The predicted spectra can be compared with measured responses to determine if the aluminum layers are bonded. The bonded system has six minima within the frequency range of 1 to 10 MHz. The unbonded aluminum layer has only three minima. The minima are the result of destructive interference of the waves within the test object. In the time domain, a large number of minima are associated with fewer reflections in a given time. Multiple reflections with a short time of flight identify unbonded aluminum plate and are used in a test called the *ringing technique*.

The spectral representation of the pulse echo results in Fig. 19a are shown in Fig. 19b. There is general agreement between the theoretical and measured spectra but a number of detailed features of the theoretical predictions are not reproduced in the measured spectra.

Leaky Lamb Waves

In the techniques discussed above, the ultrasonic waves were incident normal to the test object. The leaky lamb wave technique is based on insonification of the test object at an oblique angle, where the wave is refracted and mode converted to induce plate waves. When excited, these waves propagate along the plate and are strongly affected by the properties of the bond.[50,51]

The leaky lamb wave technique uses two transducers in a pitch catch arrangement. The test object is typically immersed in a water tank or a water column is maintained between the transducers and the object surface. For a fixed angle of insonification, the acoustic waves are mode converted to lamb waves at specific frequencies, resulting in leakage of acoustic radiation into the fluid.

When a leaky wave is introduced, the field of the specularly reflected wave (reflection from a half space) is distorted. The specular component of the reflected wave and the leaky wave interfere, a phase cancellation occurs and two components are generated with a null between them.[52] A schematic diagram of the leaky lamb wave technique using a plate immersed in fluid is shown in Fig. 20. A typical pulsed schlieren image of the leaky lamb wave response using a glass epoxy laminate is shown in Fig. 21.

Figures 22 and 23 show the spectral response of a uniform aluminum plate and a bonded aluminum epoxy plate immersed in water and insonified at 0.34 rad (19.5 deg). The minima often are associated with the excitation of leaky lamb wave modes in the test object. The agreement between theory and experiment is excellent for the unbonded plate and reasonably good for the bonded plate, indicating a need for further study.

The possible lamb modes at various angles of incidence are shown by dispersion curves. Figure 24 shows the calculated dispersion curves for the three possible cases of a bonded aluminum plate. The dispersion curves in Fig. 24c show good agreement between theory and experiment for unbonded plate. The agreement is good for the bonded plate, except at high frequencies and high phase velocities.

FIGURE 19. Measured data from joint in thin bonded aluminum plates immersed in water. Epoxy layer is 0.1 mm (0.004 in.) thick and plate is 0.8 mm (0.032 in.) thick: (a) time domain data; (b) spectral data.

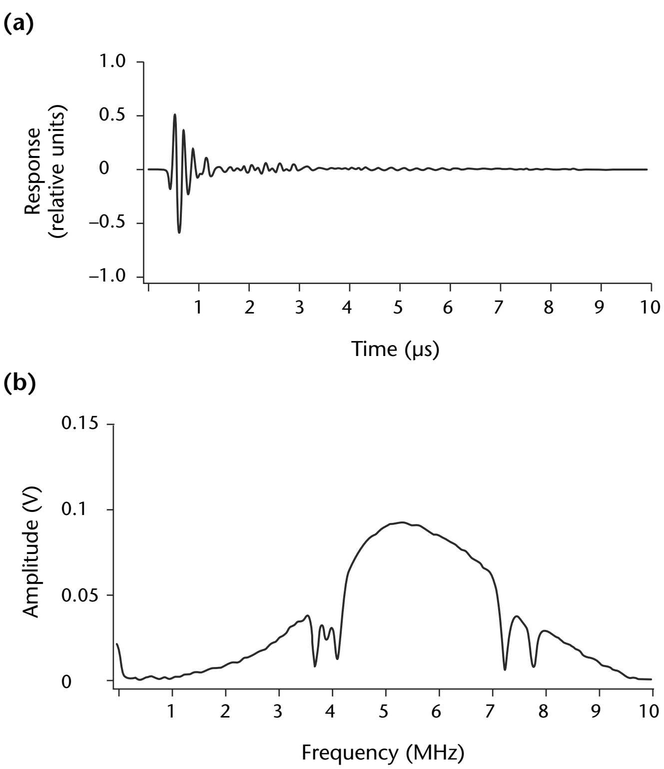
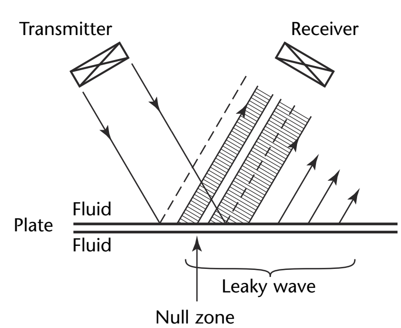


FIGURE 20. Schematic diagram of leaky lamb wave field.



Generally, a bonded structure can give rise to many possible modes that are modifications of those for a single layer. For a bonded system, the excitation of the spectral response predicted for a single layer is an indication of unbonding in the tested area. Leaky lamb waves can be used for nondestructive testing of bonds by scanning an assembly and detecting areas at which the leaky lamb wave modes appear. These modes are different from those of the bonded assembly.

Leaky Lamb Wave Characteristics

Leaky lamb wave phenomena have two characteristics that make them useful for nondestructive tests of bonds. First, phase cancellation in the null zone of the leaky lamb wave field is sensitive to changes in interface conditions. The presence or absence of bonding as well as the change in the properties of the adhesive significantly alter the leaky lamb wave response.

