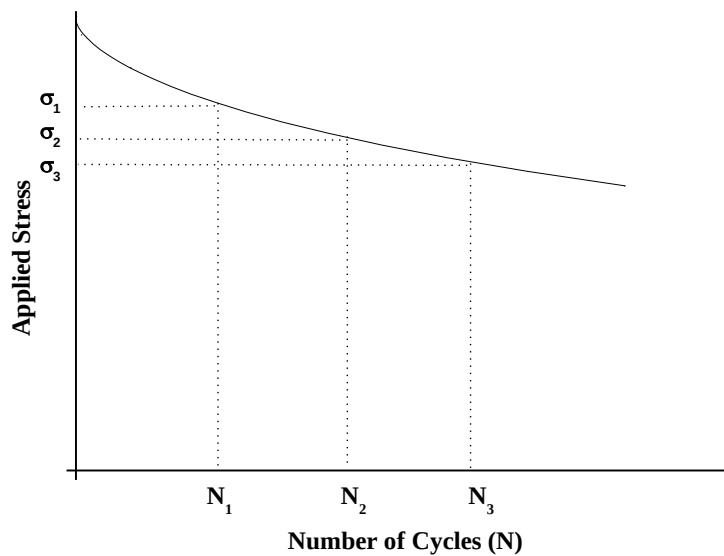


Figure 72: Schematic of Palmgren-Miner rule

Stress-based characterisation of total fatigue life using Palmgren-Miner rule is only relevant when predicting the extent of damage induced under constant amplitude fatigue loading, which may be either continuous or blocked (see Figure 72). For composite materials, Palmgren-Miner rule tends to be generally unreliable, providing non-conservative estimates of fatigue life. However, empirically derived values might prove useful to design [94]. The order (i.e. load sequence) in which the stresses are applied can be expected to affect the fatigue life. The dependence of fatigue life on load sequence for composites can be attributed to the effect of cumulative damage on the residual strength of the composite. Modelling of this process is expected to be difficult.

6.5 Assessment of Fatigue Data

This section presents observations from fatigue tests conducted at the National Physical Laboratory on a variety of laminate configurations. It highlights issues that need to be considered when analysing fatigue data from a design perspective.

6.5.1 Constant amplitude tensile fatigue

The phenomenological fatigue model, described by Equation 4, was developed to predict the fatigue behaviour of unidirectional FRPs under constant amplitude stress cycling with non-negative mean stresses. As with most models, it assumes that the failure mechanisms (damage modes), sequence of damage modes and extent of sub-critical damage associated with each damage mode are the same (self-similar), independent of the loading conditions. Although the damage mechanisms are often similar for different stress conditions, the tensile fatigue data at different R ratios may form distinct populations as indicated by the tension-tension fatigue results obtained for a notched quasi-isotropic $[45/0/-45/90]_{4s}$ GFRP laminate (see Figure 73). The mode and extent of damage is dependent on the amplitude and mean values of the applied loading conditions (see also Equation 4).

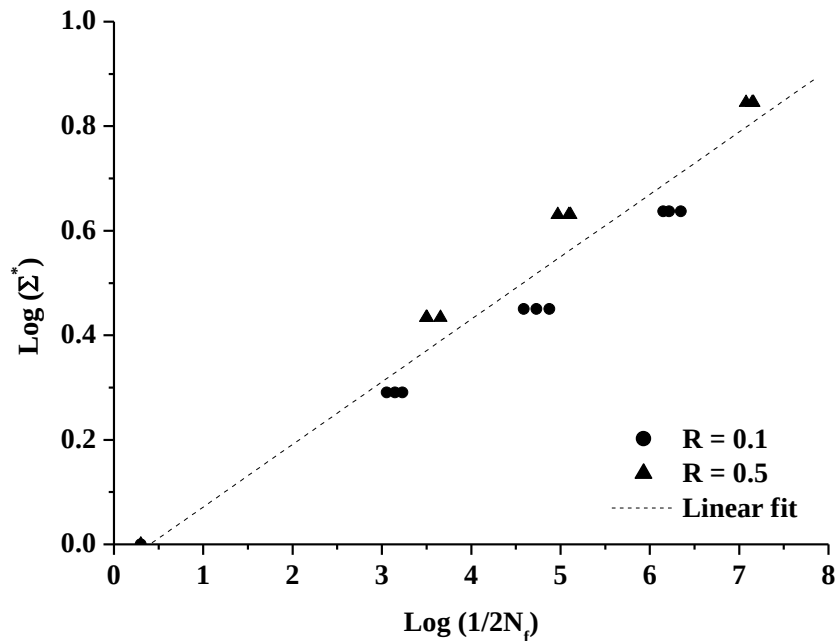


Figure 73: Modified non-dimensional effective stress versus loading cycles to failure

