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MELBOURNE, VICTORIA

Materials Technical Memorandum 379

NDI OF COMPOSITE MATERIALS

By

I.G. SCOTT and C.M. SCALA

Approved for Public Release.

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SUMMARY

A review is given of NDI methods for fibre-reinforced composite materials based on fibres such as carbon, boron, glass and KEVLAR. The capabilities of present methods, such as ultrasonics, radiography, holography and thermography, are considered with respect to defect detection. Techniques which show promise of development as predictors of failure, e.g. vibration measurement and acoustic emission, are also discussed.

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16. ABSTRACT:

A review is given of NDI methods for fibre-reinforced composite materials such as carbon, boron, glass and KEVLAR. The capabilities of present methods such as ultrasonics, radiography, holography and thermography are evaluated for defect detection. In addition, techniques which show promise of development as predictors of failure, e.g. vibration measurement and acoustic emission, are examined.

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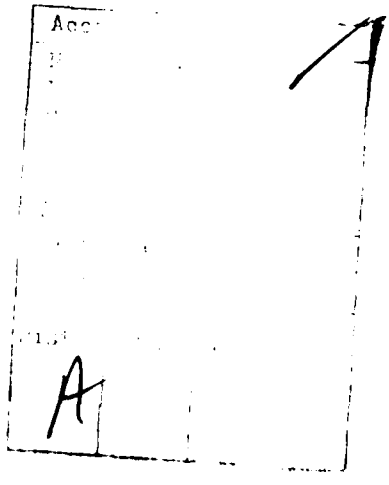

1. INTRODUCTION

Non-Destructive Inspection (NDI) of composite materials can be expected to differ from that of metallic materials because composites differ markedly from metals and their alloys. In particular, composites are highly anisotropic, they exhibit low thermal conductivity, high acoustic attenuation and poor electrical conductivity. As well, high performance metallic structures are conventionally made from material which is relatively free of unwanted defects, and in-service failures tend to originate from crack initiation at identifiable defects and occur after crack propagation. Hence NDI procedures can be based on the detection/location of growing cracks, the importance of which can be determined using fracture mechanics. No similar predominant failure process has yet been identified for composite materials, no procedure similar to fracture mechanics has been developed and many of the NDI needs are as yet not clearly defined.

It is proposed to look firstly at those NDI procedures which are reasonably well established for composite materials and which seek identifiable features believed to be of importance. Developments in additional techniques will be evaluated. Finally, techniques which show promise of development as predictors of failure e.g. acoustic emission, will be examined.

The use of composites in aeronautical situations will be emphasized, but not to the complete exclusion of other uses. Similarly, we shall mostly be concerned with organic based composites e.g. carbon, glass, boron fibres in (say) an epoxy matrix and shall largely ignore some of the newly developed metal/metal-fibre composites. Although considerable effort has been spent elsewhere in the recalcitrant problem of bonds involving fibre composite material, it is largely disregarded in this paper - bond strength measurement is almost a separate problem in its own right. An attempt at uniformity of nomenclature will be made by describing materials in the fibre/matrix form.

2. THE IDENTIFICATION OF DEFECTS

For composite materials, much of the NDI is conducted either during or immediately after manufacture of the component and consists of looking for delaminations, debonds, etc. Subsequently, damage to composites can accrue from impact, environmental effects or from unidirectional or cyclic load application, all of which have different effects on the defects already present or may introduce different types of defect altogether.

2.1 Commonly used NDI methods

Most NDI of composites is conducted using X-radiography or ultrasonic C-scan.

2.1.1 X-radiography

Although radiographic testing is believed by many to be a panacea for all problems of NDI of composites, radiographic techniques are unsuited to the detection of many defects found in composite material.

Typically, low energy X-rays (a few tens of keV) are used with a beryllium window for composite testing. Currents are held to a few mA and exposures to about one minute. Specimen-to-generator distances vary greatly, usually from 0.3 to 3 metres.

Determination of resin content in a composite should be feasible using X-radiography. However, consideration must be given to the relative absorption coefficients of the particular fibre and matrix in the composite under investigation. Martin (1) determined mass absorption coefficients for a carbon-fibre composite, both theoretically and experimentally (using attenuation measurements), in an attempt to obtain resin contents. However, neither this method nor an attempt to relate measured film density to resin content worked very well. Ferli and Torp (2) studied a glass-fibre composite in which the absorption coefficient was 20 times higher in the glass than in unpigmented polyester. They were able to determine total glass content from film density measurements, and were also able to observe the reinforcement type and orientation.

There appear to be contradictory findings about what types of defects can be detected by X-radiography. Harris (3) claims that radiography can be used to identify voids, that fibre/resin debonding or cracks resulting from thermal contraction cannot be distinguished and that interlaminar cracks cannot be identified. Prakash (4) suggests that thermal cracks are readily detected, as are foreign objects and inclusions, but that interlaminar debonds and fibre debonds are generally hard to detect. Salkind (5) was unable to find void or crack indications in his tests but Nevadunsky et al (6) were able to detect large voids, cracks and porosity in adhesives.

Enhancement of some forms of cracks for radiographic testing is possible but the effects on life have yet to be established. Hagemaier and Fassbender (7) brushed specimens containing edge delaminations with di-iodobutane (DIB) or s-tetrabromethane (TBE). Radiographs taken an hour later were enhanced, and the chemicals evaporated completely after 2-3 days. However, they noted that DIB was an irritant, while TBE was a severe poison and a potent mutagent which should not be used in the future. Lead oxide in gelatine has sometimes been used for impregnation. Mention is often made of penetration of suitable materials into voids but the process must surely be very slow unless there is coalescence of microvoids forming a channel to a free surface of the material. (Dye penetrant is excellent for finding surface-breaking cracks and edge delaminations but difficulty is experienced in removing it from the defects prior to repair).

