ULTRASONIC NDE OF THICK COMPOSITE LAMINATES

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ABSTRACT

The feasibility of using relatively low frequency leaky Lamb waves (LLW) for the quantitative characterization of thick composites is discussed. A coordinated theoretical and experimental program of research has been carried out in an effort to understand the behavior of the leaky wavefield produced by thick composite laminates. Good correlation between theoretical predictions of the LLW spectra and laboratory measurements has been achieved for the specimens. The need for further research to develop a full or understanding is indicated.

INTRODUCTION

With increasing use of relatively thick, multilayered composite laminates as primary structural components, it has become necessary to have reliable NDE tools for their quantitative evaluation. Considerable efforts are being exerted in several fronts to develop such tools by various research groups. Two promising techniques are based on X-ray radiography and low frequency ultrasonics. Radiography appears to be best suited for the detection of production defects such as inclusions, resin pockets, and voids. However, in this method, the smallest detectable flaw size is a fixed percentage of the total thickness. Thus as the thickness of the specimen increases, so does the size of the smallest detectable flaw. Ultrasonic methods are potentially capable of identifying and characterizing very small defects in the specimen. But the penetration depth of the waves is reduced in proportion to the thickness of the laminate due to an increase in their attenuation in thick composites.

The presence of high porosity and resin pockets in the material may be responsible for removing energy from the interrogating waves due to scattering and internal reflection, especially at higher frequencies. To overcome the effects of high attenuation, it is necessary to employ lower frequency and higher power. In this paper, the feasibility of employing low frequency leaky Lamb wave technique for the quantitative characterization of relatively thick composite laminates is considered. Attention is focused on understanding the behavior of the guided waves, which are generated in the LLW experiment. The dependence of certain observable wave characteristics on the mechanical properties of the composite and the ability to predict such behavior on the basis of theoretical models are discussed.

THE EXPERIMENTAL SETUP

A pitch-catch arrangement was used (Fig.1) with the receiver placed at the null zone of the leaky wave field for each angle of acoustic wave incidence. Low frequency broadband transducers with 1 MHz center frequency were employed to examine the LLW field in the frequency range of .1 to 1.7 MHz. Tone-burst signals, with a duration sufficiently long to establish a steady-state condition in the test specimen were produced with the aid of an HP3314A Function Generator. The received signals were amplified by a Panametrics 5052PR and a Matec receiver Model 605. At specific angles of incidence, the computer acquired the amplitude of the reflected signal as a function of frequency, which was transmitted to the Function Generator. The amplitudes were digitized with the aid of a gated integrator (made by SRS). The amplitude spectra of the reflected signals were thus obtained for each angle of incidence, for several graphite/epoxy specimens. In addition, the reflected spectra from a tungsten film placed over the specimen was also recorded for each experiment. Since the tungsten film is a nearly perfect reflector of the acoustic waves, these spectra provide the tranducer response for the theoretical calculations. In this paper the results for a unidirectional specimen (G/E T650/1901 [0] 176) of approximately 25 mm thickness is presented and compared with those obtained from theory.

