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3.12 Inspection and Monitoring of Composite Aircraft Structures

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3.12.1 Introduction

Composite materials are finding many applications across diverse industry sectors because of their unique properties, combining lightweight materials with tailored strength and stiffness to match the application. In principle, composites can be made of any two materials, which together bring an increased structural performance. In reality, composite materials are usually taken to mean polymer composites with directional fiber strengthening and stiffening. For aircraft applications carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) are in common use, together with fiber-metal laminates, such as glass laminate aluminum reinforced epoxy (GLARE), which was developed in the Aerospace Materials Group of Delft University of Technology by Schijve *et al.*¹ Since 2016, I have been Acting Chair of this group under its new name Structural Integrity & Composites. The focus of this chapter will be on the new polymer composite materials that are being introduced in the latest generation of large civil airlines, as these present the current challenges to the composites community in manufacturing, structural design, structural integrity, and inspection and monitoring techniques.

Composites exhibit different manufacturing defects and failure mechanisms to metals, as will be discussed in Sections 3.12.2.3 and 3.12.2.4. Because of different defects and damage mechanisms, the objective of the inspection and monitoring systems for composites can be different to metals, for example, aiming to detect distributed rather than localized damage. A second challenge for measuring composites is their anisotropic properties, which is particularly important when using ultrasonic methods. A further challenge is that composites have different electromagnetic properties compared to metals and techniques, such as eddy current, either do not work at all or need recalibrating. Not all differences are negative, for example, various sensors can be embedded within composite structures during their manufacturing, a process that would not be possible when molten metal is present.

The other differences in the needs of inspection and monitoring derive from the different in-service performance of composite structures. Composite materials demonstrate a larger scatter under mechanical testing. This is considered to be due to a higher variability in manufacturing and the multiple failure mechanisms of composites: matrix cracking, fiber breakage, fiber matrix failure, and delamination. These have implications for both safe life and damage tolerant design. To achieve a safe component, additional weight is added to composites structures to maintain the same safety factor, to compensate for these material variations. In damage tolerant design, both the damage initiation and the damage growth are important. Damage initiation can be considered

in the same way as for safe life structures, but damage growth in composites is more complicated because of their multiple failure modes and brittle behavior. It would be reasonable to state that understanding damage initiation and growth in composites is an ongoing research topic from the point of view of physical models. An alternative approach for prognosis of composite structures is to use stochastic methods, as will be discussed in Section 3.12.5.1.

In the following sections, this chapter will first consider materials and structural elements of composite aircraft and define some of the more common manufacturing defects and in-service damage. This will set the scene for a detailed discussion of non-destructive testing (NDT) and structural health monitoring (SHM) technologies in Sections 3.12.3 and 3.12.4. One of the current challenges in NDT/SHM is the processing of data for better decision making. This will be discussed in Section 3.12.5. Finally the chapter concludes with a summary of the chapter content and some perspectives on the future of inspection and monitoring of composite aircraft structures.

3.12.2 Composite Materials in Aircraft Structures

3.12.2.1 Background

Many developments have been made in the design of aircraft over the years. The Montgolfier brothers, Joseph-Michael and Jacques-Étienne Montgolfier, achieved unmanned flight in Annonay, France with a balloon on June 4th, 1783. This balloon later carried animals in flight on September 19th of the same year, followed by the first manned flight on October 15th, 1783. Another milestone was the first manned flight by a heavier-than-air vehicle by the Wright brothers, Orville and Wilbur Wright, on December 17th, 1903. The structure of the Wright Flyer from 1903 was made of composite materials, such as wood and fabric, together with metal tensioning wires to make a wire braced structure. Wood continued to be an important structural material for aircraft until the late 1940s, by evolving into wooden truss structures, in aircraft, such as the Hughes H-4 Hercules "Spruce Goose." In the following period aluminum became the main structural material, first as part of truss structures, then evolving into skin stiffened structures.

Composite materials found their way back into large aircraft structures in the 1990s through GLARE, a fiber-metal laminate, composed of aluminum and glass fiber, in the 1990s. GLARE is both a lightweight material and also has improved crack growth behavior, compared with aluminum. The current generation of large aircraft with increased polymer composite content became available within the past 10 years, including the Airbus A380, which flew for the first time in 2005, the Boeing 787 in 2009, and the Airbus A350 in 2013. The move toward composite aircraft structures, especially primary structures, is driven by weight reduction, which has the dual benefit of reducing fuel costs and also making a reduced impact on the environment. Both are important as the number of commercial flights continues to increase and also the increasingly competitive business environment, which drives cost reduction for aircraft fleet operators.

Hybrid and composite materials are important to the Dutch aircraft industry, both in the past and the future. GLARE was developed by researchers at Delft University of Technology¹ and new materials have been developed by Bose *et al.*² in the chair Novel Aerospace Materials (NovAM) at TU Delft. Composite prepreg is manufactured by Ten Cate at Nijverdal. Composite aircraft structures and components are manufactured at companies, such as Fokker at Dordrecht and Hoogeveen, at Airborne and KVE Composites Group at the "Old Fokker Factory," in Ypenburg, The Hague and by Dutch Thermoplastic Components (DTC), Almere. Bridging between universities and industry are the National Aerospace Laboratory (NLR) at Amsterdam and Marknesse, and the ThermoPlastic Composites Research Centre (TPRC), Enschede. Composite materials are becoming increasingly important also in maintenance, repair, and operations (MRO). Two important fleet operators in the Netherlands are Air France KLM, based in the Netherlands at the hub airport of Schiphol, Amsterdam, and the Dutch Air Force, with airbases around the country, but with maintenance increasing concentrated at Woensdrecht Airbase in the south of the Netherlands. Smaller maintenance hubs are also present at Lelystad and Maastricht airports. A notable cluster of aerospace activities is in the South Holland Region, the southern part of the Randstad. Together with partners in the space sector including European Space Research and Technology Centre (ESTEC) and European Space Agency (ESA), industry, research institutes and universities have developed the Aero-Space Agenda Zuid-Holland 2016–2025 to address future aerospace challenges, which include the manufacture and maintenance of composite aircraft structures.

