LEAKY LAMB WAVE PHENOMENA IN COMPOSITES USING PULSES

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ABSTRACT

The leaky Lamb wave (LLW) phenomenon in composite laminates has been studied using pulses rather than tone burst or continuous waveforms. For unidirectional laminates, the leaky wave pulses propagating obliquely to the fibers are shown to be strongly influenced by the presence of flaws within the laminate. The differences in the pulse characteristics have been employed to detect and image ply-gaps, delaminations, and variations in the resin/fiber ratio in laboratory specimens. Moreover, the depth distribution of porosity, simulated by microballoons, has been clearly shown with a C-scan system. Theoretical simulations of pulse propagation have been conducted for multilayered, multiorientation laminates, and the calculated reflected pulses are in close agreement with those obtained from the LLW experiments for a variety of specimens.

INTRODUCTION

Fiber-reinforced composite laminates are being used increasingly for primary structures in the aerospace and other high-tech industries. With such applications, reliable nondestructive evaluation (NDE) methods are needed to determine the integrity and serviceability of structural composites at various stages of production and service. Flaws are particularly difficult to detect in composites because these materials are inhomogeneous, anisotropic, and layered materials. The leaky Lamb wave (LLW) phenomenon has shown considerable potential as an NDE method while responding to these material characteristics [1-2].

Lamb waves can be generated in composite laminates at 0.5 to 15 MHz, the frequencies commonly used in ultrasonic NDE. When a laminate is immersed in a fluid, the Lamb waves leak energy into the fluid at an angle that is established by

Snell's law. Lamb waves can be induced in a laminate by means of an incident beam of acoustic waves at a properly selected transmission frequency. When the LLW is induced, the reflected beam is split into two beams separated by a null zone that is created by interference between the specularly reflected and leaky wave fields.

LLW tests to detect defects can be performed in two ways: (1) by using the tone-burst waveform and evaluating the amplitude changes at a selected frequency, which induces a leaky Lamb wave in the defect-free sample, or (2) by evaluating changes in the spectral response while sweeping through a given frequency range. Both methods were found to be very sensitive to small changes in elastic properties or thickness of the plate. As a result, with these methods, it may be difficult to discriminate between small property or thickness variations and the presence of defects.

Thus, although the frequency domain test methods have been generally successful in locating and characterizing important flaws in composite laminates, they have been found to have limited sensitivity and to be unreliable when defects were located at specific depths. Recent studies have shown that the use of pulses can increase the sensitivity and reliability of the LLW technique irrespective of the location of the defects. Further, pulsed LLW can be used with conventional pulser/receivers and it is therefore more likely to find greater acceptance in the NDE community. The results of this investigation will be discussed in this paper.

TIME DOMAIN RECORDING AND ANALYSIS OF LLW DATA

In the time domain approach, the receiver is placed in the null zone of the reflected beam using a tone-burst setup. Then, the transmitter is switched to a pulser/receiver (Panametrics, Model 5052PR), and pulses are used instead of tone bursts. Using this method, several specimens of unidirectional, cross-ply, and other laminates were insonified by acoustic pulses at various angles of incidence and at different orientations of the laminate relative to the incident beam. The reflected pulses were recorded in each case. A reference signal was also recorded for each arrangement of the LLW system by placing a tungsten film over the specimen.

In the theoretical studies, each lamina was modeled as a transversely isotropic material with the symmetry axis along the fiber direction. Uniaxial laminates were modeled as homogeneous plates, while the cross-ply and other laminates were modeled as multilayered plates with their respective arrangement of the laminae. Material dissipation was modeled by using complex wave numbers with frequency-dependent imaginary parts. The interfacial zones between adjacent laminae were ignored in these studies, although they could easily be incorporated in the models.