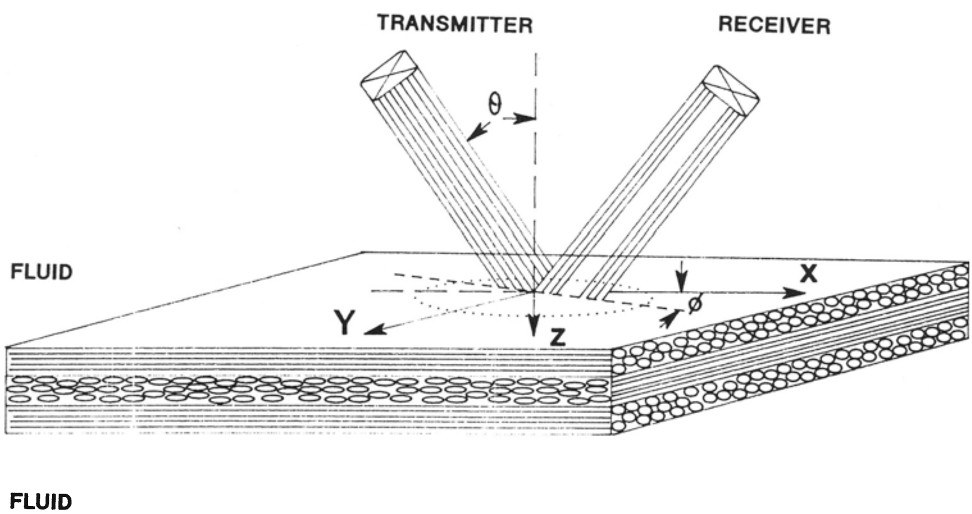

Figure 1. Schematic diagram of the LLW experiment for a composite laminate.

THEORETICAL MODEL

The main task of the theory is the calculation of the reflected field for the arrangement shown in Fig. 1. It has been demonstrated in a number of previous papers that the incident wavefield can be accurately represented by plane waves propagating parallel to the beam [1,2]. The calculation procedure for a given model of the laminate is also available and will not be repeated here. We have developed a computer code which can handle multilayered laminates of arbitrary thickness and orientation of the laminae in presence or absence of material dissipation. However, before the reflection coefficients can be calculated by means of the code, it is necessary to specify the properties of the laminate.

As indicated above, the unidirectional specimen used in the experiment is composed of 176 laminae. At the frequencies used in the experiment, the waves present in the laminate are much longer than the diameter of the fibers, so that the material of each lamina can be assumed to be transversely isotropic, with the symmetry axis along the fibers. Using a Cartesian coordinate system with 1-axis along the fibers and the 3-axis along the normal to the laminate, the stiffness matrix $[C_{ij}]$ for the material of each lamina can be described by means of five indepenendent elements, namely, C_{11}, C_{22}, C_{12}, C_{23} and C_{55}. The values of these constants were assumed to be given by

$$C_{11} = 160.73 \text{ GPa}, \quad C_{22} = 13.92 \text{ GPa}, \quad C_{12} = 6.44 \text{ GPa},$$

$$C_{23} = 6.92 \text{ GPa}, \quad C_{55} = 7.07 \text{ GPa}. \tag{1}$$

The density, ρ of the material was assigned the value 1.58 g/cc.

In order to complete the model of the laminate, it is necessary to consider the nature of the interface between the laminae. This region is generally known to be matrix rich and of small thickness compared to the laminae. For the present specimen, the thickness of each lamina is approximately 125 μm while the interfacial zones are on the order of 10 μm. For an angle of incidence of 20°, the phase velocity of the induced Lamb waves is about 4.4 mm/μsec and their minimum wavelength at 1.7 MHz is about 2.6 mm, much greater than the thickness of the interfacial layers. Thus, as a first approximation, the laminate can be represented by a homogeneous transversely isotropic plate with the properties given in equation (1) above.

For a specified model of the laminate, the amplitude and phase of the reflection coefficient, normalized to those of the incident field were calculated by means of the computer code. In order to compare the theoretical results with those obtained from the experiments, these spectra were multiplied by the tranducer response provided by the tungsten film.

The results of the calculations based on the uniform plate model of the laminate are compared with experimental data in Fig. 2 (first two columns) for 15° angle of incidence and three directions of propagation. It can be seen that the agreement is excellent for propagation in the direction of the fibers. However, for the other two directions of propagation, the agreement is reasonable at lower frequencies, but becomes progressively worse at higher frequencies.

