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Improved Transverse Crack Detection in Composites

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IMPROVED TRANSVERSE CRACK DETECTION IN COMPOSITES

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SUMMARY

A modified ultrasonic C-scan technique was implemented for improving the detection of a certain type of damage in composite specimens. The type of damage being studied is transverse (through the thickness) cracking of unidirectional off-axis graphite/epoxy specimens. These cracks are difficult to detect using standard through-transmission C-scan techniques.

The modification is based on mode conversion to produce transmitted shear waves form incident longitudinal waves. While mode conversion is used extensively with isotropic materials, its use with composites is more limited. This is largely because the computation of wave propagation parameters is significantly more complicated with highly anisotropic composite materials than with isotropic materials.

In this study, the appropriate incident angles to produce the desired mode conversion were computed based on the mechanical properties of the composite. Once the angles were computed the technique was simple to implement and resulted in marked improvement in detection of the transverse cracks being studied.

INTRODUCTION

The ultrasonic C-scan is a common technique for detecting flaws or damage in composite laminates as well as in many other materials.[1] The technique is well established, relatively simple to implement and is an effective method of detecting local inhomogeneities in composite laminates. It is particularly effective in detecting interply delaminations which occur parallel to the laminate plane and can result from applied loads or manufacturing flaws. However, there are certain defects which are difficult to detect using the method. One type is the transverse (through the thickness) matrix crack which may be oriented perpendicular to the laminate plane in graphite/epoxy composites. This type of damage is a common result of thermal fatigue[2] and may also occur as a result of mechanical fatigue or static in-plane loading.[3] Detection of transverse matrix cracks is important because when they propagate to a ply interface they may initiate delamination, further degrading the structural integrity of the laminate.

Several methods have recently been developed to improve the ability to detect transverse cracks in composite laminates. These include the method of acousto-ultrasonics[2] and the use of Lamb waves.[4] These methods are sensitive to overall changes in in-plane mechanical properties due to the presence of transverse cracks. In this study a technique was implemented for the local detection of this type of crack. The technique is based on the hypothesis that oblique shear waves may be more sensitive to the presence of cracks than are longitudinal waves propagating normal to the panel. It involves producing only shear wave transmission through the panel, and has the advantage that only minor changes need to be made to existing C-scan procedures.

The ability to utilize shear wave transmission results from the mode conversion that occurs when a longitudinal wave traveling through a fluid is incident upon a solid. In an isotropic solid an incident longitudinal plane wave will typically produce three refracted waves, a longitudinal wave and two shear waves, known as P (primary compressional), SV (vertically polarized shear) and SH (horizontally polarized shear) waves. The directions of the refracted waves may be easily determined using Snell's law.[5] By selecting the correct incident angle (the "critical" angle) it is possible to produce total reflection of one of the waves, such as the P wave. In addition, if the incident plane is perpendicular to the plane of the laminate, SH waves are not generated. The mode conversion phenomenon also occurs in anisotropic media, such as the fiber composite laminates considered here. However, the anisotropy produces several important differences that must be taken into account when computing the desired incident angles.[5,6] In particular, although Snell's law still applies, it is not sufficient to compute both wave propagation directions and angles of refraction, since the wave velocity is a function of its direction of propagation.

In this study the wave directions and critical angles were computed for unidirectional off-axis graphite/epoxy panels with varying fiber angles. Ultrasonic C-scans were conducted on a 60° off-axis panel with an artificially induced through-the-thickness transverse matrix crack. Scans were conducted using both normal through-transmission and the proposed shear wave transmission technique. The results show that the crack image was significantly enhanced using the shear wave transmission.

THEORY

An analysis was conducted to determine critical angles, phase and group velocities, amplitudes and displacements for reflected and refracted waves resulting from a longitudinal plane wave in a fluid incident on a composite panel (fig. 1). The methods used were similar to those outlined in reference 6, so only a cursory discussion is given here. In the analysis, the composite panel was modeled as an orthotropic solid lying in an inviscid fluid. The ultrasonic wave was modeled as a plane wave propagating in the $X_2 - X_3$ plane with an incident angle, ϕ (fig. 1). The displacement at a point $\bar{x}$ was given as

$$u_i = A_i e^{-i(\bar{k}\cdot\bar{x}-\omega t)} \qquad (i = 1,2,3) \tag{1}$$

where u_i is the displacement in the X_i direction, A_i is the wave's amplitude, $\bar{k} = (\omega/c)\hat{n}$ is the wave vector, ω is the frequency, c is the phase velocity, $\hat{n}$ is the unit wave normal vector and t is time.