The incident waves were assumed to be plane-wave acoustic pulses propagating at a given angle and orientation relative to the laminate. The complex reflection coefficients were first calculated in the frequency domain under the assumption of an impulsive time history of the incident field by means of a matrix method [2]. These were then multiplied by the complex fast Fourier transform of the reference signal in order to account for the transducer response. The resulting spectra were inverted to obtain the predicted time history of the reflected waves.

The measured and calculated results are compared in Fig. 1, 2, and 3 for three directions of Lamb wave propagation in each laminate. Similar results were obtained for other cases. As shown, there is good agreement between the measured and calculated time histories. The major reflected pulses are correctly predicted by the theory in all cases. The agreement is substantially improved when attenuation is included in the theory (Fig. 1c, 2c, and 3c). The multiorientation case showed a more complex waveform with good agreement between theory and experiment as shown in Fig. 3. This will be discussed in more detail in forthcoming papers.

In the case of the unidirectional laminate (Fig. 1), both the recorded and calculated results show a significant difference in the characteristics of the reflected pulses for propagation at 45 degrees to the fibers as compared to propagation along the fibers. For propagation at 45 degrees, the response beyond the first major pulse is rather weak with a complex waveform, in contrast to that along the fibers, where a repetitive pattern appears. The regular pattern of the pulses for propagation along the fibers and the absence of secondary pulses for propagation at 45 degrees to the fibers have been used to develop a C-scan based technique for defect characterization in composite laminates. The basic idea behind the system is described in the next section.

DEFECT CHARACTERIZATION USING LLW PULSES

The time-domain video response from a graphite/epoxy T300/CG914 [0] 24 laminate for propagation along the fibers is shown in Fig. 4. The response from a

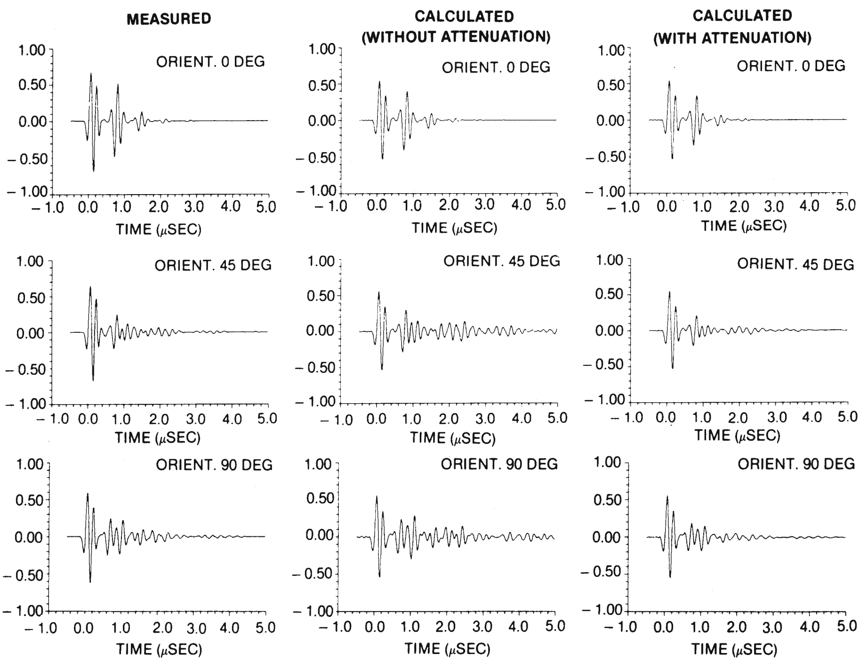

Figure 1. LLW time histories for unidirectional graphite/epoxy laminate of 1 mm thickness. Incident angle is 15 degrees. Laminate is modeled as a homogenous plate.