Furthermore, two types of stress (compression and shear, corresponding to longitudinal and transverse waves) are encountered simultaneously when a lamb wave travels in a plate. Only one type of

FIGURE 21. Pulsed schlieren image of leaky lamb wave mode for tone burst signal before and after impinging on glass-to-epoxy sample: (a) incident beam; (b) reflected and transmitted beams.

(a)

(b)

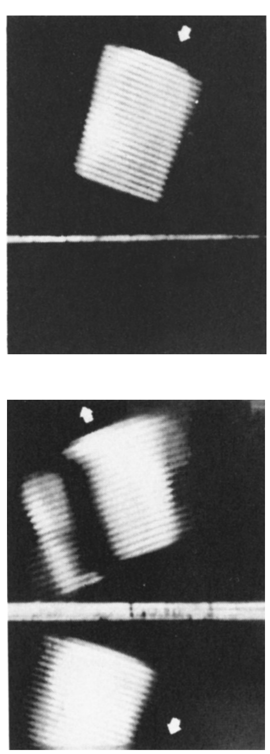


FIGURE 22. Leaky lamb wave spectra from unbonded aluminum plate (0.8 mm [0.032 in.]) immersed in water with incidence angle of 0.34 rad (19.5 deg): (a) measured spectrum; (b) calculated reflection spectrum.

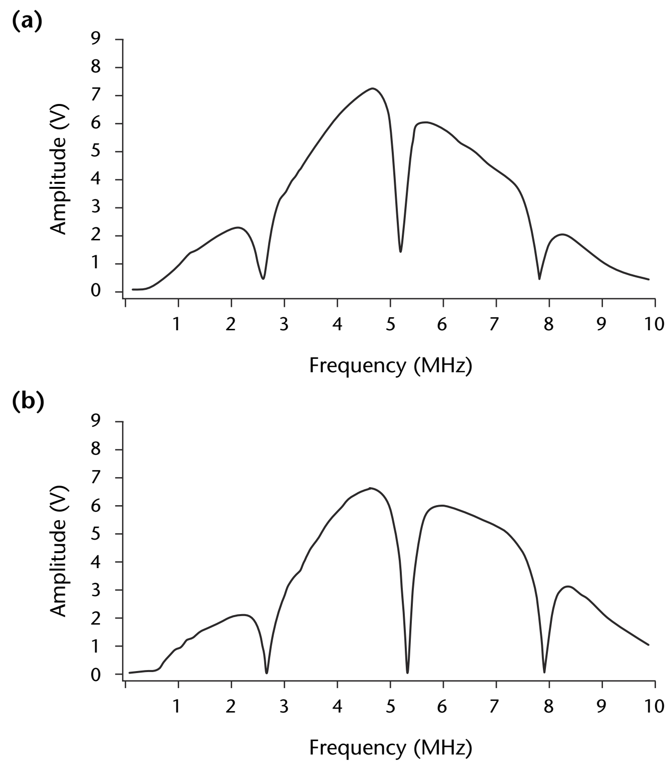
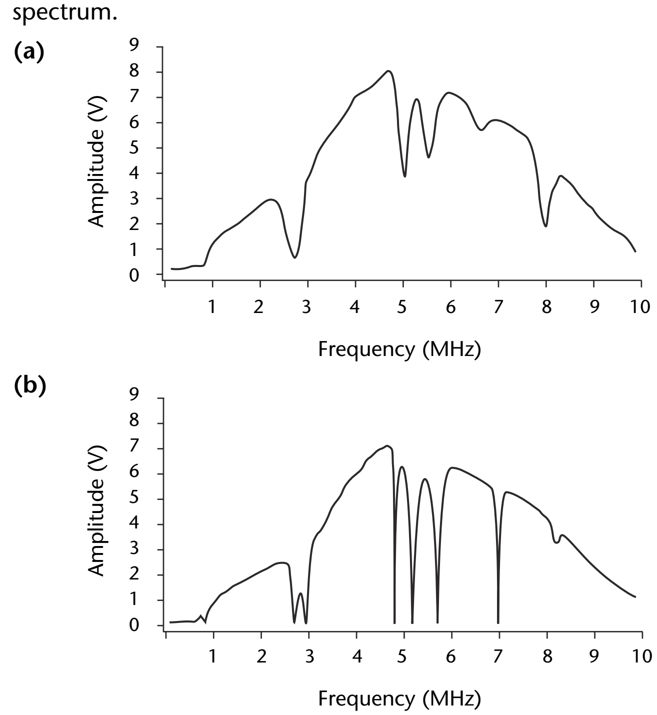


FIGURE 23. Leaky lamb wave reflection spectra from bonded aluminum plate [0.8 mm (0.032 in.)] immersed in water with incidence angle of 0.34 rad (19.5 deg). Epoxy layer 0.1 mm (0.004 in.): (a) measured spectrum; (b) calculated spectrum.



stress is involved in other ultrasonic tests. Because the two types of stress are affected differently by different material and discontinuity parameters, the lamb wave technique can potentially provide better diagnostics of interfacial bonds.

An example of the influence of bonding layer properties on leaky lamb waves is given in Fig. 25. In Figs. 25a to 25c, the reflected amplitude spectra from a single layered half space are shown for three possible cases: perfect bonding, a weak bond and complete disbond at the interface. The strong influence of bond quality on the location of the minima in the spectra is shown. In Fig. 25d, the dispersion curves for the same bonded system are shown.

The influence of the bonding layer's elastic properties on the lamb wave phase velocity is significant over a specific frequency range. An inversion technique has been developed to extract the elastic properties of the adhesive from the bonded joint dispersion curve.[53]

FIGURE 24. Calculated dispersion curves for lamb waves: (a) in bonded plate of 1 mm (0.04 in.) aluminum, 0.1 mm (0.004 in.) epoxy and 1 mm (0.04 in.) aluminum; (b) with disbonding at lower interface of plate with 1 mm (0.04 in.) aluminum and 0.1 mm (0.004 in.) epoxy; (c) with disbonding at upper interface of 1 mm (0.04 in.) aluminum plate.

