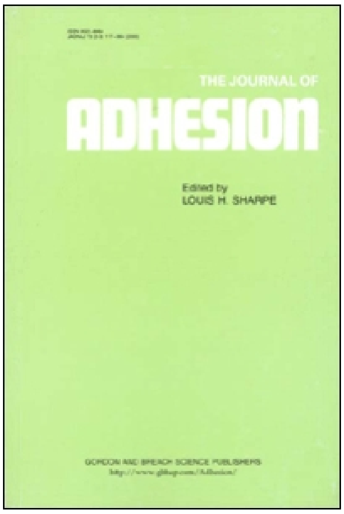

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The Non-destructive Testing of Adhesively Bonded Structure: A Review

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The Non-destructive Testing of Adhesively Bonded Structure: A Review

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The types of defect encountered in adhesive joints and the non-destructive testing techniques available to detect them are reviewed. Three types of defect: complete voids or dis-bonds, poor cohesive strength of the adhesive layer and poor adhesion between the adhesive layer and adherend are commonly present. It is shown that a variety of techniques is available for dis-bond and void detection, ultrasonics and sonic vibration being the most commonly used. The detection of poor cohesive and adhesive properties, however, is much more difficult than void and dis-bond detection and is the subject of current research. At present there is only one commercially available instrument which claims to predict cohesive strength. There is no reliable non-destructive test to detect poor adhesion.

KEY WORDS Adhesively bonded structures; bond defects; dis-bonds; flaw detection; non-destructive testing (NDT); voids; adhesion; cohesion.

INTRODUCTION

Adhesive bonding has been used extensively for many years in aerospace and other high-technology industries and has great potential for application to other areas of manufacturing. It is attractive because it distributes stress over the entire bond area and thus avoids the stress concentrations which can occur with mechanical fasteners. Also, the high temperatures of welding and brazing are avoided and improved appearance, together with reduced weight, can frequently be obtained. In spite of its potential advantages, the use of adhesive bonding in primary structure has been limited by a lack of adequate non-destructive testing procedures: without such procedures, the reliability of a structure cannot be guaranteed. Such testing will usually be performed after manufacture or at stages during manufacture; however, in more stringent applications, inspection during service may also be required.

Ideally, the non-destructive test would predict the strength of the bond. This is very difficult to achieve, partly because a direct measurement of strength cannot be non-destructive, so it is necessary to correlate strength with other properties such as bond area, stiffness, damping, etc. Also, the stress distribution in a typical adhesive joint is far from uniform (see, for example, Adams and Peppiatt[1]) so the strength is much more sensitive to the integrity of some areas of the joint than to others. Measurement of bond area, stiffness, and so on do not necessarily give good correlations with strength. Changes in these properties do, however, give an indication that a joint may be defective.

There are three main types of defect which occur in practice; these are:

i) Complete voids, dis-bonds or porosity.
ii) Poor adhesion, *i.e.*, a weak bond between the adhesive and one or both adherends.
iii) Poor cohesive strength, *i.e.*, a weak adhesive layer.

Voids or large gas bubbles in the adhesive are caused either by a lack of adhesive or by the presence of foreign matter on, or even in, the adherends. Porosity of the adhesive is similar to voiding except that the size of the bubbles can be much smaller. It is usually caused by volatiles or gases trapped in the adhesive. A major problem can occur with composite adherends if these are not adequately dried before bonding as absorbed moisture can vapourise during the cure cycle to produce bubbles in the adhesive.

Dis-bonds, or zero volume unbonds (areas where no void exists but also no adhesion is present), can occur during manufacture due to the presence of a contaminant, such as grease, on an adherend. The surfaces of a dis-bond are generally in close proximity, or are touching, but are incapable of transferring load from the adherend to the adhesive. Dis-bonds also occur as a result of impact or environmental degradation after manufacture. Environmental degradation generally takes place at an interface between the adhesive and an adherend, causing the bond to fail. Resistance to this mode of failure can be improved by use of the correct surface treatment prior to bonding.[2]

No reliable non-destructive test for the adhesion strength of a bond has been developed. Standard practice in the aerospace industry is to test the adherend surface prior to bonding[3,4] on the grounds that failures due to poor adhesion are always a result of inadequate surface preparation. Great care must therefore be taken to ensure that surface contamination does not occur between the time of this test and the bonding operation.

Provided the adherend preparation has been satisfactory, the adhesion strength of a joint is always greater than its cohesive strength. This is desirable since cohesive strength is more predictable than adhesion strength and hence can be used in design calculations. Variations in the physical properties, such as modulus and density, of a particular adhesive are primarily due to changes in the cure cycle. If, for example, the cure temperature is too low then insufficient cross-linking of the polymer takes place and an adhesive of incorrect modulus results. However, the non-destructive measurement of cohesive properties is much less reliable than the detection of dis-bonds and voids. Consequently, in practice, if the cohesive properties are to be checked, destructive tests are often performed on specimens manufactured under the same conditions as the actual structure.

TIME DOMAIN ULTRASONICS

Basis of the technique

The monitoring of ultrasonic echoes in the time domain forms one of the most widely used methods of non-destructive testing for bonded joints and composites. The method is commonly used for the detection of dis-bonds, bond line voids and porosity in adhesive joints.[5,6,7] Time domain methods are also being investigated as a method of predicting the cohesive properties of the adhesive.[8] This is discussed below.

An incident pulse of ultrasound will be reflected and transmitted, (assuming normal incidence, and hence no refraction), at each interface of the joint. The amplitudes of the reflected and transmitted pulses are dependent on the reflection coefficient of the interface, which may be calculated from

$$R_{12} = (Z_2 - Z_1)/(Z_1 + Z_2) \tag{1}$$

Also

$$T_{12} = 1 + R_{12} \tag{2}$$

where

R_{12} = Reflection coefficient
T_{12} = Transmission coefficient
$Z = c\rho$ = Acoustic impedance

where

c = Velocity of sound in medium
ρ = Denisty of medium

If a defect is assumed to contain air or any other low density substance then it will have a very low acoustic impedance relative to the adhesive or adherend. At a boundary between either an adherend or the adhesive and a defect, the reflection coefficient therefore approaches unity. An incident pulse at the defect is then practically totally reflected leaving negligible energy to be transmitted through the defect. Measurement of the reflected or transmitted energy may therefore be used to indicate the presence of a defect.

Due to the severe impedance mis-match between solid materials and air, it is difficult to propagate ultrasound from a transducer through air to the test structure. It is therefore vital that there is a satisfactory coupling agent between the transducer and test piece. This is often achieved by immersing the test piece and transducer in a water bath. The ultrasound then propagates across the water filled gap (typically 25–100 mm depending on the transducer) into the test piece. Alternatively, the transducer can be held in contact with the test structure, coupling being provided by a thin layer of gel or grease. Both methods tend to have problems since the immersion technique is often impractical for large components and buoyant honeycombs. The contact technique is slow when large areas need to be examined, and can be sensitive to contact pressure.[9] A further alternative is that of a water jet transducer or "squirter" in which the ultrasound propagates along a water jet which surrounds the transducer, as shown in Figure 1.

