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**A NATIONAL MEASUREMENT
GOOD PRACTICE GUIDE**

No. 101

**The Assessment of
Damage Tolerance Under
Long-Term Loading**

Measurement Good Practice Guide No.101

Good Practice Guide for the Assessment of Damage Tolerance Under Long-Term Loading

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ABSTRACT

This Guide provides best practice guidance for fatigue loading of composite materials and on the use of traditional static defect tolerance test methods under long-term fatigue loading. Guidance is also given on the use of non-destructive evaluation (NDE) techniques for defect growth detection, and in particular those techniques that can be used for real-time measurements. The Guide is primarily concerned with carbon and glass fibre-reinforced polymer composite material systems.

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Contents

Introduction and Scope	1
1.1 Introduction	2
1.2 Scope	3
Long-Term Fatigue Loading - Principles	4
2.1 BS ISO 13003 - constant amplitude and frequency	5
2.1.1 Fatigue regimes	5
2.1.2 Stress/strain amplitude	6
2.1.3 Selection of test frequency	7
2.1.4 Determination of ultimate material properties	8
2.1.5 Analysis of fatigue data.....	8
2.1.5.1 Monitoring stiffness using direct techniques.....	8
2.1.5.2 Monitoring stiffness using hysteresis loops.....	8
Defect Tolerance Assessment Methods.....	13
3.1 Compression-after-impact (CAI).....	14
3.1.1 Draft static ISO CAI method.....	14
3.1.1.1 Phase 1 - impact resistance	15
3.1.1.2 Phase 2 - inspection and measurement of damage	15
3.1.1.3 Phase 3 - residual compression tests.....	15
3.1.2 CAI method under fatigue loading.....	16
3.1.2.1 Experimental set-up	16
3.1.2.2 Fatigue test programme	18
3.1.3 Comparison to undamaged plain compression data.....	20
3.1.4 Comments on CAI fatigue results	21
3.2 Open-Hole Tension (OHT).....	24
3.2.1 Static method.....	24
3.2.2 OHT method under fatigue loading	24
3.2.2.1 Experimental set-up	25
3.2.2.2 Fatigue test programme	26
3.2.3 Comments on OHT fatigue results.....	27
3.3 Open-Hole Compression (OHC)	29
3.3.1 Static method.....	29
3.3.2 OHC method under fatigue loading	30
3.3.2.1 Experimental set-up	30
3.3.2.2 Fatigue test programme	31
3.3.3 Comments on OHC fatigue results	32
3.4 Concluding comments	34

Methods for Damage Detection	35
4.1 Impact Excitation Method	36
4.1.1 Vibration modes of beams	36
4.1.1.1 Out-of plane flexure.....	37
4.1.1.2 In-plane flexure.....	37
4.1.1.3 Torsion	37
4.1.1.4 Longitudinal.....	38
4.1.2 Practical use of the impact excitation method.....	38
4.1.2.1 Test panel requirements	38
4.1.2.2 Support method.....	39
4.1.2.3 Impact excitation.....	40
4.1.2.4 Vibration detection	40
4.1.3 Identification of fundamental frequencies	40
4.1.4 Examples of impact excitation results.....	42
4.1.4.1 Evaluation of the repeatability of the impact excitation method.....	42
4.1.4.2 Open-hole tension fatigue.....	43
4.2 Pulse Thermography.....	43
4.2.1 Principle	43
4.2.2 Evaluation of technique for damage growth monitoring	43
4.2.3 Depth calibration.....	47
4.2.4 Example of damage depth detection	47
4.3 Radiography using dye penetrant	48
4.4 Ultrasonic C-scan	50
 Acknowledgments and Contact Details	 52
 References.....	 54
 Appendix A: Mechanical Fatigue Data	 57
 Appendix B: Elastic Property Database	 63

List of Figures	Page
Figure 2.1 Examples of fatigue cycle types	6
Figure 2.2 Schematic of sinusoidal waveform cycle	7
Figure 2.3 Material (a) elastic response and (b) viscoelastic response	9
Figure 2.4 Out of phase stress-strain response for viscoelastic material, $\delta=20^\circ$	9
Figure 2.5 Sine wave phases	10
Figure 2.6 Hysteresis loop, $\delta = 20^\circ$	10
Figure 2.7 Determination of area of hysteresis ellipse	12
Figure 2.8 Storage and loss modulus changes	12
Figure 3.1 Principle of the compression-after-impact (CAI) test	15
Figure 3.2 CAI jig (inverted) mounted on hydraulic fatigue machine	16
Figure 3.3 Recommended position of strain gauges on CAI test panels	17
Figure 3.4 Compression-compression fatigue cycle for CAI tests ($R = 10$)	19
Figure 3.5 End-loading compression jig mounted on hydraulic fatigue machine	20
Figure 3.6 Fatigue results for CAI and plain compression tests	21
Figure 3.7 Normalised fatigue results for CAI and plain compression tests	22
Figure 3.8 Example of minimum and maximum strain levels for CAI fatigue tests	22
Figure 3.9 Example of normalised compressive modulus vs. $\log(\text{fatigue cycles})$	23
Figure 3.10 Example of normalised storage modulus & damping factor vs. $\log(\text{fatigue cycles})$	23
Figure 3.11 Open-hole tension specimen	24
Figure 3.12 Extensometers used for measurement of strain in OHT tests	25
Figure 3.13 Tension-tension fatigue cycle ($R = 0.1$)	26
Figure 3.14 Residual OHT strength results	27
Figure 3.15 Residual OHT modulus results	28
Figure 3.16 Pulse thermography image of OHT fatigue specimen (70% of static UTS for 10,000,000 cycles)	28
Figure 3.17 Surface ply splitting ($+45^\circ$) - OHT fatigue specimen	29
Figure 3.18 Open-hole compression specimen	29
Figure 3.19 OHC specimen gripped in hydraulic wedge action grips	30
Figure 3.20 Tension-compression (fully reversed) fatigue cycle ($R = -1$)	31
Figure 3.21 Residual OHC strength results	32
Figure 3.22 X-radiography image of OHC fatigue specimen (70% of static UCS after 1,000,000 cycles)	33
Figure 3.23 Fully reversed OHC fatigue results	33
Figure 4.1 Vibration modes of a 'free-free' beam with nodal lines indicated	37

Figure 4.2	Impact excitation equipment with OHT specimen supported on wires	39
Figure 4.3	Example of FEA mesh divisions for OHT model	41
Figure 4.4	Flexural, longitudinal and torsional modes of vibration for 'free-free' OHT specimen (FEA analysis)	41
Figure 4.5	Elastic moduli for 55% UTS OHT fatigue specimens	44
Figure 4.6	Elastic moduli for 70% UTS OHT fatigue specimens	44
Figure 4.7	Elastic moduli for 80% UTS OHT fatigue specimens	44
Figure 4.8	Principle of pulse thermography technique for damage monitoring and ThermoScope™ pulse thermography system	45
Figure 4.9	Pulse thermography images of CAI specimens after various fatigue cycles	45
Figure 4.10	Pulse thermography images of OHT fatigue specimens	46
Figure 4.11	Depth calibration procedure for pulse thermography	47
Figure 4.12	Delamination depth detection using pulse thermography	48
Figure 4.13	X-radiography images of OHC fatigue specimens	49
Figure 4.14	Ultrasonic C-scan double through-transmission method (immersion)	50

List of Tables		Page
Table 2.1	Fatigue test duration versus frequency for typical fatigue lifetimes	7
Table 3.1	Details of materials used in CAI fatigue evaluation	16
Table 3.2	Percentage and absolute stress levels for CAI and plain compression fatigue tests	18
Table 3.3	Percentage and absolute stress levels for OHT fatigue tests	27
Table 3.4	Percentage and absolute stress levels for OHC fatigue tests	32
Table 4.1	Impact excitation modes and elastic moduli measured	40
Table 4.2	Predicted and measured modal frequencies and moduli by impact mode for OHT specimen	42
Table 4.3	Elastic moduli for un-fatigued OHT specimens by impact mode	42
Table A1	CAI fatigue results (material 1)	58
Table A2	CAI fatigue results (material 2)	59
Table A3	Plain compression-compression fatigue results	60
Table A4	OHT tension-tension fatigue results	61
Table A5	OHC compression-compression fatigue results	62
Table A6	OHC fully reversed fatigue results	62
Table B1	Elastic property database - material 1	64

Introduction and Scope

1

IN THIS CHAPTER

- Introduction
- Scope

1.1 Introduction

The use of polymer matrix composite (PMC) material systems can provide designers, manufacturers and end-users with a number of key advantages over traditional materials (e.g. metals, concrete etc.) including high specific strength and stiffness ratios, excellent durability, chemical and corrosion resistance, and good damage tolerance.

Despite the advantages, PMC usage is still far less than their potential and that of traditional materials, which can be largely attributed to a current lack of design methodologies, reliable test methods and useable data. The situation is improving with the recent publication of a test plate manufacture standard (BS ISO 1268 [1]), a suite of harmonised ISO test methods (mechanical, thermal and physical [2]) and a data-sheet database standard (ISO 10350-2 [3]). However, there is still a requirement to develop test procedures that will allow accurate assessment of the criticality and influence of defects on the performance of composite structures, particularly under long term loading. The recently completed DTI funded project MMS13 - “Assessment and Criticality of Defects and Damage in Material Systems” developed a procedural guide [4] to facilitate the assessment and criticality of defects and damage in material systems, however its remit was not to develop new test methods. From a review carried out in MMS13 and communications with industry, it was clear that there were still gaps in the knowledge base and requirements for tools and test methods for the assessment of defect criticality for a range of loading modes (static and long-term loading) for composite material systems.

Defects and stress concentrations may be introduced during manufacture, accidentally in-service or perhaps unavoidably in design because of the requirement to introduce discontinuities such as cut-outs, ply drops or structural connections. The type of defect or flaw produced when composite materials are damaged in-service depends on the structural design, material type and format, and the conditions of damage such as the energy and momentum of an impact event. In general terms, damage tolerance is used in the context of the ability of a material system containing damage, i.e. a severe stress concentration, to continue to bear load and hence continue to operate safely.

Considerable work has been undertaken to investigate the significance and assessment of defects in materials systems, but this has mainly resulted in the development of static test methods where damaged specimens are loaded at a slow rate until failure. This has covered test coupon samples (e.g. compression-after-impact (CAI)) through to failure analysis of full-scale components. However, static loading is not totally realistic as the component is likely to experience fatigue loading rather than, or before, a static overload. The damage is more likely to propagate to a large size, or catastrophically, under a long-term cyclic load rather than a one-off overload. Therefore, guidance is needed on the assessment of defects under long term loading and regarding suitable techniques (e.g. non-destructive methods) for monitoring damage propagation particularly in real-time.

1.2 Scope

The aim of this Good Practice Guide (GPG) is to provide guidance on general procedures for the assessment of defect criticality in fibre-reinforced plastic composites under long term-loading. Whilst long-term loading includes both creep and fatigue, the methods detailed in this guide are for cyclic fatigue loading conditions of constant amplitude and frequency only. Fatigue loading is generally more destructive than constant long-term creep loads, as the behaviour is more dependent on the magnitude of the stress range ($\sigma_{\min} - \sigma_{\max}$) than the mean stress. In addition, details of NDE techniques suitable for damage detection and monitoring are provided with particular reference to real-time measurements.

This guide does not provide guidance on testing for all defect types as there are far too many individual types to consider, but rather, it provides guidance for generic defects e.g. delamination, fibre fracture, machined holes etc. under long-term loading.

The guide is generally applicable to preimpregnated (prepreg) continuous fibre-reinforced thermoset and thermoplastic material systems. Individual standards referred to provide more details as to which classes of materials are suitable.

Long-Term Fatigue Loading - Principles

2

IN THIS CHAPTER

- BS ISO 13003 - constant amplitude and constant frequency
- Analysis of fatigue data

This section provides guidance on best practice for constant amplitude and frequency fatigue loading for PMC material systems and is largely based on BS ISO 13003 [5]. However, it is noted that for the vast majority of applications variable amplitude and frequency loading i.e. spectral loading is more realistic of service conditions. In terms of analysis and life prediction, spectral loading is more complicated than constant amplitude and frequency regimes, but control software packages do exist that allow the user to input spectral loading waveforms (e.g. Instron Wavemaker).

2.1 BS ISO 13003 - constant amplitude and frequency

This standard defines general procedures for fatigue testing of fibre-reinforced plastic composites under cyclic loading conditions of constant amplitude and frequency. The standard is based on previous experiences of tensile and flexural fatigue testing using the equivalent (monotonic) static test methods.

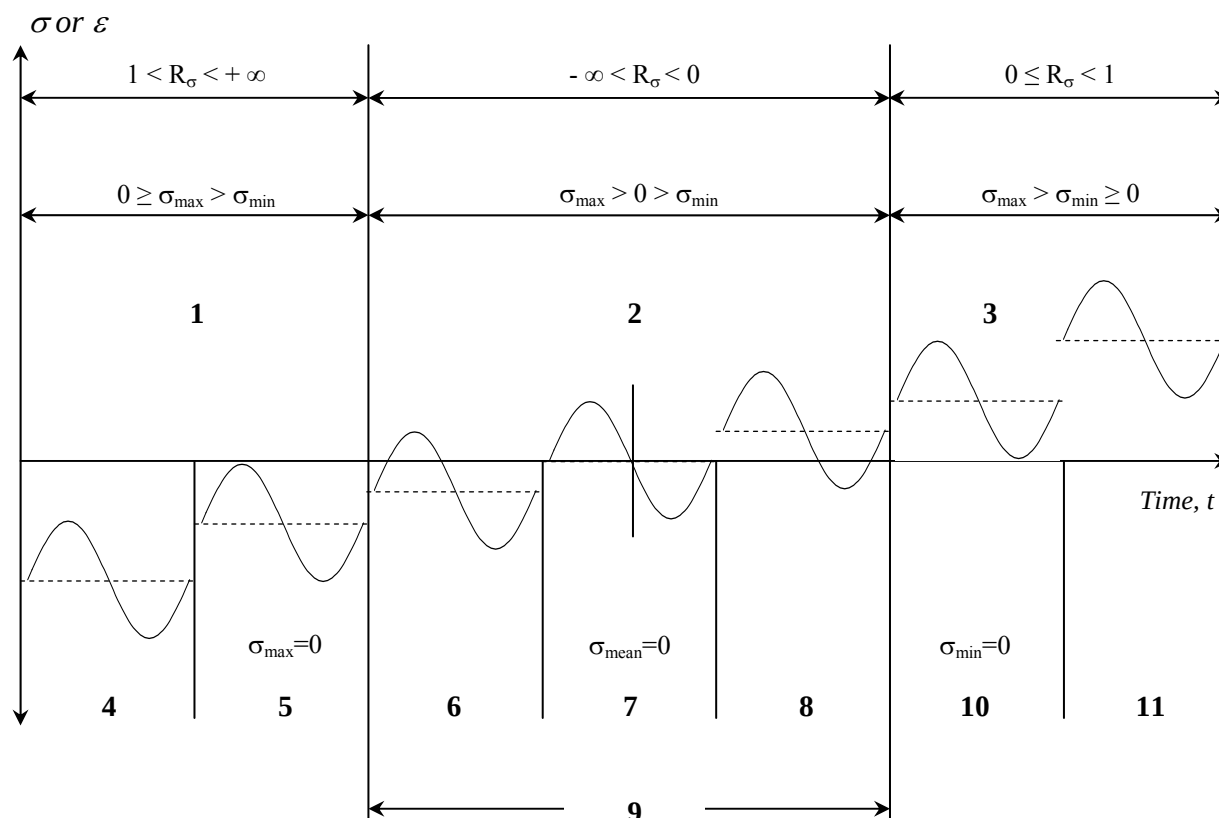
The principle of the method is that a continuously alternating mechanical load or displacement is applied at a constant frequency to the specimen under test until the specimen either fails or reaches a certain number of fatigue cycles (fatigue life). By testing specimens at each of several percentage levels of the ultimate stress or strain (section 2.1.4), a plot of the stress/strain versus number of fatigue cycles can be constructed. This plot provides information as to the fatigue life of the material or how many fatigue cycles the material can sustain at a certain stress/strain level before failure will occur.

2.1.1 Fatigue regimes

The variety of fatigue regimes that exist is shown in Figure 2.1 and ranges from compression-compression to tension-tension. The work detailed in this guide has looked at a sinusoidal cyclic waveform only (Figure 2.2) but it is noted here that other shapes of waveform are commonly used i.e. triangular, square, saw-tooth etc. and that proprietary test machine control software allows the user to input bespoke waveforms*.

The selection of the most appropriate fatigue regime to use is directly linked to the material application requirements and anticipated stress field.

** - Note - prior work on a glass-fibre fabric/epoxy showed that at longer fatigue lives there was no difference between the common cyclic waveforms.*



- 1 compression-compression region
- 2 tension-compression region
- 3 tension-tension region
- 4 compression-compression cycle
- 5 zero-compression alternating cycle
- 6 compression-dominated alternating cycle
- 7 fully reversed or fully alternating cycle
- 8 tension-dominated alternating cycle
- 9 alternating cycles
- 10 zero-tension cycle
- 11 tension-tension cycle

Where:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} = \text{load ratio}$$

N.B. For the waveforms used in this study:

- 1. compression-compression, $R=10$
- 2. fully reversed, $R=-1$
- 3. tension-tension, $R=0.1$

Figure 2.1: Examples of fatigue cycle types

2.1.2 Stress/strain amplitude

The stress or strain amplitude is dependent on the anticipated application stress/strain field and will be selected as a range of percentage levels of the measured static ultimate stress or strain (see section 2.1.4).