The contrast available from conventional radiographic techniques is usually insufficient to permit resolution of individual fibres. However, Roderick and Whitcomb (8) placed the X-ray source close to a boron-epoxy laminate and a high resolution glass plate, and were able to discern breaks in the tungsten cores (3 mm diam.) of the boron fibres resulting from fatigue testing. Crane et al (9) proposed that boron fibres be added to the edge of each composite tape of carbon fibre so that fibre alignment could be assessed. Crane (10) also proposed using the fringe patterns, which appear in radiographs due to misaligned fibres, to measure misalignment.

To maximise the information available from radiographs, exposures should be made from at least two directions. For metal honeycomb material, one exposure should be made in a direction normal to the surface of the skin, while the second should be perpendicular to the ribbon of the core but angled to avoid interrogating too many cells. Imperfect beam collimation will cause image distortion except when very small areas are under examination. Using a high resolution system, Cooper et al (11) were successful in locating corrosion damage in advanced composite aircraft structure made from metal honeycomb with a boron-epoxy skin, using radiography.

2.1.2 Ultrasonic C-scan

The principal established ultrasonic NDI technique for composite materials is the C-scan in which an ultrasonic pulse is propagated through the specimen reflected from a back surface or a defect and received (usually) by any transmitting sensor. The ultrasonic pulse is scattered or reflected from any defect which differs largely in acoustic impedance from the surrounding material. The readily available information in the echo signal is the amplitude and the time for the signal to travel from transmitter to receiver. The latter may be measured by means of an electronic gate. The width of the gate may be set to select only a thin plane within the specimen for examination (a similar effect can be obtained by means of focussing transducers) or to average an acoustic parameter through the thickness of the specimen. C-scan testing is usually done in a water tank, although bubbler techniques are available for large structures. A permanent record is available from a Matox or similar recorder fitted with line-intensification capabilities for amplitude recording. Complications arise when the specimen surfaces are either curved or non-parallel, although Liber et al (12) claim that these are largely overcome by using front-surface triggering of the gate.

Interrogation of a specimen by ultrasonic pulses yields information relating to material acoustic properties and specimen dimensions. Dimensions can be obtained from the signals reflected from the front and back faces of the specimen, and information can also be obtained about non-planar surfaces or the presence of scratches. Similarly, delaminations or cracks normal to the ultrasonic wave beam will be detected. Commonly, frequencies from 1 to 10 MHz are used, for which cracks parallel to the beam or small defects of any nature are unlikely to be seen. Van Dreumel (13) showed several C-scans in which fibres could be seen and alignment judged but the frequency was not given. This probably occurred due to bunching of fibres or to diffraction of waves around bundles of fibres. Small voids cannot be detected unless they appear in large numbers; large voids will be found when their size approaches the wavelength of the probing wave.

Mool and Stephens (14) made a composite panel comprising eleven layers of boron/epoxy tape sandwiched between aluminium alloy skins. Defects were introduced into the specimen (delaminations, missing plies, extra plies, misaligned filaments, etc.). Commercial through-transmission C-scan equipment was used, which included 5 MHz flat transducers, a long focus 10 MHz transducer and a short focus 15 MHz transducer. The tests were completely successful, all the artificial defects being positively located as well as other defects which were confirmed destructively. The higher frequency transducers gave sharper defect definition than the lower frequency transducers but attenuation was very much higher. No indication was given of techniques for identifying an unknown defect.

Bargeman (11) used 5 MHz short-focus C-scan equipment to examine honeycomb material. Once again cross voids, cell wall voids and continuous cell voids were readily located but identification remained difficult; greater success was obtained by using simple contact pulse-echo techniques.

Liber et al (12) detailed C-scan equipment and test results from cross-ply graphite/epoxy test specimens which underwent cyclic loading. Difficulties associated with detection of standard defects were discussed; initial flaws, designed to simulate in-service flaws, were introduced to the test specimens. A 'Natural' standard for gapless delamination was obtained from specimens with drilled holes which were known

to contain delaminations extending from the boundary of the hole to the interior of the specimen. For surface defects, it was sometimes observed that, in successive scans, the flaw indication reduced in size - this was traced to water penetration and was largely overcome by sealing edges. Liber et al (12) adopted a realistic approach to flaw type discrimination, stressing the need to interpret ultrasonic indications on the basis of previous experience and knowledge of material.

2.2 Additional NDI Methods

Whitcomb (13) described the fatigue process in composite material as a complicated combination of 'matrix crazing, delamination, fibre failure, fibre/matrix interfacial bond failure, void growth and cracking' and decided that it was 'difficult or impossible to handle using traditional NDE techniques'. Clearly, better (or at least different) techniques are needed, and many alternatives have been proposed.

For several such techniques, little information is available or application appears to be only marginally useful. For example, Prakash (4) measured the intensities of light transmitted through glass fibre specimens and found that transmittance was a function of fibre volume-fraction. For thicker specimens, he used an X-ray diffraction technique and found a linear relationship between peak heights of relative diffracted intensities and fibre volume-fraction. Resin and adhesive cure times are conventionally studied by measuring their dielectric constant. Highly stressed regions of components can be identified from strain measurements, either by means of foil gauge, photoelastic or Moire fringe techniques.

Far more promise is shown by the techniques discussed below.

2.2.1 Neutron Radiography

In recent years, neutron radiography has received much attention as a possible new and exciting NDI technique to complement ultrasonic and X-ray techniques; it is particularly well suited to examining bond lines and to composite material in close proximity to metal. The neutron radiography technique has been developed using thermal neutrons (i.e. fast neutrons moderated by water or polyethylene) from a nuclear reactor. In-service application awaits the development of a suitable safe, cost-effective, portable neutron source.