The section below further describes the materials, manufacturing, structural elements, and expected damage mechanisms of composite aircraft structures.

3.12.2.2 Composite Aircraft

It is well known that the percentage composition of composite structural materials is increasing in the latest generation of civil aircraft. The A380-800 contains GFRP at the leading edge of the tail, quartz fiber-reinforced polymer (QFRP) at the nose section and CFRP extensively used for the engine pylons, fairing sections at the wing, flaps, and major part of the tail, comprising 25% of total structural weight. Hybrid and metal materials are used for the fuselage and wings. In the Boeing 787, the primary structures of the fuselage and wings are made of CFRP laminate. CFRP sandwich structures are used for part of the tail and the engine pylons. CFRP is used for the fairing sections and nose cone. Aluminum is relegated to potential impact locations at the leading edges of the wings and tail. In total, composites provide 50% of the structural weight of the B787. The Airbus A350 contains 52% composite by

weight. This aircraft also has a CFRP laminate primary structures of fuselage and wings, but also the tail. GFRP is used for the leading edge of the tail and QFRP for the nose, like the A380. Aluminum is again used for the leading edges of the wings, together with the cockpit section, the leading edge of the engines case and the tips of the tail.

This overview of material usage shows that CFRP and GFRP, both laminate and sandwich structures, are the most important structural composite materials in civil aircraft. According to the design philosophy of the airframer, GFRP is used for some potential impact areas by Airbus, whereas Boeing use aluminum. Both companies are using CFRP laminate for primary structures, and increasingly for the other structural components. These materials are assembled into parts and structural elements of the aircraft as described below.

3.12.2.3 Damage Mechanisms of Materials

Structural materials can fail due to exceeding the ultimate stress level or by repeated loading at much lower stress levels, which causes a progressive deterioration of the strength of the material or structural component.

The first is due to a single event, such as a hard landing, impact damage or redistribution of stresses after a structural failure. These events occur in a rapid timeframe and should be managed by a fail-safe philosophy and multiple-load paths, where possible. Events below the ultimate stress level of the material may act as crack initiators that need to be managed by damage tolerant designs, including structural designs to stop cracks propagating. Crack initiation can be considered as starting from a smooth surface, a notch or a defect. At the microscale level, local surface, and volume defects, such as surface scratches, inclusions, and pores act as nucleation sites for the crack formation due to the locally higher stresses. The crack propagation rate is assessed by measuring the crack growth per cyclic load applied to the specimen and is material dependent and must be determined experimentally. The loading regime is defined by the R ratio, the ratio of maximum and minimum loads, with $R = +1$ and $R = -1$ being common parameters used. The loading spectrum may also be based on a realistic loading spectrum, for example, from a typical recorded aircraft loading spectrum during take-off, flight, and on landing.

3.12.2.4 Manufacturing and Product Quality

The starting point for the structural integrity is the quality of the subcomponents that are manufactured, assembled, transported, and installed on the aircraft. For aerospace, well-defined combinations of fiber and matrix are used, together with carefully controlled process parameters and nondestructive inspection (NDI) as a postproduction quality assurance step.

Composite materials are available as separate fiber and polymer matrix components, or as pre-impregnated (prepreg) laminates. Prepreg is also available as prepreg tape with a fixed width, suitable for automated tape layup. These manufacturing processes are briefly described below. Carbon and glass fibers are most commonly used in the aircraft industry. Carbon fibers typically have diameters of 5 to 10 μm and a tensile strength in the range 4000 to 6000 MPa. Glass fibers also have typical diameters in the range 5 to 10 μm and come as two main types, E-glass is the most common with a tensile strain of approximately 3500 MPa and S-glass is used for high strength applications with a tensile strain of about 5000 MPa. Both carbon and glass fibers are made into bundles of hundreds to thousands of fibers, known as tows, which are used to form unidirectional or woven meshes for the manufacture of composites. The matrix material is usually epoxy and gives the composite stiffness in the shear direction. Different formulations are used to adapt to the manufacturing and curing process and to tailor the properties of the final composite. Composite matrices are classified as thermoset, which may only undergo a one-time curing process, and thermoplastics, which melt on the application of heat and may be reformed in processes, such as pressing or welding.

Separate fiber and matrix components are used to manufacture composites using resin transfer molding (RTM). The mold may be as simple as a flat plate or complex shaped. The mold is cleaned, prepared, and the fibers are placed in a defined way to construct a composite with defined strength. The mold and fibers are placed in a vacuum bag and prepared for infusion from a liquid epoxy reservoir. On applying a vacuum, resin is drawn into the vacuum bag and the resin front progresses across the mold until the mold is fully filled with resin. The infusion process is subject to process control monitoring to minimize voids and inclusions. At the end of the infusion process, the composite is cured either at room temperature, in an oven or in an autoclave.

Prepreg offers a more controlled material layup, but with higher cost and less flexibility for highly curved molds. Prepreg is a preformed resin-fiber matrix, that is part cured, but still flexible enough to perform automated or hand layup. It needs to be stored carefully in a freezer, and has a shorter shelf life at room temperature. The material has a well-defined fiber direction, fiber percentage, and thickness and a high quality composite can be achieved during manufacturing. Prepreg is available in sheets, which are supplied as rolls of material with a fixed width. For hand layup an operator can prepare laminates on flat or gently curved molds with well-defined thicknesses and fiber directions. The material is cut to a finished size after curing. Prepreg may also be used to manufacture hybrid laminate materials, for example, by adding glass fiber and aluminum layers in the manufacture of GLARE. Prepreg is also available as prepreg tape with a width of 100 mm, or similar, for automated tape layup. In this case, a robot is used to precisely place the tape in the mold, with careful control of the tape (fiber) direction, overlap, and gaps. Prepreg is cured in an oven or autoclave.

