NDE of Strength Related Properties of Adhesive Joints

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ABSTRACT

The existing ultrasonic nondestructive evaluation (NDE) methods for the quality of bonds in structural components are reviewed. Some recent results of a joint theoretical and experimental program of research using ultrasonic spectropy and leaky Lamb waves (LLW) in laboratory specimens are presented. Potential applications of the technique to nondestructively determine the quality of bonds are discussed.

KEYWORDS

Leaky Lamb Waves, cohesive strength, adhesive strength, dispersion curves

INTRODUCTION

With increasing use of bonded components in flaw-sensitive structures in recent years, it has become necessary to have reliable nondestructive methods to evaluate the integrety and quality of bonds. The existing ultrasonic NDE methods are capable of detecting and characterizing unbonds with adequate reliability (Cagle, 1966; Hagemaier, 1977; Bar-Cohen, Arnon and Meron, 1978). However, many other factors can have a weakening effect on the bond, resulting in a loss of strength of the component. Thus, it is desirable to develop techniques that can be used with equal reliability to determine the parameters that are related to the strength of the bond (see, for example, Rose and Meyer, 1973).

The strength of an adhesive bond depends on two factors, cohesion and adhesion. Cohesive strength is determined by the type of the adhesive, its elastic properties, and its thickness. These properties of the adhesive can be significantly different from those in its bulk state, depending on the curing process and must be determined in-situ. There are no reliable NDE methods at present that can yield accurate estimates of all the properties.

Adhesive strength is dependent upon the nature of the bond between the adhesive and the adherents. The quality of adhesion is critical to the performance of the adhesive as a bond between the components of an assembly. Since the interfacial layer between the adhesive and the adherent is often very thin, it is difficult to characterize it nondestructively. Weakness of this layer, which can be caused by poor surface preparation and other factors, can not be detected by existing NDE methods.

Results of recent research using ultrasonic spectroscopy and leaky Lamb waves have shown that it is possible to determine, nondestructively, the thickness and elastic proerties of the adhesive layer, (which determine the cohesive strength of the bond), and the degree of departure of the interface from perfect bonding, (i.e adhesive strength) in laboratory specimens. Some of these results are presented and discussed in this paper.

ULTRASONIC SPECTROSCOPY

In conventional ultrasdonic techniques, broadband signals obtained in standard pulse-echo or through-transmission experiment are analyzed on the basis of the flight times of the reflected and transmitted longitudinal waves propagating within the specimen. Such analysis can be used to identify and characterize strong dicontinuities, e.g. complete debonding in the specimen, but is difficult or impossible to use in determining material properties or imperfect bonding. A significant improvement in the capability of the technique is achieved through the application of frequency domain analysis of the signals. The main advantage of this approach is in its ability to reveal frequency dependent features which can not be easily identified in the time domain signals.

The frequency dependent reflection and transmission coefficients can also be calculated from theoretical models of the bonded specimen immersed in the coupling fluid by means of several available techniques. Dissipative properties of the constituent materials as well as imperfect bonding can be incorporated in the model (Mal, Yin nd Bar-Cohen, 1987). Comparison between experimental and theoretical spectra can then be used to estimate the elastic properties (e.g. Young's Modulus) and thickness of the adhesive layer.

An example of the application of this technique is given in Fig. 1. where the measured and calculated pulse echo signals and their spectra for a uniform and a bonded aluminum plate are presented. A number of interesting points should be noted. First, the agreement between theoretical and experimental results can be seen to be excellent in all cases. Second, the time domain signals for the unbonded and bonded specimens are somewhat different from each other, but the differences are not significant enough to indicate the properties or even the presence of the interfacee zone. In contrast, the difference in the spectral response of the bonded plate from that of the uniform plate is significant enough to be detected in the experiment. In particular, the number and location of the minima in the spectrum are related to the properties of the adhesive which can be estimated from the theoretical model (Cawley and Hodson, 1988).