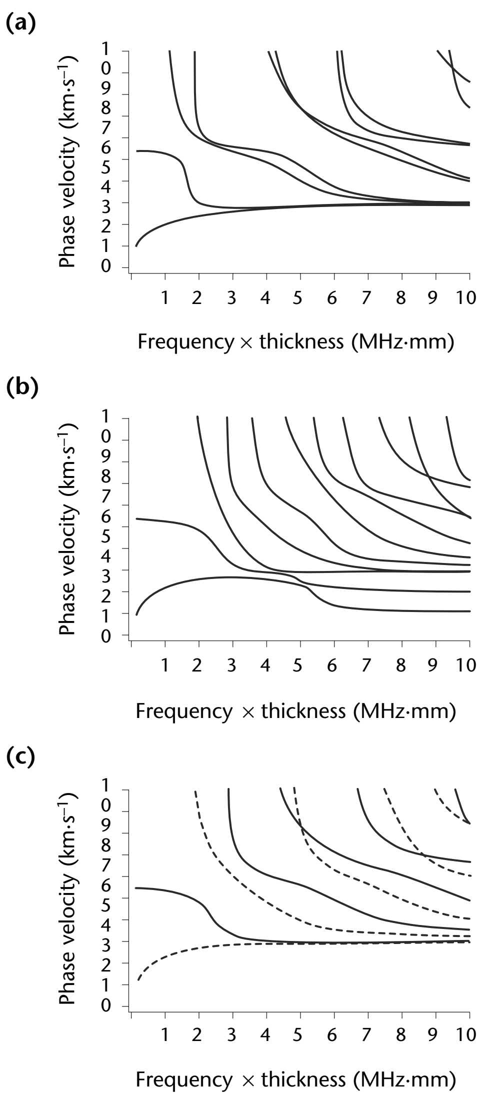
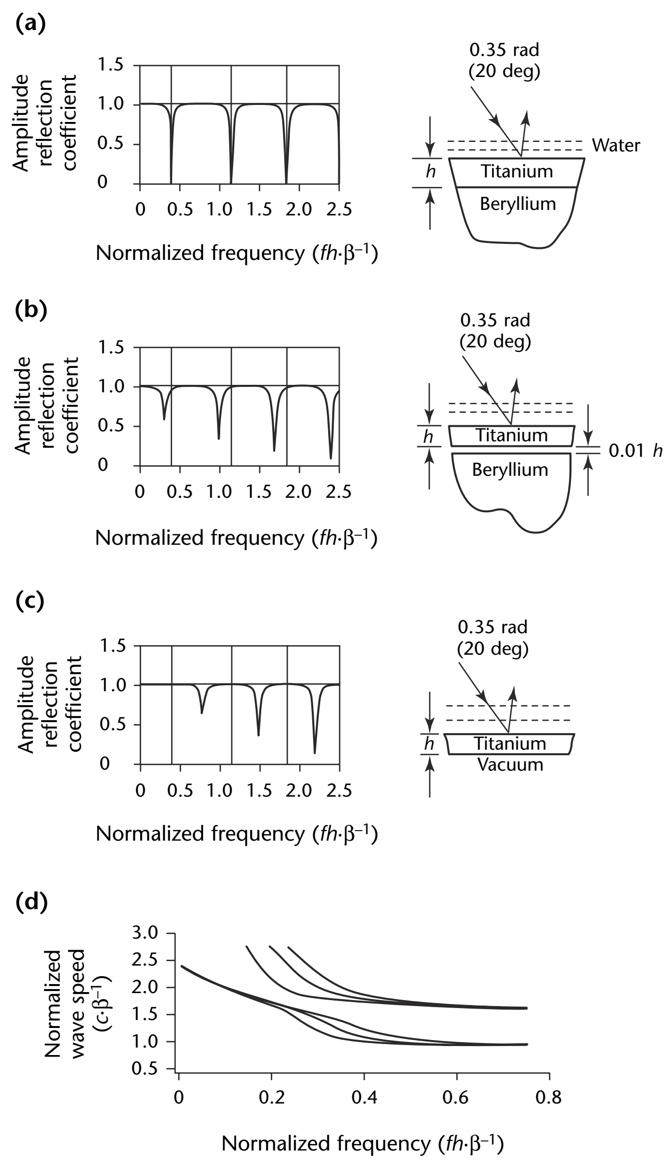


FIGURE 25. Influence of bond properties on leaky waves in single-layered medium (titanium bonded to beryllium substrate): (a) perfect bonding; (b) thin low velocity interfacial layer; (c) complete disbonding at interface; (d) frequency versus wave speed.



Legend

f = frequency (MHz)
h = thickness (mm)
β = transverse wave speed in titanium (mm·s^{-1})

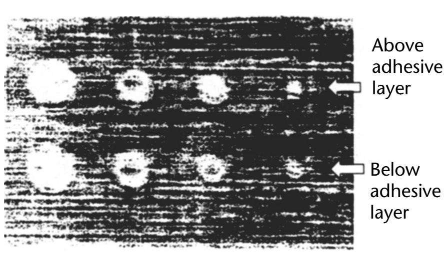
Applications of Leaky Lamb Wave Tests

Various applications of the leaky lamb wave phenomenon have been investigated for nondestructive tests of bonds. For studies of composites, a precured sandwich was prepared, containing $[0,90]_{2S}$ carbon epoxy skins with a 13 mm (0.5 in.) high, 3.2 mm (0.13 in.) polyamide paper, phenolic honeycomb cell and simulated unbonds made of synthetic fluorine wafers of 25, 19, 13 and 6.4 mm (1, 0.75, 0.5 and 0.25 in.) diameter.[54] The reference standard was insonified at 0.26 rad (15 deg) and the leaky lamb wave modes were measured.