The speed of curing of an epoxy is determined by its chemical composition and temperature. Room temperature curing can be used to cure molds filled by RTM, especially for large structures, however, the process is often somewhat slow. It can be speeded up by placing the composite in an oven or by applying local heating of critical parts of the mold. This is usually in combination with

Table 1 Occurrence of manufacturing defects at aerospace composite manufacturing companies in North-West Europe as a percentage of the number of companies reporting the defect type

Defect type	Percentage of companies reporting defect
Unremoved foil in layup	100%
Incorrect number of layers in layup	60%
Temperature incorrect in curing	
Pressure incorrect in curing	
Fiber bridging/wrinkling in layup	40%
Incorrect overlap in layup	
Anomalies enclosed	
Leakage vacuum in curing	
Delamination in curing	
Incorrect fiber orientation in layup	20%
Too high stress due to incorrect packing in curing	
Leakage due to incorrect packing in curing	
Incorrect autoclave charge in curing	

Source: Reproduced from Miesen, N., Sinke, J., Groves, R.M., *et al.*, 2015. Laser displacement sensing for flaw detection during pre-preg CFRP production. *Journal of Advanced Manufacturing Technology* 82, 341.

the application of vacuum pressure. The effective pressure can be increased by combining an autoclave pressure of 6 bar in combination with a vacuum bag pressure of 1 bar in the autoclave. The autoclave also provides controlled heating for the curing process. After curing, the rate of cooling of the manufactured composite needs to be controlled to reduce the formation of residual stresses. The optimization of the composite layup process, automated tape layup, and the curing process is an active research area in universities and industry. At the end of the manufacturing process, the manufactured composite undergoes NDI to check product quality. If the quality standard is not met, the part would be either reworked or scrapped. Considerable costs are incurred by rework and scrapping of parts, as typically 30% of manufactured parts contain defects. This provides an impetus and opportunity for companies to reduce costs.

The manufacturing process is not finished at the end of the autoclave and inspection process. Thermoplastic composite may be stamp pressed into defined shapes by the application of heat and pressure. Parts may be adhesively bonded or welded into more complex substructures. Also parts are cut to specification size, using, for example, a water jet cutter, and may also be drilled to accept rivets or other fittings. Each of these additional manufacturing process steps must be well-controlled as they have the potential to introduce defects into the product. In some cases the subcomponent is difficult to inspect after this stage, as it can now contain box sections or difficult to access surfaces. There is also the potential to introduce accidental damage into the part, or subcomponent, during transportation, storage, or in the final assembly or during a repair process. Additional NDI checks are in place to cover these damage possibilities.

To conclude the manufacturing section, the most common types of manufacturing defects will be discussed. A market survey at aerospace composite manufacturers, reported in Miesen *et al.*,³ has identified the following occurrence of defects. Results are reported as a percentage of the five companies surveyed that experienced the defect type during hand layup (Table 1). From Table 1, it can be seen that many defect types are common to a number of companies. These defects impose additional costs on the composite manufacturer and for some instances additional in-service costs. For example, delaminations and voids which are below the NDI detection limit, could act as precursors for the initiation and growth of damage in service. The philosophy of damage tolerant design⁴ provides a means to mitigate and minimize these risks.

After considering the materials and the manufacturing processes in a generic way, the next step is to consider the effects of the structural elements of the aircraft in its structural integrity.

3.12.2.5 Aircraft Structural Elements

Damage in aircraft structures is also structural element related. Blade-stiffened structures are strengthened by ribs or stringers and they carry high loads in wings, fuselages, and tail assemblies. Impact is a common damage event for these elements, for example, from hail, tool damage during maintenance and runway debris. These impacts cause delaminations in composite skins, debonding between stiffeners and the panel and edge delaminations. The next level of complexity is a hat-stiffened structure, which can carry high compression loads. Hat-stiffened structures have an enclosed volume, usually placed on the inside of the aircraft. The hat-stiffened structure is like a blade-stiffened structure subject to debonding from the skin, however, with the additional complexity that its volume is totally enclosed and only the external surface can be inspected.

Multi-rib and multi-spar structures combine a relatively thick composite skin with multiple rib, or spar, elements to increase the stiffness of the structure and reduce local buckling. The thick skin offers good resistance to impact, but the bond between ribs/spars and skin is both sensitive to impact and is an essential part of the structural integrity of the subcomponent.

Sandwich constructions are composed of a sandwich material of foam, honeycomb, etc., bonded between two face sheets. They are used for lightweight structures, which require high shear stiffness, for example, flaps, rudders, elevators, and helicopter rotor blades. Sandwich constructions are susceptible to disbonding between the sandwich and face materials, which may be due to impact, moisture ingress, or fatigue loading. Sandwich constructions are difficult to monitor as they need to be assessed from both sides to assess the two face-sandwich bonds.

The other important aspect of a structural element is the joining method used. The conventional method for aircraft is to use rivets to form mechanically fastened joints. They have been studied extensively for metal structures and have been adapted for composite materials. However, this joining method is not ideal for composites due to the compression loading and edge effects involved. Riveting composites causes delaminations and buckling/cracking of both the fiber and the matrix around the holes. Co-curing of composites in the manufacturing phase produces chemically strong joints, which are, however, prone to peel failure and impact failure. Thermoplastics may also be welded to produce polymer-polymer chemical bonds. It is critical to control the welding process parameters, temperature, pressure, and displacement to ensure a good quality weld. It is normal to load these welded joints in shear in the structural element. More recently, adhesive bonding has become prominent as a joining method for aircraft structures. The bonding process is sensitive to surface preparation and cleanliness and failure modes involving kissing bonds and weak bonds have led to caution in the use of adhesive bonding, especially for primary aircraft structures.

Considering the challenges posed by the introduction of defects in the manufacturing process and damage in-service, NDT, and SHM have been developed to address the failure modes present in composite aircraft structures. These are a combination of adaptations and improvement of techniques used for metal aircraft and new technologies that have been developed recently. NDT is discussed in Section 3.12.3 of this chapter and SHM in Section 3.12.4.