LEAKY LAMB WAVE (LLW) TECHNIQUE

A generalization of the above technique can achieved by considering obliquely incident acoustic beams and by changing the incidence angle in a specified range. The corresponding experimental set up requires a pitch-catch arrangement of the transducers. For a fixed angle of insonification,

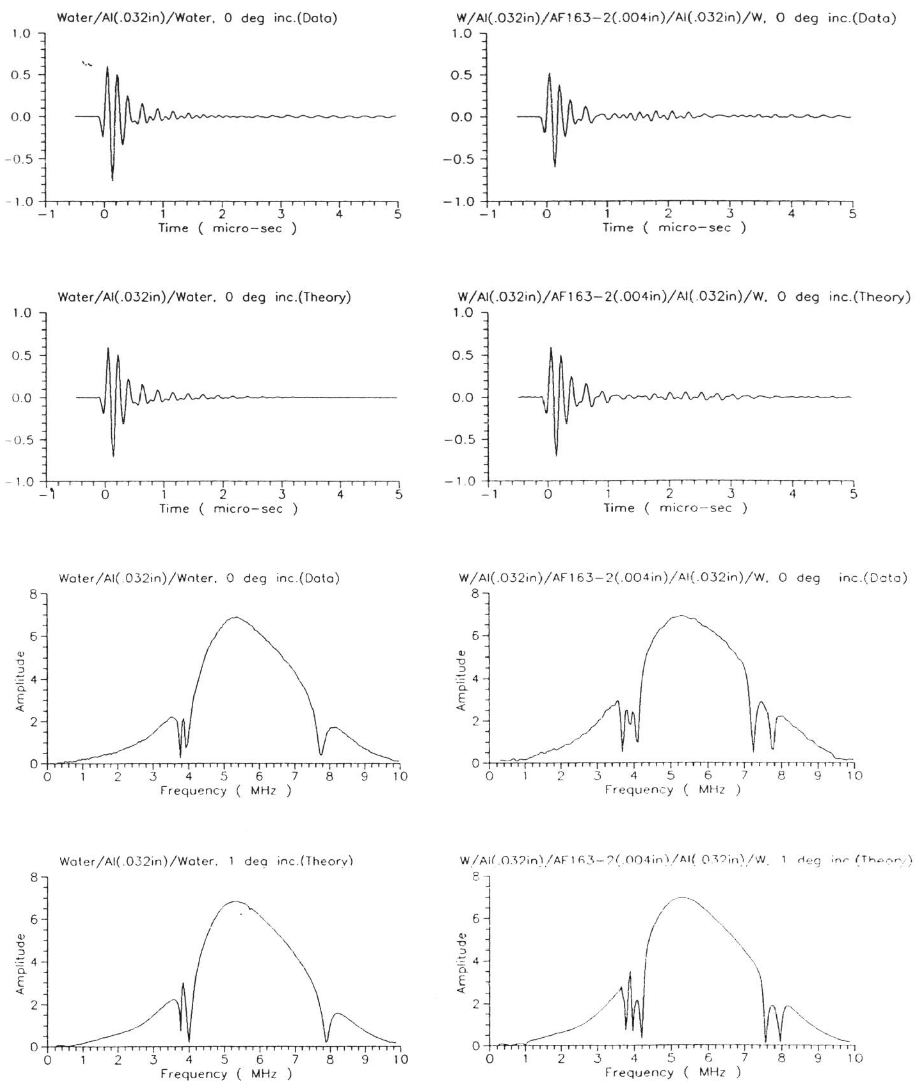

Fig. 1. Measured and calculated time histories and spectra of pulse-echo from a uniform and a bonded aluminum plate.

the acoustic waves are mode converted to induce guided waves in the specimen at certain specific frequencies, resulting in leakage of radiation into the fluid. A schematic diagram of this so called leaky Lamb wave set up is shown in Fig. 2. The details of the experiment and the nature of the recorded signals has been described in several earlier papers (e.g. Bar-Cohen, Mal and Yin, 1988) and will not be repeated here. For a given sample, the main output of the experiment is a suite of reflected signals, either in the time domain (LLW pulses) or, in the frequency domain (LLW spectra). In addition, processing of the spectra yields the dispersion curves for the guided waves in the specimen in a broad range of frequencies.

