National Composites Network

Best Practice Guide

Non-Destructive Testing of Composite Materials

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Non Destructive Testing of Composite Materials

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1 Introduction

This guide will introduce composite materials and address some techniques of how they can be inspected non-destructively. This document is meant as a guide to those who are not NDT specialists and are looking to buy in NDT services or set up some minimal services in-house.

This best practice guide covers NDT methods for detecting flaws in monolithic composites with polymer matrices (PMCs); it excludes composites that have either a metal or ceramic matrix.

All flaw types have the potential to adversely affect the performance of a structure or material in some way. When a flaw degrades the in-service performance of a composite to a point where the component or structure can no longer perform its intended function safely, it is classified as a defect.

The point at which the severity of the flaw becomes safety-critical depends on the application and can only be determined by mechanical destructive tests and knowledge of the behaviour of the flaw in service. It is beyond the scope of this guide to discuss acceptance criteria in great detail. A detailed discussion can be found in AGARD (1983), Conference proceedings Number 355, 'Characterisation, Analysis and Significance of Defects in Composite Materials'. A summary discussion on acceptance criteria for composites is provided in Chapter 7.

2 Composite Materials

2.1 What is a composite?

Composite materials consist of two or more elements, one of which, the fibre, is dispersed in a continuous matrix phase. The two elements work together to produce material properties that are different to the properties of the elements on their own.

Composites offer the designer a combination of properties not available in traditional materials. It is possible to introduce the fibres in the polymer matrix at highly stressed regions in a certain position, direction and volume in order to obtain the maximum efficiency from the reinforcement, and then, within the same member to reduce the reinforcement to a minimal amount at regions of low stress value. Other advantages of composites are lightness, resistance to corrosion, resilience, translucency and greater efficiency in construction compared with the more conventional materials

2.2 Composite Manufacture

A wide range of different processes have developed for moulding composites parts ranging from very simple manual processes such as hand lay to highly sophisticated and industrialised processes such as SMC moulding. Each process has its own particular benefits and limitations making it suitable for particular applications. The choice of process is important in order to achieve the required technical performance at an economic cost.

The main technical factors that govern the choice of process are the size and shape of the part, the mechanical and environmental performance and aesthetics. The main economic factor is the number of identical parts required or run length. This is because composite parts do not generally come as standard components but are custom designed for a particular application. Pultrusion and continuous sheeting are exceptions but most processes will have an initial investment or set up cost that must be amortised over the length of the project. This is a major factor in the choice of process and is one of the reasons for the proliferation in processing methods.

3 Typical Flaws in Composite Materials

As with all materials that are used to make objects and structures there is a need to be able to inspect the material to determine its fitness for purpose or use. Inspection of composite materials poses a particular challenge, since the materials are often non-homogeneous and anisotropic.

Examples of flaws found in composites are:

Delaminations; cracks; disbonds; voids; Impact or Barely Visible Impact Damage (BVID); porosity; inclusions; erosion; core splices; core disbonds; core crushing; matrix cracking; fibre breakage; kissing bonds; environmental ingress; fibre wrinkling or waviness; fibre and ply misalignment; incorrect cure and incorrect volume fraction.

Flaws can be classified according to the composite constituent that is affected, or the stage of the lifecycle at which the fault occurs. Composite flaws can occur:

- in fibres or fibre distribution;
- in the matrix or fibre-matrix bond;
- during production;
- in-service.

3.1 Fibres

There are different grades and types of fibre reinforcement, and care must be taken to ensure that the correct grade/type is used in production. For example, glass fibres come in different grades such as E and S type (electrical and strong), which have little difference in modulus but do have different strengths. Carbon fibres of different types or grades do however have large differences in modulus and strength. Current manufacturing processes for the fibre materials mean that it is unusual for batches of nominally the same fibre to vary widely in their properties. If the incorrect grade or type of fibre is used, then the composite material produced will not have the expected properties. However, standard QA procedures used during composite production make it unlikely that the wrong fibre would be used.

Fibres may be broken, and sometimes bundles of fibres may be kinked or wavy rather than straight, all of which will reduce the tensile and compressive strength of the final composite material. Defects in fibres may make them weaker or introduce stress concentrations. Irregular distributions of fibres lead to resin-rich or resin-starved regions.

3.2 Matrix

Problems with the matrix component of PMCs are most likely to be due to incorrect storage or contamination. Polymers and resins, particularly thermosetting systems, need to be stored at the manufacturer's specified temperature and humidity. Most polymers for PMC use will have a designated shelf-life, but only if the storage temperature is kept within the specified range. If the temperature is too high, this leads to the resin starting to cure. If the resin is already partly cured this makes it difficult to use in production, but the most severe consequence is that the final material will have reduced mechanical properties. If humidity is too high, both during storage and in the PMC production environment, then the polymer can pick up water. This excess water can degrade the polymer's properties and also lead to problems during cure when the water can turn to steam, producing porosity.
Porosity can also be caused by the 1-2% volatile organic liquids that may become trapped during the production process for pre-preg materials. Whatever the cause of porosity, the pores can coalesce to become voids. Voids can also occur during the lay-up process when air is trapped between layers of pre-preg, for instance at an overlap, or between the layers of fabric used in hand lay-up or resin transfer moulded (RTM) composites. Porosity and voids cause internal stress concentrations, leading to reductions in mechanical

performance. The voids within a PMC can potentially lead to bigger problems by creating delaminations in the laminate material.

Contamination of the resin material will lead to poor cure and will also lead to poor fibre-matrix adhesion. Poor fibre-matrix adhesion will reduce the PMC strength in compression, transverse tension and interlaminar shear, and will also reduce the fatigue performance and resistance to aggressive environments.

3.3 Production

The production process for PMCs has the potential to introduce a variety of defects. Fibre misalignment can occur when fibres are laid up. Fibres in the same layer may be misaligned relative to each other or there may be misalignment between layers. During production, the sequence in which the plies or layers are stacked might be incorrect, or a layer could be omitted altogether. In multi-ply composites, the stacking sequence is chosen to carry the load most efficiently. If layers are missing or are at the wrong angle, the result is a reduction in composite mechanical performance and/or possible warping of the structure.
Discontinuities will occur at any butt joints between layers or plies. Such ply-end discontinuities may well be unavoidable, and they will act as a potential point of weakness. These ply-ends will also cause resin rich areas, which are also likely to occur when fabrics are used, since it is more difficult for the resin to flow through and fully penetrate a woven material. Resin-rich areas cause local variations in the fibre volume fraction, and the possibility of reduced performance.

Foreign inclusions such as dirt and debris may contaminate the matrix or act as a local stress concentration in the finished product. These foreign inclusions can lead to delamination either during the production process or later on when the component is in service.

Polmers must be cured correctly. An incorrect cure cycle using the wrong temperature, heating rate or pressures will lead to a badly cured laminate. The wrong heating rate or temperature can cause cracking, due to high exotherms in thermoset resins, or delaminations, as the laminate expands or contracts too quickly.

3.4 In-service defects

In service, composites are subjected to static, fatigue (cyclic) and impact forces, all of which have the potential to degrade the performance of the material. Composites can also be exposed to high temperatures, humidity and various chemicals.

The various loads and environments can cause four major types of damage: matrix cracking; fibre-matrix de-bonding; delamination; and fibre breakage. A generic type of damage is often classed as barely visible impact damage (BVID), which takes account of the fact that under impact most composite laminates do not show much external evidence of damage. This is because most of the damage is inside the PMC material, or on the back face (i.e. the side opposite the impact point), and the damage can include all four of the types just mentioned.

The various types of in-service damage vary in significance, but all of them have some effect on the performance of the composite. Matrix cracking and fibre-matrix de-bonding can allow water to penetrate the material, causing reductions in modulus. Delamination will reduce the compressive strength, due to the increased possibility of buckling, whilst fibre breakage will reduce the tensile performance.

4 Inspection Methods

This best practice guide provides an overview of non-destructive testing methods for monolithic composites. It describes established methods but does not attempt to be comprehensive: a full description of all methods is beyond the scope of this guide. Although the literature on NDT for polymer composites is voluminous, there are few specific standards for these materials. Those that have been cited in this guide are either codes relating to a general practice or codes specific to a particular application.

In all methods, the composite is assessed by the detection of some test signal. When the signal is used specifically to derive material properties the process is sometimes arbitrarily designated as Non-Destructive Evaluation (NDE). In NDT methods, however, localised features within the composite (such as flaws) may also be identified. Composites generally allow poorer flaw resolution than microscopically homogenous materials because of the greater contribution of noise from matrix-additive (fibre or particle) boundaries (although large-grained metals present a similar problem). There are several factors that might influence the choice of inspection method. Some composite materials will absorb moisture and therefore any technique that involves substantial wetting of the surface should be avoided where possible. On the other hand, some methods can only be applied to materials which exhibit certain properties such as ferromagnetism. For these and other reasons many of the inspection methods commonly applied to metals find only limited application on composites.

This guide does not cover all methods used to test monolithic polymer composites. The emphasis is on those which are used the most widely: namely, vibration-based methods and radiography. The principles of each method are described, followed by a discussion of the specific applications in composite testing. It should be borne in mind that in most methods the test signal is wave-like, and the minimum resolution attainable increases with decreasing wavelength. For radiography the maximum test range increases with decreasing wavelength, whereas for physical vibrations, the test range decreases with decreasing wavelength.

The largest part of this guide is on vibration-based methods and this reflects the popularity of such methods of inspection. These cover a wide variety of techniques in which the condition of a specimen is deduced by measuring its response to a transient or continuous mechanical disturbance, whether macroscopic or microscopic. Vibration methods are often broadly classified as either low frequency or ultrasonic methods. In low frequency methods, the difference in acoustic impedance between air and the test-piece is often low enough to permit either non-contact inspection or contact inspection without the use of a coupling fluid. This makes low frequency techniques particularly attractive for moisture-sensitive composites. Conversely, at ultrasonic frequencies an aqueous or organic coupling fluid is generally required between the transducer and the composite to overcome the large difference in acoustic impedance between air and solids.

Two topics relevant to all methods are: *Contact and Non-contact testing* and *Material evaluation* -

5 Inspection Techniques

5.1 Ultrasonic inspection

5.1.1 Introduction

Ultrasonic testing (UT) is the most widely used non-destructive inspection method for the examination of composites. On microscopically homogenous materials (i.e. non-composite) it is commonly used in the frequency range 20kHz to 20 MHz. With composite materials the testing range is significantly reduced because of the increased attenuation, so the operating frequency limit is usually 5 MHz or less. However, the ability to resolve small flaws will also be reduced and this must be borne in mind.

In most techniques short pulses of ultrasound (typically a few microseconds) are passed into the composite material and detected after having interrogated the structure. The techniques include *pulse-echo, through-transmission, back-scattering, acousto-ultrasonics* and *ultrasonic spectroscopy*. In these methods it is important to avoid frequencies at which resonance occurs between ply interfaces. For unidirectional plies spaced at 8 plies/mm this frequency is usually about 12Mhz. There may be an additional resonance for woven fabrics at approximately 6Mhz for 0.25mm plies, although resonance at other frequencies has been seen in practice.

In manual ultrasonic testing (UT) the area is contact-tested by scanning a probe by hand; this is suitable for fieldwork, provided the inspection area is small. Manual UT requires a high level of operator skill to get consistent results because the signal amplitude is dependent on the thickness of the coupling fluid layer, which itself is dependent on the pressure applied. However, provided a recognised calibration procedure is carried out, variations between properly trained operators should not pose a problem. For some composites that are water-sensitive or absorbent, the use of roller probes with water retentive rubber tyres are preferred as they leave the surface dry. However, these operate at the lower end of the UT frequency range and therefore are not best suited to detailed defect characterisation.

These examples of contact testing illustrate that the probe-specimen distance must be maintained within a narrow tolerance (typically less than a millimetre) otherwise the ultrasound transmitter will become de-coupled from the specimen.

By contrast, in non-contact ultrasonic testing, significant probe movements can be tolerated without de-coupling the transmitter. One way of doing this is by generating the ultrasound with a laser. This has the added advantage of speed and that the signal can be generated and detected in any orientation up to 60 degrees relative to the specimen. The technique is presently exploited commercially, e.g. the Laser Ultrasonic Inspection System (LUIS) developed by UltraOptec. However, this approach is obviously relatively expensive and there is the risk of surface ablation and the physical safety measures required when using high powered lasers can be restrictive in a production or field environment. Another alternative is to use magnetostrictive transducers but these operate only at the lower end of the ultrasonic frequency range (200 kHz or less).

A more practical solution, known as immersion testing, or IUT, is to maintain a continuous column (preserved when the specimen probe distance changes significantly) of coupling fluid (usually water) between the probe and the specimen. When the specimen is small enough, an immersion test can be implemented by conducting the test with the probe and specimen completely submerged in coupling fluid. However, when the specimen is very large submersion is impractical because of the excessive cost and size of immersion tanks. Another problem is that if the specimen is buoyant, large forces are needed to keep it submerged. An alternative to submersion is the jet probe technique in which the ultrasound is coupled by a water jet applied by two specially designed probes, one transmitter and one receiver. This propagates the ultrasound along a narrow column of water, which is constantly projected onto the specimen surface. This is much more tolerant of changes in surface contours and is clearly a more practical solution for large or highly buoyant specimens.

5.1.2 Pulse-echo

5.1.2.1 Description

Ultrasonic pulse-echo is a well-established and widely used non-destructive testing technique. A pulse of ultrasonic energy, typically a few microseconds, is transmitted into the specimen in a direction normal to the surface. The pulse is reflected from good matrix-reinforcement boundaries and also from boundaries associated with flaws. *Figure 2.1* shows a typical pulse-echo set-up for a submerged immersion test.

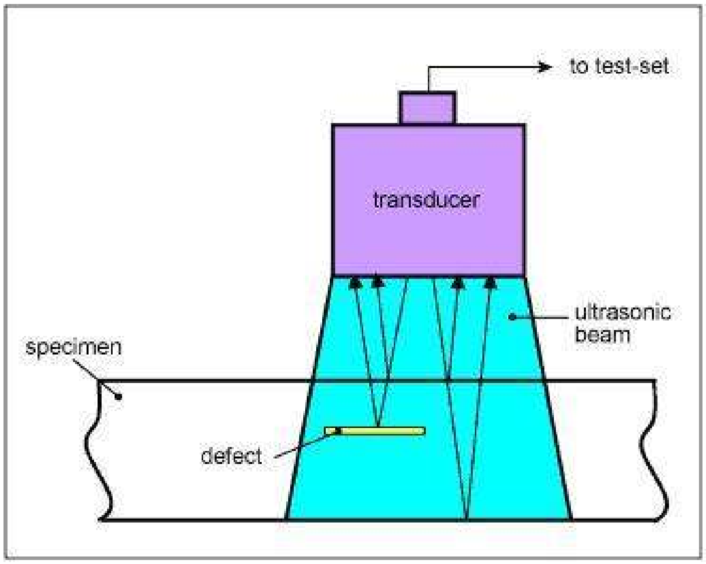

Fig.2.1. Immersion pulse-echo test with submerged specimen

Those signals which travel back towards the probe are detected and the position and size of a flaw is determined from the total pulse travel time and detected amplitude respectively. This is the 'A-scan' display and it consists of a series of peaks, the position of which along the horizontal axis can be calibrated in terms of the depth in the composite. The amplitude of each echo will give some indication of the size and nature of the reflector, which might be a flaw or a specimen boundary.

Figure 2.2 shows a typical A-scan display from a pulse-echo immersion test. In this display, the echoes from different features within the composite do not merge (i.e. they are well resolved) because the pulse duration is short to avoid it interacting with any of the features at the same time. The first peak (a) is due to the electrical pulse used to excite the transducer (also called the 'main bang') and is a convenient reference for the following peaks. These are the front surface of the component (b), a flaw (c); and the rear surface of the component also known as the back-wall (d).

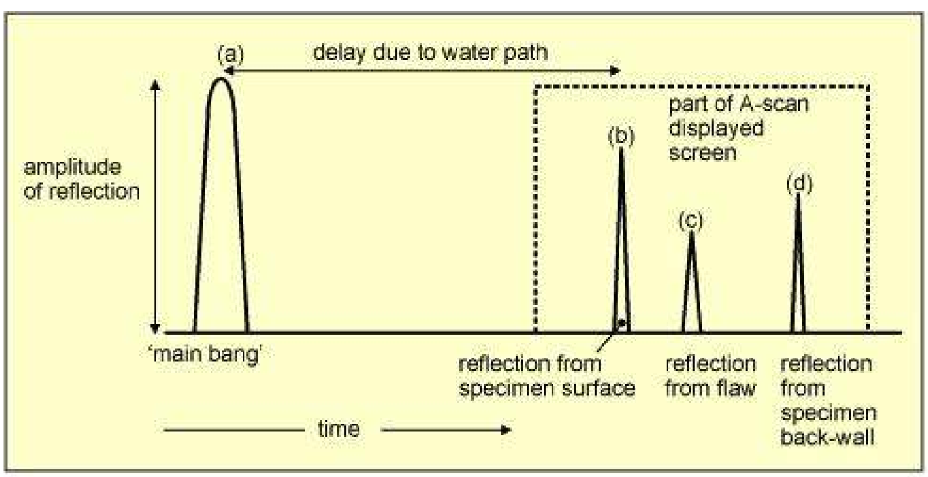

Fig.2.2. Diagrammatic A-scan display for a typical pulse-echo immersion test

Typically immersion testing is used to carry out area scans where the ultrasonic data can be represented in ways that make it easier to interpret. In the 'B-scan' display a 2D 'slice' through the specimen is produced by scanning the probe along the surface and capturing an A-scan at each point along the scanning direction. A 'D-scan' is also a slice through the specimen taken at a fixed scanning point in each of a set of parallel B-scans.

