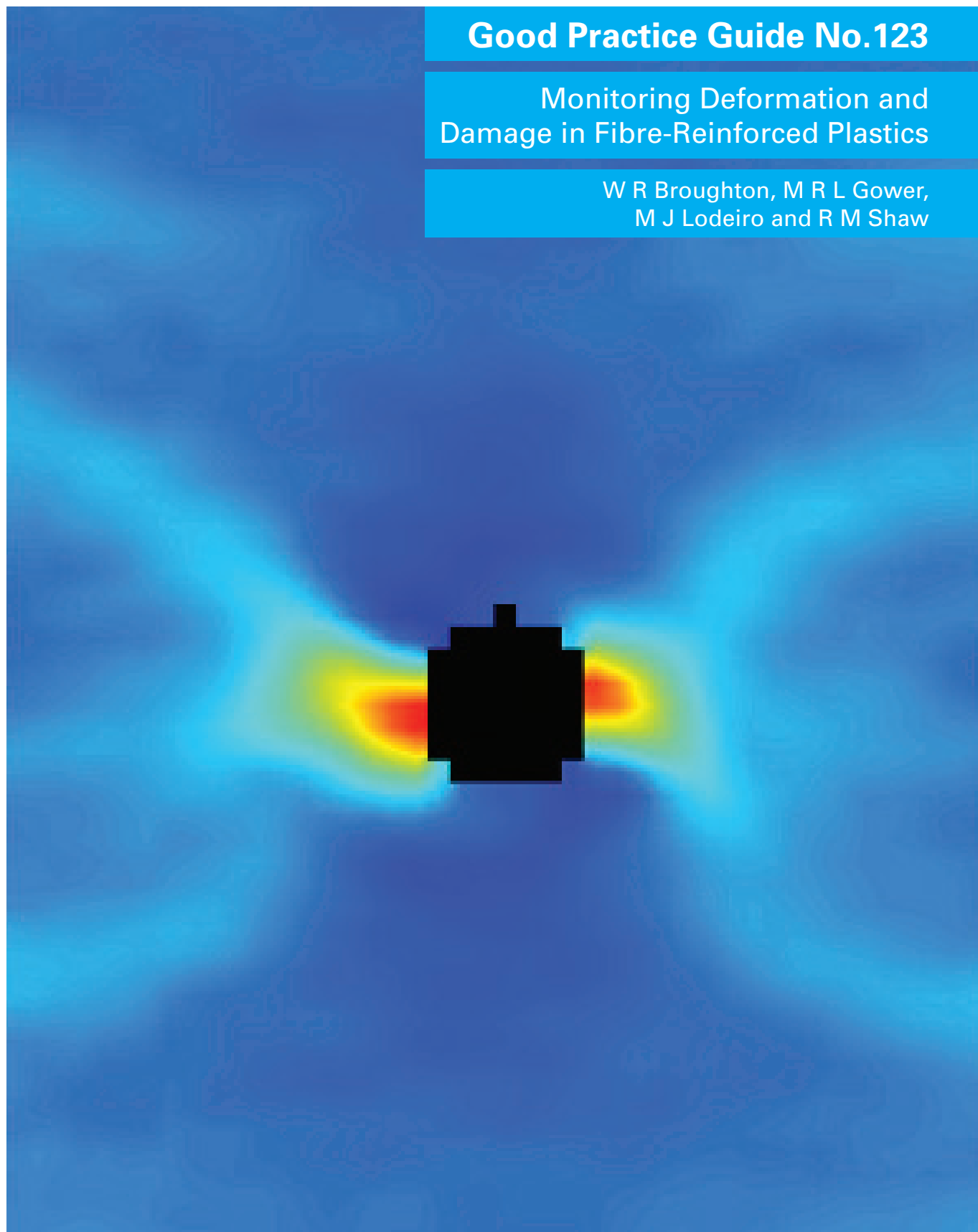


Good Practice Guide No.123

Monitoring Deformation and Damage in Fibre-Reinforced Plastics

W R Broughton, M R L Gower,
M J Lodeiro and R M Shaw



Measurement Good Practice Guide No. 123

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Materials Division, National Physical Laboratory

ABSTRACT

This Guide provides best practice guidance for *in-situ* monitoring of deformation (strain) and damage in fibre-reinforced plastics (FRPs). It covers static and cyclic fatigue loading conditions, and examines the effect of temperature and moisture on material response. Guidance is given on the use of contact and non-contact strain and damage measurement techniques, and data analysis and interpretation. It considers the application of LVDT (linear variable differential transformer) displacement transducers, contact extensometers, strain gauges, digital image correlation (DIC), optical fibres, electrical self-sensing and impact excitation. It also covers non-destructive evaluation (NDE) techniques, such as acoustic emission, ultrasonic C-scan, pulse thermography and X-radiography. The guide is primarily concerned with continuous carbon and glass fibre-reinforced laminated materials.

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ISSN 1368-6550

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Approved on behalf of the Managing Director, NPL by *Dr M G Gee*,
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Acknowledgements

This guide has been produced as part of the *Measurements for Materials 2009 programme* sponsored by the National Measurement Office of the United Kingdom's Department for Business, Innovation and Skills. The advice and technical support from the members of the Industrial Advisory Group, Amir Rezai (BAE Systems), Emiliano Bilotti (Nanoforce Technology Ltd), and colleagues (present and past) at the National Physical Laboratory, especially Crispin Allen, Louise Crocker, Michael Hall, Richard Mera, Gordon Pilkington and Tim Young, are gratefully acknowledged.

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Executive Summary

IN THIS CHAPTER

- Executive Summary

Fibre-reinforced plastics (FRPs) are increasingly being used in a wide range of safety critical applications involving long-term exposure (20 to 50 years or longer) to severe stress and environmental conditions. Examples of such applications include aerospace structures, civil structures (e.g. bridges), offshore gas/oil platforms, marine vessels and wind turbines. Long-term durability is a serious issue, which can have health and safety, and economic implications. The repair or replacement of a damaged or deteriorated part can be labour and capital intensive. In addition, there is the added economic costs and inconvenience of removal of a structure from service. 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 *in-situ* metrology techniques for detecting and monitoring deformation and damage, and methods of data analysis and interpretation.

The current approach is to carry out periodic visual and manual non-destructive evaluation (NDE) inspections in order to detect damage and assess structural integrity (including remnant life) of engineering structures, which requires shutdown or removal from service of the inspected structure. Predictive analysis is also limited by the accuracy and reliability of measurements obtained using current NDE techniques. The tendency is to "over design" structures to compensate for a lack of confidence or sensitivity in existing NDE technology and predictive analysis; hence the incentive to develop reliable *in-situ*, real-time structural health monitoring (SHM) methods for determining structural integrity and remnant life of composite structures.

This Measurement Good Practice Guide aims to provide guidance to technologists, laboratory and quality assurance personnel, and engineers generating and assessing long-term performance of FRPs for material qualification and design purposes. Guidance is provided on the use of contact and non-contact strain and damage measurement techniques, and data analysis and interpretation. It considers the application of LVDT (linear variable differential transformer) displacement transducers, contact extensometers, strain gauges, digital image correlation (DIC), optical fibres, electrical self-sensing and impact excitation. NDE techniques, such as acoustic emission, ultrasonic C-scan, pulse thermography and X-radiography are also covered. The guide is primarily concerned with continuous carbon and glass fibre-reinforced laminates.

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 Business, Innovation and Skills.

Introduction

1

IN THIS CHAPTER

- Background
- Scope

1.1 Background

Fibre-reinforced polymer (FRP) composites are a highly versatile group of materials that can be tailored to fit a wide range of industrial applications involving demanding service conditions. The wide range of processing routes, fibre types and formats (two- and three-dimensional architecture), and resin matrices provides the means of producing thick, complex engineering structures suitable for use in safety critical applications such as bridges, fuselage of commercial and military aircraft, wind turbine blades and off-shore drilling platforms. FRPs offer a number of advantages compared with traditional materials (metals, concrete, etc.), including high specific stiffness and strength, excellent fatigue, chemical and corrosion resistance, and good damage tolerance, hence the increased usage of these materials in large secondary and primary load-bearing structures.

Despite the advantages, the severe service conditions often encountered present a variety of challenges to designers and maintenance engineers to ensure the long-term structural integrity of these versatile materials. There is growing demand for manufacturers to guarantee the life expectancy of engineering structures, particularly where inspection and/or maintenance can be difficult or failure catastrophic. The current approach adopted by industry is to carry out periodic visual and manual non-destructive (NDE) inspections in order to detect damage and assess structural integrity (including remnant life) of engineering structures, which often requires shutdown or removal from service of the inspected structure. NDE techniques frequently employed for this purpose include ultrasonic C-scan, acoustic emission (AE), thermography and X-radiography.

Continuous health monitoring of engineering structures, such as aircraft and bridges, is possible through the use of integrated sensors or sensor systems (i.e. smart structures). These systems, which enable real-time in-situ measurements are particularly suited to remote and inaccessible areas of the structure, employ either an array of attached or embedded metal-film strain gauges, or in more recent times acoustic emission and optical fibre sensors for strain and damage monitoring. Optical fibre based sensors can be used to monitor degradation processes and fracture. Fibre optic devices are small with low weight and in many cases can be embedded into or bonded to a composite structure (to produce smart structures), and can be located in obscure locations not readily accessible by conventional NDE methods. However, large complex structures require an extensive array of sensors strategically located at safety critical locations (e.g. stress raisers - cut-outs, flanges, changes in thickness, etc.). As a consequence, installation, operation and maintenance costs of the sensors and auxiliary equipment can be prohibitive.

An alternative approach is to take advantage of the inherent electrical properties of conductive fillers, such as carbon fibres and/or dispersed conductive reinforcement (e.g. carbon nanotubes (CNTs) and nanographene platelets), embedded in the matrix for real-time in-situ monitoring of strain, and damage initiation and growth in engineering structures. The concept of structural materials capable of self-sensing (self-diagnostics) strain or damage has special attraction to designers and engineers. It dispenses with the need to attach or embed sensors, thus reducing operation and maintenance costs.

1.2 Scope

This Measurement Good Practice Guide aims to provide guidance to technologists, laboratory and quality assurance personnel, and engineers generating and assessing long-term performance of FRPs for material qualification and design purposes. Guidance is provided on the use of contact and non-contact strain and damage measurement techniques, and data analysis and interpretation. It considers the application of LVDT (linear variable differential transformer) displacement transducers, contact extensometers, strain gauges, digital image correlation (DIC), optical fibres, electrical self-sensing and impact excitation. NDE techniques, such as acoustic emission, ultrasonic C-scan, pulse thermography and X-radiography are also covered. The guide is primarily concerned with continuous carbon and glass fibre-reinforced laminates.

The intention of the Guide is to provide designers and users with sufficient information, which when coupled with their own expertise can be used to measure and monitor deformation (strain) and damage in composite structures. 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 that provide comprehensive coverage of composites technology, testing, design and analysis [1-25]. Other NPL Measurement Good Practice Guides [26-33], provide advice on issues relating to the preparation and testing of plastics, adhesives and adhesive joints. The intention of this 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 engineering structures, and the detailed requirements specified by the manufacturer should be completely satisfied. This also applies to the selection and use of SHM and NDE sensors and associated instrumentation. **Organisations that can provide specialist advice are listed at the back of the Guide along with relevant standards and publications.**

Laminate Theory

2

IN THIS CHAPTER

- Introduction
- Unidirectional Laminae
- Elastic Behaviour of Unidirectional Lamina
- Hygrothermal Effects
- Multidirectional Laminates

2.1 Introduction

Fibre-reinforced laminates may consist of several distinct layers of unidirectional (UD) laminae with each lamina often made of identical constituent materials. Individual layers (or plies) may differ from each other in: (i) relative volumes of the constituents; (ii) form of the reinforcement as continuous or discrete fibres; and (iii) orientation of fibres with respect to a common reference axes. The directional properties in the three mutually perpendicular planes of the material symmetry may therefore differ between individual layers because of variations in (i), (ii) and (iii). As a result, the relationships between the in-plane engineering elastic constants of fibre-reinforced lamina differ from those that apply to unreinforced polymers. This section will address the relation between in-plane and through-thickness (interlaminar) elastic properties of UD and multidirectional fibre-reinforced laminates.

2.2 Unidirectional Laminae

It is assumed for the analysis of engineering properties of UD continuous fibre-reinforced composites that [34-36]:

- (i) The matrix and fibres are both homogenous and isotropic;
- (ii) Fibres and matrix, and subsequently the composite exhibit linear elastic behaviour;
- (iii) Fibres are uniform, regularly spaced and perfectly aligned;
- (iv) Perfect bonding between fibres and matrix (i.e. no interfacial layer); and
- (v) No voids present in the composite.

Note: Elastic and strength properties can be adversely affected by the presence of voids, irrespective of fibre-matrix system or the fibre treatment used, and hence determination of the void content present in the composite is recommended.

In addition, the longitudinal (1-direction) strains experienced by the fibre (ϵ_{11f}), matrix (ϵ_{11m}) and composite (ϵ_{11c}) are assumed equal (i.e. $\epsilon_{11f} = \epsilon_{11m} = \epsilon_{11c}$) under either longitudinal tensile or compressive stress, σ_{11c} (see Figure 1).

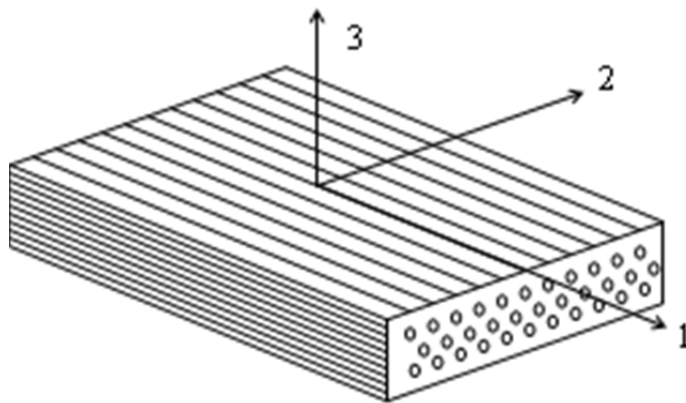


Figure 1: Principal material axes 1, 2 and 3 of unidirectional lamina

For a two constituent composite system, longitudinal modulus E_{11c} for the composite can be determined using:

$$E_{11c} = \frac{\sigma_{11c}}{\epsilon_{11c}} = E_{11f} V_f + E_m V_m = E_{11f} V_f + E_m (1 - V_f) \quad (1)$$

where E_{11f} is the longitudinal modulus of the fibre, E_m is the elastic (Young's) modulus of the polymer matrix, and V_f and V_m are the volume fractions of the fibre and matrix, respectively.

Equation (1) is a “rule of mixtures” relationship, which can be generalised as:

$$E_{11c} = \sum_{i=1}^n E_{11i} V_i \quad (2)$$

The major Poisson's ratio ν_{12c} of the composite, defined as:

$$\nu_{12c} = -\frac{\epsilon_{22c}}{\epsilon_{11c}} \quad (3)$$

can also be expressed by the “rule of mixture” relationship:

$$\nu_{12c} = \nu_{12f} V_f + \nu_m V_m = \nu_{12f} V_f + \nu_m (1 - V_f) \quad (4)$$

where ϵ_{22c} is the lateral (or transverse) strain in the 2-direction, ν_{12f} is the longitudinal Poisson's ratio of the fibre and ν_m is the Poisson's ratio of the matrix.

The generalised form of Equation (4) is:

$$\nu_{12c} = \sum_{i=1}^n \nu_{12i} V_i \quad (5)$$

Transverse elastic modulus E_{22c} can be determined using the Halpin-Tsai equation described below [33-35].

$$E_{22c} = \frac{\sigma_{22c}}{\epsilon_{22c}} = E_m \left(\frac{1 + \xi \eta V_f}{1 - \eta V_f} \right) \quad (6)$$

where:

$$\eta = \frac{(E_{22f}/E_m) - 1}{(E_{22f}/E_m) + \xi} \quad (7)$$

where σ_{22c} is the mean applied stress in the 2-direction and $\xi = 2$ is the reinforcement constant. The value of ξ is the measure of reinforcement and depends on fibre geometry, packing geometry and loading conditions. A value of $\xi = 2$ was obtained by comparing Equations (6) and (7) with exact elasticity solutions through a curve fitting exercise.

Similarly, the in-plane shear modulus G_{12c} can be approximated using the following Halpin-Tsai equation [36-37]:

$$G_{12c} = \frac{\tau_{12c}}{\gamma_{12c}} = G_m \left(\frac{1 + \xi \eta V_f}{1 - \eta V_f} \right) \quad (8)$$

where:

$$\eta = \frac{(G_{12f}/G_m) - 1}{(G_{12f}/G_m) + \xi} \quad (9)$$

where the reinforcement constant ξ is equal to unity. A value of $\xi = 1$ was obtained by comparing Equations (8) and (9) with exact elasticity solutions through a curve fitting exercise. In equation (8), G_m is the shear modulus of the matrix, and τ_{12c} and γ_{12c} denote the mean in-plane shear stress and shear strain of the lamina, respectively.

The minor Poisson's ratio of the composite can be determined from the following equation:

$$\nu_{21c} = -\frac{\varepsilon_{11c}}{\varepsilon_{22c}} = \nu_{12c} \frac{E_{22c}}{E_{11c}} \quad (10)$$

For isotropic materials, such as polymers (i.e. matrix) and glass fibres the following relationships apply.

$$G_m = \frac{E_m}{2(1 + \nu_m)} \quad (11)$$

$$E_{11f} = E_{22f} = E_f; \quad \nu_{12f} = \nu_{21f} = \nu_f; \quad G_{12f} = G_f = \frac{E_f}{2(1 + \nu_f)} \quad (12)$$

For carbon fibre and aramid fibres, which are anisotropic these simplifications cannot be used. Extensive data on the non-axial properties of these fibres are difficult to measure and are generally not available.

Through-thickness (3-direction) modulus E_{33c} for the composite can be determined using [38-39]:

$$E_{33c} = \frac{\sigma_{33c}}{\varepsilon_{33c}} = \frac{E_m}{1 - \sqrt{V_f} \left(1 - \frac{E_m}{E_{22f}} \right)} \quad (13)$$

where σ_{33c} and ε_{33c} are the mean applied stress and strain of the lamina, respectively.

Poisson's ratios ν_{31c} , and ν_{23c} and ν_{23c} of the composite can be determined from the following equations:

$$\nu_{13c} = \nu_{12c} = \frac{\nu_{12f} V_f}{3} + (1 - V_f) \nu_m \quad (14)$$

$$\nu_{31c} = \nu_{13c} \frac{E_{33c}}{E_{11c}} \quad (15)$$

$$\nu_{23c} = \nu_{23f} V_f + (1 - V_f) \left(\nu_m - \frac{E_{33}}{E_{11}} \right); \quad \nu_{23f} = \nu_{12f} \quad (16)$$

$$\nu_{32c} = \nu_{12c} \frac{E_{33c}}{E_{22c}} \quad (17)$$

Through-thickness shear moduli G_{13c} and G_{23c} of the composite can be determined using the following equations [38-39]:

$$G_{13c} = \frac{\sigma_{33c}}{\epsilon_{33c}} = \frac{G_m}{1 - \sqrt{V_f} \left(1 - \frac{G_m}{G_{12f}} \right)} \quad (18)$$

$$G_{23c} = \frac{\sigma_{33c}}{\epsilon_{33c}} = \frac{G_m}{1 - \sqrt{V_f} \left(1 - \frac{G_m}{G_{12f}} \right)} \quad (19)$$

2.3 Elastic Behaviour of Unidirectional Lamina

In general, the state of stress at a point in a body can be described by the nine components of the stress tensor σ_{ij} . Correspondingly, the strain tensor ϵ_{ij} has nine components. The linear relationship between stress and strain is known as the “generalised Hooke's Law” and can be expressed as [34-36]:

$$\sigma_{ij} = E_{ijkl} \epsilon_{kl} \quad (20)$$

where the components of the fourth-order tensor E_{ijkl} are the elastic constants.

The stress-strain relation given in Equation (20) can be expressed in the inverted form as:

$$\epsilon_{ij} = C_{ijkl} \sigma_{kl} \quad (21)$$

where C_{ijkl} is the compliance tensor.

For an anisotropic body the fourth-order tensors contain 81 components, which can be reduced to 36 by accounting for the symmetry of the stress and strain tensors of which only 21 are independent. In the case of two-dimensional (2-D) orthotropic material, the two relationships given by Equations (20) and (21) can be written in a more convenient form as:

$$\sigma_{ij} = Q_{ij} \varepsilon_{ij} \quad (22)$$

and

$$\varepsilon_{ij} = C_{ij} \sigma_{ij} \quad (23)$$

where σ_{ij} are the stress components, ε_{ij} the strain components, Q_{ij} is the stiffness matrix and C_{ij} the compliance matrix.

The general orthotropic material has three mutually perpendicular planes of elastic symmetry and is characterised by nine independent constants, which reduces to 5 for transversely isotropic material. The UD lamina is assumed to be under plane-stress conditions and hence the number of independent stiffness or compliance components reduces to 4. It is assumed that all layers are solvable as 2-D orthotropic problem.

The constitutive relations for the UD lamina (see Equation (22)) are:

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12} \end{bmatrix} \quad (24)$$

where the components of the lamina stiffness matrix Q_{11} , Q_{22} , Q_{12} and Q_{66} are related to the elastic constants as follows:

$$Q_{11} = \frac{E_{11}}{(1 - \nu_{12} \nu_{21})} \quad (25)$$

$$Q_{22} = \frac{E_{22}}{(1 - \nu_{12} \nu_{21})} \quad (26)$$

$$Q_{12} = \frac{\nu_{21} E_{11}}{(1 - \nu_{12} \nu_{21})} = \frac{\nu_{12} E_{22}}{(1 - \nu_{12} \nu_{21})} \quad (27)$$

$$Q_{66} = G_{12} \quad (28)$$

The inverse constitutive relations are:

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & 0 \\ C_{12} & C_{22} & 0 \\ 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{bmatrix} \quad (29)$$

The components of the lamina compliance matrix in Equation (29) are given by:

$$C_{11} = \frac{1}{E_{11}} \quad (30)$$

$$C_{22} = \frac{1}{E_{22}} \quad (31)$$

$$C_{12} = -\frac{\nu_{12}}{E_{11}} = -\frac{\nu_{21}}{E_{22}} \quad (32)$$

$$C_{66} = \frac{1}{G_{12}} \quad (33)$$

The components of the stiffness matrix and the compliance matrix are related as follows:

$$Q_{11} = \frac{C_{22}}{C_{11}C_{22} - (C_{12})^2} \quad (34)$$

$$Q_{22} = \frac{C_{11}}{C_{11}C_{22} - (C_{12})^2} \quad (35)$$

$$Q_{12} = \frac{C_{12}}{C_{11}C_{22} - (C_{12})^2} \quad (36)$$

$$Q_{66} = \frac{1}{C_{66}} \quad (37)$$

The relations between the five elastic constants and the four independent stiffness components can be written as follows [36]:

$$E_{11} \equiv \frac{\sigma_{11}}{\varepsilon_{11}} = \frac{Q_{11}Q_{22} - (Q_{12})^2}{Q_{22}} \quad (38)$$

$$E_{22} \equiv \frac{\sigma_{22}}{\varepsilon_{22}} = \frac{Q_{11}Q_{22} - (Q_{12})^2}{Q_{11}} \quad (39)$$

$$\nu_{12} \equiv -\frac{\varepsilon_{22}}{\varepsilon_{11}} = \frac{Q_{12}}{Q_{22}} \quad (40)$$

$$\nu_{21} \equiv -\frac{\varepsilon_{11}}{\varepsilon_{22}} = \frac{Q_{12}}{Q_{11}} \quad (41)$$

$$G_{12} \equiv \frac{\tau_{12}}{\gamma_{12}} = Q_{66} \quad (42)$$

A laminated structure is constructed by stacking several UD laminae in a specified sequence of orientation. The orientation of the principal material directions in each lamina to the loading or reference axes (x, y) is denoted by the angle θ as shown in Figure 2. For an orthotropic lamina with the principal material 1-2 axes rotated at an angle to the reference coordinate axes x-y, the following transformation relations can be used to transform stresses and strains from the x-y axes to the 1-2 axes [34-36]

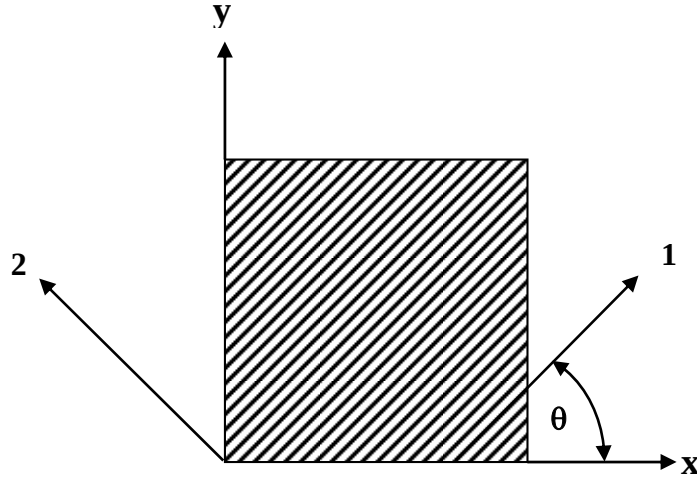


Figure 2: Rotation of principal material axes from reference coordinate system

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{bmatrix} = [T] \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} \quad (43)$$

$$\begin{bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \gamma_{12}/2 \end{bmatrix} = [T] \begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \gamma_{xy}/2 \end{bmatrix} \quad (44)$$

$$[T] = \begin{bmatrix} m^2 & n^2 & 2mn \\ n^2 & m^2 & -2mn \\ -mn & mn & m^2 - n^2 \end{bmatrix} \quad (45)$$

where $m = \cos\theta$ and $n = \sin\theta$.

The inverted form of Equations (43) and (44) are:

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} = [T]^{-1} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{bmatrix} \quad (46)$$

$$\begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \gamma_{xy}/2 \end{bmatrix} = [T]^{-1} \begin{bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \gamma_{12}/2 \end{bmatrix} \quad (47)$$

Where the inverse transformation matrix $[T]^{-1}$ is given by:

$$[T]^{-1} = \begin{bmatrix} m^2 & n^2 & -2mn \\ n^2 & m^2 & 2mn \\ mn & -mn & m^2 - n^2 \end{bmatrix} \quad (48)$$

The angle θ is positive when the angle of the 1-2 axes measured from the x-y axes is counter-clockwise and negative when clockwise.