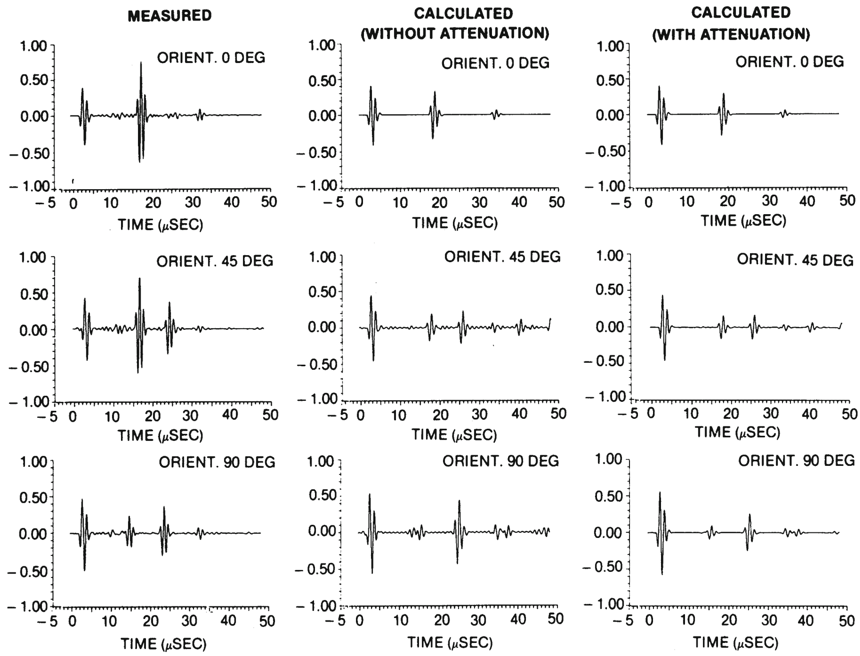

Figure 2. LLW time histories for a 25-mm-thick unidirectional graphite/epoxy laminate. Incident angle is 20 degrees. Laminate is modeled as a homogenous plate with and without attenuation.

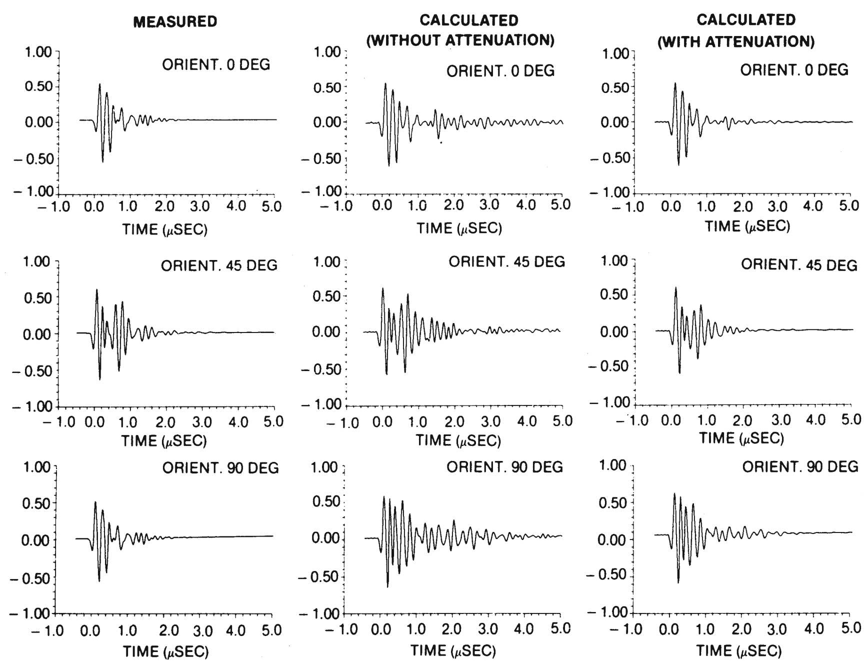

Figure 3. LLW time histories for a 1-mm-thick graphite/epoxy $[0,90]_{2S}$ laminate. Incident angle is 15 degrees. Laminate is modeled as a multilayered plate with and without attenuation.

