11 Quality Assurance

11.1 Introduction

Quality control for composites is often seen simply as validation of the physical and mechanical properties of the cured laminate. However, thorough control begins long before the part is completed and is more correctly termed *process control*—overseeing its application is the task of quality assurance. Quality control involves control of the incoming material, control of the process, and finally, inspection for defects.[1,2]

Section 11.2 presents an overview of the quality control of composites. Control of the cure process is especially important and is discussed in Section 11.3, where some of the current direct measurement methods of control are discussed.

Non-destructive inspection (NDI) is the final quality check on the finished part, and this is discussed in Section 11.4. This section also covers inspection of service defects.

Most aerospace composite parts are manufactured by autoclave curing of pre-preg, and the following discussion refers specifically to this fabrication route. Many of the quality requirements are, however, common to all fabrication processes.

11.2 Quality Control

11.2.1 Raw Materials

The raw material for producing aerospace composites is usually obtained as pre-impregnated yarn, unidirectional tape, or fabric (frequently abbreviated to *pre-preg*) but quality control starts with the component materials of the pre-preg, namely the fibers and the resin.

11.2.1.1 Fibers. Fiber testing is performed principally by the fiber manufacturer, although pre-preg manufacturers may also test incoming material to verify the manufacturer's data and to check for damage during shipping and handling. Tests may also be done to monitor the fiber properties during the fabrication process. The most common fiber properties used for composite control are longitudinal tensile strength, elastic modulus, elongation, yield, density, twist, and sizing content.[3] These properties may be tested on single fibers, multifilament yarns, or impregnated strands. In many cases, the incoming material contains a textile fabric rather than a simple yarn, and fabric testing, such as measurement of aerial weight, may additionally be required. Standard tests for tensile testing of fibers, yarns, strands, and fabrics are available as ASTM standards.[4] An example is given in Table 11.1. Additionally, chemical assay tests are conducted by the fiber manufacturers to check the chemical composition of the fibers while surface analysis techniques, such as X-ray photoelectron spectroscopy (XPS) and electron spectroscopy for chemical analysis (ESCA), are used for determining the surface characteristics of the fibers.[5]

11.2.1.2 Resins. Testing is performed by the resin manufacturers during formulation of the resin. The tests involve physical, chemical, and spectrographic techniques. The tests are typically performed on the individual component materials, on mixtures of several ingredients, and on the blend in its final composition. Typical tests are gel time, viscosity, chromatography, and infrared spectroscopy. Gel-time tests measure the time for the resin to undergo gelation (gel) at a predetermined temperature. The simplest method involves probing the heated resin until gel is reached. *Gel* is defined as the point at which the resin strings break sharply when probed and strung. Chromatography and infrared spectroscopy[1,6] provide a "fingerprint" of the resin chemistry.

11.2.1.3 Pre-Preg. Both the pre-preg manufacturer and the composite fabricator perform tests on the uncured pre-preg. The latter is either recommended or specified because further curing may have occurred during transport to the fabricator. These tests are a mixture of physical and chemical tests and are intended principally to ensure that the component materials are

Table 11.1 ASTM Standards for Tensile Testing of Fibers, Yarns, Strands, and Fabrics

Standard	Title
D 3379	Standard Test Method for Tensile Strength and Young's Modulus for High-Modulus Single-Filament Materials
D 2256	Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method
D 4018	Standard Test Methods for Tensile Properties of Continuous Filament Carbon and Carbon Fiber Tows
D 5034	Standard Test Method for Breaking Strength and Elongation of Textile Fabrics

present in the correct proportions and to confirm the processability of the pre-preg. The requirements for these tests are usually given in the user's specification and may vary somewhat from user to user.

Physical tests typically include resin content, areal fiber weight, resin flow, volatile content, tack, and, sometimes, drape.[6]

Resin content is the weight fraction of active resin/hardener/catalyst. Areal or dry fiber weight is the weight of reinforcing fiber in the pre-preg per unit area. This test is usually measured on the same sample as used for resin content. Subjecting samples to heat and pressure tests the degree of resin flow. The resin lost through either lateral or perpendicular flow under these conditions is measured. The test may not be appropriate for controlled-flow resins because values are typically near zero. Volatile percentage is determined by heating either a single ply or a ply stack at the curing temperature and recording the mass loss. This is an important test because trapped volatiles in a component can result in excessive surface pores and internal voids.

Tack and drape are both more subjective tests. Tack is an assessment of the stickiness of the pre-preg. Drape is the ability of a pre-preg to be formed around defined radii and to remain tacked for a specified period of time.

The most widely used tack test involves "tacking" a ply of pre-preg to a tool and then tacking a further ply of pre-preg to the first. The test requires that the second ply be capable of being removed and repositioned without either excessive distortion or removal of the underlying ply.[6] However, even a material of low tack can pass this test but still prove to have poor drape. A superior test is to measure the adherence strength of two plies rolled together under controlled conditions. The plies are then pulled apart in the form of a "T" peel test and the force recorded.

Chemical tests performed on the pre-preg by both the material supplier and the composites manufacturer include gel time, high-pressure liquid chromatography (which provides a good fingerprint of the resin components), and differential scanning calorimetry [which measures the degree of resin cure and can also provide a crude measure of the glass-transition temperature (T_g) of the resin]. Infrared spectroscopy is usually carried out by both the pre-preg manufacturer and the fabricator to ensure that no major changes have occurred in the resin during impregnation or B-staging of the pre-preg (partial cure by pre-preg manufacturer) or during its subsequent transport.

In addition to the tests done on the uncured pre-preg, tests are also performed on cured laminates. Physical and mechanical tests are performed to ensure that the material is closely similar to that originally qualified to the specification from which engineering design properties were measured and calculated. Many of these tests are covered by ASTM[4] and Suppliers of Advanced Composite Materials Association SACMA[7] standards. Physical tests typically include fiber and resin volume fractions, void content, cured ply thickness and T_g. Mechanical tests are selected to cover critical material properties. Typical tests are 90° or 0°

tensile strength and modulus, 90° or 0° compression strength, and short beam shear strength or ±45° tension strength. Short beam shear strength testing is of limited value because the failure mode is frequently by compression, but it is useful as a monitor of the degree of cure in process control panels. The ±45° tension strength test is, however, preferable because it is more sensitive to resin-dominated properties and it is easier to perform with simpler specimens and test jigs. Compression and ±45° tension strength testing is sometimes performed at the maximum design temperature, after conditioning at the maximum humidity/temperature, as well as at room temperature, to ensure the material's temperature capability.[1] Mechanical property measurement is discussed in Chapter 7.

The ultimate user needs to define the suite of tests to be used on incoming material, the frequency of testing, and the criteria for retesting if the material fails some or all of the specified tests. Also necessary are appropriate tests when the normal storage life expires; these tests should be resin-dominated ones. These requirements are normally documented in the user's specification for the material. As use and confidence increase, the test frequency is often reduced.

11.2.2 Process Verification

It is necessary to verify that the fabrication process is performed in accordance with the engineering requirements. These are normally specified in an engineering process specification.

11.2.2.1 Material Control. Before fabricating a component, the material to be used must first be identified as the correct material ordered; must have been tested to the correct material specification by the manufacturer, and met its requirements; and must have satisfied the specified receipt inspection testing requirements by the user/fabricator. Perishable materials such as pre-pregs and adhesives must also be within their allowable storage life and below the maximum specified storage temperature at the time of removal from storage. During this period, materials should be stored and packaged in a manner that precludes contamination or damage, for example, horizontally in sealed polyethene (polyethylene) bags. Once removed from storage, pre-pregs and adhesives must be within their working life (able to be draped, laid, and tacky) and within their allowed mold life (able to flow and gel) at the time of cure. To avoid contamination by condensed moisture, it is important to allow refrigerated materials to reach ambient temperature before removal from the package. The accumulated time at temperature may be recorded for the remaining unused material to assess remaining life.

It is necessary to control both the composite work area environment and the equipment used for composite fabrication. These requirements are normally embodied in the engineering process specification. Particulate or chemical matter that could affect the manufacturing process must be prohibited from the work area, and lay-up and clean rooms should be pressurized to a slight positive pressure. Because epoxies degrade with excessive temperature and humidity, clean rooms need to be air-conditioned. Typical conditions are 20–30°C, 60% relative humidity maximum, with a filtered air supply.

Lay-up tools need to be thermally profiled to check conformance with the heating rates required in the engineering process specification and thermocouples subsequently attached to the areas of the part or tool that show the fastest and slowest heating rates. Calibration requirements must be specified for autoclaves and ovens as well as the requirements for temperature uniformity. The latter is best performed with a dummy load so as to better simulate gas flows, rather than test an empty autoclave or oven.

