COMPOSITE DEFECTS AND THEIR DETECTION

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Contents

Summary

Defects can inadvertently be produced in composite materials either during the manufacturing process or in the course of the normal service life of the component. The most significant defects in monolithic structures are porosity, caused by incorrect manufacture, and impact damage during in-service use. For sandwich structures with honeycomb cores the presence of bond failure or core crushing is equally significant.

By far the most commonly used non-destructive test for composite structures is ultrasonic inspection, often producing a two-dimensional map of the structure. In composite structures defects are often in the form of disbonds or delaminations in the plane of the material, or porosity. The reason for favoring ultrasound is that it is very sensitive to these types of defect commonly found in composites. It is one of the few methods available for detecting porosity after manufacture and it can detect most of the other defects at the same time.

Low-frequency vibration methods are utilized for in-service inspection of sandwich structures with honeycomb cores where ultrasound is not sensitive to all the types of defect. For glass-fiber reinforced pressure vessels acoustic emission is in common use for monitoring pressure tests to detect damage. X-ray imaging has some uses for damage characterization where the damage is surface-breaking and a contrast medium can be injected.

Numerous other methods are being developed with potential for rapid or large-area inspection capabilities. However, at present, these have limitations that have prevented them being used extensively. Laser ultrasound generation is one of these newer methods, but the cost is currently prohibitive. Optical and thermal methods are not as expensive but have limited depth penetration and are still considerably more expensive than conventional ultrasound methods.

1. Introduction

1.1. Scope

This article deals with manufacturing and in-service defects in monolithic composites and sandwich structures with honeycomb or foam cores. Because they have yet to be applied extensively, metal-matrix and ceramic-matrix composites will not be considered explicitly in this discussion. The techniques described are applicable to long and short fiber composites although, in general, short fiber composites have a more random arrangement of fibers and are not so susceptible to delamination damage. Most of the current inspection techniques are discussed in the initial overview. The more frequently used methods are then described in detail in the main body of the article.

1.2. Defects in Composites

Defects can inadvertently be produced in composite materials, either during the manufacturing process or in the course of the normal service life of the component.

The manufacturing process has the potential for causing a wide range of defects, the most common of which is "porosity," the presence of small voids in the matrix. Porosity can be caused by incorrect, or non-optimal, cure parameters such as duration, temperature, pressure, or vacuum bleeding of resin. Porosity levels can be critical, as they will affect mechanical performance parameters, such as inter-laminar shear stress.

Preparation of the resin-impregnated fiber layers (pre-preg), prior to curing, can be by hand or machine. In either case there is the potential for the inclusion of foreign bodies ranging from backing film to just greasy marks from fingers. More recent low-cost manufacturing techniques, involving the infusion of resin into pre-formed dry fibers in moulds, have introduced other potential defects such as fiber misalignment, or waviness, both in the plane of the material and out-of-plane. Stitching of fiber tows (bunches of fibers), to hold them in place and prevent misalignment during cure, can itself introduce numerous regularly-spaced sites for void formation.

Sandwich structures with honeycomb or foam cores can suffer from poor bonding of the skin to the core. Disbonds can occur at the skin-to-adhesive interface or at the adhesive-to-core interface.

In service damage is most often caused by impacts. In monolithic composites this results in matrix cracking and delaminations of the ply layers. In some cases the surface is punctured, but often this is not the case, despite the internal delamination damage being extensive. Such damage is termed “barely-visible impact damage” (BVID). Sandwich structures can suffer from the same matrix cracking and delaminations in the skins when impacted, but other types of failure can also occur. For example, disbonding can be caused at the skin-to-adhesive interface. Fillet-bond failure is where the honeycomb-to-adhesive bond is weakened. Core crushing occurs where the impact energy is absorbed by the core, which distorts and folds, often being returned to its original shape but with greatly reduced compressive strength.

1.3. Significance of Defects in Composites

It is clear that in many ways, a composite can differ from the ideal either during manufacture or in service. The extent to which any of these deviations from ideal should be considered as a defect is a function of the intended use of the material and the significance of the deviation on the required performance. All defect types are known to adversely affect performance in some way. However, the type and size of defect that needs to be found can only be set for each application based on the results of mechanical destructive tests and a detailed knowledge of how such defects grow, if at all, in the expected service environment. This process sets the acceptance criteria for manufacturing and in-service defects.