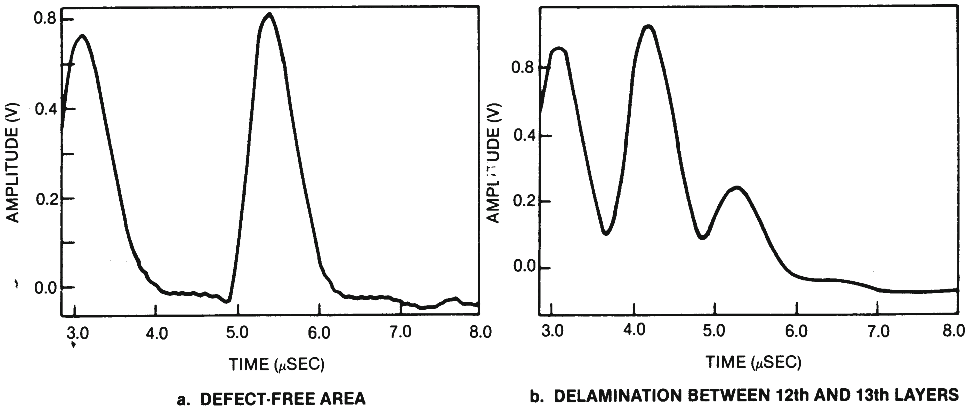

Figure 4. Time domain RF video response from a $[0]_{24}$ graphite/epoxy laminate tested along the fibers.

defect-free region of the specimen is given in Fig. 4a, while that from a region containing a delamination between the 12th and 13th layers is depicted in Fig. 4b. As indicated, the time-domain approach clearly identifies the presence and depth of the delamination.

The RF response from the same sample for propagation at 45 degrees to the fibers is shown in Fig. 5, with and without the delamination. The prominent secondary pulse in Fig. 5b is clearly caused by the delamination since it is absent in the response of the defect-free area (Fig. 5a). The significant difference in the responses of the two regions has provided an excellent NDE means of defect detection and characterization. A C-scan setup has been used with a time gate beyond the position of the specular reflection. The host computer acquired the peak-to-peak value of the highest reflection as well as its time-of-flight value. Fig. 6 shows a C-scan image presenting the amplitude variations of the highest signal obtained beyond the specular reflection. As shown, all three types of embedded defects – delamination, ply-gap, and porosity – were clearly identified. Further, changes of the resin/fiber ratio significantly affected the amplitude. On the other hand, Fig. 7 shows a C-scan image presenting the variations of the time-of-flight values for the $[0]_{24}$ sample. In this case, all the embedded defects were detected with greater sensitivity than obtained from tone-burst LLW tests. Different colors were assigned to the various time-of-flight ranges in order to present the depth of the defects in the sample. The dark lines along the C-scan image are parallel to the fiber orientation and result from the migration of porosity (microballoons 40 μm in diameter) from the center of the sample outward during the laminate cure. A close look at the image shows that during cure, the porosity also migrated through the plies. Further, the depth distribution of the trapped porosity can be identified from the color of the dots representing the porosity. This result clearly indicates the need for new criteria for porosity evaluation which will not be based only on volume percent.

The success of the theory in predicting the pulsed LLW behavior and the fact that the technique can be employed with commercial pulser/receivers make this approach attractive for industrial applications. However, it is necessary to develop a fuller understanding of the behavior of the waves in the laminate before the technique can be applied with confidence to practical problems.

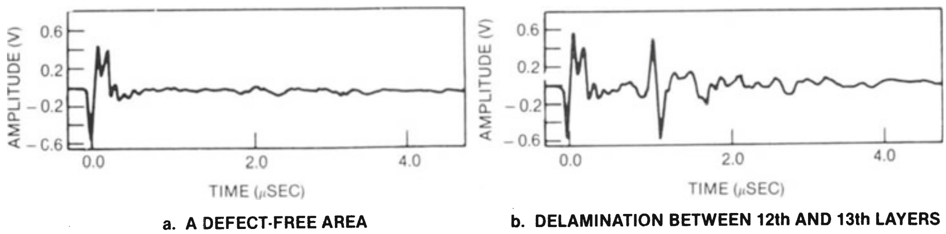

Figure 5. Time domain response from the graphite/epoxy $[0]_{24}$ specimen tested at 45 degrees from the fiber orientation.