Techniques which monitor ultrasonic echoes can detect very small defects such as bond line porosity with a high degree of reliability. However, a major limitation arises if the coupling agent, water or fuel is allowed to penetrate the defect. The presence of the liquid reduces the reflection coefficient and the defect becomes much more difficult to detect. When the technique is used in production control, liquid ingress can usually be prevented. However, when

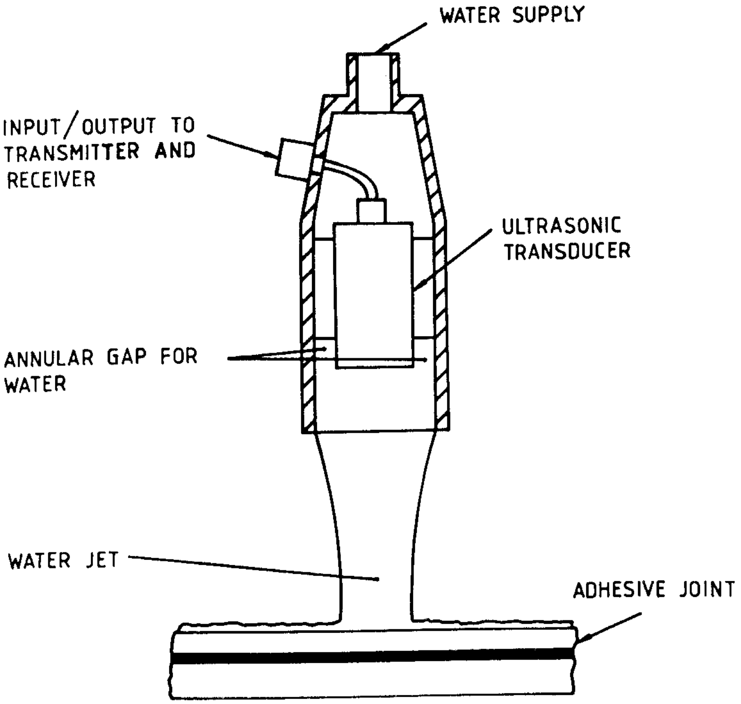


FIGURE 1 Typical water jet ultrasonic probe.

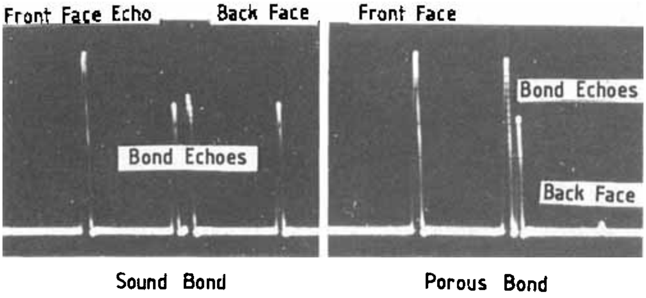


FIGURE 2 Typical A-Scan from a carbon fibre composite lap joint (from Clarke *et al.*[7]).

joints with an unknown history are examined, the results need to be interpreted with care.

Several methods of displaying the ultrasonic reflections are available, the most common being A, B, and C-Scans, which can be chosen to show the defect as required. The simplest presentation is an A-Scan which shows the amplitude of the echoes or reflections as a function of time (or distance, if a value for the velocity of sound in the medium is known), as shown in Figure 2. An A-Scan can be obtained at each point of the work surface, the relative amplitude of the echoes being used to establish whether defects are present.

The information can also be presented as a B-Scan. The time axis of the A-Scan becomes the vertical axis in the B-Scan (see Figure 3). Hence an image of the cross section of a component is built up. The horizontal lines in the B-Scan show areas where the echo from

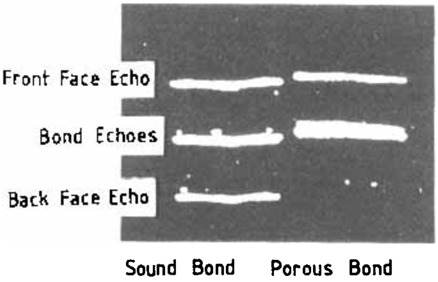


FIGURE 3 Typical B-Scan from a carbon fibre composite lap joint (from Clarke *et al.*[7]).

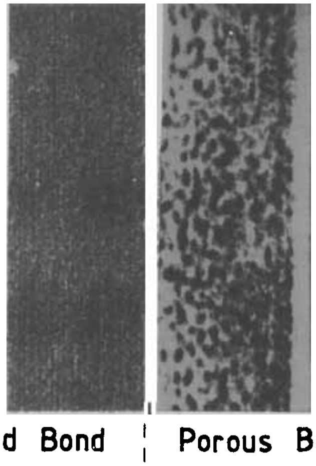


FIGURE 4 Typical *C*-Scan from a carbon fibre composite lap joint (from Clarke *et al.*[7]).

a feature at a particular depth exceeds a pre-set level. Information on the depth of features is therefore produced. In the case of an adhesive dis-bond, echoes from interfaces below the defect are very small so gaps appear in the horizontal lines from features below the dis-bond.

If the amplitude of a particular echo is monitored at each point on the surface of the work, a *C*-Scan can be produced. Measurements at each point are taken using a scanning mechanism, which produces a plan of the defect positions but gives no information on their depth (see Figure 4).

The automatic scanning mechanisms required to produce *B* and *C*-Scans usually employ immersion or water jet coupling whereas *A*-Scan devices often use the contact technique.

Ultrasonic transducer and equipment requirements

Many types of ultrasonic transducer are commonly available for use with non-destructive testing equipment. For time domain analysis it is desirable to use a transducer which produces short ultrasonic pulses so that echoes from the features of a joint may be more easily resolved. The pulse length obtained from a given transducer

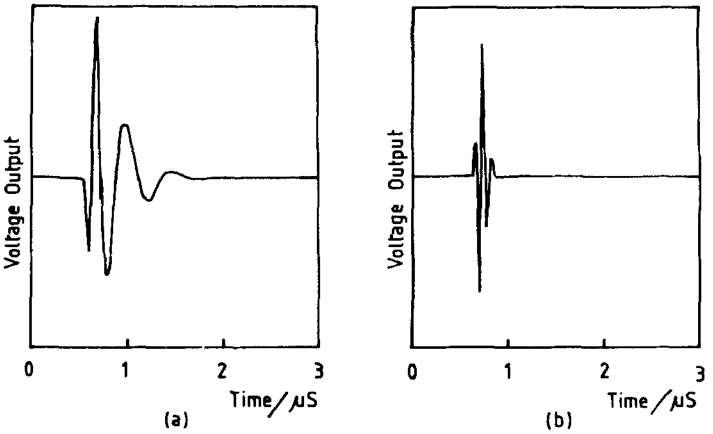


FIGURE 5 Transducer output voltage—Reflection off a flat surface separated from a 10 MHz transducer by approximately 25 mm of water. (a) 450 V excitation pulse and 2.25 MHz "narrow band" reciever (b) 200 V excitation pulse and 10.0 MHz "narrow band receiver".

is dependent on the excitation pulse and on the characteristics of the receiving amplifier. Figure 5 shows two ultrasonic pulses from the same transducer used with different excitation pulses and receiver ranges.

