Inspection of Composites – Current Status and Challenges

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Abstract. The common inspection needs for composite structures and the currently available solutions are reviewed. A continuing problem with composites inspection is the need to cover large areas of structure. This has been addressed with laser ultrasound, thermography and holography/shearography and the pros and cons of these approaches are addressed, together with recent work on sonic-IR (sometimes called thermosonics) that has shown advantages for some types of defect. There is also much current interest in the use of Structural Health Monitoring (SHM) on composite structures and the challenges of producing a reliable system are briefly discussed.

Introduction

The nondestructive testing of composite laminates becomes more important and demanding as composite materials are increasingly used in safety critical applications, such as aircraft primary structures. Conventional NDE of composite materials by ultrasonic techniques such as the C-scan usually uses waves propagating normal to the surface of the laminate, the area under interrogation at any instant being limited to the region covered by the transducer. This type of point testing is very time consuming for the inspection of large plate-like structures since the transducer must be scanned over the whole area to be tested. In practice, composite laminates are often damage tolerant and it is frequently only necessary to find relatively large defects, for example 10 - 20 mm diameter delaminations. There is therefore a need to develop a testing technique which will detect defects of this type quickly and reliably; if a defect is found, conventional methods may, if necessary, then be used to characterise it in detail.

Commercial availability is an important consideration when reviewing potential techniques since there are a large number of methods which could in principle detect the relatively large defect sizes which it is necessary to find, but the engineering effort and expense to convert them from laboratory systems into robust, reliable field units is considerable.

The most promising techniques that meet the required specifications and are commercially available as fully engineered systems are transient thermography, shearography and laser ultrasonics. This paper reviews these methods and also discusses thermosonics (sometimes termed Sonic-IR) that has advantages over conventional transient thermography for deep defects in thick composites. There is also a great deal of interest in structural health monitoring of composites and this is discussed. Part of the paper is an updated version of an earlier review article [1].

Transient Thermography

Transient thermography was originally developed at the National NDT Centre at Harwell, UK [2-3] and has since been developed commercially, particularly by Thermal Wave Imaging in USA [4]. The technique is based on the effects that occur when a material is subjected to a rapid pulse of heat on one of its external surfaces. Initially, the heat pulse causes the surface temperature to be raised, and shortly afterwards the surface begins to cool as the heat pulse diffuses into the material. Thus the process can be viewed as a 'wavefront' of heat that flows from the exposed surface into the material.

For a perfectly homogeneous material, the 'wavefront' of heat passes through uniformly. However, where there are defects such as delaminations, these create a higher thermal impedance to the passage of the 'wavefront'. Physically, when the defects are close to the surface, they restrict the cooling rate due to the diffusion process, so producing 'hot spots'. When the surface is viewed by a thermal imager, temperature differences arising from the presence of the defect appear shortly after the deposition of the heat pulse. Similarly, on the opposite side of the structure, the defect appears as a 'cold spot' because the defect impedes the passage of heat to this surface. These effects are shown schematically in Fig 1.

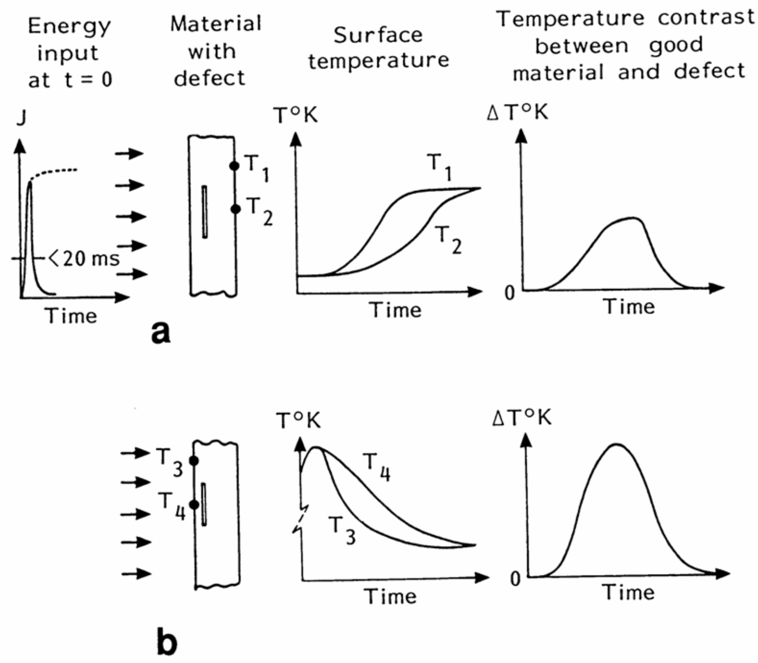

Fig 1. Schematic representation of the transient thermography method (a) through transmission (double sided); (b) reflection (single sided). (after [1,3])