It is beyond the scope of this article to discuss the significance of defects in detail but it should be stressed that defect significance must be assessed before meaningful acceptance and rejection criteria can be established.

In order to discuss the use of NDE for composites it will be necessary to assume that some of the defects mentioned will reach a significant size and must therefore be found. This will be done by taking the conclusions that are emerging from defect significance studies for long fiber CFC materials for aerospace applications. This will serve as a general guide since this is one of the most demanding applications due to the necessity of reducing weight as much as possible. These assumptions may not, however, be applicable to another application or composite type.

1.4. Detection methods

For a defect detection method to be reliable, its response on a defective structure must be significantly different to that on a sound structure.

By far the most commonly used non-destructive test for composite structures is ultrasonic inspection, often producing a two-dimensional “C-scan” map of the structure. In composite structures, defects are most often in the form of either disbonds or delaminations in the plane of the material, or porosity. The reason for favoring ultrasound inspection is that it is very sensitive to these types of defect commonly found in composites. It is also one of the few methods available for detecting porosity and it can detect most of the other defects at the same time.

Low-frequency vibration methods are utilized for in-service inspection of sandwich structures with honeycomb cores where ultrasound is not sensitive to all the types of defect. They are particularly useful as a rapid search tool to detect trouble spots but have difficulty when identifying the type or extent of defects.

For glass-fiber reinforced pressure vessels acoustic emission is in common use for monitoring pressure tests to detect damage. X-ray imaging has some uses for damage characterization where the damage is surface-breaking and a contrast medium can be injected.

Numerous other methods are being developed with potential for rapid or large-area inspection capabilities. However, at present these have limitations that have prevented them being used extensively. Laser ultrasound generation is one of the most promising of the newer methods but the cost is currently prohibitive. Optical and thermal methods are not as expensive but have limited depth penetration and are still considerably more expensive than conventional ultrasound methods.

The two most commonly used detection methods: ultrasound and low-frequency vibration, are now assessed in the remainder of this overview. More detailed explanations of most of the NDE methods are given in Sections 3 to 8.

1.4.1. Ultrasound

Ultrasound pulses are reflected by interfaces between materials of different properties. In the case of delaminations and disbonds, this can cause a discrete reflection from a particular depth in the material. Such a reflection also results in a loss of transmission through the material.

Porosity does not produce a discrete reflection but scatters the ultrasound in a range of directions, also resulting in a transmission loss. These transmission losses can be detected by mapping the transmitted signal over the whole structure, known as a Through-transmission C-scan. Variations in the transmitted signal can be caused by delaminations, disbonds or porosity.