A C-scan system was connected to the leaky lamb wave setup and the amplitude was recorded as a function of location. Initially, a frequency sweep was made and the minima associated with the leaky lamb wave modes were recorded. The test was conducted at 5.31 MHz, which represents one of the leaky lamb wave modes in the unbonded skin. The test results are shown in Fig. 26, where the unbonds are clearly identified — the generation of a leaky lamb wave mode creates a null detected by the receiver.

Detection of unbonds between metals and rubber is another difficult nondestructive test application. The problems result from the low acoustic impedance of rubber and the large mismatch in acoustic impedance between rubber and metals. This makes the difference in the reflected signal from bonded and unbonded rubber relatively small. Because the leaky lamb wave technique is based on measurement of the amplitude of the null due to a phase cancellation, the technique is very sensitive to changes in boundary conditions.[55] A 6.4 mm (0.25 in.) thick steel plate bonded to a 3.2 mm (0.13 in.) thick rubber mat has been tested with the pulse echo technique at 10 MHz and with the leaky lamb wave technique at 4.63 MHz. The results are shown in Fig. 27. The pulse echo technique shows a relatively small difference, at the level of the material variations across the bonded area. On the other hand, the unbond is clearly indicated when using leaky lamb waves.

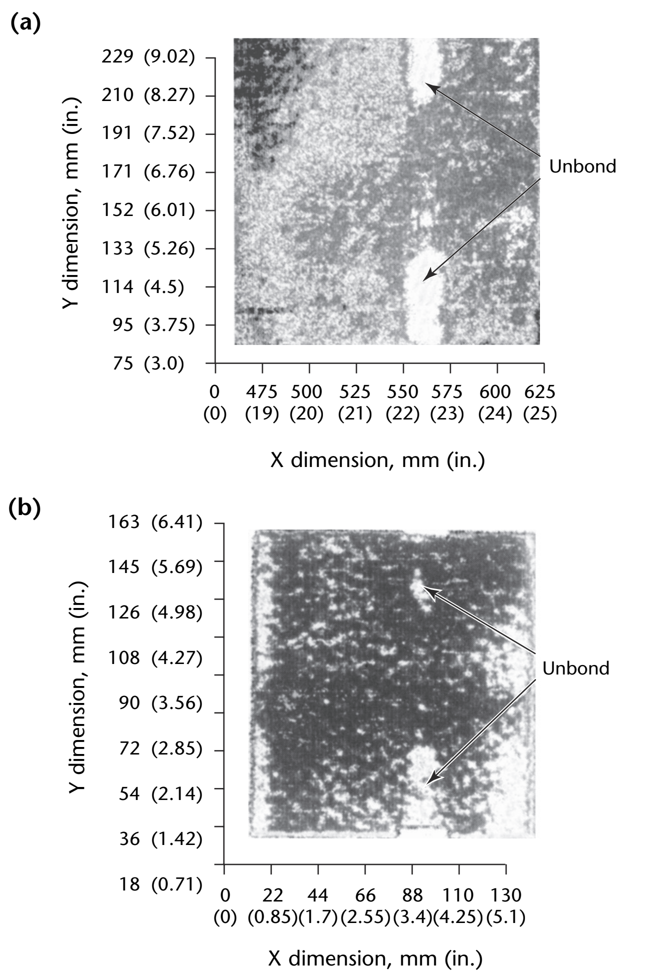
Figure 26. Leaky lamb wave C-scan showing disbonds in substrate of graphite epoxy sandwich.[54]



Assessment of Ultrasonic Tests of Bonds

Technology does not provide a physical parameter that can be directly correlated with bond strength for a practical test method. Nondestructive test techniques are more capable of detecting unbonds either at the adhesive layer or at its interface with the adherend. Because adhesive bond strength strongly depends on surface preparation, a nondestructive means for determining surface quality (the presence of contamination, for instance) is essential.[56]

Figure 27. C-scan images of steel-to-rubber bonds: (a) leaky lamb wave image from 4 to 2 V in 15-color scale; (b) pulse echo image from 0.55 to 0.25 V in 15–color scale, showing 13 mm (0.5 in.) unbond.[54]



Ultrasonic techniques can provide information about adhesive bond properties but some relevant parameters in the detected signals may be unused. An increase in the signal acquisition speed, an improvement in signal processing techniques and an increase in the size and speed of access to computer memory are expected to improve the capability of the technique. Improved techniques should allow several parameters to be captured while a bonded area is being scanned and this should enable an accurate assessment of bond quality.

One approach assesses the durability of commercial epoxy adhesive bonds by measuring ultrasonic reflection from an interphase region between the adhesive and the adherend.[57] The technique uses a specimen geometry that overcomes the drawbacks of the conventional adhesive sandwich. The interphase region is modeled with spring boundary conditions. The normal and tangential spring constants are determined as a function of epoxy degradation, from normal incidence longitudinal and from transverse wave measurements. Obliquely incident transverse waves are also measured with a dual-sensor thermoplastic (polyvinyllidene difluoride) transducer. An efficient angular spectrum approach was used to model the oblique incidence measurements, and the predictions of the model are compared with the measurements for various levels of degradation.