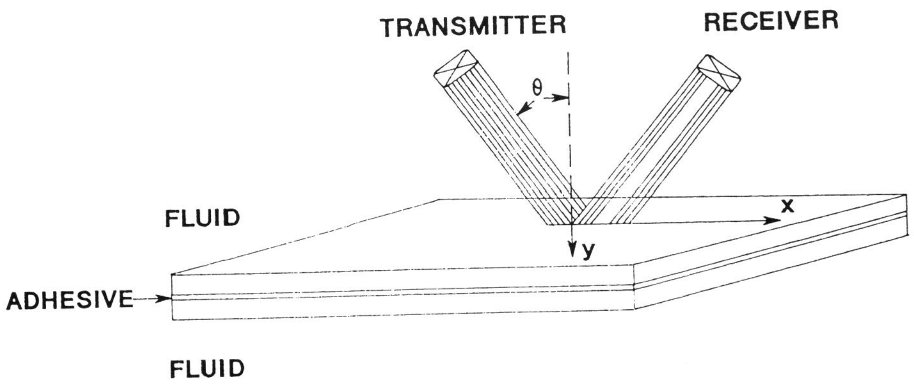

Fig. 2. Schematic diagram of the leaky Lamb wave experiment.

Theoretical simulation of the LLW experiment is relatively complex due to the presence of a variety of waves, namely, longitudinal, shear, and multimode guided waves in the specimen. Direct, propagator matrix or other treatments lead to numerical instability in the calculation of the reflected field at higher frequencies and special care is required in the formulation and solution of the resulting boundary value problem. An accurate and efficient code based on a global matrix formulation of the problem has been recently developed (Mal, 1988).

The measured and calculated LLW time histotries and spectra for a uniform and a bonded aluminum plate immersed in water and insonified at specified angles are shown in Fig. 3. Again, the spectral response for the bonded plate can be seen to have strong distinguishing features in the number and location of its minima. The agreement between theory and experiment is also excellent as in the case of normal incidence.

We now consider how the LLW data can be used to estimate the elastic properties and thickness of the adhesive layer, and to determine the soundness of the interfacial adhesion. The LLW have two characteristics that make them useful for NDE of bonding. First, the velocity of the guided waves is very sensitive to the properties of the adhesive as well as the nature of the interfaces between the adhesive and the adherents. Second, the guided waves produce both compressional and shear stresses at the interface, in contrast to only the compressional stress in conventional pulse-echo and through-transmission methods. Thus the LLW method is capable