The temperature rise on the heated surface is governed by the amount of energy deposited and the speed of application, combined with the thermal properties of the surface material. However, from this point on, provided that the pulse is short enough, the ensuing diffusion process is totally controlled by the material itself. The contrast observed at either surface due to the presence of defects is a function of the defect size, its depth from the observed surface, the initial surface temperature rise and the thermal properties of the material. While these parameters change from one specimen to another, the testing technique is always to record the temperature variation of either surface directly after the thermal transient has been applied. The contrast due to the presence of defects may be seen over timescales ranging from sub-millisecond to several seconds depending on the material properties and thickness. In many applications, the useful information is obtained within 500 ms so it is necessary to use a system which can acquire many sequential images over this time window.

The equipment required to perform transient thermography falls into two separate areas: the heat source and the thermal imaging/analysis system. The source of heat must have a sufficiently fast rise time to provide a rapid temperature rise since it is the steepness of the temperature gradient that provides the contrast between defective and non-defective areas. In metals and carbon composites, this rapid temperature rise can conveniently be provided by discharging several kilojoules of energy from a bank of capacitors through Xenon flash tubes which are directed at the area of interest. When poor conductors such as glass fibre composites are to be inspected, the rate of heating produced by hot air blowers is frequently adequate.

Major strides in the thermal imaging equipment have been made in recent years. The early work on the method was done using a thermal imaging camera whose output was recorded on video tape, the analysis being performed on the recorded image using slow motion replay and freeze frame facilities. (The technique was once called pulse video thermography [3].) Quantitative analysis could then be performed by using line stripping to access particular lines of thermal data from the image. However, the equipment required was bulky, and considerable care was required in the analysis of the images, which made it difficult to apply the method outside the laboratory. Now, however, the thermal images can be digitised in real time. This makes reviewing of the data much more rapid than was possible previously, and also facilitates the use of data processing to identify anomalies in the temperature-time curves [5,6]. The equipment required is much more compact than that which was used previously and represents a major step forward towards field application.

In general, the sensitivity of the method is reduced as the depth of the defect from the surface monitored by the thermal imaging camera is increased. Quek and Almond [6] have investigated the sensitivity of the technique as a function of depth in carbon fibre composites and Almond et al [7] report the results of a round-robin survey of thermographic inspection techniques.

The sensitivity is best expressed as the defect diameter/depth ratio required for the defect to be detectable. This sensitivity is material specific and must be determined practically using specially fabricated test plates, flat bottomed holes of different diameters and depths frequently being the most convenient type of defect to consider. The defect diameter/depth ratio required for the defect to be detectable is a function of depth and tends to decrease as the depth increases (the sensitivity defined by this ratio improves though the absolute minimum defect diameter detectable increases with depth). However, this is counteracted by a reduction in the temperature differences observed, which leads to resolution problems. In general, the best results are obtained if the maximum possible amount of energy is deposited on the surface of the structure, though care must be taken to avoid thermal damage.

A wide range of sensitivity values have been reported in the literature and it is wise to carry out tests on the particular material and geometry of interest in potential applications of the method. However, minimum detectable defect diameter/depth ratios in carbon fibre composites in the region of 2 might be expected. The method is also applicable to honeycomb constructions but it should be noted that the detectability of defects is strongly dependent on the core material and cell dimension.

There has recently been a great deal of interest in thermosonics (also called Sonic IR) [8,9]. The technique typically uses a pulse of high power ultrasound in the 20-100 kHz range applied at one point on the test structure to generate a high frequency vibration field in the structure. This causes the surfaces of any cracks or delaminations present to rub together, so dissipating energy which causes a temperature rise local to the defect. This transient temperature rise is then detected by a thermal imaging camera whose field of view covers a significant area of structure. It has been shown [7] that this technique is more sensitive to deep defects in thick composite than conventional transient thermography.

Barden et al [10] have shown that the technique can be implemented at low ultrasonic power by using a long input pulse, so avoiding surface damage problems at the exciter. Dillenz et al [11] have also achieved low power via a more complex lock-in system.

Shearography

Shearography is an optical method which uses speckle shearing interferometry to measure displacement gradients at the surface of a structure. The speckle patterns produced with the component in stressed and unstressed states are subtracted, differences revealing changes in displacement gradient. These are generally more rapid in damaged regions.