The velocities and displacements were found by substituting the assumed displacement field (eq. 1) into the equations of motion,[6] giving

$$\left(C_{ijk\ell}n_j n_\ell - \rho c^2 \delta_{ik}\right)A_k = 0 \tag{2}$$

where $C_{ijk\ell}$ are the elastic stiffness constants, δ_{ik} is the kronecker delta and ρ is the density. The eigenvalues, c, of equation (2) correspond to the phase velocities of the three possible waves, while the eigenvectors are the unit displacements. Both depend on the direction of wave propagation. The elastic constants of the composite laminate were determined from the constituent properties using a micromechanics analysis and laminate plate theory.[7] Dividing equation (2) by ρc^2 put the equation in a form which could be used for determining wave vectors and velocities,

$$\left(\frac{1}{\rho} C_{ijk\ell}m_i m_\ell - \delta_{ik}\right)A_k = 0 \tag{3}$$

where $m_i = n_i/c$ are known as the components of the slowness vector. The slowness vector has the same direction as the wave normal and a magnitude equal to the inverse of the velocity. The slowness vectors were computed from equation (3) by choosing a configuration in which the incident plane was normal to the plane of the sample. In this case m_1 was zero and m_2 was the same as the X_2 component of the slowness vector of the incident wave,[5] which was computed independently. This left m_3 as the only unknown quantity within parenthesis of equation (3). Setting the determinant of the quantity in parenthesis equal to zero resulted in a sixth order polynomial in m_3 which was solved numerically. With m_1, m_2, and m_3 known, the velocities and normalized displacements were found from the eigenvalue problem of equation (2).

EXPERIMENTAL PROCEDURE

The effect of using shear wave transmission in the C-scan rather than longitudinal wave transmission was evaluated experimentally. A T300/934 graphite-epoxy laminate laid up in a $(60)_8$ configuration with a nominal thickness of 1.1 mm was manufactured according to the manufacturer's specifications. A specimen was cut from the panel in such a way that the angle, Θ, (fig. 1(c)) was 30°. The specimen was split in two along the fibers, and the two pieces placed back in contact and supported mechanically in such a way that the crack was not detectable visually. Two different types of ultrasonic C-scans were then performed. The first was a regular through-transmission scan in which the sound travelled along a straight line between the transmitting transducer and receiving transducer, normal to the plane of the sample (fig. 1(a)). In the second scan the sound travelled along a line in the $X_2 - X_3$ plane but was at an angle, ϕ, from the X_3 axis (fig. 1(b)). In this case an offset, δ, occurred as a result of a deviation in the direction of propagation in the solid from that in the liquid (fig. 1(b)). The angle, ϕ, was chosen to be slightly larger than the computed critical angle for longitudinal waves so that only shear waves were transmitted through the sample. 10 MHz broadband transducers were used, with a focused transmitter and an unfocused receiver.

RESULTS AND DISCUSSION

The mechanical properties in the material coordinate system for the unidirectional composite used in this study, computed from the micromechanics analysis, are shown in table I.

For unidirectional off-axis composites, the incident angle at which total reflection of the longitudinal wave occurs is a function of fiber angle (fig. 2). In particular, when the fibers are parallel to the incident plane ($\Theta = 90°$) the critical angle is quite low (9°). In contrast, there is no critical angle for SV waves. That is, refracted shear waves are generated even for grazing incidence, allowing a large range over which the incident angle can be chosen.

Some insight into an appropriate choice for the incident angle can be obtained from a plot of the locus of the slowness vectors (the slowness surface). For the longitudinal (P) wave the direction of energy flow, which is normal to the slowness surface, deviates significantly from the wave vector direction near the critical angle (fig. 3). For the transverse shear wave, however, the direction of energy flow is almost collinear with the wave vector direction, meaning that for a thin laminate the offset, δ, (fig. 1(b)) will be relatively small.

These results allow some simplification in an experimental arrangement for using shear wave propagation to detect damage. Because the energy of the P wave is deflected significantly near the critical angle, some error is permissible in the experimental apparatus used for orienting the transmitter-receiver pair relative to the sample to produce the calculated incident angle. That is, for incident angles somewhat less than the critical angle, the energy of a refracted P wave would be directed far enough away before emerging from the other side of the sample that it may not be sensed by the receiving transducer. For the detection of transmitted SV waves on the other hand, very little correction needs to be made for a lateral shift, δ, (fig. 1(b)) in the path of an ultrasonic beam due to the change in direction of energy flow. From a practical point of view, this means that for thin samples, the proposed method may be implemented by simply changing the angular orientation of the transmitter-receiver pair relative to the sample.