11.2.2.3 Process Control. Processing of composites involves both laying the material and its subsequent cure. During the laying process, it is necessary to ensure that all plies are laid in the correct orientation; that they are positioned in the correct sequence in the stack; that they are laid in the correct position, and that the number of plies used is correct. The cure cycle must then be monitored to ensure that the heating rate, time at temperature, and cooling rate all comply with the engineering requirements. Pressure, vacuum, and temperature must be maintained within the prescribed tolerances and sequence.

Some manufacturers require physical and mechanical tests to validate the processing. The requirement for test specimens can also depend on the class of part being fabricated. Parts that are non-critical or secondary structure may not require any test specimens.[1] Test pieces may be from special panels laid and cured with the production parts, from material trimmed from the parts themselves (trim sections), or from coupons attached to the part and subsequently removed. If test specimens are absolutely necessary (there are many arguments to the contrary if proper process control has occurred), then the two latter specimen types are the best. Typical tests conducted are flexural strength and modulus, short beam shear strength, fiber volume fraction, void content, T_g, and degree of cure.

11.2.3 Final Inspection

After fabrication, the parts must be inspected for conformance with dimensional and workmanship requirements (i.e., visually inspected) and, depending on part criticality, inspected non-destructively for possible processing-induced defects. Some destructive testing may also be required; this is described below, and non-destructive testing is discussed separately in Section 11.4.

When part integrity cannot be ensured simply by dimensional, visual, and non-destructive testing, destructive testing may be required. Destructive tests may be done by dissection of an actual part or by examination of trim sections taken from the part. The type and frequency of destructive testing depends on both the part type and the experience of the user or fabricator. Tests can range from simple tests such as fiber volume fraction and porosity to full-scale, proof tests. Although the use of trim sections is clearly preferable, full dissection is frequently required for the first article (a production part subjected to a series of destructive tests to verify the production process) of a complex, critical part, even when manufactured by an experienced fabricator. Periodic, full dissection, with increasing intervals, may be more appropriate when experience is low.

11.3 Cure Monitoring

Cure procedures for thermosetting composite materials often follow a rigid recipe of temperature, vacuum, and pressure provided by the material manufacturer. Such an approach does not take account of material batch variations, material age, and deviations from the recommended cure cycle due to the presence of thermally massive tooling or exothermic chemical reactions within thick sections of the curing part causing excessive temperatures. Also, it does not allow the cure cycle to be optimized for a particular part under manufacture. Knowing when a part is fully cured can save production time and costs.

The use of cure monitoring systems[8,9] can be effectively applied to both traditional autoclave curing procedures as well as to resin-transfer molding (RTM) manufacture, where information such as pressure, resin viscosity, and the gel point can be critical in optimizing manufacturing processes. An ideal cure-monitoring system would be able to show basic information such as the degree of compaction, pressure, and temperature as well as information specific to the resin itself either through physical and chemo-rheological properties such as the resin viscosity, gel point, and the degree of cure.

The use of a sensor to directly monitor some critical property or properties of the cure process is required to give confidence in the manufacturing process and component quality. Such sensors may also be used in a feedback loop to drive the application of temperature, pressure, and vacuum. The use of a suitable cure-monitoring sensor will usually lead to the production of high-quality parts on a consistent basis.

11.3.1 Sensor Placement

The placement of sensors in a cure monitoring system is of primary importance. Many sensors can only provide detail about a small area within the component. This is a limitation of the most popular type of cure sensor, the thermocouple. In production, thermocouples are placed at numerous locations over the composite tooling and part. The same approach may not be feasible for expensive or complex sensors.

For this reason, the placement of sensors should be made to examine problem areas on a component or those regions that are likely to have the lowest or highest values of interest. For example, the placement of thermocouples at the hottest and coldest part of a tool would meet this requirement. Such regions of interest often involve those that are most likely to undergo a runaway exotherm reaction (thick sections) or regions that are likely to be under-cured (cold parts of the tool). These areas may be chosen on the basis of part thickness, thermal mass behind the curing part, and other important process variables.

There are many techniques and sensors that have been used to measure the extent of cure in thermoset-resin-based composite materials. A complete description of all these techniques is beyond the scope of this book. Sensors[8] can measure the extent of cure directly or indirectly through calibration or modelling of the process. An example of a direct measure could be determining the chemical spectroscopic makeup of the resin at any time. An indirect measure could be to determine temperature.

The suitability of a sensor for embedding into a laminate for the purposes of cure monitoring of composite structure (or repairs) needs to be considered carefully before implementation in production. These criteria should include the effectiveness of the sensor in assessing the state of cure, its suitability for embedding into a composite component, size, weight, complexity, cost, and applicability to a wide variety of components as well as its capability for multi-parameter sensing. The last criterion is important in that it is desirable to keep the overall number of sensors as low as possible. For example, combined dielectric and temperature sensors can reduce the number of sensors and provide a much more detailed picture of the curing process.

The techniques currently developed for cure monitoring can be broadly classified into five areas that base the sensing system on electrical, acoustic, optical, thermal, and indirect or other properties.

11.3.2 Electrical Measurements

Electrical measurements include capacitance, conductance, dielectric constant, and dielectric loss tangent. Dielectrometry has created much interest in cure monitoring but has not been used extensively in production environments. Electrical techniques are subject to electrical interference in a processing environment and need to be carefully shielded when used with conductive fibers such as carbon fibers.

11.3.2.1 Dielectrometry. Dielectric monitoring has been used for some time in cure monitoring systems. Essentially the technique depends on the measurement of the mobility of polymer molecules in an oscillating electric field.

Dipoles arise in the polymer molecules due to electronic asymmetries in their structure.[10] Thus, if an electric field with varying polarity is applied to a liquid polymer, the molecules attempt to rotate into alignment. The rate of rotation in an oscillating electric field depends on the resin viscosity and thus on the temperature and on the degree of cross-linking. The mobility decreases rapidly as the resin viscosity increases and ceases once gelation is complete.

Heating the resin thus results in a reduction in polarization and permittivity as cure occurs, which is measured as the loss factor ε. This parameter can be correlated[11] with the degree of cure, as a shown in Figure 11.1.

The dielectric technique has several shortcomings.[12] The main concern is that the degree of cure and viscosity are not easily deduced from resulting capacitance and dielectric loss tangent curves. However, dielectric sensing units and sensors are available commercially and have found their way into some production processes.

11.3.2.2 Electrical Conductivity. This technique is based on a measurement of electrical conduction as a function of the degree of cross-linking. Conductivity in a polymer melt arises from the impurity ions that may be present in the polymer and arise from the solvent and catalyst. When the

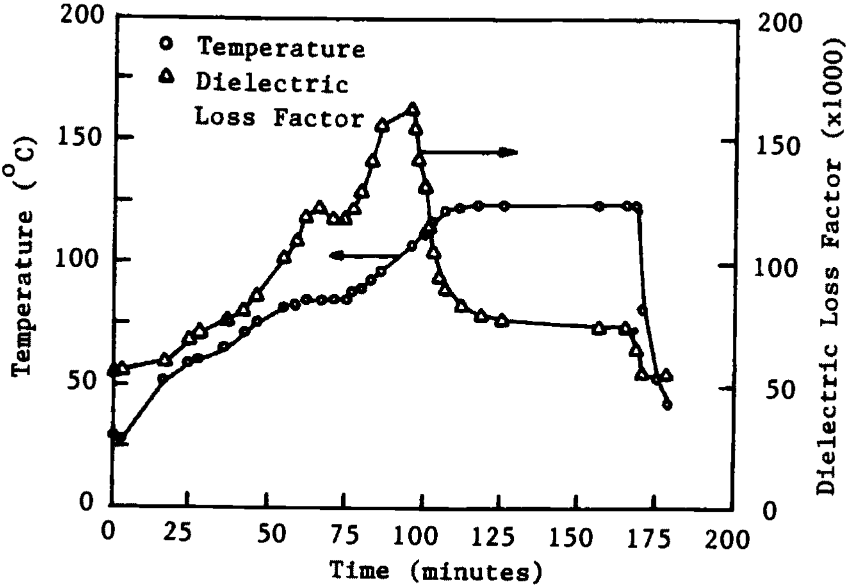

Fig. 11.1 Plot of changes in dielectric loss factor and cure temperature versus time for a glass epoxy pre-preg. Taken from Ref. 11.

resin is in a liquid state, the ions can migrate rapidly in a polarized electric field, therefore the conductivity is high. As the viscosity increases, the conductivity falls off with increasing rapidity as gelation is approached. Conductivity is considered to have a clearer functional relationship with the degree of cure. For example,[11] it is shown that the ionic conductivity is maximum at approximately the same time as the resin viscosity reaches a minimum, as shown in Figure 11.2, and that the conductivity falls to zero as the rate of change of conductivity reaches zero.