In the case of a UD lamina loaded in either tension or compression along the principal material directions or in shear, there is no coupling between the extensional and shear deformations. However, this is not the case where the lamina is loaded along the arbitrary axes x and y. In this case, the stress-strain relations are expressed as:

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} = [\bar{Q}] \begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \gamma_{xy} \end{bmatrix} \quad (49)$$

The components of the transformed lamina stiffness matrix are given by:

$$[\bar{Q}] = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \quad (50)$$

$$\bar{Q}_{11} = Q_{11}m^4 + 2(Q_{12} + 2Q_{66})m^2n^2 + Q_{22}n^4 \quad (51)$$

$$\bar{Q}_{22} = Q_{11}n^4 + 2(Q_{12} + 2Q_{66})m^2n^2 + Q_{22}m^4 \quad (52)$$

$$\bar{Q}_{12} = (Q_{11} + Q_{22} - 4Q_{66})m^2n^2 + Q_{12}(m^4 + n^4) \quad (53)$$

$$\bar{Q}_{66} = (Q_{11} + Q_{22} - 2Q_{12} - 2Q_{66})m^2n^2 + Q_{66}(m^4 + n^4) \quad (54)$$

$$\bar{Q}_{16} = (Q_{11} - Q_{12} - 2Q_{66})m^3n + (Q_{22} - Q_{12} - 2Q_{66})mn^3 \quad (55)$$

$$\bar{Q}_{26} = (Q_{11} - Q_{12} - 2Q_{66})mn^3 + (Q_{22} - Q_{12} - 2Q_{66})m^3n \quad (56)$$

Similar transformation relations exist for the components of the compliance matrix in the stress-strain relation:

$$\begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \gamma_{xy} \end{bmatrix} = [\bar{C}] \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} \quad (57)$$

The components of the transformed lamina compliance matrix are given by:

$$[\bar{C}] = \begin{bmatrix} \bar{C}_{11} & \bar{C}_{12} & \bar{C}_{16} \\ \bar{C}_{12} & \bar{C}_{22} & \bar{C}_{26} \\ \bar{C}_{16} & \bar{C}_{26} & \bar{C}_{66} \end{bmatrix} \quad (58)$$

$$\bar{C}_{11} = C_{11}m^4 + (2C_{12} + 2C_{66})m^2n^2 + C_{22}n^4 \quad (59)$$

$$\bar{C}_{22} = C_{11}n^4 + (2C_{12} + 2C_{66})m^2n^2 + C_{22}m^4 \quad (60)$$

$$\bar{C}_{12} = (C_{11} + C_{22} - C_{66})m^2n^2 + C_{12}(m^4 + n^4) \quad (61)$$

$$\bar{C}_{66} = 2(2C_{11} + 2C_{22} - 4C_{12} - C_{66})m^2n^2 + C_{66}(m^4 + n^4) \quad (62)$$

$$\bar{C}_{16} = 2(2C_{11} - 2C_{12} - C_{66})m^3n - 2(2C_{22} - 2C_{12} - C_{66})mn^3 \quad (63)$$

$$\bar{C}_{26} = 2(2C_{11} - 2C_{12} - C_{66})mn^3 - 2(2C_{22} - 2C_{12} - C_{66})m^3n \quad (64)$$

The elastic properties E_{xx} , E_{yy} , G_{xy} , ν_{xy} and ν_{yx} for the x-y coordinate system can be obtained using the above approach.

$$\frac{1}{E_{xx}} = \frac{\cos^4 \theta}{E_{11}} + \frac{\sin^4 \theta}{E_{22}} + \frac{1}{4} \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_{11}} \right) \sin^2 2\theta \quad (64)$$

$$\frac{1}{E_{yy}} = \frac{\sin^4 \theta}{E_{11}} + \frac{\cos^4 \theta}{E_{22}} + \frac{1}{4} \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_{11}} \right) \sin^2 2\theta \quad (65)$$

$$\frac{1}{v_{xy}} = E_{xx} \left[\frac{v_{12}}{E_{11}} - \frac{1}{4} \left(\frac{1}{E_{11}} + \frac{2v_{12}}{E_{11}} + \frac{1}{E_{22}} - \frac{1}{G_{12}} \right) \right] \sin^2 2\theta \quad (66)$$

$$\frac{1}{v_{yx}} = E_{xx} \left[\frac{v_{21}}{E_{22}} - \frac{1}{4} \left(\frac{1}{E_{11}} + \frac{2v_{12}}{E_{11}} + \frac{1}{E_{22}} - \frac{1}{G_{12}} \right) \right] \sin^2 2\theta \quad (67)$$

$$\frac{1}{G_{xy}} = \frac{1}{E_{11}} + \frac{2v_{12}}{E_{22}} + \frac{1}{E_{22}} - \left(\frac{1}{E_{11}} + \frac{2v_{12}}{E_{11}} + \frac{1}{E_{22}} - \frac{1}{G_{12}} \right) \cos^2 2\theta \quad (68)$$

2.4 Hygrothermal Effects

As fibre-reinforced composites are processed at elevated temperatures, thermal strains introduced during cooling the composite material to room temperature may lead to residual stresses and changes in structural dimensions. Polymer composites have a tendency to absorb moisture, which may induce swelling strains and stresses in these materials. Equation (57) may be modified to account for temperature (T) and moisture (M) induced strains [36]:

$$\begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \gamma_{xy} \end{bmatrix} = [\bar{C}] \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} + \begin{bmatrix} \epsilon_{xx}^T \\ \epsilon_{yy}^T \\ \gamma_{xy}^T \end{bmatrix} + \begin{bmatrix} \epsilon_{xx}^M \\ \epsilon_{yy}^M \\ \gamma_{xy}^M \end{bmatrix} \quad (69)$$

Inversion of equation of Equation (69) gives:

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} = [\bar{Q}] \begin{bmatrix} \epsilon_{xx} & -\epsilon_{xx}^T & -\epsilon_{xx}^M \\ \epsilon_{yy} & -\epsilon_{yy}^T & -\epsilon_{yy}^M \\ \gamma_{xy} & -\gamma_{xy}^T & -\gamma_{xy}^M \end{bmatrix} \quad (70)$$

Thermal and moisture induced strains, which often vary linearly with temperature and moisture concentration, can be expressed as:

$$\begin{bmatrix} \epsilon_{xx}^T \\ \epsilon_{yy}^T \\ \gamma_{xy}^T \end{bmatrix} = \Delta T \begin{bmatrix} \alpha_{xx} \\ \alpha_{yy} \\ \alpha_{xy} \end{bmatrix} \quad (71)$$

$$\begin{bmatrix} \epsilon_{xx}^M \\ \epsilon_{yy}^M \\ \gamma_{xy}^M \end{bmatrix} = \Delta C_M \begin{bmatrix} \beta_{xx} \\ \beta_{yy} \\ \beta_{xy} \end{bmatrix} \quad (72)$$

In Equations (71) and (72), ΔT is the temperature change and ΔC_M moisture concentration change with respect to the reference state; α_{xx} , α_{yy} and α_{xy} are thermal expansion coefficients, and β_{xx} , β_{yy} and β_{xy} are the expansion coefficients due to moisture. It should be noted that in the principal material coordinate system 1-2 no shear strain is induced as a result of a change in temperature or a change in moisture concentration (i.e. $\alpha_{16} = \beta_{16} = 0$).

The off-axis thermal and moisture expansion coefficients can be expressed in terms of the thermal and moisture expansion coefficients along the principal material directions:

$$\alpha_{xx} = m^2\alpha_{11} + n^2\alpha_{22}; \quad \alpha_{yy} = n^2\alpha_{11} + m^2\alpha_{22}; \quad \alpha_{xy} = 2mn\alpha_{11} - 2mn\alpha_{22} \quad (73)$$

$$\beta_{xx} = m^2\beta_{11} + n^2\beta_{22}; \quad \beta_{yy} = n^2\beta_{11} + m^2\beta_{22}; \quad \beta_{xy} = 2mn\beta_{11} - 2mn\beta_{22} \quad (74)$$

2.5 Multidirectional Laminates

Lamination theory for multidirectional laminates (see Figure 3) is based on the following assumptions:

- (i) The laminate is considered quasi-homogeneous and anisotropic;
- (ii) Each layer of the laminate is orthotropic and transversely isotropic;
- (iii) All layers have identical constituent material properties unless the laminate is a hybrid structure;
- (iv) The laminate has the properties of a thin plate;
- (v) Displacements are linear through the laminate thickness and continuous throughout the composite; and
- (vi) Perfect bonding between two adjoining laminae in a laminate (i.e. laminae cannot slip over each other and the displacements remain continuous across the laminae interface).

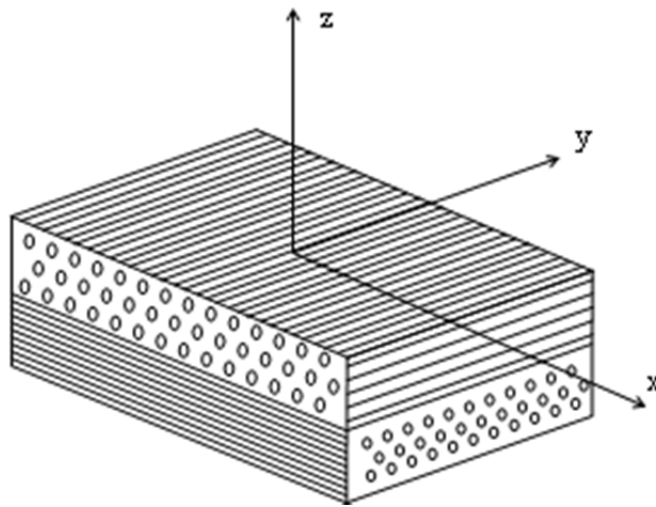


Figure 3: Principal material axes x, y and z of multidirectional laminate

The strains at any point in the laminate are related to the mid-plane strains and plate curvatures as follows:

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \varepsilon_{xx}^0 \\ \varepsilon_{yy}^0 \\ \gamma_{xy}^0 \end{bmatrix} + z \begin{bmatrix} k_{xx} \\ k_{yy} \\ k_{xy} \end{bmatrix} \quad (75)$$

Inversion of Equation (75) gives:

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} = [\bar{Q}]_k \begin{bmatrix} \varepsilon_{xx}^0 \\ \varepsilon_{yy}^0 \\ \gamma_{xy}^0 \end{bmatrix} + z [\bar{Q}]_k \begin{bmatrix} k_{xx} \\ k_{yy} \\ k_{xy} \end{bmatrix} \quad (76)$$

where the superscript 0 denotes the mid-plane, k_{xx} , k_{yy} and k_{xy} are plate curvatures, z is the distance from the laminate mid-plane, and $[\bar{Q}]_k$ is the transformed lamina stiffness matrix for the k th lamina of the laminate (see also Equation (50)).

The variation in stress through the laminate, which is generally nonlinear can be obtained by calculating the stress variations in all the laminae. Stresses are in practice discontinuous at the interface of two laminae, and the gradients across two adjoining laminae are also different.

The resultant forces N_{xx} , N_{yy} and N_{xy} can be obtained by integration of the stresses in each layer over the laminate thickness, h [34]:

$$N_{xx} = \int_{-h/2}^{h/2} \sigma_{xx} dz; \quad N_{yy} = \int_{-h/2}^{h/2} \sigma_{yy} dz; \quad N_{xy} = \int_{-h/2}^{h/2} \tau_{xy} dz \quad (77)$$

The resultant moments M_{xx} , M_{yy} and M_{xy} can be obtained by integration of the stress in each layer times the distance of the laminae from the mid-plane:

$$M_{xx} = \int_{-h/2}^{h/2} \sigma_{xx} z dz; \quad M_{yy} = \int_{-h/2}^{h/2} \sigma_{yy} z dz; \quad M_{xy} = \int_{-h/2}^{h/2} \tau_{xy} z dz \quad (78)$$

The resultant forces have the units of force per unit length and the resultant moments the units of moment per unit length.

$$\begin{bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \end{bmatrix} = \sum_{k=1}^n \int_{h_{k-1}}^{h_k} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} dz \quad (79)$$

$$\begin{bmatrix} M_{xx} \\ M_{yy} \\ M_{xy} \end{bmatrix} = \sum_{k=1}^n \int_{h_{k-1}}^{h_k} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{bmatrix} z dz \quad (80)$$

Combining Equations (76) and (79) gives:

$$\begin{bmatrix} N_{xx} \\ N_{yy} \\ N_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx}^0 \\ \varepsilon_{yy}^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} k_{xx} \\ k_{yy} \\ k_{xy} \end{bmatrix} \quad (81)$$

where:

$$A_{ij} = \sum_{k=1}^n (\bar{Q}_{ij})_k (h_k - h_{k-1}) \quad (82)$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^n (\bar{Q}_{ij})_k (h_k^2 - h_{k-1}^2) \quad (83)$$

Combining Equations (76) and (80) gives:

$$\begin{bmatrix} M_{xx} \\ M_{yy} \\ M_{xy} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx}^0 \\ \varepsilon_{yy}^0 \\ \gamma_{xy}^0 \end{bmatrix} + \begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} k_{xx} \\ k_{yy} \\ k_{xy} \end{bmatrix} \quad (84)$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^n (\bar{Q}_{ij})_k (h_k^3 - h_{k-1}^3) \quad (85)$$

The matrices [A], [B], and [D] are the extensional, coupling and bending stiffness matrices, respectively. The extensional stiffness matrix relates the resultant forces to the mid-plane strains and the bending stiffness matrix relates the resultant moments to the plate curvatures. Generally, normal forces applied to an arbitrarily oriented orthotropic lamina will produce shear strains in addition to the mid-plane normal strains. Similarly, a resultant shearing force will produce mid-plane normal strains in addition to the shearing strain. For a balanced laminate (i.e. equal number of $+\theta^\circ$ and $-\theta^\circ$ fibre orientations), the shear coupling stiffness components $A_{16} = A_{26} = 0$. In the case of a symmetric laminate (i.e. laminae positioned symmetrically about the laminate mid-plane), the components of the coupling stiffness matrix [B] are equal to zero ($B_{ij} = 0$). Whilst the in-plane shear and normal terms are uncoupled for the symmetric and balanced laminate, the twisting components of the bending stiffness matrix [D] are non-zero.

The total plate constitutive equation can be written as follows:

$$\begin{bmatrix} N \\ \text{---} \\ M \end{bmatrix} = \begin{bmatrix} A & | & B \\ \text{---} & | & \text{---} \\ B & | & D \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ \text{---} \\ k \end{bmatrix} \quad (86)$$

Mid-plane strains and plate curvatures can be obtained from the fully inverted form of the laminated constitutive equations as follows:

$$\begin{bmatrix} \varepsilon^0 \\ \kappa \end{bmatrix} = \begin{bmatrix} A' & | & B' \\ \hline C' & | & D' \end{bmatrix} \begin{bmatrix} N \\ \hline M \end{bmatrix} = \begin{bmatrix} A' & | & B' \\ \hline B' & | & D' \end{bmatrix} \begin{bmatrix} N \\ \hline M \end{bmatrix} \quad (87)$$

where:

$$\begin{aligned} [A'] &= [A^*] - [B^*][D^*]^{-1}[C^*] = [A^*] + [B^*][D^*]^{-1}[B^*]^T \\ [B'] &= [B^*][D^*]^{-1} \\ [C'] &= -[D^*]^{-1}[C^*] = [B']^T = [B'] \\ [D'] &= [D^*]^{-1} \end{aligned} \quad (88)$$

$$\begin{aligned} [A^*] &= [A]^{-1} \\ [B^*] &= -[A]^{-1}[B] \\ [C^*] &= [B][A]^{-1} = -[B^*]^T \\ [D^*] &= [D] - [B][A]^{-1}[C] \end{aligned} \quad (89)$$

Strain and Deformation Measurement

3

IN THIS CHAPTER

- Introduction
- Crosshead Displacement
- Linear Voltage Differential Transformers
- Contact Extensometers
- Strain Gauges
- Optical Extensometers

3.1 Introduction

This section considers the use of crosshead movement (indirect), contact extensometers, strain gauges, optical extensometers, digital image correlation (DIC) and electronic speckle pattern interferometry (ESPI) for measuring strain and displacement under ambient and hostile environments, and static and fatigue loading conditions.

3.2 Crosshead Displacement

Crosshead displacement provides an approximate measurement of strain; therefore 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 (or compliance) measurements directly obtained from the crosshead movement need to be corrected to take into account the compliance of the loading train. The loading train compliance can be measured by substituting the specimen for a stiff bar (tension) or block (compression or flexure) and then measuring the load versus displacement. It is difficult to accurately measure small displacements with the crosshead. Given the small adhesive layer deflections that can 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.

3.3 LVDT Displacement Transducers (LVDTs)

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. Full stroke ranges from 0 to 750 mm, or greater. Linearity can be better than $\pm 0.05\%$ full-scale deflection (FSD). LVDTs can operate under dynamic conditions (operating speed is ~ 500 mm/s), although life expectancy is typically 25 to 50 million cycles. Operating temperature range is typically $-40\text{ }^{\circ}\text{C}$ to $150\text{ }^{\circ}\text{C}$, although commercial devices capable of operating outside this range are available. Protection from the effects of hostile environments may be required. Checks should be carried out to ensure drift of the output signal due to fluctuations in temperature is minimised and that the signal is valid (i.e. due to movement of the part). Use of a sensor manufactured from corrosion-resistant materials (e.g. stainless steel) for environmental testing is recommended. High levels of shock should be avoided as this can seriously affect the operation of the sensor, either permanently damaging the LVDT or degrading the output.

3.4 Contact Extensometers

Contact extensometers are commonly used for measuring strain and displacement, and hence modulus (stiffness) of the test specimen. These high precision devices can be used to measure small to relatively large displacements. Gauge-lengths range from 1 mm to over 100 mm. Clip-on extensometers of the type shown in Figure 4 are generally preferred to other types of extensometers (e.g. digital sensor arm extensometers) due to lower cost and ease of use. Clip-on extensometers are mounted directly on the specimen and can be held in place using tension springs, special high shear strength rubber bands or rubber "O" rings stretched around the specimen, which are supplied in a range of sizes to accommodate variations in specimen width. Tension springs and "O" rings can be attached using a crochet hook. Specimen movement is monitored via knife edges attached to the arms (short and stiff) of the transducer. Relative movement between the specimen and extensometer is negligible. The range of movement for a clip-on extensometer is limited to a few millimetres. Clip-on extensometers are capable of measuring to less than 1 mm with a resolution of 0.1 μm .

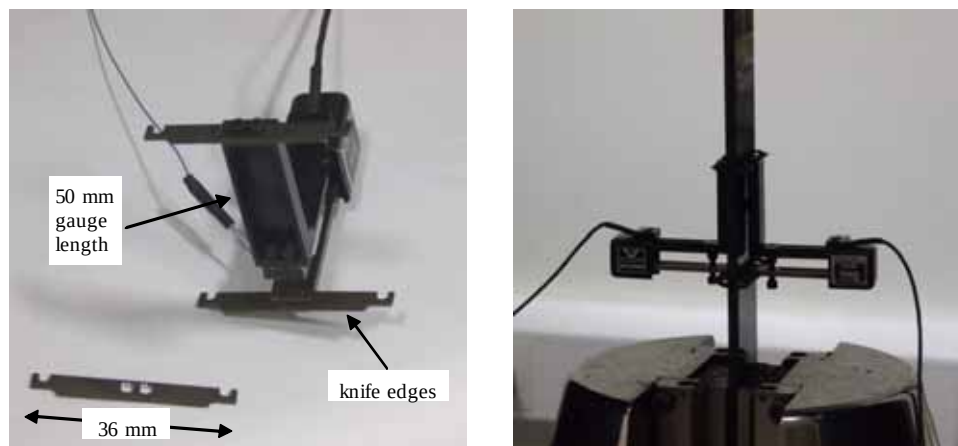


Figure 4: Extensometers used for measuring longitudinal tensile strain (Non-standard width knife edges (left) and standard width (right))

Digital sensor-arm extensometers are also used, especially where large batch testing is involved (i.e. quality assurance of production). These devices are usually equipped with a motorized system for attachment and removal of the extensometer and are available with a counterbalanced weight and double-sided measurement system to compensate for superimposed bending strains. Digital sensor-arm extensometers devices typically have a resolution of 0.1 μm , or better (0.02 μm) and a large measurement range (up to 40 mm). Extensometer linearity is typically $\pm 0.15\%$ FSD, or better. Longitudinal and transverse strain can be measured simultaneously using either separate extensometers or a biaxial device.

It is recommended that two extensometers, attached to opposite faces of the specimen, be used to measure displacement (see Figure 4). 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.

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 – see Section 3.6). 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 premature failure of 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 (e.g. fibre splintering and delamination) of the specimen 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. A gauge-length of 50 mm is typically used for uniaxial tensile tests (see ISO 527-1 [40]). Contact extensometers and the associated data acquisition system must have a sufficient response time to cope with the test frequency in cyclic fatigue testing. The frequency range of dynamic extensometers is typically 0 to 100 Hz. It is important that 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. The operating temperature range is typically -80 °C to 200 °C, although extensometers capable of operating at lower and higher temperatures are available. Precautions may need to be taken to insulate the leads to prevent moisture ingress.

Commercial clip-on extensometers allow interchangeable sensor-arms and knife edges, which can be quickly and easily replaced or adjusted. Sensor-arm extensometers are also available that can operate at very high temperatures (1600 °C). The extensometer body is designed to operate outside of the test environment (e.g. furnace) at room temperature. The arms are designed to be in contact with both sides of the specimen, and thus superimposed bending strains are largely compensated. Silicon carbide knife edges are used for high temperature testing. These devices are large and not easy to use.

3.5 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. 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 20%. Typical resolution is 0.1 $\mu\text{m/m}$, or better. Gauge-length selection is dependent on the application (0.2 to ~1 mm for stress concentration, 5-10 mm general use). 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.

Three-element rosette strain gauges (gauge axes oriented at 0°, 45° and 90°) can be used where the maximum principal strain, minimum principal strain and maximum shearing strain need to be determined (see [41]).

Maximum principal strain:

$$\varepsilon_{\max} = \frac{1}{2} \left[\varepsilon_1 + \varepsilon_2 + \sqrt{2 \left\{ (\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_2 - \varepsilon_3)^2 \right\}} \right] \quad (91)$$

Minimum principal strain:

$$\varepsilon_{\min} = \frac{1}{2} \left[\varepsilon_1 + \varepsilon_3 + \sqrt{2 \left\{ (\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_2 - \varepsilon_3)^2 \right\}} \right] \quad (92)$$

Maximum shearing strain:

$$\gamma_{\max} = \sqrt{2 \left\{ (\varepsilon_1 - \varepsilon_3)^2 + (\varepsilon_2 - \varepsilon_3)^2 \right\}} \quad (93)$$

where ε_1 is the longitudinal (0°) axis strain, ε_2 is the transverse (90°) axis strain and ε_3 is the strain along the 45° axis. Theoretical values of the maximum principal strain and maximum shearing strain can be determined using the analysis given in Section 2.

The principle of operation for strain gauges is that when strain is generated in the specimen, it is relayed via the gauge base to the resistance wire or foil in the gauge. The change in resistance is directly proportional to strain [41-42].

$$\varepsilon = \frac{\Delta L}{L} = \frac{\Delta R / R}{K} \quad (94)$$

where ε is the measured strain, R is the gauge resistance, ΔR is the resistance change due to strain and K is the gauge factor.

Strain gauges also exhibit sensitivity in the transverse direction perpendicular to the axial direction. The transverse strain sensitivity K_T is related to longitudinal strain ε_L by [41]:

$$K_T = \frac{\Delta R / R}{\varepsilon_L} \quad (95)$$

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. Frequency response ranges from 0 to 660 kHz. Fatigue performance is variable 10^5 – 10^6 cycles. 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 operating temperature range of conventional strain gauges is -40 °C to 350 °C, which for most FRP applications is sufficient. Strain gauges exist that operate at either cryogenic temperatures (-270 °C) or very high temperatures (1300 °C). Self-temperature compensating gauges (accurate to approximately $2 \times 10^{-6}/^{\circ}\text{C}$) are commonly used to minimize the thermal output of strain gauges bonded to materials having a linear thermal expansion coefficient in the specified range. Accuracy can be improved by using apparent strain versus temperature as supplied by the strain gauge manufacturer.

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.

The following procedure is recommended for applying strain gauges to FRPs with cyanoacrylate adhesive (see [42]):

- (i) First lightly abrade the surface of the specimen using 400 silicon carbide grade wet and dry paper to remove the surface resin and provide mechanical keying. A brush or a blast of clean dry air should be used to remove dust.
- (ii) Wipe the surface clean using acetone. This is to remove oil, grease or other contaminants from either the whole component or a large region surrounding the installation area.
- (iii) It is important that the position of the gauge is accurately marked out as misalignment leads to inaccurate readings during testing. Using a sharp pencil and set square/ruler mark out the centreline on the specimen or location for the strain gauge. A sharp tool **must not** be used, as it will damage the composite substrate.
- (iv) Place tape onto the surface of the strain gauge and carefully place the gauge onto the surface of the specimen in the correct position (see Figure 5).
- (v) Peel the tape back and, covering the back surface of the strain gauge, spray the surface of the specimen with cyanoacrylate activator.
- (vi) Place a drop of cyanoacrylate onto the back surface of the strain gauge and pull the tape over onto the surface of the specimen. It is important that only enough cyanoacrylate is applied to the strain gauge, as too much may cause the gauge not to lie flat on the surface which can give unsatisfactory strain readings. Handling and storage of adhesives should be in accordance with manufacturers specifications. Adhesive stored in a refrigerator must be allowed to reach ambient temperature before it is opened.

- (vii) Carefully peel back the leads of the strain gauge so they are not in contact with the surface of the specimen. It is extremely important that care is taken when connecting the terminals to the strain gauge, as the substrate may be conductive (e.g. CFRP). Should the leads of the strain gauge touch the specimen during testing; the gauge will short out causing the loss of test data. Inspect the wiring and check resistance, leakage and strain (should be zero).
- (viii) It may be necessary to apply a clamping pressure if a heat curing adhesive is used. It is recommended that the installation is inspected after un-clamping, and before post-curing (if required).
- (ix) Apply protective coating (if required), ensuring correct cure times are used.

Note: The strain gauges should be connected up to a data logger capable of recording all the strain-gauge data and load throughout the duration of the test.

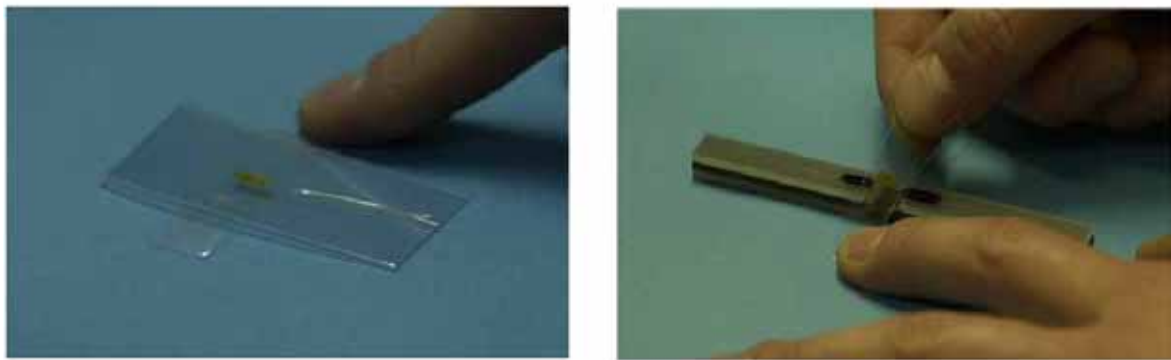


Figure 5: Strain gauging: applying tape (left) and strain gauge (right) to the specimen

3.6 Optical Extensometers

3.6.1 Video extensometers

Non-contact or optical extensometers (e.g. video extensometers) avoid the problems of contact damage and can be used up to failure. There is no temperature or environmental restrictions as video extensometers can be located outside the test chamber (provided that the specimen can be imaged clearly). In addition, non-contact extensometers can be operated up to failure without the concern of damage occurring to the extensometer (provided the optics are protected from flying debris). Standard systems measure the separation of marks in one direction, mimicking contact extensometers, but some systems provide capabilities for dot location measurements, which allow 2-D 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. Special lighting for surface or background illumination of the specimen may be required in order to optimise the contrast for identifying measurement marks.

Changes in light intensity from reflections off surrounding objects during testing can influence the optical centre point, resulting in scatter of the test data. The accuracy tends to be low for small strain measurements. Video extensometers tend to be best suited for measuring large deformations. Improvements 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 on one side of the specimen so that bending cannot be evaluated.

3.6.2 Digital Image Correlation (DIC)

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 [43-44]). 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 monitor the displacement of a block of pixels between different load levels 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 6 (see [42]). Calculation of 3-D deformations is possible if two or more cameras are used. Calibration of the image by using a calibration plate is straightforward.

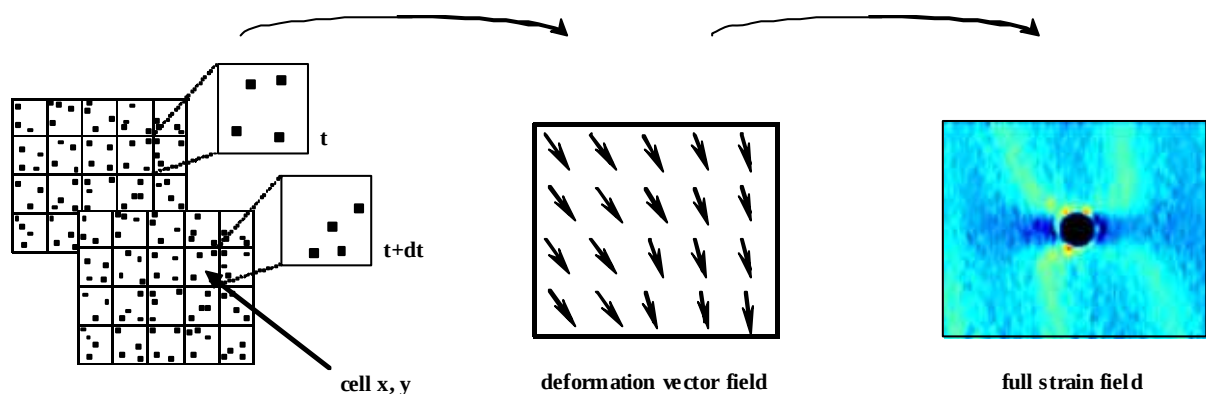


Figure 6: Principle of digital image correlation [43]

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 1 and is illustrated in Figure 7. 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.