Transducers are often characterised by their frequency response. The frequency response (or spectrum) gives an indication of the energy available at particular frequencies when the transducer is used under certain conditions. The frequency at which the maximum energy occurs for a particular transducer and test set is often quoted and is typically in the range 1–25 MHz. It should be emphasised, however, that the pulse length produced by a transducer, and hence its performance, is not only dependent on the frequency response of the transducer but also on the pulser and amplifier used. The quoted 'frequency' of the transducer is therefore not a reliable measure of performance on its own.

The exact limit of resolution of two pulses or echoes depends on both their length and shape. As a rough guide, however, resolution becomes difficult when the separation between pulses is reduced to less than the pulse length; see Figure 6. The resolution of individual echoes is important if the depths of defects in a multilayered

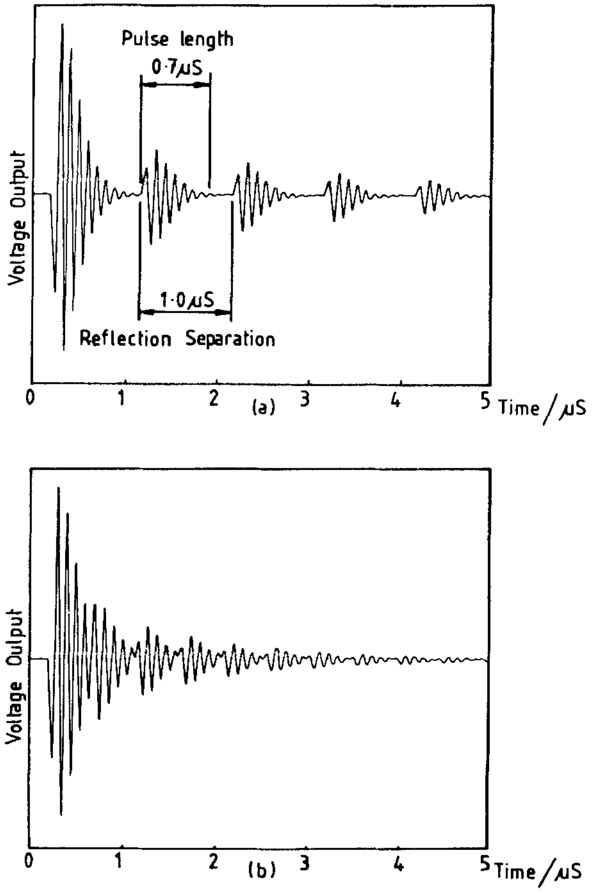


FIGURE 6 Resolution of ultrasonic pulses, from a 10.0 MHz probe, with varying separation (a) reflections 1.0 μs apart, from a 3.2 mm aluminium plate in water, (b) reflections 0.46 μs apart, from a 1.5 mm aluminium plate in water.

structure or the position of a defect within a thick bond line is required. Clarke, *et al.*,[7] showed that it is possible to distinguish between dis-bonds at either the top or bottom adherend/adhesive interface with a bond line thickness of approximately 0.1 mm provided pulse lengths of 0.05 μs or less are used.

The problem of resolution is less critical if large adhesive dis-bonds, whose position in the bond line is unimportant, are to be detected. The more commonly used transducers, giving pulse lengths of approximately 0.5 μs, are adequate for detecting disbonds in bond lines thicker than 0.2 mm. Although the front and back bond line echoes are typically only 0.16 μs apart, the dis-bond causes multiple echoes or ringing of the ultrasonic signal.[5] The multiple echoes are caused by repeated reflections from the dis-bond within the top adherend. These echoes can readily be distinguished from the rapidly decaying echoes produced by a sound joint; see Figure 7. It is also possible to use echoes from features

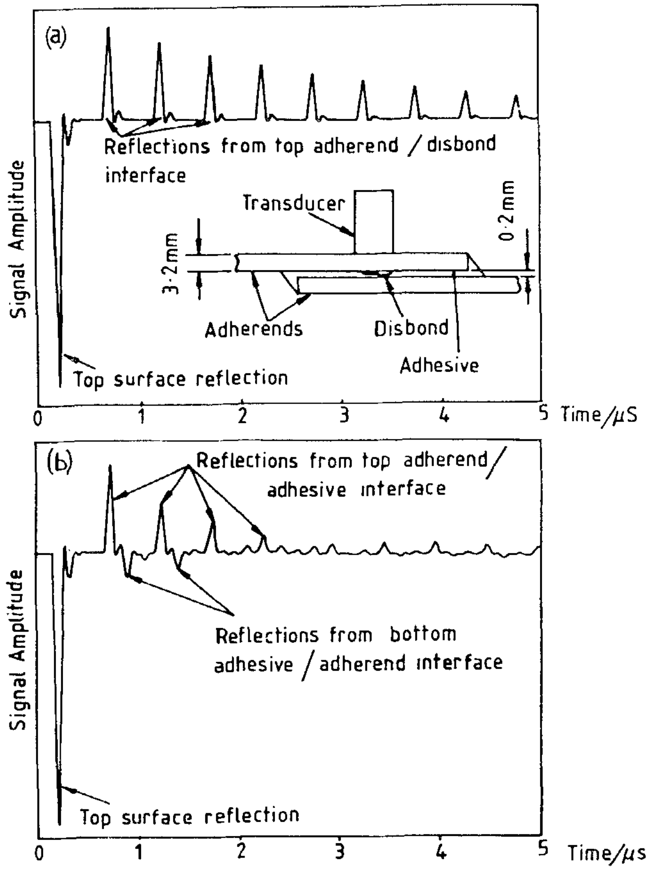


FIGURE 7 *A*-Scans of (a) disbonded and (b) sound adhesive joints showing transducer output voltage against time.

below the bond line for dis-bond location, since they will disappear in the presence of a dis-bond. However, in practice, it is difficult to distinguish such echoes from those produced within the top adherend, unless very short pulses are used. A number of transducer configurations are used with ultrasonic time domain analysis, the commonly used one being described below.

Through-transmission

The through-transmission technique uses separate transmitting and receiving transducers positioned either side of the structure to be tested, as shown in Figure 8. Alignment of one transducer above the other is important and can present difficulties when large components are tested. Alignment of the transducer axis perpendicular to the surface to be tested, however, is not as critical as with other techniques. Instead of monitoring the reflections from each interface, the magnitude of the transmitted signal is used to detect defects. The signal at the receiving transducer either reduces or disappears when a defect is present.