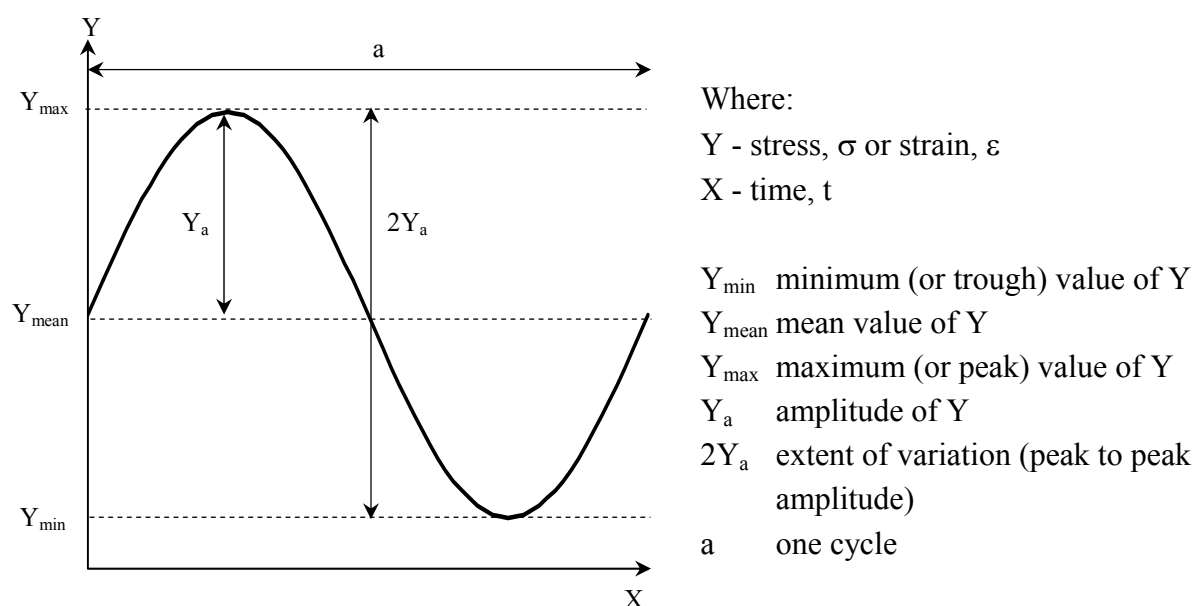


Figure 2.2: Schematic of sinusoidal waveform cycle

2.1.3 Selection of test frequency

Due to the typically extensive test durations involved with fatigue testing (see Table 2.1), it is desirable to use the highest test frequency possible. However, selection of the correct test frequency is essential as too high a frequency can lead to excessive self-generated heat (autogenous heating) leading to thermal damage of the material under test and hence incorrect measurement of material properties. The amount of heat generated in a material under fatigue loading will depend on a number of factors including stress/strain amplitude, specimen displacement range (stroke), and the material itself e.g. fibre format, lay-up and the ability of the material to dissipate heat.

The temperature rise of the specimen surface is normally limited to 10°C, but this does depend on the sensitivity of material properties to rises in temperature. It is recommended that even where prior knowledge of test frequency versus heat rise is known for a material, a thermocouple should be attached to the surface of initial test specimens, at each stress level, to monitor the degree of autogenous heating.

Table 2.1: Fatigue test duration versus frequency for typical fatigue lifetimes

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

2.1.4 Determination of ultimate material properties

To determine the relative stress/strain levels to use in a fatigue test the ultimate properties i.e. strength, strain to failure etc. should first be measured. When undertaking measurements of ultimate properties it is important to realise that a distinction must be made between glass and carbon fibre-reinforced systems. Unlike carbon fibre-reinforced plastic (CFRP) systems, where the material properties tend to be relatively insensitive to the testing rate, glass fibre-reinforced systems will exhibit a test rate dependency. Therefore for GFRP materials, ultimate properties should be determined at the anticipated fatigue test rate. (N.B. other fibre systems would need to be checked experimentally). The fatigue test rate is defined as that resulting in failure in a time equivalent to $0.5 \times$ the cycle time.

Mean values for ultimate properties should be determined from tests undertaken on at least five specimens.

2.1.5 Analysis of fatigue data

In addition to recording the number of cycles to failure, the stiffness properties of specimens can be monitored throughout the test at each logged cycle. This is carried out to see whether changes in stiffness occur due to growth of the damage throughout the fatigue tests, and if there are changes in stiffness, where in relation to the failure cycle they occur. (N.B. other measurements can also be made during the test e.g. specimen temperature, acoustic emission etc.).

2.1.5.1 Monitoring stiffness using direct techniques

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

2.1.5.2 Monitoring stiffness using hysteresis loops

The recommended method of calculating specimen stiffness is to monitor the hysteresis loops of logged cycles to determine the *storage* and *loss moduli*.

When a material is subjected to fatigue loading the stress-strain response observed is related to its ability to store and dissipate energy. Figure 2.3 shows the stress-strain responses for (a) perfectly elastic behaviour and (b) viscoelastic behaviour.

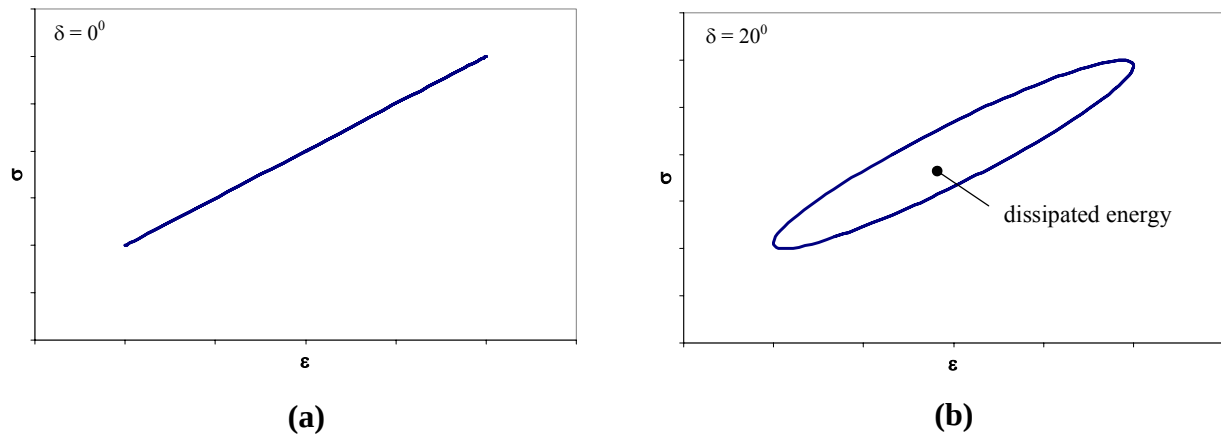


Figure 2.3: Material (a) elastic response and (b) viscoelastic response

For sinusoidal waveform loading (Figure 2.4) changes in the response of the stress and strain curves over time, indicate changes in the mechanical properties of the material. These changes are measured by looking at the change in amplitude and phase angle (δ) of the two curves. For a perfectly elastic material the mechanical energy stored during loading is returned completely when the specimen is unloaded. Thus the stress and strain curves for the material are completely in phase with each other i.e. $\delta=0^\circ$, resulting in no hysteresis (Figure 2.3a). Conversely, a perfectly viscous material ($\delta=90^\circ$) which exhibits no elasticity, results in all of the mechanical energy being dissipated and the stress and strain curves being out of phase with each other. Materials that fall between these two categories are classified as viscoelastic.

For viscoelastic materials subjected to cyclic fatigue, a proportion of the mechanical energy per cycle is converted to heat with the rest of the energy being stored and returned on

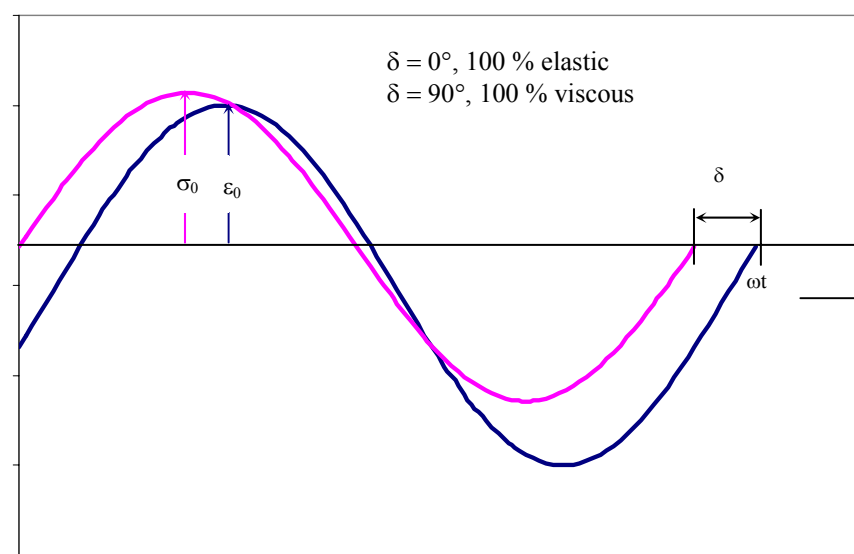


Figure 2.4: Out of phase stress-strain response for viscoelastic material, $\delta=20^\circ$

unloading. This produces stress and strain curves which exhibit a phase lag (Figure 2.4) and a hysteresis loop of which the area enclosed within the ellipse is equal to the dissipated energy per cycle, Figure 2.3b.

The viscoelastic behaviour for stress and strain can be represented as:

$$\varepsilon = \varepsilon_0 \sin(\omega t)$$

and

$$\sigma = \sigma_0 \sin(\omega t + \delta)$$

Where:

ε =strain, σ =stress, ω =period of oscillation, t =time and δ =phase angle (radians).

To monitor the changes in material during fatigue, individual fatigue cycles can be investigated for changes in: (i) the *storage modulus*, which is as a measure of the elastic properties of the material i.e. the ability to store energy, and (ii) the *loss modulus*, which is a measure of the viscous component of the material i.e. the energy dissipated as heat. Where:

$$\text{Storage modulus} = M' = \frac{\sigma_0}{\varepsilon_0} \cos \delta$$

$$\text{Loss modulus} = M'' = \frac{\sigma_0}{\varepsilon_0} \sin \delta$$

To calculate these changes, the area of the hysteresis loop and damping factor must first be derived. In order to calculate the area of the ellipse the fatigue data has to be modified from its original sine wave form and converted into a stress/strain hysteresis loop for the particular cycle being analysed. This can be done by scanning the data and splitting it into phases, as shown in Figure 2.5. By identifying these phases the data can then be accurately reordered to obtain upper and lower slopes creating a complete hysteresis loop (Figure 2.6).

The trapezium method (Figure 2.7) can then be used to analyse the area under each of the two curves, upper and lower. The method analyses the area under the curve by breaking the curve into small segments of known width. For each segment it evaluates the function at the start, $f(x1)$, and end, $f(x2)$, and then calculates the area of each segment by fitting a trapezium to the segment. These segments are then summed to give the total area for the curve.

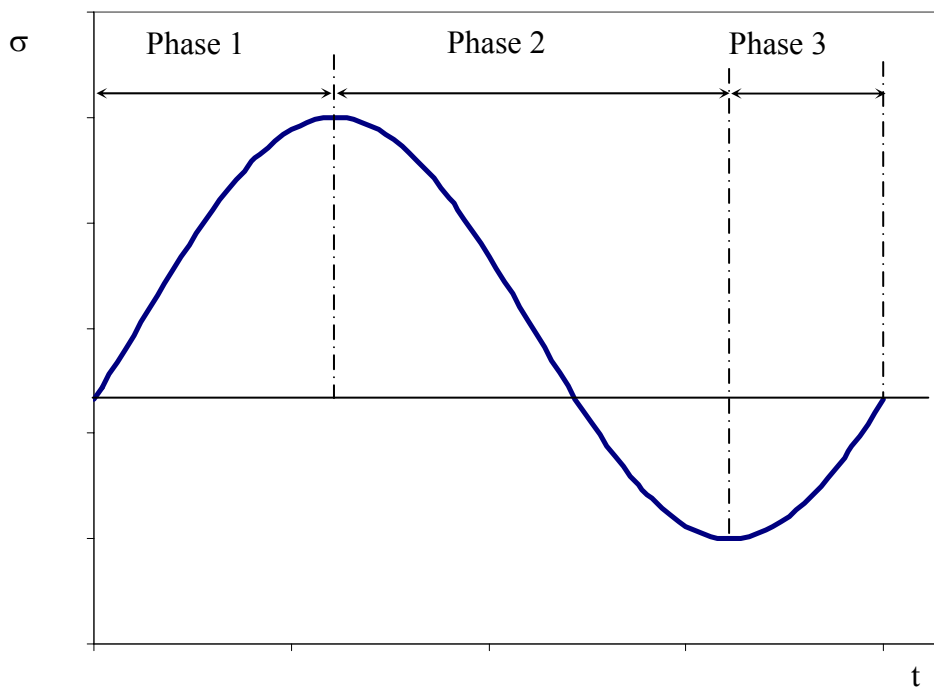


Figure 2.5: Sine wave phases

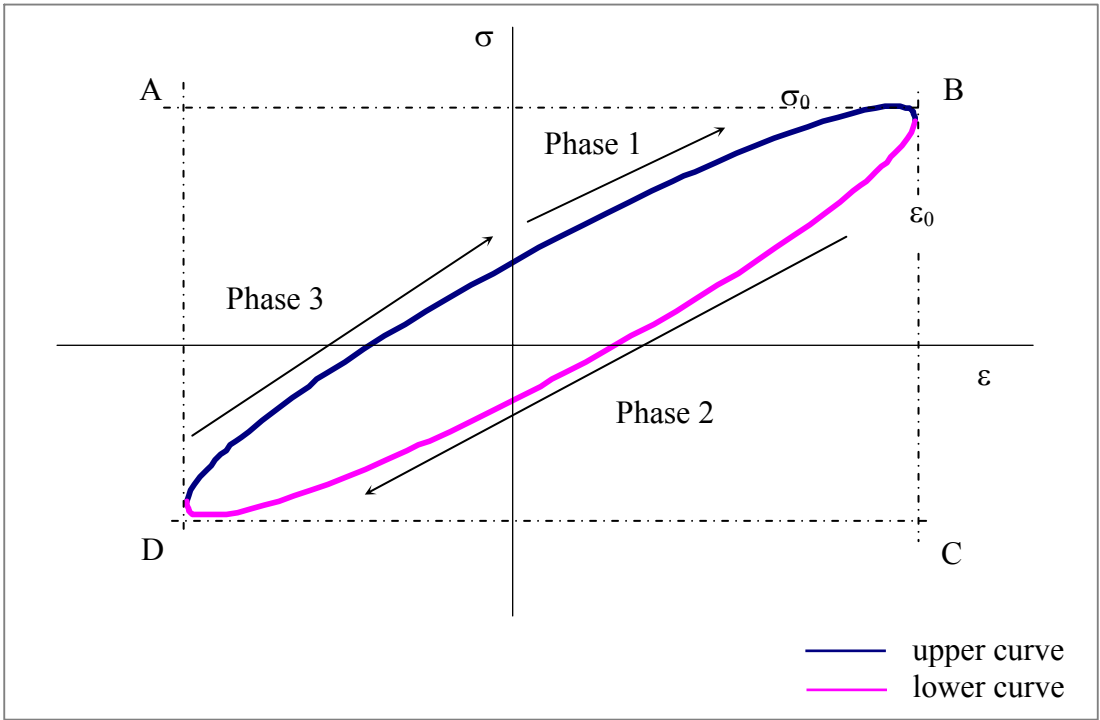


Figure 2.6: Hysteresis loop, $\delta = 20^\circ$

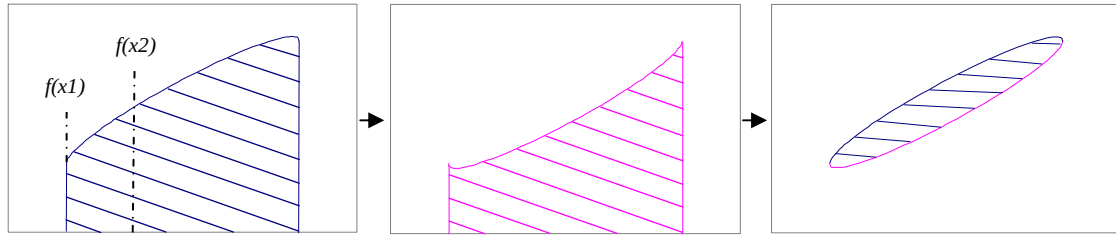


Figure 2.7: Determination of area of hysteresis ellipse

The damping factor can then be calculated from the following equation:

$$\text{Damping factor} = \sin \delta = \frac{4 \cdot (\text{Area of ellipse})}{\pi \cdot (\text{Area of rectangle ABCD})}$$

If damage formation and growth occurs under fatigue loading, the storage and loss (damping factor) moduli can be expected to decrease and increase respectively with increasing number of fatigue cycles (Figure 2.8).

In order to analyse the material changes over time, each recorded cycle of data must be analysed. Due to the large amount of data generated during fatigue testing this is best done using a computer program. For the tests undertaken in formulating this guide (detailed in Section 3), a macro was written in Visual Basic (Microsoft Excel) to analyse all fatigue data.

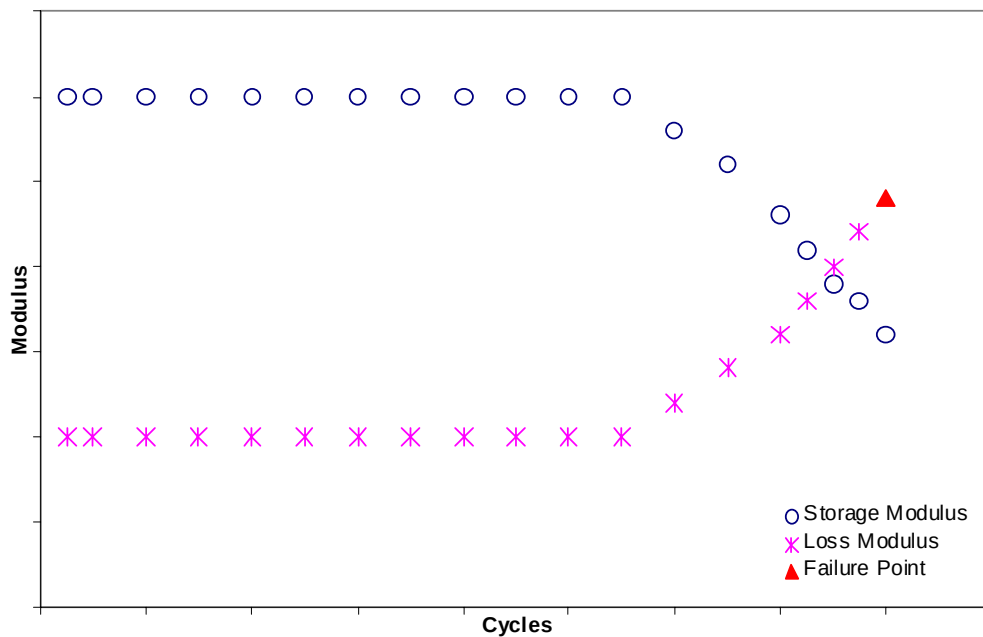


Figure 2.8: Storage and loss modulus changes

Defect Tolerance Assessment Methods

3

IN THIS CHAPTER

- Compression-after-impact (CAI)
- Open-hole tension (OHT)
- Open-hole compression (OHC)

As previously stated, BS ISO 13003 was formulated using prior experience gained from tensile and flexural fatigue testing based on the equivalent static test methods. Following a similar approach, the methods investigated within this guide for assessing defect tolerance under long-term loading are based on equivalent static methods that are commonly used to assess defect tolerance after a one-off monotonic overload.

3.1 Compression-After-Impact (CAI)

The use of the compression-after-impact (CAI) test method for laminated fibre-reinforced plastic (FRP) materials, where the critical loading mode (compression) is directly linked to the predominant and critical damage type (i.e. delamination), is common within the aerospace industry. Laminated wing skins are typically designed with compression performance as one of the main design drivers. Therefore compression stress and/or stiffness/strain are key material properties that need to be characterised as they will be significantly affected by the presence of damage within the material.