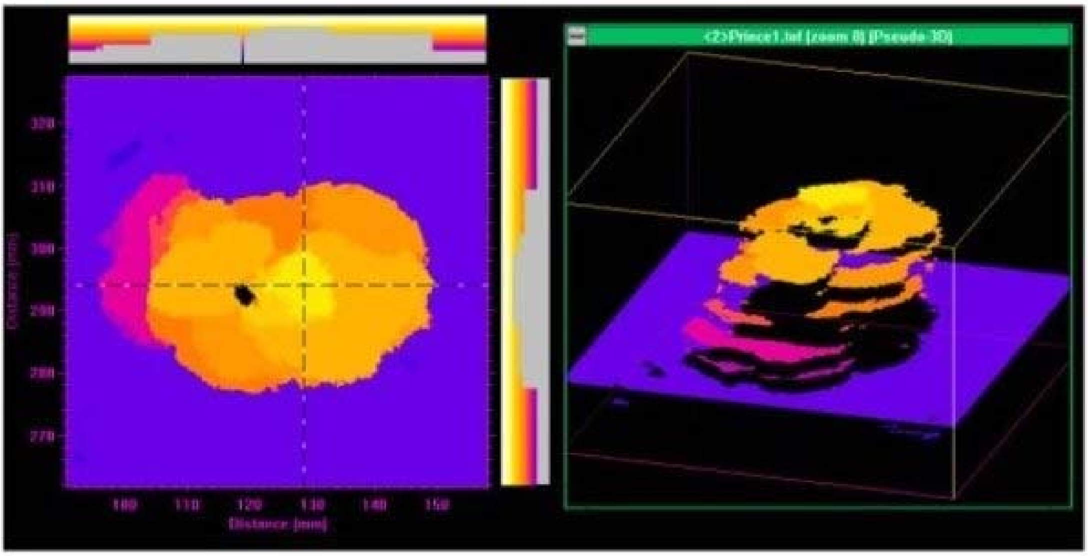

Figure 1. Distribution of Delaminations through the Thickness of a Monolithic Composite Skin in the Region of an Impact Site. A depth scan (left) and a pseudo-3D image (right)

Mapping the time delay to reception of the reflected signals provides information about the depth of the damage and this is known as a Depth (or Time-of-Flight) Scan. The information about defect depth can be used to view the ultrasound data as a pseudo-3D image.

For the measurement of porosity levels, it is possible to determine a monotonic relationship between porosity and ultrasonic bulk attenuation at a given frequency. A draft European Standard exists to optimize the measurement technique for absolute accuracy in the measurement of bulk attenuation.

Ultrasound offers a good compromise between depth penetration, sensitivity and depth resolution. The inherent attenuation of ultrasound in materials increases with the frequency of the ultrasound, whereas both the sensitivity and depth resolution improve. Thicker materials generally require the use of a lower frequency, thus reducing the detection capabilities. However, some of this sensitivity can be recovered by using focused beams to reduce the size of the sample volume being inspected.

Well-established defect-sizing methods are available for ultrasound inspection of delaminations and disbonds in composites. A draft European Standard exists to optimize the defect-sizing measurement technique.

For in-service inspection, it is possible to improve the rate of scanning significantly by using multi-element arrays of ultrasonic transducers, or by sweeping several single transducers in a raster pattern.

Although there is a wide range of other techniques that are applicable to defect detection in composites, they are far less universal than ultrasound for various reasons.

1.4.2. Low-frequency Vibration Methods

Low-frequency vibration methods fall into two categories: global assessment by forcing a vibration of the whole structure to determine its natural frequencies (e.g., the old railway wheel-tapping test where the whole wheel resonated after being tapped), and local assessment by investigating the modes of vibration (e.g., tapping a wall to find the fixing battens).

For inspection of composite structures, the local methods are more appropriate. The simplest of these is the tap test where the inspector listens to the sound made when the surface is tapped by anything from a coin to a toffee-hammer. Experienced inspectors can identify defects with a good reliability but the method is highly operator-dependent.

A more sophisticated tapping method involves the use of an instrumented hammer, where the reactive force on the hammer is monitored as a function of time after the impact. Different defect types will cause different changes to the response of the structure.

Instrumentation exists for inspecting structures using these transient excitation (tapping) methods or using continuous or swept-frequency excitation.

There is the potential for scanning with these local assessment systems to produce a map of the structure's response. Some such systems are already used with scanners and the two-dimensional image is extremely helpful in assessing the integrity of the structure.

2. Types of Defect in Composites

2.1. Manufacturing Defects

Composite materials can be manufactured by a number of techniques, which aim to combine the fiber and resin into a well-consolidated product. The fiber and resin may be separate before manufacture or, more usually, they may already be combined in the form of pre-preg material. The manufacturing technique selected depends partly upon the size and quality or the composite required. For example, a very large item such as a ship's hull will generally be manufactured by hand lay-up techniques in which the resin is applied by brush to sheets of fiber, often in the form of woven cloth, and the excess resin squeezed out with a roller. The resin then cures at ambient temperature. It is extremely difficult to obtain very high quality laminates by this method and it will therefore be used when the lower strength can be tolerated and allowed for in design. Lower strength items requiring high quality finish might be made by the injection moulding of short fiber composites. Higher quality materials are usually required for aerospace components to minimize the weight so complicated techniques such as hot pressing or autoclaving will be used.