In general, for off axis propagation, the theory predicts significantly higher number of Lamb wave modes than could be observed in the experiments. Since a lower number of modes are associated with a smaller plate thickness, better agreement could be achieved by reducing the thickness of the laminate. However, the amount of reduction needed for a

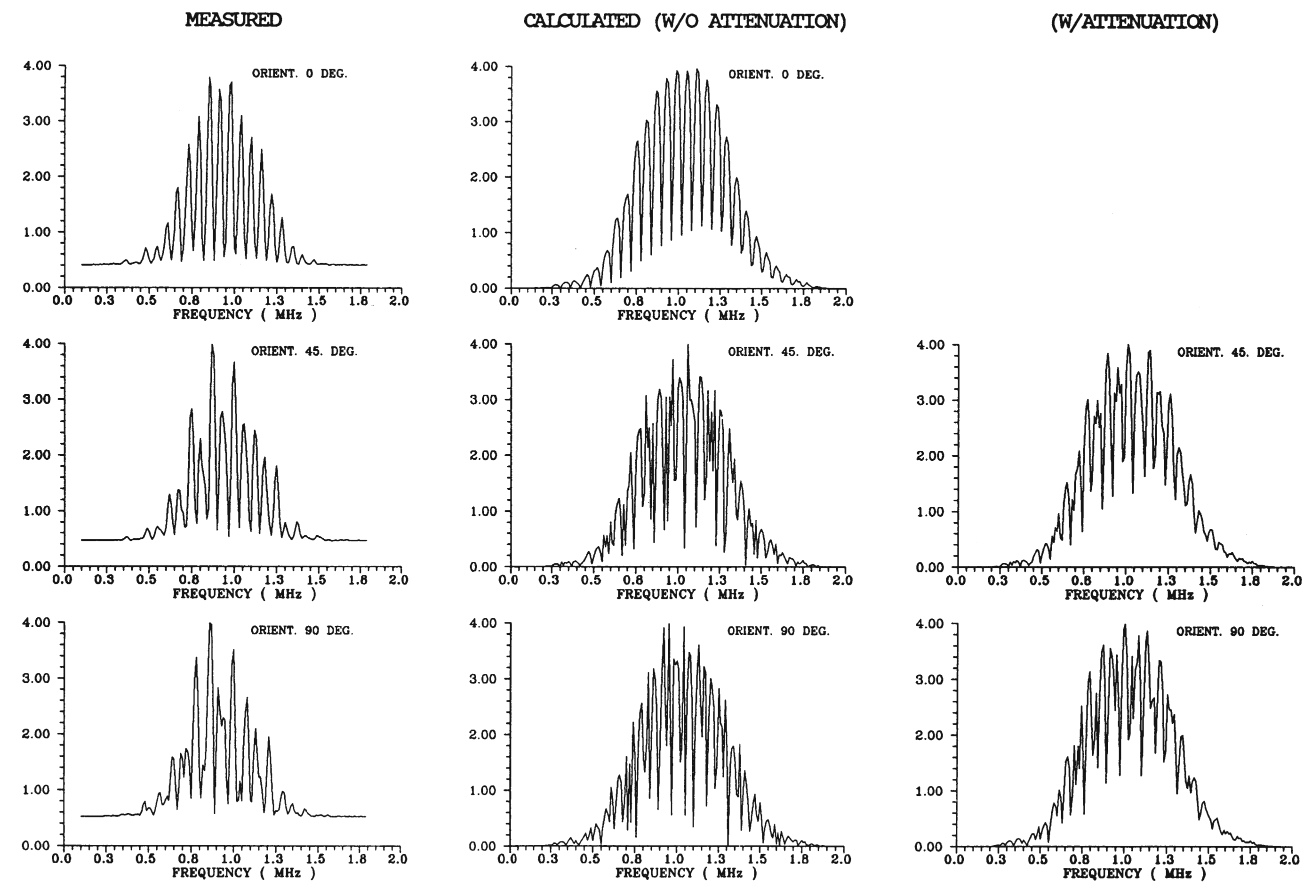

Figure 2. LLW spectra for a 25 mm thick unidirectional graphite/epoxy laminate. Incident angle is 15°. Laminate is modeled as a homogeneous plate without or with attenuation.

reasonable agreement in the entire frequency range was found to be about 60%, clearly an unacceptably high figure.