In B and D scans, the amplitude at each point is displayed as a colour or a greyscale value according to a predetermined pallette. In general, the higher the amplitude the brighter or more intense the displayed point.

C-scans may be thought of as ‘Top down’ or ‘Plan’ views of the component. Here the A-scan is 'gated' to display either the amplitude or the depth of signals occurring within a predefined depth range within the component. *Figure 2.3* shows a C-scan of a multi-ply CRP composite with artificially induced delaminations (Teflon inserts). The upper image represents a B-scan and the lower image represents a C-scan.

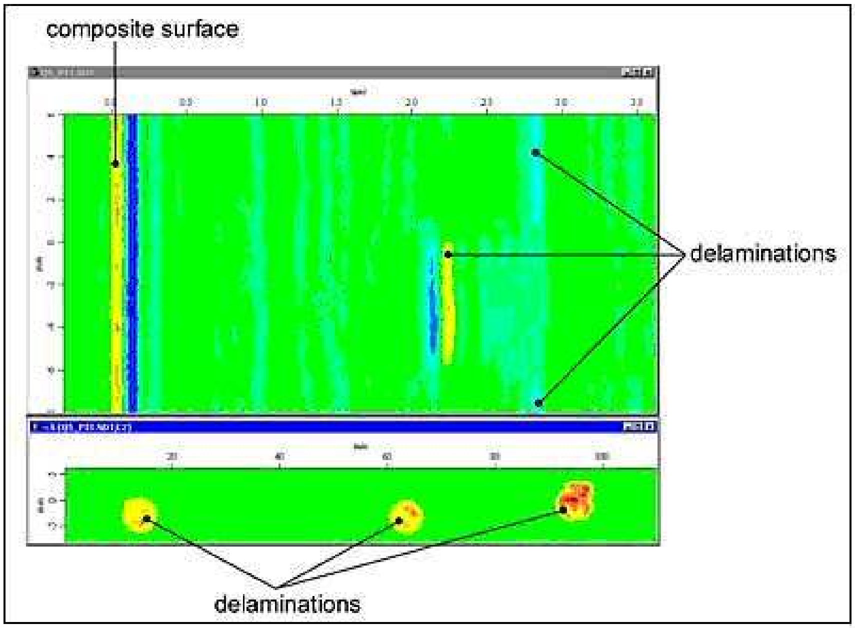

Fig.2.3. Ultrasonic image of delamination in carbon fibre composite (B and C-scans)

5.1.2.2 Applications

A **delamination** which is large compared with the diameter of the ultrasonic beam will reflect as strongly as the back-wall. Therefore, the presence and depth of a de-lamination can be determined from a sudden apparent reduction in the back-wall echo coincident with the appearance of a similar peak located at the depth of the de-lamination. Smaller flaws such as **voids** and **foreign inclusions** can be identified either because they cause a loss of back-wall signal with no associated reflected signal or, when a reflected signal is detected it is significantly weaker than a **crack** or **delamination** (note that cracks aligned parallel to the beam produce weak signals and may not be detected unless an alternative testing configuration is used).

Matrix properties related to ultrasound velocity or attenuation can be evaluated in a pulse-echo set-up. Examples are **fibre volume fraction, moisture ingress** and **porosity**. The ultrasonic attenuation is derived from the rate of degradation of the pulse amplitude as a function of distance. Provided the sample thickness is well known, it is common to determine the attenuation by measuring the height of successive back-wall echoes, and the velocity by the spacing between them.

5.1.2.3 Strengths

The pulse-echo technique allows flaws to be sized and located in the direction of the ultrasonic beam. This allows the depths of flaws within the composite to be determined as well as their location along the scanning axes. It can be used in cases where it is only possible to gain access to the composite from one side. This is a particularly useful advantage as such testing situations often occur in practice.

5.1.2.4 Limitations

There is a time period approximately equal to the pulse length during which the probe cannot detect signals because it is either emitting a pulse or reverberating. This is sometimes referred to as the dead zone. Consequently, there is a region near the probe in which defects cannot be detected. This problem can be limited by using a shorter pulse, immersion testing, a stand off probe, or employing a twin crystal probe. A twin crystal probe has two transducers slightly angled toward each other: one dedicated to emitting, the other dedicated to receiving. A similar problem occurs when attempting to resolve defects very near to the front surface of the component. The solution here may be to increase the frequency and thereby shorten the pulse length, or scan from the other side of the sample.

5.1.3 Back-scatter

5.1.3.1 Description

Fibre orientations and their stacking order determine the final product properties. In its most common configuration, back-scatter is a variation on pulse-echo in which the transducer is inclined at an acute angle, α, to the normal to the test structure surface. The echoes received by the transducer are monitored as the component or transducer is rotated about an axis normal to the component surface, the angle α being kept constant. *Figure 2.4* shows a typical back-scatter set-up.

When the angle of rotation, β is such that the transducer is normal to the fibre direction in any of the layers of the structure, the back-scattered signal reaches a maximum. A plot of the signal intensity versus the angle of rotation is recorded.
The method can also be applied with a variable angle α or with separate transmitting and receiving transducers located on opposite sides of the specimen.

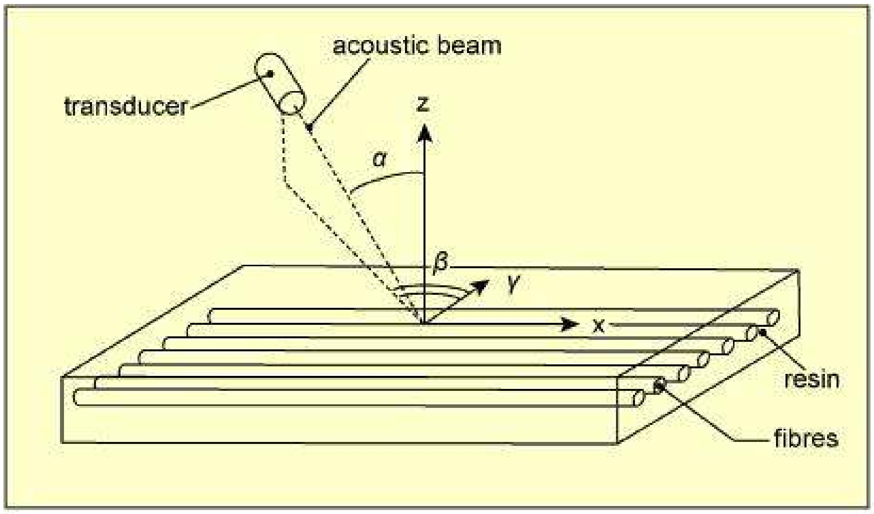

Fig.2.4. The back-scatter technique

5.1.3.2 Applications

This technique may be used to check the **stacking sequence**. For example, the fibre orientation of graphite epoxy laminates in several lay-ups is easily resolved. It can also detect **porosity** because if it is present, the back-scattered signal is higher at all angles of rotation compared with a sound specimen. However, surface roughness produces a similar effect, so it may be necessary to smooth the surface before testing. This technique will also detect **local fibre waviness, ply-end discontinuities** and **trans-laminar** cracks. It can also be used to detect matrix cracks due to thermoelastic stress.

5.1.3.3 Strength

This technique is one of the few ways to actually quality assure the ply lay-up sequence.

5.1.3.4 Limitations

The angle α is critical and has to be maintained precisely. Therefore, the technique is very surface-orientation sensitive and a sophisticated set-up is required to maintain correct alignment.

5.1.4 Through-transmission

5.1.4.1 Description

Through-transmission is an ultrasonic technique that typically uses two transducers: one emitter and one receiver, the receiver being placed on the opposite side of the component and facing the transmitting probe. It is sometimes referred to as the 'obscuration' technique because it measures total attenuation within the material caused by features that 'obscure' the beam. Comparisons can be made of the attenuation between different specimens and between different regions of the same specimen.

Figure 2.5 shows a through-transmission immersion test in the jet probe set-up. The ultrasound is coupled to the specimen through a jet of water projected onto its surface. The probe/sample distance can be as long as the water column, and since this acts as the ultrasound guide, small changes in the probe alignment or surface orientation can be tolerated.

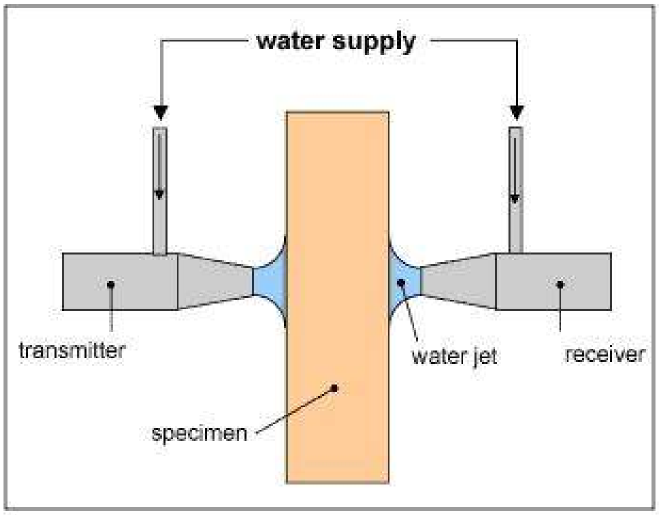

Fig.2.5. Immersion through-transmission test set-up implemented with jet probes

Where a water jet system is not available a standard immersion tank may be used to carry out double through transmission. Here the pulse passes through the material and is bounced off a reflector, such as a glass plate, before passing back through the specimen to the original transducer.

5.1.4.2 Applications

Through-transmission testing is used to produce attenuation C-scans which can detect most common flaws in a monolithic pre-preg, including **delamination, porosity,** some **inclusions, fibre volume fraction** changes and **displaced fibres** (although these latter two are only just detectable). Another example is in the detection of 'race-tracking' in RTM composites. This is where resin preferentially flows at the edges of the mould, closing off the central vent and trapping air. **Cracks** can also be detected but, as with pulse-echo, their alignment should not be parallel with the beam direction.

5.1.4.3 Strengths

Compared with pulse echo there is no 'dead zone' which means that flaws can be detected at all depths throughout the thickness of the specimen at the measurement location.

5.1.4.4 Limitations

One disadvantage of through-transmission is that it does not provide any information about flaw depth. Furthermore, the transmitter and detector must be kept well aligned making the inspection of contoured surfaces very difficult. Also, it requires access from both sides and this may not be possible.

5.1.5 Ultrasonic spectroscopy

5.1.5.1 Description

Ultrasonic spectroscopy is a form of ultrasonic test in which the pulse arriving at the detecting transducer is analysed harmonically and information relating to the composite or features within it can be deduced from characteristic changes to the frequency spectrum. This is illustrated in *Figure 2.6*, which shows a specimen inspected in through-transmission. The layer of porosity significantly reduces the amplitude of the highest frequency harmonic but barely alters the lowest frequency. This is because in this example the pores are comparable in size to the highest frequency wavelength. Consequently, a minimum will be observed in the pulse's spectrum at the high frequency harmonic.

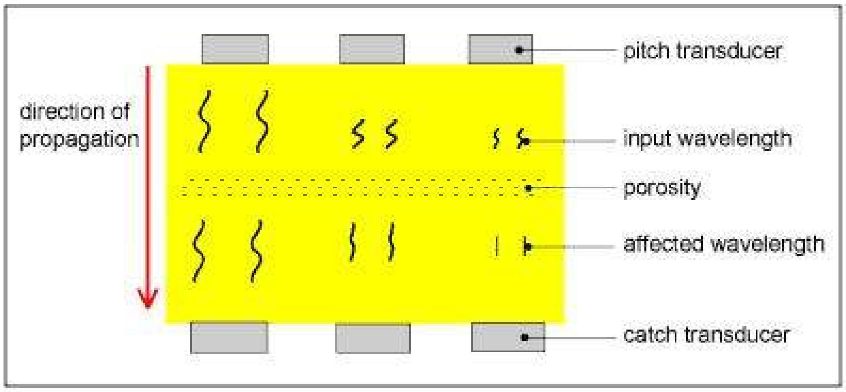

Fig.2.6. Wavelength interaction illustration for ultrasonic spectroscopy

The preceding discussion is relevant when the specimen is much thicker than the pulse length. In this case, the pulse spectrum can be analysed to reveal frequencies at which the ultrasound is attenuated or scattered by features in the composite. At the identified frequencies, the reduced amplitude can be correlated with flaws, provided a calibration standard is available for comparison.

When the pulse length is greater than the specimen thickness, e.g. for thin-walled specimens, interference can occur between transmitted and internally reflected beam components, so that the detected amplitude is the superimposition of these. Inside the specimen, the interference that the internally reflected pulse undergoes depends on the relationship between thickness and wavelength; four examples are illustrated in *Figure 2.7* for the through-transmission configuration (the technique can also be applied in pulse-echo).

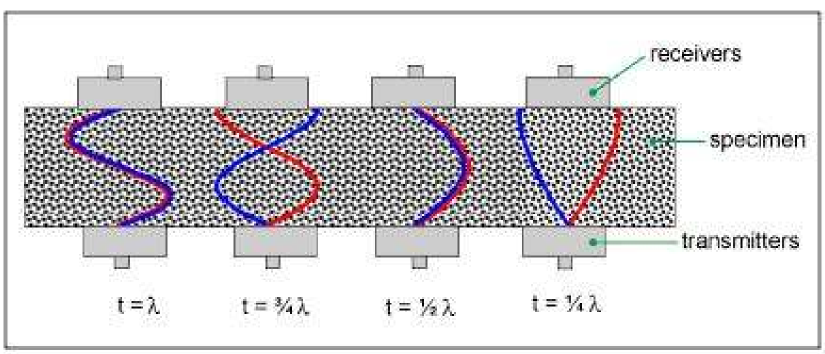

Fig.2.7. Interference effects in thin specimens tested by ultrasonic spectroscopy (through-transmission configuration shown). Two phases of received signal shown by red and blue lines

In this example, the detected amplitude reaches a maximum at frequency f_{max}, which is related to the thickness, t, and ultrasound velocity, V, by the formula:

$f_{max} = V/2t$ [1]

This is illustrated by the conditions t = λ /2 and t = λ in *Figure 2.7*. Since the f_{max} is a function of the velocity of sound in the specimen, the velocity can be determined if the thickness of the composite is well known or, conversely, the thickness can be determined if the velocity of sound in the composite is well known. The technique can also be applied in pulse-echo configuration.

5.1.5.2 Applications

As well as thickness scans, a spectroscopic system can be used to determine the **delamination** depths as differences in these will also affect the resonance frequency. If the thickness is stable and well defined, the ultrasonic velocity changes can be used to monitor the location (in the scanning direction) of **poor matrix curing**. Regions of **porosity** may also be detected with ultrasonic spectroscopy.

5.1.5.3 Strengths

Ultrasonic spectroscopy can be better than pulse-echo for determining the thickness of thin specimens. This is because for such specimens it may be difficult to resolve pulses reflected from the front and back-walls in the time domain. By comparison, resolution in the frequency domain may be much easier, hence spectroscopy would be preferable.

5.1.5.4 Limitations

The frequency spectrum of the returning signal will be affected by attenuation within the material and therefore comparisons between different specimens are only possible when the attenuation is well known in both. Also, most techniques use a wide-band, pulsed input which can suffer from poor signal-to-noise ratio.

5.1.5.5 Standards and Specifications

At the time of writing there were no relevant Standards or Specifications for the ultrasonic testing of thermosetting or thermoplastic polymer composites.

5.2 Acoustography

5.2.1 Description

In this approach, a wide-area acousto-optic (AO) sensor is employed to provide real-time ultrasonic images over the area of the sensor. The UT field is generated by a conventional probe and focused onto the sensor by a system of lenses after having interrogated the test specimen.

The two systems currently on the market use different technologies in their sensors to convert ultrasound into visual images. The AcousticScope ™ (www.santecsystems.com) uses the birefringent properties of a proprietary liquid crystal layer contained in the sensor. In the absence of ultrasound the layer is not birefringent and appears dark. When insonified however, there is a change in brightness that is dependent on the ultrasound intensity. A video camera captures the image on the birefringent layer and, in combination with a frame-grabber, the image is digitised for storage and processing. The integrated system operates submerged and performs C-scans.

The other system is called the Acoustocam ™ (www.imperiuminc.com) and uses an ultrasound-sensitive array to convert the acoustic energy falling upon it directly to a voltage that is digitised and processed by low-cost commercial video electronics. This system is hand-held making it applicable for field measurements. It also works in reflection mode allowing one-sided inspection.