For the last two of these methods, the quality of the finished material depends strongly on compaction pressure being applied at the correct moment during the heating cycle. The precise technique used to bleed off excess resin will also affect quality and surface finish. The details of the technique adopted will depend upon the resin system used.

During all these manufacturing processes, defects can be introduced into the material, although the size and frequency of occurrences of each type depends upon the particular process cycle. A number of defect types have been identified including, in order of importance:

- Porosity (voids) due to volatile resin components, or air not properly controlled during cure.
- Foreign bodies.
- Incorrect fiber volume fraction due to excess or insufficient resin. Local variations in volume fraction will always occur, but large departures from specifications may be caused by inappropriate process conditions.
- Bonding defects. During manufacture, components may be bonded together and it is possible for defects to occur in the bondline due to incorrect cure conditions for the adhesive or contamination of the surfaces to be bonded.
- Fiber misalignment. This causes local changes in volume fraction by preventing ideal packing of fibers.
- Ply misalignment. This is produced as a result of mistakes made in lay-up of the component plies. This alters the overall stiffness and strength of the laminate and may cause bending during cure.
- Incompletely cured matrix due to incorrect curing cycle or faulty material.
- Wavy fibers. These are produced by in-plane kinking of the fibers in a ply and can seriously affect laminate strength.
- Ply cracking. Thermally induced cracks occur with certain ply lay-ups due to differential contraction of the plies after cure.
- Delaminations. These are planar defects usually at ply boundaries and are fairly rare during the manufacture of the basic material but may be produced by contamination during lay-up or by machining.
- Fiber defects. The presence of defects in the fibers themselves is one of the ultimate limiting factors in determining strength, and sometimes faulty fibers can be identified as the sites from which damage growth has been initiated. These defects are always likely to be present, and probably must be considered as one of the basic material properties.

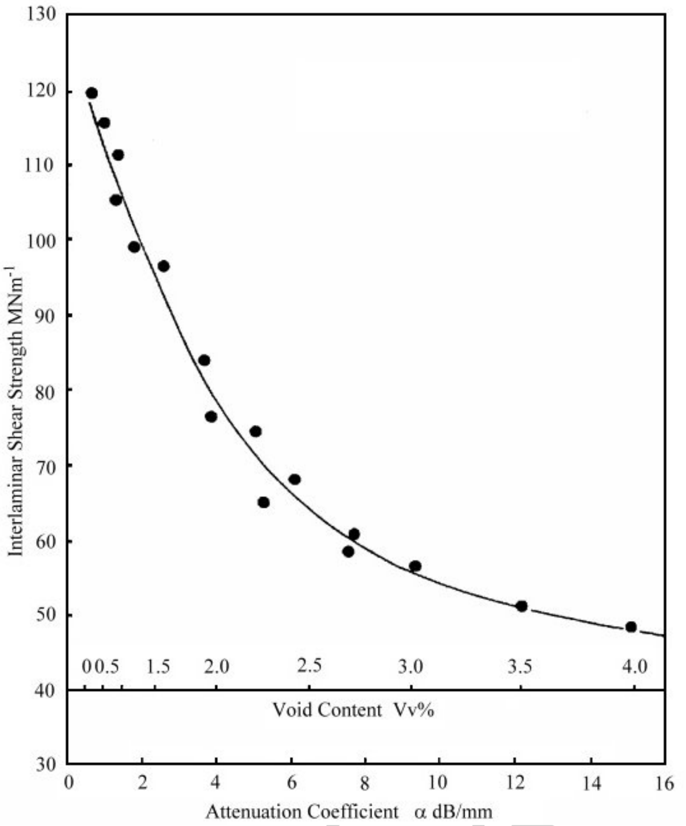

Figure 2. Relationship between Interlaminar Shear Strength and Porosity (Void Content) for Unidirectional HTS Carbon Fibers in an ERLA 4617 Epoxy-resin Matrix. (Source: Stone D. E. W. and Clarke B. (1974). Nondestructive Determination of the Void Content in Carbon Fiber Reinforced Plastics by Measurement of Ultrasonic Attenuation, *RAE Technical Report* 74162)

Recently, a considerable amount of effort has been put into reducing the costs of composite manufacture. Methods are being developed such as Resin Transfer Moulding (RTM) where the resin is drawn into a structure which has already been prepared with fibers stitched or woven into fabrics, and Resin Film Infusion (RFI) where separate layers of fiber and resin fuse together during the curing cycle. These new methods are likely to suffer from different kinds of defects, such as fiber waviness, and may pose new inspection problems.