Low velocity impact events such as tool drop or stone impact, often give rise to local delaminations within laminated composite structures. Even though the impact may be transverse to the laminate, damage often propagates along the planes between adjacent layers since these planes do not benefit from the reinforcing effect of the fibres. Growth of the defect will in many cases occur by extension of the delamination into the surrounding material that may not have been directly affected by the initial impact event. The CAI method is typically used to compare residual compression properties to critical design values (or plain compression properties) in order to assess the susceptibility of a material to the growth of such delaminations under quasi-static compressive loading.

The following sections provide details on a static compression-after-impact (CAI) test method proposed by the Japanese Plastics Industry Federation (JPIF) to ISO (International Standards Organisation) and best practice for its use in fatigue.

3.1.1 Draft static ISO CAI method

This section provides brief details of a static compression-after-impact (CAI) test method proposed by the JPIF for ISO standardisation and supported by NPL. More detail on the method can be found in an NPL Measurement Note [6] that evaluated the JPIF CAI proposal and the full draft procedure can be found in a report [7] detailing an inter-laboratory round-robin validation exercise that was undertaken by NPL to provide supporting precision data. The CAI test detailed consists of three phases as shown schematically in Figure 3.1.

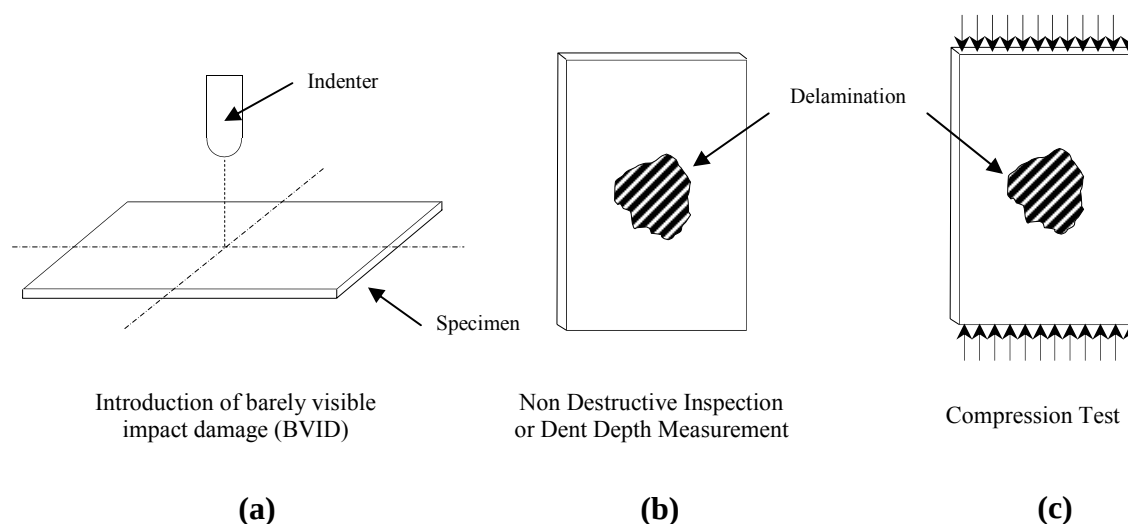


Figure 3.1: Principle of the compression-after-impact (CAI) test

3.1.1.1 Phase 1 - Impact resistance - the first phase is to generate barely visible impact damage (BVID) avoiding penetration of the test plate. BVID is defined as a 0.3 mm deep dent caused by the impact event. The preferred method of introducing BVID is based on a specified level of impact energy (6.67 J per mm thickness) applied to one face of specimens made of a balanced and symmetric composite laminate. An alternative method allows the operator to vary the level of impact energy in order to determine the energy level required to cause BVID. An additional ISO method is to be proposed and drafted to cover this method of setting the impact energy.

For impact resistance tests, rectangular specimens (100 x 150 x ~4 mm) should be positioned on a steel support plate above a 75 mm x 125 mm cut out. Specimens should be centrally placed over the cut out region and four toggle clamps with rubber tips used to hold the specimens flat against the test jig. The impact support plate should be positioned centrally on the axis of a drop weight impact tower and the impact tests performed. The drop mass and height can be varied in order to give the correct level of impact energy. Each impact test should be performed on a separate specimen and a second strike prevention device should be employed to ensure that each specimen receives only one impact.

3.1.1.2 Phase 2 - Inspection and measurement of damage - the second phase consists of assessing the level of impact damage by non-destructive inspection or by measurement of dent depth on the impacted face. The area and geometry of the damage created by the impact should be measured by means of an appropriate non-destructive evaluation (NDE) technique, and/or the dent depth can be measured by a suitable device.

3.1.1.3 Phase 3 - Residual compression tests - measurement of residual compression properties is undertaken in the third and final stage. An in-plane compressive load is applied to impacted specimens until failure and the compression-after-impact strength, modulus and strain are calculated from the load-strain response.

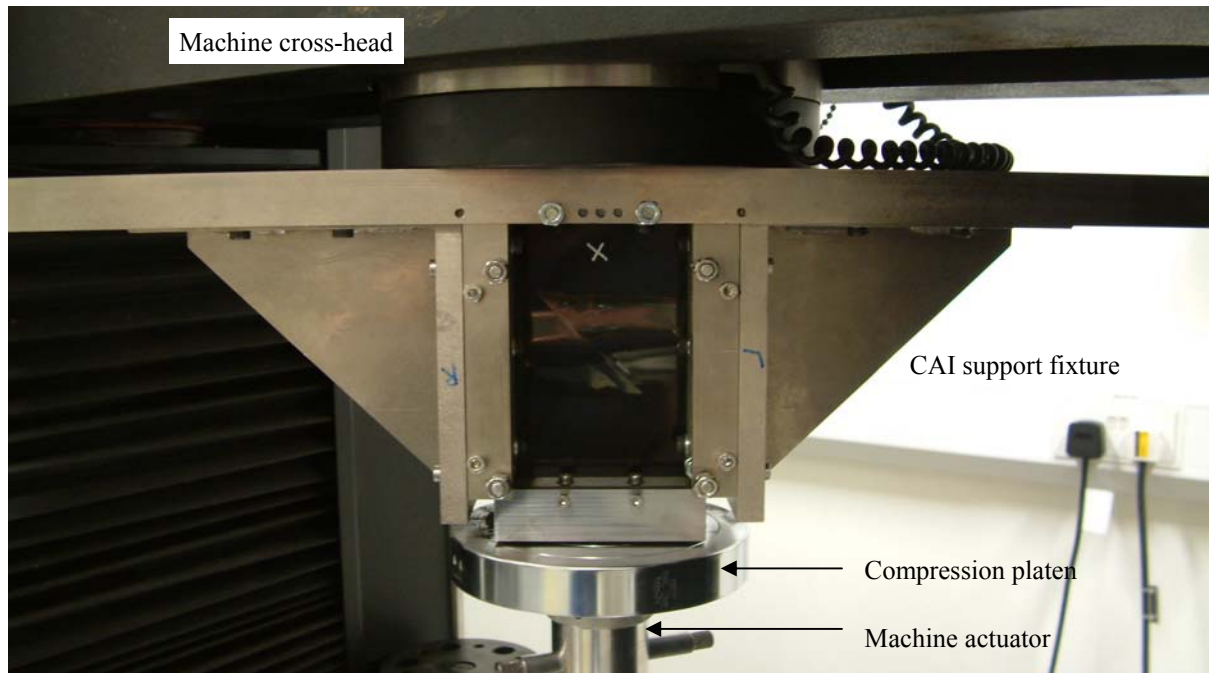


Figure 3.2: CAI jig (inverted) mounted on hydraulic fatigue machine

3.1.2 CAI method under fatigue loading

The following sections detail the use of the CAI method under fatigue loading. Tests on two material systems, supplied by Hexcel Composites Ltd. and Gurit Holdings AG (previously SP Systems Ltd.) as industry co-funding contributions, are reported to illustrate the method. Both materials were unidirectional (UD) carbon fibre-reinforced epoxy pre-pregs. The material systems used and measured fibre volume fractions are detailed in Table 3.1.

3.1.2.1 Experimental set-up

For residual CAI fatigue tests, the CAI support jig should be used on an appropriate hydraulic test machine (Figure 3.2). In order to improve the control of the test machine, the heavy base of the CAI support jig should be bolted onto the load cell, which in turn should be mounted on the stationary crosshead of the machine. (Figure 3.2 shows an inverted support jig attached to the stationary crosshead). The top loading plate should then be positioned on a compression platen screwed into the actuator.

Table 3.1: Details of materials used in CAI fatigue evaluation

Material	Supplier	Generic Description	Measured fibre volume fraction V_f (%)
1	Gurit	• unidirectional carbon fibre-reinforced epoxy	57.2
2	Hexcel	• autoclave cured	
		• quasi-isotropic lay-up $(+45^\circ/0^\circ/-45^\circ/90^\circ)_{2s}$	56.5

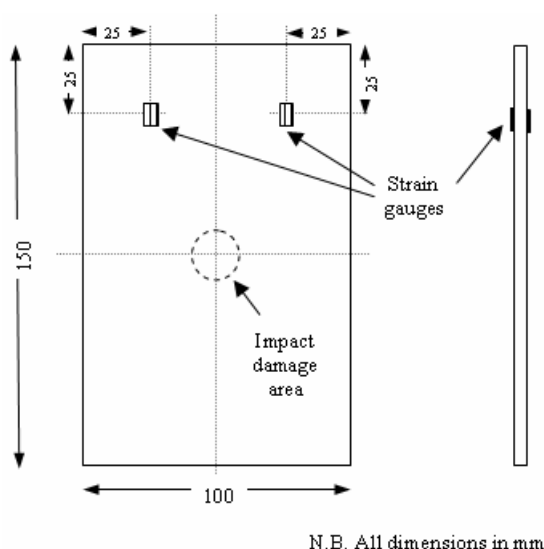


Figure 3.3: Recommended position of strain gauges on CAI test panels

For static CAI tests, the support jig is typically used on a servo-electric test machine, where good alignment is relatively easily achieved. As the fatigue tests will be performed with the test jig mounted on a hydraulic machine, correct alignment of the loading jig is critical. Alignment checks should be made before any tests are undertaken.

It is recommended that the alignment is checked for at least two impacted, strain gauged specimens by monitoring the degree of bending during loading. (N.B. un-impacted specimens can also be used for alignment checks). Pairs of strain gauges should be bonded to specimens as per Figure 3.3 and trial compression tests undertaken, initially elastically to ~ 3000 microstrain and then to failure. In the proposed static ISO CAI method, bending is deemed acceptable if the difference between average strains recorded on each face of the specimen throughout the duration of the test is less than or equal to 10 %. All alignment tests undertaken in support of this guide resulted in less than 10 % bending and hence the alignment of the CAI jig on the hydraulic machine was deemed acceptable.

Determination of the ultimate CAI stress for determining the relative stress levels to use in the fatigue programme, should be undertaken at the fatigue loading rate (Section 2.1.4) if the material properties are rate dependent. This is typically the case for GFRP systems, however the material properties for CFRP materials tend to be relatively insensitive to the testing rate and hence tests can be undertaken at the standard quasi-static rate (between 0.5 and 2 mm/min). In order to verify that this was the case, tests were performed at a rate equivalent to the fatigue rate and quasi-statically. As expected, little difference between the strength values was observed for both the quasi-static and fatigue rate tests. The ultimate CAI strengths used to determine the stress levels used in this fatigue programme are shown in Table 3.2.

Table 3.2: Percentage and absolute stress levels for CAI and plain compression fatigue tests

Test	Material	Mean static strength (MPa)	$\sigma_{\min}$ for percentages of static compression strength (MPa)							
			50 %	62.5 %	70 %	72.5 %	75 %	77.5 %	80 %	85 %
CAI (ISO draft)	1	136	-	85	95	98	102	105	109	-
	2	200	100	125	140	145	150	-	160	170
Compression [8]	1	454	-	-	318	-	341	-	364	-

Measurement of compressive strain during fatigue tests should be performed using one of the following methods:

- The machine actuator can be used to record displacement throughout the tests and in turn strain can be calculated using the specimen length. However, this method is likely to lead to erroneous results due to compliance in the loading jig,
- A clip gauge extensometer or LVDT can be used to monitor the displacement/extension over the specimen length and hence strain,
- Adhesively bonded strain gauges, located in positions shown in Figure 3.3, can be used to provide direct measurement of strain. However, the choice of adhesive is crucial to ensure that gauges remain bonded throughout the fatigue test and it is recommended that trial tests be undertaken to ensure that this is the case.
- Data logging equipment is required that is able to record data a sufficient frequency to fully define a load cycle.

Measurement of displacement (strain) during the tests in this study was performed using the actuator displacement. As the loading train for the CAI support jig is relatively short it was considered that there was a minimal amount of system compliance.

3.1.2.2 Fatigue test programme

For guidance on undertaking CAI fatigue tests, BS ISO 13003 [5] should be followed and the reader is referred to this standard for more details on fatigue terminology and methodology. Selection of the most appropriate fatigue regime should be made after considering the dominant defect type present in the material. For CAI specimens this is delamination and the critical loading mode is compression. Therefore it is most appropriate for CAI tests to be carried out under compression-compression fatigue loading (Figure 3.4) where:

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} = 10$$

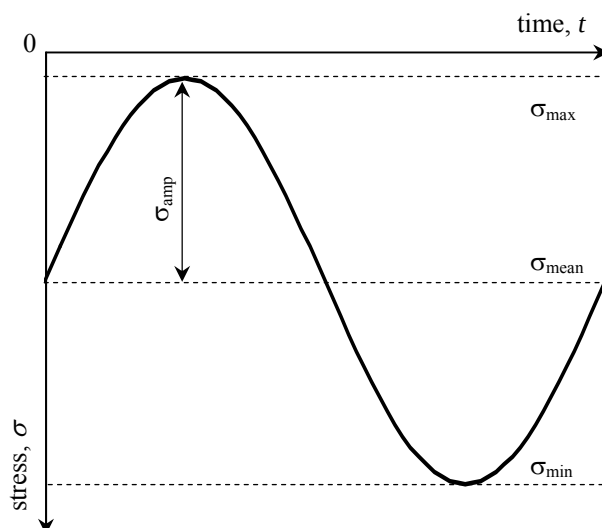


Figure 3.4: Compression-compression fatigue cycle for CAI tests (R=10)

Values of $\sigma_{\min}$ (equivalent to maximum compressive stress) should be calculated as various percentages of the measured mean static CAI strength. The maximum, mean and amplitude stress values should then be calculated using $R=10$. Ideally the fatigue life should be determined by a test programme consisting of at least 5 tests at each of 4 percentage levels of $\sigma_{\min}$ (as recommended in [5]). However this can be varied to enable tests to be undertaken at additional stress levels so that a greater extent of the stress (S) versus number of fatigue cycles (N) plot can be investigated. Stress levels used for fatigue testing of CAI specimens are detailed in Table 3.2.

A test frequency of 5 Hz was used after checks were made using a surface mounted thermocouple as to the extent of autogenous heating during loading. It was found that there was little or no rise in the temperature of specimens at this fatigue rate.

After careful positioning in the test rig (correct vertical alignment was ensured using a spirit level) specimens were tested under load control using suitable control software (e.g. Instron MAX) and a sinusoidal cyclic waveform (Figure 3.4). Using the minimum, maximum, mean and amplitude stress values for each percentage stress level and the individual specimen dimensions, the corresponding load values were calculated for each specimen and used as input into the control software.

Specimens should be tested in fatigue until failure occurs or the fatigue life, in this study 2×10^6 cycles, has been reached. Specimens that reach the fatigue life without failure are classed as 'run-outs'.

(N.B. The fatigue life is set according to the number of loading cycles the material will see in its intended application. For CFRP materials used for aerospace applications, 10^6 cycles is typically defined as material's design fatigue life).

Control software should be used to record the time, load, actuator position and cycle number for each fatigue cycle logged. Due to the large number of loading cycles required to cause failure, data is typically logged on a logarithmic scale. For the tests in this study data was logged using a logarithmic scale a cycle interval of 5 i.e. data was recorded according to the following pattern of cycles 1, 2, 3, 4, 5, 10, 15, 20, 25, 50, 75, 100, 125, 250, 375, 500 etc. Logging of each cycle should also be triggered when a pre-defined change in the load or displacement amplitude is detected by the software. This should ensure that the more rapid changes in material performance near to failure are recorded.

3.1.3 Comparison to undamaged plain compression data (BS EN ISO 14126 [8])

For static tests, it is common practice to evaluate the effect of a defect on the material properties by comparing the ultimate properties to plain, undamaged properties. In order to compare the fatigue performance of CAI specimens to the undamaged fatigue performance, a number of fatigue tests were undertaken on plain compression specimens. (It is noted that this was only performed for material 1).

Trial static tests were undertaken on un-impacted coupons with the same dimensions as the CAI specimens i.e. 150 x 100 x ~4-5 mm using the CAI support jig. As expected these tests proved unsuccessful with specimens failing by buckling rather than compression. Therefore undamaged compression tests should be carried out using the specimen dimensions (125 x 25 x ~4-5 mm) and end-loading jig detailed in BS EN ISO 14126 [8].

The four pillar die set end-loading compression jig was mounted on a hydraulic test machine (Instron 1251) as shown in Figure 3.5. The alignment of the jig on the test machine was set using a ground steel bar, in place of the specimen, to ensure that the top and bottom loading blocks were correctly aligned.



Figure 3.5: End-loading compression jig mounted on hydraulic fatigue machine

A number of static tests to failure were undertaken to determine the mean ultimate compression strength, and the maximum, mean and amplitude stress values for a range of percentage (of ultimate) stress levels were calculated (Table 3.2).

As for the CAI fatigue tests, a sinusoidal cyclic waveform was used, tests were run under software control at a frequency of 5 Hz and the same data logging sequence was also used.

3.1.4 Comments on CAI fatigue results

Results of fatigue tests, and specifically here CAI and plain compression fatigue tests, can be plotted in different ways to provide information as to the fatigue life and illustrate material changes as a function of fatigue cycles. The most common method is to plot the maximum stress level against the log of fatigue cycles (Figure 3.6) from which either the fatigue life for a specific stress level or the maximum sustainable stress level corresponding to a given fatigue life can be determined. In general the CAI and compressive fatigue S-N plots tend to be very flat as is typically the case for CFRP materials. (*N.B. some fatigue tests were run for longer than 2 million cycles to investigate how many additional cycles would be required for failure. Individual fatigue results are detailed in Tables A1-A3, Appendix A*).

In addition, the normalised compressive stress against the log of fatigue cycles can also be plotted (Figure 3.7). (*N.B. the scale on the y axis goes up to 1.1 as the compressive stresses were normalised with respect to the mean ultimate compressive strength (UCS)*). The use of the normalisation framework approach to fatigue has been previously used for glass-fibre based systems [9] and is incorporated into the CoDA predictive composites software [10].