If the progressive fatigue damage is identical for all stress conditions then the normalised stiffness reduction E/E_0 plotted as a function of normalised fatigue life N/N_f should in principle closely match, allowing for experimental scatter, to form a single master curve. The differences in the normalised residual fatigue curves shown in Figure 74 for the notched GFRP laminate suggest that the extent of sub-critical damage formation occurring in Stages I and II (see definitions below) of the fatigue life is dependent on the applied loading conditions. The residual fatigue stiffness values at the onset of Stage III (near the end of life) are similar (i.e. $E/E_0 \approx 0.63$). The predicted value was 0.62.

Stage I: initial rapid decrease in stiffness caused primarily by matrix cracking of the 90° and $\pm 45^\circ$ plies, **Stage II:** an extended period of gradual stiffness reduction resulting from additional ply cracking in all the plies and delamination at the interfaces between the 45° and 90° plies, and **Stage III:** end of life characterized by a rapid decrease in stiffness resulting from damage coalescence, and fibre fracture and pull-out (see also Figure 74 and [95-97]). Isolated matrix cracks, ply splitting and small delaminations form near the specimen free edges during Stage II to eventually merge with the expanding central damage (delamination) zone at the end of fatigue life, similar to that for monotonic loading.

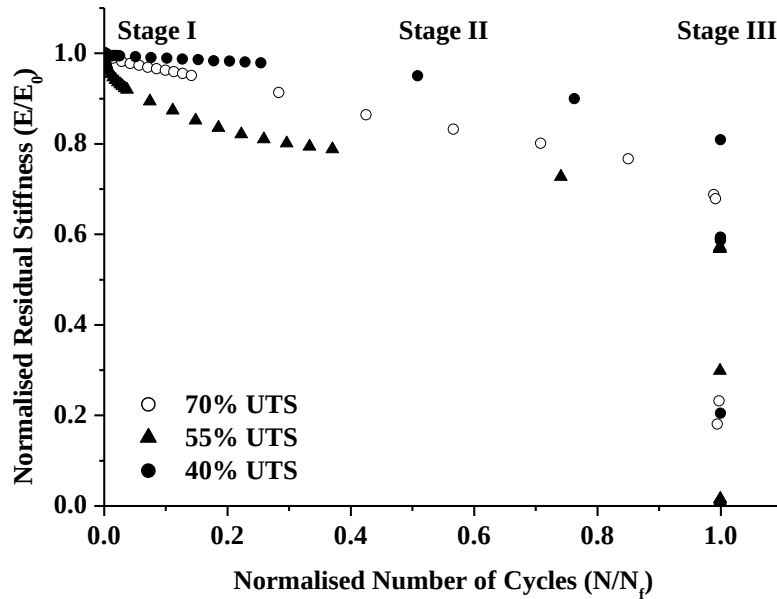


Figure 74: Normalised fatigue life data for 40%, 55% and 70% UTS ($R = 0.1$)

It is possible using classical laminate analysis to determine the residual stiffness and strength of quasi-isotropic and cross-ply laminates at the onset of ultimate failure (Stage III). This is achieved by assuming that all plies with the exception of the 0° plies have failed (last-ply failure or LPF). The failed lamina is assumed to be unable to carry stresses although physically still present in the laminate configuration (i.e. thickness and position of the lamina is unaltered after failure) – see [98].

The procedure for determining the stiffness and strength of the laminate prior to LPF consists of the following sequence:

- (i) Identify the last plies to fail
- (ii) Set the elastic constants of the failed lamina to zero (i.e. $E_{11} = E_{22} = G_{12} = 0$ and $\nu_{12} = 0$)
- (iii) Calculate laminate stiffness matrices $\mathbf{A}_{ij}$, $\mathbf{B}_{ij}$ and $\mathbf{D}_{ij}$ for the new laminate configuration
- (iv) Recalculate the lamina strains and stresses due to the stress redistribution
- (v) Determine elastic and strength properties of the remaining 0° plies

Note: $\mathbf{A}_{ij}$ - extensional stiffness, $\mathbf{B}_{ij}$ - coupling stiffness and $\mathbf{D}_{ij}$ - bending stiffness