3.12.3 NDT Techniques

Some elements of the NDI techniques of today date back to the first aircraft manufactured. Visual inspection was used to check all components were in place, to check for cracks, and splits in wood and canvas and that mountings and joints were secure. Other human senses were also used. The engine health would be checked from the sounds it makes, for excessive vibrations also by sound but also visually and by touch, the warming up of the engine possibly by touch and the combustion checked by smell and the presence of smoke.

The focus of Section 3.12.3 describes the principles of the main NDT methods used for assessing composite aircraft.

3.12.3.1 Manual Inspection Methods

Manual inspection covers all the inspection techniques that rely on the senses of the NDT inspector, including working with simple tools. The first technique is visual inspection. On approaching the aircraft, the inspector will look for something unusual, for example, a missing or displaced part. The inspector will then follow a detailed checklist including visual inspection of geometry, including using simple measuring tools. The inspector will also look for color changes that could indicate overheating or chemical contamination, and will tap or press on parts to ensure they are securely fixed. Tools, such as lamps and endoscopes, are used to inspect internal parts. Of particular interest for composite aircraft are impacts that cause barely visible impact damage (BVID). Impacts on a metal component at sufficient energy to cause damage can be seen by the naked eye and surface irregularities can be confirmed by touch. For composites the inspector has to look very closely indeed at the surface for the presence of an impact on a composite structure, which has created delamination and cracking at the below surface layers. To address this, it becomes more important to use instrumentation based methods for composite aircraft. On the positive side, heat damage to the structure is more visibly apparent for composites than metals.

3.12.3.2 Ultrasonic NDT Methods

Ultrasonic waves are acoustic waves with a frequency above 20 kHz, that propagate in solids, liquids and for short distances in gases. For NDT, low-frequency (LF) ultrasonic waves have frequencies in the range 20 to 1000 kHz and high-frequency (HF) ultrasonic waves are in the range from 1 MHz upwards. LF-ultrasonic waves are mainly used in bond testers and for the guided wave and acoustic emission (AE) sensing in SHM, described in Section 3.12.4. This section will focus on ultrasonic waves in the 1 to 10 MHz range, that are used for A-scan, C-scan, and phased-array testing. It will also consider the Fokker bond tester, used for testing at lower frequencies.

In a solid, ultrasonic waves propagate as longitudinal and shear waves and in liquid only the longitudinal wave is present. Defects are detected by reflections and scattering at acoustic impedance boundaries. Other acoustic properties of the material may also be used as indications of damage, for example, wave velocity and attenuation. The position of defects may be determined from the time-of-flight of the wave, typically using the backwall echo as a reference time signal to determine the defect depth. In the pulse-echo method the same transducer is used to both send and receive the ultrasonic signal. In the pitch-catch method, one

transducer sends the signal and a second transducer detects the signal. Ultrasonic signals can be visualized in different ways. In an A-scan the signal intensity is plotted against time to give a depth scan at a single point. Strong reflections from defects or delaminations are indicated by a higher signal intensity. A B-scan is a cross-sectional view of the material, constructed from a line of A-scan measurements. Usually the horizontal axis represents the position on the line scan, the vertical axis is time and the signal intensity is coded as color. It should be noted that the time axis in an A- or B-scan only represents distance when the ultrasonic wave velocity is constant. In a C-scan the material is viewed from the surface, with x and y positions representing sensor position and color coding used to represent attenuation or average signal intensity. Regions with defects or damage are indicated by a different color. The common types of ultrasonic NDT are described below.

Handheld ultrasonic instruments typically record A-scan signals using a pulse-echo method. The NDT inspector selects the location to measure and a suitable probe frequency. The probe frequency is usually 5 MHz, but 1, 2.5, and 10 MHz probes may be selected if they give a better response. A viscous, nontoxic liquid couplant is applied to the test surface to provide a good coupling between the ultrasonic probe and the structure under test. The transducer is pulsed to give an ultrasonic signal with constrained time and frequency bands, for example, using a five-cycle Hann window. The time resolved amplitude of the return signal is detected by the transducer and is displayed as an A-scan. From the A-scan signal the backwall echo is usually detectable and damages and defects are identified by reflections at depths that do not correspond with the geometry of the object. In particular, a delamination will give a strong reflection as the material–air interface present has a high acoustic impedance mismatch. The A-scan signal is often compared with adjacent regions by moving the probe on the surface and some instruments also display a B-scan signal, showing color-coded reflection amplitudes by depth along the line scanned by the probe. This provides additional information for the NDT inspector as a single measurement can be compared with adjacent positions for differences, which may represent damages or material, or geometry, variations.

Ultrasonic C-scan is used for through-transmission measurement of aerospace panels using a pitch-catch method. In the C-scan method, the ultrasound emitter is positioned on one side of the panel and the ultrasound receiver on the other, and they are moved in synchronization with each other to scan the panel. The ultrasonic wave travels from the emitter through a water jet couplant to the panel, passes through the thickness of the panel, and is then coupled to the receiver by a second water jet. It may also be used with the composite panel submerged in a water tank, if it is determined that water ingress does not pose a risk to the structural integrity of the panel. C-scan is effective for NDT of composites as it measures attenuation losses due to common manufacturing defects, such as voids and delaminations. It also gives some information on fiber direction, however, not in a depth resolved way through the thickness of the panel. The ultrasonic C-scan apparatus is typically large and expensive due to the needed automation and provision must be made to contain the water used in the process. The spatial resolution is determined by the water jet diameter, but may be increased by a factor of 2–3 by superresolution techniques. Another downside is that the defects are not measured in a depth resolved way, so further testing with an ultrasonic A-scan is used to determine the layer where the defect occurred.

