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NONDESTRUCTIVE CHARACTERIZATION OF ADHESIVE BONDS FROM GUIDED WAVE DATA

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INTRODUCTION

The critical role played by adhesive bonds in the fracture and failure of composites and other bonded materials is well known. A good knowledge of the mechanical properties of these adhesion joints is a prerequisite to reliable design and reliable prediction of the performance of these bonded structures. Several ultrasonic nondestructive evaluation (NDE) techniques can be used to obtain the thickness and the elastic moduli of adhesively bonded joints [1-4], In this paper we apply a recently developed technique, namely, the leaky Lamb wave (LLW) experiment, to characterize the adhesive bonds in two specimens. One is a bonded aluminum plate and the other is a $[0, 90]_{2s}$ graphite/epoxy laminate.

The LLW technique is based on an oblique insonification of the bonded specimen in the form of plate [S]. When a transducer insonifies a test part at an oblique angle, the wave is reflected, as well as mode converted to induce guided waves in the specimen. Certain characteristics of the guided waves are strongly influenced by the properties of the bond. We have carried out a coordinated theoretical and experimental program of research in an effort to determine the nature of the relationship between the adhesive properties and the measurable properties of the guided waves. We have also been able to demonstrate that a careful analysis of guided wave data can give accurate estimates of the thickness and elastic properties of the adhesive in a variety of bonded systems.

THEORY Ah'D EXPERIMENT

The theory of guided wave propagation in bonded, layered solid is well established. A theory of guided wave propagation in multilayered solids containing interface imperfections has been developed by Mal [5), where two models of the interface have been proposed. In one, the adhesive is modeled as an additional layer which is perfectly bonded to the adherents at the two interfaces. In the second, interface is assumed to have zero thickness and the effect of a thin layer of adhesive material is represented by a displacement jump which is assumed to be proportional to the interface traction. Based on these models, the properties of the interface zone can be characterized through the analysis of the measured guided wave speed; the details of the procedure can be found in [6] and are omitted here for brevity.

The ultrasonic experiment used to measure the guided wave phase velocity is basal on an oblique insonification with the test specimen immersed in water in a pitch-catch arrangement. For a given angle of incidence, the amplitude spectra of the reflected waves contain sharp minima, or nulls; these are associated with the excitation of the leaky guided waves in the laminate. This allows for accurate measurement of the phase velocity of the leaky guided waves in the laminate. The velocity data can be displayed as dispersion curves, i.e., the phase velocity of the different modes plotted vs. frequency. A detailed description of the experiment can be found in [7].

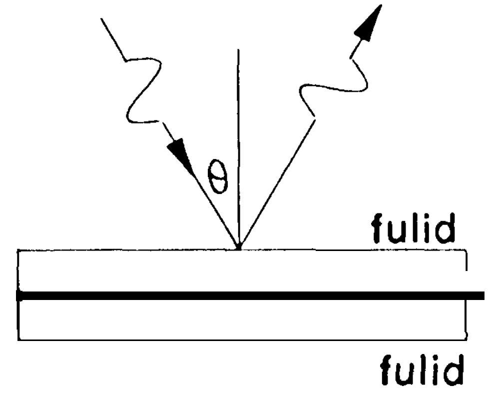

Figure 1. Geometry of the layered plate model.

CHARACTERIZATION OF ADHESIVE PROPERTIES

a) Bonded Aluminum Plate

The simplest model of a solid containing an interface and capable of supporting guided waves consists of two plates bonded together at their interface. The influence of the thickness, shear modulus and degree of adhesion of the interface zone on the dispersive properties of Lamb type waves propagating in bonded aluminum plates have been discussed in [6].

We investigate the influence of the interface zone on the reflection amplitude spectrum of a specimen composed of two identical 1 mm thick aluminum plates separated by a 0.1 mm adhesive layer (Fig. 1). The Young's modulus and shear modulus of aluminum is assumed to be 72.5 GPa, and 26.9 GPa, and those of the adhesive are 3.9 GPa, and 1.5 GPa.