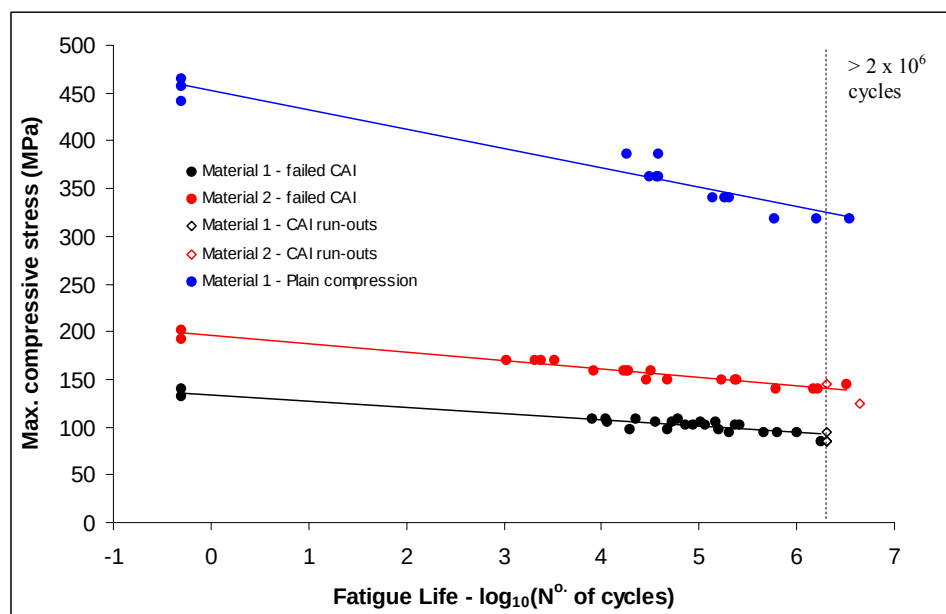


Figure 3.6: Fatigue results for CAI and plain compression tests

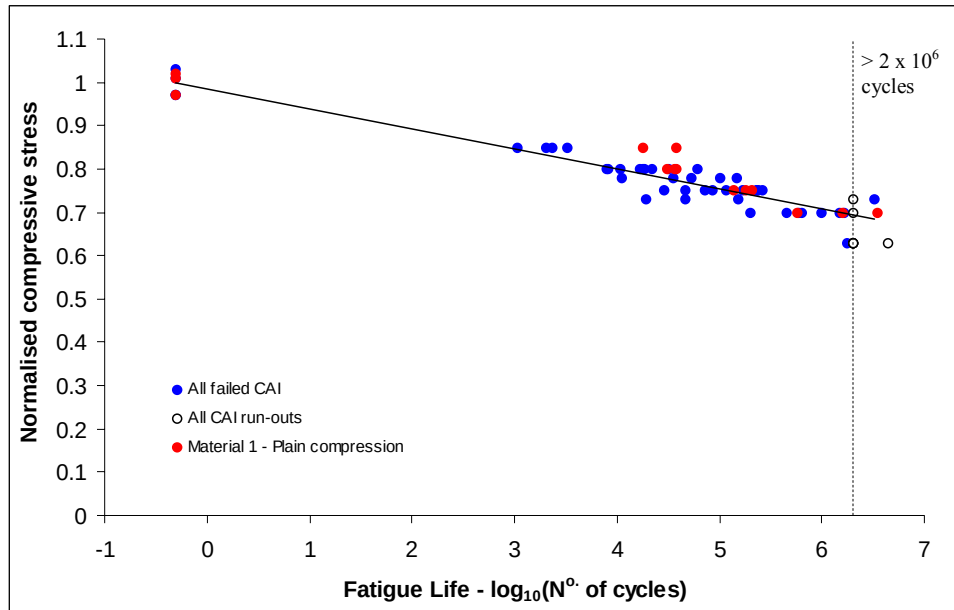


Figure 3.7: Normalised fatigue results for CAI and plain compression tests

Compressive strains can also be plotted against number of fatigue cycles in order to monitor changes in minimum and maximum levels (Figure 3.8) that may indicate damage growth and related changes in material behaviour. It is noted that the strain levels shown in Figure 3.8 have been calculated from the actuator position and generally show a low level of variation up until just prior to failure. From the calculated strain values, the compressive modulus can be determined as detailed in Section 2.1.5.1. Figure 3.9 shows the normalised compressive modulus calculated by this method plotted against fatigue life. In general there is little

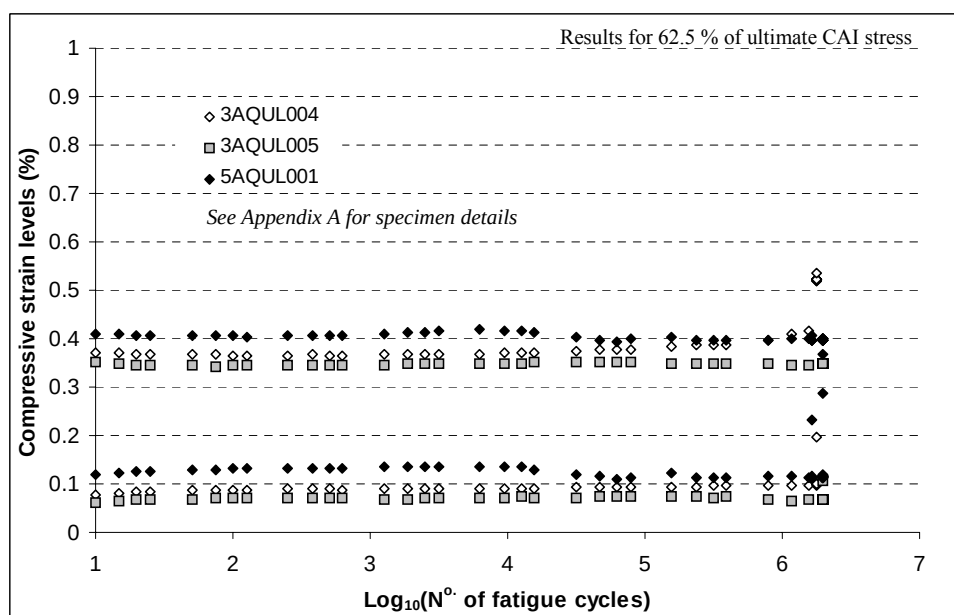


Figure 3.8: Example of minimum and maximum strain levels for CAI fatigue tests

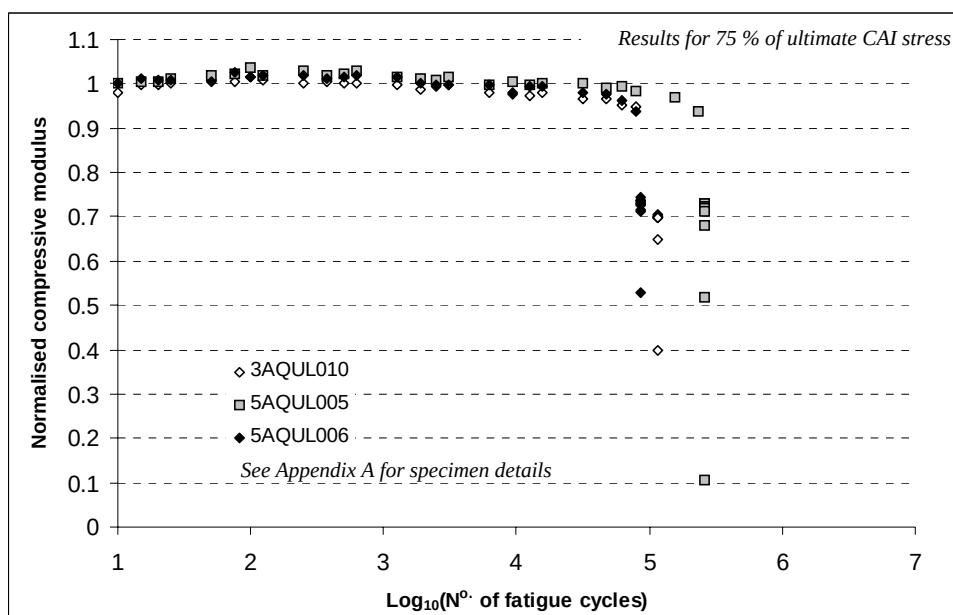


Figure 3.9: Example of normalised compressive modulus vs. log(fatigue cycles)

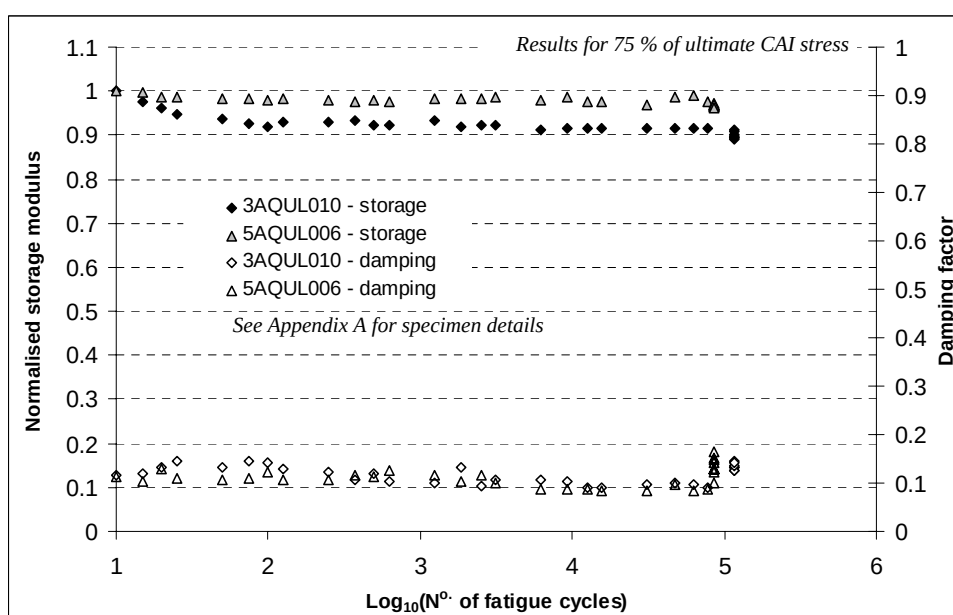


Figure 3.10: Example of normalised storage modulus & damping factor vs. log(fatigue cycles)

change in modulus until just prior to failure and this is consistent with little or no change in minimum and maximum strain levels until just prior to failure. It is noted here that the most sensitive technique for measuring specimen deflection and strain should be used in order to measure these changes prior to failure with the greatest degree of accuracy. Also, it is noted that a linear time or fatigue cycles curve will be a very different shape and could be used for more accurate detection of changes in material property.

Figure 3.10 shows a plot of storage modulus and damping factor against fatigue life determined from measured hysteresis loops according to the method described in Section 2.1.5.2. Normalised storage modulus values can be plotted if the absolute values tend to

show significant scatter as was the case for the CAI fatigue results. It is noted that a large amount of scatter was observed in the loss modulus data and hence damping factor was chosen as the indicator of damage growth/increase. Plots of storage modulus and damping factor tend to show very little change over fatigue life indicating that damage growth is minimal until just prior to failure.

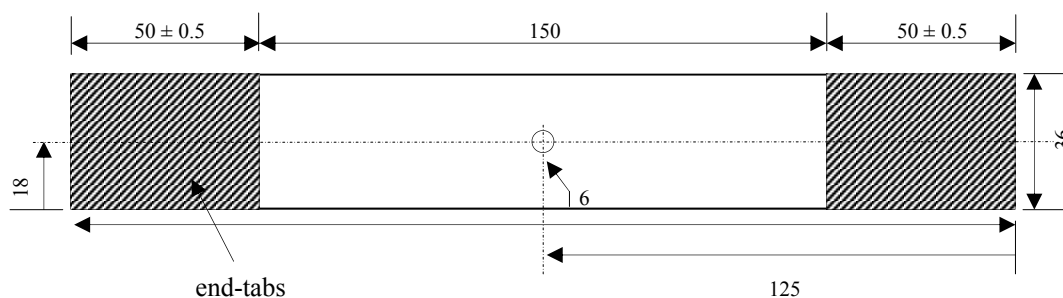


Figure 3.11: Open-hole tension specimen

3.2 Open-Hole Tension (OHT)

3.2.1 Static method

The open-hole-tension (OHT) test is a well established static method for determining the effect of a hole on the tensile strength of thermoset and thermoplastic fibre-reinforced plastic composites. The static method used under fatigue loading in this guide is currently an ISO New work item [11]. The specimen geometry and dimensions are shown in Figure 3.11. The test specimen consists of a strip of rectangular cross-section with a plain hole centrally located. End-tabs are shown in Figure 3.11, but are not normally required. The specimen is loaded in tension and the maximum load sustained by the specimen is used to determine the open-hole (notched) strength based on the gross specimen cross sectional area. A gross tensile stress concentration factor is calculated from the ratio of the unnotched tensile strength divided by the open-hole (notched) strength.

There are several similar versions of the test method including EN6035 [12], ASTM D5766 [13] and AITM 1.007 [14]. All of these methods can also be used to determine the filled-hole tensile strength, where a close fitting, plain metallic pin is inserted into the hole to mimic the effect of rivet or bolt shaft.

3.2.2 OHT method under fatigue loading

The following sections detail the use of the OHT test method under tension-tension fatigue loading. A unidirectional (UD) carbon fibre-reinforced epoxy pre-preg supplied by Gurit Holdings AG was used to illustrate this method (Table 3.1). The lay-up used was quasi-isotropic $(+45^\circ/0^\circ/-45^\circ/90^\circ)_{2s}$.

3.2.2.1 Experimental set-up

OHT fatigue tests necessitate the use of a hydraulic test machine fitted with a dynamically rated load cell with a load range large enough to apply the loads required. The OHT test method does not require a bespoke 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. It has been found that a grip pressure of between 150-200 bar provides satisfactory gripping. Care should be taken if higher grip pressures are used to ensure that damage to specimens, which can lead to premature failure, is avoided. Specimens should be gripped over the end-tabbed regions indicated in Figure 3.11, although the use of end-tabs is not generally required.

The static OHT method does not require the stiffness of specimens to be measured, however for the tests undertaken in formulating this guide, efforts were made to measure the longitudinal tensile modulus and therefore detect damage accumulation, with clip gauge extensometers.

The Instron extensometers (Figure 3.12) used have a full scale deflection of ± 2.5 mm and can monitor strain over a range of gauge lengths via the use of spacer sections. A gauge length of 50 mm is typically used for plain tensile tests (as recommended in [15]) and was therefore also used for the OHT fatigue tests. The extensometers should be attached directly to specimens via knife edges which lie flush against the specimen surface and are held by springs and/or rubber 'O' rings stretched around the specimen. To accommodate the 36 mm wide OHT specimens, wider knife edges were manufactured. Where possible it is recommended that two extensometers should be used i.e. one on each specimen surface, in order to monitor any misalignment of the specimen and record an average strain output.



Figure 3.12: Extensometers used for measurement of strain in OHT tests

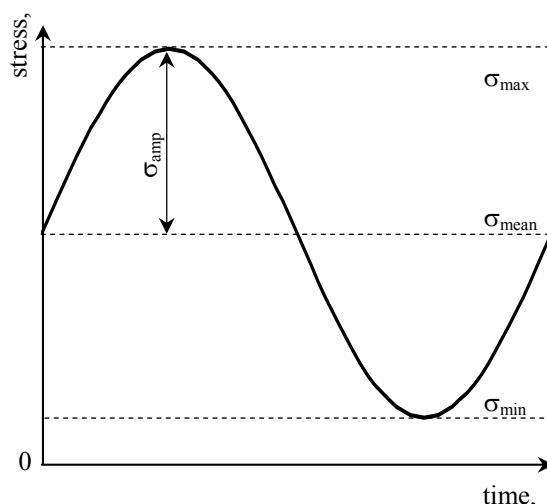


Figure 3.13: Tension-tension fatigue cycle (R=0.1)

3.2.2.2 Fatigue test programme

The principle of the OHT method is to measure the effect of a hole on the tensile performance of the material. Therefore the most appropriate fatigue regime is tension-tension with $R=0.1$ (Figure 3.13). Fully reversed loading ($R=-1$) i.e. tension-compression is also of interest here but the OHT specimen is not suitable as the long free length between grips would result in the specimen buckling when loaded in compression. Instead, the shorter open-hole-compression (OHC) specimen design is used for fully reversed loading and is examined in Section 3.3.2.2.

Determination of the ultimate OHT stress for determining the relative stress levels to use in the fatigue programme, should be undertaken at the fatigue rate (Section 2.1.4) if the material properties are anticipated to be rate dependent. For the CFRP specimens tested in this study, rate dependence was not an issue and ultimate stress tests were undertaken at a quasi-static rate of 1 mm/min. OHT modulus values were also measured.

Values of $\sigma_{\max}$ should be calculated as various percentages of the measured mean static OHT strength. The maximum, mean and amplitude stress values should then be calculated using $R=0.1$. As for the CAI fatigue tests, ideally the fatigue life should be determined by a test programme consisting of at least 5 tests at each of 4 percentage levels of $\sigma_{\max}$. If uncertainty exists over which percentage/absolute stress levels should be used, then it is recommended that trial tests should be performed at a range of levels, starting with the highest first. Care should be taken not to use too high a value as it then becomes possible that a stress level corresponding to the scatter of the static ultimate tests could be chosen. For the OHT tests undertaken, a starting stress level of 80 % of the static OHT was used. However despite a large amount of damage propagation throughout the trials the result was that no failure occurred even after 10^7 cycles. Further discussion on results is provided in Section 3.2.2.3. Higher stress levels (90 and 95 %) were used for additional fatigue tests (Table 3.3).

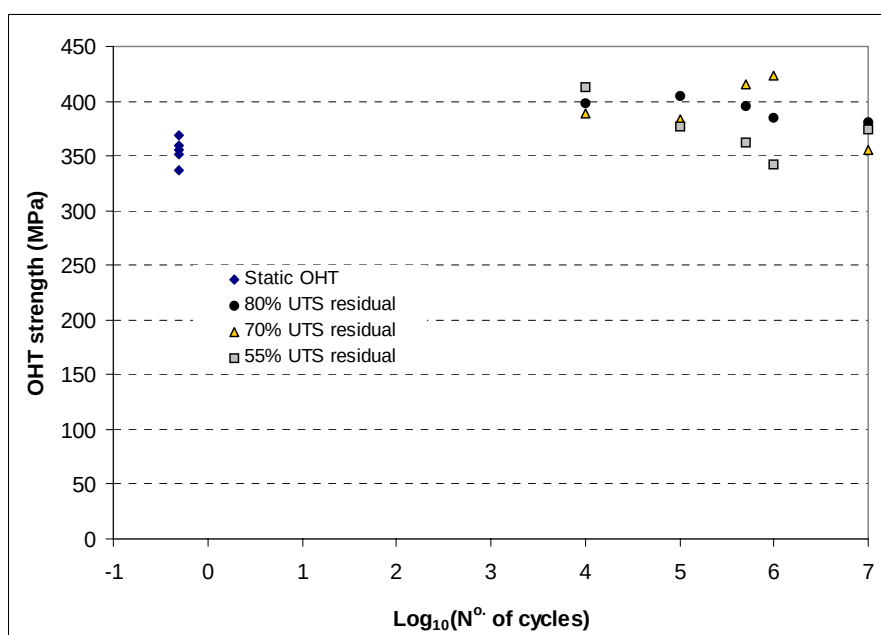
Table 3.3: Percentage and absolute stress levels for OHT fatigue tests

Test		Mean static strength (MPa)	$\sigma_{\max}$ as percentages of mean static OHT strength (MPa)						
			50 %	55 %	60 %	70 %	80 %	90 %	95 %
OHT	tension-tension, R = 0.1	354	-	195	-	248	283	319	336

In a deviation away from BS ISO 13003 an alternative approach can be adopted to investigate the effect of fatigue on materials that exhibit extensive fatigue lives ($> 10^7$ cycles). Instead of running fatigue tests until failure, the approach used is to fatigue specimens at the same stress levels as would be used for the conventional approach but for pre-defined numbers of cycles. Residual strength and modulus tests are then performed on each of the fatigue specimens. For the OHT fatigue tests, stress levels of 55, 70 and 80 % of the OHT strength were used and tests were run to 10^4 , 10^5 , 5×10^5 , 10^6 and 10^7 cycles.