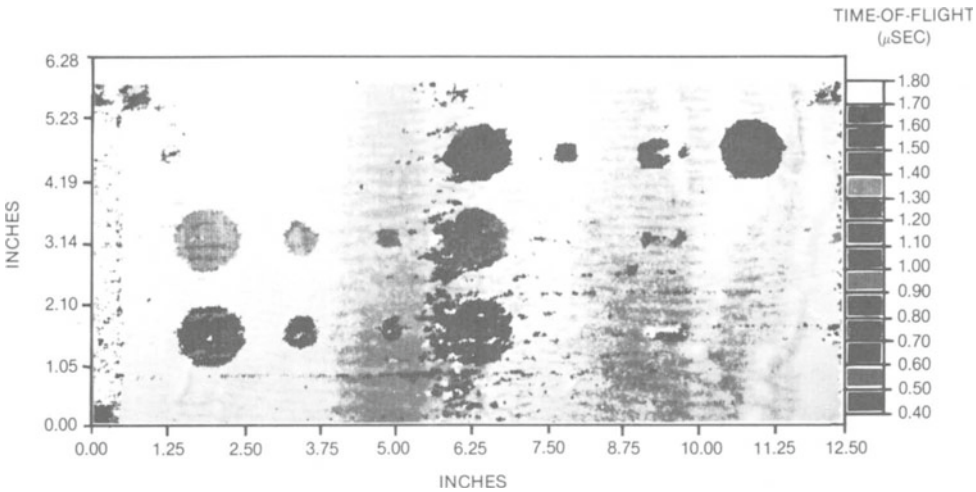

Figure 6. Pulsed LLW C-scan showing the amplitude variations in the graphite/epoxy $[0]_{24}$ laminate tested at 45 degrees from the fiber orientation.

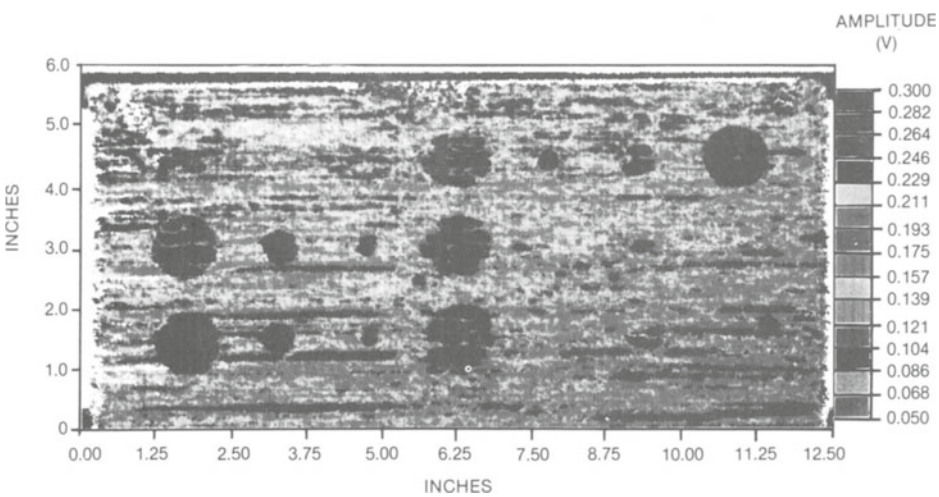

Figure 7. Pulsed LLW C-scan showing the time-of-flight variations in the graphite/epoxy $[0]_{24}$ laminate tested at 45 degrees from the fiber orientation.

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