Phased-array ultrasound testing (PAUT) is an advanced ultrasonic technique based on an array of transducers, which can be pulsed independently to emit ultrasonic waves and which can also individually detect ultrasonic waves. A PAUT probe can operate in A-scan or B-scan modes, or a pair of probes can operate in C-scan mode, as described above. A PAUT instrument can operate in two basic modes: full matrix capture (FMC) and phased-array mode. In the FMC method, the individual elements are pulsed individually and recorded in a time resolved way at each element, for example, a 32-element-probe would send 32 signals and record 1024 (32^2) signals. This technique is essentially based on post-processing of the ultrasonic signals. It is theoretically possible to reconstruct the maximum amount of information from the test structure by processing this data cube using beam propagation and material models. This is a topic of current interest for research, especially for composite materials, where the modeling of wave propagation in anisotropic layered material is not simple. In the medium term (5 to 10 years), this approach is considered the most promising. The alternative operating mode is the true phased-array mode. In this approach, multiple transducer elements are pulsed simultaneously to generate a specific wave shape and direction. For example, pulsing all elements simultaneously generates a plane wave, applying a pulsing delay from the edge to the center of the array generates a focussed beam and conversely a pulsing delay from the center to the edge of the array generates an expanded beam. Further introducing a delay from one side of the array to the other generates a steered beam, which may be used to investigate defects under a rib, stringer, or other joint. The main advantage of PAUT methods is a better resolution of imaging defects in three-dimensional (3D), with a disadvantage of complex processing for the FMC method and complex measurement setup for the phase-array setup. The FMC has theoretically the best measurement resolution, however, the phase-array method is more intuitive to use and for thick composites the increased ultrasonic wave energy by pulsing multiple elements, especially when generating a focussed beam, can lead to better depth penetration and increased signal-to-noise ratio (SNR).

Bond testers are an advanced form of *tap testing* that operate at ultrasonic frequencies. They have several standard operating modes, including pitch-catch mode, resonance frequency mode, and mechanical impedance (MIA) mode. In pitch-catch mode an ultrasonic wave is sent along the surface of the specimen to a receiving transducer. Signal processing is performed by analyzing changes in signal amplitude or phase at different locations on the surface. The pitch-catch mode may be extended by using the impulse method, exciting the structure with a short time broadband pulse or the swept method, where the object is sequentially excited at frequencies across the range 5 to 100 kHz. In resonance frequency mode, a narrowband ultrasonic source is used to generate standing waves through the thickness of the sample, in the frequency range 35 to 500 kHz. Disbonds cause a frequency shift or a change in signal phase. In MIA mode, lower frequencies in the range 4 to 30 kHz are used to investigate local stiffness variations. The received signal amplitude and phase is different at locations where a disbond is present. Previously signals from

bond testers have been difficult to interpret for the user. This is changing as analysis and display software becomes more advanced, in instruments, such as the Olympus Bondmaster 600 and the NDT Systems Bondascope 3100.

3.12.3.3 Optical NDT Methods

Optical NDT methods typically measure surface parameters in a noncontact and/or noninvasive way. Laser shearography is a method to measure surface and subsurface damage in structures using interferometry. There are several techniques available to perform laser profilometry, including photogrammetry, fringe projection, and laser displacement sensors. These techniques are described below.

Shearography, described by Steinchen and Yang⁵ and Francis *et al.*,⁶ is a full-field optical technique that is used to detect anomalies in surface deformations when loading of the object. The instrument consists of a laser light source, optics to expand the beam to illuminate the object surface, imaging optics, a shearing interferometer, and a camera. The instrument may contain a loading device based on pressure, heat, or acoustic excitation, or may use an external loading source, for example, mechanical. To perform a measurement, a reference shearogram is recorded and this is compared in the image processing software with a shearogram recorded after loading. Image processing is further used to perform phase unwrapping of the images, image filtering, and to apply false colors for display. Advanced calibration and signal processing in multi-camera shearography has been performed by Anisimov *et al.*⁷ to yield strain maps of the object surface. For NDT applications, a qualitative image showing the distribution of the strain field is sufficient to identify surface and subsurface anomalies. Commercial systems are available including the Q-810 from Dantec Dynamics GmbH, Shearography-NDT-ISIS from Carl Zeiss Optotechnik GmbH, and the Shearography SE System from Isi-sys GmbH.

In photogrammetry, shape measurement is performed by differences in perspective distortion from a system of two, or more, well-calibrated cameras. Note in this case the geometric properties of the cameras are calibrated, not the photometric properties. This calibration is commonly performed using Zhang's method,⁸ often with the camera calibration toolbox of Bouguet⁹ or the four-step camera calibration procedure with implicit image correction of Heikkila and Silvén.¹⁰ Zhang's method uses calibration targets of known dimension placed at various positions within the field of view. The calibration yields intrinsic and extrinsic camera parameters. The intrinsic parameters define the properties of each individual camera and its imaging system, focal length, image sensor dimensions, and the principal point of the imaging system. The extrinsic parameters contain the relationship between the coordinate system of the camera and that of the object, and encompass translation, rotation, and scaling. In photogrammetry, it is common to use cameras with multiple megapixels to achieve a good accuracy measurement. Photogrammetry has a surprisingly good accuracy, from 10 μm in the height direction for centimeter size objects, scaling with size for larger objects. Some objects have uncooperative surfaces which are too smooth, reflective or semitransparent and in this case measurement accuracy is decreased.

An extension of photogrammetry is fringe projection. In this technique, fringes are projected onto the object, most commonly nowadays by a digital light projector (DLP). To use this method, the projector must also be calibrated as part of the multi-camera system, usually using the approach of considering the projector as an *inverse* camera. The fringes projected onto the object are recorded by one, or more, cameras and processed digitally. A single linear fringe pattern containing a spatial carrier can be processed using a Fourier transform, or other frequency-based methods as described by Kujawinska¹¹ and unwrapped to yield a height map. Alternatively, phase-shifting methods as described by Creath¹² can be used, projecting a series of phase-shifted fringes onto the object and combining the images using a phase-shifting algorithm to generate a wrapped phase map, which can be unwrapped to yield the height map. There are several methods available to improve the measurement accuracy. Additional height maps can be generated by using multiple cameras and height maps with different height resolution can be generated by projecting fringes with a different spatial frequency. The latter is particularly important when the object contains step changes in height, which may not be resolved correctly by fringes with a high spatial frequency.