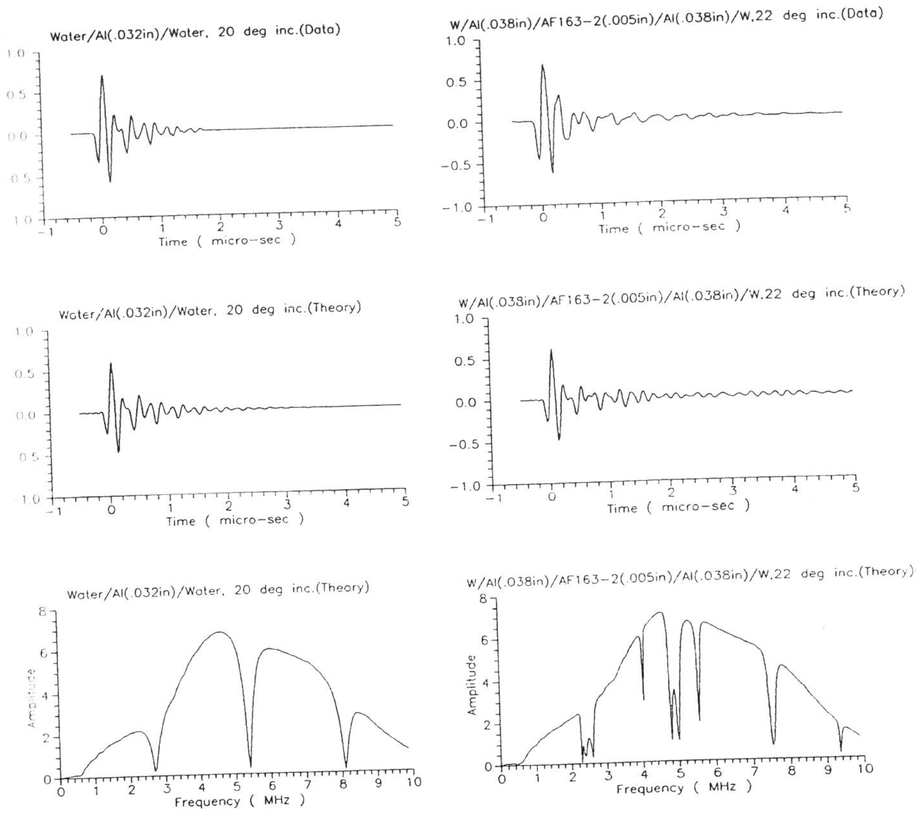

Fig. 3. Measured and calculated LLW pulses and spectra from a uniform and a bonded aluminum plate

of providing better diagnostics of the interfacial zone than conventional NDE techniques.

Our attempt to determine the properties of the adhesive layer from LLW data is summarized in Fig. 4, where the measured and calculated Lamb wave dispersion curves for a bonded aluminum plate are shown. The thickness of each plate is 1.6 mm and of the adhesive layer is .08 mm. The properties of the adhesive in Fig. 4a and 4b are,

$$\alpha = 1.17\text{mm}/\mu\text{s.}, \quad \beta = 0.58 \text{ mm}/\mu\text{s.}, \quad \rho = 1.2 \text{ g/cc} \tag{1}$$

$$\alpha = 1.04 \text{ mm}/\mu\text{s.}, \quad \beta = 0.52 \text{ mm}/\mu\text{s.}, \quad \rho = 1.2 \text{ g/cc.} \tag{2}$$

respectively, where α, β, ρ are the compresional wave speed, the shear wave speed and the density of the adhesive material, in-situ. These properties were arrived at by a trial and error process and are quite different from those of the particular adhesive in its bulk form. Clearly, both estimates fit the LLW data quite well; but the second one appears to have a better fit in those portions of the dispersion curves that are strongly influenced by the adhesive properties.

Al(.064)/Pr(.0012)/Ad(.003)/Pr(.0012)/Al(.064)