The use of transmitted SV waves rather than longitudinal waves led to a significant improvement in the ability of the C-scan to detect the presence of a through-the-thickness transverse crack (fig. 4). Figure 4(a) is a conventional C-scan (fig. 1(a)) of the specimen, in which the P-wave propagates normal to the plane of the composite panel. The transverse crack in the specimen can be seen extending from the upper left of the figure to the lower right. Figure 4(b) is a C-scan of the same crack using the shear wave transmission technique. In this figure the crack appears wider and is easier to detect visually. For this experiment, the critical angle for longitudinal waves was computed to be 18°. An incident angle of 20° was used to generate the shear waves. The plane of incidence was parallel to the longitudinal axis of the sample.

These results indicate that the use of transmitted shear waves can be useful in detecting this particular type of damage. Although more involved than for isotropic materials, the computation of critical angles is relatively straightforward. One of the principal advantages of this method over other methods of detecting transverse cracks is that in many cases, it can be implemented simply by changing the orientation of the transmitter-receiver transducer pair in a standard C-scan facility.

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TABLE I. - MECHANICAL PROPERTIES FOR T300/934 GRAPHITE/EPOXY COMPOSITE IN THE MATERIAL COORDINATE SYSTEM

E_{11} = 144.2 GPa	G_{12} = 4.098 GPa	ν_{12} = 0.26
E_{22} = 8.729 GPa	G_{13} = 4.098 GPa	ν_{13} = .26
E_{33} = 8.729 GPa	G_{23} = 2.475 GPa	ν_{23} = .42