Through-transmission is particularly suited to the inspection of honeycomb structures. Using a pulse-echo technique (*see below*), only the bonding of the top face to the core can be tested reliably, whereas using through transmission, both top and bottom bonds between skins and core can be inspected in a single test.[5] The techniques can also be used with hand-held transducers for rapid production line inspection. The transducers are held against the

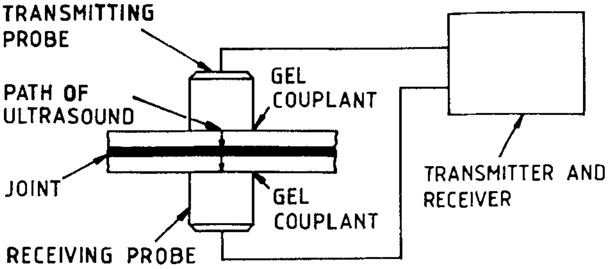


FIGURE 8 Configuration of transducers for the ultrasonic through-transmission technique. (Immersion or water jet coupling can also be used)

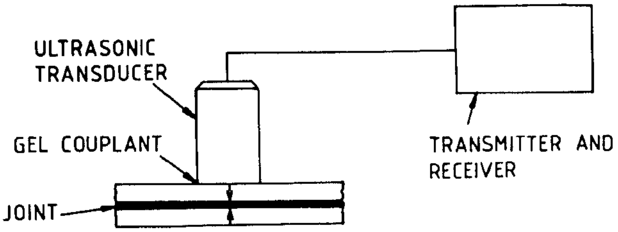


FIGURE 9 Configuration of transducers for the ultrasonic pulse-echo technique. (Immersion or water jet coupling can also be used)

specimen and are manually adjusted to give a signal of maximum amplitude. The amplitude of the signal is diminished in the presence of a defect.

Pulse-echo

The pulse-echo technique generally uses a single transducer capable of sending and receiving a pulse of ultrasound; see Figure 9. The delay between pulses and the geometry of the transducer ensure that reverberations from the transmitting crystal have died away before the echoes are received. Provided the pulses are short enough the individual echoes from each interface can be resolved, their position and amplitude being used to detect the presence of a defect. A large proportion of ultrasound will be reflected at a defect owing to its large reflection coefficient. Echoes from features behind the defect will also be reduced or disappear. This technique can use

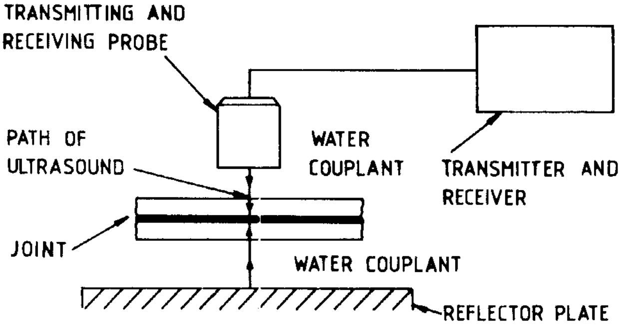


FIGURE 10 Configuration of transducers for the ultrasonic reflection technique.

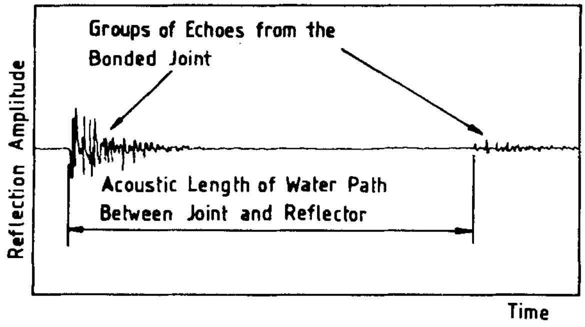


FIGURE 11 *A*-Scan from a sound joint using the reflection technique.

all types of coupling and forms the basis of most currently available ultrasonic test-sets. A minor variation is obtained by using a reflector plate beneath the structure; see Figure 10. In the absence of defects, the ultrasound passes through the structure and into the water to be reflected back up through the structure. The *A*-Scan would consist of groups of echoes from the structure separated by the time taken for the ultrasound to traverse the water path between the structure and reflector plate; see Figure 11. In the presence of a defect the incident pulse is practically totally reflected at the defect, so that no ultrasound is transmitted into the water behind the structure. Consequently, the *A*-Scan only consists of the slowly decaying echoes from the dis-bond; see Figure 12. The reflection technique can only be used with immersion coupling

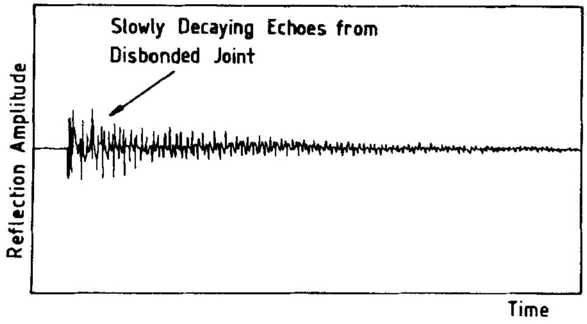


FIGURE 12 *A*-Scan from a dis-bond using the reflection technique.

owing to the need for a coupling agent between the reflector plate and rear face of the structure.

In all pulse echo testing, alignment of the transducer axis perpendicular to the surface of the structure or reflector plate is important if off-axis reflections are to be minimised.

Ultrasonic echo ratio

The methods described above are aimed at detecting defects with a high reflection coefficient, *i.e.*, dis-bonds and porosity. However, by measuring the relative amplitude of particular echoes it has been suggested[8,10] that the modulus and loss factor of the materials on either side of the interface can be found. Resolution of the individual echoes from the bond is essential, so very short pulses need to be used.[11] The resulting echo pattern is complex, the magnitude of individual echoes being dependent on the adhesive and adherend thickness in addition to the individual reflection coefficients.[12] Consequently it is very difficult to evaluate reflection coefficients and adhesive properties. As yet the correlation between predicted and measured adhesive properties has not been reliable.

ULTRASONIC IMPEDANCE AND SPECTROSCOPY

Principle of operation

Measurement of the through-thickness vibration characteristics of a bonded structure can be used to detect defects. Instruments working on this principle use transducers which operate in the frequency range 0.1–10 MHz. The transducers excite through-thickness modes of vibration of the structure via a suitable couplant. It should be noted that through-thickness resonance is quite different from membrane resonance. Membrane resonance involves flexure of the layer above a dis-bond, the strain in the direction perpendicular to the surface of the structure being negligible. However, the strain in through-thickness modes of vibration is primarily perpendicular to the surface.

Through-thickness vibration is often explained using a wavelength approach, resonance occuring when the thickness is equal to an integer multiple of half wavelengths so,

$$t = n\lambda/2 \tag{3}$$

or

$$t = cn/2f_n \tag{4}$$

where t = Thickness, λ = Acoustic wavelength
$n = 1, 2, \ldots$, c = Velocity of sound in medium
f_n = Resonant frequency of nth mode

For a solid plate, a series of equally spaced harmonics or resonances occur, each having a different deformed (mode) shape. For a given mode, the frequency of through-thickness resonance increases as the thickness decreases. The early type of ultrasonic thickness gauge used this principle[13] and was the forerunner of several 'bond testers'. The response of a bonded joint is considerably more complex than that for a single plate, the resonances no longer being equally spaced. The natural frequencies of the joint depend on the material properties and thickness of the adherends and adhesive layer(s). Instruments for the non-destructive testing of adhesive joints based on the measurement of the through-thickness vibration properties fall into two groups: those operating at a single frequency which monitor the amplitude and/or phase of the response at this frequency and those using a range of excitation frequencies, in which resonant frequency and amplitude changes are detected.