The average residual strength of the notched GFRP laminate for Stage II was 255 ± 6 MPa (74% UTS). The predicted residual strength for the notched laminate with only 0° plies remaining intact is ~ 253 MPa. The calculations assume that only the material either side of the hole are load bearing. At lower stresses, the residual strength remains unaffected for a considerable portion of the fatigue life, as previously observed by the authors for GFRP cross-ply laminates [99]. The damage zone in the vicinity of the hole increases, although slowly, throughout Stage II, with delaminations extending over a region of $\sim 50\%$ of the specimen width. A characteristic distance, a_0 , of 6.16 mm was calculated for the quasi-static loading case using the Average Stress Criterion (ASC) developed by Whitney and Nuismer

[100-101]. The effective damage width, $\mathbf{d} + 2\mathbf{a}_0$, is $\sim 50\%$ of the specimen width ($\mathbf{d}$ is the hole diameter). A Finite Width Correction (FWC) factor of 1.072 was used in the calculation.

The rate and amount at which the maximum axial (or global) strain $\epsilon_{\max}$ increases is dependent on the loading conditions. Under high alternating and mean stresses (strains), the material creeps more strongly resulting in an increase in damage, and subsequent shorter fatigue life. Table 8 compares typical $\epsilon_{\max}$ and $\epsilon_{\text{mean}} = (\epsilon_{\max} + \epsilon_{\min})/2$ strain values measured for the notched GFRP laminate at the start of the fatigue test (i.e. initial) and at the end of Stage II (i.e. final). The strain measurements during Stage III (ultimate failure) are difficult to measure with any degree of certainty due to the rapid and catastrophic nature of final failure. The results presented in Table 8 indicate that the maximum strain $\epsilon_{\max}^f$ at the end of Stage II is related to the initial maximum $\epsilon_{\max}^i$ and mean ϵ_{mean}^i strains by the following approximation:

$$\epsilon_{\max}^f \approx \epsilon_{\max}^i + \epsilon_{\text{mean}}^i \approx \frac{\sigma_{\max}}{E_0} + \frac{\sigma_{\text{mean}}}{E_0} \quad (10)$$

$\sigma_{\max}$ and σ_{mean} are the maximum and mean applied stresses, and E_0 is the initial stiffness of the notched laminate.

The maximum strain $\epsilon_{\max}^f$ can also be expressed in terms of the fatigue life N_f :

$$\epsilon_{\max}^f \approx \frac{\sigma_{\max}}{E_f} \approx \epsilon_0^f - k \log_{10} N_f \quad (11)$$

where ϵ_0^f (projected strain-to-failure under quasi-static loading) is $\sim 2.72\%$, k (the slope) is ~ 0.28 and E_f (final stiffness at the end of Stage II) is $\sim 0.62E_0$ for the notched laminate under constant amplitude tension-tension loading (see also Figure 75).

The ratio of $\epsilon_{\text{mean}}/\epsilon_{\max}$ remains constant throughout Stage I and Stage II of the fatigue life.

$$\epsilon_{\text{mean}} \approx \epsilon_{\max} \frac{(1 + R)}{2} \quad (12)$$

Table 8: Typical strain values for constant amplitude tensile fatigue tests

Stress (% UTS)	Stress (MPa)		Initial Strain (%)		Final Strain (%)		N_f (Cycles)
	σ_{mean}	$\sigma_{\max}$	ϵ_{mean}	$\epsilon_{\max}$	ϵ_{mean}	$\epsilon_{\max}$	
<u>R = 0.1</u>							
40	76.2	138.6	0.363	0.658	0.663	1.100	822804
55	104.8	190.6	0.534	0.949	0.835	1.421	26976
70	133.4	242.5	0.698	1.375	1.081	2.117	706
<u>R = 0.5</u>							
40	103.8	138.6	0.412	0.554	0.753	1.004	5993898
55	142.7	190.6	0.570	0.765	1.063	1.373	62093
70	181.7	242.5	0.763	1.017	1.331	1.775	2262