3.2.3 Comments on OHT fatigue results

When using the approach detailed in the previous section, plots of residual strength and modulus should be plotted to indicate changes in ultimate properties with fatigue cycles. Figures 3.14 and 3.15 show the OHT strength and modulus plots respectively. (*Individual results are detailed in Table A4, Appendix A*).

**Figure 3.14: Residual OHT strength results**

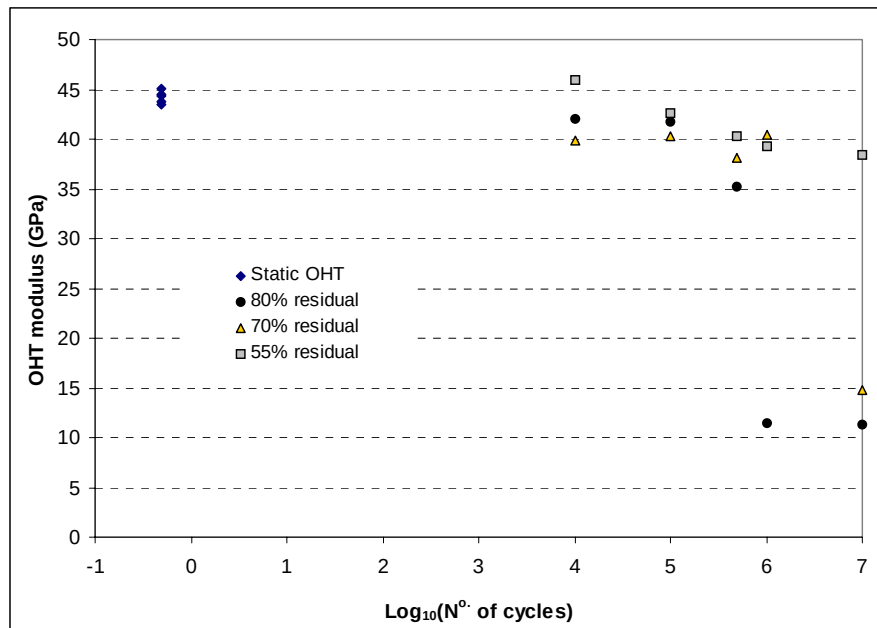


Figure 3.15: Residual OHT modulus results

It can be seen that the residual OHT strength tends to show initial increases with increasing fatigue cycles, until dropping away to approximately the un-fatigued OHT or below. The stress/strain concentration factor due to the presence of a hole lowers the tensile strength of the material. At stress levels lower than the static OHT strength, the action of fatigue causes gradual damage growth in the form of matrix micro-cracking, ply splitting and delamination (the stress/strain levels are not high enough to cause fibre fracture) which in turn relieves the stress concentration around the hole. As the tensile strength of the material is dominated by the 0° plies which may contain matrix cracking but no fibre fracture, the residual tensile strength is higher than the static OHT strength measured for un-fatigued specimens. After extensive fatigue, the damage reaches the extent that effectively the OHT specimen is divided into three separate parts. Damage growth is seen to propagate longitudinally along lines tangential to the hole resulting in the central portion of the specimen being unable to carry load. This is clearly visible in the pulse thermography image (see Section 4.2) shown in Figure 3.16.

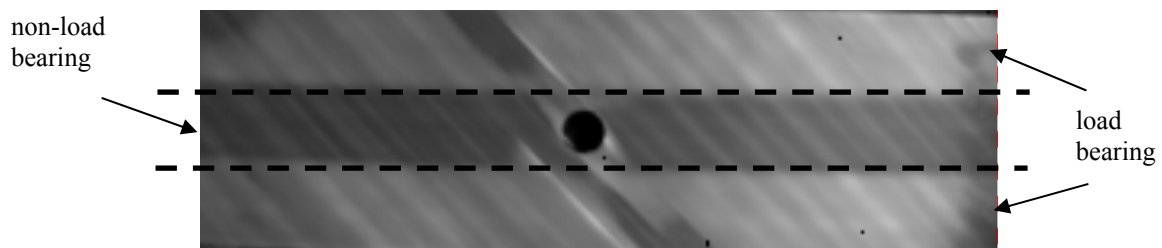


Figure 3.16: Pulse thermography image of OHT fatigue specimen (70% of static UTS for 10,000,000 cycles)

The trend for residual modulus values is that a decrease with increasing fatigue cycles is seen, the decrease being larger at the higher stress levels.

Although extensometers were used throughout the fatigue tests, the extent of surface ply splitting damage (Figure 3.17) resulted in the knife edges seated in ply cracks and also cut-through of the rubber 'O' rings used. Hence, strain data recorded was too poor for intended hysteresis loop analysis. 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.

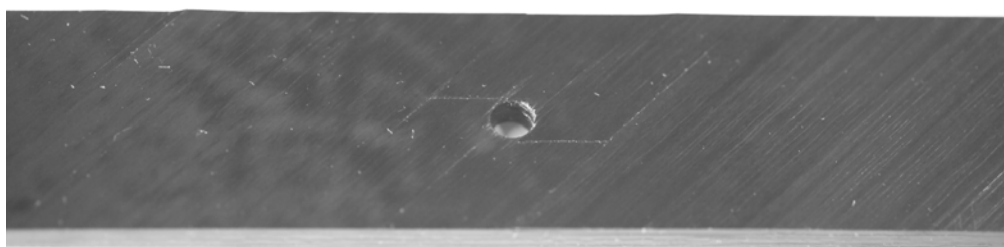


Figure 3.17: Surface ply splitting (+45°) - OHT fatigue specimen

3.3 Open-Hole Compression (OHC)

3.3.1 Static method

The open-hole-compression (OHC) test is a well established static method for determining the effect of a hole on the compressive strength of thermoset and thermoplastic fibre-reinforced plastic composites. The method used under fatigue loading in this guide is currently an ISO New work item [16]. The specimen geometry and dimensions are shown in Figure 3.18. The test specimen consists of a strip of rectangular cross-section with a plain hole centrally located. End-tabs are shown in Figure 3.18 but as for the OHT specimens they are not normally required. The specimen is loaded in compression and the maximum load sustained is used to determine the open-hole (notched) strength based on the gross specimen cross sectional area. A gross compression stress concentration factor is calculated from the ratio of the unnotched compression strength divided by the open-hole (notched) strength.

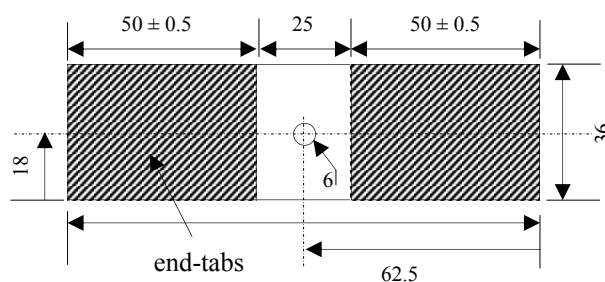


Figure 3.18: Open-hole compression specimen

There are several similar versions of the test method including EN6036 [17], ASTM D6484 [18] and AITM 1.008 [19]. All of these methods can also be used to determine the filled-hole compression strength, where a close fitting, plain metallic pin is inserted to mimic the effect of rivet or bolt shaft.

3.3.2 OHC method under fatigue loading

The following sections detail the use of the OHC test method for under compression-compression ($R=10$) and tension-compression ($R=-1$) fatigue loading. The unidirectional (UD) carbon fibre-reinforced epoxy pre-preg used for CAI and OHT fatigue evaluations (Table 3.1) was used in this work. The same quasi-isotropic lay-up was used $(+45^\circ/0^\circ/-45^\circ/90^\circ)_{2s}$.

3.3.2.1 Experimental set-up

The test machine and gripping set-up for OHC fatigue tests should be the same as for OHT tests (section 3.2.2.1). However, due to the relatively short gauge length (25 mm) of the OHC specimen and the proximity of the hydraulic grips to each other (Figure 3.19) it is not possible to use an extensometer to measure specimen deflection/strain. If accurate measurement of the strain is required (note that strain is not required to be measured in the static method [16]) then a specially designed extensometer of appropriate size or strain gauges positioned away from the hole would be needed. It is emphasised here that strain data



Figure 3.19: OHC specimen gripped in hydraulic wedge action grips

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.

3.3.2.2 Fatigue test programme

The OHC test method can be used to assess the criticality of a hole on material performance under compression-compression fatigue loading. The test method does not require a special loading jig, as is the case for other OHC methods [18], and compressive load is transferred into the coupon by shear loading via the hydraulic gripping arrangement. The test set-up has the advantage that if the hydraulic grips are fatigue rated then tensile loading can also be applied and the coupon can be loaded in tension-compression fatigue. The work performed in this study has evaluated the OHC test method under both fatigue regimes using the sinusoidal waveforms in Figures 3.4 and 3.20. As before a test frequency of 5 Hz was used.

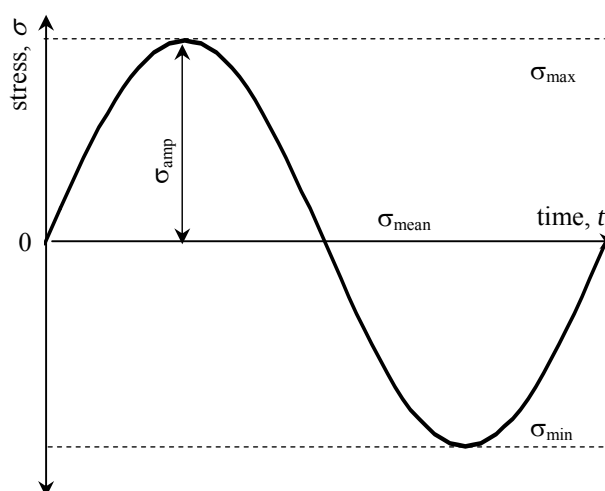


Figure 3.20: Tension-compression (fully reversed) fatigue cycle ($R=-1$)

Determination of the ultimate OHC stress for determining the relative stress levels to use in the fatigue programme, was undertaken at a quasi-static rate of 1 mm/min. For compression-compression fatigue, values of σ_{min} should be calculated as various percentages of the measured mean static OHC strength. The maximum, mean and amplitude stress values should then be calculated using $R=10$. For tension-compression fatigue, the values of σ_{min} and σ_{max} should also be calculated from the mean OHC strength and $R=-1$. The absolute and percentage stress levels used in the fatigue programme are detailed in Table 3.4.

For the initial OHC compression-compression fatigue tests undertaken, a starting stress level of 80 % of the static OHC strength was used at which three failures occurred between ~20,000 - 150,000 cycles. Tests at 70 % of OHC strength resulted in specimens achieving over 10^7 cycles and therefore the residual strength approach used for OHT tests was adopted.

Table 3.4: Percentage and absolute stress levels for OHC fatigue tests

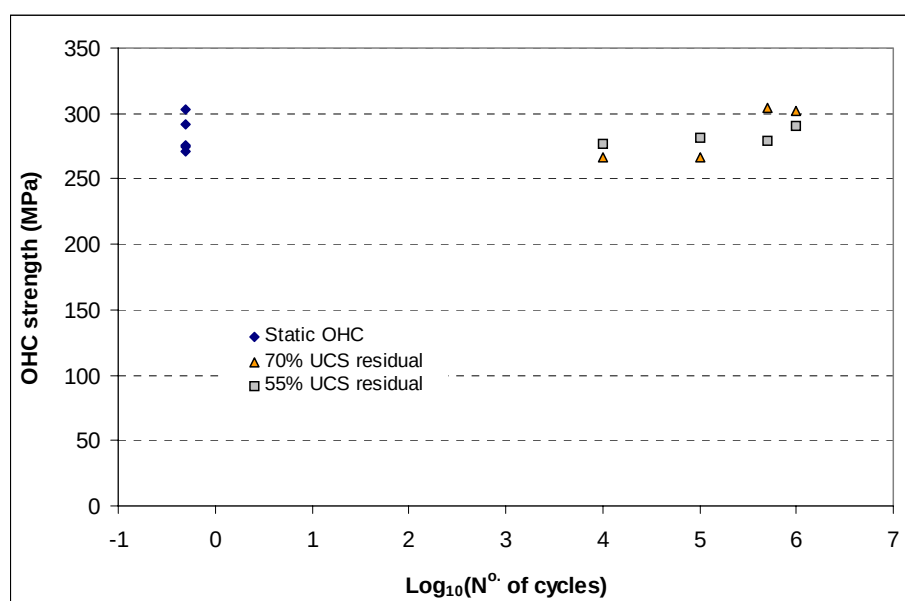
Test		Mean static strength (MPa)	$\sigma_{\max}$ (+) or $\sigma_{\min}$ (-) as percentages of mean static OHC compressive strength (MPa)						
			50 %	55 %	60 %	70 %	80 %	90 %	95 %
OHC	compression-compression, R = 10	-283	-	-156	-	-198	-226	-	-
	tension- compression, R = -1		± 142	-	± 170	± 198	± 226	-	-

Fatigue tests were undertaken at 55 and 70 % of the mean ultimate OHC strength for 10^4 , 10^5 , 5×10^5 and 10^6 cycles. It is noted that tests to 10^7 cycles were not undertaken in this case due to time constraints.

For OHC tension-compression fatigue, tests were undertaken at the stress levels shown in Table 3.4 and the approach recommended in BS ISO 13003 was followed.

3.3.3 Comments on OHC fatigue results

Figure 3.21 shows the residual OHC strength plotted against the log of number of cycles. (*Individual results are detailed in Table A5, Appendix A*). The values achieved were generally within the scatter of the ultimate values, however the 70 % stress level residual OHC strength values at around 10^6 cycles were slightly higher than the maximum ultimate stress level. This indicates that as for the OHT tests, the stress/strain concentration factor due

**Figure 3.21: Residual OHC strength results**

to the hole, is relieved due to damage initiation and propagation around the hole after fatigue loading. Damage induced due to fatigue loading is clearly visible in the X-ray image shown in Figure 3.22. As for the OHT fatigue specimens, it can be seen that damage has propagated longitudinally along lines tangent to edge of the hole. With further fatigue cycles, i.e. up to 10^7 cycles this damage would grow further resulting in detachment of the centre section and reduction in residual strength to below the ultimate OHC strength.

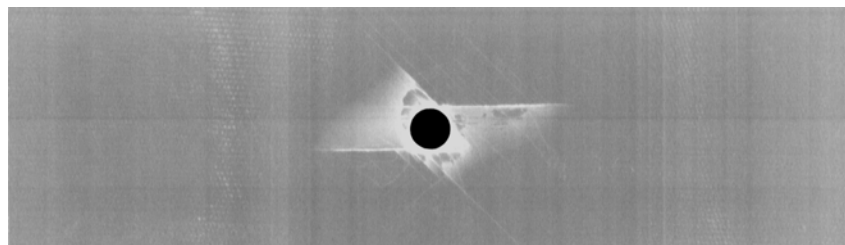


Figure 3.22: X-radiography image of OHC fatigue specimen (70% of static UCS after 1,000,000 cycles)

Figure 3.23 shows the fully reversed OHC results with a linear best fit line. (*Individual results are detailed in Table A6, Appendix A*). The results show that the fully reversed fatigue regime is much harsher than compression-compression as the fatigue life at corresponding stress levels is significantly reduced.

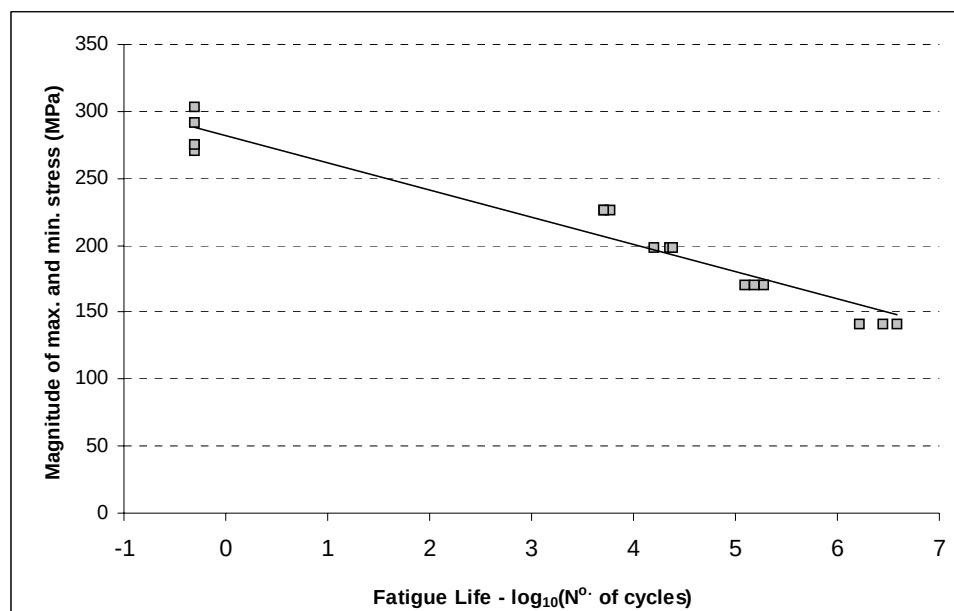


Figure 3.23: Fully reversed OHC fatigue results

3.4 Concluding Comments

This chapter has demonstrated that a number of static defect tolerance test methods (CAI, OHT, and OHC) can be readily adapted for use under fatigue loading conditions and various fatigue regimes i.e. tension-tension, tension-compression and compression-compression. When investigating the criticality of a defect on long-term performance, it is recommended that the BS ISO 13003 standard for fatigue of plain fibre-reinforced plastics is used in conjunction with the relevant static method. The guidance provided has highlighted two approaches for determining the effect of defects on plain material properties under fatigue loading, namely (i) determination of fatigue life at several stress levels as percentages of the ultimate stress and (ii) determination of residual properties after set numbers of fatigue cycles. Although some static methods may not require the stiffness of specimens to be measured, it is recommended that where possible stiffness should be monitored throughout the fatigue test in order to indicate progressive specimen degradation. In addition, suitable techniques to detect the presence of damage and measure the effect on elastic properties throughout the test by other non-destructive means should be used. Guidance on such techniques is provided in Chapter 4 through trials undertaken on fatigue test specimens detailed in this chapter.