Laser profilometry sensors to measure height were reviewed by Berkovic and Shafir¹³ and use either the interferometry or triangulation principle. In the triangulation method, a laser line is projected onto the surface and the reflected signal is recorded using a 2D-array sensor. Based on the known angle of illumination and the distance from the laser source to the detected signal on the array the object height at different positions along the laser line can be measured. Commercial sensors, such as those from Micro Epsilon, are designed for a specific working distance and accuracy range. Typical working distances are 8 to 100 mm and height accuracies up to 2 μm can be achieved. To measure a 3D-field, the line-scan sensor needs to be moved relative to the object, either by moving the sensor, or by moving the object, for example, on a production line. Also for close to vertical surfaces, some parts of the sensor height may fall into shadow and cannot be measured.

In summary, the various height measurement techniques are able to measure surface height and can be used to precisely measure component shape, gaps, and overlap during automated tape layup and the measure the size and shape of surface damage.

3.12.4 SHM

Boller¹⁴ states that "Structural Health Monitoring (SHM) is the integration of sensing and possibly also actuation devices to allow the loading and damaging conditions of a structure to be recorded, analysed, localized, and predicted in a way that nondestructive testing (NDT) becomes an integral part of the structure and a material." This is further explained by considering SHM to be composed of a number of different functionalities, defined as levels:

- SHM level 1 is online load monitoring, which is the detection of loads that exceed the design capability of the structure and possibly the quantification of the load and/or environmental parameters. This level is used to identify that the structure is operating within its design space.
- SHM level 2 is the detection and localization of the existence of damage in a structure. The detection of damage is aimed at finding damages that exceed a design specification for allowable damage. The purpose of the localization of damage is to guide an NDT inspector to the damaged part of the structure for a more detailed inspection using handheld NDT equipment. A localization accuracy of centimeters would normally be sufficient.
- SHM level 3 is the quantification of the size and type of damage, for the purpose of assessing the severity of the damage to the structure. The damage severity may be determined either online or offline using analytical or numerical models.
- SHM level 4 is the prediction of remaining life of the structure. This is intimately linked with damage growth and/or stochastic models. The predicted life determined is used to assess if the aircraft can complete its current flight plan and to future schedule maintenance intervals, without any danger or failure.

It should be remembered that a post-manufactured composite structure or component already contains defects at a sufficiently low level to pass the quality control checks at the end of production. These are often the precursors for the damage that grows during the lifetime of the structure. There may also be damage that occurs during handling, assembly, transportation, and storage that contributes to the damage state of the structure at the start of its operation. The assessment of damage at the start of the life of the structure is sometimes known as SHM level 0, and this information can form an important part of an effective and efficient SHM strategy.

SHM technologies are a combination of NDT techniques developed further for in situ monitoring and new technologies, such as optical fiber sensors, which show a high potential for SHM. They are in general complementary to NDT, providing additional measurement capability and adapted to in-flight operation, however, this line is becoming blurred.

3.12.4.1 Passive Acoustic Sensing

Structures subjected to damaging loading levels emit acoustic signals from the local damage events occurring within the structure. This effect is well-known as the cracking sounds that can be heard when a structure is overloaded. In reality these acoustic signals extend beyond the audio region and typically extend up to about 500 kHz in the ultrasonic range. AE systems take advantage of this effect to determine the onset of damage and long term AE monitoring can be used to assess the severity of damage by the number of damage events. An AE system is composed of acoustic transducers, preamplifiers, electronic or digital signal thresholding, and data logging capability. In simple terms the acoustic wave emitted by a damage event propagates through the structure and is recorded by the transducer, which is usually a piezoelectric transducer (PZT). The signal typically has a low signal amplitude and is then amplified by 20, 40, or 60 dB by a preamplifier. The preamplifier may be enclosed within the transducer housing or may be a separate component. Signal thresholding can be either an analogue electronic or digital operation. Its function is to exclude low amplitude signals from the data logging to reduce the data set size and to exclude signals, which contain only noise. Data is logged by single and multi-channel AE systems and stored to disk for later processing.

The recorded signals are amplitude (voltage) signals as a function of time. Additional metadata may be stored with these acoustic signals, including start of recording time, strain gage readings, and load and displacement readings for a testing machine. Preprocessing is used to exclude outlier data, for example, based on their energy, amplitude, or duration features. The voltage-time traces can be transformed to frequency, phase, or energy for further processing. Recently, wavelets and other transforms have been explored for signature analysis, to investigate the relationship between AE signals and damage mechanisms, such as fiber breakage, fiber matrix debonding, and delamination. Processing of AE signals is currently an active research topic with many different approaches employed, including stochastic methods, classifications based on support vector machines (SVM) and neural networks.

3.12.4.2 Active Acoustic Sensing

Ultrasonic-guided waves are LF-ultrasonic waves (frequency range 20 kHz to 1 MHz), which propagate greater distances in a structure than the HF ultrasound traditionally used for NDT. LF-ultrasound waves in particular are of interest in plate-like structures where they propagate as Lamb waves with well-defined velocities and modes. Lamb waves are sensitive to changes in the aircraft structure and analysis of frequencies, time-of-flight, phase, and amplitude reveals changes in the structure. LF-ultrasonic technologies can be used in both passive and active configurations, described below. Lamb wave ultrasonic sensing uses a transducer to send an ultrasonic signal of known frequency and waveform shape to investigate the condition of the structure.¹⁵ Recent studies by Ochoa *et al.*¹⁶ show that Lamb waves have an equivalent sensitivity to BVID to C-scan. Lamb wave sensing evaluates the condition of the structure at the time of measurement and does not need to be active at the moment the damage occurs. Guided Lamb wave monitoring shares some hardware with AE and many hardware components are in commercial production.

Several alternative approaches for signal processing of ultrasonic waves in SHM are given below. The techniques described are time reversal Lamb waves, fidelity, and Akaike information criterion (AIC) signal processing. In the classical application of Lamb waves for damage detection, the behavior of the wave on the undamaged structure is first captured, in order to obtain a baseline response.