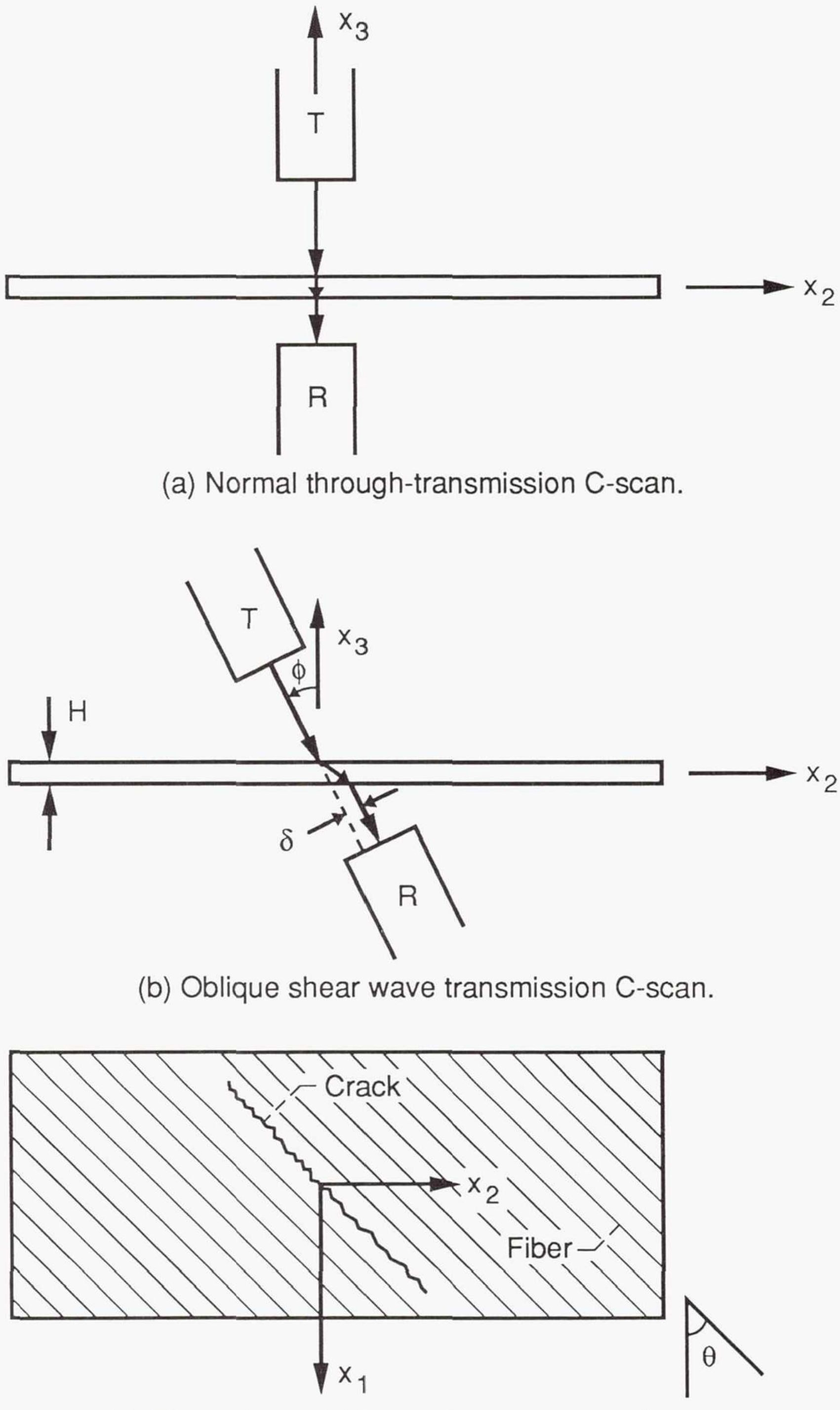


Figure 1.—Schematic of the experiments showing the relative locations of the transmitting (T) and receiving (R) transducers for the two types of C-scans used to detect the crack shown in (C).

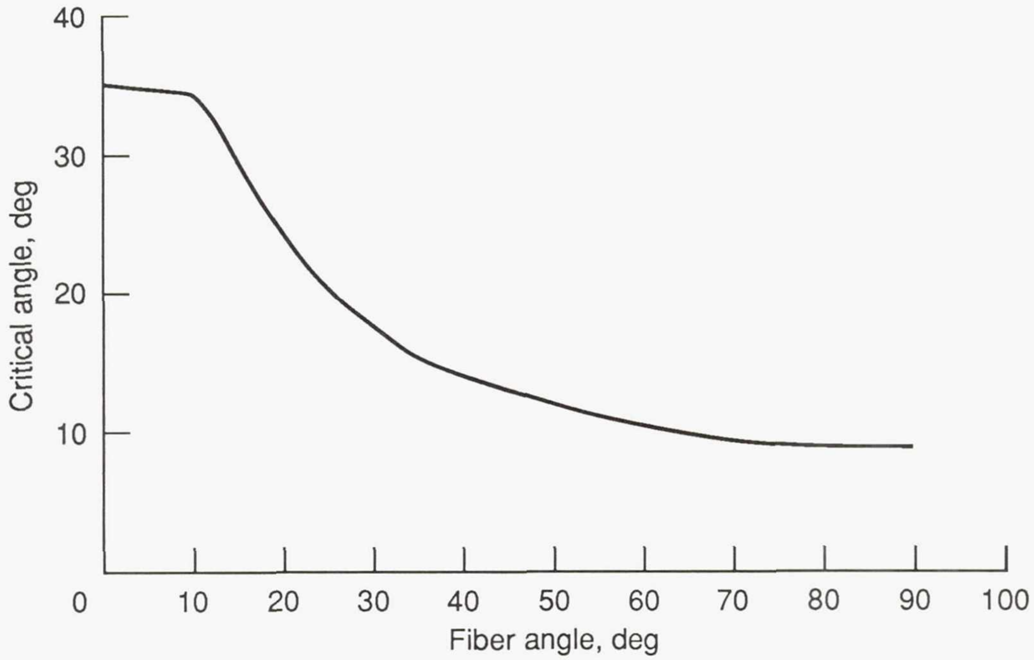


Figure 2.—Critical incident angle for full reflection of longitudinal waves, as a function of fiber angle, θ.