Another possible cause for the discrepancy is wave attenuation due to scattering from pores and other inhomogeneities within the composite. Attenuation can, in principle, reduce the effective thickness of the plate that is scanned by the Lamb waves. Numerical tests were carried out to examine this hypothesis. The effects of material dissipation and scattering can be modeled through the use of frequency dependent, complex values of the elastic wave speeds in the material. The attenuation contants were assumed to be of the form

$$\alpha_i = a_i(f/f_0) + b_i(f/f_0)^2 \qquad i = 1,2,3$$

where f is the frequency, a_i and b_i constants which determine the decay in the amplitude of the waves with propagation distance and f_0 is a prescribed frequency. The effect of material dissipation is described by a_i and that of scattering by b_i. In order to keep the number of adjustable parameters small the attenuation constants for the different waves were assumed to be in proportion to their propagation speeds. Thus only three additional parameters, a, b and f_0 were needed to model this effect.

The reflection coefficients were calculated by assigning numerical values to the constants a, b and f_o in a specified range. This resulted in considerable improvement in the agreement between the measured and calculated reflection coefficients for all orientations of the composite, as can be seen from the third column of Fig. 2.

A third possibility is that the interfacial layers may have a stronger influence on the reflected field than had appeared at first sight, so that the multilayered nature of the laminate may have to to be modeled explicitly in the theory. This could of course, be accomplished by including all 176 transeversely isotropic layers of the laminae separated by another 175 layers of the matrix rich material. However, since in the present case, the wavelengths are on the order of a few milimeters this was felt to be unnecessary. The problem was instead approached with the view that one should look for the smallest number of layers needed for the best possible agreement between data and theory. Thus the laminate was first modeled by two layers of the composite material of thickness 12.5 mm each, separated by a thin (.01 mm) interfacial layer. The properties of this material were assumed to be given by

$$C_{11} = C_{22} = 5.81 \text{ GPa}, \quad C_{12} = C_{23} = 2.90 \text{ GPa}, \quad C_{55} = 1.45 \text{ GPa}.$$

$$\rho = 1.2 \text{ g/cc}.$$

It should be noted that the above properties are similar to those of certain types of epoxy, and no attempt was made to model the effect of a small percentage of fibers in the interfacial region. The reflection coefficients calculated from this model were visually compared with those from the experiments. The total number of layers were then gradually increased until a good visual agreement was reached.

The outcome of these investigations are as follows;

(a) For propagation parallel to the fibers, the homogeneous plate model of the laminate yields excellent agreement between theory and experiment. No significant improvement was found to occur by including layering.