In presence of damage in the structure, the Lamb wave behavior changes, thus providing a different response for the same actuation signal. The time reversal technique does not require a baseline of the signal, since the actuation signal is compared to its own time reversal in each interrogation process. The simplest time reversal process consists of the comparison of the time-reversed Lamb wave signal, with the original sent signal. The modified time reversal method (MTRM) consists of one transducer acting as actuator and another four as sensors. The signal received at each sensor is time-reversed and then sent, not from the position of the sensor, but from the original actuator. MTRM using a single transducer was investigated by Barosso Romero *et al.*¹⁷ To compare the undamaged Lamb wave signal with the damaged signal, Pelt *et al.*¹⁸ used the energy method ultrasound verification (USV). Two signals are compared with fidelity, in which cross-correlation is divided by autocorrelation. This results in a number between 0 and 1 and is therefore dimensionless. The second method to compare signals is based on the difference in energy of the signal. Further options are available for studying Lamb waves, including the AIC algorithm, used by Miesen *et al.*¹⁹ to determine time-of-flight of the Lamb wave modes. Further options are median filtering with bias correction, Hilbert transforms to determine the shape of ultrasonic wavepacket envelopes and phase analysis to assess damage and mode conversion.

3.12.4.3 Fiber Optic Sensing

Fiber optic sensors are sensors which transmit, receive, or sense light. Common types are fiber Bragg gratings (FBGs), Fabry–Pérot interferometers (FPI), and distributed sensors fiber optic sensors. These sensors can be used for strain measurement, load monitoring, temperature monitoring (e.g., in fire detection systems), and LF-acoustic wave detection. All sensor types have multi-point sensing capability within a single optical fiber. FBG sensors are composed of periodic modulations in the refractive index of the fiber, which change in period, and hence reflected wavelength, due to a change in strain or temperature, according to a predefined calibration performed by the grating manufacturer. Monitoring of the change in reflected wavelength allows the strain or temperature to be determined. Up to 50 sensors can be multiplexed in a single optical fiber. In a Fabry–Pérot sensor there are two mirrors at each end of the sensing section. Light is partially reflected and the phase and amplitude change due to interference in the cavity when the distance between the mirrors changes. This spacing between the mirrors is dependent on physical phenomena, such as strain and temperature, which can be sensed with high accuracy. Commercial instruments are available for both techniques and are being flight tested by some manufacturers.

Distributed sensing relies on the scattering of the light in the optical fiber, based on Rayleigh, Brillouin, and Raman scattering. Rayleigh scattering occurs due to inhomogeneities created during the manufacturing of the optical fiber. The density and composition fluctuations of the fiber form an unique key for identification. With a narrow pulse the variation in Rayleigh backscatter can determine an approximate spatial location, enabling it to be used for fault location, loss measurement, and distributed sensing of temperature and strain, over a 70 m length. Brillouin scattering arises due to acoustic wave interaction between inhomogeneities and light. Satisfying the conservation of energy law, the frequency shift between the original light pulse frequency and the Brillouin scattering wave is measured. It consists of the Stokes and anti-Stokes components. This frequency shift is sensitive to strain and temperature enabling the use of Brillouin scattering as a sensor. The range goes up to 50 km, with range extenders giving a range of 150 km. The strain resolution is 10 microstrain, while the temperature resolution is 0.5°C. Raman scattering is also a nonlinear process. The main drawback with Raman scattering is the fact that it can only give an absolute temperature indication. There is also a low SNR, which can make interrogation challenging. Commercial instruments have become available in the past few years, however, most applications are in the oil and gas industry.

3.12.4.4 Electromagnetic Sensing

Electromagnetic parameters can also be used for damage detection in structure. For application in SHM, the eddy current technique, which uses magnetic fields to induce eddy currents, is suitable, but limited to conductive materials, such as metals or CFRP. The physical principle of eddy current sensing is based on the Lorentz force law. A time-varying current in a coil with a certain frequency creates a time-varying magnetic field and this field induces an eddy current in the material with a pattern that follows the coil geometry. The presence of a flaw (e.g., crack, inclusion, and porosity) induces a local difference in the electromagnetic properties of the material. The HELP-layer system developed by Lemistre²⁰ is composed of an eddy current inducing network and a sensing network. This approach was extended by Goldfine *et al.*²¹ who developed an array of eddy current sensors to broaden the coverage area. Their meandering winding magnetometer (MWM) device was demonstrated for a study of the fatigue behavior around bolt-holes. In addition to that, they reported that corrosion and temperature monitoring with MWM was possible.

3.12.4.5 Smart Materials

Piezoelectric materials are smart materials, well suited as sensors in many applications, such as vibration monitoring, impact detection, and ultrasonic receiving sensors. Piezoelectric composites consisting of a particulate piezoelectric ceramic phase randomly dispersed within a polymer matrix are candidates for integrated sensors in structural composites. Carbon nanotubes (CNT) have also shown a potential for sensing and monitoring the health of structures. CNT networks are piezoresistive, meaning that at low strains, below any damage threshold, changes in electrical resistance can be directly related to changes in strain. Different forms of CNT materials have successfully been evaluated for this purpose including: CNT film layer-by-layer (LbL) assembly of

CNT and CNT fibers. The formation and propagation of matrix cracks and delamination will disrupt these networks and will manifest themselves via a monotonic increase in the overall volumetric resistance.

3.12.5 Data Processing

This section gives an overview of the data processing methods used for NDT and SHM sensors. Recently, there has been a great increase in interest in smart use of data under the “big data” banner. Three of the main approaches for processing of NDT and SHM data are described below.

3.12.5.1 Stochastic Analysis

Following reliable assessment of the current condition of the structure, a risk-informed approach to predict remaining service life is desired. The amount of degradation as a result of a certain damage mechanism is dependent on a number of factors including environmental conditions, geometry of the structure, material properties, and loading conditions. As part of a prognosis framework, Eleftheroglou *et al.*²² demonstrated that the remaining fatigue life of composite materials can be estimated using strain data and stochastic modeling. Together with a knowledge of the amount of damage present and the expected loading conditions, the cumulative degradation of the structure over a number of flights can be estimated. The described approach necessarily includes uncertainties, and one important role of SHM is to provide an improved estimation of the true amount of degradation taking place in the monitored structure. This can be used to update the results of an idealized model reducing the uncertainty associated with it, which in turn increases the reliability of the predictions.