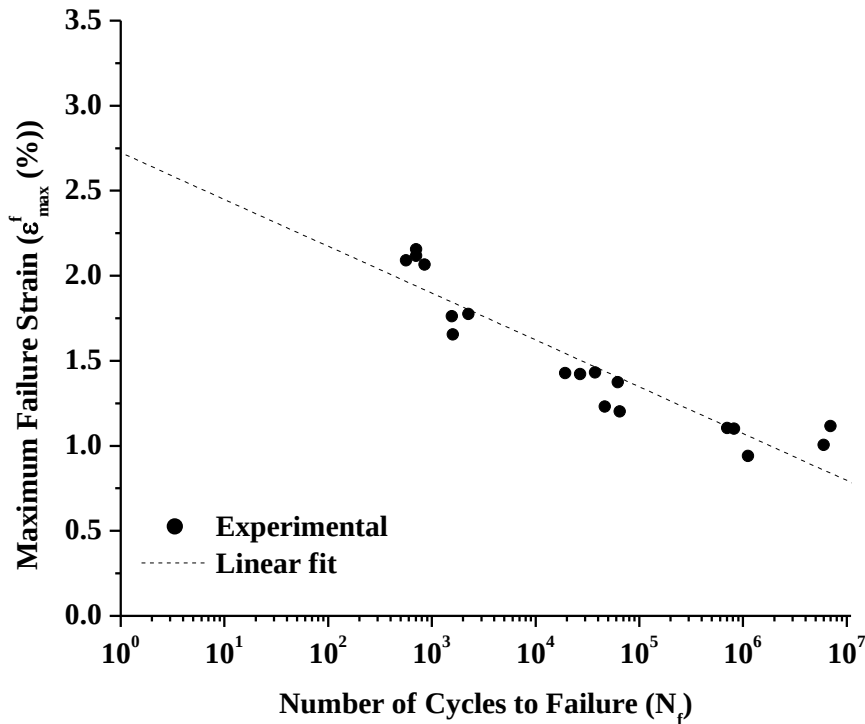


Figure 75: Maximum failure strain $\epsilon_{\max}^f$ versus number of cycles to failure

6.5.2 Variable amplitude tension-tension block loading

The fatigue behaviour of the notched laminate was also investigated where constant amplitude cyclic loads were applied in alternative blocks of 1000 cycles at two or three stress levels at $R = 0.1$ and test frequency 5 Hz. Four different multiple-step (stress) conditions were considered:

Condition 1: Block 1 ($\sigma_{\max} = 0.4\sigma_{\text{UTS}}$) + Block 2 ($\sigma_{\max} = 0.25\sigma_{\text{UTS}}$) or 40% - 25% UTS

Condition 2: Block 1 ($\sigma_{\max} = 0.55\sigma_{\text{UTS}}$) + Block 2 ($\sigma_{\max} = 0.25\sigma_{\text{UTS}}$) or 55% - 25% UTS

Condition 3: Block 1 ($\sigma_{\max} = 0.55\sigma_{\text{UTS}}$) + Block 2 ($\sigma_{\max} = 0.4\sigma_{\text{UTS}}$) or 55% - 40% UTS

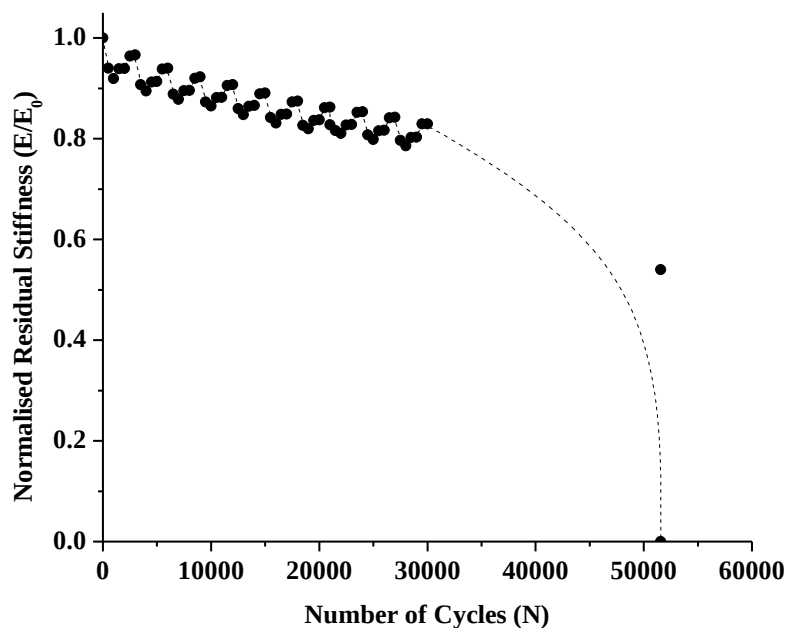
Condition 4: Block 1 ($\sigma_{\max} = 0.55\sigma_{\text{UTS}}$) + Block 2 ($\sigma_{\max} = 0.4\sigma_{\text{UTS}}$) + Block 3 ($\sigma_{\max} = 0.25\sigma_{\text{UTS}}$) or 55% - 40% - 25% UTS

The loading sequences were repeated until the specimen failed. Three fatigue tests were performed at each stress condition. Table 9 presents typical initial and final strain values obtained for each stress condition.