The techniques can be used in both through-transmission and reflection modes. In both configurations, the sensor provides total attenuation information but no information on the depth of indications. This is similar to conventional ultrasonics operating in through-transmission mode. However, it is quite different from conventional ultrasonics in reflection mode which gives valuable information about the depth of flaws. Acoustography does not provide this information.

5.2.2 Applications

The NDT of PMCs has been one of the main applications of acoustography to date. It can be used to detect **voids, delaminations, cracks, impact damage**, and sub-surface **inclusions**.

5.2.3 Strengths

The most important advantage that acoustography has over other UT inspection methods is speed. Manufactures claim that the Acoustocam can C-scan a 9.2m ^{2} panel in 8 minutes (compared with 17 hours for a typical conventional UT C-scan), and that the Acoustoscope can scan a 56cm ^{2} area in under 10s (although step size was not quoted in these examples). The ability to scan from one side would be a clear advantage in field measurements and this is possible with the Acoustocam.

5.2.4 Limitations

The resolution of images obtained by acoustography are generally more grainy than typical conventional UT C-scans. Improvements can be achieved but only at the expense of time by allowing the sensor to dwell longer at each scan point. The other main drawback of acoustography is the inability to obtain information on depth of features detected in the specimen.

5.3 Low frequency methods

5.2.5 Introduction

Low frequency vibration methods are those in which bulk disturbances are excited in the structure. The frequencies of these vibrations are dependent on the dimensions of the structure but for composites the frequency range below 20 kHz is often used. They can be grouped into *global* and *local* methods.

Global methods measure the response of the entire structure from a single point. The measured global properties are modal *frequency*, modal *damping* or mode shape measurement. In local methods the specimen is excited and its measured response is only representative of its local condition. These methods include measurement of *mode shape* changes, the *coin tap-test*, and the *mechanical impedance* method.

In both global and local methods, the excitation source may be a transient or continuous signal. As the acoustic impedance difference between air and composite structures is less at the lower frequencies, actuators (vibration transmitters) and sensors can be mechanically coupled, i.e. acoustic coupling fluid is not necessary. However, the lower frequency means that these methods cannot detect flaws as small as ultrasonic techniques.

5.2.6 Global methods

5.2.6.1 Introduction

All structures have a unique set of modal frequencies (otherwise known as natural frequencies) which are dependent on the size, shape and material properties, at which the excitation force and the response amplitude are in anti-phase. At the modal frequency energy is most efficiently transferred from the actuator to the structure and the structure attains a characteristic dynamic profile (the mode shape). Furthermore the structural damping is also a characteristic minimum at this frequency.

5.2.6.2 Description

Modal frequencies and damping can be conveniently measured with modern spectrum analysers implementing a Fast Fourier Transform (FFT) on the time history of response. The location of the sensor should be chosen to correspond to the modal anti-nodes of a prominent vibration mode because this is where the amplitude of vibration, and therefore sensitivity, will be greatest. The sensor should be lightweight so as not to greatly influence the local dynamic properties of the structure. Modal frequency changes are used more often than damping because it is harder to measure damping accurately, and the signal-to-noise ratio in composites is significantly lower than for metals (because of the greater matrix damping).

5.2.6.3 Applications

Natural frequency measurements have been used in production control for filament wound carbon fibre reinforced plastic (CFRP) tubes. Variations in **fibre volume fraction** (of 4%), and **fibre alignment** (of 1° to 1.5°) are detectable. *Figure 2.8* shows a typical set-up to measure modal frequencies for a composite tube.

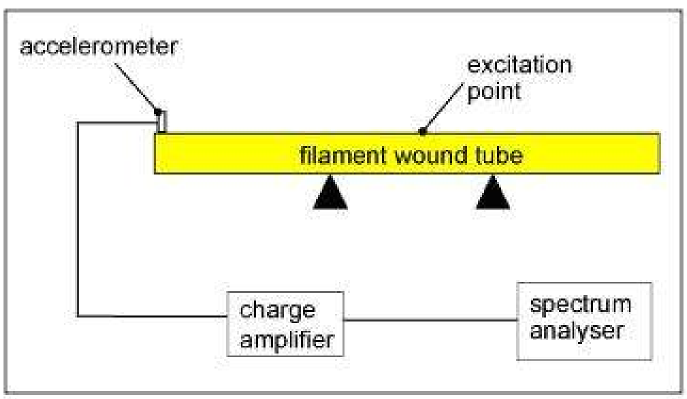

Fig.2.8. Schematic diagram of apparatus for checking modal frequencies of filament wound CFRP tubes

5.2.6.4 Strengths

Global methods offer the possibility of very rapid testing of composite structures as flaws at any point can be detected by measuring from one location. Many low frequency methods can be implemented with mechanical coupling and therefore do not require fluid. This makes them an attractive choice for moisture-sensitive composites.

5.2.6.5 Limitations

Global methods are inherently less sensitive than low frequency local methods (see below) because the influence of the flaw is spread over the whole structure rather than concentrated in the region of testing. Consequently, they are less effective at detecting small, localised defects which will be masked by variations due to the manufacturing process.

5.2.7 Local methods

5.2.7.1 Introduction

Local methods are subdivided into two generic groups depending on the excitation location. There are those in which the excitation is applied at a single point and the response measured at several other locations; and there are those in which the excitation is applied and the response measured at each location.

5.2.7.2 Descriptions

Those local methods in which the excitation point and the measurement point are generally different include *mode shapes*. The group in which the excitation point and the measurement point are always the same include the *coin-tap test*, the *mechanical impedance* method and the *membrane resonance* method.

5.2.7.3 Optical holography

The mode shape may be measured by optical holography, which is a non-contact method of measurement. This is a highly expensive approach, and unless a pulsed system is used the specimen must be mounted on a table to isolate it from extraneous vibration. Flawed regions produce local changes in the mode shape (hence this method is otherwise known as local amplitude measurement). *Figure 2.9* shows a typical optical holographic set-up for measuring mode shapes. The illumination source has to be highly coherent for holography and hence a laser is used.

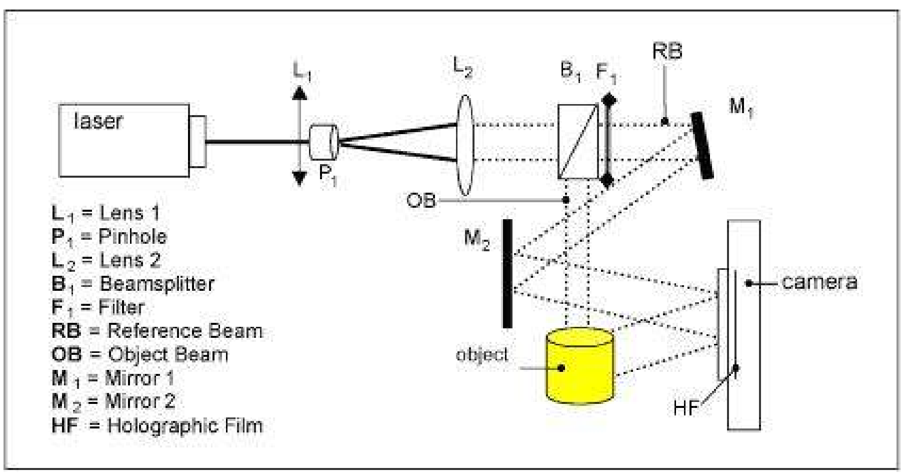

Fig.2.9. Optical holography set-up

5.2.7.4 Tap test

In the original version of this test the surface was tapped by a coin or metal hammer and the difference in local stiffness was detected by the difference in the sound produced. In fact this method is still widely used but it is limited by the inability to identify the type of flaw and to quantify its size. It is also subject to inconsistencies due to ambient noise, operator hearing sensitivity and tapping force. The use of semi-automated systems that measure the contact duration, such as the Matsui's Woodpecker, or the CATT from ISU can overcome these limitations. In the modern tap test, the structure is tapped with an instrumented hammer in various locations and a load cell mounted in the tip records the interacting force.

Where there is a difference in the local stiffness between two regions the spectra will look markedly different. *Figure 2.10* shows the dynamic response in both the frequency domain and the time domain of a hammer impact over two areas with different local stiffness.

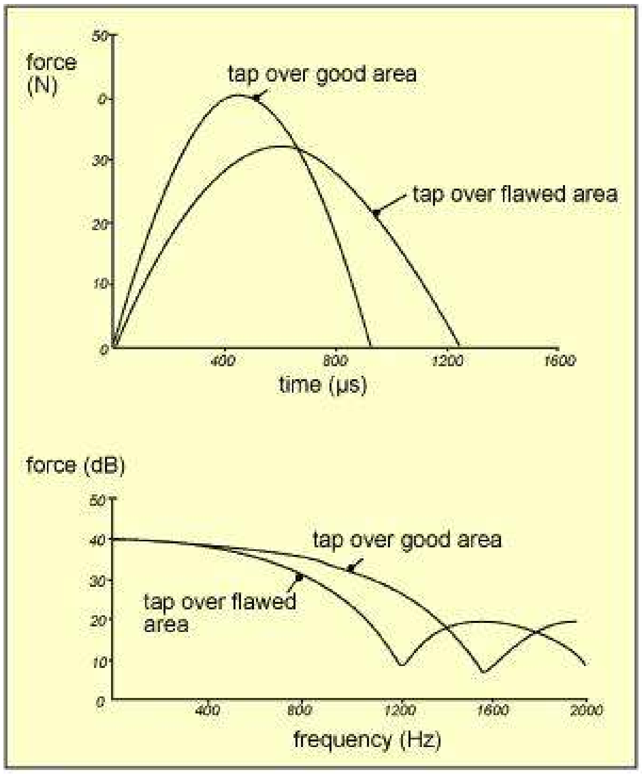

Fig.2.10. Interacting force in hammer tip produced by the coin-tap test applied over composite

The different forces input to the composite specimen cause it to vibrate differently and therefore produce a different sound, but it is the contact force itself that is used to quantitatively measure the local stiffness. The most common measure of the local stiffness is the contact duration, which can be plotted as a function of position on the surface. This can be used to produce a c-scan of the inspected area providing a permanent record of the inspection and enabling intuitive interpretation of the results. This test is fast, low cost and efficient for composites.

5.2.7.5 Mechanical impedance method

The mechanical impedance method is like the coin-tap test except that the excitation is continuous harmonic rather than impulse. The physical principles of the two techniques are very similar and therefore they have similar sensitivities. For both, their sensitivities fall off with increasing flaw depth in the specimen and so they are better at detecting near-surface flaws.

Figure 2.11 shows a device used to measure mechanical impedance. The contact tip is pressed lightly onto the specimen and a sinusoidal voltage at a pre-determined frequency is applied to the driving piezoelectric element, the resulting voltage across the receiving element being monitored. The relationship between the phase and amplitude of the driving and received voltages is dependent on the local impedance, so changes in the amplitude or phase of the received signal can indicate local changes in structural impedance. The probe is usually mounted within a spring loaded holder to ensure constant contact force. Samples containing known good and bad areas are required in order to configure the test.

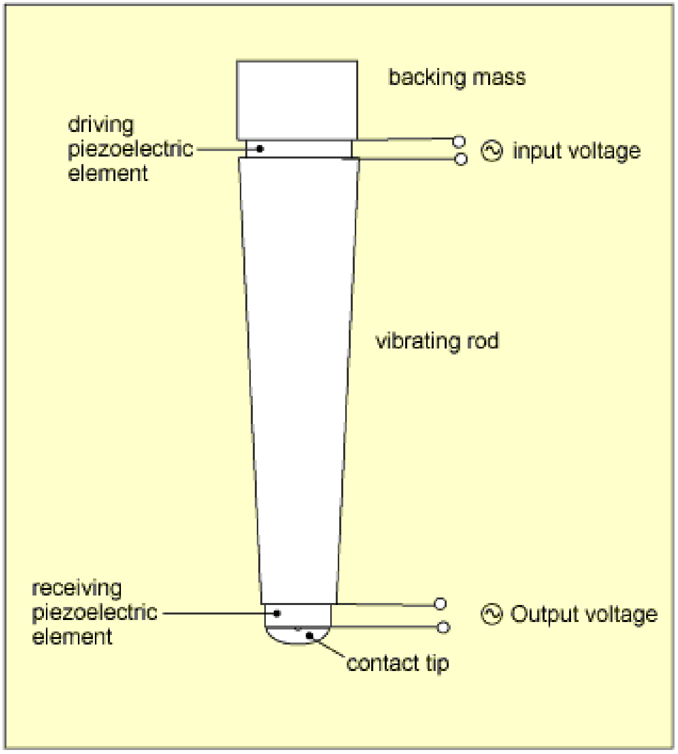

Fig.2.11. Probe for mechanical impedance method

5.2.7.6 Membrane resonance method

The membrane resonance method is similar to the mechanical impedance method except that it specifically measures local resonant vibration, and the excitation source is non-contact. It works on the principle that collectively the layers above a delamination constitute a membrane constrained at the perimeter of the delamination. It follows that the thickness of the membrane is the same as the depth of the delamination and that this together with the composite properties and the membrane equivalent diameter determine the frequency at which the membrane resonates. Therefore at frequencies around the membrane resonance, the vibration response for a given input force amplitude will be greater near the delamination than in a sound region. The difference in dynamic impedance between a good region and a defective region is significantly greater for the membrane resonance method than observed for the mechanical impedance method. Consequently it is not necessary to place such stringent controls on the input force making it a potentially simpler method.

The probe is scanned over the surface, and to ensure that the membrane resonance is found at each location, the input signal is generally broadband. One way of achieving this is by applying white noise in the frequency range 0.5 to 10kHz using piezoelectric material for both transmitter and receiver. The ratio between the transmitted and received energy is displayed on a meter. This is the principle of the Fokker type I bond tester.

5.2.7.7 Applications

The tap test and the mechanical impedance method can be used to detect delaminations in multi-ply composites. The delaminated region will produce a measurably lower local stiffness. The tap test is widely used in the testing of aircraft carbon and glass composite structures.

5.2.7.8 Strengths

In the low frequency regime/domain, local methods are more sensitive than global methods. As they are low frequency they do not require fluid, unlike many of the contact methods, and can be implemented with mechanical coupling. This makes them an attractive choice for moisture-sensitive composites.

5.2.7.9 Limitations

The sensitivity of low frequency local methods may not be sufficient for some field applications, particularly if defects at a significant depth are to be found. In such cases other methods may be necessary.

On thin specimens the general increase in structural flexibility will produce variability from one region to another in the measured local stiffness and therefore less reliable results. This will affect both the tap test and the mechanical impedance method.

Results from both may also be influenced by contact pressure. In the case of the tap test, stiffness measurements calculated from only the peak force will be highly variable if the velocity of impact is not carefully controlled. In such cases it is better to use parameters which are practically velocity independent such as the pulse width or the ratio of areas under the spectrum. Recent research has also shown that the ratio of the peak force to area enclosed by the pulse is a good velocity-insensitive measure of local stiffness. In the membrane resonance method, the coil must be kept a constant distance from the surface, imposing practical restrictions on implementing the method.

For both methods consistency can be improved by mounting the probe using a purpose-designed holder which rests on the surface of the structure. In the case of the mechanical impedance method, variations in the pressure with which the probe is pressed into the specimen surface will produce variability in the measured mechanical impedance. Commercial systems with spring-loaded probe heads are designed to keep the contact pressure more or less constant but, in practice, variations may still be observed unless the probe is pressed hard into the surface; however, this renders automatic scanning problematic.

5.2.8 Standards and Specifications

At the time of writing there were no relevant standards or specifications for the low frequency testing of thermosetting or thermoplastic polymer composites.

5.3 Radiographic inspection

5.4.1 Introduction

Radiography is the deployment of beams of ionising radiation to the non-destructive testing of structures. For composite inspection two types of radiation are relevant: X-rays and neutrons. The basic principle is that parts of the specimen that have differing radiation absorption properties can be discriminated in an image formed by the beam transmitted through the specimen.

By far the most widely used form of radiography uses X-rays and falls into two broad categories: *conventional X-radiography*, which uses only the radiation beam; and *enhanced*

X-radiography in which specially formulated liquids are used to enhance the contrast of the radiographic images. Because the polymer matrix and some fibres such as carbon have low absorption cross-sections, good contrast is difficult to achieve and low energy X-rays must be used to ensure that some absorption takes place (10kV to 50kV). These techniques are discussed below.

5.3.1 Descriptions

5.3.1.1 Conventional radiographic inspection

In conventional radiography, a beam of X-rays bombards the specimen and the unabsorbed radiation passing through the specimen hits a radiation-sensitive target, usually film. The radiation exposes the film emulsion in a similar manner to the way that light exposes film in photography. Development of the film produces an image that is a two dimensional 'shadow picture' of the specimen. *Figure 2.12* shows a typical radiographic set-up.