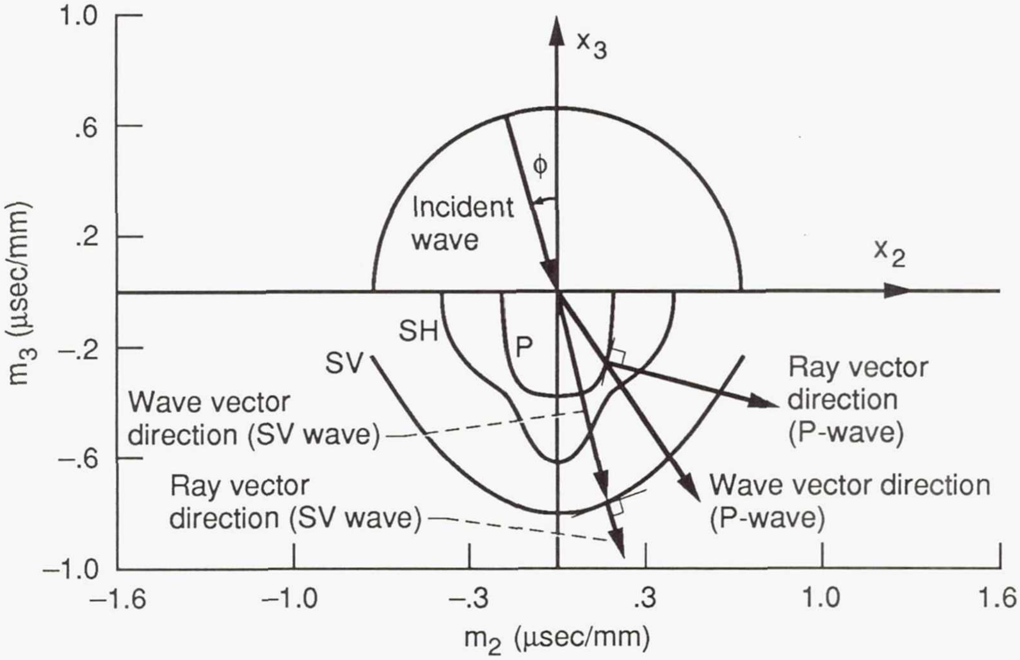
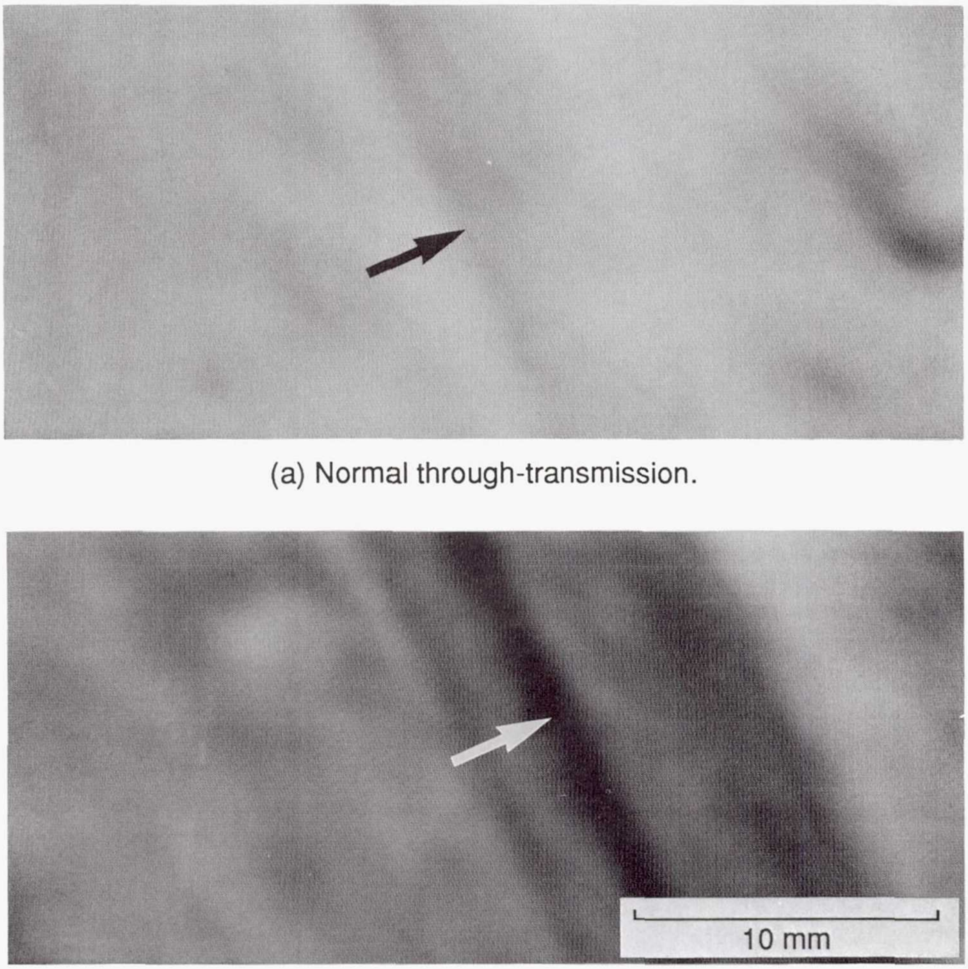


Figure 3.—Slowness surfaces for incident and refracted waves for a 60 degree off axis (θ = 30 degrees) sample. Near the critical angle the energy flow (ray) direction for longitudinal waves deviates significantly from the wave direction. For SV waves the ray and wave directions are approximately the same.



(a) Normal through-transmission.

(b) Oblique shear wave transmission.

Figure 4.—Images of a transverse crack in a 60 degree off-axis unidirectional sample using the two types of C-scans. The shear wave method produces an enhanced image. Arrows indicate location of crack.

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