Table 9: Typical strain values for block tensile fatigue tests (R = 0.1)

Stress (% UTS)	Stress (MPa)		Initial Strain (%)		Final Strain (%)		N _f (Cycles)
	σ_{mean}	σ_{max}	ϵ_{mean}	ϵ_{max}	ϵ_{mean}	ϵ_{max}	
40 - 25							<u>1980584</u>
25	47.6	86.6	0.230	0.418	0.353	0.642	990000
40	76.2	138.6	0.368	0.669	0.581	1.065	990584
55 - 25							<u>74796</u>
25	47.6	86.6	0.244	0.444	0.515	0.684	37000
55	104.8	190.6	0.538	0.978	0.940	1.548	37796
55 - 40							<u>82569</u>
40	76.2	138.6	0.385	0.700	0.591	1.047	41000
55	104.8	190.6	0.530	0.963	0.812	1.478	41569
55 - 40 - 25							<u>51564</u>
25	47.6	86.6	0.238	0.433	0.303	0.681	17000
40	76.2	138.6	0.381	0.693	0.485	0.994	17000
55	104.8	190.6	0.524	0.953	0.666	1.574	17564

The fatigue results indicate that Equations 10, 11 and 12 also apply to multiple-step loading. A small decrease in stiffness can be observed as the applied load is increased (see Figure 76). The overall trend is for stiffness to decrease with loading cycles approaching a similar stiffness value at the end of Stage II as that observed for the constant amplitude tests (i.e. $E/E_0 \approx 0.63$). A similar variation in surface temperature between loading blocks can be observed for the multiple-step tests (see Figure 77) with temperature increasing with an increase in applied load. The overall trend is for the surface temperature to steadily rise with loading cycles with a rapid increase in temperature occurring at the onset of ultimate failure (Stage III). Specimens invariably fail within the block with the highest stresses.

**Figure 76: Normalised residual fatigue stiffness for three-step loading (R = 0.1)**

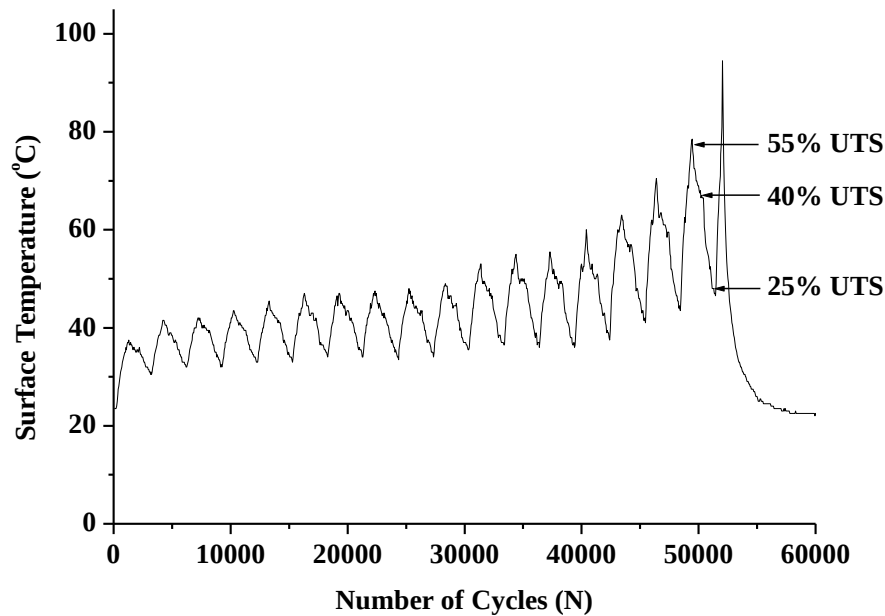


Figure 77: Surface temperature at the hole perimeter for three-step loading ($R = 0.1$)

Table 10 compares the measured fatigue life for the two-and three-step block loading conditions with values predicted using the Palmgren-Miner's (or linear damage accumulation) rule (Equation 9) using both the $S-N$ (Equation 3) and $\epsilon_{\max}^f - N$ (Equation 11) fatigue life data.