The most important manufacturing defect that is likely to occur in practice is “porosity”—the presence of voids. Some of the other defects occur only very rarely or do not occur in isolation. Thus incorrect fiber volume due to insufficient resin will usually be accompanied by voids as will incorrectly cured resin. As will be seen, other defects such as foreign bodies, delaminations and disbonds will also be detected when an assessment of void content is made.

Void content is important because of its influence on the inter laminar shear strength (ILSS) and can be estimated ultrasonically by measurement of attenuation; the reduction in wave amplitude on passing through a specimen. The dependence of ILSS on void content is shown in Figure 2. and while experience shows this to be the general shape of such curves, the details depend on resin system and fiber type.

Fiber misalignment is a potentially disastrous defect, but is rarely encountered due to high standards of quality control. Often an off-cut of the material is examined to ensure that the correct ply stacking sequence was used. However, the increased use of sub-contractors to produce structural components requires the ability to check the quality of the product on delivery.

2.2. In-service Defects

Composites can be degraded in service by a number of mechanisms and those of most importance will obviously depend upon the environment experienced and the sensitivity of the particular materials used. The mechanisms of degradation include static overload, impact, fatigue, hygrothermal effects, overheating, lightning strike and creep. However, although the mechanisms by which defects are initiated and grow are varied, only a small number of different types of defect result. These are, in order of importance:

- Delaminations
- Bond failures
- Cracks
- Ingress of moisture
- Fracture or buckling of fibers
- Failure of the interface between the fibers and matrix.

The major in-service defect requiring detection is the presence of delaminations. These may be produced by fatigue, bearing damage, impact, etc. Disbonding can also be found but as yet, no method is available to measure adhesive strength. It is not generally expected that cracks will need to be found since they will lead to delamination growth before a critical stage is reached. It is possible to find a high density of cracks as a precursor of delamination growth and this can be done ultrasonically if required.

Delaminations, because they are orientated at right angles to an ultrasonic wave propagated at normal incidence into a laminate, are ideally aligned for detection by ultrasonics. Because delaminations are good reflectors of ultrasound, their presence can be revealed by detecting the sound they reflect or the corresponding loss of transmitted energy.

The ingress of moisture degrades those strength properties of the composite that are matrix dependent but also reduces residual strain. Moisture and thermal spiking can interact to cause interlaminar cracks. Although it may be possible to measure moisture content nondestructively, perhaps by measuring ultrasonic velocity or attenuation, it is likely that representative levels will have to be allowed for in design.

It should be stressed again that these comments are dependent on application and composite type. For example, in short fiber composites, delaminations are unlikely to be as important as cracking, perhaps locally aligned to the fiber orientation.

3. Ultrasonic Inspection Methods

Many of the inspection problems posed by composites can be dealt with effectively using ultrasonics. In this section a broad survey of the basis of ultrasonic techniques will be presented and their applicability described. It is hoped that there will be enough detail for the basic techniques to be appreciated. Some of the more specialist, or less frequently used techniques, can only be briefly explained but, where possible, references will be given for further study.

Because composites are being used for a variety of purposes, it is not possible to state which production or in-service defects will be important for each application. Instead, the possible defects will be described along with some of their effects and the way in which they could be detected, and perhaps measured and explained. By way of example the defect types that are emerging as being most important in aerospace structural applications will be considered in detail. This discussion should, however, also be relevant to other applications.

Some review articles are available which cover most techniques for the inspection of composites and provide a comprehensive set of references. In addition, draft European standards have been developed for ultrasonic inspection of composite materials. They include operational procedures, transducer characterization and manufacture of reference defects and specimens.