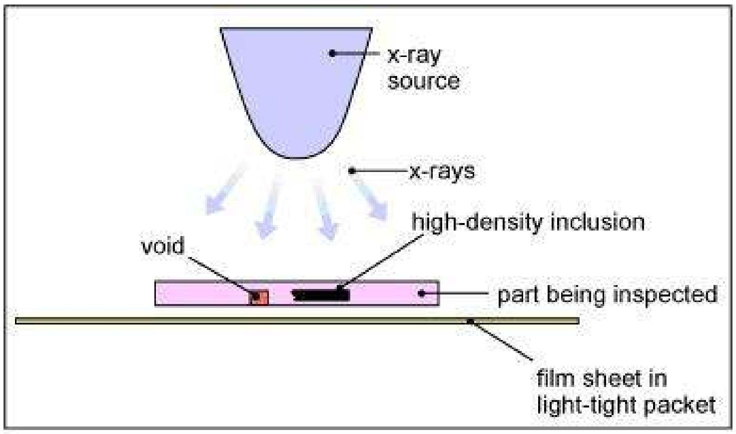

Fig.2.12. Schematic set-up of X-ray radiography test

Variations in the intensity of unabsorbed radiation, and therefore of radiation absorption in the specimen, appear as shades of grey in the developed film. Evaluation of the radiograph is based on comparison of the differences in density produced by an unknown specimen and that produced by a similar specimen of acceptable quality or neighbouring area. Using a fluorescent screen for image projection can produce real-time images, this technique is termed fluoroscopy.
In micro-focus X-radiography, the x-ray beam is emitted from a focal spot of 100μm or less. This is typically 20 times smaller than a conventional source, hence producing a sharper image. Some systems have focal spot sizes as low as 5 μm allowing geometric magnification to be used to image very small defects without the associated penumbra effect.

Flaws that do not have appreciable depth in the direction of the beam cannot be detected by conventional radiography. Cracks cannot be detected unless they lie parallel to the radiation beam. For similar reasons, delaminations perpendicular to the beam are almost impossible to find with conventional radiography. **Fibre volume fraction** variations are difficult to detect in CFRP composites with conventional radiography because both the matrix and the reinforcement have high carbon content and similar radiation absorption properties.

5.3.1.2 Computed tomography

X-ray computed tomography allows 3D images of components to be generated. A series of typically 360 to 720 radiographs are taken by rotating the object about one axis. The resulting data cloud is reconstructed in software to produce a 3D image of the component that can be viewed through any image plane. By assigning appropriate grey values, components such as metal fixings can be extracted from the image and viewed separately.

5.3.1.3 Enhanced radiographic inspection

When conventional radiography fails to produce sufficient contrast it can be enhanced by the introduction of a contrast medium, usually referred to as a radio-opaque penetrant. The method by which it is employed is known as penetrant enhanced X-radiography (PEXR). A wide range of halogenated aliphatic and water soluble inorganic chemicals show high X-ray absorption coefficients compared with composite materials. *Table 2.1* and *Table 2.2*, respectively, list some common organic and inorganic enhancement agents. The most widely used of these is zinc iodide which has high radiation opacity compared with the others.

Table 2.1 Relative radiographic opacity rating for organic chemicals

Halogenated Hydrocarbons	Relative Rating
Diiodomethane Diiodobutane	1
Dibromomethane	2
Tetrachloroethylene Tetrachloroethane	3
Tetrachloromethane Trichloroethylene	4
Trichloroethane Dichloromethane	5
Trichlro Trifluoroethane	6

Table 2.2 Relative radiographic opacity rating for inorganic chemicals

Inorganic Chemical Compounds	Radiographic Opacity
Zinc Iodide	High
Silver Nitrate	Medium
Lead Nitrate	Low
Barium Sulphate	Very Low

To be detected, the flaw must be surface breaking, e.g. caused by impact damage. The fluid is applied to the surface of the specimen before radiography. It is allowed to penetrate into the damaged regions for about 30 minutes before the excess penetrant is removed with an absorbent cloth. The radiation passing through the flawed region is now strongly absorbed and flaws undetectable with conventional radiography become visible.

5.3.2 X-ray back-scatter tomography (Compton Scattering)

X-ray back-scattered tomography was developed by Philips especially for applying the principle of Compton back-scattering to composite inspection. Back-scattered x-rays are those that are elastically scattered by interaction with atoms in the composite. They are always generated but at lower intensity to the non-scattered beam that is detected in conventional radiography. They emerge from the test-piece at a range of discrete directions, allowing one-sided inspection and tomographic imaging. It is possible to obtain twenty-two images with a single scan. It is typically used at radiation energies below 200 keV.

5.3.3 Applications

Conventional radiography can be applied to the detection of volumetric flaws such as voids in composites, but only when they exhibit absorption of 2% or more different from the surrounding material. Penetrant enhanced radiography also allows the detection of **delaminations** and **cracks** (provided they are open to the surface). Enhanced radiography can determine **fibre volume fraction** and **fibre alignment** on composites with radiation absorptive additives such as boron or glass (GFRP). Compton Backscatter is used in applications where one-sided inspection is essential, e.g. inspection of GFRP ship skins.

5.3.4 Strengths

Compared with through transmission ultrasonic testing, radiography produces better resolution images because the wavelength is considerably shorter for X-rays than for ultrasonic sound waves. Furthermore, it can inspect thicker sections than ultrasonic and can be used to inspect closed hollow components.

5.3.5 Limitations

A major limitation of X-rays is that they cannot detect delaminations without penetrant. Such an inspection of liquid-sensitive components is not non-destructive. X-rays are generally not useful for detecting in-service damage in composites since impact damage is largely composed of delaminations.

Ionising radiation is particularly hazardous to health if exposure is not carefully controlled. Consequently, it is necessary to ensure that adequate shielding is provided for technicians and to follow the guidelines set out by the national regulatory body on radiation protection (the National Radiological Protection Board or NRPB in the UK). Furthermore the chemicals used for enhancement are covered by the COSHH (Control of Substances Hazardous to Health) regulation. This means that the total cost both in terms of time and money is significantly greater for radiographic inspection methods than for other methods of NDT.
Radiographic methods form a direct 'through transmission' image of the specimen and therefore cannot be used to determine the depth at which flaws occur in a specimen without further radiographs taken from different angles. The exceptions to this are the back-scattered X-ray technique which gives some depth information and radiographic computed tomography. Considerable knowledge and experience is required in the interpretation of radiographic images as there are several types of artefacts which appear very similar to genuine flaws.

5.3.6 Standards and Specifications

A general standard relating to radiographic inspection that is also relevant to composites is BS EN-25580: 1992. 'Specification for Minimum Requirements for Industrial Radiographic Illuminators for NDT'.

5.4 Shearography

5.4.1 Descriptions

5.4.1.1 Conventional shearography

A near-surface flaw will decrease a composite component's local strength and therefore the surface will deform differently under loading if a flaw is present. These differences are very small so a technique based on optical interference is suitable to detect them. In shearography, the specimen is illuminated with a divergent laser beam and the scattered light is projected onto an image plane by a special shearing lens. This lens effectively shears the image of the specimen in the plane of the lens allowing interference between the sheared and direct images. This pattern is effectively a map of the distribution of local surface strain and represents a 'reference' image. A stress distribution is then applied to the surface (using vibration, sound, pressure, vacuum or thermal loading) and a second interference pattern is recorded. This stress distribution can be either in plane or out-of-plane. Superimposition or subtraction of the images obtained with the structure in the stressed and unstressed states will produce a fringe pattern. Each fringe is a line of strain and areas of increased strain are shown by concentrations of fringes. *Figure 2.13* shows the layout of a typical experimental set-up for a shearography test.

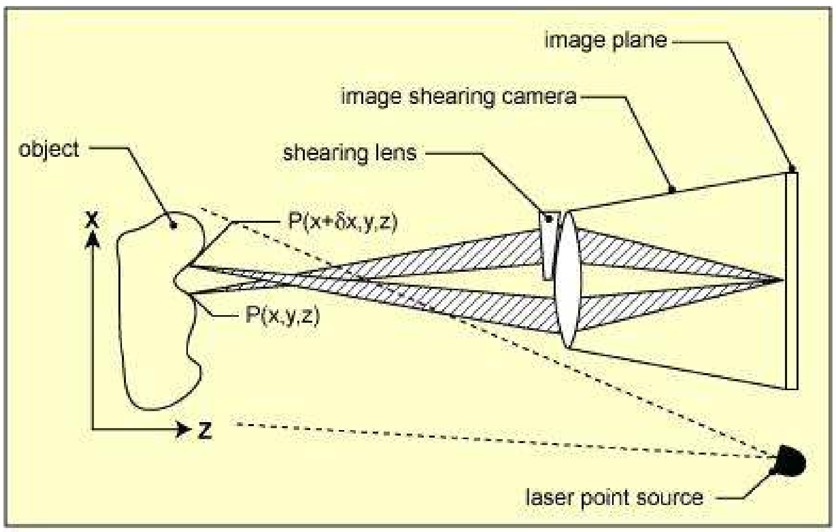

Fig.2.13. Basic Set-up for conventional shearography

Advances in phase stepping optics now allow the detection of sub-fringe deformations leading to greater detail and an image in which flaws show-up as 'moon crater' indications. Early systems were relatively insensitive to in-plane strain, but recent developments using twin angled laser beams can separate the in-plane and out of plane strain components and display them on separate images. This can aid in the characterization and detection of a variety of flaws.

There are four main techniques for comparing the interference pattern from the specimen in the distorted state with that in the undistorted state. These are the Real-time Technique, the Sandwich Technique, the Time Integrated Technique and Digital Shearography. Recent improvements in microprocessing technology have meant that digital shearography (where fringes are recorded electronically) is the main NDT method in use.

Note that Electronic Speckle Pattern Interferometry (ESPI) is similar to shearography except that the image-shearing lens is not employed. This means that the fringe pattern maps the displacement profile rather than the derivative of it. The technique is more susceptible to rigid body motion than shearography and therefore requires vibration isolation.

5.4.1.2 Digital Shearography

With the development of the video camera and relatively cheap and fast microprocessor technology, digital shearography is considered to be the norm as it allows real-time viewing and analysis of flaws without the expensive and time-consuming processes related to development of film. Reflected light from the surface passes through a shearing interferometer into a CCD camera. Additionally, the resolution that can be obtained using this method is better than any film process and furthermore image enhancement software can be employed to improve the picture quality and identification software can be used to automatically extract features characteristic of the flaws.

5.4.2 Applications

Shearography has a wide variety of applications in composites inspection, particularly in aerospace structures where it can be used to scan whole areas of fuselages and wings from tripod positions or through the use of a vacuum stressing hood. Either in-plane stresses or out-of-plane stresses can be used to deform the specimen. In-plane stress can be used to check the quality of repairs. In aircraft panels surface-breaking cracks are often repaired by bonding a boron patch over the flaw. The patch should take up the in-plane strain and therefore a map of surface strain distribution should indicate that strain concentrations are not present over the ends of the crack but stain has been distributed over the surface of the patch and surrounding area.

In GRP pressure vessels where the stressing technique is internal pressurisation, shearography can be used to detect **inclusions.** Out-of plane stressing has been applied to the detection of surface-breaking and sub-surface flaws such as **barely visible impact damage, delaminations** and internal **cracks.** These particularly weaken the strength normal to the surface. The distortion produced by local out-of-plane pressure reduction is hemispherical and this leads to the double bulls-eye interference pattern as shown in *Figure 2.14*.

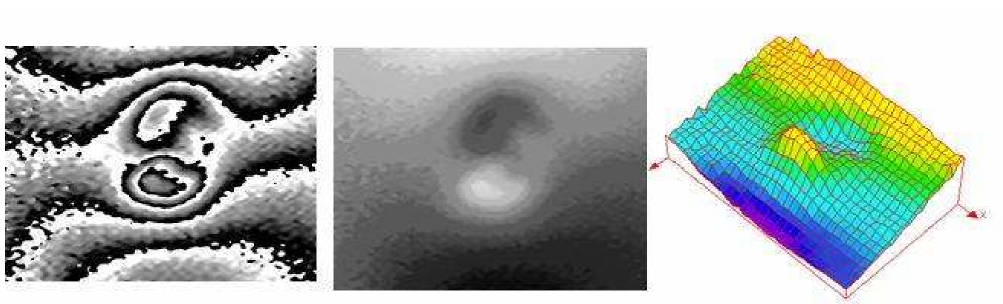

Fig.2.14. Phase stepped fringe pattern, unwrapped image and 3D processed images of impact damage in an aerospace panel.

5.4.3 Strengths

Shearography allows non-contact inspections to be conducted rapidly and with a high degree of sensitivity. Although relatively powerful lasers are used (150mW), because the beams are expanded, many instruments can be manufactured to conform to class 2M. This means that as long as the instrument case is not opened or an optical element capable of refocusing the expanded beam is not placed in the beam path, the instrument can be used without additional optical protection. It can be compared with holography as a method of determining structural condition from surface displacements. Because shearography can measure the derivative of surface displacement it is less sensitive to rigid body motion than holography since the latter measures absolute displacement. Consequently shearography is more suitable for field measurements where the conditions are less than ideal.

5.4.4 Limitations

Because the specimen must be loaded to reveal any defects there is always a possibility that damage might be incurred as a result of the testing procedure, but in practice the loads required to produce fringe patterns are several orders of magnitude less than the working load of the structure. Shearography can only be applied to specimens in which the surface roughness is of the order of one wavelength of light or more. Specimens with smoother surfaces will produce random interference that will mask the effect due to the distortion. Another drawback is that the interpretation of the results is complex and requires considerable experience. As shearography is an optical surface based technique, the influence of lighting and the location of flaws have a bearing on the resultant image.

5.4.5 Standards and Specifications

At the time of writing there were no relevant standards or specifications for the shearographic testing of thermosetting or thermoplastic polymer composites.

5.5 Acoustic emission and Acousto-ultrasonics

5.5.1 Descriptions

These are techniques in which material degradation is detected by the analysis of structural stress waves. In both techniques, the flaw or degradation causes a change in the detected response and this is identified by some form of fingerprint analysis. In acoustic emission, stress waves are generated within the material either by applying an external load or by ambient loading. In acousto-ultrasonics the stress waves are introduced to the material by some broadband external excitation. In both methods the analysis procedure seeks to distinguish stress waves produced by a flaw or degraded region from those emanating from the sound material. With acoustic emission it is the localised flaw such as a crack that is detected whereas with acousto-ultrasonics it is the collective presence of a number of flaws that is detected.

5.5.1.1 Acoustic emission

This is fundamentally different from other techniques that use stress waves as it relies on signals originating from within the specimen rather than outside it. These signals are generated from flaws in response to some physical or thermal deformation of the structure. Therefore, the flaw can only be detected while the damage is occurring, and consequently some argue that this is not truly a non-destructive technique at all. However, the effectiveness of the technique is reliant on the sensitivity of the numerical processing procedures which are applied to the monitoring data and it is possible to detect flaws before they become critical to the safety of the structure.

A number of piezoelectric sensors are placed on the structure to be monitored near to possible weak spots. The structure is then subjected to an external load that stimulates acoustic emission from features within the structure. For pipelines a physical load can be implemented by control of the internal pressure caused by the normal payload. Acoustic emission signals are transients and many such signals which exist within a structure at a given time are not associated with genuine flaws but with other processes. The first stage of identifying signals from flaws involves converting each transient into an event characterised by a number of parameters. These are:

- Peak amplitude - the maximum amplitude in dB
- Counts - the number of times the signal crosses a pre-defined threshold (between 10 and 1000)
- Duration - in microseconds, typically between 20 and 1000μs
- Rise time - the time taken for the signal to reach its maximum amplitude
- Energy - the electrical energy generated in the sensor by the signal
- Root mean square - an average parameter used for comparatively long transients

Figure 2.15 shows a signal produced by a single surface displacement, which in turn is often assumed to be the consequence of a single event inside the material.

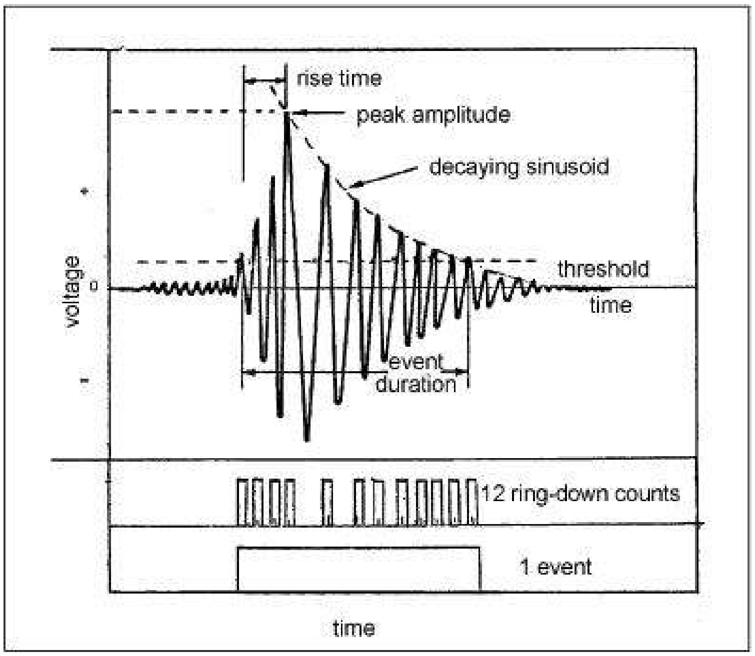

Fig.2.15. Amplified signal from a piezoelectric transducer illustrating 'ring-down' and event counting

5.5.1.2 Acousto-ultrasonics

Acousto-ultrasonics is a technique in which the received signal is processed in a similar manner as in acoustic emission testing but the acoustic signal is externally introduced to the specimen with a transmitter. Two ultrasonic transducers are placed a fixed distance apart on the specimen surface, one acting as transmitter, the other as receiver. Any flaw which affects the specimen's mechanical properties will affect the way in which stress waves travel in it. Measures such as the stress wave factor (SWF), which are computed from the received signal (see *Figure 2.16*), provide a numerical index that allows one state of the specimen to be distinguished from another.