Single frequency instruments

Bond testers which operate at a single frequency are limited to the detection of dis-bonds or gross voiding in an adhesive joint, and are essentially ultrasonic impedance measuring instruments. The instrument measures the response of the system comprising the transducer and the joint. By coupling the transducer to the joint, the modes occur at lower frequencies, the range in which the resonances occur being primarily governed by the transducer or probe. Different probes are used for different applications but they typically operate in the range 0.1–5 MHz. Bond testers of this type either measure response alone (such as the 210 Bondtester manufactured by NDT Instruments)[14] or response and the phase between excitation and response (such as the Bondascope 2100 also manufactured by NDT Instruments).[15] In both cases, however, it is important that the instrument operates at a frequency below or at the first through-thickness resonance of the good structure.[16] The response then decreases as the probe moves from a good to a dis-bonded area. If the instrument operates above the first through-thickness resonance of the good structure, for example at the through-thickness resonance of a dis-bond, it can become difficult to distinguish between dis-bonds at different depths in a multilayer structure. More importantly, distinguishing dis-bonds and undamaged structure can also become difficult.

Ultrasonic spectroscopy

Spectroscopic techniques give information on resonant frequency and amplitude of response over a wide range of frequencies rather than at a single frequency as described above. As the frequency range increases, more modes of vibration can be examined and the potential for extracting information about the bond increases.

The technique of broad band ultrasonic spectroscopy[17,18] can be used to measure frequency response over a wide frequency range, *e.g.*, 1–20 MHz. Difficulties, however, have been experienced in correlating the complex spectra obtained with cohesive properties, but current research is aimed at overcoming these.

Fokker Bond Tester Type II

The widely used *Fokker Bond Tester, Type II*[19,20] also uses a spectroscopic approach. It monitors frequency and amplitude changes in the first two modes of through-thicknesses vibration of a system comprising a transducer coupled to the joint. These parameters are dependent on both adherend and bond line thickness and the material properties, such as the adhesive and adherend moduli and damping (loss-factor). The range of frequencies over which the instrument operates depends on the transducer, but it is typically between 0.3 and 1.0 MHz. The bond tester is set-up by tuning to a resonance over a single adherend; the response of a single adherend is similar to that of a disbond. When the probe is then positioned over a good bond, the resonant frequencies of all

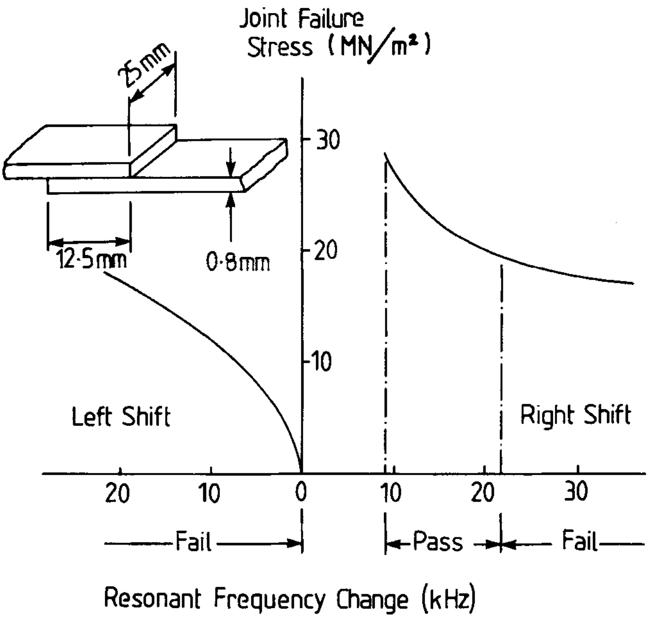


FIGURE 13 Example of a correlation curve, between resonant frequency changes and failure stress, for a *Fokker Bond Tester MK II*. A "right shift" is a decrease in frequency and a "left shift" is an increase in frequency (after Schliekelmann[20]).

the modes decrease. The instrument uses the frequency of the first mode of through-thickness vibration over a single adherend as a reference. It measures the difference between this frequency and that of the first two modes for the joint under test in addition to the amplitude of response. These differences in frequency can then be used in conjunction with a correlation curve to predict cohesive strength.

The instrument can be used reliably to locate dis-bonds and large voids, where the frequency shifts between a good bond and a defect are quite large. It can also be used to find the depth of dis-bonds in multi-layered structures by comparing the measured frequency shifts with those of a bond containing known defects. However, it is more difficult to predict cohesive properties and strengths[21,22] since the frequency shifts resulting from a change in cohesive properties or bond line thickness are much smaller and of a similar magnitude to each other. Hence an apparent change in modulus could be caused by a change in bond line thickness.

SONIC VIBRATION

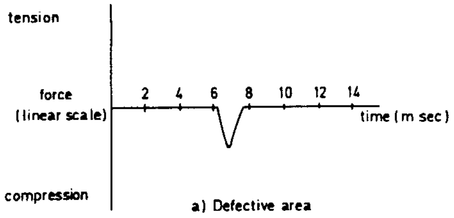
Scope of the techniques

A family of sonic vibration techniques is used for non-destructive testing of adhesive bonded structures. Most of these depend on a defect causing a local change in stiffness and hence a change in vibrational properties of the structure. The testing methods can be split into two types, those requiring excitation and response measurement at each point tested, and those using excitation at a single point and measuring response over the whole structure. The size of defect which can be detected is related to the wavelength employed. As the frequency increases, the wavelength decreases, and the minimum detectable size reduces. Instruments using sonic vibrations operate typically at frequencies up to 20–30 kHz, so they will not be able to find defects as small as those detectable at ultrasonic frequencies (up to 25 MHz). Sonic vibration techniques will generally only detect dis-bonds or gross voids, their exact size depending on the depth or thickness of adherends. Although the minimum detectable size is larger, the tests are often faster than the ultrasonic techniques and they do not require a coupling agent between the transducer and test structure. The techniques are most sensitive to defects close to the surface of a stiff structure and are therefore well suited to the inspection of honeycomb constructions.

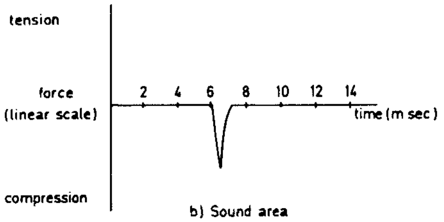
Coin tap test

The coin tap test is one of the oldest methods of non-destructive inspection. It is regularly used in the inspection of laminates and honeycomb constructions.[23] Until recently, however, the technique has remained largely subjective and there has been considerable uncertainty about the physical principles behind it. The sound produced when a structure is tapped is mainly at the frequencies of the major structural modes of vibration. These modes are structural properties which are independent of the position of excitation.