3.1. Basic Ultrasonics

3.1.1. Ultrasound

Before considering ultrasonic techniques for evaluating composites, it is instructive to review some of the basic properties of ultrasound and the way in which it can be expected to interact with defects.

Ultrasound is sound whose frequency is above the upper limit of human audibility, of ~20 kHz, although for ultrasonic materials evaluation the frequency range 0.5 to 50 MHz is most often employed. Ultrasound, unlike electromagnetic waves, requires a medium to propagate and travels through it in the form of stress waves. In solid material, several types of particle motion, or modes of propagation, can be supported. For the purposes of this article, only longitudinal waves (or compression waves) will be considered, where the particle motion is parallel to the direction of propagation. The situation is less complicated in fluids anyway, since only compressional waves are supported.

3.1.2. Interaction with Materials

When ultrasound waves propagate through a material, they are modified by the material itself, and any boundaries or defects encountered. In general, all of these interactions are complicated; the exact nature of the interaction depending on parameters, such as the relative size of the feature to the wavelength of sound and the orientation of the feature. However, it is worthwhile considering some interactions in a simplified form as illustrations, to aid discussions of inspection techniques.

The material itself can modify the sound-wave propagating through it in a number of ways. Energy can be lost due to dissipation mechanisms within the material, or by the scattering of sound from the interrogating wave by its structure; for example, by scattering from inclusions and voids. These mechanisms of energy loss are usually frequency-dependent, giving rise to changes in the shape of the propagating acoustic waveform.

A material boundary is a discontinuity in elastic properties, which can be characterized by the change it represents in the “acoustic impedance”—the product of the density and the propagation velocity in the material.

When an ultrasound wave is incident at the interface between two different materials, some sound is reflected and the rest is transmitted across the interface. The relative amplitudes and phases of these waves depend upon the change in acoustic impedance across the boundary. As the magnitude of the change in acoustic impedance increases, a greater proportion of the incident energy is reflected and hence less is transmitted across the boundary.

Defects also interact with ultrasound. A discontinuity will result in a local change in acoustic impedance from that of the surrounding material and, if its dimensions are large compared with the wavelength of sound, it will cause reflection of sound in much the same way as occurs at a boundary, as described previously. In this case, diffraction effects are small compared with the large amount of specular reflection.

If, however, the dimensions of the defect discontinuity are of the same order of magnitude as the wavelength of sound, the discontinuity will cause energy to be scattered from the interrogating beam due to diffraction effects. The angular spread of scattered sound is dependent on the size-to-wavelength ratio, the orientation of the defect relative to the direction of incident sound propagation and the mode type of the wave that is propagating.

If the defect is very small compared with the wavelength, little energy is specularly reflected; some energy is scattered in all directions causing attenuation of the sound wave, but otherwise the sound wave is unaffected.

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Biographical Sketch

Robert Smith gained an MA degree in Physics from the University of Cambridge and an MSc in Applied Acoustics from Kings College, London. During six years at the National Physical Laboratory (NPL) he was involved in establishing a National Measurement System for medical ultrasound field characterisation and contributed to the preparation of international standards. In 1989 he moved to the Royal Aerospace Establishment, Farnborough, later the Defence Evaluation and Research Agency (DERA). Whilst there he developed the ANDSCAN® portable scanning system and arranged for its commercial exploitation, receiving the DERA Technology Transfer Prize in 1997. In July 2001, when DERA split into a government laboratory and a commercial company, Robert joined the latter, QinetiQ Ltd. Robert Smith has authored over 65 publications and was awarded the John Grimwade Medal for 1995 and the Roy Sharpe Prize for 1996 by the British Institute of Non-destructive Testing, in which he is a member of the Technical Committee and the Council. He is a Fellow of the Institute of Physics, a Fellow of the British Institute of Non-destructive Testing, a Chartered Physicist and a Chartered Engineer. As a QinetiQ Fellow, his current areas of interest include: ultrasonic spectroscopy, NDE of corrosion for ageing aircraft, transient eddy-current imaging, ultrasonic inspection of structural composites, in-service scanning, and NDE instrumentation.