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. A compromise is needed between high spatial resolution (small interrogation window size) and high strain resolution and accuracy (large interrogation window). 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.

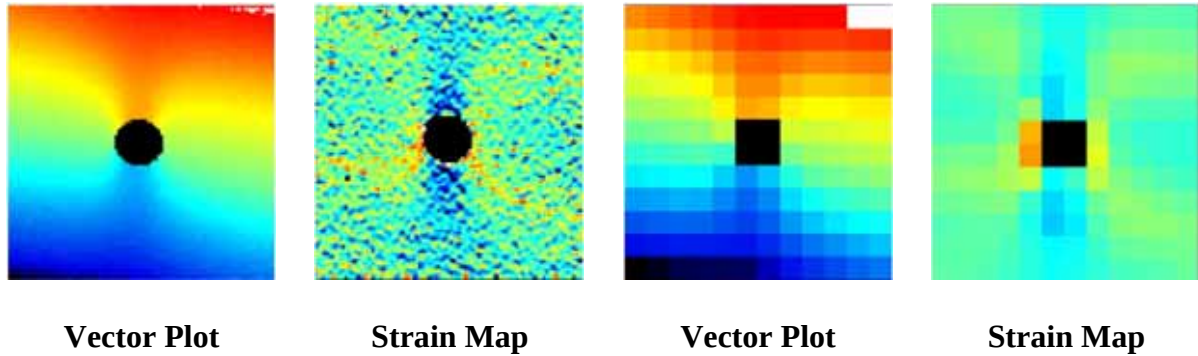


Figure 7: Vector plots and strain maps
(calculated from a 16×16 (left) and 128×128 (right) interrogation window)

Table 1: 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 8 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.

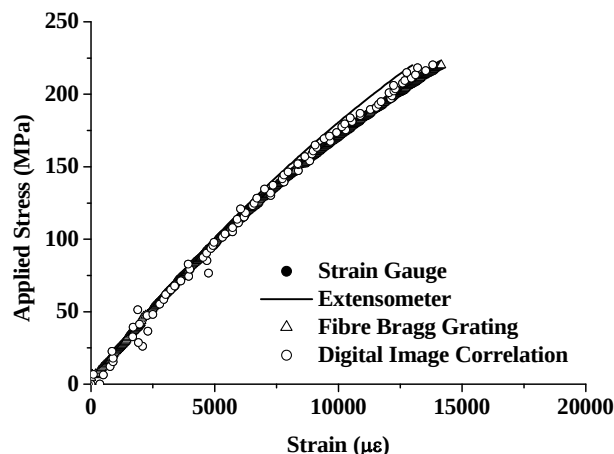


Figure 8: Comparison of strain measurements for four different techniques

3.6.3 Electronic Speckle Pattern Interferometry (ESPI)

ESPI (or Digital SPI) is a non-contact full-field strain measurement technique, based on the measurement of laser interference fringes, and is capable of measuring and monitoring non-uniform strain fields at high displacement resolution (0.01 of a pixel in-plane and 0.003 of a pixel out-of-plane). Spatial resolution is one pixel (typically 15 μm to 1mm). Very small strains (10^{-5}) can be measured. The speckle effect is produced by the interference between the reflected rays when a non-specular, dispersing surface is illuminated with a laser beam. The laser light is split in two by a beam splitter with the reference beam going to the camera and the other beam illuminating the specimen. The reflected light recombines with the reference beam to produce a reference phase map. The pattern is defined by the microscopically rough topography of the specimen surface. Any deformation of the surface results in a change of the speckle pattern. A correlation between the speckle patterns for an object in a reference state and in a deformed state provides information on the surface deformation of the structure. The technique requires minimal specimen preparation and is capable of inspecting areas ranging from 25 to 600 mm^2 , but capital outlay for equipment is generally prohibitive for most test facilities. The technique can be used to measure 3-D strain distributions under mechanical and/or thermal loads in complex geometries, and for checking finite element analysis. The technique is sensitive to small mechanical vibrations.

Optical Fibres

4

IN THIS CHAPTER

- Introduction
- Fibre Bragg Grating (FBG)
- Chirped Fibre Bragg Grating (CFBG)

4.1 Introduction

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 [45]). In addition, these sensors 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 used in awkward locations not readily accessible by conventional NDE methods. They also lend themselves to multiplexing, a number of sensors being comprised within a single optical fibre [45-46]. These devices are small with low weight and in many cases can be embedded into or bonded onto the structure (to produce smart structures).

Composite laminates are particularly suited to their implementation simply by the fibrous nature of the material, and the fact that these devices can be easily embedded during the manufacturing of composite components (see Figure 9). Bonding these devices to surfaces poses 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 or act as preferential paths for moisture ingress. Optical techniques require sensors to remain undamaged and effectively bonded to the surrounding composite, throughout the life of the component, to ensure adequate strain transfer.

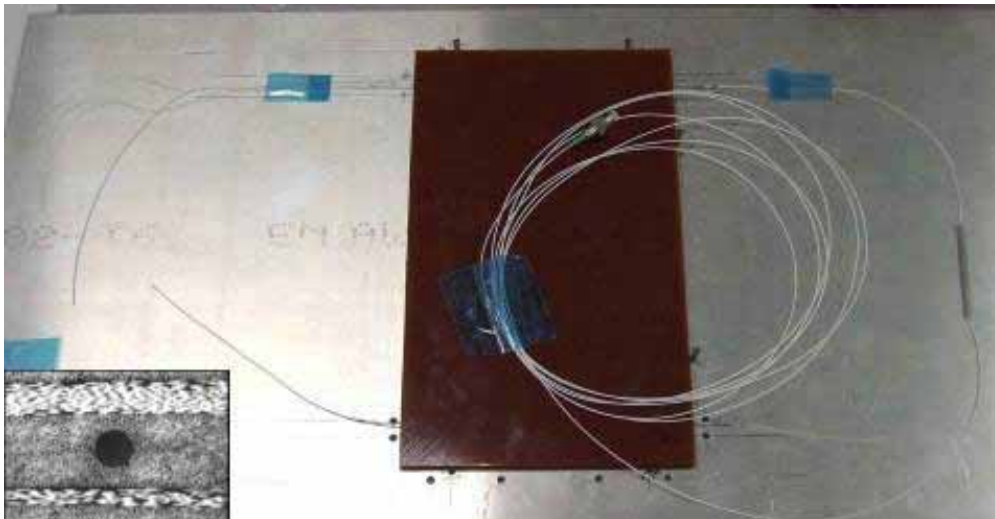


**Figure 9: GRP laminate with embedded optical fibres
(inset – micrograph of embedded fibre)**

4.2 Fibre Bragg Grating (FBG)

One of the most common fibre optic sensing methods is the fibre Bragg grating (FBG) strain sensor. This is written into the core of the optical fibre and is usually wavelength encoded, enabling multiplexing of several sensors over a length of single fibre and eliminating amplitude or intensity problems associated with many other optical sensing techniques. Advantages over conventional techniques include mechanical robustness when embedded, electromagnetic radiation immunity, large scale embedding capability to sense relevant strains, 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.

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 or cyclic loading conditions.

4.2.1 Conventional FBGs

The conventional FBG sensor is a short segment (typically 3-15 mm long) of optical fibre with an axial modulation in the core refractive index. This modulation has a regular repeating interval over the sensor length, which acts as a narrowband reflection filter, centred on a particular wavelength known as the Bragg wavelength, λ_B . The reflection bandwidth is typically below 1 nm. The basic principle of operation of FBG sensors is the measurement of changes in the peak wavelength of the reflected signal, when illuminated with a broadband light source, as shown in Figure 10 [47].

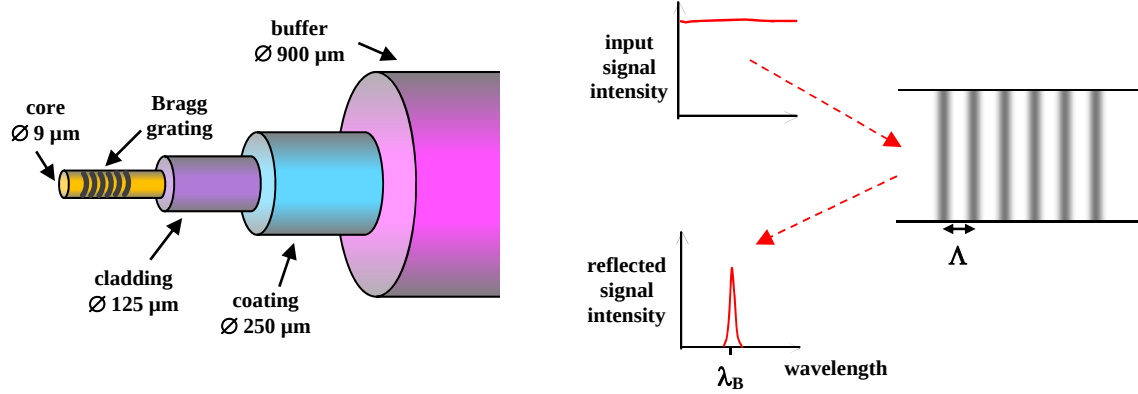


Figure 10: Optical fibre with Bragg grating and typical spectral response

The Bragg wavelength is dependent on the effective refractive index of the core, n_{eff} , and the grating periodic spacing, Λ , according to Equation (96).

$$\lambda_B = 2n_{eff}\Lambda \quad (96)$$

Consequently, any locally varying external factors, such as mechanical strain $\Delta\epsilon$ or temperature ΔT that act to alter the characteristic grating properties can cause a shift in the reflected wavelength. This is shown in Figure 11 where a change in the grating spacing caused by the application of strain, shifts the centre wavelength of the reflected spectrum. There is no change in the overall shape of the signal peak since the range of reflected wavelengths remains constant under uniform strain fields.

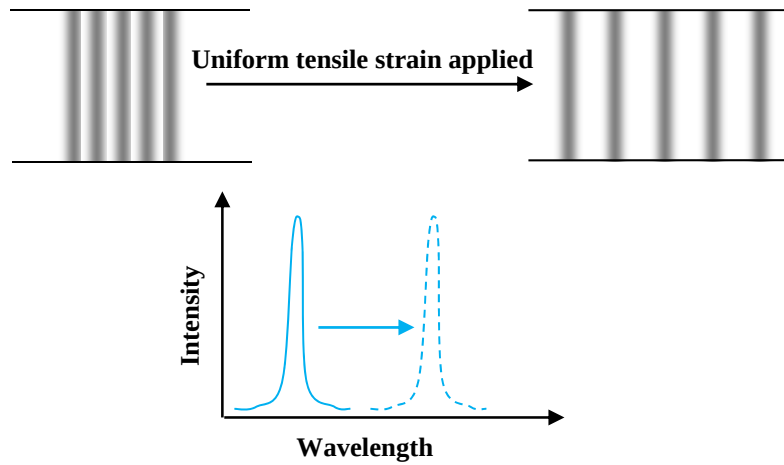


**Figure 11: Principles of strain measurement using FBG sensors
(dashed line represents strained response)**

In reality the measured changes in the Bragg wavelength incorporate both the linear effects of the imposed strains, due to both mechanical and thermal expansion, and the non-linear effects of refractive index. For a ‘free’ fibre this wavelength shift can be expressed by:

$$\Delta\lambda_B = \lambda_B (K\Delta\epsilon + \beta\Delta T) \quad (97)$$

where K is the wavelength-strain sensitive factor (typically $\sim 1 \text{ pm}/\mu\epsilon$) and β is the wavelength-temperature sensitive factor (typically $\sim 10 \text{ pm}/^\circ\text{C}$). Hence, the influence of temperature is 10 times more significant than the effect of strain and so temperature compensation is critical for accurate strain determination. Typical strain resolutions of the order of $1 \mu\epsilon$ and strain levels up to $10,000 \mu\epsilon$ are possible. FBG devices can also be used to monitor transient strain signals, of duration 1 ms , or less depending on the sampling speeds of the interrogation system.

A ‘constrained’ fibre, i.e. one which is embedded within a material, behaves as a free fibre but with an additional contribution from the thermal expansion of the surrounding material. Hence, the wavelength shift for a ‘constrained’ fibre is given by:

$$\Delta\lambda_B = \lambda_B [K\Delta\epsilon + \beta\Delta T + K(\alpha_s - \alpha_A)\Delta T] \quad (98)$$

where α_s is the coefficient of thermal expansion of the substrate or host material and α_A is the intrinsic thermal expansion coefficient of the optical fibre.

If the strain field is not uniform in the region of the FBG, such as might be seen when damage within the host material causes strain redistribution, the characteristics of the returned signals can often provide additional qualitative information about structural integrity. In general, peak splitting and peak broadening are associated with a non-uniform strain distribution over the length of an FBG, shown in Figure 12. The schematic shows the combination of a shift in the centre wavelength due to the change in average strain over the length of the FBG, as well as the broadening and splitting of the peak and accompanying reduction of intensity.

This is caused by the wider range and uneven spread of grating spacings generated under these circumstances (gratings no longer all at the same spacing as in the uniform case) and therefore the incident optical intensity being shared over a larger wavelength range. These effects can be produced as a result of any local strain non-uniformity brought about by changes in the curvature, the release of ‘locked-in’ strains (cure, bonding etc.) and any local damage (cracking, debonding, delaminations etc.). The strain interpretation is limited since all gratings in the FBG are initially the same and any changes can only be defined as being contained within the zone of influence but cannot be pinpointed to a particular location along the FBG or as a particular type of damage.

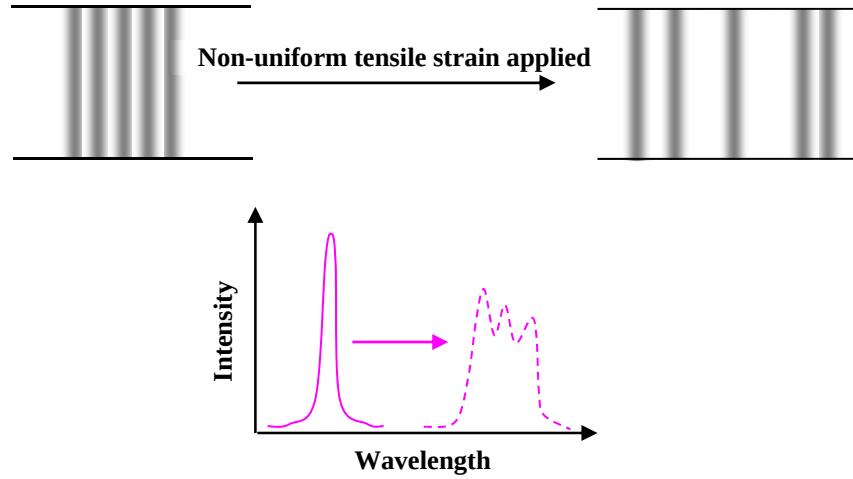


Figure 12: Characteristic FBG tensile spectra - non-uniform strain distributions (dashed line represents strained response)

4.2.2 Chirped Fibre Bragg Gratings (CFBGs)

A variation on the conventional FBG sensor is the chirped FBG (CFBG). In a CFBG the grating spacing is no longer constant but is a function of the axial position along the sensor [48]. For the simplest type of chirped structure, the grating period varies as a linear function of position. This acts as a broadband reflection filter with a large bandwidth, 10 nm or above. Essentially the signal intensity at any wavelength is a function of the number of grating periods present which correspond to that returned wavelength. Hence for a monotonically increasing grating spacing, such as a linear CFBG, the reflected spectrum takes the shape of a ‘top-hat’, as shown in Figure 13. Linear CFBGs can be described by:

$$\Lambda(x) = \Lambda_0 + \Lambda_1 x \quad (99)$$

where Λ_0 is the starting period and Λ_1 is the change in grating period per unit length along the grating. In general, the greater the grating spacing distribution for a given CFBG length, the broader the reflected spectrum and correspondingly, the lower its intensity.

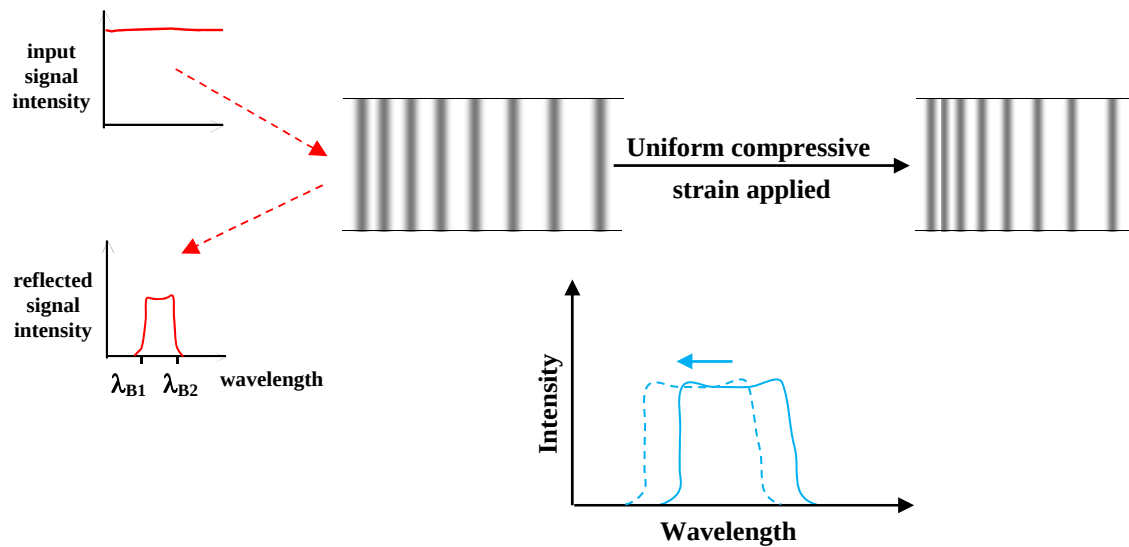


Figure 13: Typical chirped FBG sensor spectral response in compression (dashed line represents strained response)

The principle of operation for uniform strains is the same as conventional FBGs, i.e. the entire top-hat signal shifts to higher or lower wavelengths for tensile or compressive strains, respectively. However, the benefit of these sensors over conventional FBGs becomes apparent when the location of features is required.

These sensors can be considered as a closely-spaced series of many small, uniform FBGs, each with a slightly larger grating period than its neighbour. Thus, if strain changes occur in the vicinity of just one of these FBGs, the original wavelength of that FBG is the only one which shows a wavelength shift leaving the response of the others unaffected. Hence, for CFBGs, changes in the spectrum returned at a particular wavelength correspond to the grating spacings from a specific location and thus indicate a change in the strain field at that location. In this way, CFBGs easily lend themselves to pinpointing damage more precisely on the sensor length and effectively act as distributed fibre optic sensors.

Local strain changes occurring within the region of the CFBG sensor effectively disrupt the smooth, linear variation of grating spacings and a well-defined perturbation appears in the reflected spectrum, either as a peak, trough or wave in the 'top-hat' plateau. Another characteristic effect is the shift of one of the edges of the 'top hat' spectral response toward higher or lower wavelengths depending on whether a local strain increase or decrease has been experienced. These typical spectral changes can be seen in Figure 14. Since the reflected intensity at a given wavelength is related to the density of a particular grating period, a localised compressive strain causes an increase in intensity for the new smaller grating spacing and simultaneously a reduction in the maximum reflected.

As the grating perturbations occur at a wavelength directly associated with the physical location of the changes (to within a few mm), modelling can then be used to determine the location of the features causing the strain disruption in the vicinity of the sensor. Hence structural damage such as crack or delamination growth can be tracked by monitoring the movement of the spectral perturbation over time.

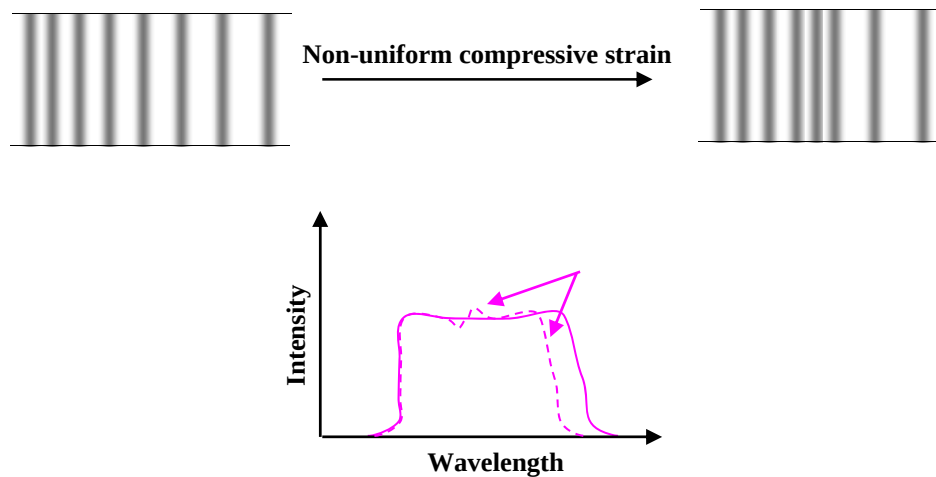


Figure 14: Characteristic CFBG spectra for non-uniform strain distributions (dashed line represents strained response, arrows mark perturbation and edge shift)

4.2.3 Incorporation of FBGs

Since FBGs detect strain changes, an important aspect of their application is deciding where to locate them. For successful damage detection they need to be placed in areas where damage or defect growth can be expected without being so close that the defects induce premature fibre failure.

When the sensors are incorporated into a patch, they are robust and can be applied without additional precautions. However, where bare fibre sensors are being utilised, there are several issues that need to be considered in order to minimise fibre failure and increase reliability. Low tack tape is normally used to hold the fibres straight, flat, suitably oriented and in position whilst laying-up or bonding continues.

Embedding Procedure

Protection of the entry point is essential when embedding fibre optics within a composite. The change of stiffness from bulk composite to single glass fibre at this point makes the fibre susceptible to localised severe bending induced failures. This can be remedied by increasing the flexibility at the exit using polymeric buffer materials. These polymer sleeves can be applied over the whole external length of the fibre, extending a short way into the composite itself, and fixed in place onto the fibre circumference using small amounts of UV curing adhesive. The additional thickness can be accommodated by cutting small sections from several of the immediately adjacent plies. The buffer sleeve also helps to prevent resin flowing out through the loose fitting tube and curing around the fibre making the whole ensemble brittle and inflexible.

Surface Application Procedure

This requires typical surface preparations carried out for any adhesion. The surface must be abraded until smooth, discontinuities or sharp surface profiles would create sharp bends and scratches in the fibre and potentially induce fibre failure. The surface must then be brushed clear of debris and cleaned. The selection of adhesive affects the sensor response. A stiff, brittle adhesive provides good strain transfer but may cause early failure in the presence of damage in the underlying material. A flexible adhesive is more damage resistant, but accommodates some of the strain changes in the primary structure viscoelastically such that less strain may be measured than is actually present. Again, the fibre is weak where it exits the adhesive so a fibre buffer layer partially held within the bonded region helps to protect it. A layer of peel ply (e.g. thin flexible polythene film) is placed over the curing adhesive and sensor assembly, which is removed once cure is complete. This is covered by thick compressible rubber sheet and clamped to control the adhesive thickness and maintain cure pressure and intimate contact between all bonding surfaces.

4.2.4 Examples

Double Cantilever Beam (DCB) Tests

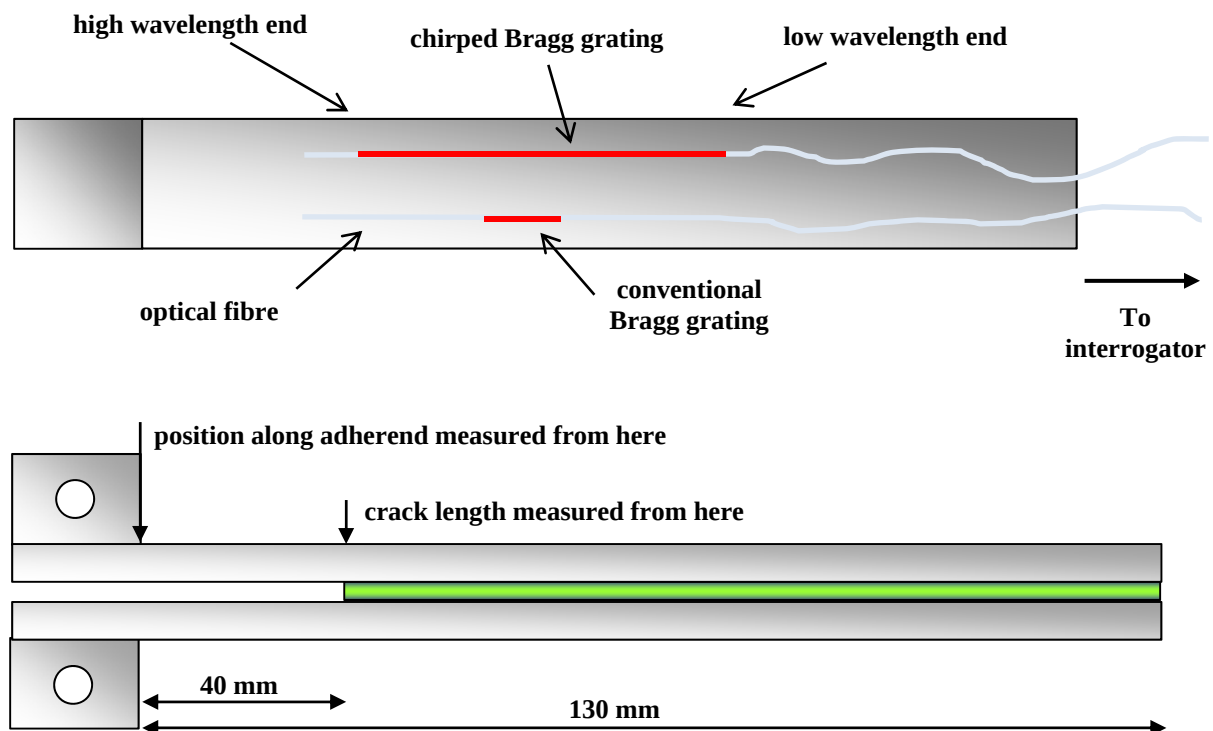


Figure 15: DCB sample sensor set-up (top view - above, side view - below)

Both conventional FBGs and CFBGs have been shown to provide useful information in monitoring mode I DCB composite samples. In both cases, the sensors were bonded onto the top surface of GRP adherends as shown in Figure 15. The CFBG sensors used were uncoated and 60 mm long. The FBG sensors were 5 mm long and polyimide recoated. All sensors were positioned roughly centrally to the bonded length of the sample. The loading blocks were pin loaded in tension using an Instron test machine and the crack lengths were monitored and recorded visually whilst the fibre sensors were interrogated simultaneously using a Smartfibres W4 interrogator. An interesting point to note is that the longer length of the CFBG means the crack growth can be monitored over a distance of 60 mm. In order to achieve the same coverage with the conventional FBGs, which are usually less than 15 mm long several sensors would be required on a single fibre, all at different Bragg wavelengths to facilitate identification.

Typical results from these tests are shown in Figures 16 and 17. For the CFBGs, the high wavelength end of the sensor is put into compression in the cracked region as the adherends bend under loading, resulting in a shift of the high wavelength end to lower wavelengths. The high compressive strain gradients ahead of the crack front reduce the grating spacings in that region to match those of some of the grating spacings in the unstrained region producing a higher intensity plateau reflection. This plateau moves from the high to the low wavelength end of the reflected spectrum as the crack travels along the length of the sample [49]. For the conventional uniform FBGs, there is a steady increase in peak width starting at the point of crack initiation. This peak broadening continues to a maximum when the crack reaches the location of the FBG. This is followed by a sudden decrease in the peak width. The peak splitting and broadening is caused by the curvature in the DCB arm to which the sensor is attached, as shown in Figure 18, and also by changes in the local strain field ahead of the crack front causing a non-uniform strain field in the vicinity of the sensor. The results are complicated by the variability in the geometry of the crack front, and the curvature of the adherends due to fibre bridging and local damage, all of which affect the strain field in the region of the crack tip.