Dielectrometry and conductivity techniques require the user to either embed a sensor within the composite lay-up or attach it to its surface. In either case, to use the sensor in the presence of electrically conducting fibers such as carbon, the sensor must have a cavity that excludes fibers and fills with resin as the part cures. The shortcoming of placing the sensor on top of the part is that the resin must be in a very liquid state before the sensing cavity fills with resin. This negates the advantage of knowing the early changes in viscosity that is critical for correct timing of the application of pressure.

11.3.3 Other Methods

11.3.3.1 Acoustic Methods. These techniques involve the use of both ultrasonic wave propagation techniques as well as acoustic emission. Ultrasonic measurements may be correlated with parameters such as degree of cure, porosity, viscosity, delaminations, and fiber volume fraction. Acoustic emission also allows the cooling phase of a cure cycle to be monitored to determine

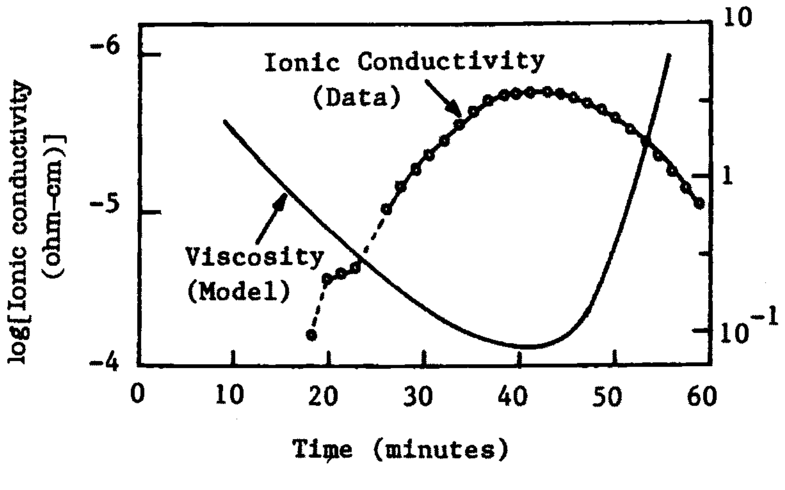

Fig. 11.2 Plot of variation in ionic conductivity and resin viscosity with time during cure of an epoxy resin. Taken from Ref. 11.

whether thermal stresses are cracking the composite. Problems can arise when a number of these parameters are changing simultaneously because it may not be possible to distinguish between them. So far, these techniques have not found their way into mainstream cure monitoring.

11.3.3.2 Optical Methods. Spectroscopic sensors provide information on the chemical changes that are occurring in the resin. The degree of cure may be related directly to the amount of unreacted resin. Sensors of this type tend to utilize optic fibers, which need to be embedded carefully into the part during lay-up. Optic fibers have been used to measure strains within composites.[13] It may be possible for the same optic fiber to be used for this purpose after it has been used as a cure sensor. The apparatus required to run these types of sensors is usually both costly and bulky.

Techniques that measure the infrared spectrum of the curing resin are perhaps the most useful because actual chemical information is being gained. Such techniques can also require special fibers (e.g., chalcogenide) that transmit light in the infrared region.[14] These fibers are expensive and can be used only once. Other types of infrared spectroscopy include Raman spectroscopy, which has a low sensitivity and requires costly instrumentation.

The fluorescence of chemical species in the UV/visible region can used for cure monitoring. Probe molecules that have a strong fluorescence in the UV/visible region but do not take part in the curing process may be used if the signal from the neat resin itself is insufficient. The necessity of adding such probe molecules to the resin may make it unsuitable for use with commercial pre-pregs. In many cases, the UV/visible spectra derived from these probe molecules can depend on other parameters such as resin viscosity rather than the actual degree of cure. Such techniques have not been widely used.

The refractive index technique works based on the fact that the refractive index of the resin changes as the cure proceeds. The correlation between refractive index and extent of cure was first established[15,16] using differential scanning calorimetry (DSC) as a more direct measure of cure. Techniques such as refractive index sensing are available to measure this property directly and accurately, but they are expensive and may only be used once.

11.3.3.3 Thermal Properties. The use of thermocouples is perhaps the simplest method of cure monitoring. They ensure that the part reaches the temperature required and that the cure cycle specified is achieved. Their worth as a cure sensor is very limited except for the fact that an exothermic reaction can be detected.

The use of heat flux sensors is a method similar to that of a DSC, which measures heat flux versus time under a controlled temperature program. The heat released during cure (the reaction exotherm) can be monitored[17] and related to the extent of cure. DSC data are used widely in chemorheological models of the resin curing process. No commercially available units are available at present, and the use of heat flux sensors is not widespread in the cure monitoring area.

11.3.3.4 Pressure and Compaction Sensors. Displacement transducers are useful for monitoring the compaction of a part during cure. If pressure application is to be optimized, this type of sensor may be essential.

Pressure sensors provide information on the pressure in a localized area. The sensors operate using a capacitive effect, which directly correlates to pressure after appropriate signal conditioning. The pressures measured by these sensors may differ to autoclave pressure in areas where the part is contoured. This type of information is useful if accurate determination of part compaction is required. Furthermore, the sensor can alert the autoclave operator of failure in the vacuum-bagging material during the vacuum cycle. Dual-function pressure/temperature transducers are available and can form a very functional sensor combination.[18]

11.3.4 Conclusions on Cure Monitoring

Table 11.2 lists the techniques and their performance against the selection criteria listed. This Table shows that the techniques that show the most promise are dielectrometry, ionic conductivity, spectroscopic techniques, and measurement of refractive index. The refractive index technique is quite new and relatively unexplored for in-field or commercial use.

Table 11.2 Summary of Performance of Various Techniques for Embedding and Cure Monitoring of Composite Components

Technique	Cure sensing ability	Size, complexity	Cost	Multi-parameter sensing	Embed into Composites
Dielectric	High	Low	Med	No/Yes	Yes
Conductivity	High	Low	Med	Yes	Yes
Acoustic	Medium	Low	Med	Yes	Yes
Spectroscopic	Excellent	Med-High	High	No	Yes
Refractive Index	Good	Low	Low	Yes	Yes
Thermocouple	Low	Low	Low	No	Yes
Heat Flux	Good	Med	Med	No	Yes
Pressure Sensor	Low	Low	Med	No	Yes
Displacement Transducer	Low	Low	Low	No	No

11.4 Non-destructive Inspection of Advanced Composite Aerospace Structures

The processes of advanced composite manufacture, described in Chapter 5, are inherently prone to errors, particularly human errors, that can lead to the formation of defects or anomalies in the structure. Many defects cause a reduction in the mechanical properties of a composite structure and in some cases can lower the properties below the design allowables, hence the importance of detecting defects in composite aircraft structures before service. The strict quality assurance policy of the aviation industry enforces components to be inspected for defects using non-destructive technologies. In some cases where the composite component forms part of the primary structure, 100% inspection is required, which is a major cost penalty.

During service, aircraft structures are prone to many mechanical and environmental conditions that can cause damage to composite structures in the form of delamination, fiber breakage, and matrix cracking. The most well known example is impact damage caused by severe mechanical contact. Monitoring the level and type of damage to a composite structure is vital to determining the component's structural integrity and preventing the failure of the structure during flight. Thus, in-service inspection is also important.

In contrast to glass-fiber composites, which are translucent, carbon-fiber composite components are opaque, preventing the visual detection of internal defects. In service, both glass and carbon composite aircraft components are typically painted. Thus, some form of non-visual inspection using various physical techniques is used to detect defects in nearly all composite structures. This section provides an overview of defects commonly found in fabricated composite structures and presents the current and emerging technologies for NDI.

11.4.1 Requirements for Quality Assurance

The knowledge of the size and location of defects is critical to assessing the flight-worthiness of aerospace components. The main function assigned to NDI is the reliable and repeatable detection of defects of a specified size in a component. In commercial aviation, the minimum allowable size of a defect for composites is typically 12.5 mm (0.5 in). For military aircraft, which operate at higher stress levels than civil aircraft, the minimum allowable defect size is generally smaller, depending on the role of the structure and the method of design. In limited cases, the design of some structures allows for typical damage so has no mandatory requirement for NDI. Table 11.3 lists typical manufacturing defects, whereas Table 11.4 lists typical defects that can develop in service.

Table 11.3 Common Defects Found in Fabricated Advanced Composite Structures

Defect	Description
Delaminations	An area of separation between fabric layers in the laminate structure.
Unbond	An area in which two adherends or pre-preg layers failed to bond together.
Disbond	An area in which two adherends have separated at the bondline.
Porosity	The entrapment of pockets of air or gas(es) within a solid material.
Crack	A fracture of material in the laminate that typically extends through the thickness.
Core crush	Damage of the honeycomb core due to impact or excessive pressure during cure.
Foreign object	An inclusion of a foreign substance, such as peel ply, during the manufacturing process.