In Fig. 2 the influence of the thickness and shear modulus of the adhesive on the reflected amplitude spectra is shown. The wave incidence angle is 20°. In can be seen that both the thickness reduction and materials degradation have measurable effects on the location of the minima and that the effect of the complete debonding is extremely strong.

b) Mutilayerd Graphite Epoxy Composite Laminate

The leaky Lamb wave technique is used to measure the dispersion curves of a $[0, 90]_{2s}$ (cross-ply) graphite/epoxy laminate of 1 mm thick. Each lamina is modeled as a transversely isotropic material. The stiffness constants of the material are obtained through inversion of LLW data for a unidirectional graphite/epoxy laminate. The values of the stiffness constants in GPa are: c_{11} = 160.73, c_{12} = 6.44, c_{22} = 17.61, %'3 = 8.75, c_{55} = 7.78. We first use these constants to calculate the dispersion curves of the laminate without adhesive layers and compare the result with measured data (Fig. 3a). It can be seen that there are significant differences in the higher modes of the dispersion curves. We carried out an extensive parameter study of the problem in an effort to resolve these differences, and concluded that they are caused by the presence of thin matrix rich layers between the

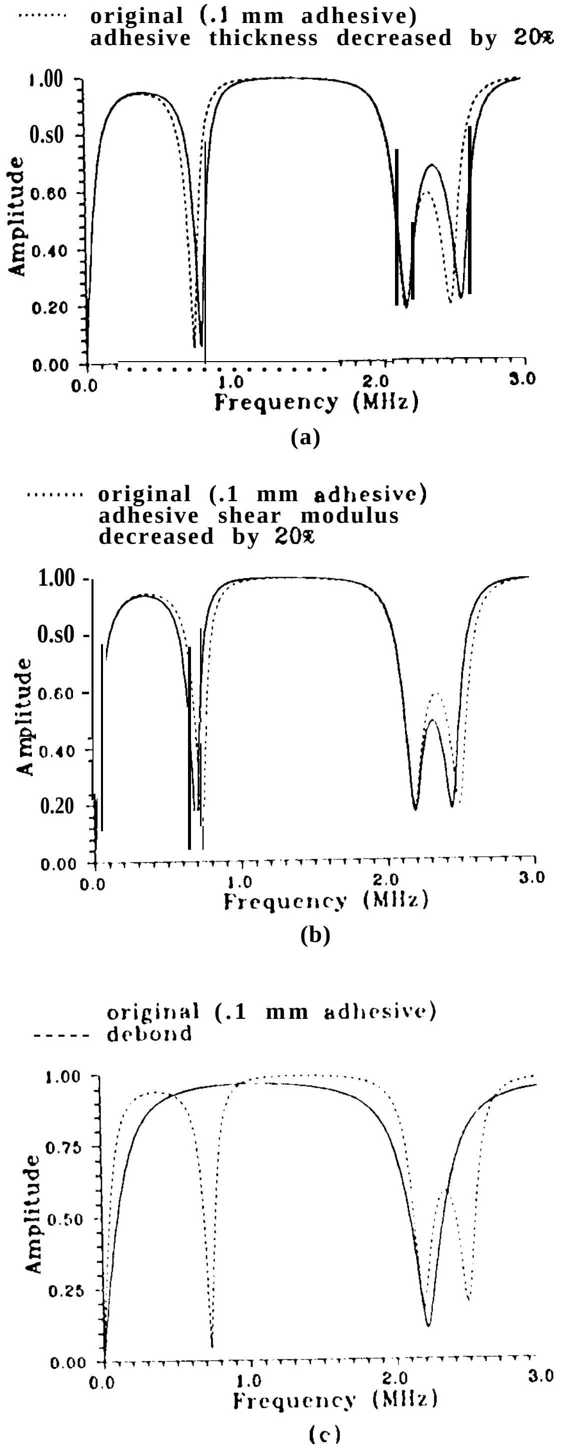

Figure 2. Influence of adhesive properties on the reflection amplitude spectra from a bonded aluminum plate.

individual laminae. Thus the specimen is modeled as a fifteen layered laminate consisting of eight graphite-epoxy laminae separated by seven epoxy layers; the thickness of the interface zones in assumed to be 5 μm. A comparison between the calculated and measured dispersion curves laminate for guided wave propagation at 0° to the top lamina is presented in Fig. 3b. It can be seen that the calculated dispersion curves with the adhesive layers agree better with the measured data than those without the adhesive layers.