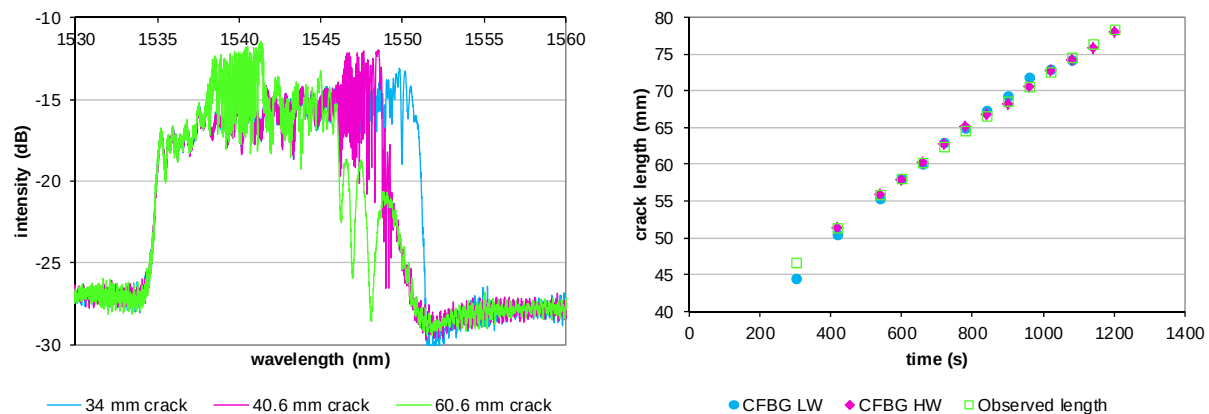


Figure 16: CFBG spectra with increasing crack length (left) and crack lengths determined with spectral features compared to visual observations (right)

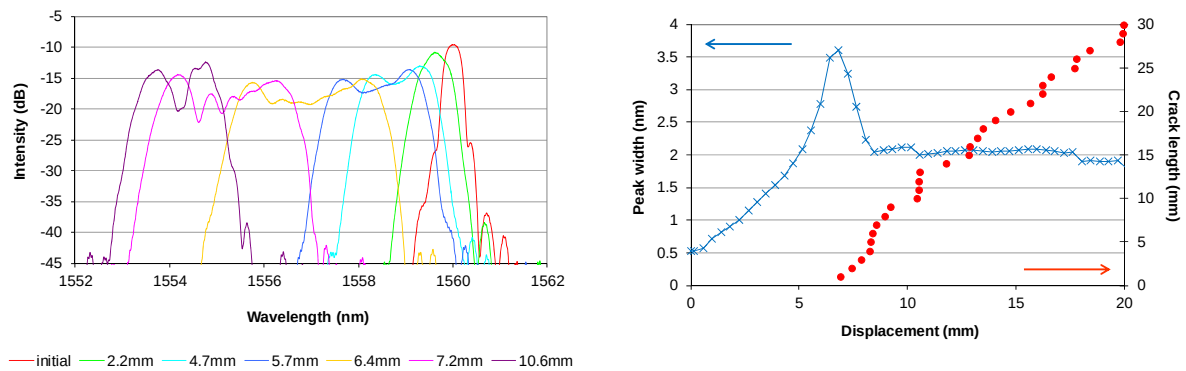


Figure 17: Conventional FBG spectra with increasing crack length (left) and peak width/crack length with adherend separation (right)

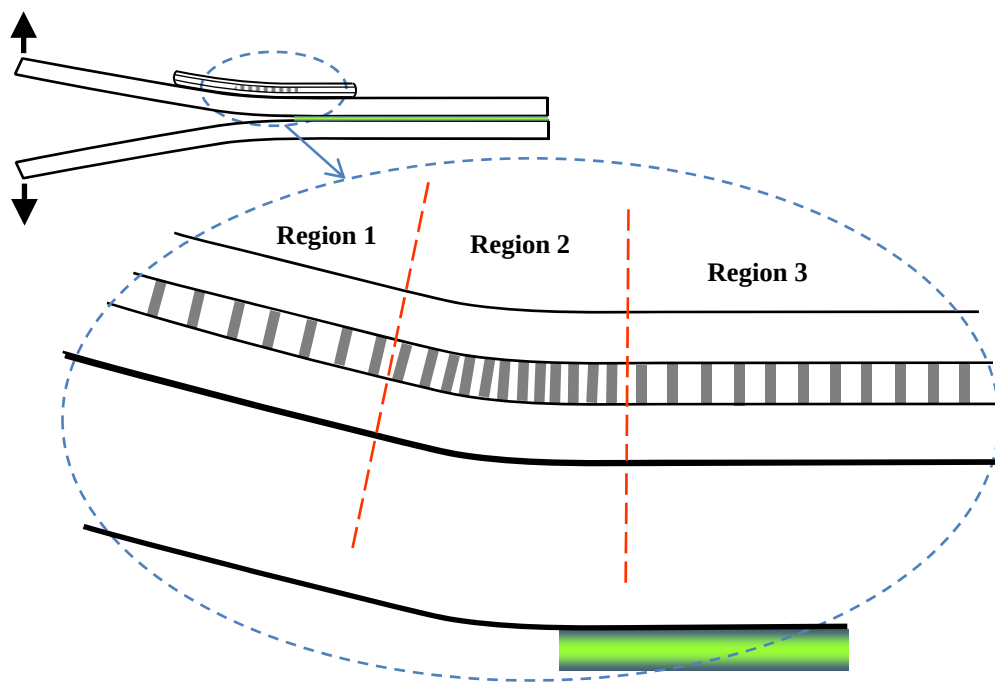


**Figure 18: Changes in grating spacings caused by adherend curvature in DCB tests
Region 1-adherend gently curved leading to slight compression, Region 2-adherend subjected to sharp bend ahead of crack tip giving rise to large compression gradient and Region 3-adherend unstrained.**

Structural Bonded Joint Component

Both FBG and CFBG sensors were trialled to assess fatigue damage development and growth in a simulated structural component. The complex bonded joint is shown schematically in Figure 19. The ultimate tensile strength (UTS) of the component was determined and tests were performed in tension-tension fatigue at 3 Hz, a peak stress of 40% UTS with an R value of 0.1. The sensors were bonded on the top surface close to the regions where damage had been observed in previous tests.

The failure of the component followed a similar pattern each time. The first observation is a crack in the foam core extending from the corner of the scarf joint through the body of the foam to the opposite face. From there a debond grows unevenly with time towards the butt joint on the top surface. Once the butt joint was seen to open significantly at the maximum load of each cycle a debond began to grow from there towards the other delamination until final failure when growth accelerated and both debonds linked together.

Due to the uncoated nature of the CFBGs, these proved too fragile to survive the first loading cycle and fractured as the first damage initiated. Consequently, tests were carried out using pairs of conventional FBGs located at either end of the expected failure zone. These sensors had a grating length of 10 mm and a polyimide coating. These sensors proved sufficiently robust to survive the test up to, and sometimes beyond, failure. Figures 20 and 21 show the spectra captured from two separate tests conducted to failure.

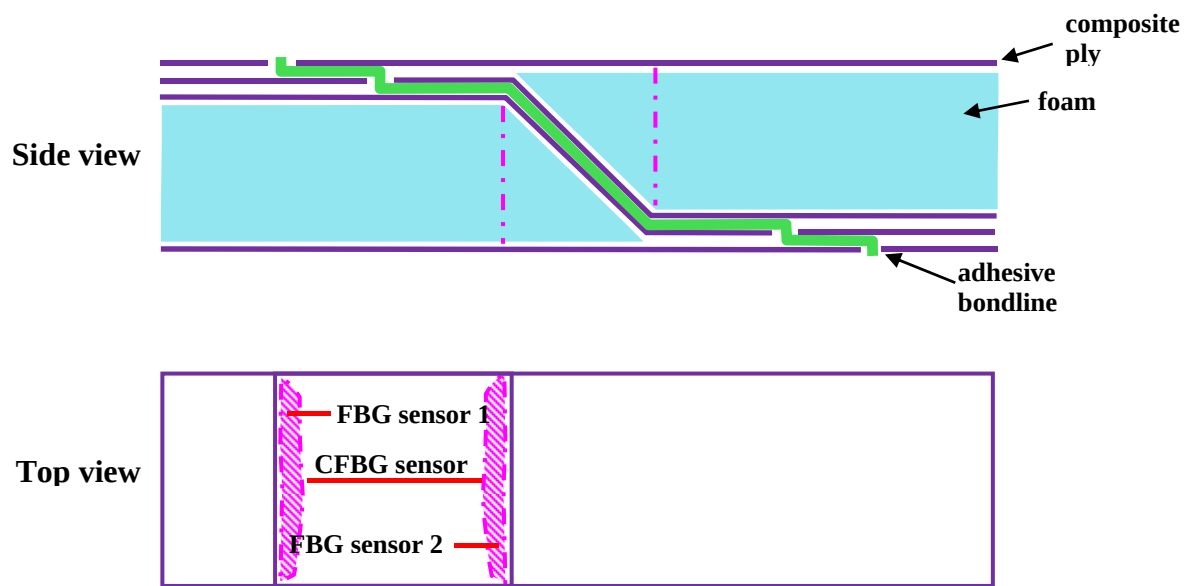


Figure 19: Cross-section of adhesively joined structural component (Dashed lines mark damage expected - cracks and delamination regions)

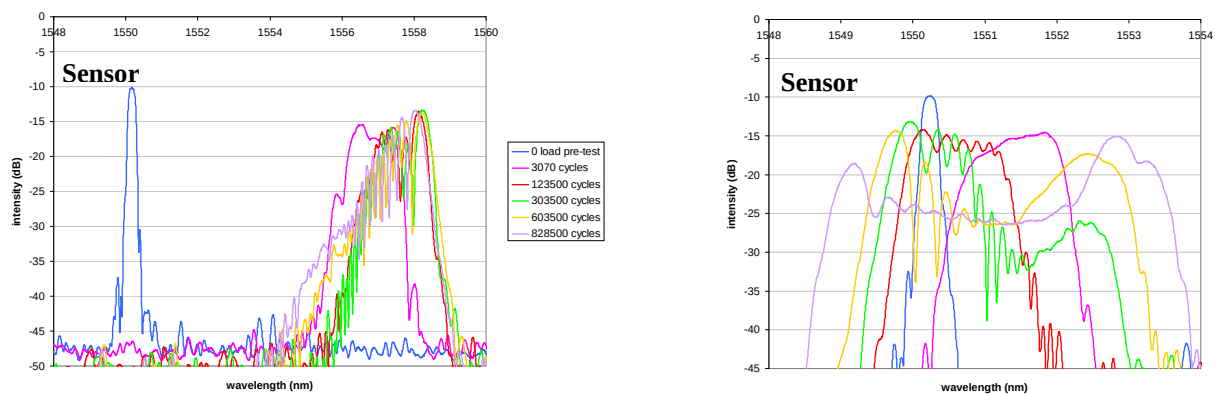


Figure 20: Spectra at 14.4kN after various fatigue cycles

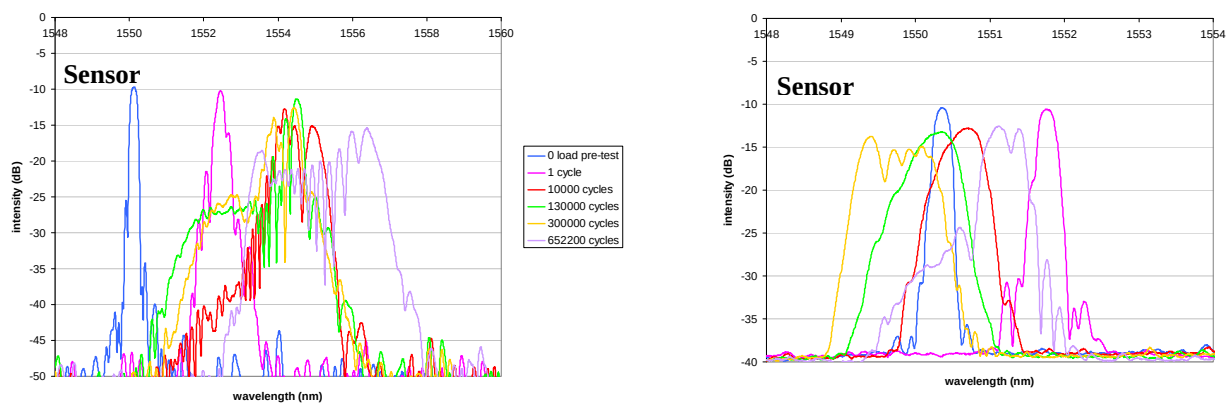


Figure 21: Spectra taken at 7.2kN after various fatigue cycles

Figures 20 and 21 show common characteristics between the conventional FBG spectra from identical sensor locations for two separate component tests, indicating similar damage patterns are generated in each case. Differences can be attributed to variability in the specific location and extent of the damage with increasing load cycles. Sensor 1 always exhibits tensile strain and shows peak broadening even after only one cycle suggesting damage occurs in the vicinity under relatively low loads. This could correspond to an invisible hairline crack at the surface butt joint. Sensor 2 shows peak broadening occurring later with time and at lower levels, and a reduction in tensile strain, in some cases even becoming compressive as cycles and damage levels increase. Due to the complexity of the load path and damage accumulation it is difficult to correlate precisely the spectra observed and the structural features which produce them but it is clear that, in all sensors, peak broadening and splitting increases with cycles indicating the successful detection of continued damage growth in the vicinity of each sensor as fatigue progresses.

Fatigue

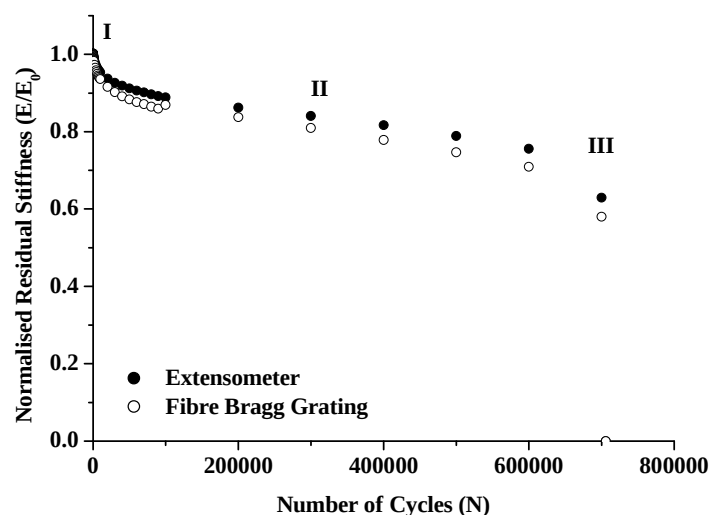


Figure 22: Normalised residual fatigue stiffness for 40% UTS at R = 0.1

The fatigue performance of optical fibres is superior to that of strain gauges. The results obtained using these devices in both static and fatigue loading conditions are comparable with those obtained using contact extensometers. Figure 22 shows the normalised residual fatigue stiffness E/E_0 versus loading cycles N for 40% UTS at stress ratio of $R = 0.1$. E_0 denotes the undamaged (initial tangent) modulus of the notched laminate and E is the secant modulus (measured over the strain limits of 0.0005 and 0.0025), corresponding to the maximum cyclic stress and strain levels, measured at selected intervals in the fatigue life. The FBG stiffness values, as shown in Figure 22, are lower than the corresponding extensometer values. An increase in temperature can be expected to affect the FBG measurements since the peak in the reflected spectrum will be shifted to a higher wavelength, suggesting a higher mechanical strain than the real mechanical strain, thus the apparent reduction in the stiffness will appear to be greater. The disparity in stiffness can be expected to increase with increasing number of cycles (due to increasing heating of the specimen), as observed.

The regions I, II and III shown in Figure 22 denote various stages in the fatigue life. 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.

Note: Calibration and traceability of strain measurements is complicated by the interaction of mechanical and thermally induced strains. The addition of residual strains and cure shrinkage can further complicate data interpretation.

Electrical Sensing

5

IN THIS CHAPTER

- Introduction
- Volume and Surface Resistance
- Electrodes and Contact Resistance
- Electrical Resistance Measurement
- Unidirectional Laminates
- Multidirectional Laminates
- Temperature and Moisture Effects
- Damage Detection

5.1 Introduction

An in-situ structural health monitoring (SHM) system based on intrinsic changes in material properties, such as changes in electrical resistance (or conductance) within a composite structure due to the presence of damage could potentially dispense with the need to attach or embed sensors (e.g. strain gauges or optical fibres) [50-61]. Using electrically conductive fillers, such as carbon fibres and/or dispersed conductive reinforcement in the matrix could enable the realisation of real-time in-situ monitoring of deformation and damage in composite structures. This section provides an overview of electrical sensing and key issues to be considered when implementing the technique.

5.2 Volume and Surface Resistance

The electrical current flow along the length L (metres, m) of a parallelepiped with a cross-sectional area A (square metres, m²) obeys Ohm's law [62]:

$$\rho_v = \frac{E}{J} = R \frac{A}{L} = R \frac{bh}{L} \quad (100)$$

In Equation (100), E is the magnitude of the electrical field (volts per metre, Vm⁻¹) inside the conductor, J is the magnitude of the current density (amperes per square metre, Am⁻²) inside the conductor, R is the electrical resistance (ohms, Ω), ρ_v is the volume or bulk resistivity (ohms metre, Ωm) of the conductive material, and b and h are the width and thickness (metres) of the rectangular section, respectively. Increasing the cross-sectional area of the conductor reduces resistance to current flow, whilst increasing the conductor length reduces the voltage per unit length, thereby increasing resistance to current flow. Volume conductivity σ is the reciprocal of volume resistivity, $1/\rho$ ($\Omega^{-1}\text{m}^{-1}$); reciprocal unit of the ohm (Ω^{-1}) is alternatively called the Siemen (S).

The simplest method of measuring volume resistance is to attach electrodes directly to the ends of the specimen, two point potential method (see Figure 23). The resistance is the ratio of applied DC (direct current) voltage V (volts) to the series current I (amperes), $R = V/I$.

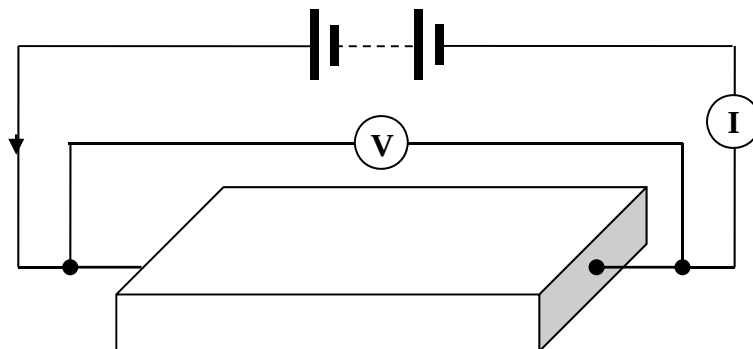


Figure 23: Measurement of volume resistivity using the two point potential method

The main obstacle to achieving accurate measurements is the uncertainty associated with contact resistance R_C (combined effect of the resistance of the electrical leads, the contact resistance between the electrical leads and electrodes, and between the electrodes and the specimen). It is possible to derive the contact resistance by plotting resistance R as a function of specimen length L .

$$R = \frac{\rho}{hL}b + R_C \quad (101)$$

The slope and y-intercept of the linear regression fit of R versus L (see Figure 24) can be used to determine the nominal volume resistivity and contact resistance, respectively. Figure 24 shows a plot of volume resistance as a function of specimen length for UD carbon/epoxy laminate. The resistance of the leads can be measured separately and subtracted from the R_C value obtained.

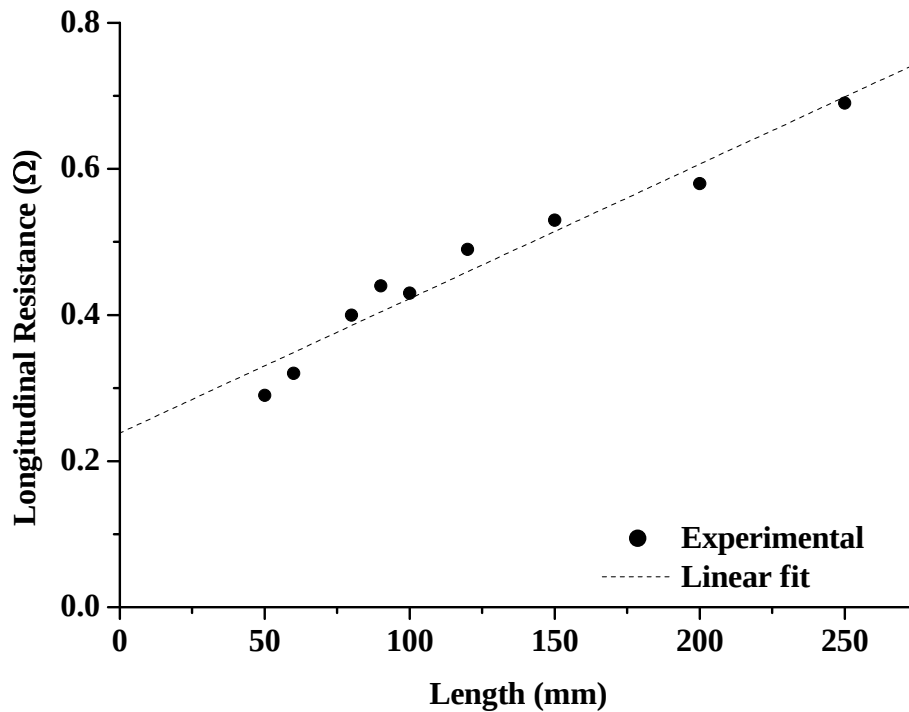


Figure 24: Volume resistance vs. specimen length for UD carbon/epoxy

In the case where the current is confined to a surface, an analogous term to that used for volume resistivity is used to define the surface resistivity ρ_s (Ω) [62]:

$$\rho_s = R_s \frac{b}{L} \quad (102)$$

where R_s is the surface resistance, L is the distance between the mid-points of the inner electrodes and b is the width. The surface resistance is the ratio of the DC voltage V to the current I flowing between the two inner electrodes in contact with the same side of the specimen under test as shown in Figure 25.

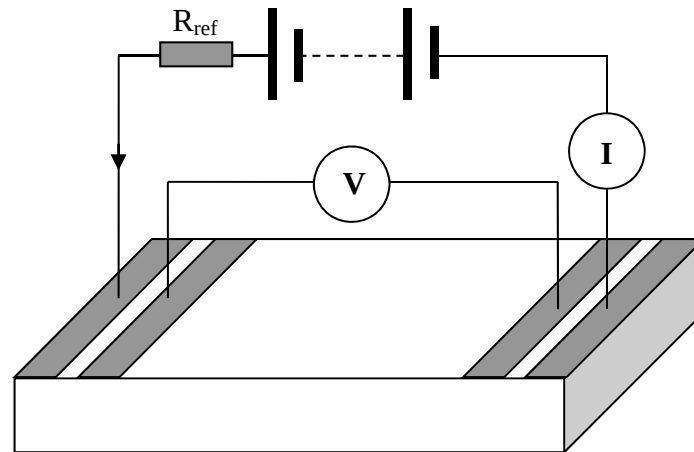


Figure 25: Measurement of surface resistivity using the four point potential method

5.3 Electrodes and Contact Resistance

Surface resistance R_s and surface resistivity ρ_s are often mixed, as both have the physical unit of the ohm. In order to differentiate between the two parameters, surface resistivity is often expressed in Ω/sq (**not** a valid unit from the dimensional analysis perspective). Materials can be divided into three categories: conductors ($\rho < 10^3 \Omega\text{m}$), semi-conductors ($10^3 \leq \rho \leq 10^9 \Omega\text{m}$) and insulators ($\rho > 10^9 \Omega\text{m}$) [62].

Electrodes attached to the composite are most commonly electrically conducting epoxy adhesive (paste) or paint (colloidal suspension of silver particles), or copper strips with pre-soldered wire contact, either embedded during laminate manufacture or glued to the cured laminate using electrically conductive silver epoxy paste. Colloidal graphite (water or alcohol DAG), vacuum-evaporated metal (e.g. gold) and chemical electroplated copper electrodes are also used. Contact resistance for electrically conductive epoxy adhesive is typically $0.2\text{--}0.3 \Omega$ for a nominal contact area of 50 mm^2 . The contact surfaces are lightly abraded (grit blasted) and cleaned with isopropanol prior to application of conductive adhesive or paint. The surfaces where the electrodes are to be located are abraded to remove the superficial insulating surface layer of resin and to expose the conductive carbon fibres. The surrounding area is masked (use masking tape) during the application of conductive adhesives and paints. Although highly effective, conductive adhesives are susceptible to environmental attack (moisture, ultraviolet radiation and erosion) precluding field applications.

Copper deposition by electroplating results in low contact resistance values of a similar order to that observed for conductive adhesives. The surfaces are polished prior to electroplating. A thin layer ($\sim 0.1 \text{ mm}$ thick) is deposited on the exposed fibres by immersing specimens in an electrolytic solution (e.g. copper sulphate solution), whilst a small current is applied to the composite, which is linked to the negative electrode of the electrolytic cell. Electrical connectivity between vacuum-evaporated metal electrodes and the composite is not particularly reliable and there are difficulties obtaining uniform deposition, thereby contributing to a large uncertainty in contact resistance across the electrode surface. The vacuum deposited metal layer is also mechanically fragile; susceptible to damage during adhesively bonding of electrical leads to the electrodes. It is also difficult to ensure good electrical contact between the electrical leads and the electrodes.

Embedding copper electrodes (0.05 mm thick) during laminate lay-up stage is preferable for field applications. For surface resistance measurements, it may be necessary to embed the copper electrodes between the first and second plies from the top and bottom surface rather than attach the electrodes directly to the surface of the laminate. This is to prevent the loss of the electrodes through mechanical handling or environmental exposure, and to optimise electrical connectivity between the electrode and the composite substrate. Any effect of contact resistance needs to be avoided (or at least minimised).

5.4 Electrical Resistance Measurement

Of the two methods for monitoring resistance changes mentioned in Section 5.2, the four point potential (or probe) technique is preferable to the two point potential technique. The four point method eliminates the effect of possible changes in contact resistance at the inner measurement electrodes during the measurement process, such as those from the influence of mechanical strain on the contact [63]. The two point and four point method configurations as shown in Figures 24 and 25 are generally restricted to resistivity below $\sim 10^6 \Omega\text{m}$, otherwise the currents become too small to measure accurately and voltmeter resistances become significant. An alternative approach is to include a reference resistor R_{ref} of known resistance (tolerance $\leq 0.1\%$, thermal stability 10 ppm/ $^{\circ}\text{C}$, or better) in series with the voltage source and the test specimen (i.e. composite), as shown in Figure 25.

The resistance of the composite R_{comp} is determined by the voltage divider relationship:

$$R_{\text{comp}} = R_{\text{ref}} \frac{V_{\text{comp}}}{V_{\text{ref}}} \quad (103)$$

where V_{comp} and V_{ref} are the voltages across the composite and reference, respectively.

The reference resistance should be of similar value to that of the test specimen. Avoid introducing large currents into the specimen due to the possibility of thermal damage to the reference resistor (and to a lesser extent the composite) and errors in measurement due to temperature increase. The supply voltage is increased incrementally (1 volt steps) from 0 to 10 volts and the corresponding voltages across the specimen and reference resistance are measured. Using Equation (103), the resistance values are calculated at each voltage increment and then averaged. It is recommended using a voltmeter with a high input resistance ($> 1 \text{ G}\Omega$); the resistance is calculated using Ohm's law. Measurements must be carried out under controlled environmental conditions.

5.5 Unidirectional Laminates

Electrical conduction of UD CFRP laminates differs from that of metallic materials. Resistivity is highly anisotropic. The longitudinal volume resistivity ρ_{11} of the composite can be determined using the following rule of mixture expression [64]:

$$\frac{1}{\rho_{11}} = \frac{V_f}{\rho_f} + \frac{(1 - V_f)}{\rho_m} \approx \frac{V_f}{\rho_f} \quad (104)$$

where ρ_f is the fibre resistivity, ρ_m is the matrix resistivity and V_f is the fibre volume fraction.

The electrical resistivity is $\sim 2 \times 10^{-5} \Omega\text{m}$ for carbon fibres and in excess of $10^{15} \Omega\text{m}$ for epoxy resin. Copper in comparison has an electrical resistivity of $16.8 \times 10^{-8} \Omega\text{m}$. The transverse resistivity ρ_{22} can be 10^4 times greater than the longitudinal resistivity with values of $200\text{--}300 \times 10^{-3} \Omega\text{m}$. According to Equation (103), the longitudinal resistivity ρ_{11} for UD T300/914 epoxy laminate with a fibre volume fraction of 62% is $2.74 \times 10^{-5} \Omega\text{m}$, which is in reasonable agreement with the measured value of $2.56 \times 10^{-5} \Omega\text{m}$ obtained from the slope presented in Figure 24. The measured contact resistance R_C is $\sim 0.235 \Omega$ (y-intercept).