Laser speckles are produced whenever a surface whose roughness is of the order of one wavelength of light or greater is illuminated with highly coherent light. The light scattered from any moderately distant point consists of many coherent wavelets, each arising from a different element of the surface. The optical path differences between these various wavelets may differ by several wavelengths and the interference between these wavelets results in a granular pattern of intensity that is termed speckle [12].

Shearography uses a laser operating in the visible light range to illuminate the target area of the structure. In practical applications [13] the light is fed from the laser to an expansion lens via a fibre optic cable as shown in Fig 2a, the target being viewed by a video camera via an image shearing lens. The operation of the system is shown schematically in Fig 2b. A thin glass wedge covers one half of the lens aperture. Without the wedge, rays scattered from a point P on the object and received by the two halves of the lens will converge to a single point in the image plane. The glass wedge is a small angle prism which deviates the rays passing through it so in the presence of the wedge, the rays from the point P are mapped onto two points, P_1 and P_2, in the image plane. Hence, two sheared images of the whole object are produced and these images interfere with each other to produce an interference pattern. This reference pattern is stored in the computer. When the object is deformed, the interference pattern will be modified, and the monitor displays the image formed by subtraction of the reference pattern from the current image.

The most common loading arrangement is to use vacuum stressing [13,14]. A system for use in a production environment has been developed which will cover a 36 inch field of view, and hand held units for field applications have also been produced [14]. Pressure drops of 20-100 mm Hg are sufficient in most applications and this can be achieved without sophisticated sealing arrangements. It is also possible to use thermal stressing [13] and the technique can be used to produce time-averaged images of the displacement gradients produced by vibration excitation [15].

Shearography detects defects from the changes in the displacement gradient which they produce when the structure is loaded. For a given loading, these changes will decrease as the depth of the defect increases, or its diameter decreases. Shang et al [16] have shown that it is possible to estimate the depth and diameter of defects from the shearograms produced by vacuum loading provided that the pressure and extent of shearing produced by the image shearing lens are known; further analysis of this is given by Guo and Qin [17].

The maximum surface deflection above a defect produced by applying vacuum pressure loading is given by

$$w = \frac{kpd^4}{t^3} \qquad (1)$$

where p is the pressure, d is the defect diameter, t is the defect depth and k is a constant depending on the modulus of the material and the effective boundary conditions around the defect. Therefore if detection at a given applied pressure requires a certain minimum value of displacement, it would be expected that the minimum detectable defect diameter would be proportional to depth to the power 3/4. However, the author is not aware of a systematic study of the defect diameter/depth ratios that can be detected in different materials. Examples of recent applications of shearography to composites inspection are given in [18-21].

Electronic speckle pattern interferometry (ESPI) [22,23] has also been proposed as a rapid nondestructive testing method. This technique uses a system very similar to that used in shearography except that the image shearing lens is not employed. ESPI therefore measures surface displacements rather than the derivative of displacement. Both ESPI and shearography are speckle methods so they do not require the same degree of vibration protection as conventional interference holography in which relative motion between the optics and the structure of half a wavelength of light (around 0.25 μm) can destroy the image. With ESPI, relative motion of the order of 100 μm can be tolerated [22]. In shearography, the position is further improved since the derivative of displacement is measured and this is unaffected by rigid body translation (though not by rotation). The use of ESPI for composite inspection has been discussed by Wang et al [24].