Table 10: Fatigue life for multiple-step loading conditions ($R = 0.1$)

Stress (% UTS)	Cycles to failure (N_f)		
	Measured	Predicted (S-N)	Predicted ($\epsilon_{\max}^f - N$)
Multiple-Step			
40 - 25	1767823 ± 230869	1938693	2,376872
55 - 25	58827 ± 13967	63183	37838
55 - 40	70410 ± 13403	61307	67597
55 - 40 - 25	45530 ± 7893	91872	45060

The predicted and experimental data are in reasonable agreement for two-step block loading for both $S-N$ and $\epsilon_{\max}^f - N$ fatigue life data with the latter also providing close agreement with the measured fatigue life for the three-step loading case. Equation 11 is highly sensitive to small variations in strain measurement, which can result in large shifts in the predicted fatigue life. Altering the sequencing of the loading blocks in three-step loading has minimal effect on the fatigue life.

6.5.3 Constant amplitude fully reversible loading

The **S-N** data for the GFRP OHT specimens at $R = 0.1, 10$ and -1 can be approximated by the following numerical expressions:

$$\frac{\sigma_{\max}}{\sigma_{\text{UTS}}} = 1 - 0.1 \log_{10} N_f \quad (13)$$

$$\frac{\sigma_{\max}}{\sigma_{\text{UCS}}} = 1 - 0.07 \log_{10} N_f \quad (14)$$

$$\frac{\sigma_{\max}}{\sigma_{\text{ULT}}} = 1 - 0.12 \log_{10} N_f \quad (15)$$

As the short-term tensile and compressive strengths were almost identical ($\sigma_{\text{UTS}} = 345 \pm 5$ and $\sigma_{\text{UCS}} = 346 \pm 54$), it was possible to determine the fully reversible **S-N** response from the product of Equations 13 and 14 as shown in Figure 76.

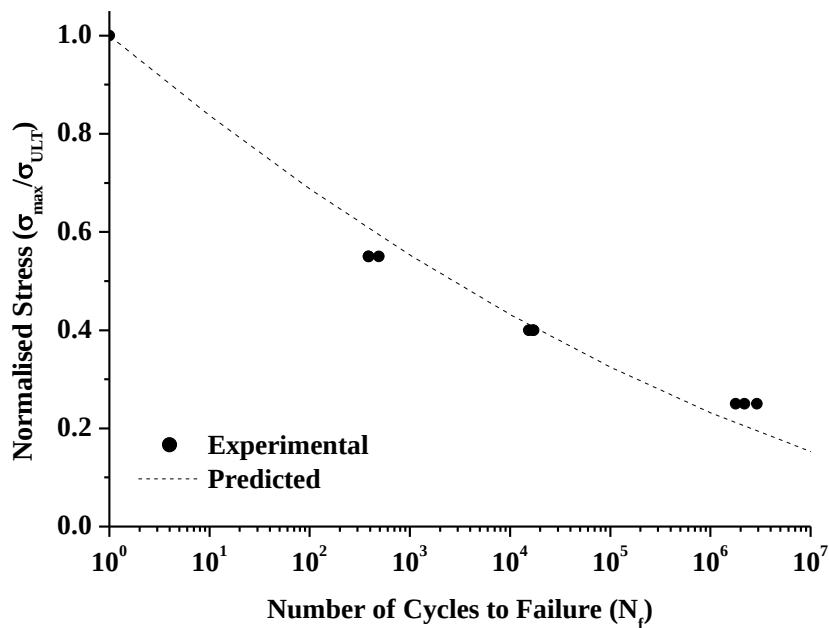


Figure 78: S-N response for fully reversed loaded notched GFRP laminate

Standards and Contacts

7

IN THIS CHAPTER

- ISO Standards
- BSI and EN Standards
- ASTM Standards
- Useful Contacts
- Recommended Websites

ISO STANDARDS

Plastics

Mechanical

EN ISO 178	Plastics - Determination of flexural properties
EN ISO 527: Part 1	Plastics - Determination of tensile properties - General principles
EN ISO 527: Part 2	Plastics - Determination of tensile properties – Test conditions for moulding and extrusion plastics
ISO 604	Plastics - Determination of compressive properties
EN ISO 10350: Part 1	Plastics - Acquisition and presentation of comparable single-point data - Part 1: Moulding materials
EN ISO 11403: Part 1	Plastics - Acquisition and presentation of comparable multi-point data - Part 1: Mechanical Properties