Therefore, if the same impulse is applied to a good area and to an adjacent defective area, the sound produced must be very similar. Therefore the difference in sound when good and defective areas are tapped must be due to a change in the force input. When a structure is struck with a hammer, the characteristics of the impact are dependent on the local impedance of the structure and the hammer used. The local change in structural stiffness produced by a defect changes the nature of the impact. The time history of the force applied by the hammer during the impact may be measured by incorporating a force transducer in the hammer. Typical force-time histories from taps on sound and dis-bonded areas of an adhesively bonded structure are shown in Figure 14. The impact on the sound structure is more intense and of a shorter duration than that on the damaged area, the impact duration on the sound structure being approximately 1 ms compared with 1.7 ms on the defective zone. The differences between the force pulses are more readily quantified if the frequency content of the force pulse is determined. This is achieved by carrying out a Fourier transform of the force-time records. The spectra of the force-time records in Figure 14 are



a) Defective area



b) Sound area

FIGURE 14 Force time records for impacts on dis-bonded and sound areas of an adhesive joint (from Adams and Cawley[24]).

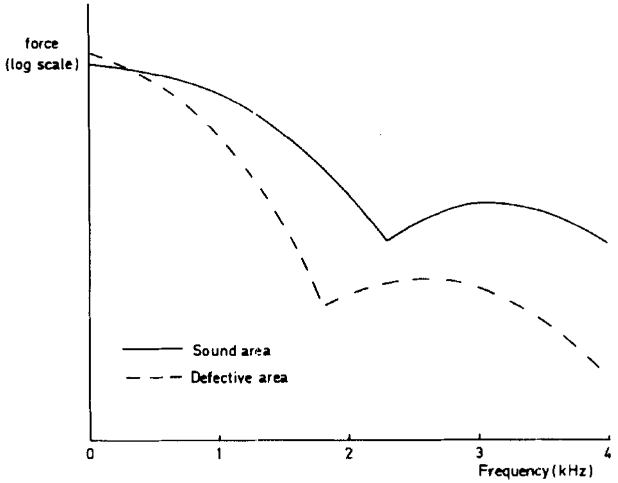


FIGURE 15 Spectra of the time records shown in Figure 14 (from Adams and Cawley[24]).

shown in Figure 15. The impact on the damaged area has more energy at low frequencies, but the energy content falls off rapidly with increasing frequency. The impact on the sound area has a much lower rate of decrease of energy with frequency. This means that the impact on the defective area will not excite the higher structural modes as strongly as the impact on the good zone. The sound produced will therefore be at a lower frequency and the structure will sound "dead".

The testing technique therefore involves tapping the area to be tested with an automatic, instrumented hammer designed to give a single, reproducible impact. The frequency spectrum of the impulse is then compared with that of an impulse, with the same hammer, on an area of the structure that is known to be sound. Data from a sound structure is stored in the testing instrument so that it can carry out the comparison and give an immediate indication of the integrity of the area under test.[24] Measurements are only based on the impact force; consequently, no transducers need be attached to the structure which avoids the coupling and alignment problems which arise with, for example, ultrasonic techniques.

A similar device, the *Acoustic Spectral Flaw Detector,*[25] uses the measurement of vibration response rather than input force. The response is measured using a transducer attached to the structure or by a microphone. However, the use of response measurements at frequencies up to membrane resonance can lead to contradictory results.[24]

Mechanical impedance

The impedance method has been used for many years in the Soviet Union.[26] More recently the Acoustic Flaw Detector and the MIA 3000, developed by Inspection Instruments Limited and based on the original Soviet design, have been available in the West. The technique uses the principle of local impedance measurement to detect flaws in the plane parallel to the test surface. The point impedance, Z, of a structure, can be defined as

$$Z = F/v \tag{5}$$

where F = harmonic force input to structure
v = resultant velocity of the structure

Commercially available instruments generally take measurements at a single pre-set frequency, typically between 1 and 10 kHz. As

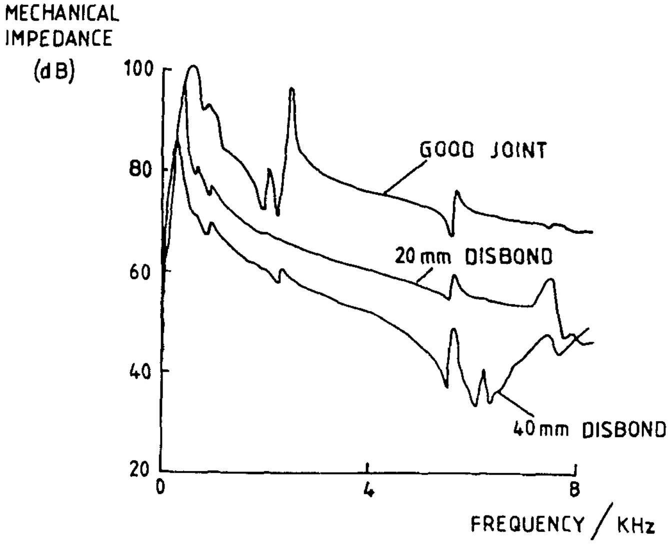


FIGURE 16 Mechanical impedance against frequency for a thick beam with an adhesively bonded skin 3.3 mm thick (from Cawley[27]).

the probe is moved from a good to a defective area, the impedance decreases. Figure 16 shows the impedance as a function of frequency for dis-bonds under a 3.3 mm thick aluminium skin adhesively bonded to a thick steel beam. As the base structure becomes more flexible, the impedance of a defective zone can be higher or lower than that of a good zone, depending on the frequency, so the test becomes less reliable.[27]

Instead of using a coupling agent, a dry point contact is used between the transducer and structure. This contact has a finite

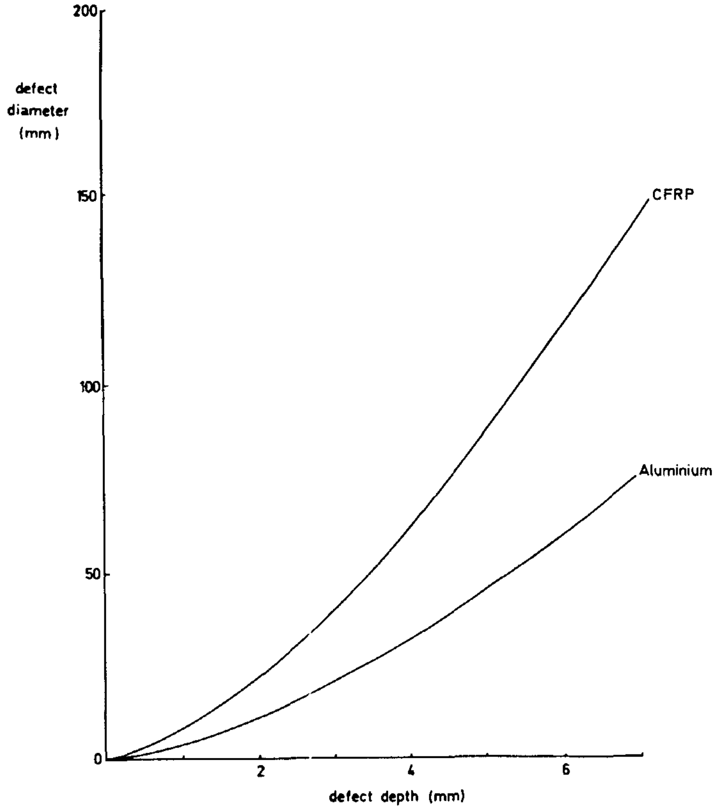


FIGURE 17 Minimum detectable defect diameter against depth in aluminium and carbon fibre composite assuming a 3 dB reliability in impedance measurements (from Cawley[27]).

stiffness[28] which must be kept as high as possible, otherwise the sensitivity of the technique will be reduced.