The SWF decreases with increasing flaw content and damage within the composite. By scanning the transmitter and receiver across the specimen surface it is possible to locate flawed regions.

The mechanical properties are influenced only by large flaws or diffuse populations of small flaws - acousto-ultrasonics cannot be used to detect small, single flaws, although it can detect large area defects such as delaminations. It is well suited to the detection of material properties.

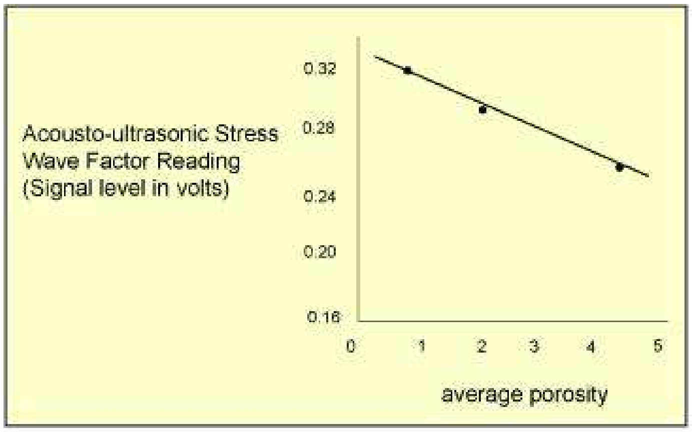

Fig.2.16. Acousto-ultrasonic detection of porosity

5.5.2 Applications

Acoustic emission is well established as a method of testing GRP tanks, vessels and piping. It can be used to detect flaws such as **cracks, broken fibres, delamination** and the breaking of the **fibre-matrix bond**, although the latter application is not always reliable.
Acousto-ultrasonics can be applied to the detection of **porosity content, translaminar cracking, delaminations** and to the checking of stacking sequence in composites. The acousto-ultrasonic method does not always give satisfactory results for reasons that are not well understood, and various degrees of success have been reported for acoustic emission. These methods are established but on-going development aims to improve their reliability.

5.5.2.1 Acoustic Emission

Acoustic emission can monitor a whole structure with only a few transducers and only limited access is required, this is very useful for field tests. The sophisticated numerical processing procedures can locate the source of a flaw anywhere on the structure without the necessity to scan a large proportion of its surface. Its potential sensitivity is very high compared with other NDT methods; for example, single fibre fractures can be detected, and the effectiveness of the method is not dependent on the orientation of the flaw.

5.5.2.2 Acousto-ultrasonics

Compared with acoustic emission, this technique has the advantage that the component under examination does not have to be stressed. This results in a truly non-destructive technique (it can be argued that acoustic emission is not strictly non-destructive as the applied stress necessary to generate the acoustic signal actually propagates the crack).

5.5.3 Limitations

5.5.3.1 Acoustic emission

The main limitation of acoustic emission is that it is not capable of detecting flaws unless they are growing. Hence it only detects flaws while damage is taking place. It is difficult to size flaws with acoustic emission, and locating flaws in complex geometries of composite materials is a particularly difficult exercise. Furthermore, the sensitivity of the test is adversely affected by ambient plant noise.

5.5.3.2 Acousto-ultrasonics

Acousto-ultrasonics cannot detect small individual localised flaws because these do not affect the mechanical properties. The wavelength is also much longer than other ultrasonic methods, thus only large defects can be detected.

5.5.4 Standards and Specifications

General standards relating to acoustic emission are also relevant to composites. These are listed below:

1. BS EN-13477: 2001. Acoustic Emission Testing.
   Part 1. Equipment Description
   Part 2. Equipment Characterisation - Verification of Operating Characteristics
2. BS EN-1330-9: 2000
   Acoustic Emission Testing. Pt. 9. Terms Used in Acoustic Emission Testing.

Specific applications of Acoustic Emission can also be found in ASTM publications:

3. E 2076-00. Examination of Fibreglass Reinforced Plastic Fan Blades Using Acoustic Emission.
4. E2191-02. Examination of Gas-Filled Filament Wound Composite Pressure Vessels Using Acoustic Emission.
5. E 1067 - 01. Acoustic Emission Examination of Fibreglass Reinforced Plastic Resin (FRP) Tanks/Vessels.
6. E 1118 - 00. Acoustic Emission Examination of Reinforced Thermosetting Resin Pipe (RTRP).

Specific Application of Acousto-Ultrasonic testing for Composites can be found in ASTM* publication -

7. E1495-2002 Acousto-Ultrasonic Assessment of Composites, Laminates and Bonded Joints.

5.6 Thermography

5.6.1 Introduction

Thermographic methods are those in which the presence of flaws is determined by monitoring the flow of heat over the surface of a structure after some external introduction of a temperature gradient. The presence of flaws disrupts the normal pattern of heat flow that would be expected in a sound structure. The method is more sensitive to flaws near to the surface. Modern thermographic systems commonly use infrared (IR) cameras to detect radiated heat and are controlled by TV video electronics which sample the field of view at a typical rate of 50Hz, allowing temperature variations on a 20ms time-scale to be resolved.
The camera is sensitive to temperature changes of about 0.005°C and covers a chosen range of temperature, 4°C and 8°C being commonly suitable, although operation is possible between -50°C and +100°C. Liquid crystal coatings and pyroelectric detectors have also been used to detect IR radiation.

Thermographic methods fall broadly into two groups: active methods, and passive methods. Active methods are those in which the thermal gradient is produced and continuously maintained by the application of cyclic stress. Passive methods are those in which the thermal gradient results from a transient change. Passive methods are the most widely applied NDT technique in composites inspection. Below, two commonly used thermographic techniques are discussed: *thermal pulse thermography*, a passive method that involves the use of an externally applied transient heat source; and *vibrothermography*, the active method.

5.6.2 Descriptions

5.6.2.1 Thermal pulse thermography

In this method the input to the composite specimen is a transient in the form of a step function such as a hot or cold object suddenly brought into contact with the surface, or a delta function such as a blast of hot air or coolant. In general, the best results are obtained when the maximum possible amount of energy is deposited on the surface, though care must be taken to avoid damage. A set-up for a thermal pulse experiment is shown diagrammatically in *Figure 2.17*.

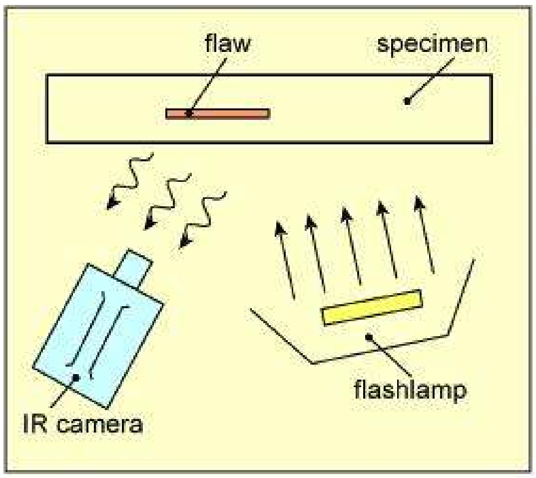

Fig.2.17. Experimental set-up for thermal pulse thermography

If a flash tube or bulb is used as the heat source the efficiency can be greatly improved by a coating of black paint but this is not essential provided the surface is not highly reflecting. The heating source can be on the same side of the specimen as the camera or on the opposite side (transmission). For a transmission test, the temperature builds up on the opposite side at a rate determined by the thermal properties of the composite. Contrast arises when an internal feature such as a delamination, which causes the temperature to rise more slowly on the monitored surface, affects these properties. In single-sided testing, an initial period of 'white-out' is followed by a period of declining surface temperature, the rate of decline being measurably lower in the region of a flaw. A number of software processing aids are available to aid defect detection and image interpretation. First and second derivatives of temperature can be viewed and the resulting thermograms can be coloured and represented as a 3D image. Figure 2 .18 refers.

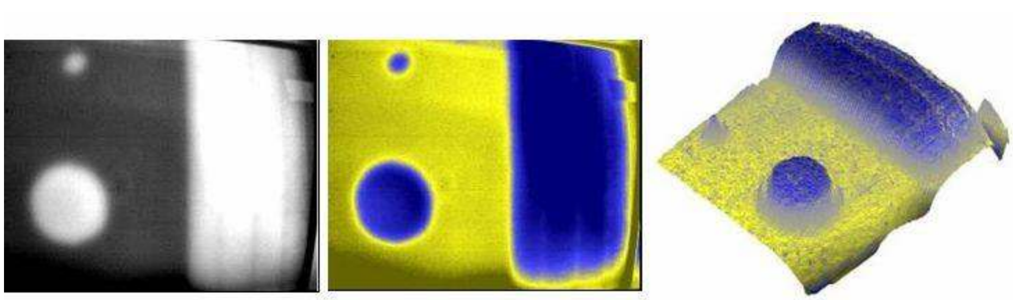

Figure 2.18. Black and white, colour enhanced and 3D images of artificial delaminations in wind turbine blade.

A wide range of sensitivity values has been reported in the literature, and it is wise to carry out tests on the particular material and geometry of interest in potential applications of this method. However, minimum detectable flaw diameter/depth ratios of about 2 can be expected for CFRP and GFRP composites.

5.6.2.2 Vibrothermography

Otherwise known as Stress Pattern Analysis by the measurement of Thermal Emission (SPATE), the interfaces of cracks in the surface are abraded by applied vibration energy and they generate heat. Scanning a thermal camera over the surface under inspection allows the detection of these localised 'hot spots'. By changing the mechanical excitation frequency, local thermal gradients appear or disappear depending on the specific resonant frequency. Numerical modelling allows the determination of suitable excitation frequencies. For instance, in a given study, a 28cm x 13cm CFRP beam was attached to a piezoelectric shaker from one side and significant thermal patterns from the simulated delamination embedded in the specimen appeared at a frequency of around 13.5 kHz.

5.6.3 Applications

Thermography can be used to detect translaminar cracks in GFRP composites and to find inclusions, impact damage, voids and cracks in CFRP laminates. However, cracks that are aligned parallel to the direction of heat flow may go undetected.

5.6.4 Strengths

Thermography can often be used in composite applications where radiography or ultrasonic inspection produces results that are difficult to interpret. It has the advantage that it can be used in applications in which access from only one side is possible. Infrared cameras can be used several metres from the specimen allowing remote sensing. Rapid area coverage is possible and image stitching software can be used to produce composite images of large areas.

5.6.5 Limitations

The main limitation in applying thermography to composites inspection is the anisotropy that produces different thermal properties in different directions. The presence of lightning protection mesh in some aerospace structures can mask indications.

5.6.6 Standards and Specifications

At the time of writing there were no relevant standards or specifications for thermographic testing of thermosetting or thermoplastic polymer composites.

5.7 Visual inspection

The common-sense approach to NDT is to first inspect visually for surface flaws. Many of the most serious defects from the perspective of strength are surface-breaking and can often be seen by careful, direct visual inspection. However, optical aids should be used wherever possible to improve the probability of detection. Such aids include improved illumination techniques, miniature video and small diameter boroscopes. Image enhancement techniques such as D-sight convert local variations in surface shape into light intensities, making the technique less subjective.

Normal eyesight is often sufficient to indicate where impact damage or delamination beneath the surface has occurred. For translucent materials it is possible to detect porosity and the fibre matrix bond condition down to a depth of 10-15mm and delamination down to a depth of 25mm.

Visual inspection is an inexpensive, simple and rapid method of finding flaws. It does not employ sophisticated equipment that might require technical training or safety provisions (although standard procedures and safety precautions apply) and provides a quick, superficial estimate of structural condition.

Visual inspection will miss any sub-surface flaws that do not cause a surface disturbance and may miss BVID (barely visible impact damage). Therefore, it cannot be used on its own as an inspection technique: it must be supplemented by other deeply-penetrating methods. Furthermore, it is particularly subjective.

Some general Standards relating to visual inspection are also relevant to composites. Some of these are listed below:

1. BS EN 13018: 2001- Visual Testing, General Principles. Amended Feb 2004.
2. CGA C-6.2 - Guidelines for Visual Inspection and Requalification of Fibre Reinforced High Pressure Cylinders. 1 Jan 2003.
3. BS EN-1330-10: 2000 - Visual Inspection, Terminology. Terms Used in Visual Inspection (part 10).
4. BS ISO -3058:1998. Aids to Visual Inspection - Selection of Low Power Magnifiers (Replaces BS 5165: 1974).
5. ISO 3058:1998. Non-destructive Testing - Aids to Visual Inspection. Selection of Low Power Magnifiers.
6. prEN-13927 - Visual Inspection Equipment.

6 Choice of Inspection Techniques

Established NDT methods for PMCs are summarised in *Table 1.1*; technologies under development at the time writing are given in *Table 1.2*. Research in NDT is an on-going process and the status of various methods may change.

In many cases the approach to testing thermosetting and thermoplastic polymers will be the same. In cases where they are different, certain methods may be preferred over others.

Table 1.1. Established NDT methods for inspecting PMCs

	Visual	Through-transmission	Shearography	Pulse-echo	Velocity	Low frequency	Radiography	Acoustic emission	Thermography
Flaw sought									
Fibre type					●				
Porosity	●	✓		✓	●				
Fibre-matrix bond	●							●	
Matrix properties				●	●				
Fibre misalignment		●				●	●		
Volume fraction		●		✓	●	●	●		
Stacking sequence									
Ply-end discontinuity				●					
Foreign inclusions		●	●	✓			✓		✓
Trans-laminar cracks		●	✓	●			●	✓	●
Fibre breakage								✓	
Delamination	✓	✓	✓	✓		✓	●	✓	✓
Moisture ingress					●				
Impact damage	✓		✓						✓

● Application limited

✓ Method has proved ability to detect given flaw

Table 1.2 Emerging NDT technologies for inspecting PMCs

	Ultrasonic back-scatter	**Acoustography**	**Spectroscopy**	**Acousto-ultrasonics**
Flaw sought				
Fibre type				
Porosity	(✓)		(✓)	(✓)
Fibre-matrix bond				
Matrix properties			(✓)	
Fibre misalignment	(✓)			
Volume fraction				
Stacking sequence	(✓)			(✓)
Ply-end discontinuity	(✓)			
Foreign inclusions		(✓)		
Trans-laminar cracks	(✓)	(✓)		(✓)
Fibre breakage				
Delamination		(✓)	(✓)	(✓)
Moisture ingress				
Impact damage		(✓)		
(✓) Method has proved ability to detect flaw				

6.1 Material evaluation

A polymer matrix composite can be evaluated by measuring the velocity or attenuation of ultrasound in the material. By measuring velocity perpendicular to the plane of the fibres, the fibre-volume fraction and extent of porosity can be determined. It is also possible to monitor moisture ingress. By positioning the probe parallel to the plane of the fibres and measuring velocity it is possible to determine the fibre-volume fraction and fibre type (where

the moduli are significantly different), although access to the fibre ends is not always possible. However, with all techniques based on velocity measurement, the differences in velocity for two different states of the composite are small and sometimes difficult to detect.
By measuring ultrasonic attenuation, poor curing can be detected because it causes an increase in ultrasonic attenuation by the increased vibration damping within the matrix. In addition, changes in porosity can be detected because the ultrasound is scattered by the microscopic spherical discontinuities. However, the changes in attenuation from one area to another are small and difficult to detect and furthermore it is not easy to distinguish between attenuation changes caused by porosity and those caused by poor curing.

The characteristics of a range of NDT methods for PMCs are described in Section 2 of the guide. The discussion considers the inspection of large areas of uniform composite. Testing corners and other areas of rapidly changing geometry is much more difficult and may require a non-standard approach. For example, standard ultrasonic probes may not be useful for pipe bends of less than 6" diameter and specially shaped 'shoes' will be required.

6.2 Choice of NDT method

In most cases the methods described in this best practice guide can equally be used for both thermosetting and thermoplastic composites. There are, however, a few issues that should be considered that might affect the choice of method

6.2.1 Heat

In all methods care must be taken to avoid heat-imposed damage. With methods that involve localised heating, such as thermography, temperature rises of only a few degrees are all that is required; however, over zealous application of the heat source may cause charring in thermosetting composites or melting in thermoplastics composites. Vibrothermography works better on composites with low thermal conductivity as these will allow heat to remain at the discontinuity interfaces longer. For this reason vibrothermography works better on GFRP composites than on CFRP composites. However, thermal pulse thermography would be recommended for thermosetting CFRP composites because of the high thermal conductivity in the planar direction.