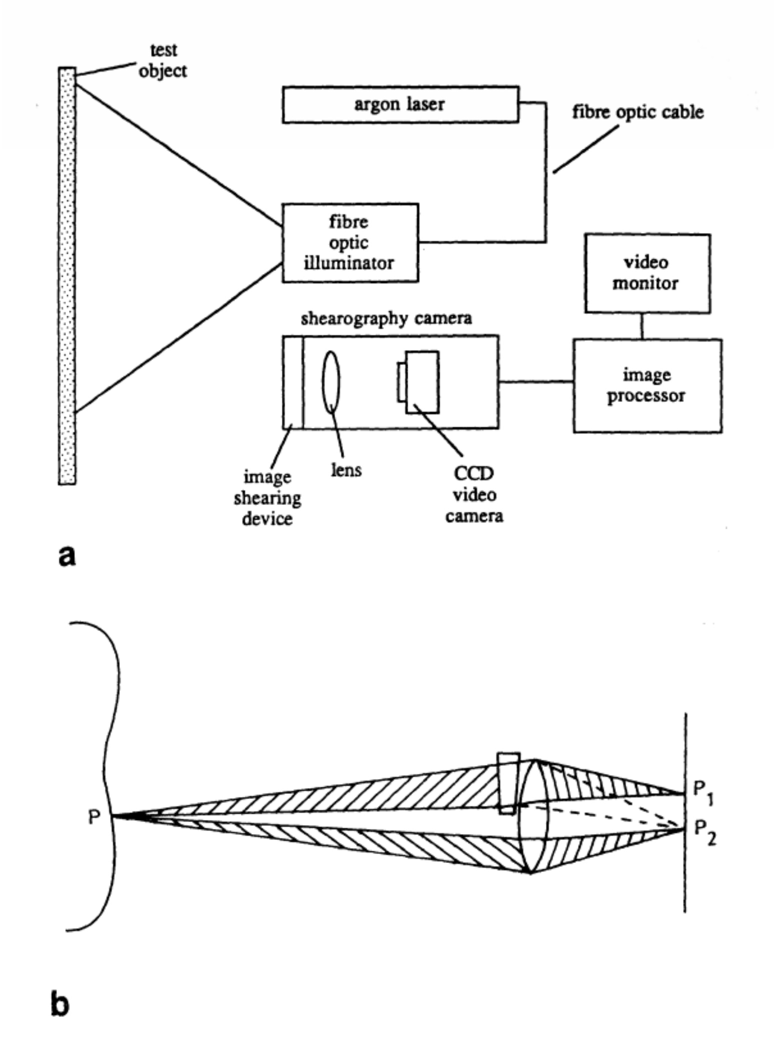

Fig 2. (a) Shearography equipment (after [1,13]); (b) schematic representation of shearing process (after [1]).

Laser Ultrasonics

Conventional ultrasonic inspection requires the transducer to be coupled to the structure via a fluid. This is often achieved by immersing the structure in a tank equipped with a scanning frame. However, this procedure is impractical for large structures such as aircraft wings and fuselages, so jet probe (squirter) systems have been developed in which the ultrasonic beam is propagated along a water jet. Hand held, contact probes are also used, coupling being achieved by a thin layer of gel, but these are very slow and inconvenient if a large area is to be inspected. Laser based ultrasound (LBU) removes these problems since it is non-contacting. Also, the need to maintain the probe normal to the structure is removed since the direction of ultrasonic wave propagation is not significantly affected by the orientation of the laser used for excitation. The LBU technique therefore potentially allows inspection of components incorporating complex curvatures. The generation and detection methods employed in LBU are very different from those used in conventional ultrasound using piezoelectric transducers. However, once the wave is generated, the physics of its propagation in the structure and interaction with defects is the same as that in conventional systems so it can in principle provide similar defect detection capabilities.

A variety of laser techniques which can be used for the generation and reception of ultrasound have been reviewed by several authors [25-27]. A spherical Fabry-Perot interferometer is usually used for the detection of ultrasound. This interferometer operates satisfactorily without the need for the stringent vibration isolation precautions which are required with conventional interferometers. This means that the Fabry-Perot system does not have to be mounted on the same base as the structure under test so the system is relatively portable. On flat panels, the results obtained are comparable with those obtained using conventional, water-coupled ultrasound [28-29]. More applications of laser ultrasound to the inspection of composites are described in [30-32]. A key advantage of laser ultrasound over conventional ultrasound is that the need for accurate alignment of the system relative to the surface of the structure is largely removed. This is extremely beneficial for the inspection of complex, curved structures [28,33].

The LBU technique does not remove the need for a two dimensional scan over the whole surface area of the structure to be inspected. However, this can be achieved by using mirrors to deflect the laser beams, rather than the X-Y scanning frames which are employed in the conventional method. Scanning rates of 100 ft^2/hr (around 10 m^2/hr) at a pixel size of 0.5 x 0.5 in (12.5 x 12.5 mm) have been achieved comfortably [29].

The signal levels obtained with LBU systems tend to be low, particularly when the detection laser beam is significantly off-normal to the structure as is sometimes the case when inspecting curved sections. It can therefore be advantageous to cover the surface of the structure with a retroreflective coating, though this is not always needed [28-30]. The signal levels can also be increased by increasing the power density delivered by the generation laser, though this approach is limited by the need to avoid surface damage. Recent work on improving signal quality is described by Dubois and Drake [34].

