CHARACTERIZATION OF GLUED BONDS USING ULTRASONIC REFLECTED BEAM

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INTRODUCTION

Adhesive bonds of laminates of metal and polymer have been extensively studied using ultrasonic techniques. The strength of the bond is of primary importance and many studies have been aimed at deducing this property from ultrasonic measurements. The quality of adhesively joined structures is mainly determined by two types of factors: i) the cohesive strength of the glue ii) the adhesive strength of the metal-glue interface. To address the last type, several ultrasonic techniques using mainly plate and interface waves have been recently considered [1-4]. Their main advantage, compared to longitudinal or shear waves, is that they are very sensitive to the interface conditions.

The purpose of this study is to use the leaky Lamb waves method to better understand the role of each separate layer. We examine several plate systems made of the same adhesive and adherends, epoxy and steel respectively, but with different number of layers and different thicknesses. The properties of the interface are acoustically characterized by considering the two extreme cases of a perfect (or rigid) bond, and of a smooth (or kissing) bond. These interface qualities are related to ultrasonic parameters such as the reflection coefficient for different Lamb modes, the dispersion curves and the beam profile. In particular, we have investigated the feasibility of separating a "good" bond from a "bad" bond. Also modeling of the acoustic wave propagation in the multilayered system has been achieved and a comparison between theoretical and experimental data is discussed.

THEORETICAL APPROACH

The analysis which is used in this approach is based on the dependence of the reflection coefficient on bonding conditions at the interface between steel and epoxy. The two dimensional wave propagation model assumes an oblique incidence of a finite beam through a laminate structure. The layers are supposed to be isotropic and stacked normal to the z-direction of a cartesian coordinate system (x,y,z). And hence the coordinate direction x and y are in the plane of the plate, as generally stated in similar layer problems.

The wave equation is solved in each layer in terms of wave amplitude. Assuming for each layer a propagation of guided waves in the x-direction, the field variables consist of the displacement components u in the x-direction and w in the z direction, and the stress

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components $\sigma_{zz}$ and $\sigma_{xz}$ normal and tangential to the layer, respectively. Appropriate boundary conditions between layers and the water-layered interfaces have to be satisfied in order to derive an analytical expression for the reflection coefficient. The two extreme types of interlayers boundary conditions have been considered: the rigid bonding and the smooth bonding conditions: a) the rigid bonding conditions, on one hand, prescribe continuity across each interface between two materials 1 and 2 for the particle displacement ($u_1 = u_2$, $w_1 = w_2$), and for the normal and tangential components of the stress tensor ($\sigma_{zz1} = \sigma_{zz2}$, $\sigma_{xz1} = \sigma_{xz2}$, respectively); b) the smooth bonding condition on the other hand, requires continuity only for the normal displacement and stress ($w_1 = w_2$, $\sigma_{zz1} = \sigma_{zz2}$, respectively) while the tangential stress for both constituents of the interface are set equal to zero ($\sigma_{xz1} = \sigma_{xz2} = 0$), and the tangential displacement $u$ is not involved.

Finally, the expression for the reflection coefficient $R(\theta)$ of a plane harmonic wave from a fluid onto a solid surface is determined by writing the Fourier transforms of the wave potentials with respect to the $x$-coordinate \cite{5}. Considering a finite beam, each Fourier component of the incident field gives a contribution to the reflected field, weighted by the value of the reflection coefficient for the corresponding wave number $k_x$. Such calculations have been performed for a variety of samples involving a single steel plate, a steel plate loaded with an epoxy layer, and a steel-epoxy-steel plate system, in order to compare with our experimental conditions. We have also expressed our results as velocity dispersion curves obtained numerically by searching for minima in the magnitude of the reflection coefficient.

APPARATUS AND METHOD

Samples

The experiments have been run on different samples made of two steel plates (0.94 mm and 1.52 mm thick) glued together by means of an epoxy layer. The structure of the specimens is presented on Fig. 1. Two different thicknesses (0.5 mm and 2.1 mm) of adhesive layer have been used. Poor surface preparation and oil introduction between the thinner steel plate and the epoxy layer are supposed to provide a smooth bond on some of the samples (in bold line on Fig.1).

Experimental procedure and setup

Three different approaches all based on the generation, the propagation and the leaking of guided waves in fluid-coupled layered systems are carried out. In the first one, we focus our attention on the analysis of the phase velocity dispersion curves. In the second one, we measure the reflection coefficient. In the last one, we consider the distortion of the reflected beam profile, when a Lamb mode is excited. All these different methods are related to the measurement of the phase velocity of a given leaky guided wave. In the first approach, dispersion curves are obtained either by the critical angle technique or by spectral analysis. The critical angle technique gives plates modes by indicating the angles at which a minimum occurs in the reflection coefficient, at a fixed frequency. With spectral analysis, the modes are obtained by measuring the position of minimum in the specularly reflected spectrum, at a fixed angle. In both techniques, the result is the phase velocity dependence of the mode versus the product of the frequency $F$ by the thickness of the plate $d$.

In the second approach, the reflection coefficient $R(\theta)$ is plotted as a function of the angle of incidence $\theta$. Information about the mode can be obtained not only from the angular position of the minimum, but also from the general shape (width, depth) of the dip.

Practically, a multilayer specimen, immersed in water can revolve around a vertical axis. Two similar broadband transducers (central frequency $F_c = 2.25$ MHz, diameter $F = 12.5$ mm) are oriented under oblique incidence. The transmitter is fixed while the receiver has two degrees of freedom. One allows it to turn around the $x$ axis to fit the geometry.
of the specular reflection for any incidence. The other allows it to translate in a direction perpendicular to the axis of the reflected beam, in order to scan the field. The mechanical positioning system affords close control of the three degrees of freedom (2 rotations and 1 translation). All the movements are computer-assisted, with a precision of 0.01° and 0.01 mm. Data acquisition of time signal and processing (averaging, normalization, Fourier transform, deconvolution) are achieved by on-line microcomputer. Storage and further processing of the data allow one to plot the dispersion curves, the reflection coefficient and the beam profile.