Often, a sampling plan is used for the inspection routine for an advanced composite component as part of manufacturing quality control. In some cases, the first 50 shipsets of a component are all inspected to form the first sample. A statistical analysis is conducted on this sample to determine the proportion of components that need to be inspected to maintain a reliable and repeatable NDI routine. A new sample plan is usually formulated when there is a change in job structure, when the installation of new processing equipment occurs, or after a period of work shutdown.

Table 11.4 Common In-service Defects Found in Advanced Composite Aircraft Structures

Defect	Description
Impact damage	Internal damage of composite caused by collision with an external body during flight or docking, typically marked by delaminations, fiber breaking, and matrix cracking.
Delaminations	Separation within the composite has occurred generally due to unexpected out-of-plane stresses.
Lightning burns	An area of the composite that has been subjected to high temperatures causing decomposition and degradation in properties of the matrix.
Disbonding	Interfacial separation in composite/composite or composite/metal bonded joints due to out-of-plane stresses or, in the case of metallic joints, to environmental degradation.
Core, degradation	Areas in honeycomb sandwich panels with cores where water has penetrated leading, in the case of metallic cores, to disbonding and corrosion.

Table 11.5 NDI Techniques to Detect Defects in Advanced Composite Structure

Technique	Operating Principles	Applications in Industry	Defect Detection Capabilities	Related Emerging Technologies
Ultrasonic	An ultrasonic pulse is transmitted through a sample and is scattered or reflected by regions with differing acoustic impedance, such as defects. Defect information is measured from A- or C-scan images.	Hand-held probes—used for inspection of small components, and complex regions of structures, relies on use of small probes and A-scan images. Automation C-scan—used for inspection of large structures, such as rudder skins.	Planar cracks, delaminations, large voids, high porosity, and some foreign object materials can be detected. Identifying through-thickness defect location reliant on pulse echo technique.	Non-contact (non-couplant) ultrasonics, including laser induced, electromagnetic acoustics, air couplant probe miniaturization
Radiography	X-rays are differentially absorbed when passed through a material, where rates of absorption are dependent on material physical density.	Film radiography—used for inspection of structures with large regions of honeycomb and material variations, such as landing gear doors.	Bond lines, core-crush, foreign object, through-thickness cracks, and voids can be detected.	Filmless radiography

Thermography	Dissipation of temperature from a material subjected to an initial heat source is measured using infrared equipment, where anomalies lead to different rates of heat release.	Being developed for rapid area inspection of structures, with possible applications for skins, spars, ribs, and control surfaces.	Delaminations, large voids, and some foreign objects can be detected, depending of thickness of structure.	Pulse thermography
Holography/ Shearography	Surface strains are measured as fringe patterns caused by the application of a load to the structure, where submerged defects affect surface strain continuity.	Being developed for rapid area inspection of large structures.	Bond lines, core crush, and delaminations.	Digital shearography
Acoustic Sensing	Elastic waves are used to induce natural frequency response from structure.	Bond-tester used to inspect bonding flaws. AE being developed for real-time inspection of in-service damage to aircraft structures, AU and AI being developed for rapid field inspection of complex structures.	Impact detection, bonding flaws.	Acoustic emission, acoustic impact, and acoustic ultrasonics

11.4.2 Current Technologies

There are a number of NDI techniques used in the aerospace industry. Some of these techniques are better suited to particular types of materials, geometries and defect types. The traditional methods of inspection for defects in fabricated laminate structures are ultrasonics and radiography. Table 11.5 lists the operational principles, capabilities and industry applications of the current NDI technologies used in the production line.[19] Table 11.5 also lists promising techniques not yet readily used in production or service, such as thermography, holography, and acoustic sensing, which have been developed to the extent that they could shortly be introduced in industry. From this Table it is seen that no single NDI technique provides all the information necessary to detect all types of defects. Often it is the geometry of the structure that limits the type of inspection technique that can be used.

Compared with the inspections of parts before service, in-service inspection is typically conducted with the structure attached to the aircraft. Damage monitoring is most usually conducted when the aircraft is undergoing routine maintenance. Restriction of access to areas of the structure requiring attention is a problem. The inspection of assembled structures is a much more difficult task than the inspection of detail parts on the production lines.

There are, however, synergies between the NDI technologies used for the inspection of fabricated and in-service defects in composite aircraft structures. As with the inspection of fabricated defects, ultrasonic inspection is the most common NDI method used to inspect and locate service defects in composite aircraft components. The development of new technologies is focused on increasing the efficiency of NDI that can be applied to the inspection of fabricated and in-service defects. These technologies include real-time radiography, thermography, and mobile automated ultrasonics.

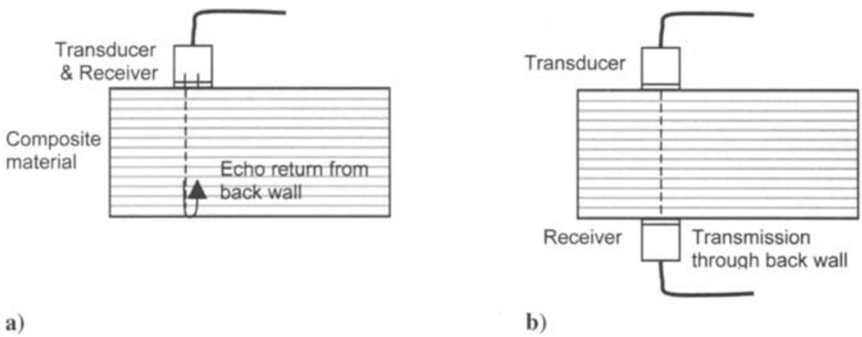

Fig. 11.3 Schematic representation of *a*) pulse-echo ultrasonic inspection and *b*) through-transmission ultrasonic inspection.

11.4.2.1 Ultrasonic Inspection. The basis of ultrasonic inspection is the propagation and measurement of a sound pulse through the composite specimen. The sound pulse is emitted from a transducer into the composite material and is recorded by a receiver. A certain percentage of the sound wave will reflect from the back surface and is recorded as a "pulse-echo" by a sensor typically located with the emitting transducer, as shown in Figure 11.3a. Another percentage will be transmitted through the back surface and can be recorded as a "through-transmission" signal by a sensor located at the opposite surface, as shown in Figure 11.3b.

The ultrasonic wave will be reflected or scattered by any defect that differs significantly from the acoustic impedance (product of the acoustic velocity and material density) of the composite material, as shown in Figure 11.4. The measured difference in the emitted signal energy compared with that received provides information on the presence of defects in the composite material. Defects such as delaminations, large voids, and cracks that are planar to the surface, or normal to the propagated pulse, will cause a loss or attenuation in the transmitted sound.

The two common methods of data presentation for ultrasonic inspection are A-scan and C-scan. An A-scan presentation displays the distance-amplitude of the transmitted sound through the thickness of the component at a single point. An A-scan image is typically displayed on an oscilloscope screen, as shown in Figure 11.5. C-scan presentations provide a plan view of a composite material, where the information of the movement of the transducer across the composite surface is combined with the distance-amplitude information and is displayed as a video image. A color scheme is used to represent different levels of sound transmission based on a calibration.

Figure 11.6 shows a C-scan image from a through-transmission ultrasonic test of a rib-stiffened box structure, with defects highlighted visually by contrast differences compared with the surrounding material. In this C-scan image, a defect at the rib-to-skin junction is shown as an area of high dB loss, identified by black pixels. Tab markers placed on the structure before inspection are placed as an aid to location and scale of defects and are evident here as darker shaded

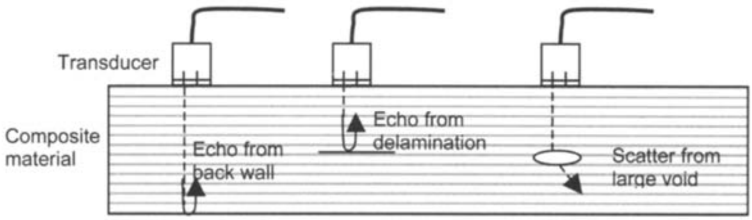

Fig. 11.4 Schematic representation of sound wave response to the presence of defects in a composite material in ultrasonic inspection.

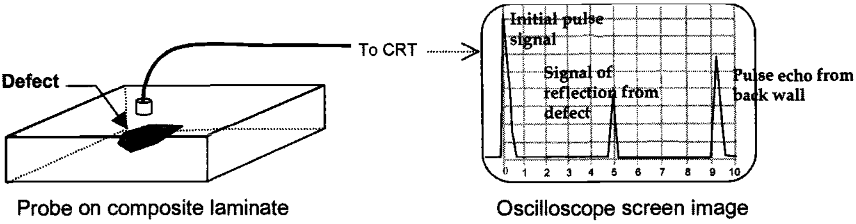

Fig. 11.5 A-scan presentation of amplitude-distance signal recording from pulse-echo inspection showing detection of defect on CRT screen.

rectangles in Figure 11.6. Thickness variations in the structure lead to differences in the greyscale. Many systems display in color, making the images easier to interpret.