6.2.2 Atomic properties

Atomic mass and atomic number will affect the interaction of ionising radiation with the composite. The effectiveness of radiographic methods depends on contrast, and where there is insufficient contrast between the surrounding air and the composite, radiography is not a valid technique. This is true of thermosetting CFRP which has similar radiation absorption properties to air. Thermoplastic GFRP on the other hand can be used with radiography because it has better contrast with air.

6.2.3 Acoustic properties

Methods that rely on stress wave propagation can be used on thermosetting and thermoplastic composites alike. However, acoustic emission has only found wide use on the thermoplastic GFRP composite.

7 Acceptance Criteria

There are many NDT methods capable of detecting flaws in thermosetting and thermoplastic composites. However, being able to detect a flaw in a composite only provides part of the required information for a NDT technique to be effective. It is equally important to determine the minimum size of flaw or contamination that significantly reduces the performance of the composite - the *acceptance criteria*. A procedure for the assessment of manufacturing defect significance in relation to ultrasonic testing is briefly discussed below -
The most important manufacturing flaws that, in practice, are likely to occur are voids. Some of the other defects do not often occur and even then rarely in isolation. For example,

incorrect fibre volume fraction due to insufficient resin will usually be accompanied by voids as will incorrectly cured resin. Other flaws such as inclusions and delaminations will also be detected when an assessment of void content is made.

Void content is important because of its influence on the interlaminar shear strength (ILSS) and can be estimated ultrasonically by measurement of attenuation; the reduction in wave amplitude as it passes through a specimen. The dependence of ILSS on void content for unidirectional HTS fibres in an ERLA 4617 resin matrix is represented by a reciprocal shaped decay curve, the exact parameters depending on the resin system and fibre type (see 'Ultrasonic Attenuation as a Measure of Void Content in Carbon Fibre Reinforced Plastics', Non Destructive Testing, Volume 8, number 3, 1975).

For a given fibre resin system, the dependence of the ultrasonic attenuation on void content can be measured and approximates to a bilinear relationship (i.e. two intersecting, but not overlapping, linear graphs with different gradients). A calibration is then conducted to take account of the attenuation of a specimen with no void content. If these factors are carefully taken into account, a quantitative assessment of void content can be made. The void content is reported in terms of an equivalent distributed void content because the same attenuation may be observed for a small number of isolated large voids as for a large number of uniformly distributed small voids (see 'Non-Destructive Inspection of Composite Materials for Aircraft Structural Applications - Part 1', Tech. Air, 1979).

8 Training and Qualification

In the UK the following institutions offer training courses in NDT of Composites:

TWI Ltd
Granta Park
Great Abington, Cambridge
CB21 6AL
UK
Tel: +44 (0)1223 899000
Fax: +44 (0)1223 892588
E-mail: twi@twi.co.uk

The South West School of Non Destructive Testing
Merton House
Croescadarn Close
Pentwyn
Cardiff
United Kingdom
CF23 8HF
Telephone:
+44 (0) 29 20540000
Fax:
+44 (0) 29 20540111
E-Mail: chgthomas@swsndt.co.uk
http://www.swsndt.co.uk/training/composite_inspection_5day.htm

Aerospace Inspection Training
Hangar A, Norwich Airport, Norwich, Norfolk. NR6 6EG, UK
Telephone +44(0) 1603 426165
Facsimilie +44(0) 1603 424019
e-mail : Aerospacetraining@yahoo.co.uk
http://www.aerospacendt.co.uk/

There is no specific standard for training personnel to NDT Composites. BS EN4179:2000, SNT-TC-1A, NAS-410 are the generic standards that are used in industry.

9 Sources of further information

9.1 Websites

Interactive Knowledge Base on NDE of Composites found at (http://www.netcomposites.com/ikb/). A very useful resource giving links to UK suppliers of NDT services and also recommending techniques depending on material.

British Institute of Non Destructive Testing (http://www.bindt.org/)

NDT Net (http://www.ndt.net/)

NDT Resource Centre (http://www.ndt-ed.org/)

9.2 Books

Damage and its Evolution in Fiber - Composite Materials: Simulation and Non-Destructive Evaluation
ISBN: 3930683903
October 2006
Language: English
Editors: Gerd Busse, Bernd-H. Kröplin, Falk K. Wittel
Universität Stuttgart
548 Pages incl. 94 color illustrations

Non-Destructive Testing of Fibre-Reinforced Plastics Composites
ISBN1851660933
AUTHOR edited by J. Summerscales, Advanced Composites Manufacturing Centre, Plymouth
FORMAT, Hardbound, 278 pages
PUBLISHER Kluwer Academic Publishers, September 1987

Nondestructive Characterization of Composite Media
ISBN0877629250
AUTHOR Ronald A. Kline
PUBLISHER Technomic Publishing Co., 1992

Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security 2007 (Proceedings of SPIE) (Paperback)
by H. Felix Wu (Author)
ISBN-10: 0819466522

Composite Materials: Properties, Non-Destructive Testing, and Repair Vol 1
by M.M. Schwartz (Author)
ISBN-10: 0133000478
Publisher: Prentice-Hall (30 Jul 1997)

9.3 Published Literature

A number of recent papers relating to NDT of composites are shown below.

TITLE: THE ULTRASONIC WAVE PROPAGATION IN COMPOSITE MATERIAL AND ITS CHARACTERISTIC EVALUATION
AUTHOR(S): Chang J; Zheng C; Ni Q Q
CORPORATE SOURCE: Dalian,Maritime University; Shinshu,University
SOURCE: Composite Structures; 75, No.1-4, 2006, p.451-456
ISSN: 0075-0001
JOURNAL ANNOUNCEMENT: 200611 RAPRA UPDATE: 200622

FILING MARK: ELS RAB0010A 02638223 00750001 06001711
DOCUMENT TYPE: Journal Article
LANGUAGE: English
SUBFILE: (R) RAPRA
ABSTRACT: The use of the ultrasonic wave technology was expected as one of important technologies in health monitoring of composite materials and/or structures. However, the propagation of ultrasonic wave becomes very complicated for polymer based composite materials due to reflection, transmission, dispersion and so on, which may occur on the interface of matrix and reinforcements. Therefore, in this paper, elastic wave motion equation was dispersed using the finite element analysis of the PZFlex code; then the propagation of ultrasonic wave in several model composite materials was simulated. Then, the influence of the fibre/matrix interface shape, fibre size and other fibre conditions on wave propagation behaviour was clarified. Moreover, the complicated wave propagation resulting from reflection, transmission and refraction on the fibre/matrix interface was visualized and the influence of the fibre arrangements and fibre volume fraction on the ultrasonic wave behaviour was investigated for both conditions with and/or without attenuation in matrix. 8 refs.

TITLE: NON-DESTRUCTIVE CHARACTERIZATION OF BONDLINES IN COMPOSITE ADHESIVE JOINTS
AUTHOR(S): Mylavarapu P; Woldesenbet E
CORPORATE SOURCE: Louisiana,State University
SOURCE: Journal of Adhesion Science and Technology; 20, No.7, 2006, p.647-660
ISSN: 0169-4243
CODEN: JATEE8 JOURNAL ANNOUNCEMENT: 200610
RAPRA UPDATE: 200618
DOCUMENT TYPE: Journal Article
LANGUAGE: English
SUBFILE: (R) RAPRA
ABSTRACT: Carbon-epoxy composites with different adherend surface preparations were bonded with an epoxy adhesive and the resulting joints with known defects in the bondline subjected to ultrasonic imaging using the pulse echo method. The results obtained were analysed to identify defects, such as voids, cracks and debonds, in the joints, and the validity of the image analysis was assessed using attenuation coefficient values. Tests were also carried out on joints of different thicknesses to determine the effect of laminate thickness on attenuation. 12 refs.

TITLE: A CRITICAL REVIEW OF INFRARED THERMOGRAPHY AS A METHOD FOR NON-DESTRUCTIVE EVALUATION OF FRP REHABILITATED STRUCTURES
AUTHOR(S): Ghosh K K; Karbhari V M
CORPORATE SOURCE: California,University at San Diego
SOURCE: International Journal of Materials and Product Technology; 26, No.4, 2006, p.241-66
ISSN: 0268-1900
JOURNAL ANNOUNCEMENT: 200606 RAPRA UPDATE: 200610
DOCUMENT TYPE: Journal Article
LANGUAGE: English
SUBFILE: (R) RAPRA
ABSTRACT: The technique of infrared thermography and its application to the non-destructive evaluation of fibre-reinforced polymer composite rehabilitated concrete structures is reviewed in terms of the detection of defects and their time-dependent changes. The requirements for real-time inspection and data interpretation for routine use of the technique under varying field conditions are also assessed. 41 refs.

TITLE: AN APPLICATION OF A NEW ULTRASONIC TECHNIQUE TO JUTE COMPOSITE LAMINATES SUBJECTED TO LOW-VELOCITY IMPACT
AUTHOR(S): Scarponi C; Valente M
CORPORATE SOURCE: Rome,Universita La Sapienza
SOURCE: International Journal of Materials and Product Technology; 26, No.1-2, 2006, p.6-18
ISSN: 0268-1900
JOURNAL ANNOUNCEMENT: 200606 RAPRA UPDATE: 200610
DOCUMENT TYPE: Journal Article
LANGUAGE: English
SUBFILE: (R) RAPRA

ABSTRACT: The determination of delamination damage in jute fabric-reinforced vinyl ester resin composite laminates subjected to low-velocity impact was studied by non-destructive investigation using an ultrasonic reflection technique. The results are discussed in terms of the correlation between damage and impact energy, and in comparison with those obtained for glass fibre-reinforced composite laminates. 10 refs.

TITLE: NON-DESTRUCTIVE TESTING TECHNIQUES FOR FRP REHABILITATED CONCRETE. I. A CRITICAL REVIEW
AUTHOR(S): Kaiser H; Karbhari V M
CORPORATE SOURCE: California,University at San Diego
SOURCE: International Journal of Materials and Product Technology; 21, No.5, 2004, p.349-84
ISSN: 0268-1900
JOURNAL ANNOUNCEMENT: 200411 RAPRA UPDATE: 200421
DOCUMENT TYPE: Journal Article
LANGUAGE: English
SUBFILE: (R) RAPRA
ABSTRACT: A critical review is presented of non-destructive testing techniques for concrete rehabilitated with fibre reinforced plastics. Techniques covered include visual inspection, acoustic impact testing, penetrant methods, ultrasonics, radiographic testing, thermographic testing, eddy current testing, microwave testing, optical methods, acoustic emission, ground-penetrating radar, strain measurement techniques, modal analysis and rapid load testing. It is shown that, although a number of techniques meet the overall requirements, none is at such a stage of development that it can be used directly with great effectiveness. Critical research and development needs are identified. 67 refs.

Preliminary Study of Ultrasonic Detection of Cracks Through Thick Composite Doublers (Conference paper)
Neal, S. P. ; Cepel, R. ; Palmer, J. D.
Missouri Univ.-Columbia.
Corp. Source Codes: 049959000; 234700
Report No.: AFRL-ML-WP-TP-2006-403
Feb 2006 13p
Languages: English Document Type: Conference proceeding; Journal article
Journal Announcement: USGRDR0620
Submitted for presentation at the Joint FAA/DoD/NASA Conference on Aging Aircraft (9th), 2006. Prepared in cooperation with The Boeing Company, Phantom Works.
Sponsored in part by National Science Foundation (NSF) under grant no. CMS-9610189.
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customers); (703)605-6000 (other countries); fax at (703)605-6900; and email at orders@ntis.gov. NTIS is located at 5285 Port Royal Road, Springfield, VA, 22161, USA.
NTIS Prices: PC A03/MF A01
Country of Publication: United States
Contract No.: FA8650-04-C-5704; 2865; 25
Composite doublers have been introduced as a repair method to take a substantial portion of the structural load away from the region around a crack in aluminium aircraft structures. The subsequent use of non-destructive evaluation methods to test the quality of the composite doubler bond and to characterize the crack beneath the doubler is described. In particular, the use of scanning ultrasound methods is evaluated along with appropriate analysis methods to characterize the crack.

Acoustic Emission and Acousto-Ultrasonic Techniques for Wood and Wood-Based Composites-A Review
Kawamoto, S. ; Williams, R. S.
Forest Products Lab.,Madison, WI.
Corp. Source Codes: 017958000
Report No.: FPL-GTR-134
Dec 2002 24p
Languages: English
Journal Announcement: USGRDR0312
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NTIS Prices: PC A03/MF A01
Country of Publication: United States
This review focuses on the feasibility of acoustic emission (AE) and acoustic-ultrasonic (AU) techniques for monitoring defects in wood, particularly during drying. The advantaged and disadvantages of AE and AU techniques are described. Particular emphasis is placed on the propagation and attenuation of ultrasonic waves in wood and the associated measurement problems. The review is divided into two sections, acoustic emission techniques and acousto-ultrasonic techniques. It includes historical background on the techniques as well as applications for wood and wood products. Because much research on nondestructive tests for wood has been published only in Japanese, considerable attention is given to those publications.

Title: NDE of RCC using digitome volumetric X-ray image system
Author: Chu, Tsuchin Philip
Corporate Source: Department of Mechanical Engineering and Energy Processes Southern Illinois University, Carbondale, IL 62901
Conference Title: SEM Annual Conference and Exposition
on Experimental and Applied Mechanics 2006
Conference Location: Saint Louis, MO, United States
Conference Date: 20060604-20060607
E.I. Conference No.: 68397
Source: Proceedings of the 2006 SEM Annual Conference and Exposition on Experimental and Applied Mechanics 2006
Proceedings of the 2006 SEM Annual Conference and Exposition on Experimental and Applied Mechanics 2006 v 2
2006.
Publication Year: 2006
ISBN: 091205395X
Language: English
Document Type: CA; (Conference Article) Treatment: T; (Theoretical)
Journal Announcement: 0611W2
Abstract: The feasibility study of using Digitome X-ray Volumetric Image System as an NDE tool for inspecting Space Shuttle wing leading edge (WLE) is presented in this paper. The Digitome system is capable of generating XY-cuts (horizontal) and Z-cuts (vertical) of the object being examined using traditional X-ray sources. The Digitome system is setup in an x-ray cell and is integrated with an X-ray source and a Varian PaxScan 2520
flat panel detector. Tests were conducted on an aluminium block with two countersunk holes and RCC panels with test holes. Three different configurations were used during the tests. The results show that, for the aluminum block, the setting with 16 stops and 22.5 degree intervals produces the sharpest and most clear cuts. A RCC panel was tested using this 16-stop configuration. The width and depth of the holes were measured using Z-cuts and XYcuts with reasonable accuracy. 3 Refs.