Pulse echo and through-transmission have traditionally been the most widely used production ultrasonic techniques for tests of adhesive bonding. Resonance and pulse echo are used in field conditions. However, leaky lamb waves have been used because of superiority in cases such as steel-to-rubber and composite bonds. Related techniques have been used for interphase characterization.[58]

For composites, the leaky lamb wave technique has been found useful for laminates with limited types of fiber orientation. Development of theoretical analysis of wave propagation in anisotropic, multilayered media would lead to a better understanding of wave behavior.[59-63] Such a development has led to an increased use of leaky lamb waves for nondestructive testing of bonded composites (the methods are presently too complex to interpret for multilayered laminates). Another area that benefits from ultrasonic testing is analysis of the bond between steel and rubber.

Assessment of Ultrasonic Tests of Coatings

Coatings require ultrasonic testing for verification of integrity in high temperature thermal barrier coatings and in some cases, evaluation of the process itself.[64] Coating means include plasma spray, chemical vapor deposition and physical vapor deposition. For instance, the chemical vapor deposition environment for silicon nitride reacts with carbon-to-carbon surfaces at 1400 °C (2550 °F). Oxidation barriers require noncontact measurement of coating thickness and modulus while undergoing deposition in real time. A laser ultrasonics system was successfully implemented for monitoring this process. This methodology for determining reaction parameters in situ also provides the opportunity to develop a system model of the process so that production runs are always controlled in the same way for repeatable coatings.

Rayleigh wave velocities have been measured in metallic coatings electrodeposited on steel and an experimental correlation was found between hardness and velocity.[65] This result suggests that surface wave velocity measurements can be used to evaluate coating hardness over regions inaccessible to conventional hardness tests. A laser ultrasonic system was set up with a chromium coating on a steel right circular cylinder. Laser generation of the surface wave and detection was accomplished using a plastic wedge with a 5 MHz broad band transducer. Dispersion curves were calculated using a wavelet decomposition for time versus frequency. The correlation was made using calibration data from these measurements.

The elastic constants of zirconia air plasma sprayed thermal barrier coatings were studied using two 15 MHz transducers in a water immersion tank.[66] Data were taken at various incident angles and fitted to a calculated theoretical transfer function for an unlimited isotropic plate with plane waves. The average longitudinal and transverse wave velocities are 2560 $m \cdot s^{-1}$ and 1710 $m \cdot s^{-1}$ respectively with variation lower than 3 percent over a wide refraction angle range, 0 to 1.1 rad (0 to 60 deg). Young's modulus was measured to be 33 GPa in comparison to compact zirconia at 241 GPa, indicating a high void count of 15 percent in the presence of a microcrack network. In another application, the elastic constants obtained from bulk wave measurements were used to assess the quality of thermal barrier coatings, which may develop a substantial amount of porosity if the process is not controlled properly.[67]

Short pulse scanning acoustic microscopy has been developed to investigate the structure, properties and geometry of highly absorptive multilayered polymer media.[68] The evaluation and visualization of internal layers having three percent of the total thickness have been demonstrated. The approach also included a time domain digital algorithm to provide the precision needed. The polymer sample was an advanced material for gas storage tanks consisting of high density polyethylene, an upper layer of the same high density polyethylene with a black pigment filler, a barrier layer of ethylene vinyl alcohol copolymer and an adhesive layer of polyethylene based modified polyolefin adhesive resins.

Testing can be implemented remotely to detect discontinuities of large metallic pipes, tubes and plates with a surface coating added for corrosion protection or insulation.[69] Because the coatings are usually viscoelastic, the guided wave ranges may be severely reduced unless a proper mode and an adequate frequency range are selected. To overcome this limitation, a hybrid finite element boundary element method which explicitly includes the attenuating properties of the coating was used to determine the lamb and transverse horizontal mode conversion factors at the corrosion discontinuities under the coating. Monotonic variations of the primary mode conversion factors with discontinuity depth enabled weakly attenuated modes to be inspected.

Part 3. Ultrasonic Tests of Composite Laminates

Composites are useful structural materials because of their high ratios of strength to weight and moduli to weight. Composites are multilayered, heterogeneous and anisotropic on both macroscopic and microscopic levels. Most discontinuities in composites are different from those in metals, and the fracture mechanisms are much more complex.

Various discontinuities or combinations of discontinuities can have specific degradation effects on the performance of a given composite and these effects are determined by several factors: discontinuity characteristics (such as dimensions and location), geometry, composition and other properties of the host composite, the type and magnitude of the applied stress and the environment to which the structure is exposed during service.

For many discontinuities, the specific mechanisms of degradation and the effects of the above factors are not well understood. The anticipated durability of composite structural components can be confirmed by efficient, reliable and cost effective ultrasonic tests. These techniques should allow the determination of performance levels and serviceability at an acceptable probability of detection.

Described below are (1) the life cycle of a composite, (2) the type of discontinuities that can be induced at each stage of the life cycle and (3) the ultrasonic techniques in use or under development for tests of composites. Although the tests described here are applicable to a wide variety of composite materials, including metal matrix composites, the following discussion concentrates on fiber reinforced plastic composites, particularly those used for aircraft structures. The fiber materials include graphite, glass and boron. Epoxy resin is the usual matrix material. Boron epoxy was the first material to be used for primary composite structures but was replaced by graphite epoxy because of cost.

Sources of Discontinuities

Fiber reinforced plastic components are commonly made by curing preimpregnated fibers stacked in layers of a certain orientation. The sequence of stacking is determined by design requirements and can be done in manual layup or by automated filament winding. Different types of discontinuities can be introduced during the production of preimpregnated fibers: (1) not enough resin, (2) inclusions and contaminations, (3) excessive variability in fiber or resin properties, (4) nonuniform hardener content and (5) fiber misalignment.