CONCLUDING REMARKS

The influence of the properties of interface zones on the phase velocity of guided waves in bonded solids is investigate. In the case of the bonded aluminum plate, both the thickness and the shear modulus of the adhesive layer are found to have a measurable effect on the reflected spectrum. In the case of the composite laminate the presence of thin adhesive layers can be detected from an analysis of guided wave dispersion data. More detailed parameter studies using data in a larger frequency range are needed for more accurate characterization of adhesive layers in bonded systems.

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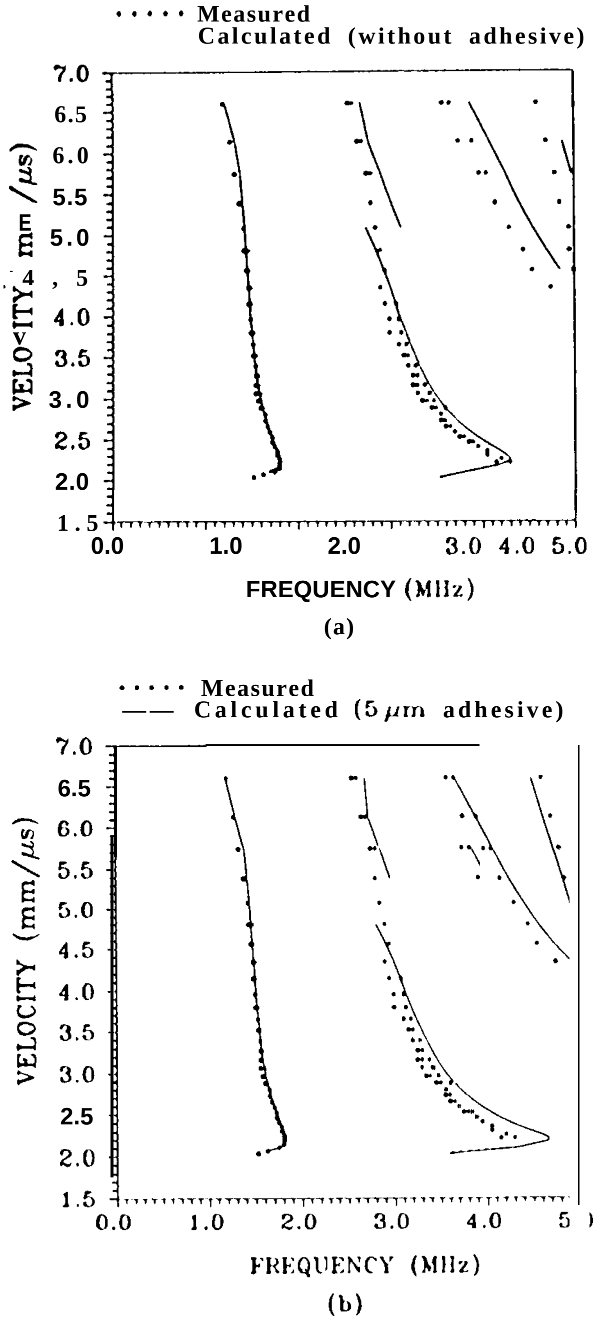

Figure 3. Comparison of the dispersion curves of a 1 mm $[0,90]_{2S}$ graphite/epoxy laminate for propagation at 0° to the fiber of the top lamina: (a) without adhesive layers (b) with 5 μm adhesive layers.

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