The amplitude or degree of attenuation of the signal can be used as a measure of the nature and size of porosity or voiding, provided a calibration of the attenuation in material of varying porosity contents is first determined. It may be

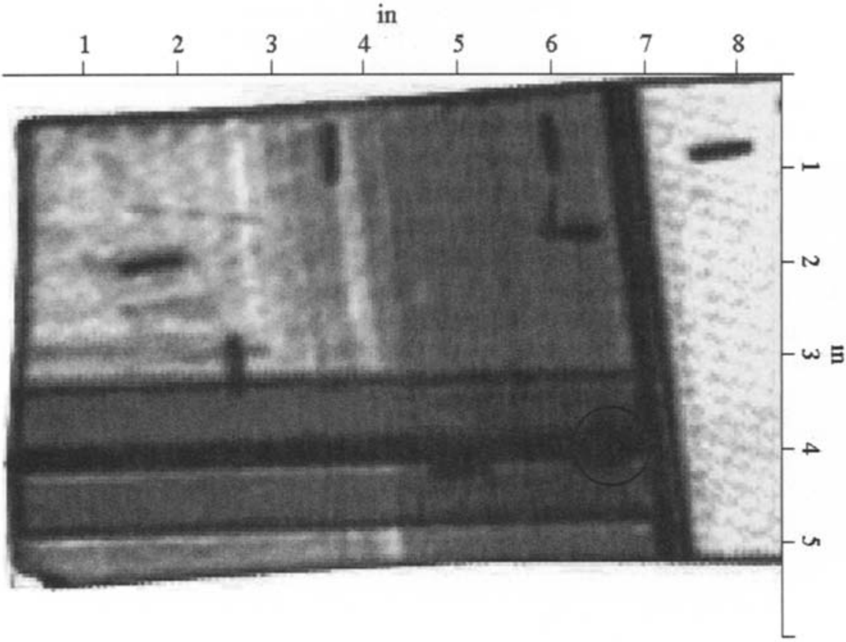

Fig. 11.6 The dark area ringed is a defect in the rib-to-skin junction. More information, such as dB loss, is indicated in the scan image by color changes (not shown here).

possible to estimate properties such as interlaminar shear (ILS) from attenuation data, provided that porosity is the only determining variable.

The transmission of sound from the probe to the structure is reliant on a couplant such as water or a suitable gel. High loss of the sound occurs when passed through air. The acoustic impedance of air is significantly lower than that of both the piezoelectric transducer and the composite material, causing loss of most of the sound energy. A medium such as water provides more efficient transmission and reception of the sound pulse to and from the component and probes. Water baths or squirter systems are commonly used in automated ultrasonic scanning of composite structures.

In industry, relatively complex composite structures that are accessible from both sides, are usually inspected using automated ultrasonic through-transmission scanning (AUSS).

The control of the probes on a gantry system allows for a more reliable and repeatable method for continuous inspection of a series of parts. Transmission of the sound is typically achieved through the application of a water jet from the probe to the surface of the part. Submersion of the part in a water bath is a technique applied to box-type structures. Here, water completely fills the box, allowing the transmission of sound from one side of the box to the other.

Hand-held ultrasonic scanning with direct contact of a probe is common in the inspection of aircraft structures, typically in localized complex areas such as radii and flanges. The development of cavity probes and mobile automated ultrasonic scanning has focused on replacing the labor-intensive hand-held ultrasonic scanning method for production inspections.

The traditional ultrasonic methods for in-service inspection involve the use of a small probe. This approach is time consuming when scanning large areas and is subject to access difficulties for particular structures on the aircraft. This has led to the development of systems better suited to rapid, large area scanning. The use

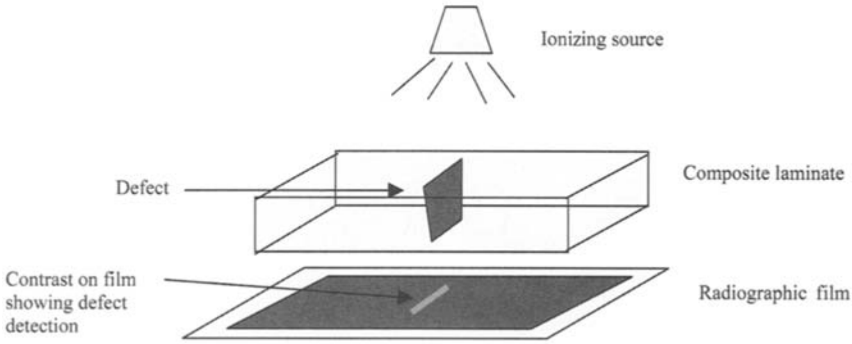

Fig. 11.7 Schematic diagram of application of X-ray to composite laminate as an NDI method.

of robotics in conjunction with ultrasonics has led to the development of equipment such as the mobile automated ultrasonics system (MAUS) that permits rapid collection of data into a C-scan image.

11.4.2.2 Radiography. X-rays, when passed through a structure, will be absorbed where the level of absorption is dependent on the physical density of the material. The differential absorption of materials allows the use of radiography for the inspection of particular defects in composite structures. The method of X-ray radiography as a NDI technique uses ionizing radiation through a structure (Fig. 11.7) where the level of absorption of the radiation is recorded by film on the opposing side of the structure. The level of contrast on the recording film is dependent on the level of radiation that has passed through the structure. The presence of varying local physical densities in the composite structure will show as a differential contrast on the film. Defects, which include foreign objects or debonds that have different physical densities to the resin and fiber of the composite, will be detected on film when oriented in the same plane as the transmitted beam. Defects such as delaminations and planar cracks are difficult to detect using radiography.

Penetrants are often used to enhance the contrast in the detection of planar defects. Penetrants used include zinc iodide, silver nitrate, trichloromethane, and diiodomethane. Choice of the penetrant is determined by the ease with which it can penetrate the delaminations and also with which it can be subsequently removed. Diiodomethane has the advantages of high opacity, ease of penetration, and ease of removal because it evaporates fairly quickly. However, it can cause skin burns.

The dangers of radiography have generally limited its use to inspection of parts removed from the aircraft. The development of real-time radiography using a localized computer controlled X-ray source and point detector has led to the wider use of the technique for in situ inspection.

11.4.3 Emerging Technologies

The development of alternative technologies for NDI of advanced composite structures has been driven by the need to dramatically reduce inspection times and increase the capability of detection for complex component design concepts. There are parallel efforts in NDI technologies for detection of defects of fabricated and in-service structures. The development of rapid and more efficient inspection technologies is being led by work in the fields of non-contact ultrasonics, real-time radiography, pulse thermography, digital shearography, and acoustic emission technologies.[20] Work in these fields focuses on improving conventional NDI techniques, such as the replacement of the expensive and time-consuming development of film in X-ray radiography using real-time imaging. The integration of the emerging NDI technologies with existing technologies using data fusion software to form an efficient multi-purpose NDI system for families of composite structures is the focus of current major research. A possible future direction of research in NDI will be toward the establishment of a technology that can be used during and immediately after cure of the component as well as during the in-service life of the structure. This could be achieved using smart structure technology with embedded sensors, such as optical fibers, in the structures.[21]

11.4.3.1 Non-contact Ultrasonics. The problems with using a liquid couplant between the probe and component, particularly in terms of access to areas of a component, has led to developments in non-contact ultrasonics. Moreover, the application of NDI as an on-line inspection routine for some composite fabrication processes, such as tape laying, has fuelled the development of these techniques. There are several techniques available for non-contact ultrasonics including air-coupled detectors and laser-induced detectors.[22]

Air-coupled ultrasonic systems focus on transmitting high-frequency sound waves using high gain and low noise amplification. The development of a transducer that allows for a more focused transmission of sound has led to the use of air-coupled probes to characterize carbon/epoxy pre-preg materials.[23] Figure 11.8 shows the use of QMI Inc. through-transmission air-coupled probes

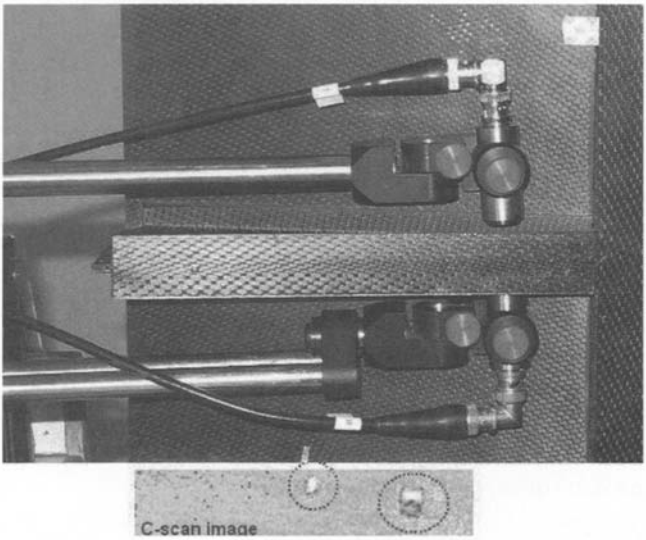

Fig. 11.8 Air-coupled non-contact ultrasonics image from QMI Inc. of web region of rib of composite box structure showing foreign object detection.

for inspection of a rib-stiffened composite box structure. Foreign object detection is shown from the inspection in the C-scan image.