Environmental Conditioning and Testing

ISO 291	Plastics - Standard atmospheres for conditioning and testing
ISO 554	Standard atmospheres for conditioning and/or testing – Specification
ISO 3205	Preferred test temperatures

Composites

Mechanical

EN ISO 527: Part 4	Plastics - Determination of tensile properties - Part 4: test conditions for isotropic and orthotropic fibre-reinforced plastic composites
EN ISO 527: Part 5	Plastics - Determination of tensile properties - Part 5: test conditions for unidirectional fibre-reinforced plastic composites
ISO 3341	Textile glass - Yarns - Determination of breaking force and breaking elongation
ISO 3597: Parts 1 to 4	Textile glass reinforced plastics – Determination of mechanical properties of rods made of roving-reinforced resin (preparation of rods, flexure, tension and shear strengths)
ISO 4899	Textile glass-reinforced thermosetting plastics – properties and test methods
EN ISO 9163	Textile glass - Rovings - Manufacture of test specimens and determination of tensile strength of impregnated rovings
EN ISO 10618	Carbon fibre - Determination of tensile properties of resin-impregnated yarn
BS ISO 11566	Carbon fibre - Determination of the tensile properties of single-filament specimens

ISO/WD 12817	Carbon fibre-reinforced composites - Determination of open-hole compressive strength
EN ISO 14125	Fibre-reinforced plastic composites - Determination of flexural properties
EN ISO 14126	Fibre-reinforced plastic composites - Determination of compressive properties in the in-plane direction.
EN ISO 14129	Fibre-reinforced plastic composites - Determination of the in-plane shear stress/shear strain response, including the in-plane shear modulus and strength, by the $\pm 45^\circ$ tension test method
BS ISO 15024	Mode I interlaminar fracture toughness G_{Ic} of unidirectional fibre-reinforced polymer matrix composites
BS ISO 18352	Test method for compression-after-impact properties of carbon fibre-reinforced plastics
<i>Mechanical (Fatigue)</i>	
EN ISO 13003	Fibre-reinforced plastics - Determination of fatigue properties under cyclic loading conditions
ISO 14269: Parts 1 to 4	Petroleum and natural gas industries - Glass-reinforced plastics (GRP) piping

BSI AND EN STANDARDS

Composites

EN 6035	Fibre reinforced plastics - Test method: Determination of notched and unnotched tensile strength
EN 12245	Transportable gas cylinders. Fully wrapped composite cylinders

ASTM STANDARDS

Plastics

Mechanical

ASTM D 638	Standard test method for tensile properties of plastics
ASTM D 695	Standard test method for compressive properties of rigid plastics
ASTM D 790	Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials

ASTM D 953	Standard test method for bearing strength of plastics
ASTM D 1043	Standard test method for stiffness properties of plastics as a function of temperature by means of a torsion test
ASTM D 5083	Standard test method for tensile properties of reinforced thermosetting plastics using straight-sided specimens
ASTM D 6272	Standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials by four-point bending

Environmental Conditioning and Testing

ASTM D 543	Standard practices for evaluating the resistance of plastics to chemical reagents
ASTM D 618	Standard Practice for conditioning plastics for testing

Composites

ASTM D 2343	Standard test method for tensile properties of glass fiber strands, yarns, and rovings used in reinforced plastics
ASTM D 3039	Standard test method for tensile properties of polymer matrix composite materials
ASTM D 3410	Standard test method for compressive properties of polymer matrix composite materials with unsupported gage section by shear loading
ASTM D 3518	Standard test method for in-plane shear response of polymer matrix composite materials by tensile test of a $\pm 45^\circ$ laminate
ASTM D 3846	Standard test method for in-plane shear strength of reinforced plastics
ASTM D 3914	Standard test method for in-plane shear strength of pultruded glass-reinforced plastic rod
ASTM D 3916	Standard test method for tensile properties of pultruded glass-fiber-reinforced Plastic rod
ASTM D 4018	Standard test methods for properties of continuous filament carbon and graphite fiber tows
ASTM D 4255	Standard test method for in-plane shear properties of polymer matrix composite materials by the rail shear method
ASTM D 4476	Standard test method for flexural properties of fiber reinforced pultruded plastic rods
ASTM D 5229	Standard test method for moisture absorption properties and equilibrium conditioning of polymer matrix composite materials
ASTM D 5379	Standard test method for shear properties of composite materials by the v-notched beam method
ASTM D 5448	Standard test method for inplane shear properties of hoop wound polymer matrix composite cylinders