Fiedler [35] gives an excellent overview of the state of laser ultrasonic technology. US Air Force sponsored studies have shown that laser ultrasound is slower and more expensive than conventional systems on flat components but that it has significant advantages on complicated geometries and sharp radii of curvature. For example, an air inlet duct was inspected in two hours using laser ultrasound whereas the equivalent conventional scan took 24 hours. Laser ultrasound systems are therefore being introduced by the major US aerospace manufacturers for the inspection of the increasing number of complex composite components used in modern aircraft. Lockheed Martin now have two laser-ultrasonic inspection systems in routine production use that have inspected over 13000 parts so far [36]. Unfortunately laser ultrasound systems are very expensive, the base cost being in the range of $1M plus the costs of gantry systems, software etc [35].

Structural Health Monitoring

Structural Health Monitoring (SHM) potentially has major advantages compared to periodic inspection using NDT. If the health of a structure is monitored, either continuously during operation or between duty cycles, the need for lengthy inspections that take the structure out of service for a prolonged period can be avoided. If an SHM system can be shown to reliably detect defects before they propagate to failure, then the design life of a structure can be increased or the design itself can be made less conservative. The application of SHM to composites in safety critical areas is particularly attractive where there is a danger of the development of barely visible impact damage due to, for example, a catering truck impact on an aircraft fuselage or tools being dropped on a wing. Boeing is committed to implementing an SHM system in some form on its 7E7 aircraft [37]. The benefits of SHM in aerospace applications have been discussed by Boller [38].

However the benefits of SHM can only be realised if the SHM system itself is reliable and does not add significantly to the mass of the structure. A key issue here is the number of sensors in the SHM system required in order to monitor the entire structure. If 1000 m^2 of aircraft structure is to be monitored, a two dimensional grid of sensors covering the whole area at a pitch of 200 mm implies approximately 25000 sensors, while if the pitch could be increased to 2 m, the number is reduced to a more manageable 250. For this reason, traditional NDT methods for damage detection, such as bulk wave ultrasound, that operate over a very short range in the vicinity of the transducer, are not practical for large area SHM. The goal is therefore to maximise the amount of structure that each sensor can monitor.

Acoustic emission is one method that offers the possibility of monitoring large areas of structure with a modest number of sensors and Airbus have invested heavily in this technology [39]. However, since the method is dependent on listening to the sound of damage growing (or of crack/delamination surfaces fretting) it has to be operational at the time the damage is created. A major concern in the case of composite aircraft structure is impacts when the engines are off and the aircraft is being serviced; the acoustic emission system must therefore be kept running throughout this period.

The waves generated in plate-like structures by acoustic emission are ultrasonic guided waves. In ultrasonic guided wave testing, the waves are generated by transducers rather than by the damage itself; the interaction of the waves with the damage is then detected. Various workers have attempted to use guided waves in different ways for SHM. A spin-out company from Stanford University [40] produces an array of piezoelectric elements on a flexible PCB that can be either embedded within a composite structure or surface mounted, connections being made via tracks on the PCB. The system is designed for localised monitoring of, for example, repair patches, and the flexible PCB platform limits its applicability to large area monitoring. The team at Sheffield University have successfully used this system and others in investigations of guided waves for localised SHM [41,42]; there is also a great deal of worldwide interest in the use of guided waves for large area SHM [43-45].

Successful guided wave inspection systems developed at Imperial College [46] have been applied to structures that are characterised by their relative simplicity and low feature density. Furthermore, the inspection strategies have all been developed from the 'traditional' NDT concept of using a single sensor unit that is only deployed onto a structure when an inspection is required. This limits the complexity of structures that can be inspected as the data obtained must be simple enough to interpret without *a priori* knowledge of the precise geometry of the structure. However, because the sensors in an SHM system can be permanently attached, the issue of complex structures with high feature densities can be tackled using subtraction algorithms; however, obtaining a sufficiently stable signal for simple subtraction to work reliably is extremely difficult [47]. There is therefore some way to go before the systems are suitable for reliable, large area inspection.

Conclusions

Ultrasonic C-scan inspection is by far the most commonly applied technique in the inspection of composite materials. However, it is slow and is particularly inconvenient to apply in the field and to highly curved surfaces. Laser ultrasound has major advantages with highly curved surfaces and has been implemented at a few sites worldwide; however, it is extremely expensive and is unlikely to achieve very widespread use. Transient thermography offers quick, large area inspection with sensitivity that is frequently adequate; the thermosonics variant shows promise for improved detection of deeper defects. Shearography is another candidate for rapid, large area inspection.

There is currently a great deal of interest in structural health monitoring (SHM) of composites as an alternative to regular inspections; however, a great deal of work is required before this technology displaces conventional NDT.

As composites are used increasingly in complex shapes there is likely to be an increasing call for the inspection of corners and stiffeners; these areas are difficult to inspect by conventional ultrasound and new research is likely to be needed.

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