Figure 17 gives an estimate of the minimum detectable defect diameter *versus* depth in aluminium and carbon fibre reinforced plastic structures. These curves assume a stiff base structure and that the impedance of the defective zone must be at least 3 dB lower than that of the sound zone for the defect to be reliably detected. The technique is less sensitive with the composite owing to the reduced contact stiffness obtained with this material.

Membrane resonance

A planar dis-bond can be modelled as a plate restrained around the edges by the surrounding structure. As the frequency of excitation increases, this plate resonates, the first mode being the membrane resonance and having a deflected shape similar to that of a diaphragm. At resonance, the impedance measured over the defect reduces to a minimum and the response for a given force input increases substantially. Hence, at or close to membrane resonance, the response amplitude of a defective zone will be much higher than that of the surrounding structure. Since this resonant amplification is high, typically greater than a factor of 10 (20 dB), resonance can be detected by measurement of response alone. This can lead to inaccuracies since it assumes that the input force is roughly constant but it can simplify the measurement technique and apparatus. Although less accurate measurements are required than for the impedance method, it is important that the operating frequency is at or close to the resonant frequency of the layer(s) above the defect. The layer(s) above a defect may be modelled as a disc clamped around its edges. The resonant frequency of such a disc is given by:

$$f_n = \frac{0.47h}{a^2} \cdot \left[\frac{E}{\rho(1-\nu^2)}\right]^{0.5} \tag{6}$$

where h = defect depth; a = defect radius
E = Young's modulus; ρ = density
ν = Poisson's ratio

In practice, this frequency would represent an upper limit, since the actual edge conditions fall somewhere between fixed and simply supported. The typical maximum operating frequency of instruments of this type is 20–30 kHz. If 1.6 mm aluminium adherends are assumed, then the minimum detectable defect diameter (*i.e.*, at 30 kHz) would be approximately 23 mm. At 10 kHz, this size would increase to 40 mm.

The *Fokker Bond Tester Type I,* (the more commonly used Mk II or Type II, model 70 operates at a much higher frequency and on a different principle, see a previous section), uses white noise excitation in the range 0.5–10 kHz[20]. A transmitting and receiving transducer are housed in the same probe which requires no coupling agent. The ratio between the transmitted and received energy is displayed on a meter and is used to identify defects.

The *Harmonic Bond Tester* manufactured by the *Shurtronics Corp.* operates at a single frequency[6] and was developed by Boeing from the *Eddy Sonic Test System.*[29] The excitation is *via* induced eddy-currents which require no coupling agent. However, part of the structure under test must be electrically conducting to support the eddy-currents. The response is measured by a microphone in the eddy-current coil.[30] The interaction between the original and induced fields produces vibration at double the frequency applied to the coil, giving an excitation frequency of 28 kHz. A single excitation frequency is also used in the "acoustic amplitude" method developed by Lange.[25] To be sure that defects are detected, it is important that they are excited at or close to their membrane resonance. If the excitation is at frequencies over a broad range, (white noise), then this can be achieved. However, if the excitation is at a single frequency, there is a high probability of missing defects.

Vibrothermography

The technique of vibrothermography (or active thermography) monitors the surface temperature of a component as it is cyclically stressed. A defect will cause a local rise in temperature due to either frictional heating at its internal surfaces or hysteretic energy dissipation. An infra-red thermal imaging camera is usually used to measure the temperature of the component by representing the isotherms on its surface as a series of colours or tones. Heating can occur during low frequency fatigue testing, *i.e.*, at 1–2 Hz. Pye and

Adams[31] showed, however, that if a component is excited at a resonant frequency the input forces required are much smaller than in fatigue testing and the method becomes feasible for non-destructive testing in the field. Russell and Henneke[32] located dis-bonds in composites by exciting them at their membrane resonances. At frequencies of up to 26 kHz, the dis-bonds could be made to show up as hot spots. As the frequency was increased further, the membrane resonance was passed, heating ceased, and the damage was not detectable.

Vibrothermography has the potential advantage of being able to monitor the response of large areas when exciting at only one location. The method depends on a local temperature rise for damage location. Since this is controlled by the thermal conductivity of the component, the sensitivity of the technique will be reduced as the conductivity rises. Pye and Adams[31] found that damage was more difficult to detect in carbon fibre composites than in glass fibre constructions for this reason. Current infra-red cameras are able to resolve differences in surface temperature of typically 0.1°C which probably limits them to the detection of dis-bonds in composite adherends, rather than metal ones.

Holographic techniques can also be used to locate defects over large areas in a similar way to vibrothermography. Holographic interferometry[33] enables the very small discontinuities in surface displacement, which occur at a defect when a component is stressed, to be measured. Although rapid inspection is possible, the technique is still under development and equipment costs are high.

PASSIVE THERMOGRAPHY

Passive thermography uses the same techniques as vibrothermography to measure the surface temperature of a component. However, passive thermography monitors the response of the structure to thermal transients created by an external heat source. Either heating or cooling transients can be used to detect dis-bonds and voids in bonded panels. Heating transients can be induced by heating the back surface of the structure and measuring temperature changes at the front. Defective areas are cooler owing to the lower conduction through voids. Heating transients can also be created by heating on the same side as the camera; the defects then appear as hotter areas. Cooling transients can be used in a similar manner by applying an aerosol freezer spray to the surface to be tested. There are significant differences between one and two sided examination; heating the back face and monitoring the temperature at the front enables deeper defects to be detected. Heating and monitoring the temperature at the same surface, however, can produce better results with near surface defects. It is important to note that thermal transients must be used because a defect would have a negligible effect on steady state heat transfer. In practice these thermal transients have to be recorded since a temperature difference sufficiently large for detection may only exist for a brief period. The use of video recording techniques has greatly simplified this process.[34] The sensitivity of the method is reduced, like vibrothermography, as conductivity increases. Difficulties can also arise if the surface to be tested has areas of different emissivity, though this effect can be reduced by spraying the surface under examination to render it matt black. The technique can be used to detect delamination and voids in composites[35] and has also been used successfully with aluminium adherends. Schliekelmann[20] reports that voids of 25 × 25 mm can be detected below 0.5 mm thick aluminium adherends.

Although the cost of thermographic equipment is high, such techniques have the potential advantage of testing large areas rapidly.