Title: Proceedings of SPIE - Health Monitoring and Smart Nondestructive Evaluation of Structural and Biological Systems V
Author: Anon (Ed.)
Conference Title: Health Monitoring and Smart Nondestructive Evaluation of Structural and Biological
Systems V
Conference Location: San Diego, CA, United States
Conference Date: 20060227-20060301
Sponsor: SPIE; ASME
E.I. Conference No.: 67795
Source: Proceedings of SPIE - The International Society for Optical Engineering Health Monitoring and Smart Nondestructive Evaluation of Structural and Biological Systems V v 6177
2006.
Publication Year: 2006
CODEN: PSISDG ISSN: 0277-786X
Language: English
Document Type: CP; (Conference Review) Treatment: T; (Theoretical)
Journal Announcement: 0610W3
Abstract: The proceedings contain 41 papers. The topics discussed include: autonomous health monitoring of a stiffened composite plate; application of time-reversal guided waves to field bridge testing for baseline-free damage diagnosis; real-time health monitoring of a thin composite beam using a passive structural neural system; structural evaluation of pavement using surface wave and portable FWD tests; ultrasonic imaging of hidden defects using dry-coupled ultrasonic probes; using

attractor localization to improve nonlinear prediction error for structural health monitoring; measurement of thin film interfacial properties using nanosecond laser source; development of piezoelectric oscillator sensor for in vivo monitoring of capsule formation around soft-tissue implants; and scanning acoustic defocused transmission microscopy with vector contrast combined with holography for weak bond imaging. (Edited abstract)

Title: Proceedings of SPIE - Nondestructive Evaluation and Health Monitoring of Aerospace Materials, Composites, and Civil Infrastructure V
Author: Anon (Ed.)
Conference Title: Nondestructive Evaluation and Health Monitoring of Aerospace Materials, Composites, and Civil Infrastructure V
Conference Location: San Diego, CA, United States
Conference Date: 20060228-20060302
Sponsor: SPIE; ASME
E.I. Conference No.: 67794
Source: Proceedings of SPIE - The International Society for Optical Engineering Nondestructive Evaluation and Health Monitoring of Aerospace Materials, Composites, and Civil Infrastructure V v6176 2006.
Publication Year: 2006
CODEN: PSISDG ISSN: 0277-786X
Language: English
Document Type: CP; (Conference Review) Treatment: T; (Theoretical)
Journal Announcement: 0610W3
Abstract: The proceedings contain 36 papers. The topics discussed include: an examination of non-destructive evaluation techniques for polymer matrix composite sandwich materials; a comparison of time series analysis algorithms for detection of barely visible impact damage to UAV wings; health monitoring of aeronautical structures based on vibrations measurements; an improved technique for modal decomposition of a double-mode Lamb wave signal; structural health monitoring of an inflatable boom subjected to simulated micrometeoroid/orbital debris damage; a mixture of experts approach for SHM measurement processing; underwater application of a structural health monitoring of Fairview Cove container terminal; accurate strain detection and localization with the distributed Brillouln sensor based on a phenomenological signal processing approach; and fiber optic strain monitor for an uninhabited aerial vehicle. (Edited abstract)

Title: On the material characterization of a composite using micro CT image based finite element modeling
Author: Abdul Aziz, A.; Saury, C.; Xuan, V. Bui; Young, P.
Corporate Source: NASA Glenn Research Center
Conference Title: Nondestructive Evaluation and Health Monitoring of Aerospace Materials, Composites, and Civil Infrastructure V
Conference Location: San Diego, CA, United States
Conference Date: 20060228-20060302
Sponsor: SPIE; ASME
E.I. Conference No.: 67794
Source: Proceedings of SPIE - The International Society for Optical Engineering Nondestructive Evaluation and Health Monitoring of Aerospace Materials, Composites, and Civil Infrastructure V v 6176 2006.
Publication Year: 2006
CODEN: PSISDG ISSN: 0277-786X
DOI: 10.1117/12.667766
Article Number: 617605
Language: English
Document Type: CA; (Conference Article) Treatment: T; (Theoretical); X; (Experimental)
Journal Announcement: 0610W3
Abstract: Novel techniques for generating robust and accurate meshes based on 3-D imaging data have recently been developed which make the prediction of macro-structural properties of composite structures based on micro-structural composition straightforward. The accuracy of reconstructions is a particular strong point of these new techniques with geometric accuracy only contingent on image quality. Algorithms developed and used are topology preserving, volume preserving and multi-part geometric models can be handled straightforwardly. In addition to modelling different constituent materials as separate mesh domains, material properties can be assigned based on signal strength in the parent image thereby providing a way of modelling continuous variations in properties for an inhomogeneous medium. These new techniques have been applied to the analysis of a ceramic matrix composite which was micro-CT scanned and the influence of imaging parameters on both

predicted bulk properties and localized stresses has been explored. This paper utilizes the Computed Tomography (CT) as the NDE technique to characterize the initial matrix porosity's locations and sizes in a Ceramic Matrix Composites (CMC) test specimen. Further, the Finite Element (FE) method is applied to calculate the localized stress field around these pores based on the geometric modelling of the specimen's CT results, using image analysis, geometric modelling and meshing software, ScanIP/ScanFE left bracket 1 right bracket. The analyses will simulate experimental loading conditions where scanned specimens are then tensile tested to a 0.07 % total strain to identify the matrix cracking locations in relation to the original pores. Additional work is carried out combining the image processing and finite element to investigate the applicability of some novel meshing techniques. Finally, the calculated Finite Element left bracket 2-4 right bracket localized stress risers are compared with the observed matrix cracking locations. This work is expected to show that an FE model based on an accurate 3-D rendered model from a series of CT slices is an essential tool to quantify the effects of internal macroscopic defects of complex material systems such as CMCs. 15 Refs.

Title: An examination of nondestructive evaluation techniques for polymer matrix composite sandwich materials
Author: Cosgriff, Laura M.; Roberts, Gary D.; Averbeck, Timothy; Jeanneau, Philippe; Quddus, Michael
Corporate Source: Cleveland State University, Cleveland, OH, United States
Conference Title: Nondestructive Evaluation and Health Monitoring of Aerospace Materials, Composites, and Civil Infrastructure V
Conference Location: San Diego, CA, United States
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Article Number: 617601
Language: English
Document Type: CA; (Conference Article) Treatment: T; (Theoretical)
Journal Announcement: 0610W3
Abstract: Structural sandwich materials composed of triaxially braided polymer matrix composite material face sheets sandwiching a foam core are being utilized for applications including aerospace components and recreational equipment. Since full scale components are being made from these sandwich materials, it is necessary to develop proper inspection practices for their manufacture and in field use. Specifically, nondestructive evaluation (NDE) techniques need to be investigated for analysis of components made from these materials. Hockey blades made from sandwich materials were examined with multiple NDE techniques including thermographic, radiographic, and laser based methods to investigate the manufactured condition of blades and damage induced from play. Hockey blades in an as received condition and damaged blades used in play were investigated with each technique. NDE images from the blades were presented and discussed. Structural elements within each blade were observed with radiographic imaging. Damaged regions and some structural elements of the hockey blades were identified with thermographic imaging. With shearography, structural elements, damaged regions, and other material variations were detected in the hockey blades. Each technique's advantages and disadvantages were considered in making recommendations for inspection of components made from these types of materials. 6 Refs.

Title: Detectability of bearing failure of composite bolted joints by electric resistance change method
Author: Shimamura, Yoshinobu; Oda, Keiko; Todoroki, Akira; Ueda, Masahito
Corporate Source: Shizuoka University, Hamamatsu,
Shizuoka 432-8561, Japan
Source: Key Engineering Materials v 321-323 II 2006. p
957-962
Publication Year: 2006
CODEN: KEMAEY ISSN: 1013-9826
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical); X; (Experimental)
Journal Announcement: 0610W3

Abstract: Bolted joints are widely used for composite structures. As is well known, excessive bearing load gives rise to bearing failure at hole boundaries. Detecting bearing failure is important for assuring integrity of composite structures. Since conventional nondestructive inspection methods are expensive, cumbersome, time-consuming, and not suitable for health monitoring, a simple, low-cost inspection method for bearing failure must be developed. Authors have demonstrated the feasibility of detecting bearing failure by using an electric resistance change method. In this study, more detailed analyses were carried out to investigate the detectability in terms of the damage size and the distance between damage and electrodes. The results show that bearing failure of less than 10mm square causes the electric resistance change of a few hundred ppm and thus can be easily detected, and that the electrodes can be mounted more than 10 mm far from a bolt hole. 36 Refs.

Title: Thermographic damage detection of ceramic matrix composites during tension testing
Author: Kim, Jeongguk; Lee, Joon-Hyun
Corporate Source: Railroad Testing and Certification Research Center Korea Railroad Research Institute, Uiwang, Kyunggi, 437-757, South Korea
Source: Key Engineering Materials v 321-323 I 2006. p 825-830
Publication Year: 2006
CODEN: KEMAEY ISSN: 1013-9826
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical); X; (Experimental)
Journal Announcement: 0610W3
Abstract: The fracture behavior of Nicalon fiber reinforced calcium aluminosilicate (CAS) glass-ceramic matrix composites (Nicalon/CAS) was investigated with the aid of a nondestructive evaluation (NDE) technique. Infrared (IR) thermography was employed for unidirectional Nicalon/CAS composite specimens. During tensile testing, an IR camera was used for in-situ monitoring of progressive damages of Nicalon/CAS samples. The IR camera provided the temperature changes during tensile testing. Microstructural characterization using scanning electron microscopy (SEM) was performed to investigate the fracture mechanisms of Nicalon/CAS composites. In this investigation, the thermographic NDE technique was used to facilitate a better understanding of the fracture mechanisms of the Nicalon/CAS composites during tensile testing. 14 Refs.

Title: Making sense of non-destructive evaluation data with an artificial intelliaence approach
Author: Nguyen, Minh; Wang, Xiaoming; Foliente, Greg
Corporate Source: CSIRO Manufacturing and Infrastructure Technology, Highett, Vic. 3190, Australia
Source: Key Engineering Materials v 321-323 I 2006. p294-297
Publication Year: 2006
CODEN: KEMAEY ISSN: 1013-9826
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical)
Journal Announcement: 0610W3
Abstract: This paper presents the feasibility of an artificial intelligence technique for processing and interpretation of non-destructive evaluation (NDE) data from assessments of engineering structures. The technique used is a learning and reasoning approach with belief network. With this technique, causal factors and consequent indicators in the data structure in relation with structure/material condition can be modelled, and their causal relationship can be established using the NDE data as the learning resource. Fundamentals of the technique are briefly presented, and then the potential applications of the technique to NDE data are demonstrated in two case studies. 5 Refs.

Title: NDE characterization and mechanical behavior in ceramic matrix composites
Author: Kim, Jeongguk; Kwon, Sung-Tae; Kim, Weon-Kyung
Corporate Source: Railroad Testing and Certification Research Center Korea Railroad Research Institute, Uiwang, Kyunggi, 437-757, South Korea
Source: Key Engineering Materials v 321-323 II 2006. p946-951
Publication Year: 2006
CODEN: KEMAEY ISSN: 1013-9826
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical)
Journal Announcement: 0610W3
Abstract: Several nondestructive evaluation (NDE) techniques, including ultrasonic C-scan, X-ray computed tomography (CT), and infrared (IR) thermography, were employed on ceramic matrix composites (CMCs) to illustrate defect information that might effect mechanical behavior and to analyze structural performance of CMCs. Prior to tensile testing, through C-scan and CT analyses results, the qualitative relationship between the relative ultrasonic transmitted amplitude and porosity based on CT was exhibited. An IR camera was used for in-situ monitoring of progressive damages

and to determine temperature changes during tensile testing. Moreover, scanning-electron microscopy characterization was used to perform microstructural failure analyses. This paper describes the use of nondestructive evaluation (NDE) techniques to facilitate the understanding of tension behavior of CMCs. 15 Refs.

Title: Acoustic emission monitoring of ablative composite liner bonded on steel nozzle under static loading
Author: Shul, Chang-Won; Lee, Kee-Bhum; Kim, Jong-Hwan; Koo, Song-Hoe
Corporate Source: Agency for Defense Development, Yuseong, P.O. Box 35-3, Daejon, South Korea
Source: Key Engineering Materials v 321-323 II 2006. p907-912
Publication Year: 2006
CODEN: KEMAEY ISSN: 1013-9826
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical)
Journal Announcement: 0610W3
Abstract: AE technique was applied to the structural strength tests of the ablative composite liner bonded on steel nozzle to figure out the unexpected problem that happened during the flight test. Two different kinds of specimen, which were specimens with some initial crack and without initial crack each, were used for the test. AE test methodology and parameters were investigated to assess the damage of them. NDT using X-ray technique was performed to improve the test reliability before and after each test. The study revealed that AE technique is a good method to evaluate damage on this kind of specimen with better accuracy. 6 Refs.

Title: Ultrasonic inspection of carbon/phenolic composites using a peak-delay measurement method
Author: Yang, In-Young; Im, Kwang-Hee; Hsu, David K.; Song, Sung-Jin; Cho, Hyeon; Kim, Sun-Kyu; Seo, Young-Hwan; Park, Je-Woong
Corporate Source: Department of Automotive Eng. Woosuk University, Wanju-kun, Chonbuk, 565-701, South Korea
Source: Key Engineering Materials v 321-323 II 2006. p889-892
Publication Year: 2006
CODEN: KEMAEY ISSN: 1013-9826
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical)
Journal Announcement: 0610W3
Abstract: Carbon/phenolic composite (CPC) materials are unique which consist of carbon fibers embedded in a carbon matrix. The CPCs are originally developed for aerospace applications and its low density, high thermal conductivity and excellent mechanical properties at elevated temperatures make it an ideal material for aircraft brake disks. The properties of the CPC are dependent on the manufacturing methods used for production and fiber arrangement. It is desirable to perform nondestructive evaluation to assess material properties and part homogeneity in order to ensure product quality and structural integrity of CPC brake disks. In this work, a CPC material was non-destructively characterized and a technique was developed to measure ultrasonic velocity in C/P composites using automated data acquisition software. Also a motorized system was adopted to measure ultrasonic velocity on the point of CPC materials under the same coupling conditions. Manual results were compared with those obtained by the motorized system with using dry-coupling ultrasonics and through transmission method in immersion. A peak-delay measurement method well corresponded to ultrasonic velocities of the pulse overlap method and through-transmission mode and C-scan image signal based on peak-to-peak amplitude. 5 Refs.

Title: Evaluation of NDT technologies for organic matrix composite testing
Author: Cargill, J. Steve; Pecina, Joseph A.; Gintert,
Lawrence; Skelton, Donald
Corporate Source: Concurrent Technologies Corporation, Hobe Sound, FL 33455, United States
Source: Materials Evaluation v 64 n 9 September 2006.
Publication Year: 2006
CODEN: MAEVAD ISSN: 0025-5327
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical)
Journal Announcement: 0610W2
Abstract: The evaluation of NDT technologies for organic matrix composite testing, is discussed. Every NDT technique demonstrated high contrast images from at least some of the test standards containing hidden impact damage and simulated delaminations. Some of the technologies performed favorably against army criteria and may be suitable for near term application to a variety of NDT

issues in organic matrix composite materials. There is a need to develop a complete library of composite test standards constructed with representative geometric features, materials, substrates, coatings, mechanical anomalies and exposure to outdoor weathering and simulate a full range of army applications. The new NDT technologies can be introduced to depot or field operations with minimal transition time and rework through appropriate use of this library of standards. (Edited abstract) 2 Refs.

Title: Analysis of PVT composite structure images using a Search Through algorithm
Author: Shilbayeh, Nidal F.; Iskandarani, Mahmoud Z.
Corporate Source: Faculty of Computer Science and Information Technology The University of Graduate Studies, 11610 Amman, Jordan
Source: WSEAS Transactions on Systems v 5 n 11 November 2006. p 2708-2712
Publication Year: 2006
ISSN: 1109-2777
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical)
Journal Announcement: 0610W2
Abstract: An effective NDT (Non-Destructive Testing) image analysis technique for detecting materials damage and defects existence has been developed successfully and applied to PVT images of composite structures. The developed technique is based on converting an image to its equivalent pixel values and then applying Search Through (ST) algorithm to the converted image such that the presence of damage in the composite structure and its extent can be easily verified. The technique has a novel approach to data analysis by employing intensity, RGB signal re-mix and wavelength variation of a thermally generated IR-beam onto the specimen under test which can be sensed and displayed on a computer screen as an image. Specimen inspection and data analysis are carried out through pixel level re-ordering and shelving techniques within a transformed image file using a sequence grouping and regrouping software system, which is specifically developed for this work. 25 Refs.

Title: Non-destructive testing & the link between environmental degradation & mechanical properties of composite honeycomb panels
Author: Crawley, N. Matthew
Corporate Source: University of Ottawa Department of Mechanical Engineering, Ottawa, Ont., Canada
Conference Title: AHS Internaitonal 62nd Annual Forum
Conference Location: Phoenix, AZ, United States
Conference Date: 20060509-20060511
E.I. Conference No.: 68073
Source: Annual Forum Proceedings - AHS International AHS Internaitonal 62nd Annual Forum - Vertical Flight: Leading through Innovation - Proceedings v II 2006.
Publication Year: 2006
ISSN: 1552-2938
Language: English
Document Type: CA; (Conference Article) Treatment: T; (Theoretical)
Journal Announcement: 0609W4
Abstract: Following the in-service failure of a Canadian CF-18 Hornet rudder, a fleet wide inspection was performed using Infrared Thermography. This resulted in several rudders being removed from service due to excessive indications of moisture ingress. The United States Navy, Spanish Air Force and the Canadian Forces have reported occurrences of CF-18 honeycomb core bond line failures. The cause of the disbonding is not completely understood, but is believed to be a result of moisture ingress through the laminate bondline and sealant. Moisture has been detected in various honeycomb components including trailing edge flaps, ailerons and especially rudders where large deposits of water have been found in the honeycomb core cells. Moisture ingress into these sandwich structures is believed to occur by one of two methods, via diffusion though the bulk adhesive layer or by wicking along the adhesive-adherend interface. Once the moisture gains access to the honeycomb cells, it leads to corrosion, bond degradation and eventual failure of the component. Current inspection of these components is difficult with conventional techniques such as CScan and Radiography which typically require long down times or component removal. Thermography has been used in recent efforts as an alternative to conventional methods, allowing for in-situ inspection and little-to-no aircraft down time. However, both for Thermography and conventional NDT techniques, the question still remains as to the exact nature of the indications and whether or not the component remains serviceable. To make this connection, an effort has been put forth to link these NDT indications to the mechanical properties and bond-line condition of these bonded honeycomb components. Testing has been performed on a series of CF-18 honeycomb rudders in an attempt to develop a correlation

between and the degraded mechanical properties and various types of NDT inspection indications, providing for a better method for assessments of serviceability of composite honeycomb panels. Copyright copy 2006 by the American Helicopter Society International, Inc. All rights reserved. 17 Refs.