To make a composite, the preimpregnated layup or the filament wound structure is cured by exposure to elevated temperature and pressure in a predetermined procedure. A vacuum is maintained in the curing environment to eliminate porosity in the resin. Resin is cured in three stages: (1) the fluid stage (the resin is liquid and its molecules combine to form a reactive polymerizable material), (2) the polymerization stage (polymers of long chains are formed) and (3) the hardening stage (polymeric chains cross link to produce a three-dimensional network).

The progressive physical condition of the curing resin determines the duration of each stage and the times when various temperatures and pressures are applied. The resin condition must therefore be within specifications to ensure the final quality.

Once curing is completed, the composite is postcured to relieve stresses. These stresses are induced mainly by a mismatch of thermal expansion coefficients between the various layers of the composite and between the fibers and the matrix. The laminate or filament wound structure might contain several types of discontinuities, depending on the production process. Each of these discontinuities degrades the performance of the host composite structure and its durability in service. Possible discontinuities induced by fabrication include (1) delamination, broken fibers and matrix cracking, (2) fiber misalignment, (3) inclusions and contaminations, (4) inadequate volume ratio of fiber to resin, (5) wrong layup order, (6) overlap or the gap between the fiber bundles in a layer, (7) insufficient curing or overcuring, (8) excessive porosity or voids and (9) knots or missing roving of the winding fibers.

Aircraft composite structures are assembled using adhesive bonds to join combinations of composite laminates to metallic or other composite structures such as honeycomb. Two basic fabrication concepts, precure and cocure, are used to build up a composite assembly. In precuring, skins made of laminates with the required layup order are cured first and then bonded to an adherend. In cocure, the assembly is prepared by stacking the adhesive layers over the adherend, laying up laminate plies at the required sequence and then curing the complete structure.

These processes can induce discontinuities such as unbonds, porosity and voids as well as contamination of the adhesive joint. Other means of assembly include rivets or bolts, but these can initiate cracking and delaminations near the fastener hole.

In service, structural composites are exposed to conditions that can induce discontinuities different from those produced during fabrication. These include environmental degradation, erosion and damage from impact, weather and fatigue. In the case of aircraft components, impact damage is typically caused by dropped tools, birds or debris encountered during taxiing or landing, military action or weather conditions during flight. Erosion is caused by rain, hail, dust or sand. These damage sources degrade the performance of the composite skins, the adhesive and the adherend.

In some cases, the mechanism of degradation is not well understood or predictable. The response of composite materials to fatigue conditions depends on the layer's orientation, on the stacking order and on the nature of the applied loads. Fatigue can cause matrix cracking and crazing, fiber failure, delamination and disruption of the bond between fibers and matrix.

Impact damage is a primary concern to users of composite materials because the damage can appear at any location over the structure and at any time. This is in contrast to fatigue damage, which can be induced only at high stress concentration areas after exposure to a sufficiently large number of mechanical loading cycles. Even low levels of impact damage can be serious over time because of growth resulting from stress concentration.

Role of Ultrasonic Testing

Ultrasonic techniques play a major role in the nondestructive testing of composites, both in research and in practical applications. Ultrasound provides many parameters that can be used to detect and characterize discontinuities and to determine the elastic properties of the composite. Anomalies and property variations affect the intensity, velocity, scattering, mode conversion and reflection characteristics of an ultrasonic beam that insonifies the test object.

Different types of information can be obtained when the incident acoustic wave is normal or at an angle to the material surface. To understand wave behavior and to predict its characteristics in composite material, a theory for the analysis of the wave behavior in anisotropic layered media is needed. A general theory of wave propagation in multilayered composite laminates has been presented in the literature.[60] The fundamental features of the theory are briefly described below.

Theory of Wave Propagation in Composites

In a general test configuration for composite materials, the composite laminate contains N layers (called *laminae*) and is of total thickness H. Each lamina is a unidirectional fiber reinforced layer and may have different orientations, depending on the design requirements of the laminate. The laminae are assumed to be perfectly bonded at their interfaces.

In many multiple-orientation laminates, the interfacial zones are matrix rich and therefore have material properties that may be significantly different from those of the adjacent laminae. In such cases, the interfacial zone should be represented by an additional layer of material with certain assumed properties and the solution procedure can still be applied to the resulting problem. The laminate is assumed to be immersed in water and insonified by a plane acoustic wave at an incidence angle θ. The incident wave can be either time harmonic or pulsed. The theory of wave propagation in multilayered composite laminates has been presented in the literature.[1,57] The equations are well behaved at all frequencies and can be solved by means of standard techniques.[70]

This general treatment of wave propagation in composites can be applied for any angle of incidence, including normal incidence at which composites behave as a layered isotropic medium. The main interest of ultrasonic testing is the reflection coefficient R as a function of the frequency and incident angle. For this purpose, the order of the system of equations that need to be solved can be somewhat reduced. Also, by treating k_0 as the unknown wave number, the dispersion equation for guided wave propagation in the medium can be derived.

Testing Composites at Normal Incidence

In most ultrasonic tests, a longitudinal beam is incident normal to the composite surface. Under these conditions, the effect of material anisotropy can be neglected and the approach is similar to tests of isotropic media. Even though the material behaves as if it were isotropic, its layers cause extraneous reflections and increase attenuation.

Two basic testing modes of normal incidence are commonly performed. In through-transmission tests, the attenuation is determined from the amplitude of the wave after it has traveled through the test object. In pulse echo tests, several parameters can be evaluated: (1) changes in the back reflection amplitude, (2) amplitude of extraneous reflections and (3) variations in time of flight measured from the front reflection to the back reflection or the extraneous reflection.