Dance and Middlebrook (17) described an expensive, short-lived, but portable, Californium-252 system containing about 2 mg of the isotope. They produced radiograms using industrial X-ray film, neutrons being converted to electrons by passage through a gadolinium metal film. Hydrogen, boron and gadolinium exhibit neutron absorption coefficients '2 or 3 orders of magnitude greater than the average value of structural metals'. Thus, organic materials such as epoxy adhesives, which contain 6 to 12 percent of hydrogen, exhibit good radiographic contrast; for constant material thickness, variations in film density indicate variations in absorber uniformity caused by voids, inclusions or material inhomogeneities. There may be difficulties in interpretation e.g. a low absorption inclusion looks like a void, but high-absorption inclusions are readily recognised. Dance and Middlebrook showed a number of X-radiographs along with neutron radiographs, to enable information available from the two techniques to be assessed. It was emphasised that the use of several NDI techniques in combination maximises the NDI information obtained from each.

2.2.2 Eddy Currents

Although resin is non-conductive, there is a measurable conductivity associated with bundles of carbon fibres and eddy current measurements can be used to determine resin content. For practical applications, present methods for determining resin content are all based on a time-consuming acid-digestion scheme. While neutron radiography is excellent for determining this parameter, there are still obvious problems in application on the factory floor. Eddy current tests were made on a carbon/epoxy combination (7), using test frequencies of 0.5 to 3 MHz and coil diameters of 3 to 1 mm (depending on specimen thickness). Good correlation between resin content and a chosen eddy current parameter (measured on a phase-diagram) was obtained.

In earlier work, Dingwall and Mead (18) found good correlation between volume fraction and an eddy current parameter using a frequency of 10-12 MHz. Their search coil formed part of the tank circuit of an oscillator, and frequency changes attributed to specimen changes were recorded. However, the test was entirely empirical, depended on the type of resin and specimen thickness, and did not work for cross-ply laminates. Moreover, the response of the system to small holes (1 mm diameter) and cracks was not easy to understand.

For the purposes of eddy current examination, composite material is assumed to comprise bundles of conducting filaments, incompletely separated from each other by dielectric material (resin). Hence the conductivity in a longitudinal direction is expected to be many (10-100) times the conductivity in the transverse direction. The near-parallel filament also possess both capacity and inductance. The effect of these reactive components will increase with increasing frequency so that eventually they will predominate at very high frequencies. Several authors (18,19,20) successfully modelled composite material in this way. Whereas Dingwall and Mead (18) found the cross-plied CFRP composites troublesome, Prakash and Owston (20) were able to use the eddy current technique to provide information on the lap-up of cross-plied material. Owston (19) was confident that eddy currents could be used in various ways (for crack detection, volume fraction and lay-up order measurement) provided frequencies could be sufficiently increased. Encouraging results were obtained at 25 MHz, and development along these lines will be followed with interest. Testing with microwaves was introduced more than ten years ago and the review by Scott (21) in 1971 concluded that 'the procedure holds considerable promise'. From the scarcity of present day references, one may conclude that such promise has not been fulfilled.

2.2.3 Optical Holography

Various techniques are used in holographic NDI - these will be defined in turn as each application is considered.

Speckles appear when a rough surface is illuminated with laser (coherent) light. The deformation of a structure by mechanical and thermal means introduces localised regions of high fringe density, to the speckle pattern, which are likely to indicate the presence of a flaw. Erf (22) used a speckle shearing camera (having a lens which brings rays scattered from one point on an object into interference with those from a nearby point) to measure surface strain. A $0.2m^2$ disbond in a hollow cylindrical structure was identified by pressurising the system to 140 kPa and examining differences in recorded images from which strains could be evaluated.

Time-averaged holography involves making a hologram of a vibrating specimen with an exposure long compared with the period of oscillation. On reconstruction, nodes appear uniformly bright, but anti-nodes show fringe patterns which provide information about mode and amplitude of vibration and, by inference about disbonds (Campbell and McLachlan (23) studied a portion of honeycomb material and successfully identified disbonding using this method).

The frozen fringe technique is a double exposure process in which 'before' and 'after' holograms are superimposed to form a fringe pattern which relates to surface deformation. In general terms, the accuracy of this process is strongly dependent on the stability of the test surface between exposures. A variant of this technique is the 'live fringe' technique in which a hologram of an unstressed object is recorded and is processed in situ, or very accurately replaced. An interferometric comparison is then made by looking through the hologram at the object; fringes are observed when the latter is slightly strained. Both the frozen fringe and live fringe techniques of holographic interferometry produce a measure of changes in surface displacement.

Marchant (24) examined Harrier CFRP wing tips (approximately 2 m x 1 m x 0.1 m) using live fringes formed from an argon ion lamp. The wing tips were mounted on a heavy steel table which was later isolated from ground-induced vibration. Minor problems were experienced with air-borne vibration. Exposure times of about 1s were used and reasonable hologram quality was obtained. Specimens were stressed by heating with a domestic radiator and, although uneven heating occurred, it always seemed possible to make indications of suspect areas reappear with repeated loading. Good agreement with radiographic tests was obtained but doubt was expressed concerning nature of defects. It would appear from Marchant's work that although the technique holds considerable promise, extensive development is still required. However, work by Meyer and Katayangi (25), in which strain distributions in composite pressure vessels were determined, suggests that many of the instrumentation problems may have been overcome although they gave no details. Daniel and Liber (26) referring to Moire fringe techniques, commented that 'the pattern is a measure of surface displacement field and gives a clear indication of surface flaws'. However, they placed little importance on the speckle shearing technique which indicates strain rather than displacement. Daniel and Liber show excellent photos of fringe patterns but their discussion is mostly in very general terms. It is not clear to what extent differences between different types of defects can be detected. Delgrosso and Carlson (27) used CW interferometry to study surface deformation during cyclic motion (i.e. time average) of jet engine composite fan blades, comprising boron filament material coated with silicon carbide. Cracking, voids between plies, and debonding after thermal fatigue were defects found and confirmed by means of C-scan ultrasonic technique.

Maddux and Sendeckyj (28) insisted that TBE-enhanced X-radiography (see 2.1.1) and holographic interferometry 'have proved to be most successful' when applied to studies of damage in composite material. They gave a detailed description of their proposed holographic techniques involving modified frozen fringe and live fringe measurements. Heat was applied in order to stress their specimens (with attendant problems), and a lens was inserted between specimen and film plate, so that non-coherent light could be used for specimen reconstruction. Although readily observable indications of damage were given, Maddux and Sendeckyj expressed some reservations concerning identification of the different types of damage

expected to be present. Their work suggests that holographic interferometry, although holding great promise, remains a laboratory technique with little prospect of immediate development for field use.