X-RADIOGRAPHY

X-Radiography is commonly used for locating defects in manufactured components and materials. Radiography has also been used to locate bond-line porosity in carbon composite joints.[7] However, if porosity is to be reliably detected, the absorption of radiation in the adhesive has to be increased by incorporating a filler, such as aluminium powder, in it. The technique cannot be used effectively when a material with high absorption is used as either of the adherends. The much greater absorption in, for example, aluminium would mask small changes resulting from voids in the adhesive and thus make them undetectable.

The location of dis-bonds in joints is more difficult because the thickness of a defect parallel to the beam is substantially less than for porosity. Dis-bond location can be improved, however, by using a radio-opaque penetrant such as zinc iodide. The technique is more commonly used to locate impact damage in composites[36] and requires a point of entry for the penetrant at the surface and this is not always present.

DISCUSSION

A variety of methods is available for the detection of complete dis-bonds in adhesive joints. However, techniques which attempt to predict cohesive strength, such as ultrasonic spectroscopy and the *Fokker Bond Tester Type II* are not yet generally regarded as reliable. Research is, however, continuing in this area and shows considerable promise. Also, the non-destructive measurement of adhesion strength is currently not possible. Two techniques being examined for quantifying adhesion strength, although not truly non-destructive, are those of acoustic emission and the debonding of weak joints. Work by Curtis[37] and Hill[38] suggests that acoustic emission counts can be used to detect adhesion failure prior to fracture, as a joint is loaded. Another approach[39] classifies weak adhesion strength by attempting to debond a joint with high energy ultrasound. Weak bonds would fail and could be detected as dis-bonds whereas bonds with a high adhesion strength would be unaffected. It is likely that such a test would only be able to separate very low from high adhesion strengths.

In practice, adhesion failure and poor cohesive properties are generally prevented by careful surface preparation and process control. This leaves the bond inspector to monitor the presence of voids and dis-bonds in the glue line. Of the many techniques used for void and dis-bond detection, some are more suitable for use in particular circumstances than others. The high frequencies used with ultrasonic attenuation are especially suited to the detection of small defects such as bond line porosity. Consequently, the technique is commonly used in conjunction with immersion coupling or a water jet probe and a *C*-Scan display to produce a defect map of a component. The ultrasonic *C*-Scanning of relatively large components, although capable of detecting small defects, can be time consuming and expensive. The method is more commonly used for post-manufacture than for in-service testing.

Ultrasonic *C*-Scan frames are also available for use on small areas of in-service components. They are commonly used with a gel couplant or a water jet probe and can be useful when a component cannot be immersed.

Larger defects than porosity, such as voids and dis-bonds, do not require the accurate scanning facility of a *C*-Scan rig and can often be detected by hand scanning. Again a gel couplant or jet probe is often used, the defects being detected using an *A*-Scan presentation. Such techniques are relatively adaptable and can be used either after manufacture or in service. A similar set-up, used with a *B*-Scan display, can be valuable for showing defect depth in a multi-layered joint.

Since a complex *C*-Scanning rig and immersion tank are likely to be a major capital expense, it is important to decide whether its accurate scanning facility is necessary. If bond line porosity can be eliminated reliably, by experience and process control, then larger defects may be more economically located by an ultrasonic hand scanning technique.

The applications of the ultrasonic impedance technique are very similar to those of time domain ultrasonics mentioned above. Ultrasonic impedance devices have been used with both *C*-Scan rigs and hand scanning; however, since most operate at low ultrasonic frequencies (0.1–2 MHz), they will not be able to detect such small defects as bond line porosity. Also, instruments of this type can give misleading results if defects at other depths are encountered. The widely used Fokker Bond Tester Type II and other instruments can, however, be used to monitor defect depth.

Ultrasonic impedance instruments also require a couplant between the transducer and the test structure, and as with all techniques which need a coupling agent, it is important to prevent the ingress of any liquid into a defect, or it can become very difficult to detect.

Techniques based on the use of sonic vibrations will only be able to detect dis-bonds or gross voiding of the adhesive layer, although they do offer some potential advantages over the ultrasonic techniques. Methods which use single point excitation and a noncontacting, scanning measurement system, such as vibrothermography and holography, have the particular advantage that large areas can be inspected rapidly. Unfortunately, the equipment required tends to very expensive. It is very probable that the thermographic system used in vibrothermography will be more expensive than an ultrasonic *C*-Scan rig. Nevertheless, in large scale applications where the techniques have the required sensitivity, the costs will be justified.

The other sonic vibration techniques, which require excitation at each test point, are slower than those requiring excitation at a single point. However, they have the advantage over the high frequency ultrasonic methods that a dry point contact between the probe and the structure is satisfactory, so no coupling fluid is required. They are therefore easier to apply, particularly *in situ,* for example on an aircraft wing. The techniques are also particularly suited to the inspection of honeycomb constructions. The mechanical impedance method operates at a single excitation frequency so the computational requirements are small. This means the probe can be moved over the surface of the structure giving a continuous reading. Unfortunately there are dangers in using only one frequency. The techniques based on the membrane resonance of the layer above the defect are quick, but problems arise with defects whose natural frequencies are above the frequency range of the instrument. The probability of missing defects is greatly increased if excitation is confined to a single frequency or a narrow band.

The automated coin-tap method requires a spectrum to be computed at each point. This means that the inspection rate is of the order of 10 positions per second. However, the reliability is improved by looking at more than one frequency. Since the tapping head only makes instantaneous contact with the structure, problems of alignment and clamping force, which can arise with the impedance technique, do not occur. Most of the vibration methods described can be used with a hand held probe or with a scanning frame to produce a *C*-Scan presentation.

Passive thermography offers similar advantages to those of vibrothermography and is likely to cost approximately the same. However, unlike vibrothermography, passive thermography does not require any attachment to the structure to be tested or that it should be excited over a broad range of frequencies.

X-Radiography is well established in other areas of nondestructive testing, particularly in the quality control of welds and castings. Unfortunately, its application to the non-destructive testing of joints is limited to cases where the absorption in the adherends is low, such as when composite adherends are used. Results can be enhanced by using a radio-opaque penetrant but this is not generally practical for voids and dis-bonds. However, the technique can be useful in research to size defects accurately.

CONCLUSIONS

No reliable nondestructive technique currently exists for measuring the adhesive and cohesive strength of a bonded joint, so it is often assumed that a joint is serviceable provided it is free from voids and dis-bonds. Poor adhesion and cohesive properties are generally avoided by careful surface preparation and process control, but joint design has to be conservative to allow for variation in these properties.

No single method of detecting dis-bonds and voids is universally applicable. Since it is likely to take longer and cost more to find smaller defects, it is important to know the size of the smallest defect which must be detected. This size, together with the type of testing environment, *i.e.*, post-manufacture or in-service, and the structure to be tested, will help to determine which type of technique is the most applicable.

The sonic vibration techniques are particularly useful in circumstances where the use of the coupling fluids required for ultrasonic testing is undesirable. They are frequently used for the inspection of honeycomb constructions to which they are particularly suited. Ultrasonic techniques, however, are generally able to detect smaller defects than those using sonic vibrations. If rapid inspection of large areas is required, then a thermographic technique can offer substantial advantages.

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