Methods for Damage Detection

4

IN THIS CHAPTER

- Impact excitation method
- Pulse thermography
- Radiography using dye penetrant
- Ultrasonic C-scan

This chapter details non-destructive techniques that can be used either for measuring the effects of damage growth via changes in mechanical properties or for detecting the presence of damage directly.

4.1 Impact Excitation Method

The impact excitation method, described in greater detail in the following sections, is a technique that can be used to measure the elastic properties of materials by exciting various of modes of vibration.

All objects have 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 deconvoluting the recorded sound spectrum. The second method is often referred to as the impact excitation method. Equations can then be used to relate the resonant frequencies to elastic moduli.

4.1.1 Vibration modes of beams

Key to understanding the principle of the impact excitation method is to understand the modes of vibration of the test panel. These modes can depend on how and where the panel is supported, and the location at which the panel is struck.

For a prismatic beam, there are basically four vibration modes of interest:

- Out-of-plane flexural
- In-plane flexural
- Torsional
- Longitudinal

The flexural vibration frequencies are governed primarily by the Young’s modulus (E) of the test panel in the longitudinal direction, essentially independently 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.

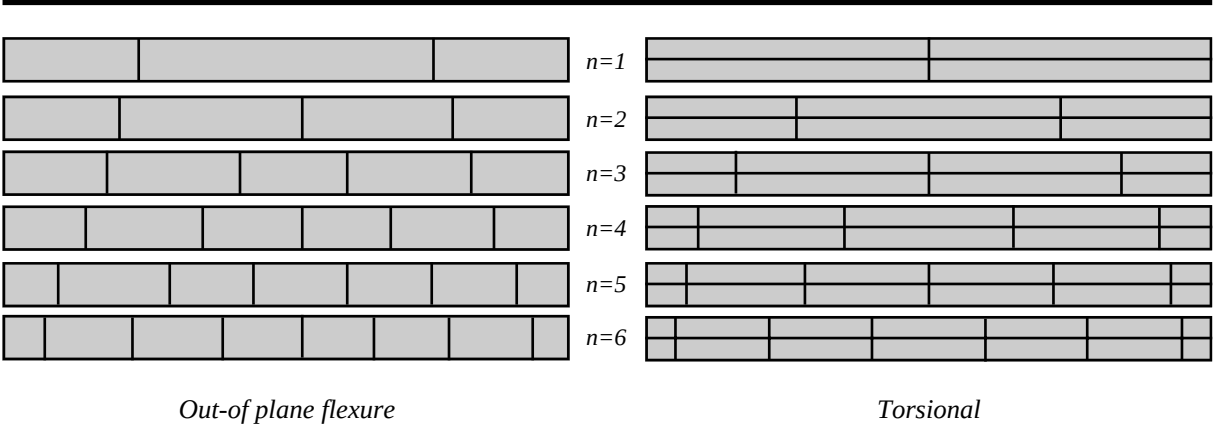


Figure 4.1: Vibration modes of a ‘free-free’ beam with nodal lines indicated

The longitudinal vibration frequencies are governed primarily by the Young’s modulus (E) of the test panel and the Poisson’s ratio in the longitudinal direction.

4.1.1.1 Out-of plane flexure

There is a series of nodes (minimum vibration) and antinodes (maximum vibration) along the length of a freely supported beam (a ‘free-free’ beam in mathematical terminology). At the lowest resonant or natural frequency (the fundamental mode), the nodes are 0.223 of the beam length from each end, with antinodes at each end and in the centre. For overtones or harmonics, there are more closely spaced nodes and antinodes, shown schematically in Figure 4.1. Since in most cases the interest is in identifying the fundamental mode ($n=1$), it is general practice to support the test panel at or close to the fundamental flexural node positions and to impact the test piece in the centre.

4.1.1.2 In-plane flexure

Turning the test-piece by 90° about an axis parallel to its length produces another fundamental and series of harmonics that relate to the geometry of the test panel. The pattern of nodes and antinodes is the same as shown in Figure 4.1.

4.1.1.3 Torsion

The torsional vibration modes for a long thin isotropic ‘free-free’ beam are different to those for flexure and are shown in Figure 4.1.

It can be seen from Figure 4.1 that in order to obtain the fundamental mode, the panel has to be supported at its centre point and vibrated at or near its ends by impacting at a position off the centre line, so that most of the energy goes towards twisting the test panel rather than flexing it. This is much harder to achieve than the simple support used for the flexure mode. Therefore an alternative approach has been used in this work to excite the $n=2$ mode. From

Figure 4.1 it can be seen that the $n=1$ mode for flexure and the $n=2$ mode for torsion have similar geometries. If the panel is simply supported at these nodal positions as in 4.1.1.1 and then impacted at the beam mid-span but to one side of the longitudinal centre line, then both the flexure $n=1$ and torsion $n=2$ modes will be excited. If the system employed can be used to detect both modes simultaneously, a second geometry set-up is not needed to obtain the Young's modulus and shear modulus.

One problem with this method is that potentially a torsional mode can interfere with a flexural mode excited at the same time. If the test panel dimensions (typically the width to thickness ratio) are not governed by a standard or test protocol then they can be selected to ensure that the flexural and torsional frequencies are significantly different to make identification clear. More information can be found in [20].

4.1.1.4 Longitudinal

Exciting the longitudinal mode vibrations is relatively easily undertaken by striking the end of the panel, but care has to be taken to ensure that rather lower frequencies due to simultaneous flexure or torsion are not also identified as the fundamental longitudinal mode. However, the fundamental longitudinal mode frequency is typically 5 to 10 times greater than that of the fundamental flexural mode and so is easier to identify.

4.1.2 Practical use of the impact excitation method

The impact excitation equipment used is shown in Figure 4.2. It 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 to nodal positions (Figure 4.1) at which positions of minimum vibration occur.

4.1.2.1 Test panel requirements

Ideally test panels should be specially prepared for this type of measurement and have dimensions and dimensional tolerances that are appropriate. However, for the work detailed in this guide, specimen dimensions have been set by the mechanical test standards used. As a result, the specimen dimensions may not be the most suitable required by the impact excitation method. However, as the purpose of using this method is to assess the effects of fatigue damage on the elastic moduli of the material and all specimen dimensions are approximately the same, measurements will be relative to each other and should indicate changes in stiffness due to cumulative damage.

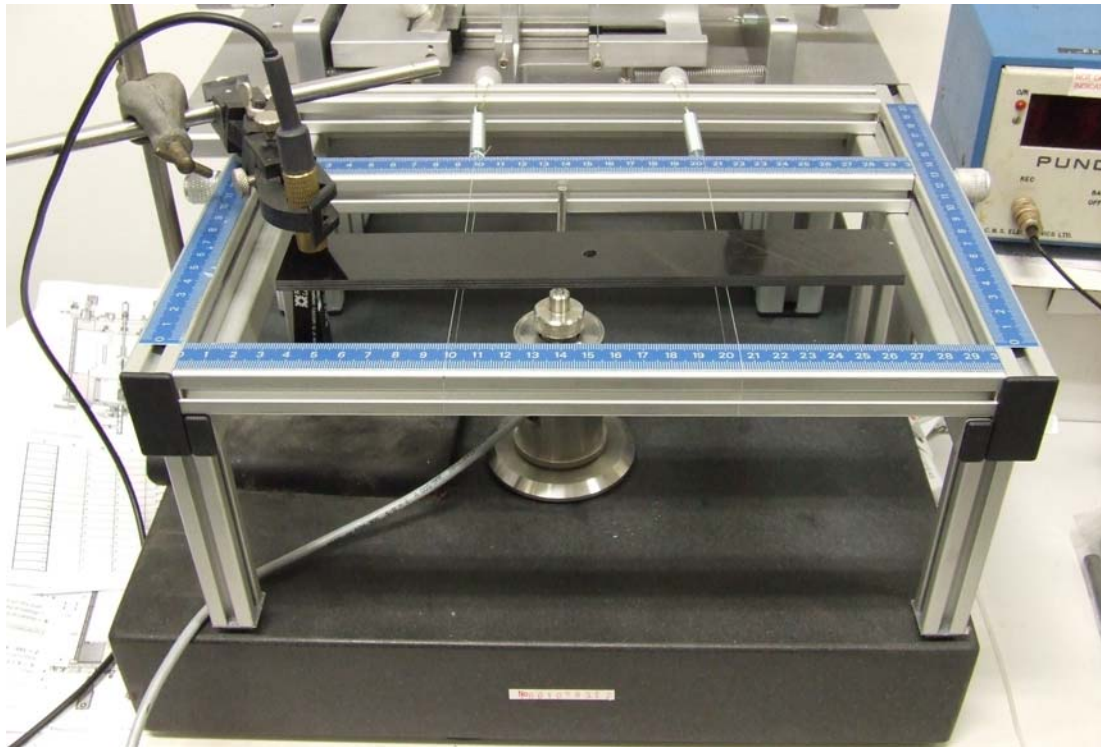


Figure 4.2: Impact excitation equipment with OHT specimen supported on wires

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 panel under consideration (Section 4.1.3).

4.1.2.2 Support method

Specimens tested in this study have been supported on taut nylon strings (Figure 4.2) at the appropriate nodal positions to ensure minimum damping as the test panel is struck. This support technique has proved successful for all modes of excitation i.e. flexural, torsional and longitudinal. It is also possible to support specimens on cotton wool or ceramic fibre however it is less likely that axial movement will be prevented during end-striking if this technique is used.

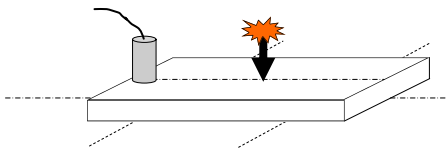
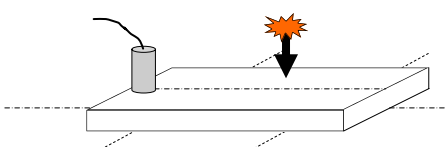
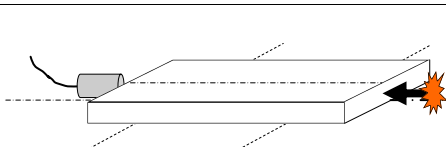
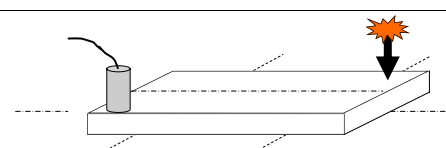
4.1.2.3 Impact excitation

The ideal impact mechanism is a single strike with a hard ball. The simplest way of doing this is to glue 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.

4.1.2.4 Vibration detection

In order to detect the vibrations of the test panel after it has been struck, a sensitive piezosensor is 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 4.1.

Table 4.1: 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

4.1.3 Identification of fundamental mode frequencies

In order to obtain an estimate of the vibration frequencies for the various modes, it is recommended that a modal analysis using finite element analysis (FEA) is undertaken for the test panel under consideration. The FEA model should replicate the shape and dimensions of the panel and where possible experimentally measured ply data should be used for input into the materials model. Modal analyses are relatively insensitive to mesh density and so a fairly

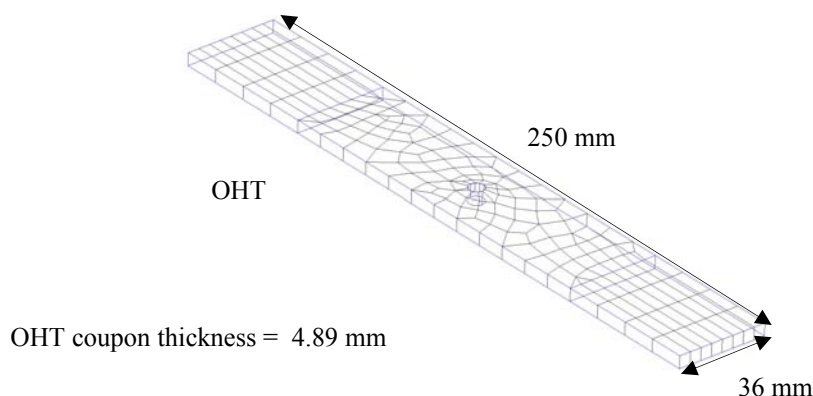


Figure 4.3: Example of FEA mesh divisions for OHT model

coarse mesh can be used which reduces the computational power and time for the analysis. An example of a mesh pattern for an OHT specimen is shown in Figure 4.3. Modal analyses should include at least the first 30 eigen values corresponding to the first 30 modes of vibration to ensure that all of the desired modes of vibration are detected. The results of modal analysis should be examined to determine the frequency for the specific vibration mode of interest. Figure 4.4 shows the flexural, longitudinal and axial modes of vibration and corresponding frequencies predicted by a LUSAS FEA analysis for the OHT specimen evaluated in Chapter 3.

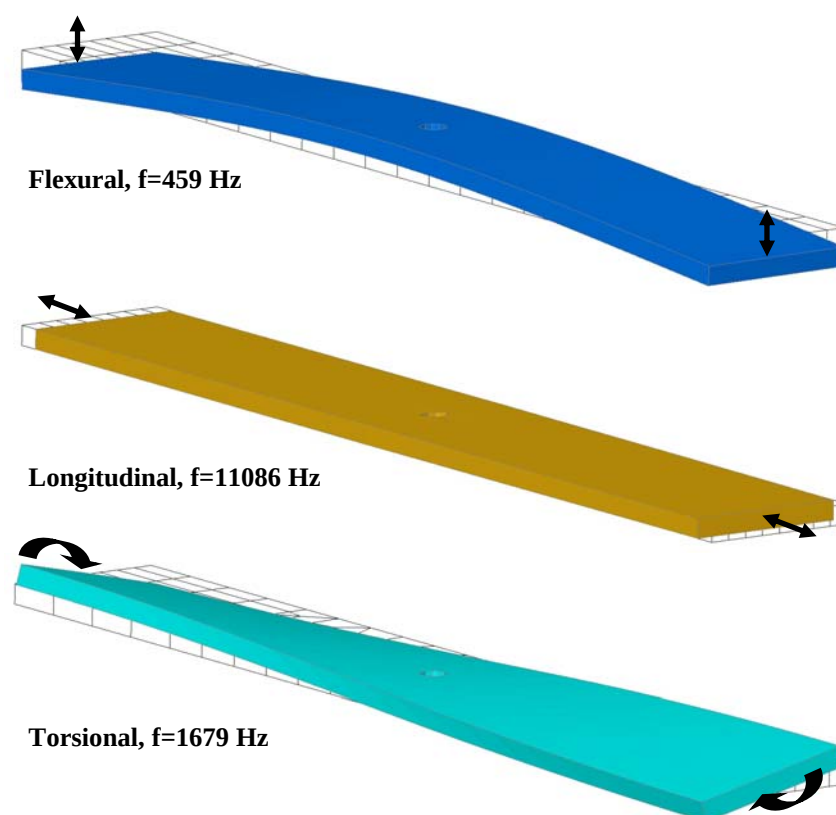


Figure 4.4: Flexural, longitudinal and torsional modes of vibration for 'free-free' OHT specimen (FEA analysis)

Table 4.2: Predicted and measured modal frequencies and moduli by impact mode for OHT specimen

Impact mode	Modulus (GPa)	Frequency (Hz)		Modulus (GPa)	
		Impact excitation	FEA	Impact excitation	CoDA
Flexure - centre	Flexural	443	459	48.0	50.5
Longitudinal	Axial	10758	11086	44.3	47.8
Flexural and torsion - end strike	Shear	1662	1679	16.2	18.3

4.1.4 Examples of impact excitation results

The impact excitation method has been evaluated using specimens tested in the OHT fatigue programme detailed in Section 3.2. Initially an FEA analysis was undertaken to identify the frequencies corresponding to the modes of vibration of interest (Figure 4.4). A comparison of measured and predicted vibration frequencies is detailed in Table 4.2 and shows good agreement. Values of moduli measured from the various modes of impact are also shown in Table 4.2 and compared to plain laminate data predicted using the CoDA software [10]. Again, the agreement is good. The material ply properties used for the FEA and CoDA analyses were measured as detailed in Appendix B.

4.1.4.1 Evaluation of the repeatability of the impact excitation method

The repeatability of the impact excitation method has been evaluated through tests on un-fatigued OHT specimens and has been shown to be very good. The results are detailed in Table 4.3.

Table 4.3: Elastic moduli for un-fatigued OHT specimens by impact mode

Impact mode	Modulus (GPa)	Specimen					
		1	2	3	4	5	Mean $\pm$ sd
Flexural - centre	Flexural	47.0	46.7	46.2	46.8	48.0	46.9 $\pm$ 0.66
Flexural - off centre	Flexural	47.0	46.7	46.2	46.8	48.0	46.9 $\pm$ 0.66
Longitudinal	Axial	44.0	44.2	43.8	44.2	44.3	44.1 $\pm$ 0.20
Flexural and torsion - end strike	Shear	16.2	16.1	16.1	16.0	16.2	16.1 $\pm$ 0.08

4.1.4.2 Open-hole tension fatigue

OHT specimens were fatigued to 10^4 , 10^5 , 5×10^5 and 10^6 cycles at 55, 70 and 80 % of the ultimate OHT strength before being removed from the test machine and examined using the impact excitation method. Flexural, longitudinal and shear modulus measurements were made and the trends in measured values are depicted graphically in Figures 4.5 to 4.7. The results show that little or no changes in any of the moduli are seen for tests undertaken at the 55 % stress level, but that reductions in the shear modulus at 70 % and in all moduli at 80 % stress levels occur with increasing fatigue cycles.

4.2 Pulse Thermography

4.2.1 Principle

Pulse thermography is a non-destructive evaluation (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 4.8. 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. Because heat diffuses sideways as well as through the specimen, 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.