2.2.4 Acoustic holography

Commercial equipment for acoustic holography/imaging frequently includes C-scan as an option. Sheldon (49) used an imaging system in which scan information was stored in a memory. On command, the various configurations could be called up. Using a 5 MHz focussed transducer, 12 mm and 25 mm debonds between graphite epoxy skin and honeycomb core were located on the reconstructed C-scan. A focussed image technique used a single focussed transducer imaging on the back side of the test sheet. Both amplitude and phase were used to record a hologram. A crack in a graphite composite wing attachment trunnion was found by imaging and confirmed by C-scan. Damaged specimens were also identified using both techniques. It was generally found that the indicated areas of impact damage were larger than those confirmed visually i.e. damage could well have been more extensive than expected.

Kroliman et al (50) make extravagant claims for their imaging which do not really appear warranted by their results. Photographic images were produced by modulating a light source with the detected acoustic signal. An acoustic image was claimed to be 'better than' that produced with conventional C-scan for a flat 14 ply graphite/epoxy laminate containing known defects. Although known defects were readily located, the manner in which unknown defects could be identified was not mentioned.

2.2.5 Thermography

For many years thermography has been presented as a NDT technique having great potential - very rapid scanning of large surface areas is possible and equipment can be some distance away from the test surface. Consequently examination can be made with minimal interference to plant operations, and the same equipment can be shifted around to monitor more than one problem area. That the potential of thermography has not been realised is undoubtedly because a thermal technique has attendant problems such as the effects of draughts, variations in surface emissivity, etc., all of which are difficult to overcome, particularly in the field. Other problem areas will be identified later.

There are two types of thermal field in materials (51): (i) stress-generated thermal fields (SGTF) which appear as a consequence of cyclic loading, and wherein maximum temperature rises can be expected where stresses are highest, e.g. around flaws, and (ii) externally applied thermal fields (EATF) where normally uniform isotherms are distorted in the presence of a flaw or a damaged region. Thermography is the science of measuring temperature changes arising from these two thermal fields.

EATF can be produced in the laboratory by means of a low airvolume heat source or a focussed radiator. (Ordway and Renius (52) canned the surface of a specimen using a 50 watt CO_2 laser).

Under fatigue loading conditions, which produce SGTF, materials dissipate energy in the form of heat, largely because of hysteresis effects but also as a result of mechanical damage (e.g. rubbing of fracture surfaces) or from manufacturing defects (e.g. friction between

delaminated layers in composite material). The resulting temperature changes are small but can be detected - Scott (33) lists recorded temperature changes during fatigue testing varying from 14 deg C in stainless steel specimens to 30 deg C for PVC specimens. For some composite materials, temperature rises of up to 36 deg C have been recorded. Consequently, regions which suffer fatigue damage can be located and identified; frequently, before damage is visible as a surface crack. Often the major temperature change occurs early in a test (15 per cent of fatigue life).

Detecting thermal fields was initially done with radiometers (34) but the AGA thermovision video-camera is now used almost exclusively. The unit is a real-time indicating device which operates at 16 frames per sec. The detector is an indium antimonide crystal which becomes photo-voltaic at liquid nitrogen temperature. Different colors are used to identify the steps in a temperature range, the border between colors representing isotherms. Very little work appears to have been done on the effects of wavelength of radiation on results - the AGA unit has a maximum sensitivity in the μm region and this presently appears to be the major determining factor.

Cholesteric (or liquid) crystals when illuminated with white light, selectively scatter certain wavelengths of the incident light, producing vivid colours which are easily seen. Changes in temperature produce changes in the wavelength of the reflected light, which can be controlled (by changing the composition) to cover a wide range of temperatures and sensitivities. Liquid crystals are applied to the surface of a specimen over an optically black coating. They are available in ready-to-spray form or encapsulated in sheets (reusable). Charles (35) and Daniel and Liber (26) showed that thermography could be carried out using liquid crystals. They are cheap and simple to use but are susceptible to physical and chemical changes, have a limited life and a limiting fixed temperature range (sensitivity is generally maximised at a fixed temperature).

Both SGTF and EATF are essentially dynamic fields which are modified by thermal gradients. Given sufficient time and uniform ambient conditions, the temperature of a specimen raised locally from a given cause will tend to stabilise to a value slightly above ambient. Hot-spots, clearly defined initially, will thus become unrecognisable. Day-to-day variations in ambient temperature may also occur. Thus, any device used for temperature measurement should contain an in-built temperature level adjustment. Unwanted variations in indicated temperature may also arise from heat loss (by convection) at the edges of specimens or from variable heat loss from flat surfaces. McLaughlin et al (31) overcame surface problems by spraying the specimen surface with flat enamel (either black or white) which also resulted in a uniform surface emissivity. Other workers have had considerable problems, particularly the users of liquid crystals who need a surface with uniform (and preferably high) emissivity as background to the crystals. High surface emissivity will cause local temperature rises to return rapidly to ambient and detail of hot spots will be smeared.

Plastics and composite materials possess a relatively low thermal conductivity and thus are well suited to the use of thermographic techniques. Their thermal conductivity is highly anisotropic (about 80 watt per metre deg C in the fibre direction and 0.5 transverse to the fibres). Thus, when applying heat by conduction at the specimen edge there is likely to be a preferred specimen orientation in terms of heat input, and problems with cross-ply layups can be anticipated if the rate of heat input or the conductivity is too low there will be smearing of the isotherms.

McLaughlin et al (31) found that heat flow parallel to high conductivity fibres resulted in the greatest perturbations. In low conductivity materials, isotherms were closely spaced indicating a high thermal gradient in the direction of heat flow and the extent of the perturbations was not so great. Clearly, for SGTF testing, anisotropy in thermal conductivity is likely to cause distortion of the observed thermal image which will worsen with time.