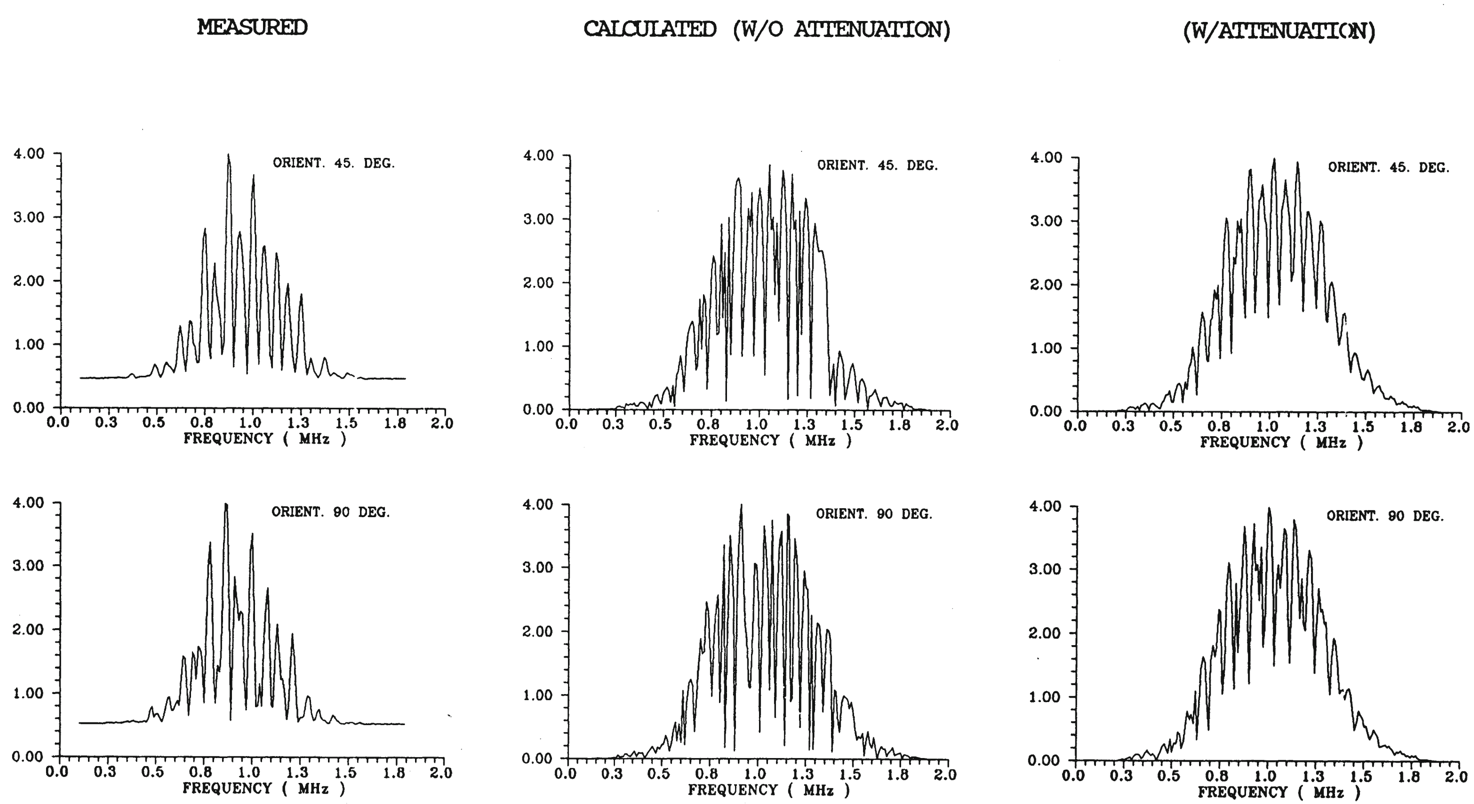

Figure 3. Same as *Figure 2* except that the laminate is modeled as a multilayered plate with 11 layers of composite and 10 layers of epoxy for off axis propagation.