Attenuation

Attenuation is relatively high in composites, primarily because of scattering by the fibers and isothermal absorption in the resin. High attenuation can be reduced by using the through-transmission mode, passing through the test object only once. For thick composites, the attenuation needs to be reduced further by using lower frequencies (0.5 to 2.25 MHz) and sacrificing resolution or by using high power signals. The through-transmission technique and C-scan systems are widely used for detection of delaminations, voids, resin rich and resin starved areas and other anomalies that significantly affect attenuation.[71]

The use of attenuation as a characterization parameter is hampered by variables such as surface roughness or wave coupling and their effects are difficult to deconvolve from the data. In addition, the transducer and instrument characteristics are difficult to control in a reproducible manner. Therefore, attenuation measurements are applied mainly to identify a significant deviation of material response from an average attenuation value for the tested laminate.

Time of Flight

The depth of discontinuities in composite laminates can be determined with relatively high precision by measuring time of flight. For this purpose, short duration pulses are used in the pulse echo mode (Fig. 28) and the test procedure is similar to those for metallic objects. Using 100 ns pulses, this technique has detected 1 mm (0.04 in.) diameter delaminations in graphite epoxy laminates with ±0.2 mm (±0.008 in.) depth accuracy.[72]

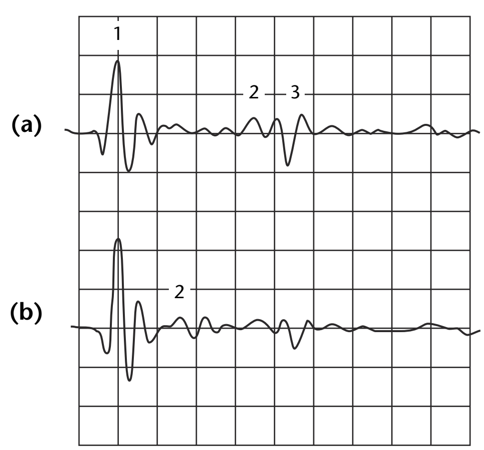
The accuracy of assessing depth depends on (1) the consistency of the ultrasonic velocity across the material and (2) the similarity of velocity in the test material to velocity in a reference material. In composites, this accuracy is limited because of elastic property variations within the materials and between various components. These property variations are caused by nonuniform volume ratios of resin to fiber, by differences in polymerization levels and by variations in material content between batches of the same composite.[73]

Velocity Measurements

Using time-of-flight measurements, the ultrasonic velocity of a given mode along the material can be determined. Studies of both longitudinal and transverse wave velocities can be used to determine some of the elastic constants of a composite. The anisotropic nature of composites is evident when examining the ultrasonic velocities of various modes parallel and normal to the fibers. Use of these measurements with lamb waves has also been shown to provide the capability to monitor fatigue and thermal damage in aerospace composite materials.[73,74]

Theoretical velocity curves for models of graphite epoxy and glass epoxy

FIGURE 28. Pulse echo response from 24-layer unidirectional graphite-to-epoxy laminate: (a) without discontinuities; (b) with discontinuities.

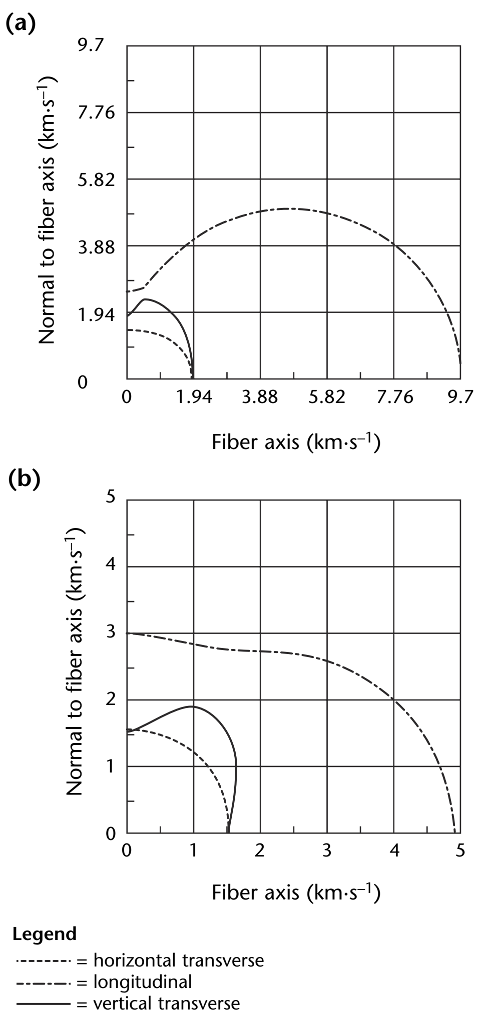


Legend

1. Front surface reflection.
2. Delamination.
3. Reflection from graphite-to-epoxy layer.

composites are shown in Fig. 29. As the figure shows, graphite epoxy is much more anisotropic than glass epoxy. Studies indicate that velocity calculations can be applied for fiber reinforced plastic materials containing matrix voids.[75] The same studies also indicate the feasibility of predicting fiber volume fraction, assuming low frequencies or small fiber diameter. Deviation from these conditions gives rise to velocity dispersion. This dispersion is most noticeable for boron fiber because it has ten times greater diameter than glass or graphite fibers.[77]

Figure 29. Theoretical velocity curves for three basic modes of propagation (longitudinal horizontal transverse, vertical transverse) in: (a) unbounded graphite-to-epoxy composite at 0.62 fiber volume fraction; (b) unbounded glass-to-epoxy composite at 0.4 fiber volume fraction.[70]



Resonance

Resonance conditions are established in a composite plate when the thickness is a numeric multiple of half the wavelength. For this purpose, low frequencies are used to reduce the effect of attenuation on the measurements. Generally the resonance technique is used to test bonded structures or to detect delaminations.