Henneke et al (36) demonstrated the use of SGTF by cyclic loading of a methyl methacrylate specimen containing a central hole; an isotherm pattern closely related to the calculated stress field was obtained. Furthermore, very good agreement between predicted and measured temperatures was obtained. Cyclic loading tests at frequencies between 15 and 45 Hz were conducted on boron/epoxy specimens containing a central hole. Early in testing, heat patterns developed (around the holes) which appeared to be related to stress fields; subsequent changes in the patterns were attributed to the development of fatigue damage. Similar successful tests were conducted on graphite/epoxy laminates containing notches from which matrix cracks propagated. McLaughlin et al (31) were less successful, probably because their test frequencies were much lower (0.5 - 5 Hz). Temperature rises were observed for glass/epoxy specimens containing a part-through hole after only 30 cycles at 1 Hz and at only 10 per cent of the static failure load of the flawed specimen. No changes were observed for graphite/epoxy material after 1000 cycles at up to 30 per cent of the static ultimate load. Thus, there appear to be limiting loading frequencies below which no observable change can be expected.

A variant of the thermographic technique, devised by Henneke and his co-workers, was termed vibrothermography. This technique involves measurement of temperature rises occurring when a specimen containing defects is vibrated at very low stress levels. Recent reports by Henneke and Jones (37) and Reifsnider et al (38) show how well this project has advanced. A two-dimensional finite element analysis was undertaken so that the effect of known defects could be computed. Quite good experimental agreement was obtained for graphite/epoxy specimens having edge delaminations. However, the heat pattern, which developed in several seconds was very sensitive to the vibration frequency e.g. a ten per cent increase in frequency nominally 18 kHz showed up a defect otherwise unnoticed. The success of the analytical approach has led to the development of a three-dimensional heat-conduction model. Whitcomb (16) sounds a word of caution - in his two-dimensional model he makes allowance for heat flow due to conduction, convection and radiation, claiming this is necessary in order to locate a heat-generation zone from temperature profiles alone. Pye and Adams (39) developed a procedure whereby laboratory specimens were vibrated at their resonant frequency (to control sensitivity) and zero volume matrix shear cracks were detected. In carbon-fibre reinforced plates, crack lengths around 80 mm were located. Cracks in glass-fibre material were much easier to detect and patterns were frequently obtained at loads which caused little or no crack growth in the material.

Clearly, thermography is an NDI technique which possesses potential but much development is needed. Sensitivities commonly quoted are about 0.1 deg C, temperature ranges are a few deg C and the detectable defect size is a few mm in diameter. There are many restrictions on the technique and its application to composite material, but delamination is reasonably easy to detect. Success-rate seems to vary considerably. Thermography is unlikely to give any information not found with ultrasonic C-scan, but it is a non-contact technique which can be used at a distance, and crack growth can be monitored as it occurs.

3. ATTEMPTS TO ASSESS STRUCTURAL INTEGRITY

It should be clear that the techniques just described are suitable for detecting and locating a restricted range of defects in composite material. Defects differ for different types of composite material but a general classification based on detectability is not hard to arrange. However, because of our incomplete understanding of failure modes, inspections tell us very little about defect severity and even less about the life to failure. Furthermore, the search for delaminations and broken fibres is more likely to be of value during or immediately following manufacture than it will be during service.

Of far greater importance than finding defects is the need to appreciate their importance i.e. to develop a failure predictor or life indicator. In this section, the remaining techniques will be discussed with this requirement in mind. Most, it will be seen, go at least part of the way towards this goal.

3.1 Vibration Measurements

Cawley and Adams (40,41,42) proposed the use of a vibration technique to locate defects in structures made from advanced composite materials. Damage can be detected, located and roughly quantified by measuring changes in natural frequencies of the structure. It is claimed that the severity of the damage can be assessed by additional analysis. This technique is potentially very attractive because properties can be measured at a single point on a structure, and hence would not require access to the whole of a structure. Actual test time can be very small, particularly if the resonant frequencies are excited by an impulse. However, it is necessary to conduct tests on composites in a constant (± 1 deg C) temperature enclosure.

It can be shown that the ratio of frequency change in two-vibrational modes is a function only of the location of damage. Initially, this can be modelled as a local decrease in structural stiffness which as O'Brien (43) confirmed, provides a useful but indirect assessment of damage. Cawley and Adams maximised their computational efficiency by outputting relative frequency changes at a number of grid points. Thereafter, they computed an error function at each point, which was a measure of the error made in assuming damage to be at that point. The point at which the error was a minimum gave the position of the damage, and the size of the frequency change was a measure of damage. Anisotropic materials could be dealt with by giving high weight to modes in which the direction of the stress vectors at the point of interest are similar.

Cawley and Adams readily located damage by saw cuts in a CFRP plate. One side of a similar plate was damaged by a steel ball, damage was successfully located by vibration techniques and was confirmed by ultrasonic measurements. Similar damage to a honeycomb panel with CFRP facings was readily located; damage equivalent to the removal of about 0.1 per cent of the area of a two-dimensional structure could be found.

Earlier Adams and Flitcroft (44) showed that matrix and interface cracking in carbon or glass-fibre reinforced composite material could be detected in the laboratory using a resonant torsion pendulum. The specific damping capacity was measured from the power needed to maintain a constant vibration amplitude at resonance, while the shear modulus was found from the resonant frequency. Crack size was reliably indicated by the amplitude-dependence of these dynamic properties of which damping was the more sensitive measure. No marked differences were found

for cracks produced under static or fatigue conditions. Knott and Stinchcomb (45) conducted similar measurements on simple cantilever beams made from boron/aluminium composite but were unable to obtain consistent results apart from vaguely commenting that damage was indicated 'through changes in the vibration signature.'