For an orthotropic material, the electrical resistivity tensor ρ_{ij} for 3-D and 2-D conditions is written as [65]:

$$[\rho_{ij}] = \begin{bmatrix} \rho_{11} & 0 & 0 \\ 0 & \rho_{22} & 0 \\ 0 & 0 & \rho_{66} \end{bmatrix}_{3D} \quad \text{or} \quad [\rho_{ij}] = \begin{bmatrix} \rho_{11} & 0 \\ 0 & \rho_{22} \end{bmatrix}_{2D} \quad (105)$$

where ρ_{11} , ρ_{22} and ρ_{66} are electrical resistivity values in the 1 (longitudinal), 2 (transverse) and 3 (through-thickness) principal material directions.

For off-axis fibre angles, the 2-D resistivity tensor in the x - y plane is represented by [65]:

$$[\rho_{ij}] = \begin{bmatrix} \rho_{11}m^2 + \rho_{22}n^2 & (\rho_{22} - \rho_{11})mn \\ (\rho_{22} - \rho_{11})mn & \rho_{11}n^2 + \rho_{22}m^2 \end{bmatrix} \equiv \begin{bmatrix} \rho_{xx} & \rho_{xy} \\ \rho_{xy} & \rho_{yy} \end{bmatrix} \quad (106)$$

where $m = \cos\theta$ and $n = \sin\theta$ (θ is the distended angle between the 1- and y - axes). Similarly, volume and surface resistances R_{ij} is given by:

$$[R_{ij}] = \begin{bmatrix} R_{11}m^2 + R_{22}n^2 & (R_{22} - R_{11})mn \\ (R_{22} - R_{11})mn & R_{11}n^2 + R_{22}m^2 \end{bmatrix} \equiv \begin{bmatrix} R_{xx} & R_{xy} \\ R_{xy} & R_{yy} \end{bmatrix} \quad (107)$$

The above relationship assumes a single conductive mechanism, independent of fibre-orientation, consisting of a direct electron path along the fibres extending the full length of the specimen. For off-axis fibre orientations, the dominant conductive mechanism is a statistical zigzag path that occurs along the fibre-to-fibre contact (see [65]). The number of electrical paths extending the length of the specimen can also be expected to decrease as the fibre orientation increases from 0° to 90° . Allowing for specimen geometry effects, surface and volume longitudinal resistance of a unidirectional laminated section can be approximated by [65]:

$$R_{xx} = (R_{22} \sin^2 \theta + R_{11} \cos^2 \theta) \left(1 - \frac{\cot \theta}{\lambda} \right); \quad \lambda > \tan \theta \quad (108)$$

where R_{11} and R_{22} are the measured resistance values in the principle material directions 1 and 2, and λ is the specimen length-to-width (or aspect) ratio.

Longitudinal volume and surface resistivity for off-axis fibre orientations can be determined by substituting measured resistance values into Equation (107) and Equation (108) - see Table 2. Measurements of volume and surface resistance were obtained for panels with either a rectangular or circular array of electrodes. The measured and predicted volume and surface resistance values for the rectangular section are generally in reasonable agreement when the specimen aspect ratio λ is taken into account. Lower resistance values observed for the panel containing circular electrodes is not unexpected since the conductive surface is relatively large compared with the small rectangular section and resistance values default to the infinite plate solution given by Equation (106) - see Figure 26.

Table 2: Effect of fibre orientation on resistance of UD CFRP laminates

Angle (deg)	Volume Resistance (Ω)		Surface Resistance (Ω)			
	Rectangular		Rectangular		Circular	
	Measured	Predicted	Measured	Predicted	Measured	Predicted
0	0.06	0.06	0.28	0.28	1.76	1.76
15	14.8	35.0/8.9	2.29	16.7/4.25	5.18	3.57
30	87.8	131/85.5	37.1	61.7/40.3	16.3	8.52
45	221	262/209	132	123/98.5	22.6	15.3
60	429	392/347	167	185/163	27.4	22.0
75	476	488/461	200	230/217	28.0	27.0
90	523	523	246	246	28.8	28.8

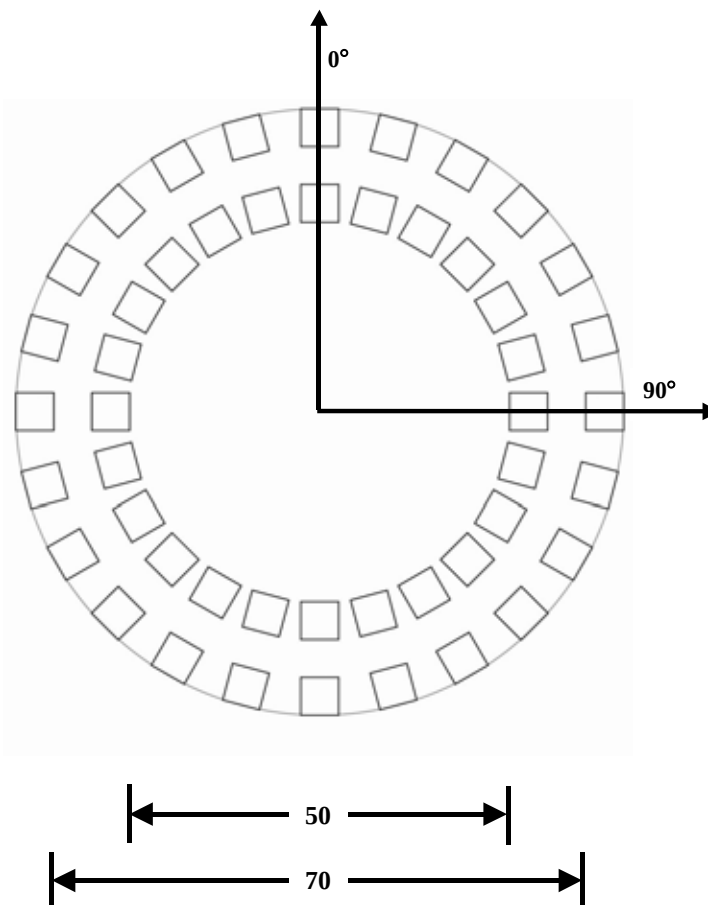


Figure 26: Circular electrode positions used for measuring surface resistance (units: mm)

5.6 Multidirectional laminates

Table 3 compares the volume and surface resistance values for various laminate lay-ups. The results indicate that the resistance values for multidirectional laminates containing a substantial proportion of 45° and 90° plies are relatively low. Resistance measurements presented in Table 3 have not been adjusted for the effects of contact resistance, which can be expected to vary between laminates. The low resistance values observed for the multidirectional laminates can be attributed to either a large contact density between adjacent fibres and/or the presence of 0° plies. It is interesting to note that the [45/-45]_{4s} laminate is far more conductive than a laminate consisting solely of 45° plies (i.e. [45]₁₆). A lattice of 0/90, 45/-45, 45/90 or 0/45 plies will result in high contact density between neighbouring fibres forming a highly conductive electrical plane along the composite.

Table 3: Volume and surface resistance of carbon/epoxy laminates

Lay-up	Volume Resistance	Surface Resistance
	(Ω)	(Ω)
[0] ₁₆	0.29	0.51
[45] ₁₆	221	132
[90] ₁₆	523	246
[45/-45] _{4s}	0.86	1.87
[0 ₂ /90 ₂] _{2s}	2.22	0.53
[0/90] _{4s}	3.38	0.37
[45/0/-45/90] _{2s}	0.68	1.54

5.7 Thermal and Moisture Effects

The volume and surface resistance of electrically conductive composites (e.g. CFRP) are sensitive to changes in temperature (see Table 4). Longitudinal and transverse volume and surface resistances for UD carbon/epoxy decrease approximately linearly with increasing temperature. The negative temperature coefficient observed for the UD laminate can be attributed to an increase in electrical contact between the carbon fibres, which is probably due to drying out of the composite (moisture desorption) and to a lesser degree softening of the matrix rather than thermal expansion. These effects mask any increase in volume due to thermal expansion, which acting alone would cause a reduction in conductivity rather than an increase. Percentage decrease in longitudinal and transverse volume resistance over the test temperature range was 25% and 4%, respectively with a corresponding percentage decrease in surface resistance of 32% and 8%. Transverse resistivity is far more sensitive to changes in temperature. The hypothesis that moisture loss is a major contributing factor is supported by the reduction in resistance following thermal cycling (Table 4). Resistance values in Table 4 have not been corrected for the effect of contact resistance.

It is common practice for testing at non-ambient temperatures to allow a soak period of 10 minutes at the test temperature prior to testing to allow the specimen temperature to equilibrate with the surrounding environment. It is recommended that the surface temperature of the specimen be monitored to determine when the specimen has reached the temperature of the surrounding environment. Testing should be carried out in a temperature-controlled chamber with fan circulation. Specimens need to be electrically insulated from the metal shelf of the environmental chamber.

Table 4: Thermal effects on volume and surface resistance of UD carbon/epoxy

Temperature (°C)	Volume Resistance (Ω)		Surface Resistance (Ω)	
	Longitudinal	Transverse	Longitudinal	Transverse
23 (initial)	0.25	612	0.25	251
23 (1 cycle)	-	-	0.20	232
23 (5 cycles)	0.24	576	-	-
40	0.21	606	0.21	251
60	0.20	604	0.20	251
80	0.19	598	0.19	248
100	0.20	596	0.19	245
120	0.19	588	0.17	232

The electrical leads used for the thermal measurements were far longer than those for ambient measurements, and hence it was necessary to adjust the results to account for lead resistance ($\sim 0.24 \Omega$) enabling direct comparison with ambient results. The reference resistor is kept at room temperature (outside the environmental chamber).

Moisture ingress can also have an effect on the electrical resistivity of FRPs. Surface resistance increases with increasing moisture content and remains elevated after re-drying. Moisture ingress probably causes a reduction in fibre-fibre interactions through matrix swelling, and formation of matrix and interfacial cracks and cavities within the composite. There is also the possibility that water chemically reacts with the functional groups attached to carbon nanotube and fibre surfaces forming a permanent thin film of water similar to that observed for glass fibres; preventing electron flow between fibres.

5.8 Damage Detection and Monitoring

Continuous aligned carbon fibres can be compared to a bunch of conductive wires. The electric current flows either in the longitudinal direction (along the fibre length) or transverse direction (across the fibre) by means of bridging between neighbouring fibres. Fibre breakage, matrix cracking and delaminations in the composite disrupt the electrical paths, thus increasing the electrical resistance of the material. The electrical response of CFRPs is dominated by fibre breakage, and is less sensitive to matrix cracking that occurs at the onset of damage evolution. Surface resistance is sensitive to fibre breakage, whilst through-thickness (volume) resistance is more sensitive to the presence of delaminations [60]. The “piezoresistivity” effect of carbon fibres allows strain sensing under monotonic and cyclic loading conditions [50-53, 61, 63-65].

CNTs can be used to form an electrically conductive network for sensing damage and deformation in-situ, applicable to both CFRP and glass fibre-reinforcement polymer (GFRP) systems [65-70]. As CNTs are extremely small (diameter three orders of magnitude smaller than conventional carbon and glass fibres), it is possible for the nanoparticles to penetrate the matrix-rich regions around the fibres and between plies of composite laminates [71]. A 3-D electrically conductive network is formed when the particle content in the polymer matrix surrounding the particles exceeds the percolation threshold (i.e. sufficient number of contacts between conductive particles to promote electric current flow).

Evidence suggests that levels of 1-5 wt. % of CNTs will result in a transition of the material from an insulator to a conductive media. Percolation threshold is marked by several orders of magnitude reduction in resistivity. The formation of micro-cracks alters the electrical (percolating) network formed by CNTs by breaking conductive pathways, thus increasing electrical resistance. Achieving an electrically conductive network can be difficult, as mixing of CNTs in the polymer matrix is dependent on resin viscosity, which increases with particle loading. There is a tendency for CNTs to agglomerate (entanglement), particularly in the presence of conventional fibres. Particle size, shape, distribution (dispersion) and surface chemistry, polymer chemistry and processing conditions play a crucial role in achieving low percolation thresholds [66-70]. The percolation threshold tends to be higher for thermoplastics compared with thermosetting resins. Chemical functionalization (e.g. amine groups) tends to interfere with electrical conductivity by acting as scattering sites [67].

It is recommended that specialist advice be sought on health and safety requirements from the manufacturer/supplier before using nanofillers, especially CNTs [69]. Since there is uncertainty about the risks of being exposed to CNTs, the regulatory and safe response is to take a precautionary approach. The toxicity of CNTs has not yet been fully investigated. Safety data sheets for CNTs that are based on conventional graphite or graphene will not provide suitable adequate information to assess the risk from CNTs. It is important that an assessment is done for all work involving CNTs and suitable and sufficient risk management measures put in place and that everyone potentially exposed to CNTs receives a high standard of information, instruction and training, particularly on controlling exposure and maintaining that control [72].

5.8.1 Damage location and size

Surface resistance measurements will be different depending on whether damage is introduced to the same surface as the electrodes or to the opposite surface. Surface resistance increases linearly with notch depth when damage is introduced on the same surface as the electrodes (Figure 27).

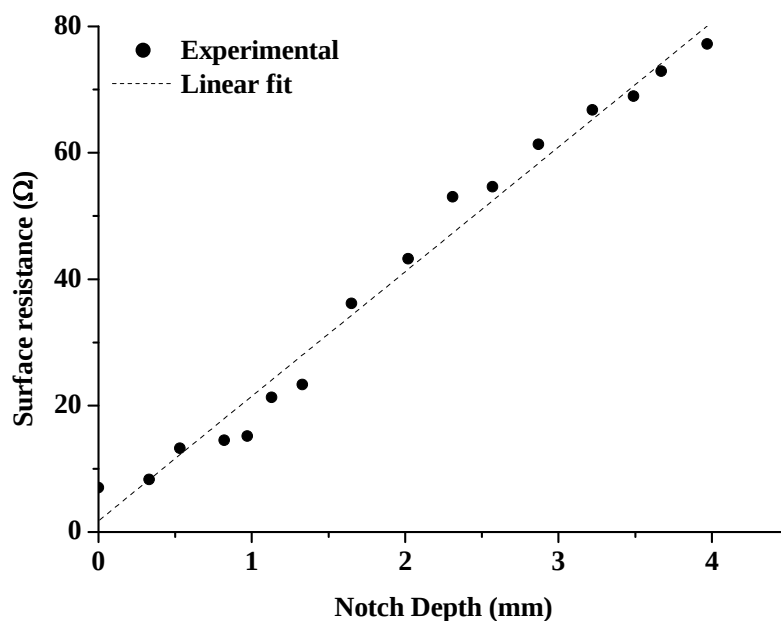


Figure 27: Notch depth vs. surface resistance - notch and electrodes on same surface

In contrast, surface resistance is notch insensitive when the damage is introduced on the opposite surface to the electrodes until the notch penetrates the top layers of the opposite surface where there is a dramatic increase in surface resistance (Figure 28). The results indicate that the current is mainly confined to a few surface layers $\sim 0.2\text{--}0.3$ mm thick (i.e. current density is largest near the surface of the conductor); analogous to the skin effect observed for alternating electrical current (AC). The reason is that the through-thickness resistivity is far higher than the in-plane longitudinal resistivity, and hence the surface current is mainly restricted to the surface layers.

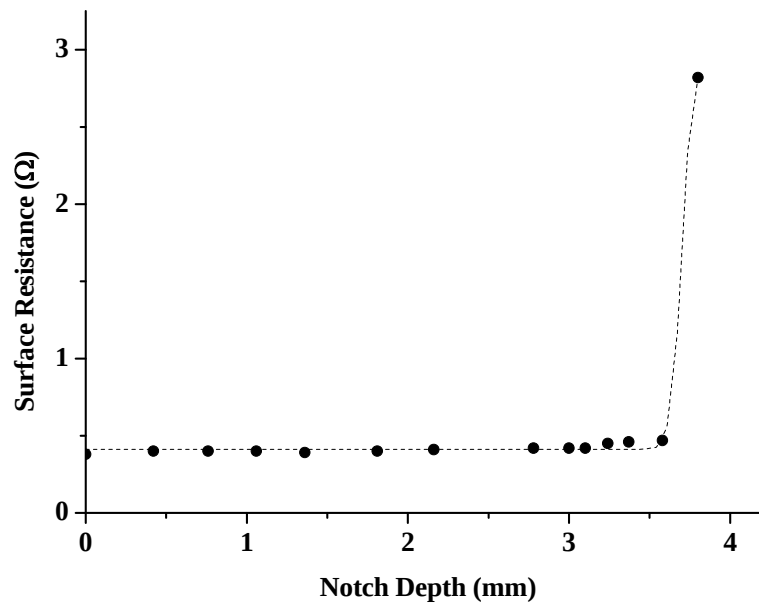


Figure 28: Notch depth vs. surface resistance - notch and electrodes on opposite faces

Location of electrodes is critical to the detection and sizing of damage in composite laminates. Figure 29 presents the surface resistance values measured on a quasi-isotropic (QI) $[45/0/-45/90]_{2s}$ carbon/epoxy panel (120 mm x 120 mm) with a thickness of 2 mm. The circular electrode configuration is identical to that shown in Figure 26. The electrodes (5 mm x 5 mm) were spaced at 15° intervals around the central axis with the distance between inner electrodes and outer electrodes being 50 mm and 70 mm, respectively. Surface resistance measurements were conducted on diametrically opposed electrodes before and after the introduction of a centrally located circular hole of 12.5 mm, which was enlarged to 25 mm diameter and further measurements conducted. The holes were produced using water-lubricated diamond tooth hole-drills.

Figure 29 indicates that the surface resistance is sensitive to the fibre orientation of the surface ply with maximum response at $+45^\circ$ (i.e. parallel to the surface fibres). Sensitivity decreases sharply either side of this orientation with a number of electrode sites around the circle circumference being entirely insensitive to the presence of a hole. Surface resistance increases by $\sim 38\%$ at $+45^\circ$ on introducing the 12.5 mm diameter hole. Increasing the diameter of the hole from 12.5 mm to 25 mm, however, only results in a small change in resistance even at $+45^\circ$ ($\sim 0.07\%$).

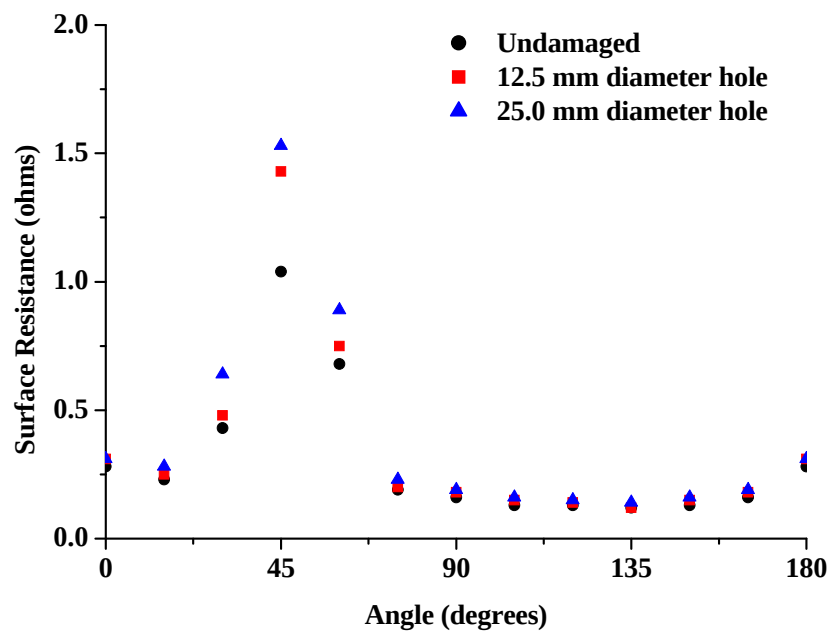


Figure 29: Surface resistance vs. electrode orientation for QI CFRP laminate

5.8.2 GFRP laminates

Damage assessment of GFRP laminates is possible by the inclusion of either conductive nanofillers (e.g. CNTs or nanographene platelets) introduced during processing or coating the surfaces of the cured laminate with a conductive film (e.g. CNT/epoxy).



Figure 30: Unidirectional GFRP tensile specimen with a CNT/epoxy coating

Conductive coatings: The use of CNT/epoxy coatings can provide favourable results, especially as a retrofit option, although the costs associated with coating specimens are high. A conductive coating, such as CNT/epoxy could potentially be used to monitor deformation and damage (including crack growth) in engineering structures. Concerns exist as to quality control (thickness and surface finish) and method of application. A room temperature curing system would eliminate the problem of residual stresses (strains) due to thermal expansion mismatch between the coating and composite substrate.

Work is still required to ensure uniform dispersion of filler within the polymer resin and to reduce viscosity of the coating to enable easy spreading and wetting of the surface. A suitable surface treatment, such as plasma treatment will also be necessary to promote adhesion between the coating and the composite substrate. Coatings can detach prior to failure as indicated by the momentary decrease in the stress-strain response shown in Figure 31. The use of mechanical abrasion (e.g. grit blasting) would be ill advised for GFRP laminates as glass fibres are sensitive to surface damage, resulting in reduced strength and lower environmental resistance. A conductive film that can be co-cured with the laminate may also be worth considering.

Tensile tests conducted on coated UD E-glass/epoxy specimens display linear stress-strain response to failure (see Figure 31). The applied load versus the percentage change in surface resistance ΔR , normalised by the initial composite resistance R_0 is approximately linear. The change in resistance $\Delta R/R_0$ can be related to the strain at failure by:

$$\frac{\Delta R}{R_0} \approx K\varepsilon \quad (109)$$

where K is the gauge factor.

Note: Checks should be carried out to ensure that clamping of the specimens induced minimal changes in surface resistance measurements; grip misalignment can result in bending and twisting loads acting on the specimens.

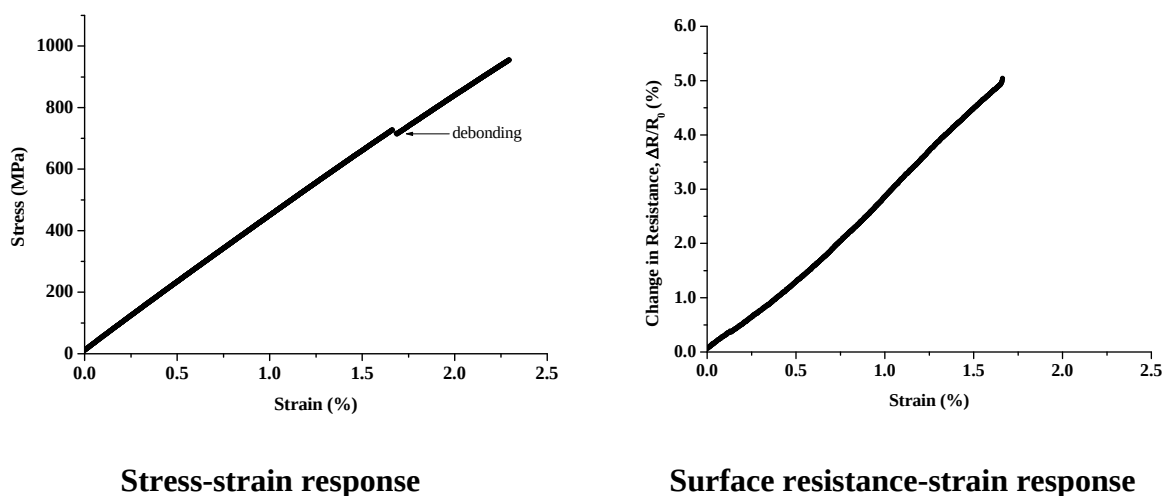


Figure 31: Tensile response of UD GFRP with CNT/epoxy coating

Laminates with embedded CNTs: It is potentially feasible to monitor strain and damage in GFRP laminates containing conductive fillers, such as CNTs. Laminates with higher CNT concentrations tend to have lower surface and volume resistance. It is possible to monitor changes in surface and volume resistance as a function of applied load for even poorly conductive systems. By customising the formulations it may be possible to achieve more prominent and reliable resistance changes through higher and more uniformly dispersed CNT concentrations. The key advantage compared with the surface coating approach is in elimination of the coating detachment issue. Surface and volume resistance values can be highly variable with variability being far higher for laminates with lower CNT concentrations. Figure 32 presents typical surface and volume resistance-strain responses for UD GFRP laminates with interspersed MWCNTs in tension.

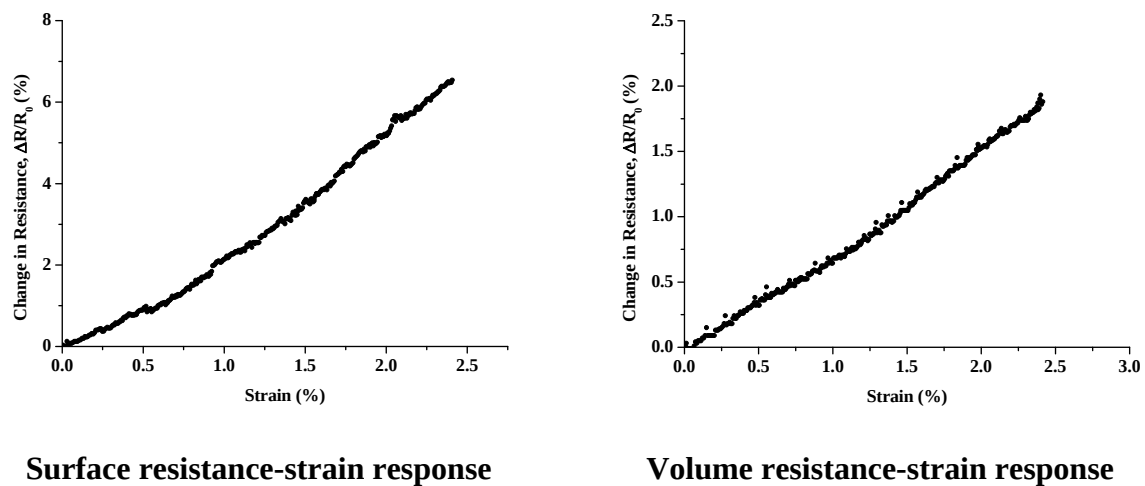


Figure 32: Tensile response of UD GFRP with embedded CNTs

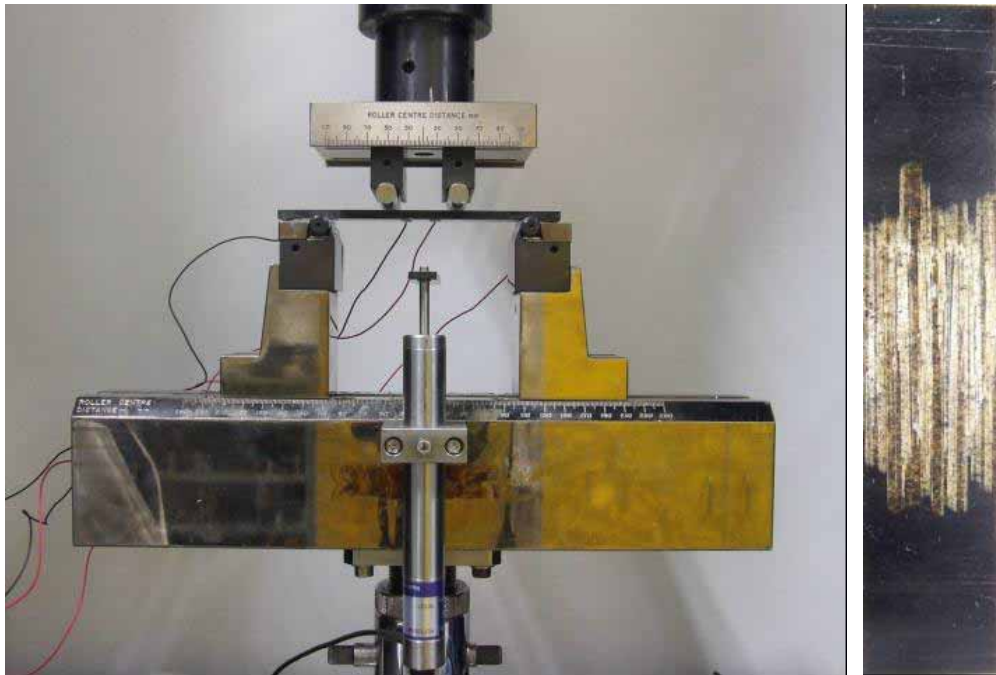


Figure 33: Four point flexure test of UD GFRP with embedded CNTs

The changes in surface resistance in flexure (see Figure 33) are very high (60-70 %) and highly non-linear (Figure 34) in comparison with tensile tests conducted on UD GFRP. In contrast, volume resistance remains constant with applied load (i.e. insensitive to the presence of damage that mainly occurs on the tensile face of the specimen). The lack of response may possibly be due to the effects of positive strain in the tensile side countering the effects of negative strain in the compressive side. Extensive longitudinal splitting occurs on the tensile face (see Figure 33). Localised compressive/shear through-thickness cracking and buckling sometimes occurs near the loading rollers on the compressive face. Electrodes need to be electrically isolated from the metal loading rollers by electrical insulation tape.