Title: Interaction of the A//0 lamb wave mode with a de-lamination type defect in GLARE3-3/2 composite material
Author: Demcenko, Andriejus; Zukauskas, Egidijus; Kazys, Rymantas; Voleisis, Algirdas
Corporate Source: Ultrasound Institute, 51368 Kaunas, Lithuania
Source: Acta Acustica united with Acustica v 92 n 4 July/August 2006. p 540-548
Publication Year: 2006
CODEN: AAACFD ISSN: 1610-1928
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical); X; (Experimental)
Journal Announcement: 0609W4
Abstract: Ultrasonic non-destructive testing and evaluation is one of the most common methods applied for inspection of composite materials. The measured wave velocity gives information about composite properties. Changes in the ultrasonic wave velocity or in the amplitude of the ultrasonic signal indicate possible defects. The application of a single-side access air-coupled ultrasonic technique for the investigation of the Lamb wave propagation in the composite material, and numerical simulations of the Lamb wave interaction with the de-lamination type defect, are presented here. The interaction between wave and damage is analysed in detail. The change of the Lamb wave velocity was measured in a de-laminated area of the composite material GLARE3-3/2. The influence of the de-lamination on the Lamb wave propagation velocity is investigated experimentally and numerically. copy S. Hirzel Verlag. 21 Refs.

Title: Damage analysis for particle reinforced metal matrix composite by ultrasonic method
Author: Yang, Zhi-Guo; Long, Shi-Guo
Corporate Source: Key Laboratory for Advanced Materials and Rheological Properties Faculty of Material
Photoelectron Physics Xiangtan University, Xiangtan 411105, China
Source: Transactions of Nonferrous Metals Society of China (English Edition) v 16 n SUPPL. June 2006. ps652-s655
Publication Year: 2006
CODEN: TNMCEW ISSN: 1003-6326
DOI: 10.1016/S1003-6326(06)60271-9
Language: English
Document Type: JA; (Journal Article) Treatment: X; (Experimental); T; (Theoretical)
Journal Announcement: 0608W3
Abstract: The damage characteristic of particle reinforced metal matrix composite (PMMC) was studied by ultrasonic non-destructive evaluation method. After the sample was damaged induced by tensile load, the ultrasonic wave that propagated in the sample were collected. The damage parameter was defined by ultrasonic parameter and the wave signals were analyzed by correlation method. The results show that with the increase of tensile load, the damage parameter increases and the correlation coefficient decreases. The fracture section morphologies of PMMC under tensile load were observed by SEM. It is found that there are many concaves in the metal matrix. Therefore the damage evolution can be concluded. The initial damage is induced by void nucleation, growth and subsequent coalescence in the matrix or interface separation. 14 Refs.

Title: System identification of partially restrained composite plates using measured natural frequencies
Author: Lee, C.R.; Kam, T.Y.
Corporate Source: Dept. Of Mechanical Engineering National Chiao Tung Univ., Hsin Chu 300, Taiwan
Source: Journal of Engineering Mechanics v 132 n 8
August 2006. p 841-850
Publication Year: 2006
ISSN: 0733-9399
DOI: 10.1061/(ASCE)0733-9399(2006)132:8(841)
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical); X; (Experimental)
Journal Announcement: 0608W1
Abstract: A nondestructive evaluation technique established on the basis of a global minimization method is presented for the system identification of laminated composite plates partially restrained by

elastic edge supports. Six natural frequencies extracted from the vibration data of the flexibly restrained plate are used to identify the system parameters of the plate. In the identification process, the trial system parameters are used in the Rayleigh-Ritz method to predict the theoretical natural frequencies of the plate, an error function is established to measure the sum of the differences between the experimental and theoretical predictions of the natural frequencies, and the global minimization method is used to search for the best estimates of the parameters by making the error function a global minimum. The accuracy and efficiency of the proposed technique in identifying the parameters of several flexibly supported plates made of different composite materials are studied via both theoretical and experimental approaches. The excellent results obtained in this study have validated the applicability of the proposed technique. copy ASCE. 17 Refs.

Title: Recent developments in digital shearography for nondestructive testing
Author: Yang, Lianxiang
Corporate Source: Laboratory of Optical Measurement and Quality Inspection Department of Mechanical Engineering Oakland University, Rochester, MI 48309, United States
Source: Materials Evaluation v 64 n 7 July 2006.
Publication Year: 2006
CODEN: MAEVAD ISSN: 0025-5327
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical)
Journal Announcement: 0607W4
Abstract: Recently there has been considerable research activity in the development of digital shearography for nondestructive testing (NDT) in production/field environments. The research has shown that digital shearography has great potential in identifying discontinuities in objects and especially in the detection of delaminations in composite materials such as honeycomb structures. This paper is a review of the state of the art of digital shearography for NDT. Recent developments of digital shearography and its potentials and limitations for NDT will be demonstrated by examples of nondestructive testing for different materials. 14 Refs.

Title: Materials evaluation with full-field laser NDT techniques
Author: Ettemeyer, Andreas
Corporate Source: Munich University of Applied Sciences, 80355 Munich, Germany
Source: Materials Evaluation v 64 n 7 July 2006.
Publication Year: 2006
CODEN: MAEVAD ISSN: 0025-5327
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical)
Journal Announcement: 0607W4
Abstract: The use of full-field laser non-destructive testing (NDT) techniques, based on the optical effect of interferometry, that provides several specific advantages to the user was discussed. Laser NDT techniques have proven to be a valuable and efficient tool for solving complex mechanical problems. They are also useful for standard applications such as material testing, fracture investigations, strain/stress analysis, and NDT of composite components in the aerospace, marine and automotive industries. The full field information provided by these techniques gives maximum safety and test speed and these data fit perfectly with modern 3D simulation tools which produce the same results. The NDT techniques provide advantages that are used to show exact stress point in a component and complex vibration modes in acoustic testing. The simplicity of operation in cooperation with the development of interfaces to standard applications will increase the number of applications of such techniques. (Edited abstract)13 Refs.

Title: Fatigue test of lightweight composite wing structure
Author: Aoki, Yuichiro; Ishikawa, Takashi; Takeda, Shin-ichi; Hayakawa, Yuichi; Harada, Atsushi; Kikukawa, Hiroshige
Corporate Source: Japan Aerospace Exploration Agency, Mitaka, Tokyo, 181-0015, Japan
Source: International Journal of Fatigue v 28 n 10 SPEC. ISS. October 2006. p 1109-1115
Publication Year: 2006
CODEN: IJFADB ISSN: 0142-1123
DOI: 10.1016/j.ijfatigue.2006.02.017
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical)
Journal Announcement: 0607W4
Abstract: Fatigue tests of hat-shape stringer stiffened panel are conducted, where this panel is a typical part of upper skin of lightweight composite wing using new production technology of stitching, co-bonding and RTM method. Impact damages are applied on skin/stringer co-bonded part and

typical skin part of the test panel by drop-weight impact machine. There are two phases in the present test. The first phase is fatigue tests to verify durability of the structure with barely visible impact damages. The second phase is flaw growth tests for evaluation of visible impact damage growth to estimate inspection intervals. The Mini-TWIST (shortened version of The Transport WIng STandard load program) spectrum loading is used for both tests. Non-destructive inspection is carried out by pulsed thermography during the test to observe damage propagation. Finally, static load is applied up to design limit load to verify the residual strength after all the spectrum loading tests. copy 2006 Elsevier Ltd. All rights reserved. 13 Refs.

Title: Synchronisation of industrial robots for ultrasonic inspection of irregular-shaped carbon-fiber composites
Author: Bosse, Juergen; Thaler, Bernhard
Corporate Source: Robo-Technology GmbH, Germany
Source: VDI Berichte n 1956 2006. p 309
Publication Year: 2006
CODEN: VDIBAP ISSN: 0083-5560
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical)
Journal Announcement: 0606W5
Abstract: Synchronization of industrial robots for ultrasonic inspection of irregular-shaped carbon-fiber composites are discussed. This approach reduces planning, manufacturing and installation time of the system, while offering a high precision solution at a competitive price. A FEM system was used to optimize the welded steel support structure, while actually reducing overall weight of the moving parts. Calibration of the robots and support structure was performed collecting data points with a Laser tracker and solving a large set of non-linear equations to estimate Denavit-Hartenberg parameters and gravity compensation coefficients for the complete system consisting of 13 degrees of freedom. The non-destructive testing system receives trigger signals synchronously along the robot path. (Edited abstract)

Title: Advances in the development of built-in diagnostic system for filament wound composite structures
Author: Qing, Xinlin P.; Beard, Shawn J.; Kumar, Amrita; Chan, Hian-Leng; Ikegami, Roy
Corporate Source: Acellent Technologies Inc. Sensor Technology, Sunnyvale, CA 94089, United States
Source: Composites Science and Technology v 66 n 11-12
September 2006. p 1694-1702
Publication Year: 2006
CODEN: CSTCEH ISSN: 0266-3538
DOI: 10.1016/j.compscitech.2005.11.007
Language: English
Document Type: JA; (Journal Article) Treatment: T; (Theoretical)
Journal Announcement: 0606W4
Abstract: Monitoring the structural integrity of filament wound composite structures such as solid rocket motor cases and liquid fuel bottles can help prevent catastrophic failures and prolong their service life. An integrated structural health monitoring system has been developed by Acellent as a non-destructive evaluation tool for detecting hidden damage in filament wound composite structures. The system includes a built-in sensor network, supporting diagnostic hardware and data processing/analysis software. A prototype of a filament wound composite bottle with embedded SMART Layers has been fabricated successfully at NASA Marshall Space and Flight Center. This demonstrated the compatibility of the SMART Layer to filament winding process. Impact tests were performed on the prototype bottle to generate damage. A scan of the entire bottle by the distributed network of sensors using Acellent's diagnostic system was able to locate the damage. The built-in signal processing and imaging techniques employed by the software demonstrated the ability of the software to display the impact damage with relative ease in the face of temperature change. Copy 2005 Elsevier Ltd. All rights reserved. 16 Refs.

Title: Ultrasonic evaluation of anisotropic damage in multiaxially textile-reinforced thermoplastic composites made from hybrid yarns
Author: Hufenbach, W.; Bohm, R.; Langkamp, A.; Kroll, L. ; Ritschel, T.
Corporate Source: Technische Universitat Dresden Institut fur Leichtbau und Kunststofftechnik (ILK), D-01062 Dresden, Germany
Source: Mechanics of Composite Materials v 42 n 2 March 2006. p 151-162
Publication Year: 2006
ISSN: 0191-5665

DOI: 10.1007/s11029-006-0026-3
Language: English
Document Type: JA; (Journal Article)   Treatment: T; (Theoretical); X; (Experimental)
Journal Announcement: 0606W4
Abstract: The basic damage and failure models of multiaxially reinforced composites with a thermoplastic matrix are presented and verified. Within the framework of continuum damage mechanics, a phenomenological model is introduced, where the damage is defined as a change in the elasticity tensor. For damage identification, a specific ultrasonic device was developed. A combination of an immersion set-up and a contact coupling device formed a system for an efficient determination of stiffness-tensor components from convenient sets of velocity measurements. Linked to a tensile machine, it allowed us to measure the anisotropic damage of the new materials group caused by tensile loading. copy 2006 Springer Science+Business Media, Inc. 19 Refs.

Title: Simultaneous shearographic and thermographic NDT of aerospace materials
Author: Gryzagoridis, Jasson; Findeis, Dirk
Corporate Source: Department of Mechanical Engineering University of Cape Town, Cape Town, South Africa
Source: Insight: Non-Destructive Testing and Condition Monitoring v 48 n 5 May 2006. p 294-297
Publication Year: 2006
CODEN: ITMOEN   ISSN: 1354-2575
DOI: 10.1784/insi.2006.48.5.294
Language: English
Document Type: JA; (Journal Article)   Treatment: T; (Theoretical)
Journal Announcement: 0606W2
Abstract: The paper describes the simultaneous use of digital shearographic and infrared thermographic techniques when testing aerospace structures made of honeycomb and composite materials. Non-destructive testing of the structures was accomplished using a proprietary portable shearographic system, produced at the Mechanical Engineering Department of the University of Cape Town, and a relatively inexpensive newcomer to the infrared thermography field known as IRISYS Universal Thermal Imager. Simply, both systems were employed to image the component simultaneously and record the effect of it cooling down after being heated with the hot air from a hair drier or a heating lamp. The techniques proved effective in identifying defects such as the crushed honeycomb core in a section of the wing of an unmanned aerial vehicle (UAV) and the delaminations at different depths in the main rotor blade of an Oryx helicopter. The images indicating the defects as produced by the shearographic system are visually more dramatic, particularly when enhanced by phase stepping and colour techniques. On the other hand, the thermographic images, besides indicating the position of the flaw, gave information regarding the temperature of the region of the defect relative to the cooler surrounding material. In addition, there was the indication that during the cooling down, the infrared system continued to indicate the presence of the flaws/defects for a longer period of time than the shearographic system. It is suggested that in similar tests, the temperature data be coupled to the out of plane displacement gradients with a view to providing quantitative thermal stress results. 4 Refs.

Title: The possibilities of electronic speckle pattern interferometry by investigation of composite materials
Author: Rusnakova, Sona; Slabeycius, Juraj; Rusnak, Vladimir
Corporate Source: Alexander Dubcek University of Trencin Faculty of Industrial Technology in Puchov, 020 01 Puchov, Slovakia
Conference Title: Photonics, Devices and Systems III
Conference Location: Prague, Czech Republic
Conference Date: 20050608-20050611
Sponsor: EOARD- Air Force Research Laboratory; EOS-European Optical Society; SPIE Czech/Slovak Chapter; ICO-The International Commisssion for Optics; OSA-Optical Society of America; et al.
E.I. Conference No.: 66976
Source: Proceedings of SPIE - The International Society for Optical Engineering Photonics, Devices and Systems III v 6180 2006.
Publication Year: 2006
CODEN: PSISDG   ISSN: 0277-786X
DOI: 10.1117/12.675735
Article Number: 61801G
Language: English
Document Type: CA; (Conference Article)   Treatment: X; (Experimental)
Journal Announcement: 0604W2

Abstract: The article is considering by applications of electronic speckle pattern interferometry (ESPI) in the composite materials industry. The use of composite materials in various construction elements has substantially increased over the past years. These materials are widely used in situations where large strength-to-weight ratios are required. This paper collects some information about possibilities, advantages, and disadvantages of ESPI applications by nondestructive testing of composite materials and briefly introduces a damping feature of composites. Theory of plate vibrations allows us to determine Poisson's ratio v, Young's modulus E and shear modulus G from the measured resonant frequencies. We are able to analyze the damping behavior of various types of composite materials from measured mode shapes. 6 Refs.

Title: Relationship between non destructive and static modulus of elasticity of commercial wood plastic composites
Author: Nzokou, Pascal; Freed, Jason; Kamdem, D. Pascal
Corporate Source: Department of Forestry Michigan State University, East Lansing, MI 48824, United States
Source: Holz als Roh - und Werkstoff v 64 n 2 April 2006.
Publication Year: 2006
CODEN: HOZWAS ISSN: 0018-3768 eISSN: 1436-736X
DOI: 10.1007/s00107-005-0080-x
Language: English
Document Type: JA; (Journal Article) Treatment: X; (Experimental)
Journal Announcement: 0603W5
Abstract: The relationship between stress wave nondestructive (NDE) modulus of elasticity (MOE) and static MOE determined by four point bending test of commercial wood-plastic composites was evaluated in this study to assess the potential of using the NDE technique as a grading tool for wood plastics as it is currently done for solid lumber. The NDE MOE was evaluated on a Metriguard Model 340 E computer system, and the static MOE of the same boards measured on an Instron Universal Tester model 5587 according to the ASTM standard D 6109. Results showed that the NDE MOE values overestimated the static MOE from 3.5% to 17.6% depending on the boardwalk type. Regression analysis showed no significant correlation between the NDE MOE and the Static MOE. These results suggest that the stress wave NDE technique may not be appropriate to estimate the static MOE of wood plastic lumber. The trend however needs to be confirmed by further testing using a larger sample size and different combination of the raw materials. 27 Refs.

Title: On-line measurement of material properties for composite wing structures
Author: Cheng, S.H.; Hwu, Chyanbin
Corporate Source: Institute of Aeronautics and Astronautics National Cheng Kung University, Tainan 70101, Taiwan
Source: Composites Science and Technology v 66 n 7-8 June 2006. p 1001-1009
Publication Year: 2006
CODEN: CSTCEH ISSN: 0266-3538
DOI: 10.1016/j.compscitech.2005.08.004
Language: English
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Abstract: Structures will encounter degradation of material properties in changing service environments. To improve structural safety and prevent accident, it is necessary to examine material properties of structures in nondestructive ways. Although several non-destructive evaluation techniques have been developed in the literature, most of them detect local damages not global material properties. In this paper, an on-line and real-time detection system is developed through the concept of inverse analysis. In this system, the detectors are selected to be natural frequencies and static strains whose relations with material properties can be obtained from analytical solution or commercial finite element software or experimental data. Transferring their relations into training patterns of artificial neural networks, the elastic properties of composite wing structures can be determined on-line with frequency and strain sensors embedded into structures. To illustrate this on-line measurement system, an example of NACA 2412 composite wing is provided in this paper. This example shows that the material properties determined through this on-line system well agree with the values obtained from the conventional testing methods. The difference is that the present method determines the properties on-line and real-time without cutting any specimen on the structures and testing specimens in the laboratory. copy 2005 Elsevier Ltd. All rights reserved. 23 Refs.