4.2.2 Evaluation of technique for damage growth monitoring

This technique has been used to investigate the extent of damage (delamination) growth for several CAI and OHT fatigue tests detailed in Chapter 3. A ThermoScope™ pulse thermography system (supplied by LOT-Oriel Ltd.) was used for these tests. One of the key advantages of pulse thermography for damage detection compared to other techniques such as ultrasonic C-scan and X-ray, is that the inspection can be performed without the need to remove the specimen from the loading jig. After various numbers of fatigue cycles had been

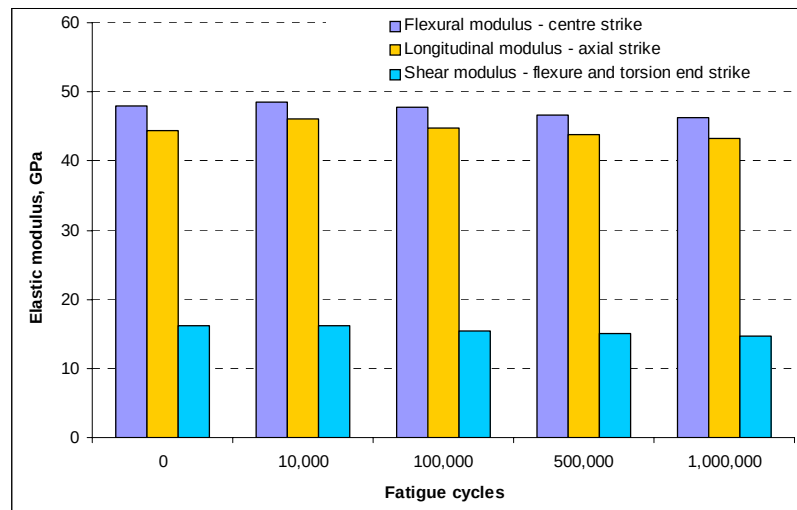


Figure 4.5: Elastic moduli for 55% UTS OHT fatigue specimens

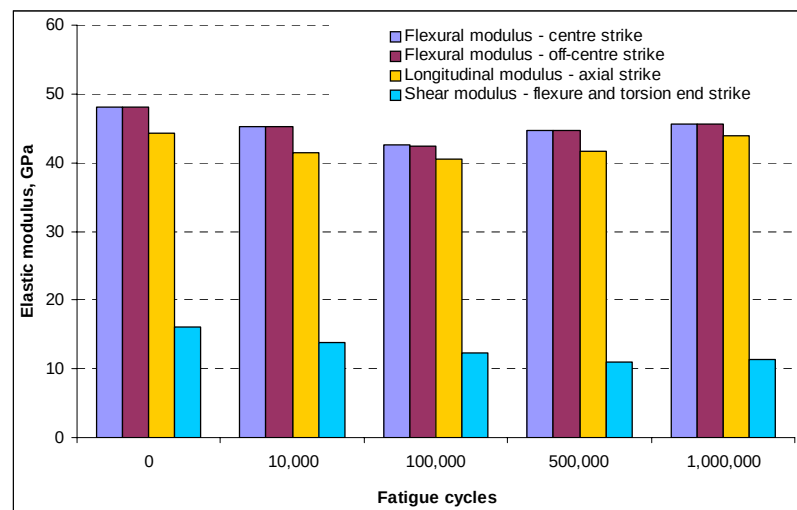


Figure 4.6: Elastic moduli for 70% UTS OHT fatigue specimens

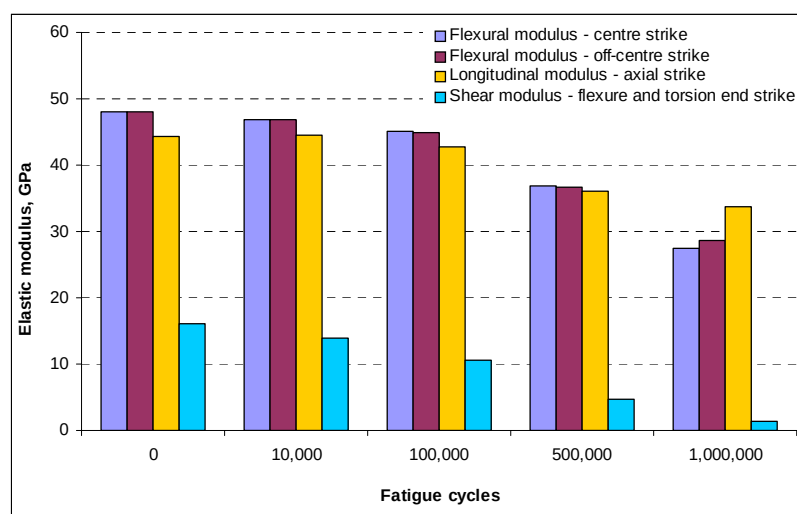


Figure 4.7: Elastic moduli for 80% UTS OHT fatigue specimens

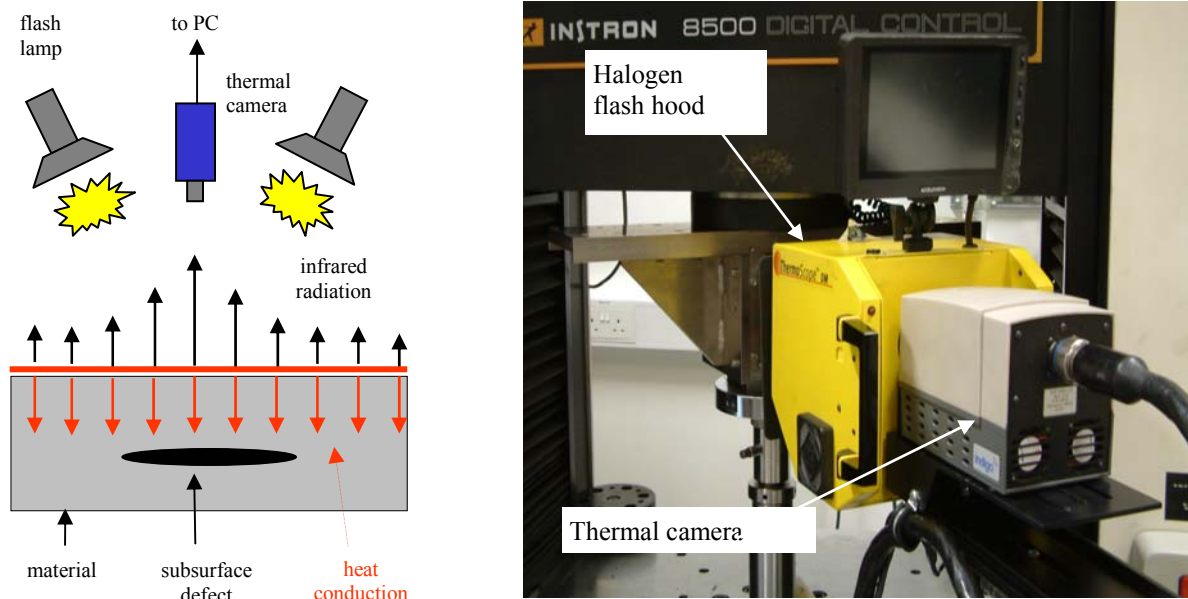


Figure 4.8: Principle of pulse thermography technique for damage monitoring and ThermoScope™ pulse thermography system

completed, tests were stopped and the specimen under test was held briefly at the maximum compressive load ($\sigma_{\min}$). The specimen was then interrogated using the ThermoScope™ equipment before the fatigue test was resumed. As for the impact excitation method, in order to trace the extent of damage growth measurements should be made at intervals throughout the fatigue life and at several different stress levels. Figures 4.9 and 4.10 show typical results obtained using pulse thermography for CAI and OHT fatigue tests respectively.

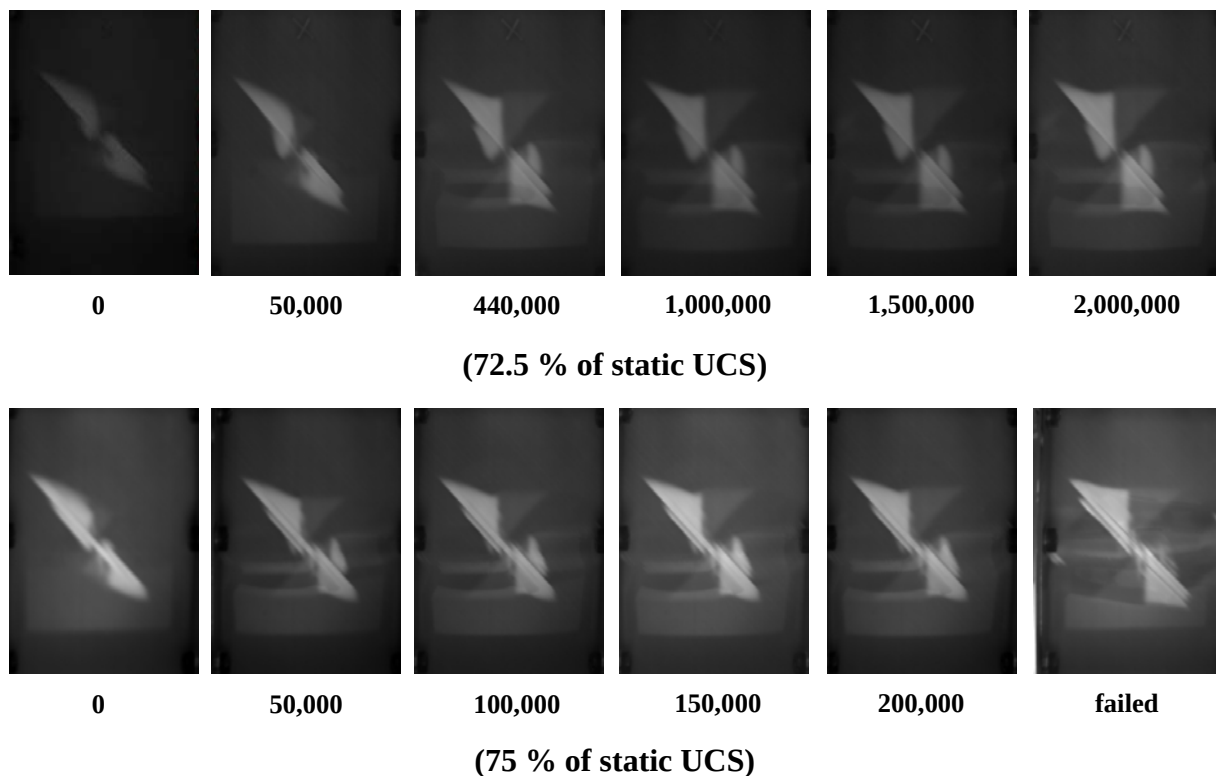


Figure 4.9: Pulse thermography images of CAI specimens after various fatigue cycles

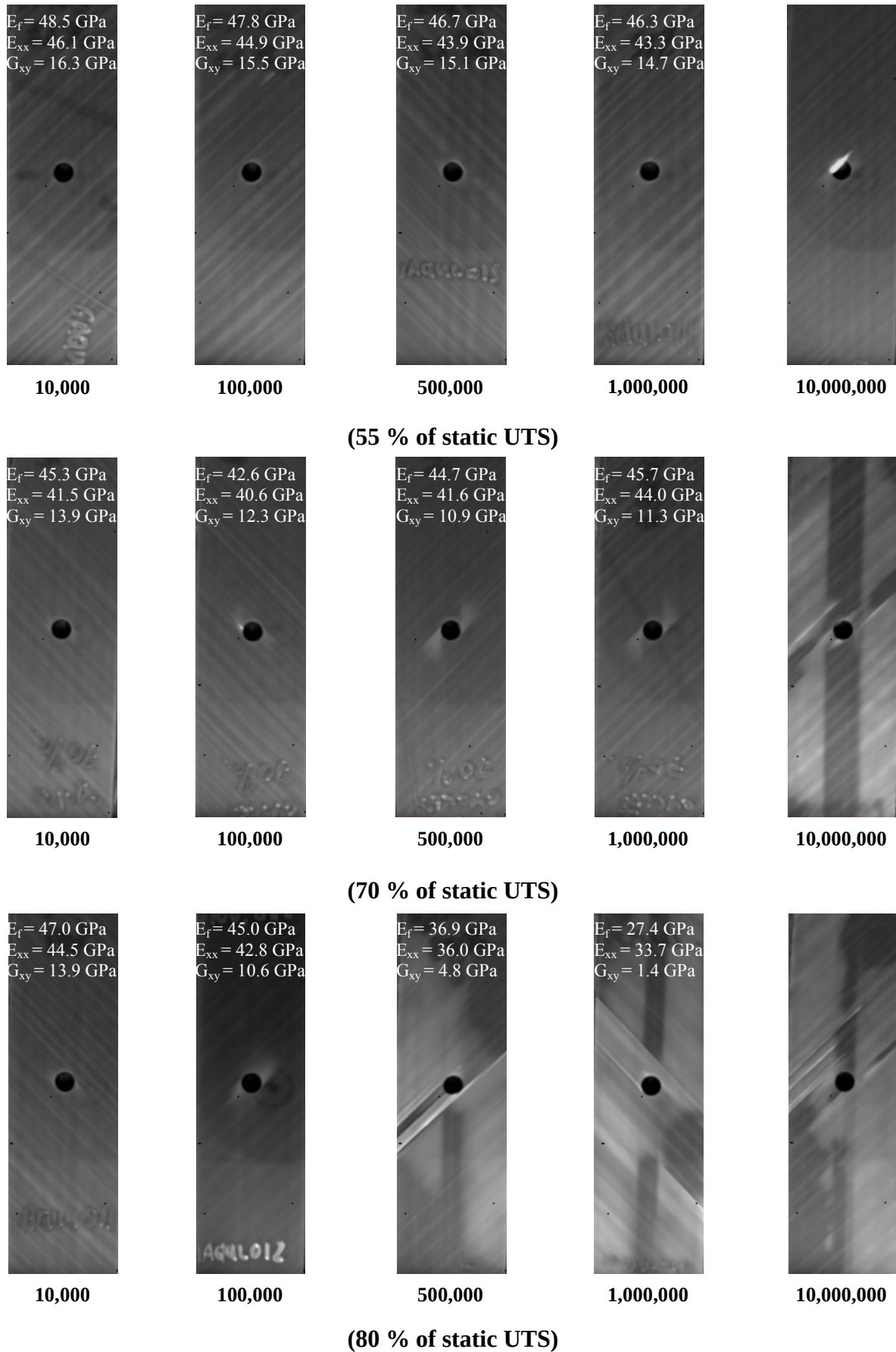


**Figure 4.10: Pulse thermography images of OHT fatigue specimens
(Moduli values measured using the impact excitation method)**

4.2.3 Depth calibration

Pulse thermography can be used to measure the depth of damage within a material, but in order to do this the system must be calibrated, ideally with the same material being inspected, or a material with a similar emissivity.

An example of a suitable calibration procedure is provided here using a CFRP stepped thickness reference plate previously used for ultrasonic C-scan inspection [21]. The plate consisting of four regions of different thickness; 1, 2 3, and 4 mm, is inspected using the pulse thermography system and the amplitude of the reflected heat is recorded against depth for areas within each region of thickness (shown by coloured boxes in Figure 4.11). Plots of heat amplitude versus depth are then examined to pin-point the depth at which the lines for each thickness become non-linear indicating breakout of heat at the back face of the panel. From Figure 4.11 it can be seen that as expected, this occurs first for the 1 mm thickness zone, followed by the 2 and 3 mm zones. The heat source used in the pulse thermography system employed for this calibration was not strong enough for heat to penetrate through the 4 mm thick zone.

4.2.4 Example of damage depth detection

Having calibrated the pulse thermography system it is then possible to determine the depth of damage within a material. This is illustrated here using a CAI specimen, with various regions of the coupon being inspected. Figure 4.12 depicts the regions interrogated and the

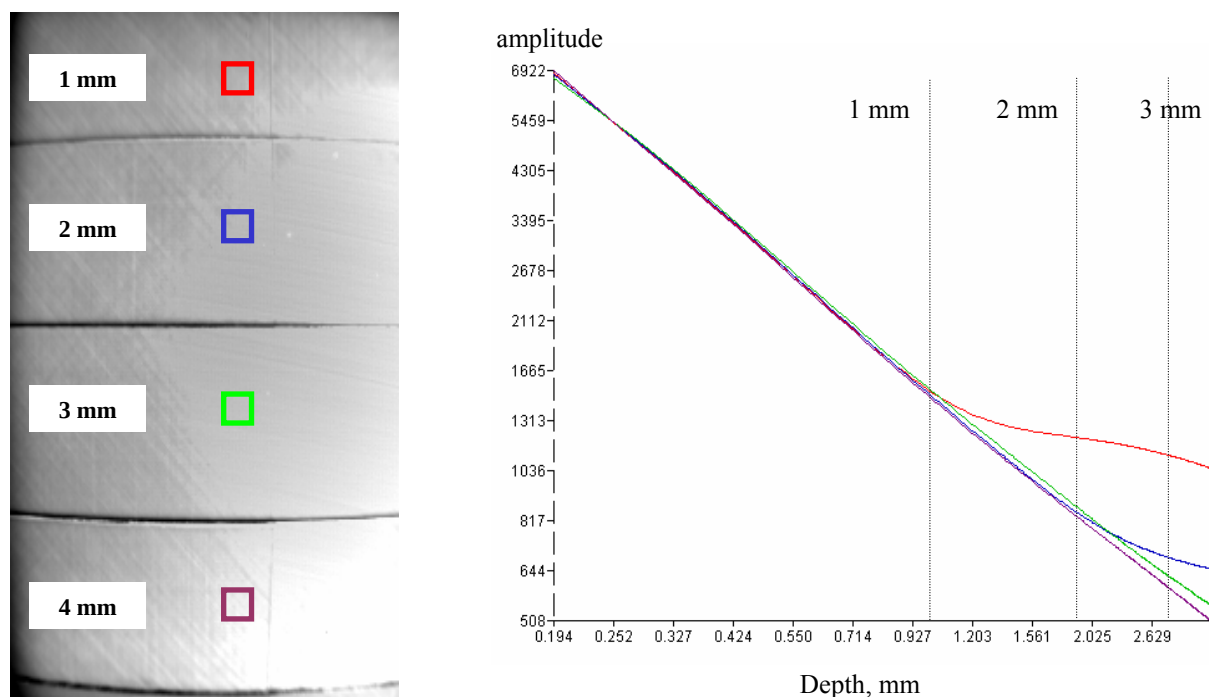


Figure 4.11: Depth calibration procedure for pulse thermography

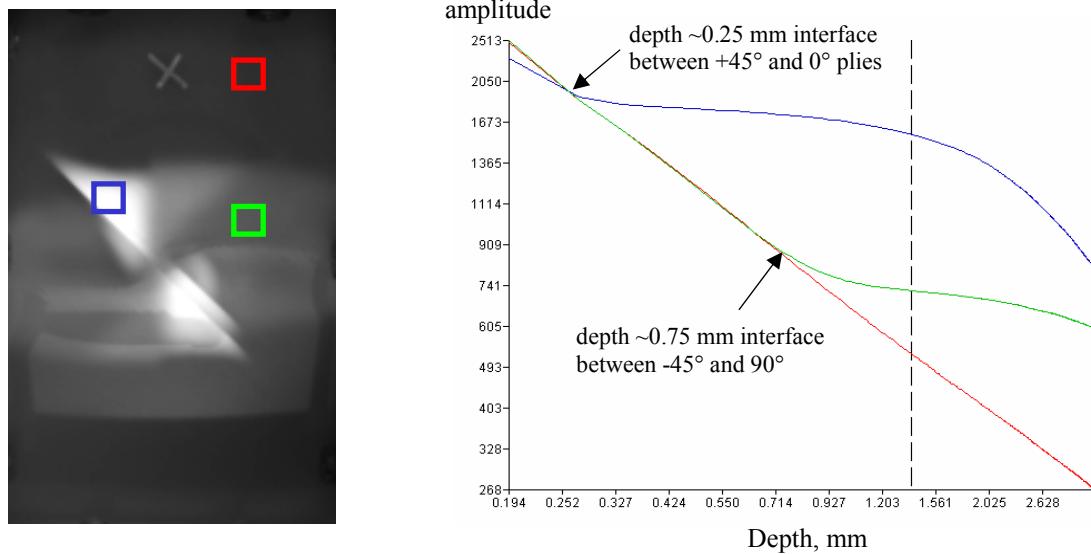


Figure 4.12: Delamination depth detection using pulse thermography

corresponding amplitude versus depth plots showing points at which the transmission of heat becomes non-linear indicating the presence of a delamination. Note the red line is for a region where there is no damage and hence the linear nature of the amplitude versus heat trace.