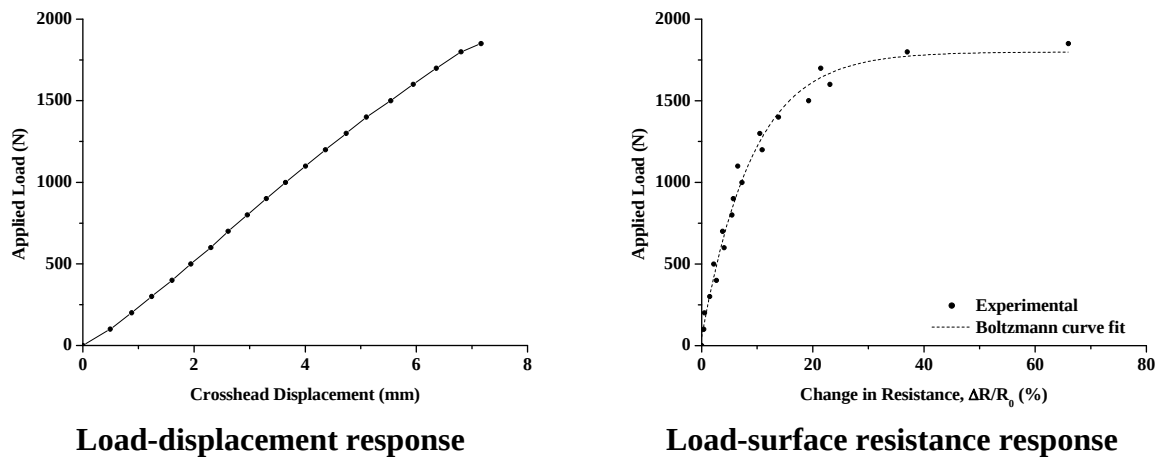


Figure 34: Four point flexure response of UD GFRP with embedded CNTs

5.8.3 CFRP laminates

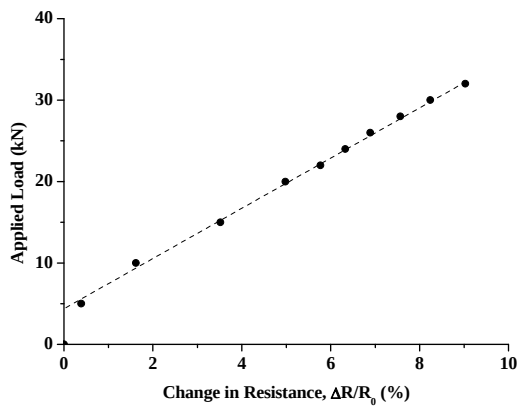


Figure 35: Four point method for measuring surface resistance of CFRP in tension

Surface resistance is dependent on geometric factors, such as specimen width and thickness, laminate lay-up and loading mode. Changes in surface resistance of CFRP laminates under tensile loading (see Figure 35) are relatively small, as shown in Table 5, and Figures 36 and 37. The presence of a 6 mm diameter hole has minimal effect on the initial surface resistance (and the initial modulus) of the open-hole tension (OHT) specimen.

Table 5: Surface resistance of CFRP laminates

Laminate	Surface Resistance (Ω)	
	Initial	Final
<u>T300/913</u>		
$[0]_8$	0.60 - 0.65	0.69 - 0.82
$[45/0/-45/90]_{4s}$ OHT	0.84 - 0.88	0.90 - 0.95
<u>T300/914</u>		
$[0/90]_{4s}$	0.47 - 0.48	0.62
$[45/-45]_{4s}$	0.73 - 0.74	1.09 - 1.22
$[45/0/-45/90]_{2s}$	0.84 - 0.88	0.91 - 0.95



Unidirectional

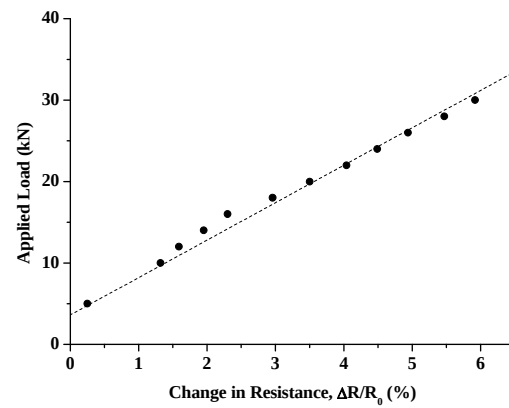
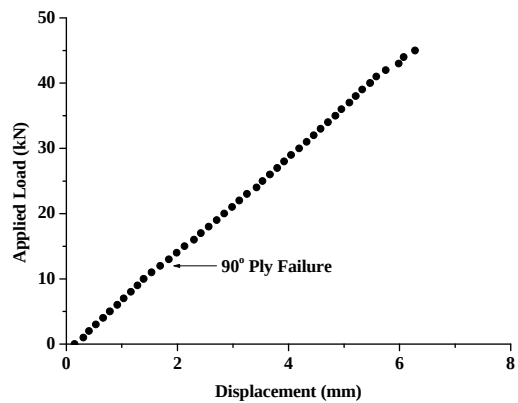
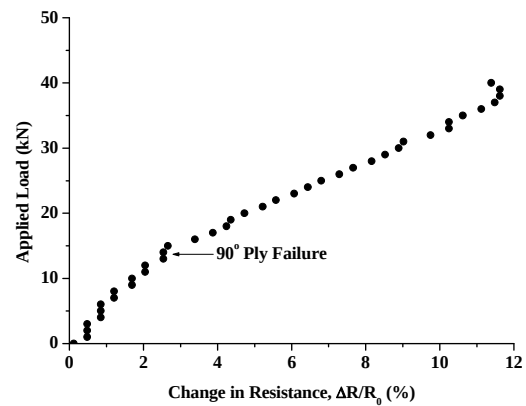
Quasi-isotropic $[45/0/-45/90]_{2s}$

Figure 36: Load vs. surface resistance of CFRP laminates in tension



Load-displacement response



Load-surface resistance response

Figure 37: Mechanical and electrical response of $[0/90]_{4s}$ CFRP laminate in tension

It is important that GFRP end tabs are used in all cases to electrically isolate the CFRP specimens from the metal grips. When conducted volume resistance measurements ensure that the electrodes attached to the specimen ends are electrically isolated, suggest using electrical insulation tape. End regions should also be masked using electrical insulation tape. Surface resistance is far more sensitive to ply failure events than displacement or strain as shown in Figure 37. The resistance increases by a factor of ~ 2 for the $[0/90]_{4s}$ cross-ply laminate following 90° ply failure, and consequently the gradient of the curve decreases by a similar amount.

Monitoring volume resistance of CFRP laminates is not as straightforward as that for GFRP laminates with either a conductive coating or containing electro-conductive filler. The tensile response of CFRP laminates can exhibit both positive and negative piezoresistivity during tension loading, which makes it difficult to detect and relate specific failure events to changes in volume resistance. Positive piezoresistivity refers to the behaviour in which the resistivity increases with increasing strain, and is commonly observed in longitudinal tension. Negative piezoresistivity refers to the behaviour in which the resistivity decreases with increasing strain. The latter can result from Poisson's effect (through-thickness contraction) forcing adjacent fibres closer together, thus increasing electrical conductivity or through damage producing increased conductive pathways. It is recommended that the ends of the specimen are polished to remove any resin present at the ends and to expose the fibres before applying electrodes (e.g. electrically conductive epoxy adhesive).

Surface and volume resistance of CFRP laminates in flexure tend to be insensitive to the presence of damage, remaining fairly constant throughout the duration of the flexure tests only to increase rapidly when the specimen fails.

5.8.4 Impact damage

Electrodes located around the perimeter of a structure, such as that shown in Figure 38 can be used to detect the presence of impact damage (see also Section 5.3). Tables 6 to 8 show surface and volume resistance measurements obtained at five locations (1&5, 6&16, 7&15, 8&14 and 9&13) across quasi-isotropic CFRP laminates before and after impact for three different impact energies, using either copper or silver paste electrodes. More detailed analysis can be obtained by measuring the resistance for other electrode combinations. Ultrasonic C-scan images and visual inspection revealed extensive impact damage had occurred in all laminates with severe delaminations and fibre splitting (see Figure 38). The impactor had penetrated through the laminates to the back surface in all cases with the size of damage increasing with impact energy.

Although extensive, impact damage has only a “small” effect on the surface and volume resistance values (see Tables 6 to 8). The tendency is for resistance to increase with the formation of damage, however small decreases were also recorded. These may be due to measurement errors or the possibility that localised crushing and fibre fragmentation is providing additional conductive pathways. The larger damage present on the back surface results in larger differences between the undamaged and damaged states compared with the front face. Volume resistance is higher for the copper electrodes due to the larger contact resistance between the composite substrate and the copper electrodes (Table 6). Volume resistance is $\sim 3 \Omega$ for copper electrodes compared with $\sim 0.4 \Omega$ for the electrically conductive epoxy paste. It may be argued that the electrodes in both cases are not exclusively measuring volume resistance nor are the electrodes sampling the same electrical network.

For embedded copper electrodes, current is mainly restricted to the material between the electrodes, whereas the electrodes produced using electrical conductive paste probably include edge effects. The surface resistance between the copper electrodes on the front and back faces was extremely high ($> 10 \text{ M}\Omega$) due to the presence of a resin rich layer beneath electrodes, thus preventing electrical current flow. Compaction during lamination was sufficient to force the embedded electrodes (volume measurements) to be in close contact with the carbon fibres.

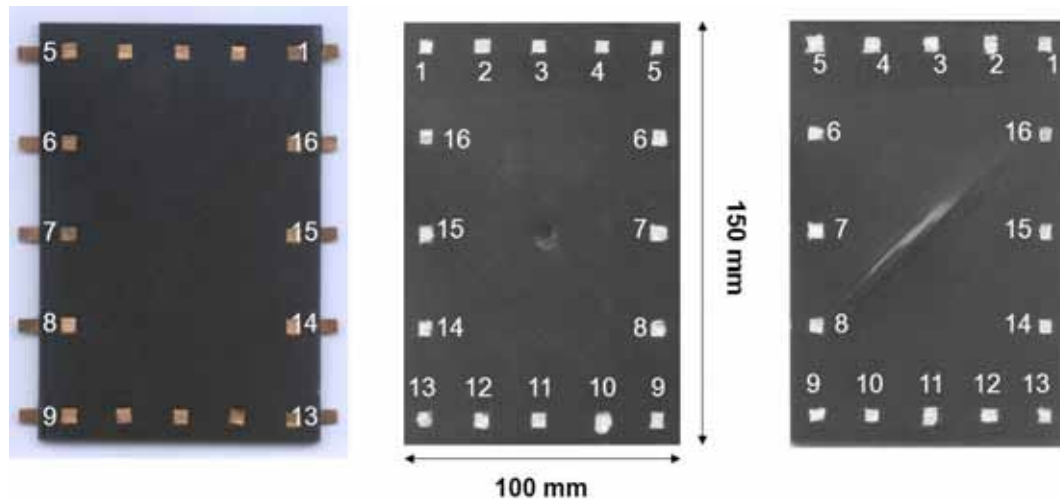


Figure 38: Impact specimens showing location and numbering of electrodes (undamaged laminate with copper electrodes (left); impact damaged laminate top face (middle) and bottom face (right) with electrically conductive epoxy electrodes)

Table 6: Volume resistance (Ω) of impacted QI CFRP - copper electrodes

Electrode Pairs	Impact Energy		
	29.00 J	36.25 J	43.50J
<u>1-5</u>			
Undamaged	3.76	2.42	2.07
Damaged	3.82	2.39	2.09
<u>6-16</u>			
Undamaged	6.03	2.38	4.47
Damaged	5.87	2.27	4.28
<u>7-15</u>			
Undamaged	2.40	2.52	2.49
Damaged	2.25	2.25	2.22
<u>8-14</u>			
Undamaged	2.82	3.38	2.52
Damaged	2.70	3.24	2.35
<u>9-13</u>			
Undamaged	2.63	2.60	1.88
Damaged	2.77	2.54	1.89
<u>Average</u>			
Undamaged	3.53 ± 1.33	2.66 ± 0.37	2.69 ± 0.92
Damaged	3.48 ± 1.46	2.54 ± 0.41	2.57 ± 0.97

Table 7: Volume resistance (Ω) of impacted QI CFRP – silver paste electrodes

Electrode Pairs	Impact Energy		
	29.00 J	36.25 J	43.50J
<u>1-5</u>			
Undamaged	0.39	0.45	0.41
Damaged	0.40	0.46	0.41
<u>6-16</u>			
Undamaged	0.38	0.50	0.41
Damaged	0.34	0.51	0.54
<u>7-15</u>			
Undamaged	0.39	0.39	0.40
Damaged	0.42	0.46	0.35
<u>8-14</u>			
Undamaged	0.41	0.41	0.40
Damaged	0.55	0.41	0.38
<u>9-13</u>			
Undamaged	0.48	0.52	0.53
Damaged	0.61	0.52	0.59
<u>Average</u>			
Undamaged	0.41 $\pm$ 0.04	0.45 $\pm$ 0.05	0.43 $\pm$ 0.06
Damaged	0.47 $\pm$ 0.11	0.47 $\pm$ 0.04	0.47 $\pm$ 0.10

Table 8: Surface resistance (Ω) of impacted QI CFRP – silver paste electrodes

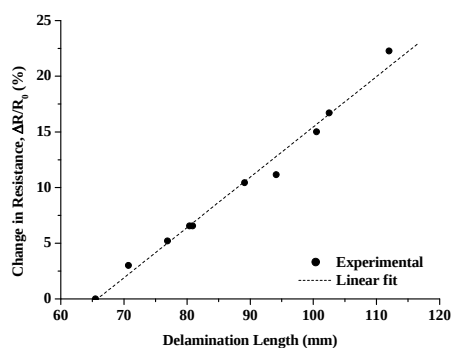
Electrode Pairs	Impact Energy		
	29.00 J	36.25 J	43.50J
<u>1-5</u>	Front/Back	Front/Back	Front/Back
Undamaged	7.55/5.76	6.01/5.83	4.13/3.87
Damaged	7.49/5.77	6.02/5.78	4.23/3.94
<u>6-16</u>			
Undamaged	5.08/3.11	5.10/4.51	4.48/3.44
Damaged	5.19/3.13	5.22/4.71	4.51/4.51
<u>7-15</u>			
Undamaged	4.39/3.74	3.64/3.74	3.27/3.14
Damaged	4.37/3.76	3.69/3.83	3.28/3.22
<u>8-14</u>			
Undamaged	4.46/6.84	4.08/4.05	3.34/3.54
Damaged	4.43/6.37	4.04/4.31	3.27/4.32
<u>9-13</u>			
Undamaged	6.76/5.94	5.03/5.85	4.64/4.84
Damaged	6.75/5.91	5.10/5.79	4.72/5.51
<u>Average</u>			
Undamaged	5.65 $\pm$ 1.28/5.08 $\pm$ 1.41	4.77 $\pm$ 0.83/4.79 $\pm$ 0.99	3.97 $\pm$ 0.57/3.76 $\pm$ 0.59
Damaged	5.64 $\pm$ 1.41/4.99 $\pm$ 1.09	4.81 $\pm$ 0.94/4.89 $\pm$ 0.88	4.00 $\pm$ 0.68/4.30 $\pm$ 0.84

5.8.5 Delamination growth

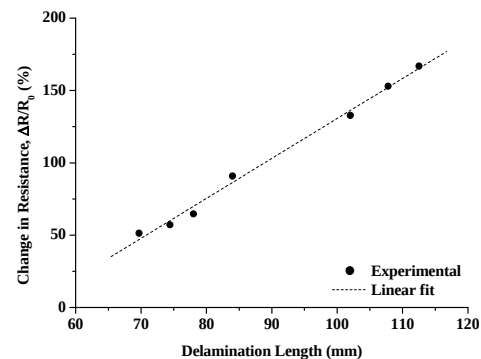
It is possible to accurately monitor delamination (crack) growth in electrically conductive composites. Electrodes can be applied to the top and bottom surfaces of a composite structure or along the composite edges. Figure 39 shows mode I test conducted on a double cantilever beam (DCB) specimen manufactured from UD GFRP with a CNT/epoxy coating. Linear relationships exist between surface resistance and delamination length for both crack opening and crack closure (i.e. zero load state) with resistance being lower on crack closure (increase in electrical contact between surfaces) – see Figure 40.



Figure 39: Mode I test of UD GFRP DCB specimen with a CNT/epoxy coating (Electrodes attached to specimen edges)



CFRP



GFRP with CNT/epoxy coating

Figure 40: Resistance vs. delamination length for UD CFRP and GFRP laminates

Optical measurements should be carried out simultaneously with the electrical measurements in order to calibrate the latter. The associated uncertainties with electrical measurements as a function of delamination length are large, and therefore care is needed to ensure accurate electrical measurements. Crack fronts tend to be curved and difficult to locate due to extensive whitening occurring ahead of the crack tip due to plastic deformation. Fibre bridging can affect electrical resistance measurements particularly if fibre bridging is extensive (see Figure 41). DCB tests conducted on CFRP specimens with electrodes attached either to the ends of the specimen or attached to the top and bottom faces of the specimen produce similar responses to that observed for the electrodes attached to the specimen edge. The resistance-delamination length plots are approximately linear in both cases. The percentage change in volume resistance with delamination length tends to be approximately twice that observed for surface resistance measured using either electrodes attached to the specimen edge or specimen faces.



Figure 41: Optical image of mode I crack with extensive fibre bridging

NDE Methods

6

IN THIS CHAPTER

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

6.1 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 [27, 73]. 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.

6.2 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 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).

6.3 Ultrasonic and Acoustic Techniques

Acoustic and ultrasonic techniques are frequently used for detecting, measuring and characterising 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.

6.3.1 Acoustic emission

Acoustic emission (AE) is the transient elastic (stress) waves within a material caused by the release of elastic energy through deformation or fracture. AE may arise from friction (including bearing wear), micro-crack formation, delamination growth and material changes such as corrosion. AE testing involves the detection of transient elastic waves in the radio frequency range of 1 kHz to 100 MHz propagating through the material. Microscopic events can be detected if sufficient energy is released. Source location is also possible using multiple sensors attached to the surface or embedded within a structure. AE sensors convert minute mechanical movements into electrical signals, which are analysed using computer based instrumentation. AE can be used to monitor the "state of health" of a structure. The technique relies on the operator having sufficient experience to be able to identify particular defect types from the AE data.

6.3.2 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. Viscoelastic 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 [74-77].

A large range of ultrasonic transducers are 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 [78]:

- 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 42).

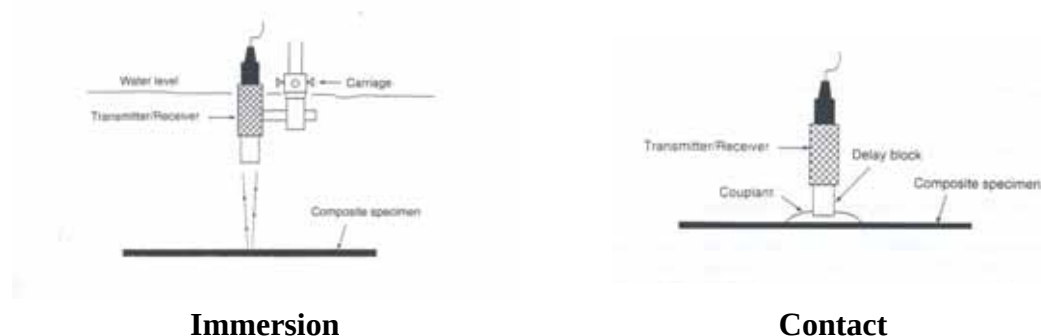


Figure 42: Pulse-echo method

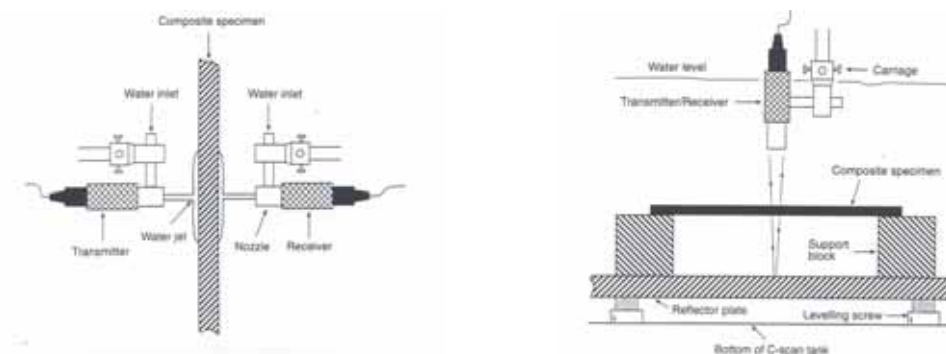
In some circumstances exposure to water may be detrimental to the product (e.g. water absorption). Water may also enter the structure (e.g. honeycomb structures) and act as a block to ultrasonic signals, thus inhibiting the detection of flaws. One solution is to employ a contact probe. For the contact mode, water is replaced by gel, oil or grease couplant. It should be noted that considerable pressure is required 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 43). 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) and honeycomb structures. It is also applicable to thick composite sections where the occurrence of multiple reflections due to the presence of numerous interfaces, often prevents 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.



Single

Double

Figure 43: 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 43). 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.

6.4 X-radiography

X-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 volume 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 44 shows typical X-radiograph images obtained for CFRP open-hole compression (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 integration time of 300 ms.

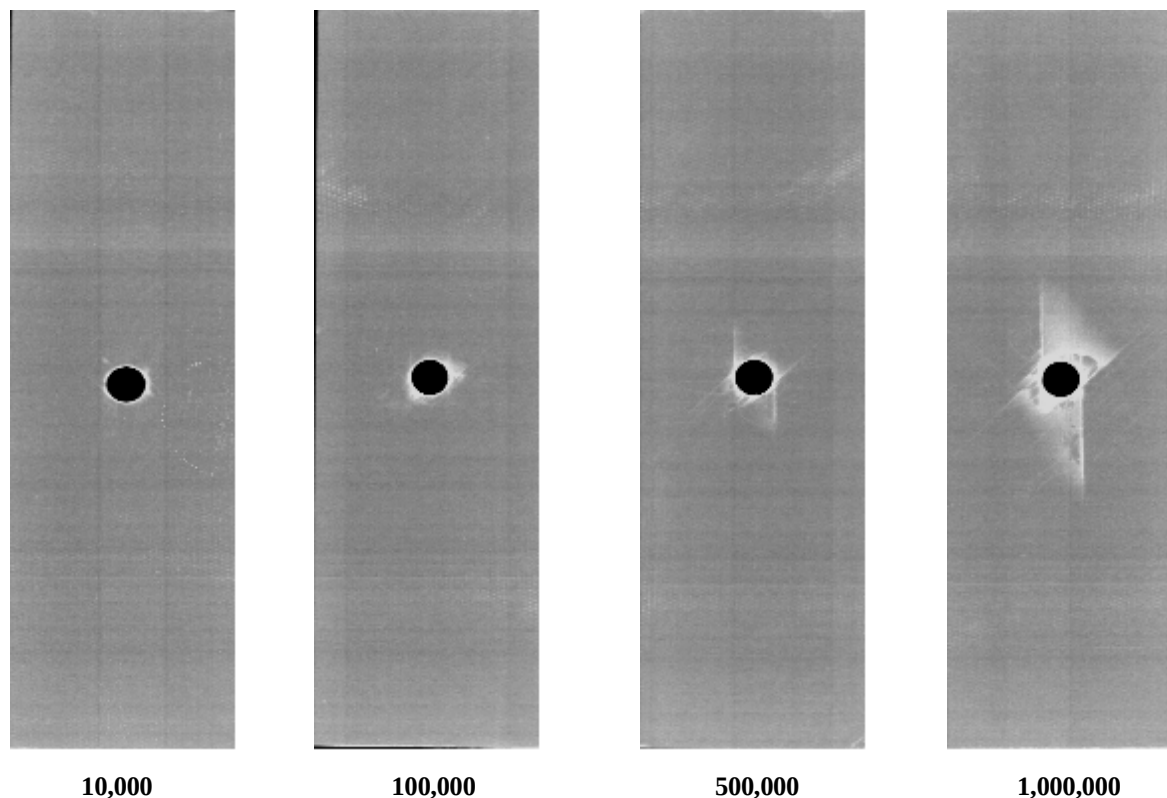


Figure 44: X-radiography images of CFRP OHC specimens

6.5 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 45. 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.

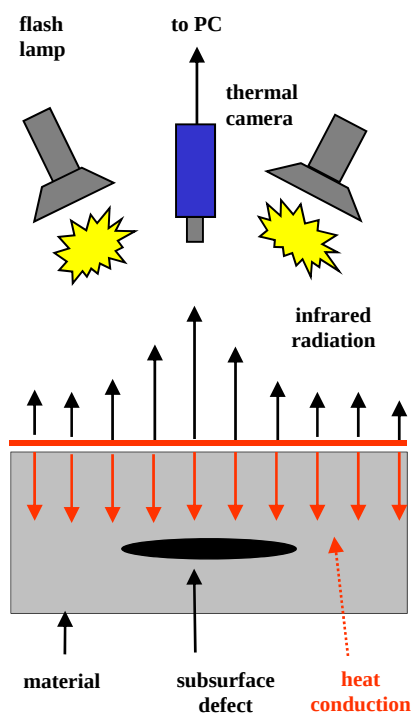


Figure 45: Principle of pulse thermography for damage monitoring

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 46 show typical results obtained using pulse thermography for fatigued GFRP OHT specimens.

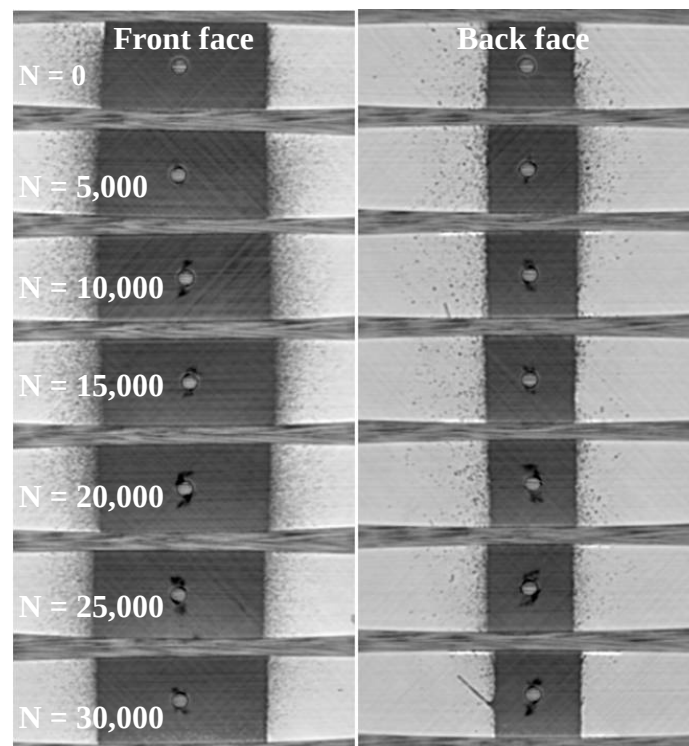


Figure 46: Pulse thermography images showing fatigue damage in OHT specimens

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.

6.6 Impact Excitation

The impact excitation method (see Figure 47), described in greater detail in NPL Measurement Good Practice Guide No 101 [29], is a technique that can be used to measure the elastic properties of materials by exciting different of modes of vibration (i.e. out-of-plane flexural, in-plane flexural, torsional and longitudinal).