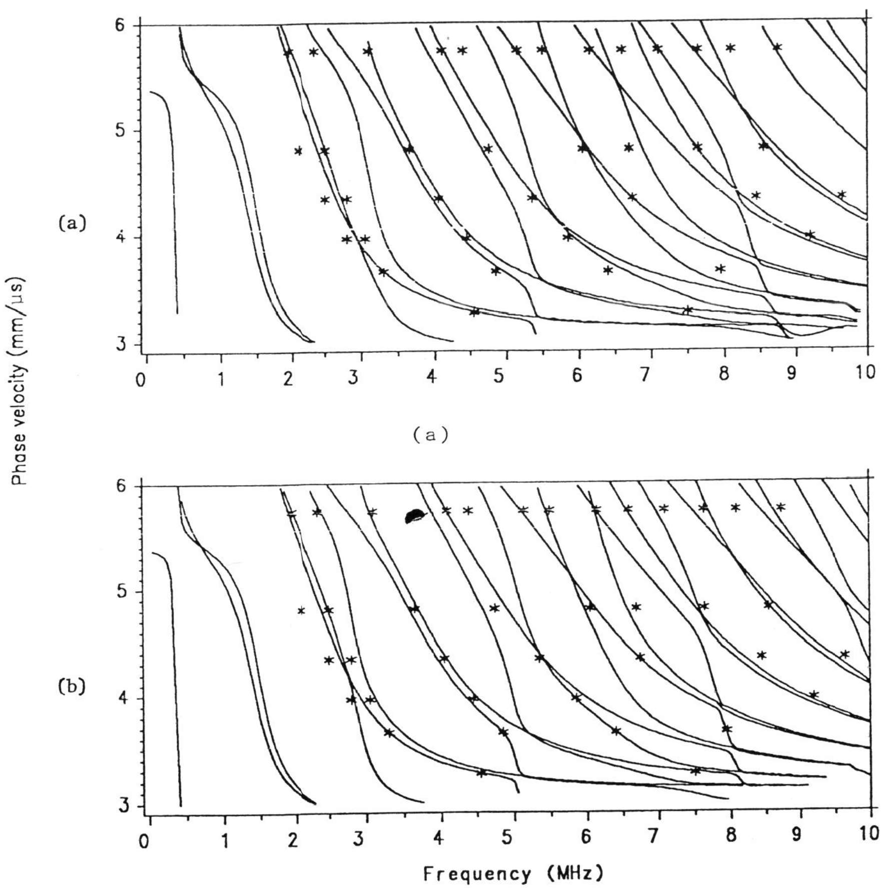

Fig. 4. Calculated (solid lines) and measured (*'s) Lamb wave dispersion curves in a bonded aluminum plate.

The calculated effect of imperfect bonding at the interface on LLW dipersion curves is shown in Fig. 5. The calculations were based on the theory presented earlier (Mal and Xu, 1988). In this theory, the 'quality' of the interface is described by two parameters p and q, related to the properties of the adhesive layer through the relations

$$p = h/(\rho\alpha^2), \quad q = h/(\rho\beta^2) \tag{3}$$

where h is the thickness of the layer. Smaller values of p and q indicate an interface of better quality than that for larger values. For the bonded aluminum plate considered here, the influence of these parameters was found to be the strongest on the first symmetric Lamb mode; the other modes were not affected significantly to be of interest in the present context. Thus, only the first symmetric mode is plotted in Fig. 5. The curve labeled 'b'

AL(1)/ADHESIVE(.1)/AL(1) mm

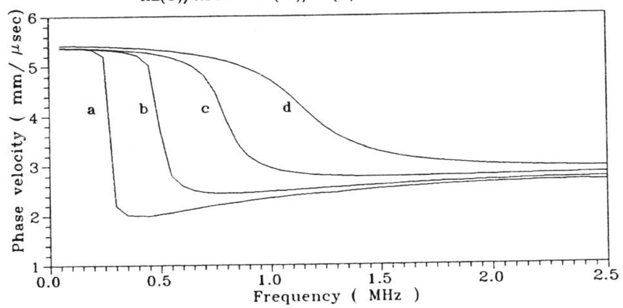

Fig. 5. Influence of interfacial features on the first symmetric Lamb mode in a bonded aluminum plate. Top curve is for a perfect interface, lower curves correspond to deteriorating conditions of the interface.

is for values of p and q which correspond to an adhesive layer of 0.1 mm thickness with properties given in equation (1); we denote these values by p_o and q_o. The curve labeled 'd' is for $p = q = 0$ (i.e. perfect bonding); "c" is for the case $p = p_o/4$, $q = q_o$ (better bond than 'b') and 'a' is for $p = 4p_o$, $q = q_o$ (worse than 'b'). Clearly, the predicted effects are large enough to be detected in the LLW test. Attempts are currently under way to prepare and test bonded specimens with controlled imperfections at the interface.

CONCLUDING REMARKS

Since adhesive bond strength depends upon the quality of the surface preparation, an NDE method to determine the quality of the surface preparation, such as the presence of contamination, is essential. Ultrasonic NDE methods are capable of providing information about adhesive bond properties, but not all relevant quantities in the detected signals are being used at present. Improved NDE techniques should allow several parameters to be captured and examined while a bonded area is being scanned, so that an assessment of the bond quality.

Presently, pulse-echo and through-transmission are the most widely used NDE techniques for bonding in a production environment, whereas resonance and pulse-echo are used in field conditions. An increase in the usage of the LLW method is expected due to its advantages as discussed above. For composites, the LLW technique has so far been found to be useful for laminates with limited types of fiber orientations. Recent progress in the theoretical analysis of wave propagation in anisotropic, multilayered media should lead to a better understanding of the wave behavior (Mal and Bar-Cohen, 1988) and should allow LLW modes to be predicted for bonded laminates as well as steel-rubber and other joints.

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