3.12.5.2 Physics-Based Models

Finite element (FE) methods are based on Hamilton's principle, which states that the motion of the system within a certain interval vanishes under infinitesimal variations of the displacements. See the work of Cerniglia *et al.*²³ and Duczek *et al.*²⁴ for example, in NDT/SHM. This motion is formulated as a Lagrangian function in the volumetric integral area (Ω), and describes the difference between the kinetic energy, elastic strain energy, and external work in both Ω and surficial integral area (Γ). To numerically solve this partial differential equation, the geometry involved is divided into mesh elements over which the equation can be approximated, as explained by Zienkiewicz *et al.*²⁵ and Wriggers.²⁶ The mesh element is a spatial discrete representation of the geometry. For a 3D problem, there are four element types: prism, pyramid, tetrahedron, and brick. In commercial FE software, there are two polynomial approximation methods: linear ($p=1$) and quadratic ($p=2$). Both determine the number of nodes in each element type. To reach a better calculation result, the mesh can be refined by decreasing the distance between each node so that the size of the mesh element becomes smaller and thus increasing the required number of elements to cover the whole geometry. This is called h -type refinement, where h signifies the mesh element size. Gopalakrishnan *et al.*²⁷ demonstrate p -type refinement, which in contrast to h -type, focuses on higher order p -polynomial approximation, such as cubic ($p=3$) and quartic ($p=4$). Higher order p -type refined FE is also called spectral element (SE) or p -FE. The p -FE method for Lamb wave propagation was investigated in detail by Pahlavan²⁸ in his PhD Thesis. Besides spatial discretization, time discretization is needed to model Lamb waves. The minimum requirement to ensure numerical stability of the time integration is the Courant–Friedrich–Lewy (CFL) condition, demonstrated by Duczek *et al.*²⁴ The CFL condition stipulates that the wave should not travel more than one element width h in single time increment Δt_{CFL} . For the Newmark time integrator, the recommended time step Δt_{rec} is 20 increments per cycle of the maximum frequency f_{max} so that solutions can be calculated in efficient manner, as demonstrated by Cerniglia *et al.*²³ for ultrasound in the MHz frequency range.

3.12.5.3 Machine Learning

With a wider perspective, principal component analysis and artificial neural networks (ANN) can be used to classify (processed) signals, to assist in decision making with SHM systems. This algorithms described typically need to be tuned for the application. The origin of ANN comes from the work of McCulloch and Pitts.²⁹ They recognized that combining together many simple artificial neurons was a potential source of increased computational power. Accordingly, this modeling is called McCulloch–Pitts Neuron. These “artificial” neurons were connected to other neurons by directed weighted paths, which are then termed as “inputs.” To decide whether the sum of all inputs is normal or abnormal, Tarassenko *et al.*³⁰ describe a novelty threshold β that can be defined using the unconditional probability distribution $p(x) < \beta$. As $p(x)$ is a distribution function, it is necessary to integrate it to give the cumulative probability $P(x)$. The inputs traveling through the directed weighted paths are then summed to activate this neuron model.

3.12.6 Perspectives and Challenges

NDT techniques are in general well developed and the main research and development focus is on improving usability, portability, and in the case of PAUT, measurement resolution. For AE the specific challenges are noise reduction, damage classification, robustness of the classification, false positives. Active Lamb wave sensing is used to monitor the general health of the structure and

can be used to detect preexisting damage in an unloaded structure on the tarmac. The specific challenges for Lamb wave sensing are optimization of the sensor location with respect to detection capability, damage classification, and modeling wave propagation in complex structural elements. Fiber optic sensing can be used for strain and load monitoring. The main challenges are the embedding of fiber optics and fiber optic connectors, resolving 3D-strain components and reducing cross sensitivities to strain parameters.

3.12.6.1 Raising the Technology Readiness Level of SHM

Together the three SHM techniques allow detection of damage in real-time damage, post-event damage monitoring and strain/load monitoring. Final selection is based on the monitoring needs of the structure. To raise the technology readiness level (TRL) level, the challenges are sensor and cabling integration in the composite structure (embedded or surface mounted), developing robust manufacturing processes, design for high levels of sensor reliability or design for possibility for repair, and on-board/ in-flight processing capability. AE is very sensitive to damage and therefore is capable of generating large amounts of data. However, proper filtering reduces data rates to manageable levels when damage events, such as delamination growth or impact are not present. AE sensors, particular, generate large amounts of potentially useful data for maintenance. Integration with maintenance procedures must be considered. How is the data downloaded and interpreted to be useful for the NDT technician? Smart algorithms to reduce the computing/processing power are needed.

3.12.7 Conclusions

In conclusion, aerospace composite materials provide many challenges for NDT and SHM techniques. They are susceptible to the presence of defects during the manufacturing process due to the rapid development in manufacturing technologies and methods and due to the inherent anisotropic behavior of a combination of fibers and epoxies. Composites exhibit different failure mechanisms to metals and in particular BVID makes them challenging for NDT inspection. Also new NDT methods need to be developed to inspect anisotropic materials. This drives the inspection technology toward SHM. SHM provides additional inspection data, which needs to be processed by advanced data processing methods, such as stochastic analysis, physics-based models and machine learning. It also needs to be mentioned that the objectives for NDT and SHM to inspect aerospace composite materials have already been set by the needs of the latest generation of composite aircraft, the A380, B787, and A350, which are already in service and require more efficient inspection techniques to support them through their lifetime.

See also: 3.1 Certification and Compliance Considerations for Aircraft Products with Composite Materials. 3.2 Scaling Crucial to Integrated Product Development of Composite Airframe Structures. 3.3 The Impact of Large Integrated and Bonded Composite Structures on Future Military Transport Aircraft. 3.5 Design, Manufacture and Test of Cryotank Components. 3.9 Lessons Learned on Supportability and Repair of Composites. 3.15 Composite Applications for Ground Transportation

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Further Reading

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