The resonance technique can also be used to measure the depth of discontinuities but is not as practical as other techniques. Depth testing requires fabrication of a large set of calibration standards with controlled discontinuity size and depth. In addition, test results are significantly affected by pressure on the transducer, variations in the material surface roughness and variations in the elastic properties of the test object.

Spectroscopy

Conventional ultrasonic tests are based on studies of the time domain acoustic intensity integrated over the transducer area.[78] If these data are analyzed in the frequency domain using signal processing techniques, frequency dependent features can be determined. The interaction between ultrasonic waves and discontinuities — for example, scattering, absorption and, in particular, interference of wavelets scattered from various parts of discontinuities — depends on the wave frequency. The frequency dependence of the signal, detected by a wideband transducer, contains useful information for characterizing discontinuities. Using spectral analysis, discontinuities such as delaminations have been studied by several investigators.[79]

Spectral analysis is finding limited application for discontinuity testing because of the large number of factors (coupling and surface roughness) affecting the spectrum and the fact that their effects cannot be predetermined. Deconvolution methods have been used to extract the relevant signal from the characteristic signal of the transducer,[80] thus reducing the number of factors contaminating the signal scattered from the discontinuity. It remains difficult, however, to evaluate the scattered field from discontinuities in composites as a function of frequency.

Testing Composites at Oblique Incidence

The behavior of an acoustic wave impinging at an angle on a composite is significantly affected by the layered, heterogeneous and anisotropic nature of a composite. Oblique incidence is used to test composites in two modes. First is the backscattering mode, where a single transducer is used. Scattering sources in the composite are identified as a function of fiber orientations.

Second is the leaky lamb wave mode, where two transducers are used in a pitch catch arrangement. The transducers can be on the same side or on opposite sides of the laminate. The leaky lamb wave receiver is placed at the null zone caused by the interference of the specular reflection and the leaky wave components. As detailed below, many discontinuities are detectable by these two oblique incidence modes.

Backscattering

When a composite half space or a plate is insonified at an angle, a specular reflection occurs. The characteristics of reflection depend on the material and the fluid loading. While an unperturbed specular reflection is observed along the fiber direction, strong scattering takes place as the wave propagates normal to the fibers. A schlieren image of this behavior is shown in Fig. 30.[81,82] Many investigators have tried to develop theories to predict this scattered field from the fibers but none of the proposed models has been corroborated by experiment with composites.

The scattered field has been studied extensively at different frequencies.[81,82] An experimental setup was prepared with a transmitter set in a fixed location normal to the sample and rotating with it on a turntable. To eliminate the side lobes, transducers with a gaussian directivity were used. The laminate was placed so that the fibers were parallel to the axis of rotation and its front surface matched this axis. The receiver was placed in a stationary position outside the turntable to allow measuring the scattered wave amplitude as a function of the angle.

The measured field consists of side lobes that strongly depend on the frequency but do not present any consistent trend. The side lobes are dominated by local variations and irregularities in the order of the fibers within the laminate. Even when the fiber volume fraction is high, as in the case of graphite epoxy, the diffracted field is strongly perturbed by local variations.

Although it is difficult to obtain a typical or characteristic scattered field, backscattering measurements using pulses and spatial averaging have been highly successful. Because a single transducer is used, the number of variables associated with the test setup is limited, making such a setup more practical. Another advantage of the backscattering method is

Figure 30. Schlieren image of incident and reflected waves from unidirectional glass-to-epoxy laminate: (a) along fiber direction; (b) normal to fiber direction.[70]

(a)

(b)

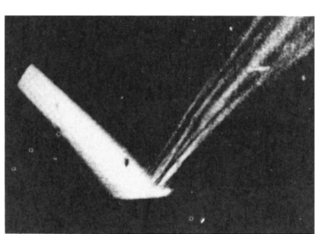
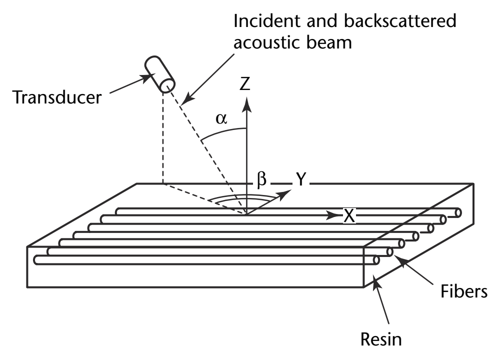
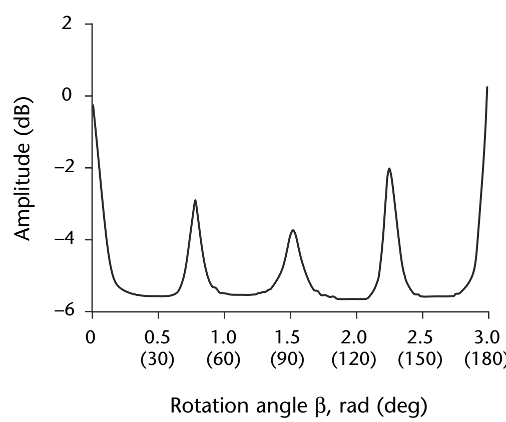


Figure 31. Acoustic backscattering from $[0,\pm45,90]_s$ graphite-to-epoxy laminate: (a) setup; (b) as function of rotation angle β for 0.5 rad (30 deg) incident angle.[71]

(a)



(b)



Legend

α = angle of incidence
β = angle between Y axis and transmitter beam trajectory on layer plane