4.3 Radiography using dye penetrant

Radiography uses localised differences in attenuation under X-ray illumination to provide a cross-sectional picture of the density of a materials system. Traditionally images have been recorded on film although increasingly, digital or real-time recording systems are used. The method is well suited to volumetric defects and to complex components, which might be difficult to inspect by other methods. The method is not popular because of health and safety implications. Increasingly portable low intensity systems are available, such as those used in the offshore industry, which reduce the associated hazards, however, previous studies have found that the technique is not really suitable for real-time, on-line measurements [22].

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 to occur of the chemical into the damaged areas.

X-ray inspection using a Faxitron X-ray cabinet together with a digital X-ray scanning device, was used to investigate the extent of damage for several OHC fatigue specimens

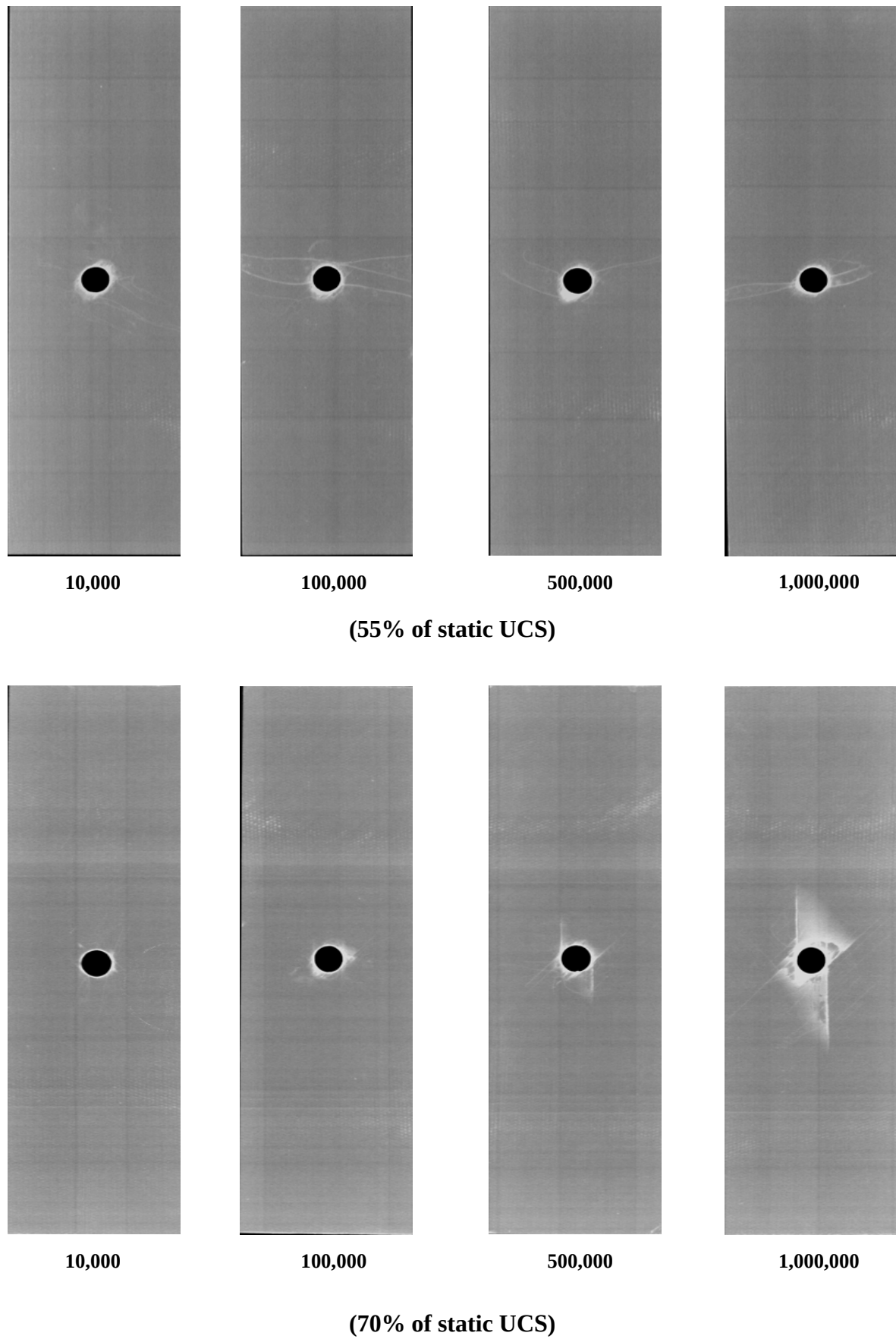


Figure 4.13: X-radiography images of OHC fatigue specimens

tested as detailed in Chapter 3. OHC specimens were fatigued to 10^4 , 10^5 , 5×10^5 and 10^6 cycles at 55 and 70 % of the ultimate OHC strength before being removed from the test machine. Prior to X-ray inspection the specimens were soaked in zinc iodide dye penetrant for 24 hours. Excess penetrant was wiped from the surfaces of specimens before being placed on the digital scanner inside the X-ray cabinet. The inspection setting used were; a voltage of 35 kV, tube current of 3 mA and an integration time of 300 ms.

X-ray images are shown in Figure 4.13. It can be seen that there is little damage growth for the 55 % specimens but that for the 70 % OHC tests, damage growth is clearly seen emanating from around the hole at 5×10^5 and 10^6 cycles.

4.4 Ultrasonic C-scan

Ultrasonic C-scan inspection using the double through-transmission method is a common technique for measuring the area of damage within composite materials. In this inspection mode, a single transmitter-receiver transducer scans along the material surface capturing signals that have propagated through the specimen twice (Figure 4.14). The specimen is supported above a flat glass 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.

The damage area is typically determined by measuring that area of a specimen which has a level of attenuation 6 dB below the average attenuation level of un-damaged material. This

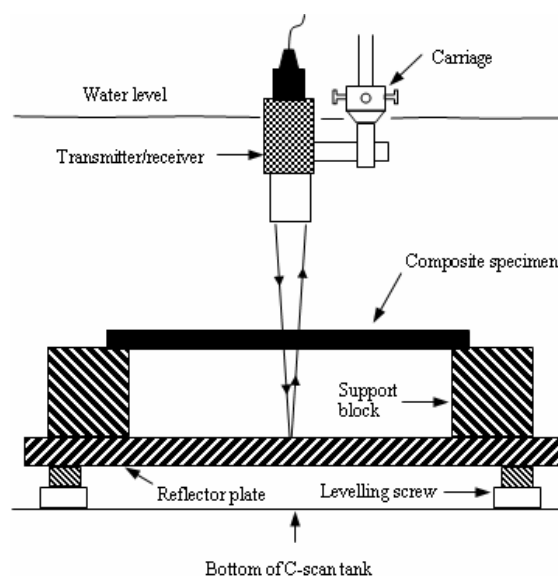


Figure 4.14: Ultrasonic C-scan double through-transmission method (immersion)

level corresponds to a signal loss of ~50%. This method of measuring the damage area is detailed in NPL developed procedures [23].

The ultrasonic C-scan technique usually requires specimens to be removed from the test jig and immersed in water for inspection. The technique can be adapted for real-time measurements either by use of water jet coupling or by a hand held probe with a gel coupling such as ANDSCAN®.

Acknowledgements and Contact Details

5

5.1 Acknowledgements

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- GKN Aerospace Engineering Services
- Gurit Holdings AG
- Hexcel Composites Ltd.
- Imperial College of Science Technology and Medicine
- LOT-Oriel Ltd.
- Loughborough University
- Qinetiq

5.2 Contact Details

For further information on *Materials Measurement* contact Mike Gower or the Materials Enquiry Point at the National Physical Laboratory:

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Appendix A

7

IN THIS CHAPTER

- Mechanical fatigue data

Table A1: CAI fatigue results (material 1)

Specimen number	Minimum compressive stress, $\sigma_{\min}$ (MPa)	Normalised peak stress*	Cycles to failure, N	Log ₁₀ (N)
5AQL002	139.7	1.03	0.5	-0.30
5AQL003	131.9	0.97	0.5	-0.30
6AQL006	108.6	0.80	10,887	4.04
6AQL007	108.6	0.80	59,962	4.78
6AQL008	108.6	0.80	7,907	3.90
4AQL001	108.6	0.80	22,245	4.35
5AQL012	105.2	0.78	35,433	4.55
6AQL002	105.2	0.78	11,227	4.05
6AQL003	105.2	0.78	52,959	4.72
6AQL004	105.2	0.78	149,597	5.17
6AQL005	105.2	0.78	103,307	5.01
3AQL010	101.8	0.75	115,161	5.06
5AQL004	101.8	0.75	72,195	4.86
5AQL005	101.8	0.75	261,805	5.42
5AQL006	101.8	0.75	86,116	4.94
5AQL007	101.8	0.75	231,818	5.37
4AQL003	98.4	0.73	156,280	5.19
4AQL004	98.4	0.73	46,419	4.67
4AQL005	98.4	0.73	19,468	4.29
3AQL003	95.1	0.70	460,729	5.66
3AQL006	95.1	0.70	999,615	6.00
3AQL007	95.1	0.70	2,000,000	6.30
3AQL008	95.1	0.70	197,251	5.30
3AQL009	95.1	0.70	632,587	5.80
3AQL004	84.9	0.63	1,788,290	6.25
3AQL005	84.9	0.63	2,000,000	6.30
5AQL001	84.9	0.63	2,000,000	6.30
5AQL008	84.9	0.63	2,000,000	6.30
5AQL009	84.9	0.63	2,000,000	6.30

* - normalised with respect to the mean UCS determined by static tests
grey shading indicates specimens that did not fail, but were stopped after 2×10^6 cycles

Table A2: CAI fatigue results (material 2)

Specimen number	Minimum compressive stress, $\sigma_{\min}$ (MPa)	Normalised peak stress*	Cycles to failure, N	Log ₁₀ (N)
3AQUN009	202.2	1.01	0.5	-0.30
3AQUN010	193.2	0.97	0.5	-0.30
4AQUN001	170.0	0.85	3,292	3.52
4AQUN002	170.0	0.85	2,056	3.31
4AQUN003	170.0	0.85	1,072	3.03
4AQUN009	170.0	0.85	2,346	3.37
4AQUN004	160.0	0.80	8,407	3.92
4AQUN005	160.0	0.80	16,443	4.22
4AQUN006	160.0	0.80	32,038	4.51
4AQUN008	160.0	0.80	18,611	4.27
4AQUN010	160.0	0.80	17,642	4.25
3AQUN001	150.0	0.75	241,129	5.38
3AQUN002	150.0	0.75	28,584	4.46
3AQUN003	150.0	0.75	170,982	5.23
3AQUN007	150.0	0.75	230,149	5.36
4AQUN007	150.0	0.75	46,316	4.67
3AQUN011	145.0	0.73	3,202,899	6.51
3AQUN012	145.0	0.73	2,000,000	6.30
3AQUN005	140.0	0.70	605,703	5.78
3AQUN006	140.0	0.70	1,478,957	6.17
3AQUN008	140.0	0.70	1,649,892	6.22
3AQUN004	125.0	0.63	4,328,050	6.64
2AQUN010	100.0	0.50	2,125,403*	6.33

* - normalised with respect to the mean UCS determined by quasi-static tests
grey shading indicates specimens that did not fail, but were stopped after 2×10^6 cycles

Table A3: Plain compression-compression fatigue results

Specimen number	Minimum compressive stress, $\sigma_{\min}$ (MPa)	Normalised peak stress*	Cycles to failure, N	Log ₁₀ (N)
3AQL012	457.1	1.01	0.5	-0.30
3AQL013	464.8	1.02	0.5	-0.30
3AQL014	441.5	0.97	0.5	-0.30
ABDQ018	386.3	0.85	37,901	4.58
ABDQ019	386.3	0.85	18,084	4.26
ABDQ015	363.6	0.80	30,731	4.49
ABDQ016	363.6	0.80	37,521	4.57
ABDQ017	363.6	0.80	36,204	4.56
ABDQ012	340.8	0.75	138,318	5.14
ABDQ013	340.8	0.75	204,240	5.31
ABDQ014	340.8	0.75	178,464	5.25
ABDQ010	318.1	0.70	3,459,001	6.54
ABDQ011	318.1	0.70	1,575,779	6.20
ABDQ009	318.1	0.70	576,000	5.76

* - normalised with respect to the mean UCS determined by quasi-static tests

Table A4: OHT tension-tension fatigue results

Specimen number	Maximum tensile stress, $\sigma_{\max}$ (MPa)	Normalised peak stress*	Fatigue cycles, N	Log ₁₀ (N)	Residual OHT strength (MPa)	OHT modulus (GPa)
1AQUL002	350.9	0.99	0.5	-0.30	-	45.0
1AQUL003	337.3	0.95	0.5	-0.30	-	43.8
1AQUL004	359.1	1.01	0.5	-0.30	-	44.5
1AQUL005	355.4	1.00	0.5	-0.30	-	43.5
1AQUL006	368.3	1.04	0.5	-0.30	-	44.3
4ABDQ004	336.5	0.95	238,013	5.38	-	-
4ABDQ005	336.5	0.95	76,208	4.88	-	-
4ABDQ003	318.8	0.90	2,411,354	6.38	-	-
4ABDQ006	318.8	0.90	46,570	4.67	-	-
1AQUL013	283.4	0.80	10,000	4.00	397.5	42.1
1AQUL012	283.4	0.80	100,000	5.00	404.3	41.7
1AQUL011	283.4	0.80	500,000	5.70	396.0	35.3
1AQUL010	283.4	0.80	1,000,000	6.00	384.3	11.4
1AQUL008	283.4	0.80	10,000,000	7.00	380.8	11.3
4ABAU015	247.9	0.70	10,000	4.00	388.2	39.8
4ABAU014	247.9	0.70	100,000	5.00	383.6	40.2
4ABAU013	247.9	0.70	500,000	5.70	415.9	38.2
6AQUL051	247.9	0.70	1,000,000	6.00	423.0	40.5
1AQUL009	247.9	0.70	10,000,000	7.00	356.1	14.8
6AQUL050	194.8	0.55	10,000	4.00	412.6	46.0
1AQUL016	194.8	0.55	100,000	5.00	376.2	42.7
1AQUL015	194.8	0.55	500,000	5.70	362.0	40.3
1AQUL014	194.8	0.55	1,000,000	6.00	342.0	39.2
1AQUL007	194.8	0.55	10,000,000	7.00	374.5	38.4

* - normalised with respect to the mean UTS determined by quasi-static tests

grey shading indicates specimens fatigued to pre-defined numbers of cycles following which residual tests were performed

Table A5: OHC compression-compression fatigue results

Specimen number	Minimum compressive stress, $\sigma_{\min}$ (MPa)	Normalised peak stress*	Fatigue cycles, N	Log_{10} (N)	Residual OHC strength (MPa)
4AQL002	303.2	1.07	0.5	-0.30	-
4AQL001	291.4	1.03	0.5	-0.30	-
4AQL003	275.1	0.97	0.5	-0.30	-
4AQL005	275.0	0.97	0.5	-0.30	-
4AQL004	270.8	0.96	0.5	-0.30	-
4AQL006	226.5	0.80	19,208	4.28	-
4AQL008	226.5	0.80	27,802	4.44	-
4ABAU002	226.5	0.80	134,666	5.13	-
4ABAU001	198.2	0.70	10,000	4.00	266.1
4AQL016	198.2	0.70	100,000	5.00	266.8
4AQL015	198.2	0.70	500,000	5.70	304.2
4AQL010	198.2	0.70	1,000,000	6.00	302.5
4AQL014	155.7	0.55	10,000	4.00	277.1
4AQL013	155.7	0.55	100,000	5.00	281.7
4AQL012	155.7	0.55	500,000	5.70	279.5
4AQL011	155.7	0.55	1,000,000	6.00	290.3

* - normalised with respect to the mean UcS determined by quasi-static tests

grey shading indicates specimens fatigued to pre-defined numbers of cycles following which residual tests were performed

Table A6: OHC fully reversed fatigue results

Specimen number	$\pm \sigma_{\min}/\sigma_{\max}$ (MPa)	Normalised peak stress*	Cycles to failure, N	Log_{10} (N)
4AQL002	303.2	1.07	0.5	-0.30
4AQL001	291.4	1.03	0.5	-0.30
4AQL003	275.1	0.97	0.5	-0.30
4AQL005	275	0.97	0.5	-0.30
4AQL004	270.8	0.96	0.5	-0.30
4ABAU012	226.48	0.8	5,076	3.71
ABDQ002	226.48	0.8	5,775	3.76
ABDQ008	226.48	0.8	5,185	3.71
4ABAU004	198.17	0.7	16,090	4.21
4ABAU010	198.17	0.7	22,375	4.35
4ABAU011	198.17	0.7	24,176	4.38
4ABAU005	169.86	0.6	123,233	5.09
4ABAU006	169.86	0.6	191,404	5.28
4ABAU009	169.86	0.6	150,563	5.18
4ABAU003	141.55	0.5	3,806,221	6.58
4ABAU007	141.55	0.5	2,821,739	6.45
4ABAU008	141.55	0.5	1,670,514	6.22

Appendix B

8

IN THIS CHAPTER

- Elastic property database

Table B1: Elastic property database - material 1

Elastic Property	Value			
	Measured PLY	Predicted QI LAMINATE (CoDA)		Measured QI LAMINATE
		Axial	Flexural	
E_{xx}^T (GPa)	124.3 ± 4.4	47.8	50.5	45 ± 0.5
E_{yy}^T (GPa)	8.14 ± 0.1	47.8	33.8	
E_{zz}^T (GPa)	7.8 ± 0.12	9.94		
E_{xx}^C (GPa)	110.0 ± 5.6			44 ± 2.5
E_{yy}^C (GPa)				
E_{zz}^C (GPa)	8.3 ± 0.14			
G_{xy} (GPa)	4.49 ± 0.07	18.3	19.7	
G_{xz} (GPa)	3.93 ± 0.21	3.01		
G_{yz} (GPa)	2.44 ± 0.10	3.01		
ν_{xy}^T	0.32 ± 0.02	0.310		
ν_{yx}^T		0.310		
ν_{xz}^T		0.239		0.352 ± 0.028
ν_{zx}^T	0.017 ± 0.004	0.050		
ν_{yz}^T		0.239		
ν_{zy}^T	0.505 ± 0.005	0.050		
ν_{xy}^C				
ν_{yx}^C				
ν_{xz}^C				
ν_{zx}^C	0.020 ± 0.009			
ν_{yz}^C				
ν_{zy}^C	0.518 ± 0.007			
E_{xx} (OHT)				44.2 ± 0.6