Laser beam ultrasound is applicable to both electrically conducting and non-conducting materials with less disturbance in detection as a function of distance from part surface compared with the other non-contact techniques. Laser beam ultrasonics provides access in geometrically difficult-to-reach locations. In this method, short pulses are induced that cause rapid heating and expansion of the component surface. Laser detection of the reflected signals from the excited component is performed using an interferometer system. Fiedler et al.[24] have shown the capability to generate a three-dimensional C-scan image of a curved part with discontinuities at various depths using laser ultrasonics. The main limiting factor of laser ultrasonics is the cost of the hardware. Buynak et al.[25] inform of work that has demonstrated the relative ease for introducing perpendicular sound pulses on round surfaces using laser-based ultrasonic (LBU) technology, a task that is said by the same authors to be difficult to achieve with the traditional water jet systems.

A hybrid system that uses lasers to induce ultrasonic signals and electromagnetic acoustic transducers (EMAT) to measure the signals is reported.[26] This system overcomes the shortfalls of EMAT to induce ultrasonic signals when used alone.

11.4.3.2 Real-Time Radiography. Recent developments in real-time imaging technology have raised interest for expanding radiographic testing. Advances have been achieved in the areas of reverse geometry X-ray and microfocus X-ray microscopy.

Real-time reverse X-ray systems that allow for portable and filmless inspection have been successfully used to detect in-service defects.[27] In the reverse X-ray technique, a component is placed adjacent to the large scanning source and a point detector. A computer controls the X-ray tube and image construction. This technology is demonstrated for inspection of water entrapment and core crush in honeycomb core composite sandwich structures. The development of an integrated robotic X-ray system, as shown in Figure 11.9 demonstrates the potential implementation of an automated system for inspection in a production line and in the field for aerospace structures.

11.4.3.3 Thermography. In thermography, heat-sensing devices are used to measure temperature variations caused by differences in heat capacity or thermal conductivity in a structure. Thermography is well suited to detecting disbonds and delaminations.

The advantages of thermography are based on its non-contact application and high scanning rates. Passive thermography has been able to provide qualitative assessment of sub-surface defects, but has failed to match the quantitative capabilities of ultrasonics. This technique relies on heat diffusion driven by

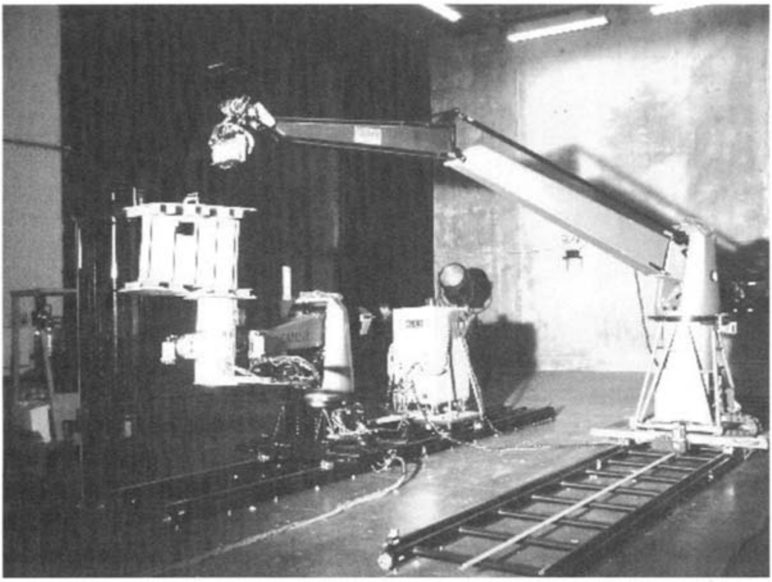

Fig. 11.9 Robotic Digital X-ray probe. Courtesy Digiray Corporation.

ambient or process-related temperature fluctuations as the basis for detecting hidden structural flaws.

Developments in the field of pulse thermography have largely bridged the gap between the capabilities of ultrasonics and thermography. In pulsed thermography, the surface of the sample is irradiated by a pulse of heat from a high-powered light source and monitored using an infrared sensor. Ideally, the heating should be highly uniform; however, it is often very difficult to achieve uniform heating (this being dependent on the shape and complexity of the component). The relative time and amplitude of the measured signal provides information about the depth and size of sub-surface defects. Areas located near defects will cool (heat diffuses away) at a different rate compared to defect-free areas. Figure 11.10 shows the basic set-up of the thermography NDI method, where the application of a flash lamp heats the composite component and an infrared camera measures the temperature distribution in the component over time. The thermal image shows defective areas as lighter regions compared to dark for the surrounding material.

Limitations on thermography include optical reflectivity, infrared emissivity and thermal diffusivity of the material. Thermography is most suited to large planar structures, or curved components with large radii of curvature. It is generally found that parts thicker than 12 mm are not practical for thermographic inspection. The low infrared emissivity, or high reflectance, of unprepared metal

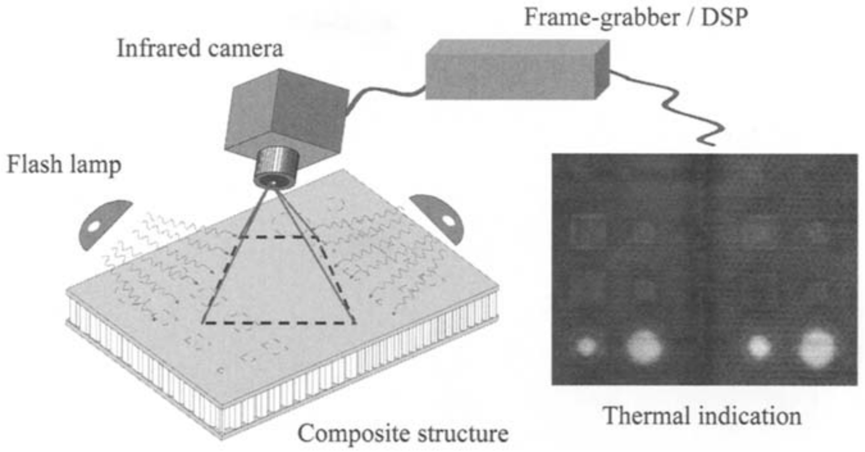

Fig. 11.10 Schematic of pulse thermography NDI method, courtesy of DSTO.

surfaces can present a problem in allowing stray infrared emissions to potentially contaminate a thermogram. This can be overcome with the application of paint. Developments in pulse thermography have focused on advanced signal processing and synthetic imaging that considers the behaviour of each pixel over the entire cooling sequence.

A comparison, has been undertaken of results for detection of Teflon inserts in a carbon/epoxy 5 ply laminate with aluminium honeycomb core using flash thermography and through transmission ultrasonics. A high level of defects was found using thermography; however the resolution of data images from the use of ultrasonics were superior to those obtained by thermography. These findings suggest a need for work on advanced signal processing and synthetic imaging.

Thermographic imaging successfully detected disbonds between an 11 ply carbon/epoxy skin and a titanium spar in a rudder leading edge, adhesive voids in boron patch repairs, water incursion in composite radomes, and interstitial voids at the skin to rib junction in a co-cured carbon/epoxy flap structure, as shown in Figure 11.11.

An alternative thermographic technique is to detect heat directly generated by the defects themselves In this approach, called vibrothermography, low-amplitude mechanical excitations induce local heating by friction when relative motion of the flaw surface occurs. Figure 11.12 shows thermal images at various delays after excitation of an impact damaged composite laminate sample with a photographic flash lamp. The defect indication is observed to develop gradually over time, consistent with a diffusion governed process that this technique is suited to the detection of delaminations and matrix cracking.