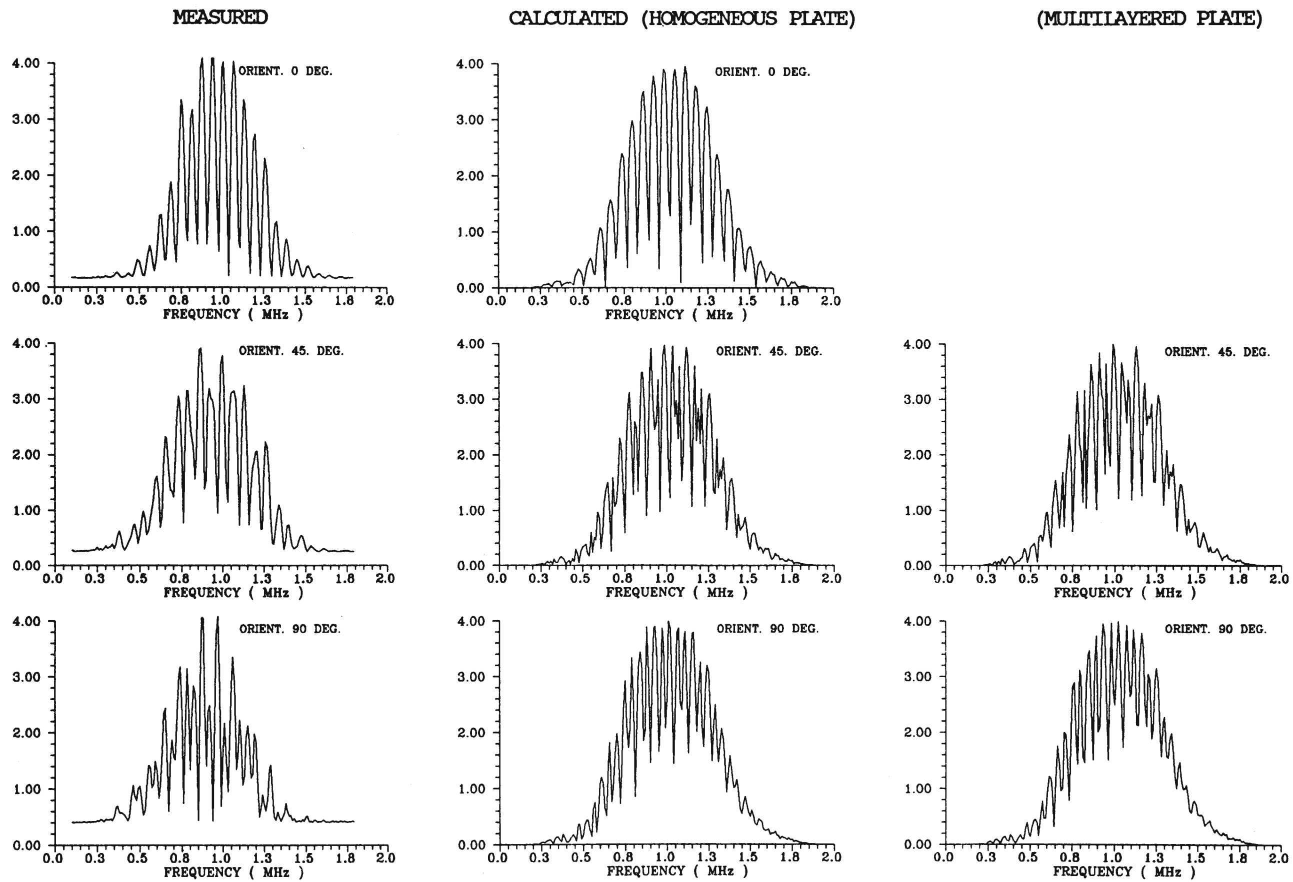

Figure 4. LLW spectra for a 25 mm thick unidirectional graphite/epoxy laminate. Incident angle is 20°. Laminate is modeled as a homogeneous plate or as a multilayered plate as in *Figure 3* with attenuation.

(b) For propagation at right angles to the fibers, it was necessary to include at least 8 laminae separated by 7 layers of adhesive in order to achieve a good agreement. No improvement could be gained by further increasing the number of layers.

(c) For propagation at 45 degrees to the fibers, the total number of layers had to be increased to 21 for a reasonable agreement.

The final results are shown in Figs. 3 and 4. Comparison between figures 2, 3 and 4 clearly show the significant improvement in the agreement between the calculated and measured values of the reflected amplitude spectra for off axis propagation.

The main conclusions that can be drawn from this study are as follows:

(a) The nature of guided waves in a thick laminate is quite different from that in a thin laminate composed of the same type and arrangement of the lamina.

(b) The influence of wave scattering appears to be significant even at frequencies below 2 MHz.

(c) For general direction of propagation, a thick laminate should be modeled as a multilayered solid, even though all its laminae are oriented in the same direction.

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