ASTM D 5449	Standard test method for transverse compressive properties of hoop wound polymer matrix composite cylinders
ASTM D 5450	Standard test method for transverse tensile properties of hoop wound polymer matrix composite cylinders
ASTM D 5766	Standard test method for open-hole tensile strength of polymer matrix composite laminates
ASTM D 5961	Standard test method for bearing response of polymer matrix composite laminates
ASTM D 6115	Standard test method for mode I fatigue delamination growth onset of unidirectional fiber-reinforced polymer matrix composites
ASTM D 6484	Standard test method for open-hole compressive strength of polymer matrix composite laminates
ASTM D 6641	Standard test method for compressive properties of polymer matrix composite materials using a combined loading compression (CLC) test fixture
ASTM D 6671	Standard test method for mixed mode I-mode II interlaminar fracture toughness of unidirectional fiber reinforced polymer matrix composites
ASTM D 6742	Standard practice for filled-hole tension and compression testing of polymer matrix composite laminates
ASTM D 6856	Standard guide for testing fabric-reinforced "textile" composite materials
ASTM D 7078	Standard test method for shear properties of composite materials by v-notched rail shear method
ASTM D 7137	Standard test method for compressive residual strength properties of damaged polymer matrix composite plates
ASTM D 7205	Standard test method for tensile properties of fiber reinforced polymer matrix composite bars
ASTM D 7248	Standard test method for bearing/bypass interaction response of polymer matrix composite laminates using 2-fastener specimens
ASTM D 7264	Standard test method for flexural properties of polymer matrix composite materials
ASTM D 7291	Standard test method for through-thickness "flatwise" tensile strength and elastic modulus of a fiber-reinforced polymer matrix composite material
<i>Mechanical (Fatigue)</i>	
ASTM D 3479	Standard test method for tension-tension fatigue of polymer matrix composite materials
ASTM D 6873	Standard practice for bearing fatigue response of polymer matrix composite laminates

USEFUL CONTACTS

NPL

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Middlesex, TW11 0LW, UK
Tel: +44 (0)20 89436701
E-mail: enquiry@npl.co.uk
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ASTM

American Society for Testing and Materials
100 Barr Harbor Drive
West Conshohocken
Pennsylvania 19428, USA
Tel: 001 610 8329578
Web: <http://www.astm.org>

BSI

British Standards Institution
British Standards House
389 Chiswick High Road
London, W4 4AL, UK
Tel: +44 (0)20 8996 9001
E-mail: cservices@bsigroup.com
Web: <http://www.bsigroup.com/>

ISO

International Standards Organisation
1, ch. de la Voie-Creuse, Case postale 56
CH-1211 Geneva 20, Switzerland
Tel: +41 22 7490111
E-mail: central@iso.org
Web: <http://www.iso.org>

IoM³

Institute of Materials, Minerals and Mining
1 Carlton House Terrace
London, SW1Y 5DB, UK
Tel: +44 (0)20 7451 7300
Web: <http://www.iom3.org>

Composites UK

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Tel: +44 (0)1246 266245
E-mail: info@compositesuk.org
Web: www.compositesuk.org

BPF

British Plastics Federation
6 Bath Place, Rivington Street
London, EC2A 3JE, UK
Tel: +44 (0)20 74575000
E-mail: bpf@bpf.co.uk
Web: <http://www.bpf.co.uk>

BASA

British Adhesives and Sealants Association
5 Alderson Road, Worksop
Nottinghamshire, S80 1UZ, UK
Tel: +44 (0)1909 480888
E-mail: secretary@basaonline.org
Web: <http://www.basa.uk.com>

NetComposites

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RAPRA

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Shropshire, SY4 4NR, UK
Tel: +44 (0)1939 252413
E-mail: info@rapra.net
Web: <http://www.rapra.net>

TWI

(Formerly The Welding Institute)
Granta Park, Great Abington
Cambridge, CB1 6AL, UK
Tel: +44 (0)1223 899000
E-mail: twi@twi.co.uk
Web: <http://www.twi.co.uk>

RECOMMENDED WEBSITES

<http://www.materialssolutions.info/>

<http://www.adhesivestoolkit.com>

<http://www.bpf.co.uk>

<Http://www.netcomposites.com>

<http://iom3.org>

<http://www.ncn-uk.co.uk>

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8

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