Sims et al (46) have a different approach in that they appear to be more interested in evaluating specimen life rather than determining the presence of defects. Most of their results were obtained on $0^{o}/90^{o}$ cross-ply laminate glass/epoxy material. Complex dynamic moduli and damping factor were determined using a simple resonance technique as well as a torsion pendulum technique. For the former, parameters were evaluated by utilising different modes of vibration over a limited frequency range (20 Hz to 20 kHz) and at low strains ($\sim 10^{-6}$). For the latter, the frequency range was much lower (~1 Hz) and the strains much higher (up to 2×10^{-3}). It was shown that high strain amplitudes significantly affected results for damping factor; consequently results were quoted for a fixed strain (10^{-3}). For all systems, dynamic moduli decreased while loss factor increased with the introduction of damage. It was concluded that energy dissipated per cycle by the cracks during dynamic testing was proportional to total crack area. Guild and Adams (47) defined specific damping capacity in terms of energy absorbed during one cycle and total strain energy stored during the same cycle. Measurements were made only for the fundamental flexural mode of vibration, the stress level being varied by varying the energy input per cycle. Differences in damping capacity with stress levels in the specimen were demonstrated and it was claimed that, by controlling variations in stress level, much greater accuracy could be achieved than by using the resonant peak method of Sims et al (28).

3.2 Measurement of Ultrasonic Parameters

In any C-scan measurement, the effects of ultrasonic attenuation are evident. However, attenuation is an ultrasonic parameter of value in its own right, measurement of which can be made in various ways. Other ultrasonic parameters, e.g. velocity and stress wave factor, will also be considered for use in assessing structural integrity.

3.2.1 Attenuation, Velocity and Dispersion

Bar-Cohen et al (48) showed that a great deal of useful information can be extracted from manual A-scan examination of glass/epoxy composites. Seven different types of defect were listed, each of which could be identified from the reflection pattern, using a simplified pattern recognition approach. This identification was largely based on the overall appearance of the scan, but also involved the amplitude of the first reflected signal, a measure of attenuation and an estimated average sound wave velocity. Saluja and Henneke (49) claimed, and were able to justify, that transverse cracks which develop in the weakest plies tend to attain a uniform, equilibrium spacing. These cracks diffract sound waves giving rise to a measured sound wave attenuation. Attenuation was claimed to give a good indication of damage; it varied with changes in crack-opening for a fixed number of cracks, was sensitive to frequency, and was likely to depend on the number of cracks for a given constant crack-opening. Saluja and Henneke, unlike many other workers, confirmed their findings by destructive examination. Although they worked on specific material (graphite/epoxy 0^{o}, $\pm 45^{o}$, 90^{o} and 0^{o}, 90^{o}, $\pm 45^{o}$ in the form of tension specimens), their detailed description of damage is of interest. Transverse cracks began on the 90^{o} plies at about one-third ultimate load, reaching a stable density

at two-thirds ultimate. Delamination in the 90^{o} plies began at the free edges and resulted in cracking spreading to the $\pm 45^{o}$ plies. Most of the observed damage occurred during the first few hundred cycles but attenuation increased up to 10^4 cycles and steadied until 5×10^5 cycles. Hayford et al (50) used a standard short-beam test (ASTM D2344-76) along with a fused quartz buffer block to make a simple calculation of attenuation in a carbon/epoxy composite material. For each group of 20-30 specimens tested at 5 MHz, attenuation was roughly linear with the 'per cent of dark area in C-scans'. A relationship between initial attenuation and failure load in the shear mode was also observed.

Hayford and Henneke (51) proposed a model 'based on the suggestion that the formation of damage in a composite specimen serves as a rudimentary diffraction grating for the ultrasonic beam and thereby causes an apparent attenuation change due to beam spread'. Some unexplained irregularities in the load/attenuation curve were observed but not explained. It seems obvious that they can be traced to the over-simplified model used. However, the model adequately predicted trends and the technique holds promise for development. Importantly, attenuation changes were related to damage rather than individual defects.

Hagemaier and Fassbender (7) found attenuation (which was frequency dependent) correlated well with void content in simple graphite/epoxy laminates. Unfortunately, no correction was made for specimen thickness (number of plies) which turned out to be another variable. Prakash (4) applied a thickness correction but obtained a linear rather than a curved correlation. However, he made the valuable observation that attenuation is not particularly sensitive to fibre volume fraction.

Attenuation, simply determined, appears to be sensitive to hygrothermal effects for glass/epoxy composites but not for carbon/epoxy composites (52). Accompanying the increased attenuation in the former material is a drastic reduction in flexural strength. However, for both materials (and with the KEVLAR material), good correlation between changes in normalised strength and attenuation was found, although no real indication was given for strength reductions greater than 30 per cent. Clearly, confusion could well arise from attenuation results unless it can be shown that degradation from various processes arises from the same physical phenomena, which seems unlikely. In a later paper, Ishai and Bar-Cohen (53) claimed that dispersion of the attenuation data increased consistently with the duration of above-ambient water exposure and the physical reasons for this finding were demonstrated and discussed. Sachse et al (54) described methods for measuring dispersion of ultrasonic waves which showed promise for evaluating moisture-related effects in composites. For shear waves propagating along the fibres in boron/epoxy material, pronounced dispersion was measured but measurements on graphite/epoxy were unsuccessful.

Williams and Doll (55) measured longitudinal wave velocity and attenuation at intervals of 3×10^4 cycles during a compression-compression fatigue test on graphite-fibre/epoxy composite material. Measurements were made at 4 frequencies between 0.5 and 2.0 MHz; testing was conducted at 30 Hz and the peak stress amplitude was varied from test to test. For all except the maximum peak stress amplitude, no measured changes in group velocity or attenuation were observed for up to 10^6 cycles of testing, at which stage the tests were stopped. Neither was any material degradation observable under microscopic examination. At the highest peak

stress amplitude (0.8 of ultimate), velocities remained constant but some unexplained variations in attenuation occurred. However, there appeared to be a correlation between initial attenuation and cycles to fracture, which improved with increasing test frequency. A second set of test specimens cured to a different standard behaved in a similar way but possessed markedly different attenuation. No fatigue fracture precursor could be found.