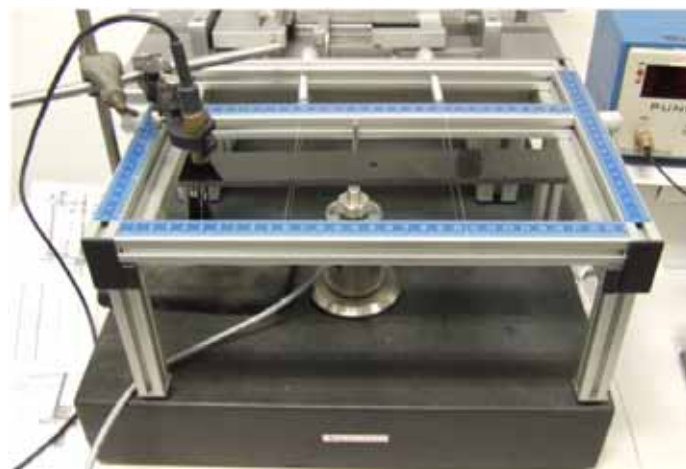


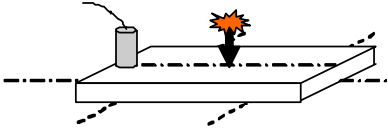
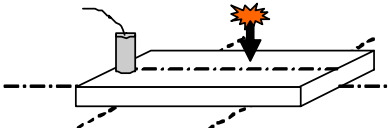
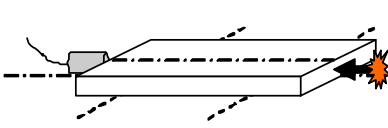
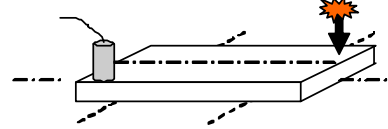
Figure 47: Impact excitation equipment with OHT specimen supported on wires

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 47 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 9. 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 9: 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 48 shows elastic moduli for CFRP OHT specimens that have been subjected to tension-tension fatigue (stress ratio $R = 0.1$ 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.

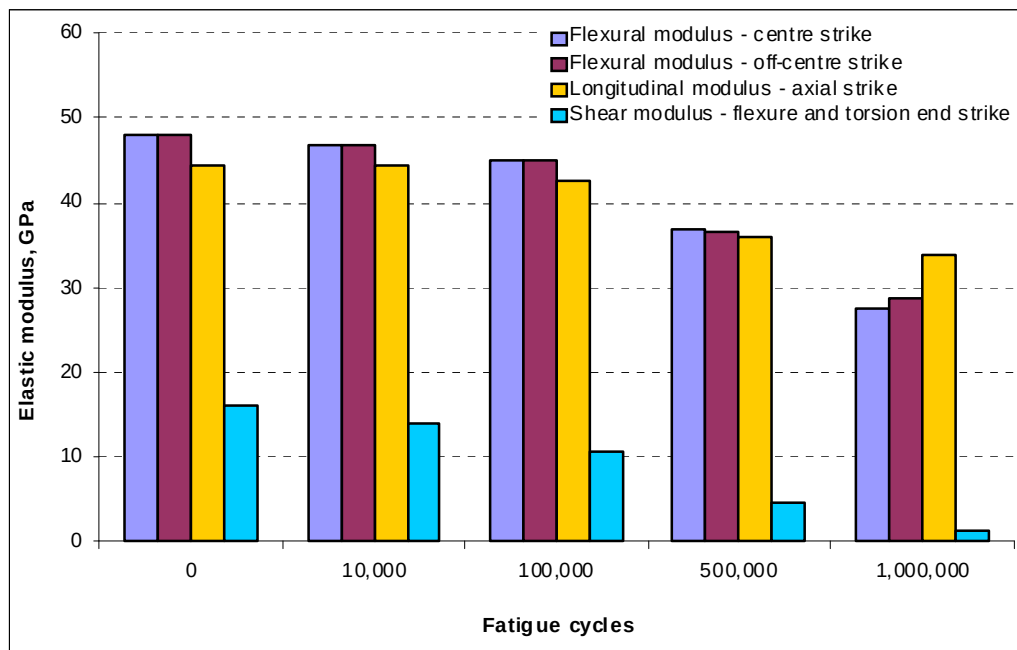


Figure 48: Elastic moduli for 80% UTS OHT fatigue specimens

Loading Modes and Damage Accumulation

7

IN THIS CHAPTER

- Introduction
- In-Plane Tension
- In-Plane Compression
- In-Plane Shear
- Flexure
- Through-Thickness (T-T) Testing

7.1 Introduction

This section is concerned with loading modes and test specimen geometries used in assessing mechanical behaviour of composites. It examines methods for measuring deformation and damage under static and fatigue loading conditions.

7.2 In-Plane Tension

ISO 527-4 and 5 [79-80] provide tensile testing specifications for determining the ultimate tensile properties of multidirectional and continuous aligned (longitudinal (0°) and transverse (90°)) laminates, respectively (see Figure 49). 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 widths of longitudinal and transverse unidirectional laminates are 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, but the advantages are minimal as the short-and long-term properties are similar to those obtained using adhesively bonded end tabs. Polishing specimen edges and thus removing cracks can significantly increase fatigue life. Longitudinal and transverse strain can be measured using either contact extensometers, strain gauges or FBGs (see Section 4).

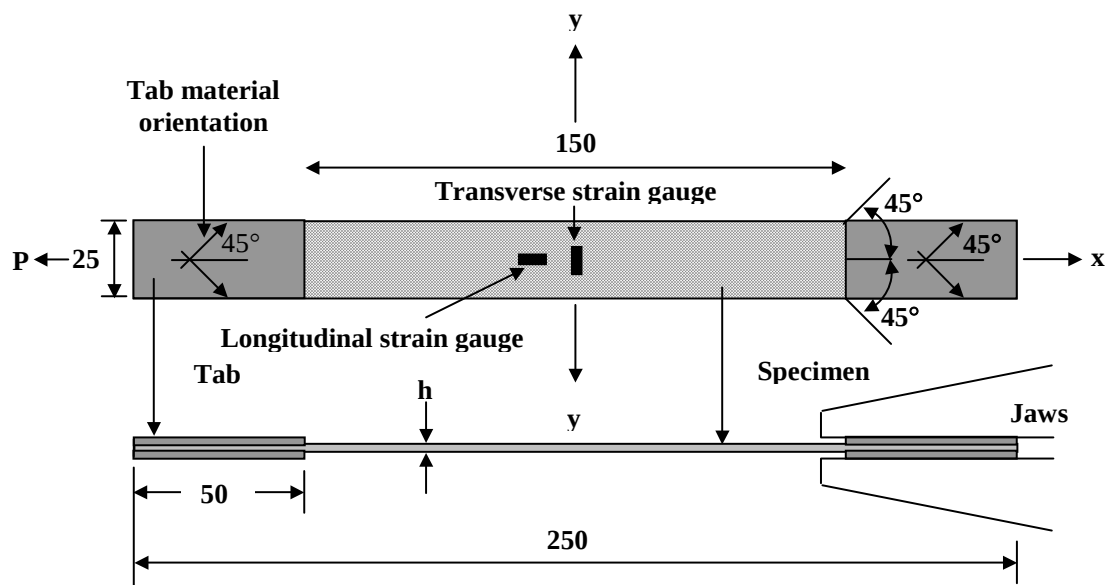


Figure 49: Schematic of multidirectional laminated tensile specimen

7.2.1 Unidirectional laminates

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 50 and 51). 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 52).



Figure 50: Fibre debonding and matrix cracking in fatigued unidirectional GFRP (damage indicated by narrow, whitened areas along gauge-length)



Figure 51: Longitudinal splitting in fatigued unidirectional GFRP



Figure 52: 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 53 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 54 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.

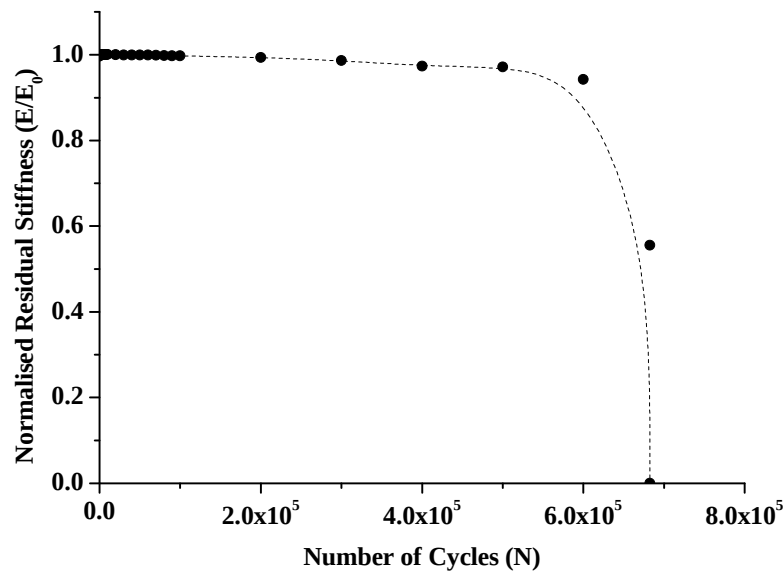


Figure 53: Normalised residual fatigue stiffness curve for unidirectional GFRP

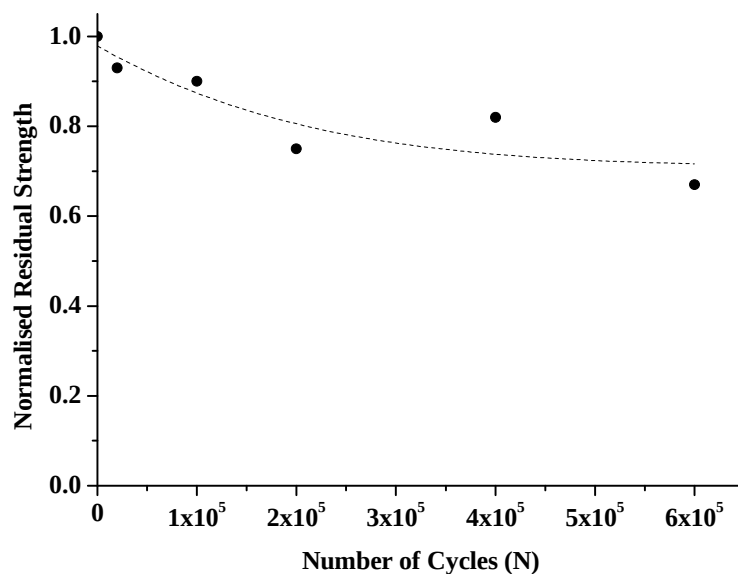


Figure 54: Normalised residual fatigue strength curve for unidirectional GFRP

7.2.2 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 55, to promote failure within the gauge-section. Using waisted (or dumbbell) specimens, eliminates the tendency for the end tabs to debond, which can occur at high loads and/or high cycles. Figure 56 shows typical failures for straight-sided and dumbbell specimens. The test geometry shown in Figure 56 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 57) as failure invariably occurs within the gauge-section and not at the end tabs.



Figure 55: Dumbbell cross-ply specimen with bonded end tabs

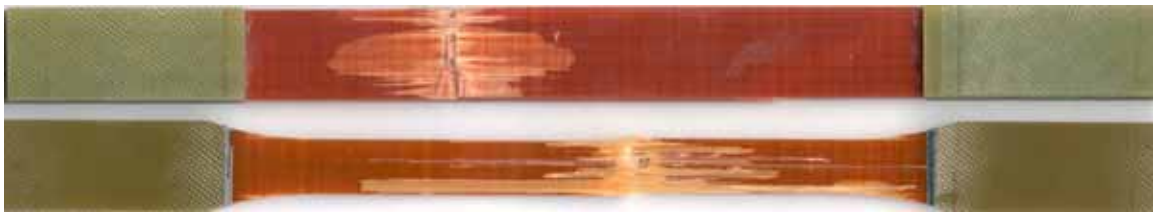


Figure 56: Typical failures for straight-sided and dumbbell specimens

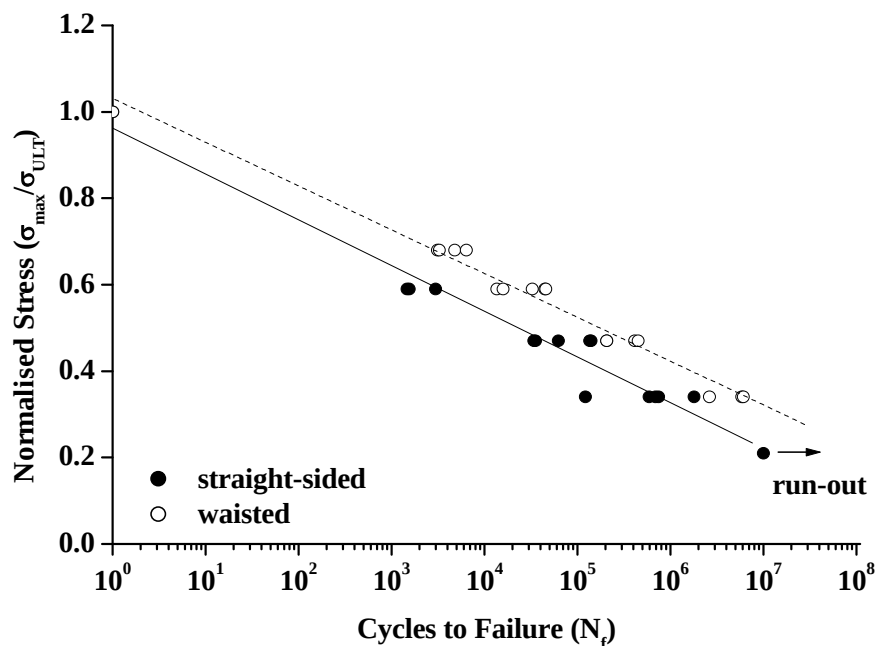


Figure 57: Fatigue performance for waisted and straight-sided GFRP specimens

Cross-ply (0°/90°) laminates: 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 Figures 58 and 59;
- Transverse crack density increases with loading cycles forming a regular array of matrix cracks;
- Formation of edge and local delaminations (see Figure 56); 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.

Note: End tabs are prone to debond during testing, and hence prevention of end tab debonding is essential for ensuring reliable fatigue data.



Figure 58: Transverse cracking of a cross-ply GFRP laminate



Figure 59: 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 58). 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 60).

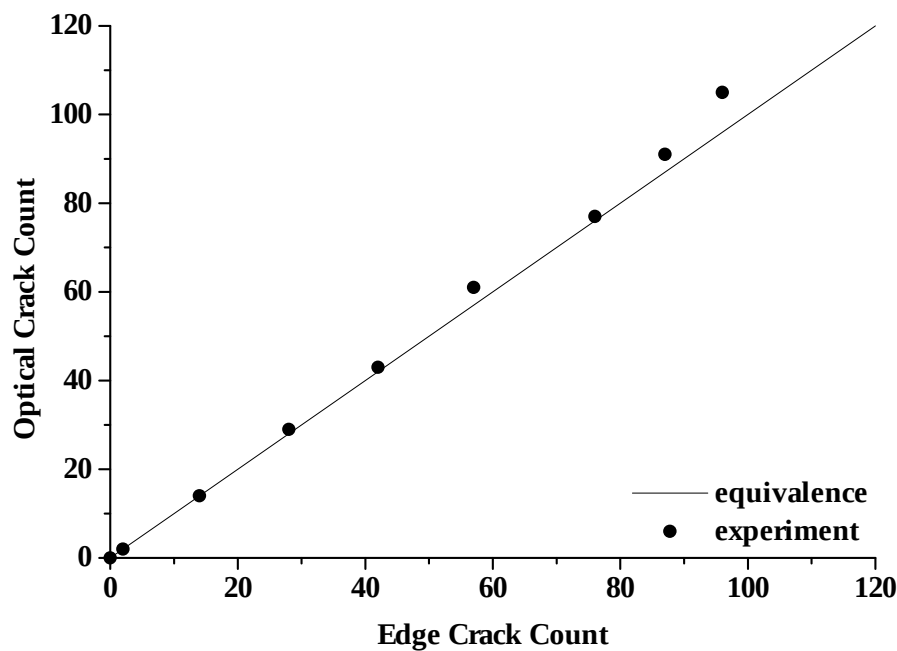


Figure 60: Optical crack versus edge crack counts for $[0_2/90_2]_s$ GFRP laminate

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 6). 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 61). Bifurcation of transverse cracks, which occur frequently in thicker laminates, are difficult to identify using AE.

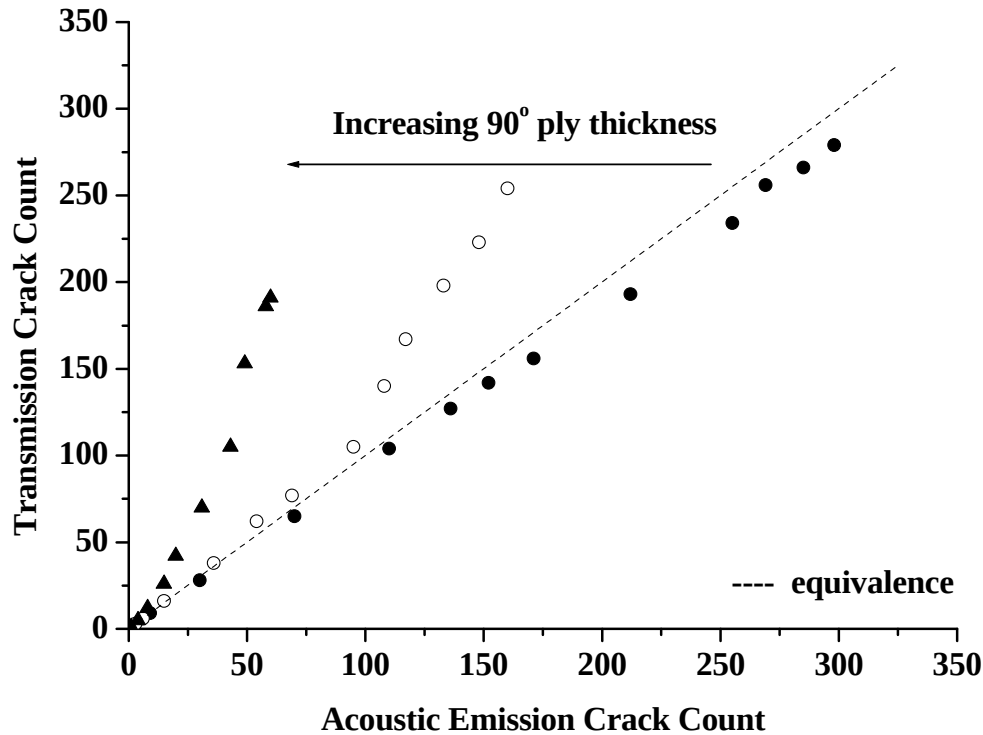


Figure 61: Edge crack versus optical crack counts for cross-ply GFRP laminates ($[0_2/90_2]_s$, $[0_2/90_4]_s$ and $[0_2/90_8]_s$)

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 58). Transverse cracking will often cause adverse effects, such as stiffness, Poisson's ratio and strength reduction (Figures 62 and 63). Figures 62 and 63 show typical responses of a GFRP cross-ply laminate. 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. The scatter in data is far larger for Poisson's ratio compared with elastic modulus.

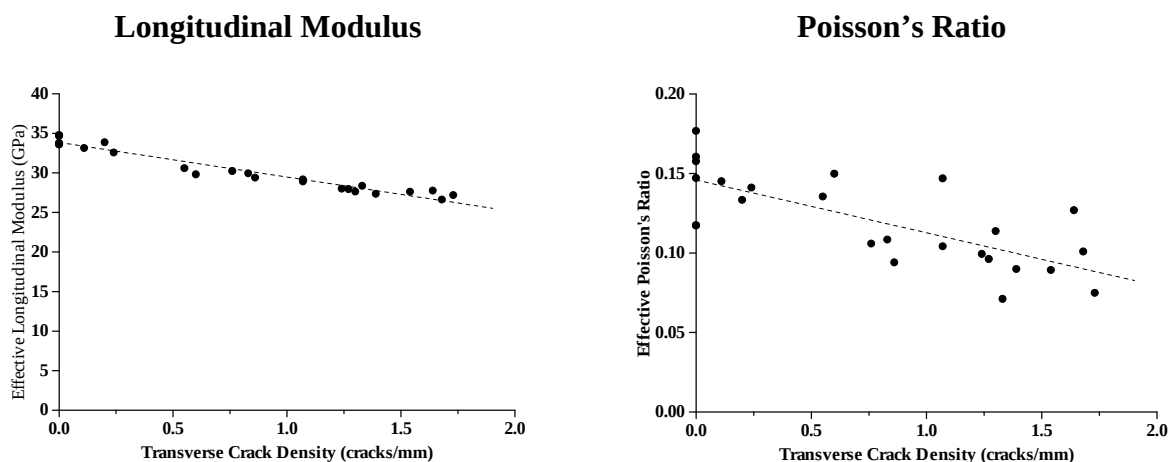


Figure 62: Axial stiffness and Poisson's ratio reduction for $[0_2/90_2]_s$ GFRP laminate

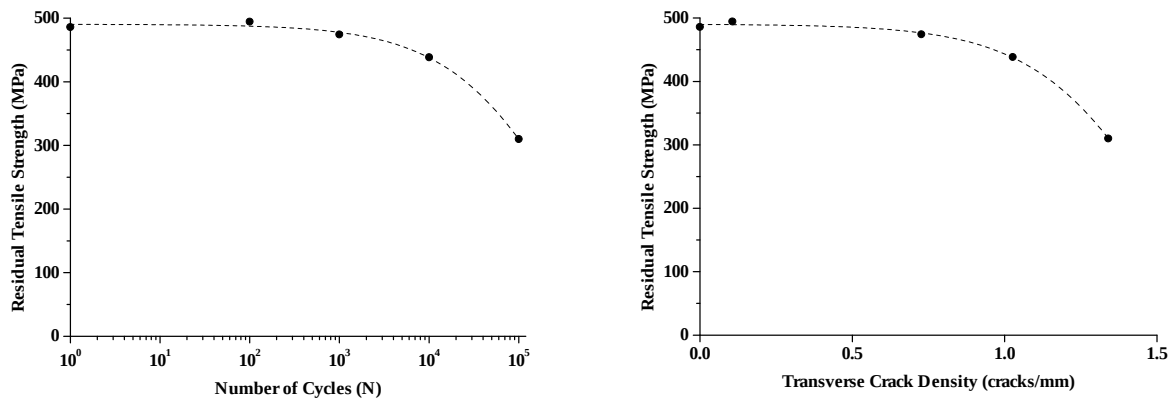


Figure 63: Strength reduction for $[0_2/90_2]_s$ GFRP laminate

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. 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).

7.2.3 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 [81]. The centre-notched (or open-hole) specimen with a width-to-hole diameter ratio of 6:1 (see Figure 64) is routinely used for determining the effect of a hole on the tensile strength of thermoset and thermoplastic FRPs – see [29]. The static method used under fatigue loading in this guide is ASTM D5766 [82]. There are several similar versions of the open-hole tension (OHT) test including EN6035 [83] and AITM 1.007 [84].

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 that 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 un-notched tensile strength divided by the open-hole (notched) strength.

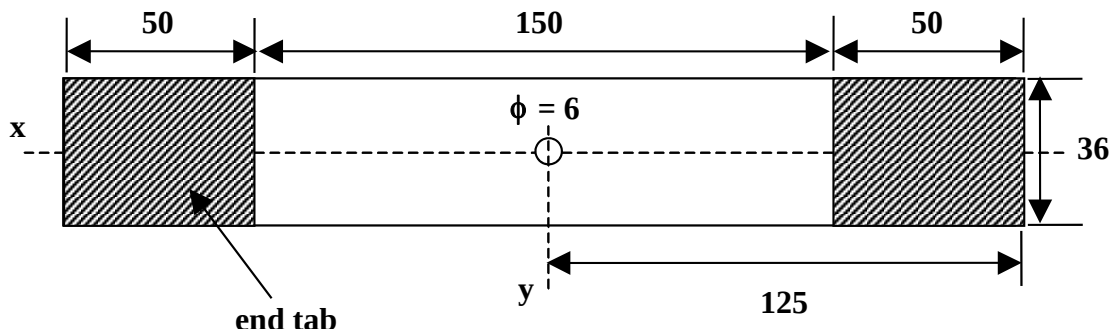


Figure 64: Open-hole (notched) tension specimen (units: mm)

The specimen stiffness according to ASTM D5766 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 65 is only suitable for tension-tension loading conditions. Fatigue test parameters are similar to those employed for un-notched specimens. Figure 65 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 65: 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 66). 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).

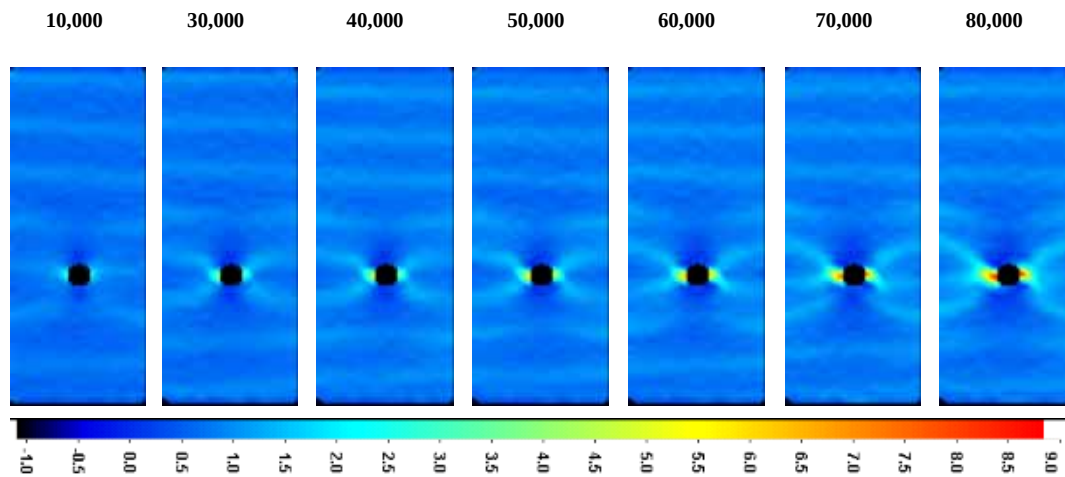


Figure 66: ϵ_{xx} strain distribution versus loading cycles for GFRP OHT (measured at a static stress following cyclic loading)

The DIC images shown in Figure 66 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 67). The maximum value of ϵ_{xx} strain at the perimeter of the hole tends to increase linearly with loading cycles, as shown in Figure 68. 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).

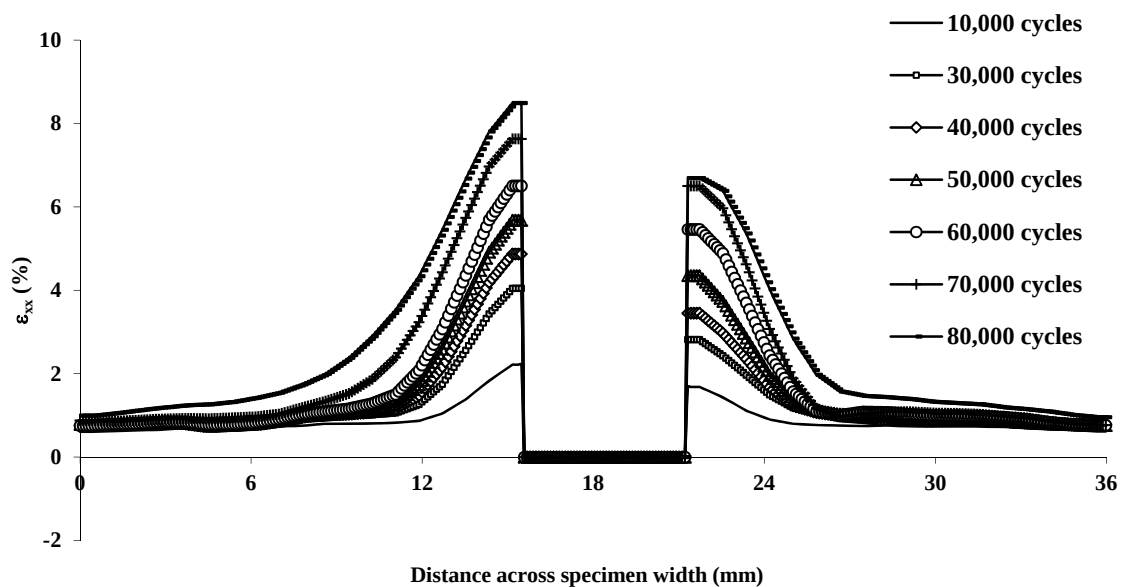


Figure 67: ϵ_{xx} strain across the specimen mid-length versus loading cycles (measured at a static stress following cyclic loading)

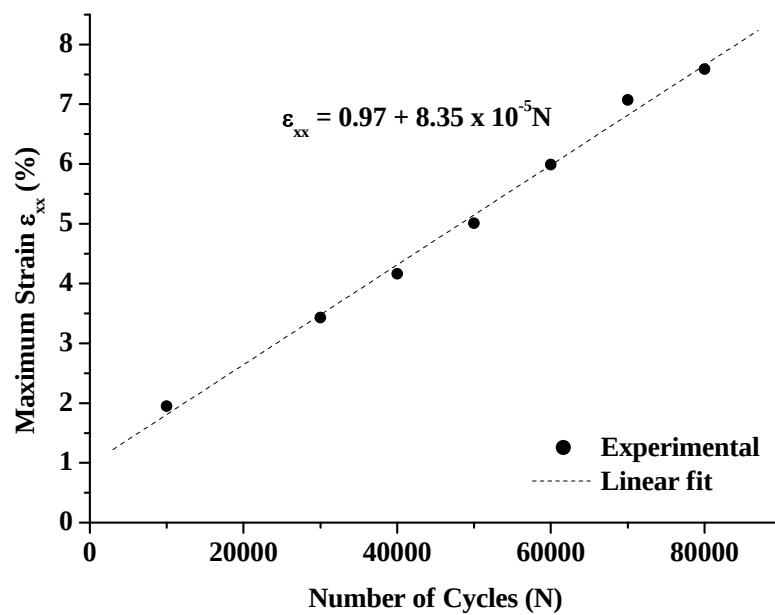


Figure 68: Maximum ϵ_{xx} strain at hole perimeter versus loading cycles (measured at a static stress following cyclic loading)

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 up to 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 10 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 10: 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 69) can potentially be used as a damage parameter to determine remnant stiffness and fatigue life. Figure 70 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 (110).

$$\frac{E}{E_0} \approx 1 - AT \quad (110)$$

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.