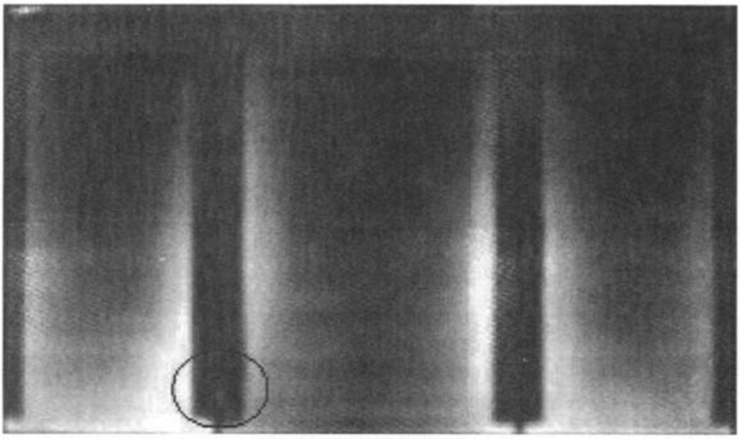

Fig. 11.11 Digital image from EchoTherm (thermal wave imaging) showing detection of interstitial void at skin to rib junction of a carbon/epoxy flap.

11.4.3.4 Optical Methods, Shearography, and Holography. In shearography a load is applied to a laminated structure that causes submerged defects to create surface strain discontinuities that are visually shown in a fringe pattern. The strain levels in the structure are measured by a digital interferometry system before and after a load is applied. Digital mapping of the component using image acquisition equipment generates fringe patterns permitting real-time inspection.

The basis of forming a shearographic fringe pattern is the application of a load to the structure. This is achieved through thermal and surface vacuum techniques. Davis[28] demonstrated the capabilities of inspecting large areas of composite materials using thermal-stress shearography, whilst Bar-Cohen[20] demonstrated the use of thermal shearography on an aircraft. Figure 11.13 details the detection of a void at the junction of a rib to skin for a rib stiffened carbon/epoxy box structure. This image was generated by Steinbichler with the stationary Shearography System by using thermal excitation with an 8-mm objective.

Environmental disturbances, such as thermal currents and room vibrations are overcome in shearography by integrating the use of a common path optical arrangement and surface strain measurement. This system overcomes the problem of conventional holography. This technique can also detect very small defects through the formation of fringe patterns under stress. However, it is more sensitive to the mechanical stability of the structure.

11.4.3.5 Acoustic Excitation and Sensing. The use of low frequency acoustic waves to excite a natural frequency response from a structure is the basic principle of the tap testing method. The tap test is the simple technique of using a

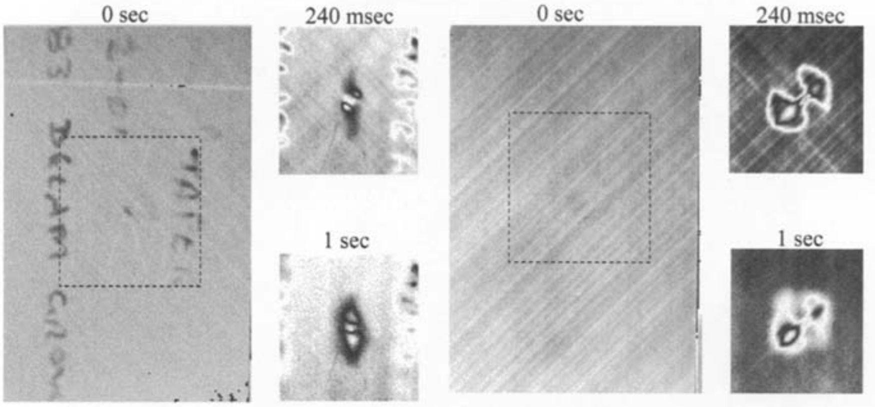

Fig. 11.12 Flash thermographs of an impact damaged 50 ply carbon/epoxy composites at three stages in the cooling process. Taken from impact surface left and opposite surface right, courtesy of DSTO.

coin or light hammer to tap a structure, where the resulting natural frequency response at a sub-surface defect will give a hollow sound. The methods of exciting a structure and recording the vibrational response have led to the development of instruments such as the digital bond-tester and techniques such as acoustic-ultrasonics and acoustic impact. These methods being developed using sensing of acoustic waves are applicable to non real-time inspection. The real-time monitoring of acoustic waves caused by an impact to a structure during service is a technique under development. The following describes these developing acoustic excitation and sensing technologies.

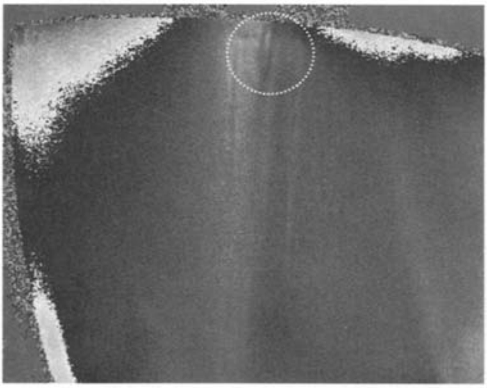

Fig. 11.13 Shearography image at 8-mm objective of rib to skin junction of composite box structure showing detection of a void. Courtesy of Steinbichler Optotechnik GmbH.

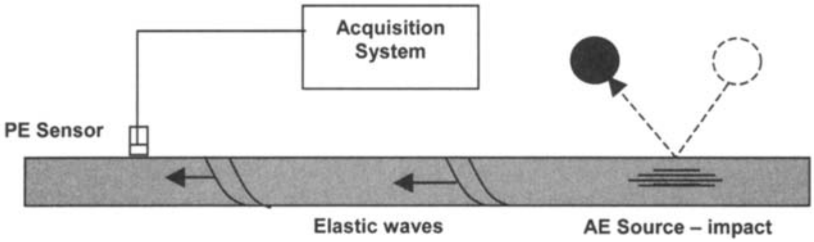

Fig. 11.14 Schematic of acoustic emission method.

11.4.3.6 Acoustic Emission. Acoustic emission (AE) is defined as the generation of a transient elastic wave caused by the rapid release of energy from a localised source within a structure. AE may be used to detect crack initiation and growth, impact damage and to determine the location of damage. In AE, piezoelectric sensors are used to detect elastic waves generated within the structure, as shown in Figure 11.14. The generation of elastic waves within a composite structure is attributed to failure mechanisms, such as fiber fracture, matrix cracking or delamination. A good analogy for the AE source location is the detection of the epicenter of an earthquake. Hamstad et al.[29] have investigated a correlation between the recorded emission signal and the location of the defect in composite structures. The progress of this work is focused on complex analysis of the emission signal using fixed threshold techniques. A more primitive method of identifying the general location of the impact is reliant on detecting the first of an array of AE sensors across a structure hit by an emitted signal, known as the "first hit" method.[30] The need to use sensors on the structure carries concerns of extra weight and possible failure sites. The development of wireless technology and electronic miniaturisation will assist in the viability of this technology to be applied as a NDI method.

The technique is found to be of limited use for NDI purposes. However, it may find some value for proof testing where it could be used to detect serious hidden defects.

11.4.3.7 Acousto-Ultrasonics. In contrast to placing two transducers in line of sight of each other, a technique known as acousto-ultrasonics (AU) uses two transducers on the same side of a structure, one to transmit the signal, the other to receive the signal after the wave has propagated along the material. This is shown schematically in Figure 11.15. The method is reliant on the use of a transmitting piezoelectric transducer where issued acoustic waves are propagated through the structure, and the responding emitted wave components are received by at least one remotely located transducer.[31] The initial development of this method[32] focused on correlation between the mechanical strength of the structure with a stress wave factor. An investigation[33] on the application of AU as a

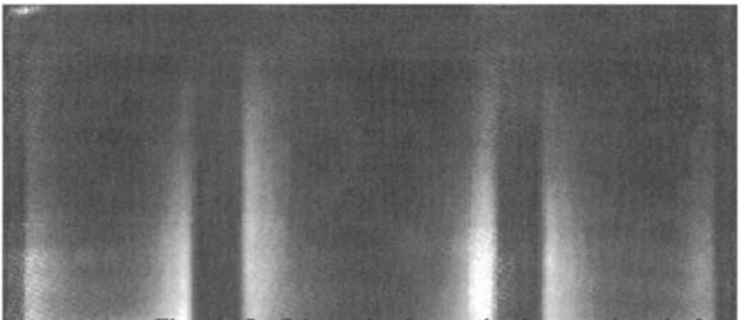

Fig. 11.15 Schematic of acoustic ultrasound method.

quality control mechanism for thick radial ply composite shows the capability of applying this technology to detecting defects in composite structures. The application of AU to aircraft structures is reliant on using multiple sensor configurations, a technology that requires further analysis of wave propagation with transducer and receiver pairing.