Williams et al (56) found that attenuation of longitudinal and shear waves in the composite material and the epoxy matrix was strongly frequency dependent. The attenuation for longitudinal waves propagating perpendicular to the plies was found to be sensitive to the 'interlaminar quality' of the component. It was proposed that such attenuation measurements might well serve to identify damage. In a later report (57) an attempt was made to model the above behaviour.

Williams et al (56) found that both shear and longitudinal velocities in graphite/epoxy specimens varied with the direction of measurement but were invariant with frequency. Scott and Gordon (58) showed that structural composites had acoustic properties which could be described by means of a model based on simple laminates. However, unlike Williams et al, they found that ultrasonic velocity was frequency-dependent in their graphite/epoxy material. They found that forbidden frequency bands existed for which ultrasonic wave transmission was strongly attenuated, and that these bands could be used to monitor variations in elastic constants. Reynolds and Wilkinson (59) considered the uniaxially reinforced orthotropic sections, which form the basis for the complex structures. Rather than the complex structures e.g. multi-layer laminates themselves. Significantly, they were able to show that velocity measurements could be used not only to determine void content and fibre volume fraction, but might also be eventually used to estimate ultimate strength.

3.2.2 Stress Wave Factor

The concept of a stress wave factor was developed by Vary and Bowles (60). They studied the inter-relation between various parameters which influence the strength of a unidirectional graphite/polyimide composite. Specimens were fabricated with varying void content and fibre/resin ratio. These were examined using several NDI techniques, and direct (destructive) confirmation of NDI findings was made. Through - transmission C-scan at a nominal frequency of 2.25 MHz was conducted in distilled water. Through-thickness velocity was measured using the pulse overlap method (reflected pulses are overlapped to permit minimisation of phase change by variation of the driving frequency) while attenuation was estimated by fitting the envelope of a train of reflected pulses to an exponential curve. Accuracy and meaning of these measurements may be criticised but it can be reasonably assumed that both are adequate for a fixed installation. A measure was also made of surface wave velocity i.e. velocity perpendicular to the fibre direction. Interlaminar shear strength was measured from short beam shear tests, composite density was measured in methyl alcohol, fibre fraction by acid digestion and void content by density measurements. On the basis of all these measurements, Vary and Bowles derived the concept of a stress wave factor. This factor was determined by injecting a repetitive ultrasonic pulse into a specimen using a broadband transducer, and detecting the resulting signal some distance away by means of a resonant transducer. The two sensors could obviously be located in various ways. The stress wave factor ε was defined by $\varepsilon = grn$ where

q is the period over which measurement is made

r is the repetition rate of the input pulse

and n is the ring down counts per burst.

Vary and Bowles claimed to be able to predict the relative mechanical strength of a composite material by means of ultrasonic-acoustic measurements made within a relatively 'narrow frequency domain' (0.1 to 2.5 MHz) and without the need for sophisticated equipment. Although the stress wave factor was shown to correlate strongly with interlaminar shear strength for the particular material, an even better correlation was found with density! However, when used in conjunction with surface velocity, an excellent estimator could be derived. There is no detailed physical basis for any of this work but it is clear that physical properties should be determinable from a study of sound wave propagation.

Later work by Vary and Lark (61) deal with more specific NDI applications of the stress factor approach. During scanning of tensile specimens of graphite/epoxy composite prior to a test, minimum values of stress factor were observed at a few positions along the specimen. After testing it was confirmed that failure occurred only at the previously indicated positions. It was claimed that stress wave factor 'may be described as a measure of the efficiency of stress wave energy transmission' in a given composite. Hence it was a sensitive indicator of strength variations and could aid in predicting potential failure locations. Williams and Lambert (62) attempted to use the Vary technique to characterize impact damage in graphite/epoxy composite. They modified the stress wave factor by summing (totally) the positive amplitudes of each ringdown. Through-thickness attenuation and the modified stress wave factor correlated with the number of standard drop-weight impacts and the residual strength.

A recent paper by Vary (63) deals with the whole topic in more general terms and extends use of the factor to metallic materials. Commercial equipment is now available for measurements of stress wave factor.

3.3 Acoustic Emission

Acoustic emission is defined by ASTM 610-77 (64) as 'The class of phenomena whereby transient elastic waves are generated by the rapid release of energy from a localized source or sources within a material, or the transient wave(s) so generated'. These waves propagate through a structure and are usually detected by a piezoelectric transducer. The resulting electrical signals can then be processed in various ways to give a wide variety of parameters (65). AE signal analysis has the potential not only to locate sources and thereafter to define defects in a structure but also to monitor structural integrity during proof-testing and in service. However, the case of a single source in a 'simple' material was only recently addressed by Hsu and Eitzen (66). In practice, the deconvolution of the detected signals into a precise measure of the source function is a complex problem even for relatively uncomplicated metal structures.

There are additional problems which must be solved before AE can be used for routine monitoring of the structural integrity of composite materials. Some of these problems have been detailed in the reviews by

Williams and Lee (67) and Duke and Henneke (68). In this review, we consider only signal-processing and AE source location, and discuss some applications.

There are numerous specific mechanisms which produce AE in composite materials (69), e.g. fibre fracture, matrix cracking, delamination, etc., many of which have already been mentioned. Wave propagation characteristics are complex and are dependent on composite type and design. Signal modification occurs during wave propagation due to:

(i) geometric spreading of the wave,

(ii) the effects of structural boundaries,

(iii) frequency-dependence of attenuation, and

(iv) the anisotropic nature of composite material.

The effects of all these phenomena must be considered during signal analysis. Finally, we need to know the relationship between the AE parameter and the structural integrity of the component.