RESULTS AND DISCUSSION

In order to characterize the quality of adhesion between a plate and an epoxy layer, we have concentrated our attention to the reflection coefficient of a single steel plate immersed in water which is then compared to that of a steel-adhesive and a steel-
adhesive-steel sample with various thicknesses of steel and epoxy layer. A schematic diagram of the studied specimen is presented on Fig.1 (ultrasonic waves are incident on the top of these samples).

Fig.2 shows the measured velocity dispersion data for a single steel plate and a steel-epoxy sample compared to the predicted values calculated for a steel plate. Agreement is very good. But more surprising is that no difference is noted between the experimental data given by the two types of sample. Theoretical confirmation is given by comparing the calculated reflection coefficient of these two samples, as shown on Fig.3. No significant difference is observed when water is change for epoxy although these two materials have a rather different impedance for the longitudinal waves ($Z_w = 1.48 \times 10^6$ Pa.s/m, $Z_e = 2.89 \times 10^6$ Pa.s/m).

![Fig.2](image_url)  
**Fig.2.** Velocity dispersion curves for a single steel plate and steel epoxy samples.

![Fig.3](image_url)  
**Fig.3.** Theoretical curves of the reflection coefficient of a single steel plate and a steel-epoxy specimen immersed in water (with same thickness of the steel plate).
For practical application, it is more realistic to consider the case of adhesion between two steel plates separated by an adhesive layer. A systematic study has been carried out by varying a) the thickness of the plate and that of the adhesive layer, b) the quality of bonding (rigid, smooth), and c) the position of the bonding defect (between the upper steel plate and epoxy or between epoxy and the lower steel plate): see Fig.1.

**Thickness of the plate and of the adhesive layer**

The reflection coefficients presented on Fig.4 exhibit no difference when the thickness of adhesive is changed (Fd being constant), and is very similar to that of a single steel plate. The results demonstrate that only the first steel plate irradiated by the ultrasonic beam contributes to the reflection coefficient. In other words, neither the epoxy nor the lower steel plate are detected. The whole system behaves as a single steel plate with thickness of the upper plate immersed in water as shown by its reflection coefficient also plotted on the same figure. Comparison of calculated values of $R(\theta)$ with experimental measurements shows, on Fig.5, that an excellent agreement exists for the position of the modes.

The sensitivity of the reflection coefficient $R(\theta)$ to the first encountered plate only, is again demonstrated by turning the sample upside down. By doing so, the only change is the thickness $d$ of the steel plate facing the incident ultrasonic beam. Plots of $R(\theta)$ in the two situations, shown on Fig.6, are very similar as long as the frequency value $F$ of the ultrasound is changed in order to maintain constant the Fd product when $d$ varies. As a result, the only detectable mode arises from the first irradiated plate. And hence no other possible mode generated either by the whole multilayer system, or by individual layers situated below the upper plate, gives a contribution to the leaky Lamb modes.

![Experimental plots of the reflection coefficient for a single steel plate and two three-layers plate systems with different thicknesses of epoxy (0.50 and 2.10 mm).](image)
Fig. 5. Comparison between experimental and theoretical reflection coefficient for a three layer plate system.

Fig. 6. Reflection coefficients of a three layer plate system at a fixed Fd, after turning it up-side-down.
Quality of bonding

The discrimination between rigid and smooth bond has been examined by looking at the variation of the reflection coefficient \( R(\theta) \) for two similar samples (same thickness of layers, same materials) which only differ by the quality of adhesion. A first set of experiments has been made with a defect of adhesion situated under the upper plate (see Fig. 11 and II2). The plots of \( R(\theta) \) presented in Fig. 7 exhibit for the rigid as well as for the smooth bond three minima associated with three modes. Modes \( A_1 \) and \( S_0 (\theta =15^\circ \) and \( 26.5^\circ \) respectively) are exactly the same for "good" and "bad" adhesion, whereas mode \( A_0 \) is shifted by \( 1.5^\circ \) between the two samples from \( 30.5^\circ \) to \( 32^\circ \) for the "smooth" interface. Similar results have been obtained with various samples and at different frequencies (2 MHz < \( F < 5 \) MHz).

![Graph](image)

Fig. 7. Reflection coefficients for a rigid and a smooth bond. Slip interface is under the upper plate.

Position of the bonding defect

A second set of experiments have been carried out with a defect located above the lower steel plate (see Fig. 1, II and III1). Comparison of the reflection coefficient \( R(\theta) \) for rigid and smooth bond shows on Fig. 8 that no change can be noted. Such a defect is not detectable at least for the thicknesses and the frequency range of the experiments. These data are coherent with the above mentioned results showing that ultrasound is not sensitive to the part of the layered specimen situated under the epoxy layer.
Fig. 8. Reflection coefficients for a rigid and a smooth bond. Slip interface is above the lower plate.

CONCLUSION

The purpose of this study was to determine the quality of adhesive bonds, using ultrasonic leaky Lamb waves. Results, obtained for the two layer system, have shown that the reflection coefficient is not significantly affected by changing from a steel-water system to a steel-epoxy one. Theoretical computations have confirmed this result. Also three layer plate structures made of two steel plates bonded together with an epoxy layer have been examined in order to differentiate between rigid and smooth bond. Small changes in the reflectivity have been detected when an artificial adhesive defect exists at the first steel-epoxy interface.

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