11.4.3.8 Acoustic Impact. The impact of a structure with an acoustic wave is a method used to excite natural frequencies in a structure.[34] Changes in structure, such as sub-surface defects, will locally affect the natural frequency response. Recording of the relaxation frequencies across the surface of a structure using a scanning laser Doppler vibrometer can detect sub-surface defects. Figure 11.15 shows how the generation of a pressure wave at distance from the structure leads to an impact by an acoustic wave.

11.5 Conclusion

Non-destructive inspection for advanced composite aerospace structures plays a significant role in the assurance of forming high quality composite components

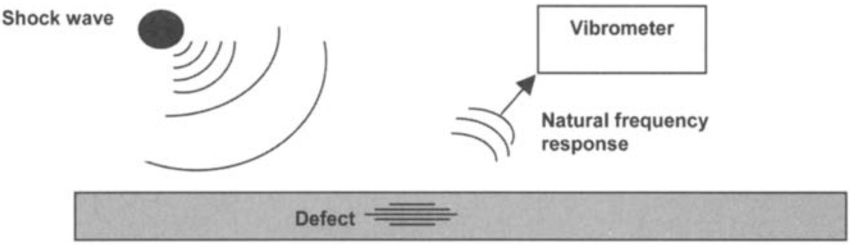

Fig. 11.16 Schematic of acoustic impact method.

that meet the stringent product quality demands of the aerospace industry. The current NDI technologies used in industry employ a combination of automation and hand-held labor. In many instances these technologies are slow, and contribute significant cost to the final product. The continual development of a lower cost, simple and reliable system for detection of defects in all current and future families of advanced composite structures is a main driver in research and development activities in the aerospace industry.

References

[1]"Polymer Matrix Composites", *Military Handbook*, MIL-HDBK-17-ID, U.S. Department of Defense, 1994.

[2]*Quality Control for the Manufacture of Composite Structures*—FAA Advisory Circular, AC 21–26, 1989.

[3]"Composites," *Engineered Materials Handbook*, Vol. 1, ASM International, Materials Park, OH, 1987.

[4]*Annual Book of ASTM Standards*, American Society for Testing and Materials.

[5]Strong, A. B., *Fundamentals of Composites Manufacturing*, SME, Dearborn, MI, 1989.

[6]"Polymer Matrix Composites", *Military Handbook*, MIL-HDBK-17-ID, U.S. Department of Defense, 1994..

[7]*SACMA Recommended Methods (SRM)*, Suppliers of Advanced Composite Materials Association, Arlington VA, 1994.

[8]*Assessment of the State-of-the-Art for Process Monitoring Sensors for Polymer Composites*, U.S. Department of Commerce, NISTIR 4514, 1 June 1991.

[9]Kent, R., "Process Control for Composite Materials," *Comprehensive Composite Materials*, Vol. 2, edited by A. Kelly, C. Zweben, R. Talreja, J. Anders, and E. Manson, Elsevier, 2000.

[10]Mallick, P. K., "Non-Destructive Tests" *Composite Engineering Handbook*, edited by P. K. Mallick, Marcel Dekker, 1997.

[11]Ungarish, R., Joseph, R., Vittoser, J., and Kenig, S., "Cure Cycle Optimization by Dielectric Measurments," *Composites*, Vol. 21, 1990, p. 481.

[12]Ciriscioli, P. R., and Springer, G., "Dielectric Cure Monitoring: A Critical Review," *SAMPE Journal*, Vol. 25, No. 3, May/June 1989, pp. 35–42.

[13]Turner, R. D., Valis, T., Dayle Hogg, W., and Measures, R. M., "Fiber-Optic Strain Sensors for Smart Structures," *Journal of Intelligent Material Systems and Structures*, Vol. 1, 1990, pp. 26–49.

[14]Young, M. A., Druy, W. A., Stevenson, W. A., and Compton, D. A. C., "In-situ Composite Cure Monitoring Using Infrared Transmitting Optical Fibres," *SAMPE Journal*, Vol. 25, No. 2, 1989, pp. 11–15.

[15]Lam, K.-Y., and Afromowitz, M. A., *Applied Optics*, Vol. 34, No. 25, 1995, pp. 5635–5638.

[16]Lam K.-Y., and Afromowitz, M. A., *Applied Optics*, Vol. 34, No. 25, 1995, pp. 5639–5644.

[17]Perry M. J., and Lee, L., "On-Line Cure Monitoring of Epoxy/Carbon Composites Using a Scaling Analysis and a Dual Heat Flux Sensor," *Journal of Composite Materials*, Vol. 26, No. 2, 1992, pp. 274–292.

[18]Fanucci, J. P., Nicolet, S. C., Koppernaes, C., Chou, H.-N., *Thin Disposable Pressure Sensors for Composite Material Process Monitoring*, 35th International SAMPE Symposium, pp. 1205–1219, Apr. 1990.

[19]Hoskin, B. C., and Baker, A. A., *Composite Materials for Aircraft Structures*, AIAA Education Series, AIAA, New York, 1986.

[20]Bar-Cohen, Y., "Emerging NDT Technologies and Challenges at the Beginning of the Third Millennium," Part 1, *Materials Evaluation*, Jan. 2000, pp. 17–30.

[21]Bar-Cohen, Y., "Emerging NDT Technologies and Challenges at the Beginning of the Third Millennium," Part 2, *Materials Evaluation*, Feb. 2000, pp. 141–150.

[22]Green, R. E., "Emerging Technologies for NDE of Aging Aircraft Structures," *Proceedings of the Workshop on Intelligent NDE Sciences for Aging and Futuristic Aircraft*, C. Ferregut, R. Osegueda, and A. Nunez, (Eds.), Univ. of Texas at El Paso, 1997, pp. 267–278.

[23]Grandia, W. A., and Fortunko, C. M., "NDE Applications of Air-coupled Ultrasonic Transducers," *Proceedings of the 1995 IEEE Ultrasonic Symposium*, Vol. 1, 1995, pp. 697–709.

[24]Fiedler, C. J., Ducharme, T., and Kwan, J., "The Laser Ultrasonic Inspection System (LUIS) at the Sacramento Air Logistic Center," *Review of Progress in Quantitative NDE*, Vol. 16, Plenum Press, New York, 1997, pp. 515–522.

[25]Buynak, C., Cordell, T., Golis, M., "Air Force Research Laboratory Program for Nondestructive Testing of Composite Materials," *43rd International SAMPE Symposium*, 1998, pp. 1724–1729.

[26]Oursler, J. D., and Wagner, J. W., "Narrow-Band Hybrid Pulsed Laser/EMAT System for Non-contact Ultrasonic Inspection Using Angled Shear Waves," *Materials Evaluation*, Vol. 53, 1995, pp. 593–559.

[27]Albert, R., Pember, W., Garrison, J., and Reyna, D., "Aircraft Inspection with a Portable, Filmless X-ray System using Reverse Geometry," *Materials Evaluation*, May 2000, pp. 643–645.

[28]Davis, C. K., "Shearographic and Thermographic Non Destructive Evaluation of the Space Shuttle Structure and Thermal Protection Systems (TPS)," *Nondestructive Evaluation of Aging Aircraft, Airports, and Aerospace Hardware, SPIE Proceedings*, edited by R. D. Rempt and A. L. Broz, Vol. 2945, Scottsdale, AZ, 1996, pp. 36–47.

[29]Hamstad, M. A., and Downs, K. S., "On Characterisation and Location of Acoustic Emission Sources in Real Size Composite Structures: A Wavefrom Study," *Journal of Acoustic Emission*, Vol. 13, Nos. 1–2, Jan–Jun 1995, pp. 31–41.

[30]Hamstad, M. A., Whitaker, J. W., and Brosey, W. D., "Correlation of Residual Strength with Acoustic Emission from Impact-Damaged Composite Structures Under Constant Biaxial Load," *Journal of Composite Materials*, Vol. 26, No. 15, 1992, pp. 2307–2328.

[31]Vary, A., "The Acousto-Ultrasonic Approach," *Acousto-Ultrasonics, Theory and Applications*, edited by J. C. Duke, Jr., Plenum Press, 1988.

[32]Vary, A., and Bowles, K. J., "Ultrasonic Evaluation of the Strength of Uni-directional Carbon-Polyimide Composite," NASA TM X–73646, 1979.

[33]Gill, T. J., and Bartos, A. L., "An Acoustic-Ultrasonic Platform for the Quality Assessment of Thick Radial Ply Composite Structures," *Nondestructive Characterisation of Materials VI*, edited by R. E. Green, Jr., K. J. Kozaczek, and C. O. Rudd, Plenum Press, 1994.

[34]Webster, J. M., "Method and Apparatus for Non-Destructive Inspection of Composite Materials and Semi-Monocoque Structures," US Patent No. 505,090, 1996.