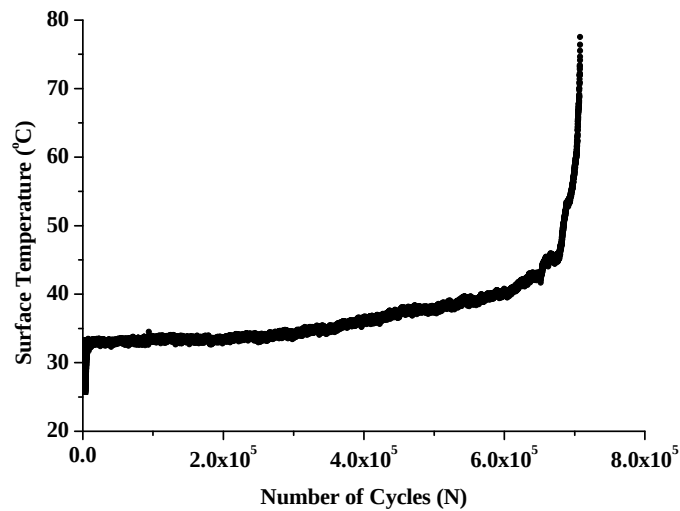


Figure 69: Surface temperature at hole-perimeter for GFRP OHT specimen

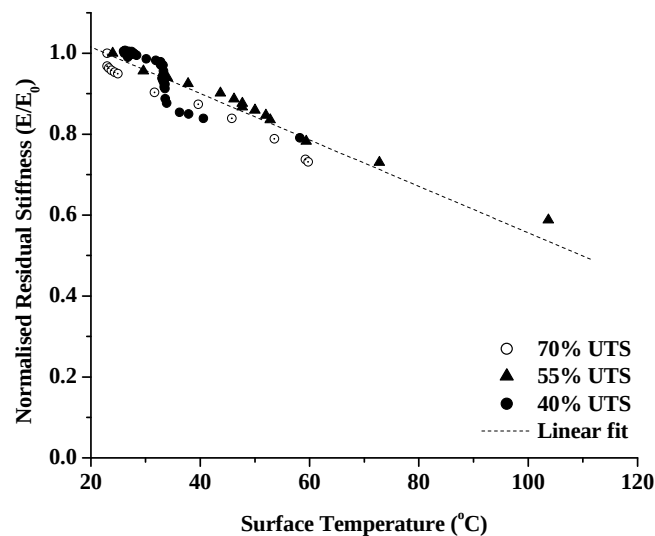


Figure 70: Normalised residual fatigue stiffness versus surface temperature (notched quasi-isotropic GFRP laminate at 40%, 55% and 70% UTS at $R = 0.1$)

7.3 In-Plane Compression

In-plane compression specimens are far smaller than their tensile equivalents. 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 [85] 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.

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 71). In all cases, the gauge-length is unsupported. The end-loading fixture shown in Figure 72 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.

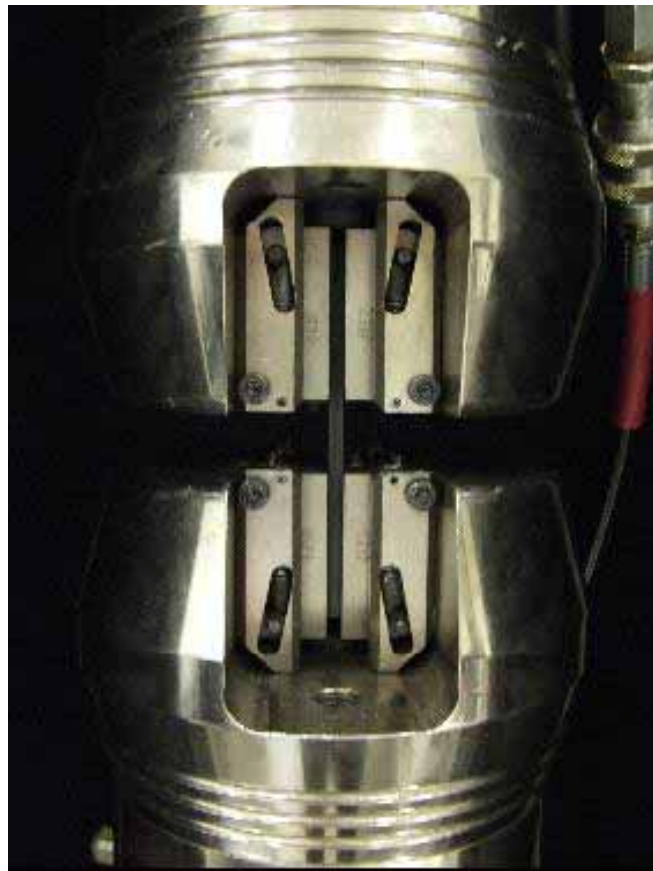


Figure 71: Compression specimen gripped in hydraulic wedge action grips



Figure 72: End-loading compression fixture with specimen

The servo-hydraulic gripping and end-loading methods shown in Figures 71 and 72 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.

7.3.1 Open-hole compression (OHC)

The open-hole compression (OHC) test (ISO/DIS 12817 [86]) 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 73. The test specimen consists of a strip of rectangular cross-section with a plain hole centrally located. End-tabs are shown in Figure 73, 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 un-notched 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.

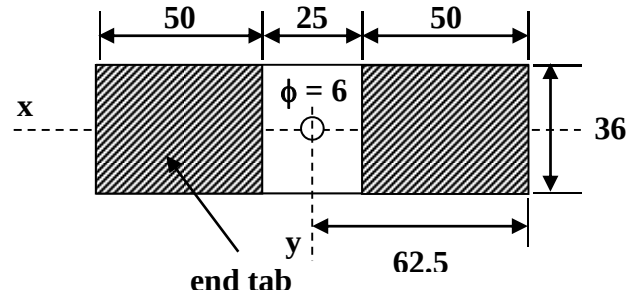


Figure 73: Open-hole (notched) compression specimen (units: mm)

The OHC specimen is suitable for both compression-compression and tension-compression testing. An end-loading fixture (see Figure 74) 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.

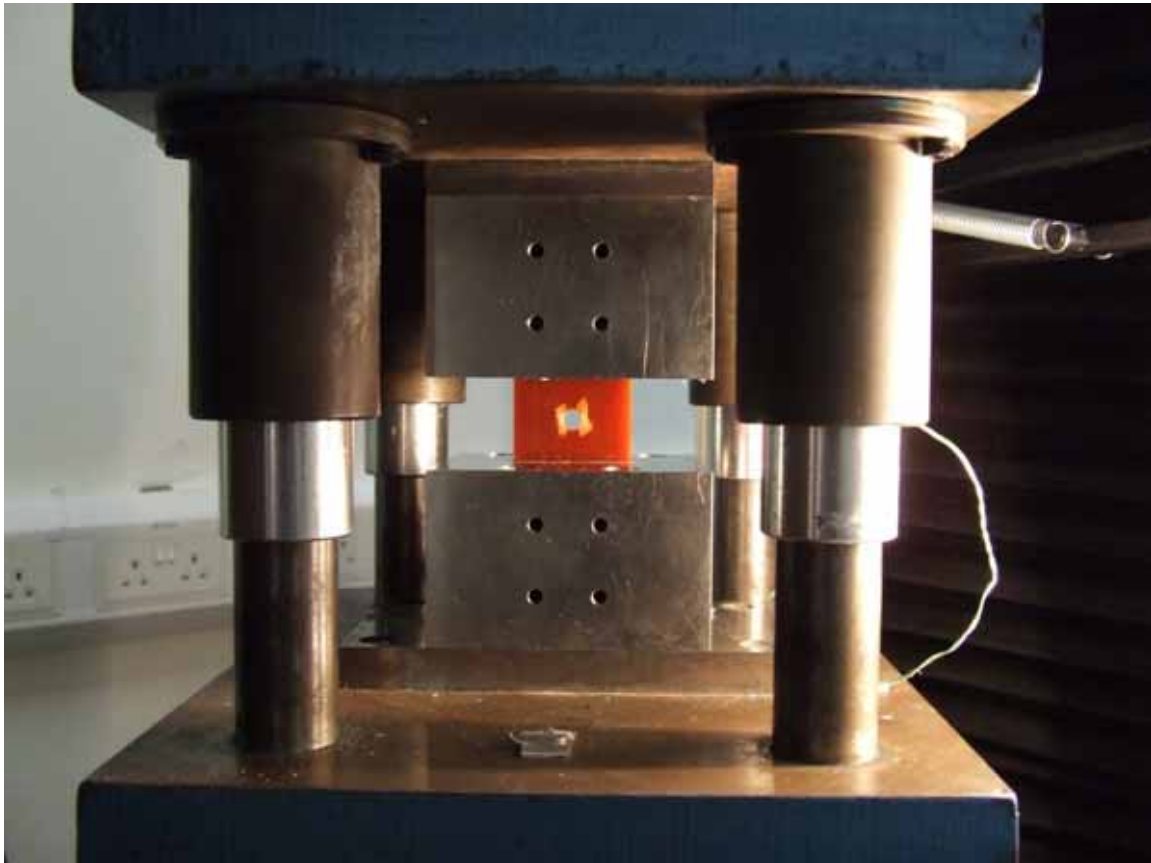


Figure 74: Open-hole compression-compression loading arrangement

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 11).

**Table 11: 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 (un-notched)	45

Typical damage observed for compression-compression loaded CFRP and GFRP OHC specimens are shown in Figures 75 and 76, respectively. 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 77.

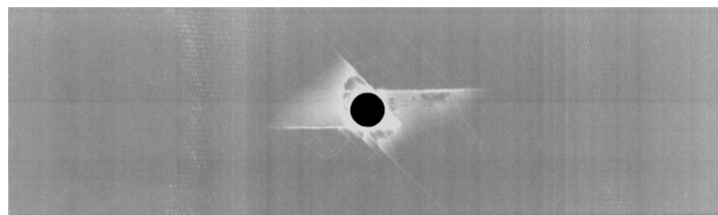


Figure 75: X-radiography image of a fatigued quasi-isotropic CFRP OHC specimen

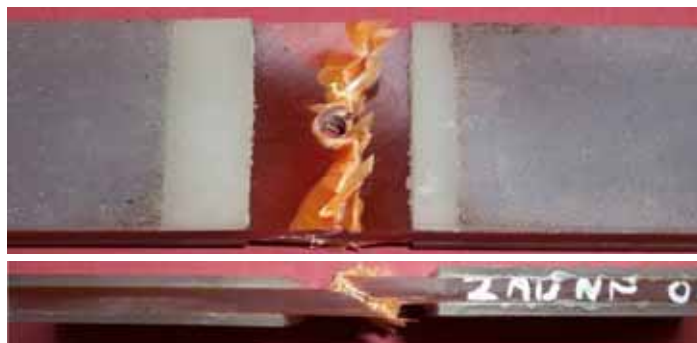


Figure 76: Fatigue failure of quasi-isotropic GFRP OHC specimen

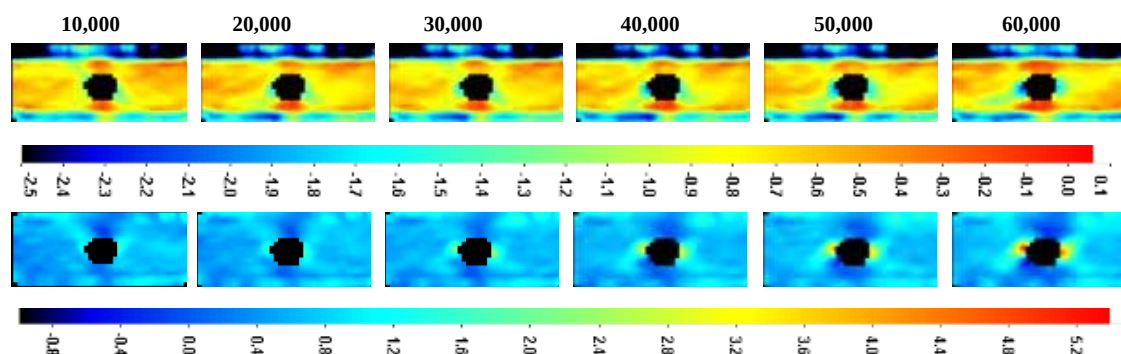


**Figure 77: ϵ_{xx} strain distribution vs. loading cycles for GFRP OHC
compression-compression (top) and tension-compression of fully reversed (bottom)
measured at a static stress following cyclic loading**

7.4 In-Plane Shear

Shear methods, such as uniaxial tension of a balanced symmetric $\pm 45^\circ$ laminate (ISO 14129 [87] and ASTM D3518 [88]) and the V-notched beam (ASTM D5379 [89]) 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). The method employs a double edge-notched, flat rectangular specimen (76 mm $\times$ 20 mm $\times$ 5 mm) – see Figure 78. 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 $\pm 45^\circ$ 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 $\pm 45^\circ$ 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 78).

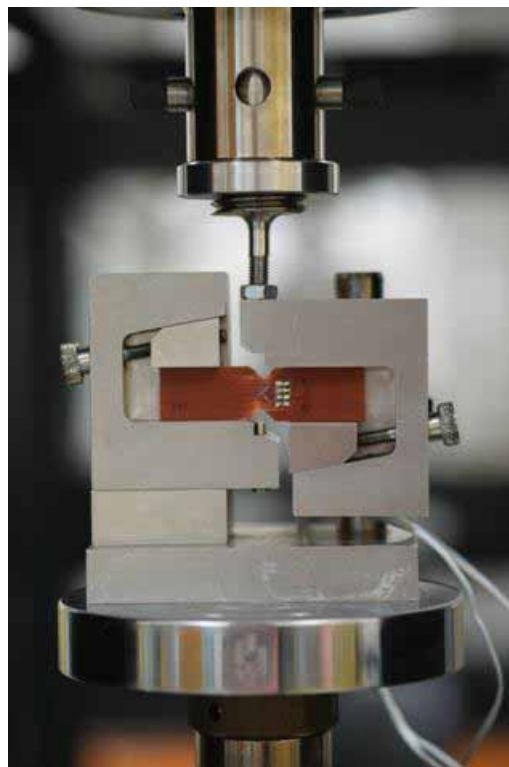


Figure 78: V-notched beam shear method and strain-gauged specimen

The $\pm 45^\circ$ tension test (Figure 49) can be used to determine in-plane shear properties of continuous aligned fibre-reinforced systems. The test geometry and loading configuration is similar to that employed for tensile loading of the multidirectional laminates (250 mm $\times$ 25 mm $\times$ 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. $[\pm 45]_{4s}$).

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.

7.5 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 [90]), 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 [91] 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.

7.6 Through-Thickness (T-T) Testing

7.6.1 Though-thickness tension

There are two contrasting methods and several associated geometries that can be used to measure T-T tension (i.e. direct and indirect tensile loading) and compression properties [16, 92-95]. 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 79) – see also ASTM D7291 [96]. 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.

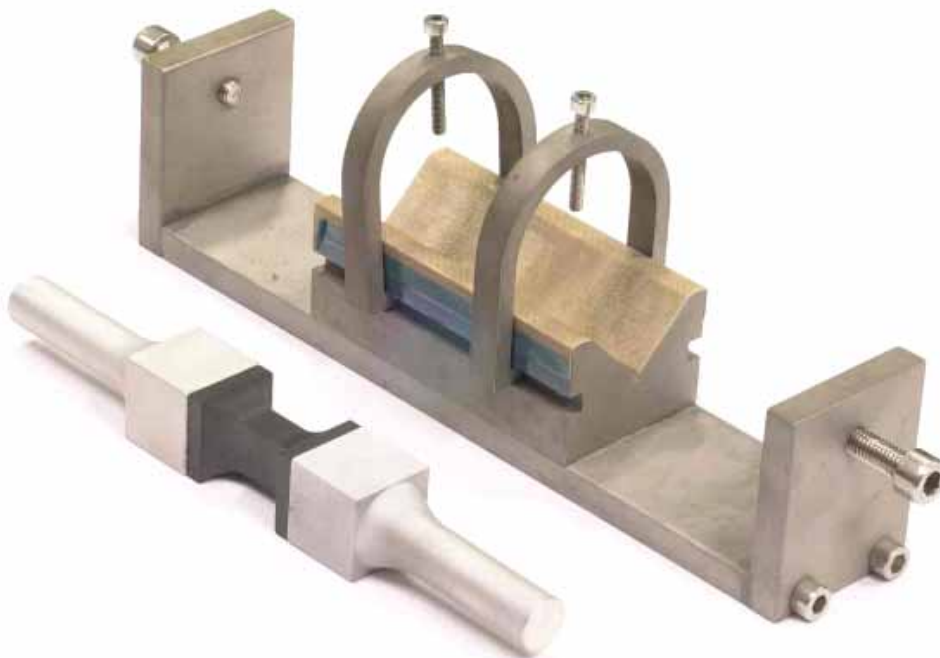


Figure 79: RARDE T-T tension specimen with bonding fixture

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 79) 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 D7291 and the NPL draft procedure [97] 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 80) [26, 94, 95, 98]) enables both strength and elastic properties to be obtained using the same specimen. 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 [95]). 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 80: Tensile loading of RARDE T-T specimen

7.6.2 Though-thickness compression

The direct tensile specimen geometries described previously can also be used to determine T-T compression properties [94-95]. 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 81). Shear is the predominant cause of failure in all cases, independent of material microstructure, loading configuration or specimen size [98].

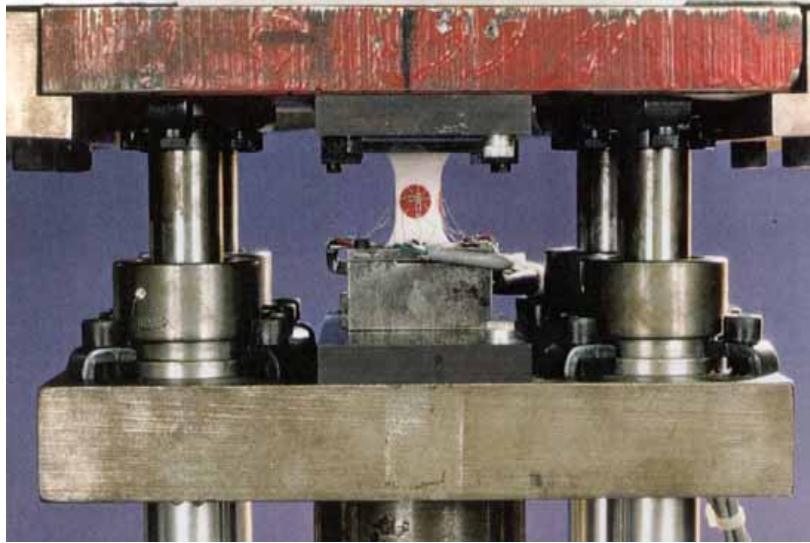


Figure 81: Compression loading of RARDE T-T specimen (courtesy of QinetiQ)

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 82).

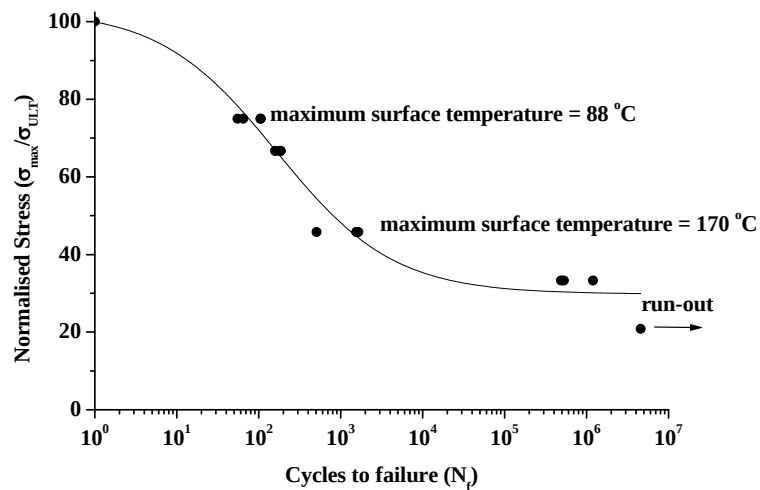


Figure 82: S-N compressive fatigue data for a woven GFRP laminate

Standards and Contacts

8

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

ISO 527: Part 4	Plastics - Determination of tensile properties - Part 4: test conditions for isotropic and orthotropic fibre-reinforced plastic composites
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
ISO 9163	Textile glass - Rovings - Manufacture of test specimens and determination of tensile strength of impregnated rovings
ISO 10618	Carbon fibre - Determination of tensile properties of resin-impregnated yarn
ISO 11566	Carbon fibre - Determination of the tensile properties of single-filament specimens

ISO/DIS 12817	Carbon fibre-reinforced composites - Determination of open-hole compressive strength
ISO 14125	Fibre-reinforced plastic composites - Determination of flexural properties
ISO 14126	Fibre-reinforced plastic composites - Determination of compressive properties in the in-plane direction.
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
ISO 15024	Mode I interlaminar fracture toughness G_{Ic} of unidirectional fibre-reinforced polymer matrix composites
ISO 18352	Test method for compression-after-impact properties of carbon fibre-reinforced plastics
<i>Mechanical (Fatigue)</i>	
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 D638	Standard test method for tensile properties of plastics
ASTM D695	Standard test method for compressive properties of rigid plastics
ASTM D790	Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials
ASTM D953	Standard test method for bearing strength of plastics

ASTM D1043	Standard test method for stiffness properties of plastics as a function of temperature by means of a torsion test
ASTM D5083	Standard test method for tensile properties of reinforced thermosetting plastics using straight-sided specimens
ASTM D6272	Standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials by four-point bending

Environmental Conditioning and Testing

ASTM D543	Standard practices for evaluating the resistance of plastics to chemical reagents
ASTM D618	Standard Practice for conditioning plastics for testing

Composites

ASTM D2343	Standard test method for tensile properties of glass fiber strands, yarns, and rovings used in reinforced plastics
ASTM D3039	Standard test method for tensile properties of polymer matrix composite materials
ASTM D3410	Standard test method for compressive properties of polymer matrix composite materials with unsupported gage section by shear loading
ASTM D3518	Standard test method for in-plane shear response of polymer matrix composite materials by tensile test of a $\pm 45^\circ$ laminate
ASTM D3846	Standard test method for in-plane shear strength of reinforced plastics
ASTM D3914	Standard test method for in-plane shear strength of pultruded glass-reinforced plastic rod
ASTM D3916	Standard test method for tensile properties of pultruded glass-fiber-reinforced Plastic rod
ASTM D4018	Standard test methods for properties of continuous filament carbon and graphite fiber tows
ASTM D4255	Standard test method for in-plane shear properties of polymer matrix composite materials by the rail shear method
ASTM D4476	Standard test method for flexural properties of fiber reinforced pultruded plastic rods
ASTM D5229	Standard test method for moisture absorption properties and equilibrium conditioning of polymer matrix composite materials
ASTM D5379	Standard test method for shear properties of composite materials by the v-notched beam method
ASTM D5448	Standard test method for inplane shear properties of hoop wound polymer matrix composite cylinders

ASTM D5449	Standard test method for transverse compressive properties of hoop wound polymer matrix composite cylinders
ASTM D5450	Standard test method for transverse tensile properties of hoop wound polymer matrix composite cylinders
ASTM D5766	Standard test method for open-hole tensile strength of polymer matrix composite laminates
ASTM D5961	Standard test method for bearing response of polymer matrix composite laminates
ASTM D6115	Standard test method for mode I fatigue delamination growth onset of unidirectional fiber-reinforced polymer matrix composites
ASTM D6484	Standard test method for open-hole compressive strength of polymer matrix composite laminates
ASTM D6641	Standard test method for compressive properties of polymer matrix composite materials using a combined loading compression (CLC) test fixture
ASTM D6671	Standard test method for mixed mode I-mode II interlaminar fracture toughness of unidirectional fiber reinforced polymer matrix composites
ASTM D6742	Standard practice for filled-hole tension and compression testing of polymer matrix composite laminates
ASTM D6856	Standard guide for testing fabric-reinforced "textile" composite materials
ASTM D7078	Standard test method for shear properties of composite materials by v-notched rail shear method
ASTM D7137	Standard test method for compressive residual strength properties of damaged polymer matrix composite plates
ASTM D7205	Standard test method for tensile properties of fiber reinforced polymer matrix composite bars
ASTM D7248	Standard test method for bearing/bypass interaction response of polymer matrix composite laminates using 2-fastener specimens
ASTM D7264	Standard test method for flexural properties of polymer matrix composite materials
ASTM D7291	Standard test method for through-thickness "flatwise" tensile strength and elastic modulus of a fiber-reinforced polymer matrix composite material

Mechanical (Fatigue)

ASTM D3479	Standard test method for tension-tension fatigue of polymer matrix composite materials
ASTM D6873	Standard practice for bearing fatigue response of polymer matrix composite laminates

Electrical

ASTM D257	Standard test methods for DC resistance or conductance of insulating materials
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ASTM D 4496

Standard test method for D-C resistance or
conductance of moderately conductive materials

USEFUL CONTACTS

NPL

National Physical Laboratory
Hampton Road, Teddington
Middlesex, TW11 0LW, UK
Tel: +44 (0) 20 89436701
E-mail: enquiry@npl.co.uk
Web: <http://www.npl.co.uk>

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>

IEEE Standards Association

Institute of Electrical and Electronics Engineers
501 Hoes Lane, 3rd Floor
Piscataway, NJ 08855
Tel: 001 732 981 0060
Web: <http://standards.ieee.org>

Composites UK

4A Broom Business Park
Bridge Way
Chesterfield, S41 9QG, UK
Tel: +44 (0) 1246 266245
E-mail: info@compositesuk.org
Web: www.compositesuk.org

NCN

National Composites Centre
Feynman Way Central,
Bristol & Bath Science Park
Emersons Green, Bristol, BS16 7FS, UK
Tel: +44 (0) 117 370 7600
E-mail: info@nccuk.com
Web: <http://nccuk.com>

BSSM

The British Society for Strain Measurement
PO Box 839
Flitwick, Bedford, MK45 9DU, UK
Tel: 0845 1668382 (UK only)
Tel: +44 (0) 1525 712779 (non-UK)
E-mail: ingfo@bssm.org
Web: <http://www.bssm.org>

NetComposites

4a Broom Business Park
Bridge Way
Chesterfield
S41 9QG, UK
Tel: +44 (0) 1246 266244
Email : info@netcomposites.com
Web: <http://www.netcomposites.co.uk>

BPF

British Plastics Federation
5-6 Bath Place, Rivington Street
London, EC2A 3JE, UK
Tel: +44 (0) 20 7457 5000
E-mail: reception@bpf.co.uk
Web: <http://www.bpf.co.uk>

BINDT

The British Institute of Non-Destructive Testing
Newton Building, St George's Avenue
Northampton, NN2 6JB, UK
Tel: +44 (0) 1604 89 3811
E-mail: info@bindt.org
Web: <http://www.bindt.org>

RECOMMENDED WEBSITES

<http://www.astm.org>

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

<http://www.bindt.org>

<http://www.bsigroup.com>

<http://www.bssm.org>

info@compositesuk.org

<http://standards.ieee.org>

<http://iom3.org>

<http://www.iso.org>

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

<https://connect.innovateuk.org/web/nanoktn>

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

<http://www.netcomposites.com>

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