Several authors have reported success in the rise of amplitude distributions to distinguish AE sources and hence identify failure modes - Bailey et al (70), Ryder and Wadin (71) and Graham (72) worked with carbon/epoxy material while Rotem (73) examined both carbon and glass/epoxy material. Becht et al (74) worked with glass/epoxy material. However, Guild et al (75) were unable to obtain direct correlation between micro-failure events in glass/epoxy material and the detected AE distributions. They went further and claimed that no simple correlation can be expected because, for the case of AE from fibre fracture, the amplitude of a fibre failure event depends sensitively on the condition of the local fibre/resin interface, the extent of debonding and the presence of an environment hostile to the glass. There are no doubt other factors which were not considered. Graham (72), Curtis (76) and Russell and Henneke (77) made detailed analyses of AE frequency spectra in the range 0.1 to 1 MHz and related features to different AE sources.

Location of an AE source may be determined from the measured difference in arrival times at two or more transducers, of a wave generated by a single AE event. AE location techniques are often essential in both laboratory and field to separate valid AE data from AE from extraneous sources. There are obvious problems in applying this technique to composite materials. In fibre-reinforced plastic structures, so many events occur during loading that sensors may be unable to isolate a single event (78). Hamsford (69) clearly defined problems relating to signal modification by wave propagation in attempting to use AE for source location on a KEVLAR spherical pressure vessel. Ryder and Wadin (71) successfully located damage during fatigue of a quasi-isotropic carbon-fibre reinforced composite. While Bailey et al (79) located damage in composite material fabricated in a balanced 'cross-ply' configuration.

In selected special situations, AE has been used successfully for monitoring structural integrity but it is far from viable as a universal method. In an early application, Wadin (80) described how AE counts, measured during a proof test, were used to predict impending failure of the fibre-glass boom of an aerial lift device. His flaw predictions were confirmed destructively. Fowler (78) and Fowler and Grey (81) developed acceptance projection criteria for fibre-glass tanks, pressure vessels and

piping, based on laboratory and fatigue tests. They introduced the Felicity ratio defined as the load at onset of AE divided by the maximum load previously attained. Their criteria are based on a combination of total counts, signal amplitude, AE activity during a load hold and the Felicity ratio.

Hamstad (69) and Wadin (82) discussed the presence or absence of the Kaiser effect (defined as the lack of detectable AE until previously reached stress levels are exceeded) in composite materials in terms of the viscoelastic matrix. Deformation at any stress level is significantly time-dependent, resulting in time-dependent AE. Thus, the absence of a Kaiser effect allows the determination of a Felicity ratio (as observed by Fowler). This ratio, in conjunction with observed AE, can be used to assess structural integrity. Bailey et al (79) used a similar approach to assess impact damage.

In addition to the above, many papers deal primarily with 'data gathering'. Future research will need to concentrate on developing a suitable universal model to describe composite material behaviour, before the potential of AE as an indicator of structural integrity can be fully realised.

4. DISCUSSION AND CONCLUSIONS

It has been found that most defects in composite material can be detected but not necessarily identified using the techniques discussed in 2. The most important limitations of each of these techniques are listed in the Table. To a marked extent, the success or failure of a chosen approach will be determined by these limitations.

TECHNIQUE	MAJOR LIMITATIONS
X-radiography	orientation of defect (crack) is critical
Ultrasonic C-scan	orientation of defect is critical; water immersion or application of jet may cause deterioration of composite (e.g. ingress at edges)
Neutron radiography	orientation of defect is critical; source is expensive and dangerous
Eddy currents	limited to carbon/epoxy composites
Optical holography	measures surface effects which are then related to defects; still essentially laboratory technique because accuracy greatly deteriorates with vibration
Acoustic holography	no major limitations but not yet fully developed; although commercial equipment is available, it is still essentially a laboratory technique
Thermography	sensitivity is presently marginal; strongly susceptible to ambient effects (temperature, draughts)

TABLE: Major limitations of NDI techniques

The use of several techniques in combination frequently yields far more information about defect location and extent than would result from using the same techniques in isolation. Similarly, knowledge of material behaviour frequently leads one to confirmatory evidence concerning damage. Often the use of techniques omitted from this presentation, e.g. coin-top or dye penetrant, can also provide useful information provided limitations are appreciated. The coin-top is strongly subjective and probably applies only to delaminations. Penetrants are only useful for surface-breaking (or edge) cracks and may prove troublesome if repair is attempted at a later date.

Different problems occur in field and laboratory. Radiographic and acoustic techniques are best applied to material in sheet or laminar form e.g. fibre-composite material during or after manufacture. Cooper et al (11) described some of the complex structures encountered in service (e.g. rudders were constructed using boron/epoxy 4 - 7 ply thickness for the skin which was bonded to aluminium full-depth honeycomb with cut-out members of aluminium titanium and fibre-glass). Not only are these structures much harder to inspect but a whole new range of in-service defects becomes apparent. Foremost is damage arising from impact, e.g. dropping of a hand tool, which may be hard to see from the surface but may involve multiple damage internally, particularly fibre breakage. Corrosion of metal components and degradation of composite strength from the presence of moisture is also important. These may form part of a general degradation process leading to eventual failure of the component.

Detection of manufacturing or in-service defects can be accomplished, but the significance of defects remains a major problem. So little progress has been made in solving this problem that one must perforce look to other solutions which may enable us to predict failure or identify a failure precursor. Four contrasting techniques have been proposed for the assessment of structural integrity.

(i) Vibration measurements, from which damage (of any nature) can be located and a measure of damage severity can be obtained.

(ii) Ultrasonic attenuation, in which changes can be related to damage rather than individual defects. From measurements of initial attenuation, failure loads or cycles to failure could be predicted.

(iii) Stress wave factor, which is a measure of energy transmission, is essentially a bulk ultrasonic parameter and enables potential failure sites to be predicted.

(iv) Acoustic emission, is presently only confirmed as a failure predictor which is derived during proof-testing.

None of these candidate techniques are entirely satisfactory. Attenuation and stress wave factor techniques appear to have little scope for future development. Both vibration and acoustic emission techniques appear to possess the potential for predicting failure, although considerable research and development is necessary. Whatever eventuates in the future, it can be certain that NDE of composites presents a real and exciting challenge to the materials Scientist.

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