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Lamb Modes for the Characterization of Bonded Structures

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1. Introduction

The use of adhesives is very common in industry, thanks to their various well-known advantages. Therefore it is very important to evaluate the bonding quality by means of non destructive testing methods [1, 2, 3, 4], such as guided ultrasonic waves. The influence of the glue properties evolution on the bonding quality for a given structure has not been the subject of the most published studies in non destructive testing. In this paper the bulk properties of the thin layer of adhesive is varied by adding grease. The cohesive model of Jones is used to describe the bonding quality [5, 6, 7] of the structure. In this model the thin layer is replaced by a distribution of springs. The values of the spring stiffness, called in the following parameters of Jones, are infinite in the case of perfect adhesion while approaching zero in the case of delamination. Therefore, one can evaluate the quality of the bonding by measuring their values. It is interesting to know the range of these parameters values when modifying the quality of the glue. The structure studied in this work consists of two glass plates bonded by a thin film of glue (Araldite) which is gradually degraded by addition of grease. The paper is organized as follow. In the second section, dispersion curves of Lamb modes are experimentally obtained for different samples. Theoretical results are then obtained in the third section and compared to the experimental ones. The fourth section is devoted to the model of Jones and the determination of its parameters which take into account the quality of the bonding.

2. Experimental study and dispersion curves

The thickness of each plate of glass is 3 mm and the thickness of the adhesive film is 0.5 mm. To the original glue (araldite), grease is added and six different samples are studied. The proportion of grease in the glue varies from 0% (pure araldite, reference sample SRef) to 75% (S75) of the total volume. The other samples correspond to different ratios of grease: 5% (S5), 15% (S15), 25% (S25) and 50% (S50).

The experimental set up is represented in Figure 1 [8]. A transducer with a central frequency of 1 MHz is fixed on a Plexiglas wedge with 38.5° angle, placed on the surface of the structure

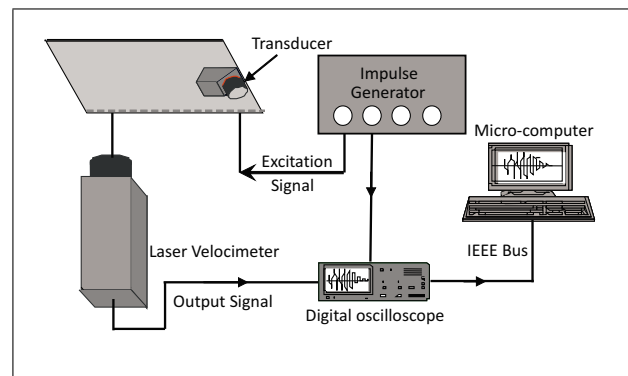


Figure 1. Experimental set up.

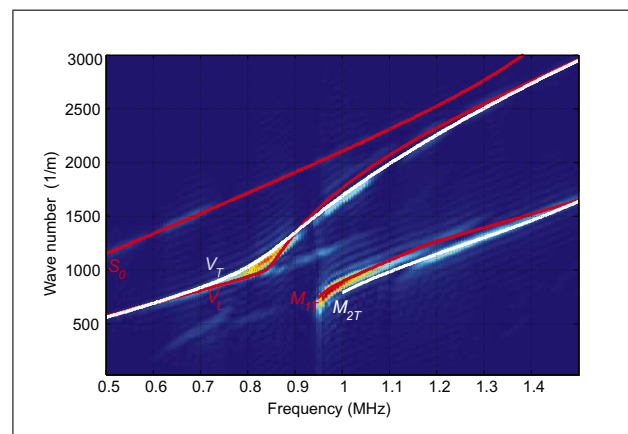


Figure 2. Experimental dispersion curves for the sample SRef Glass/Glue/Glass. Theoretical data from model A are superimposed (red or white solid line in order to separate close modes). The modes are labeled S_0 (close to the mode S_0 of one single plate), V_L and V_T (the longitudinal and transversal mode) and M (global mode of the structure).

[8]. The transducer is excited by a short pulse (about $0.5 \mu s$ duration) with an amplitude of $-300 V$. The targeted modes by this type of excitation are the shear and longitudinal vertical modes which are sensitive to the bulk variations of the adhesive [9]. The normal displacement related to the propagation of the generated Lamb waves, is measured using a laser velocimeter, for several positions on the surface in the propagation direction. The velocimeter is translated by steps of $0.2 mm$ over $60 mm$ propagation distance. Each temporal signal is averaged (200 signal sweeps), sampled with 12500 data points and stored in a micro-computer. A double space-time FFT is applied in order to get the experimental dispersion curves of the propagating modes [10].

Figure 2 shows the experimental dispersion curves for the sample SRef (pure glue) while the case of mixing of araldite/grease are presented in Figures 3 and 4. In these figures theoretical curves computed from tri-layer models are superimposed: this is explained in the following sections.

3. Trilayer models

Two configurations are considered: for the first one the layers are welded and the bonding is considered as perfect and for the second one a total delamination between the layers is considered.

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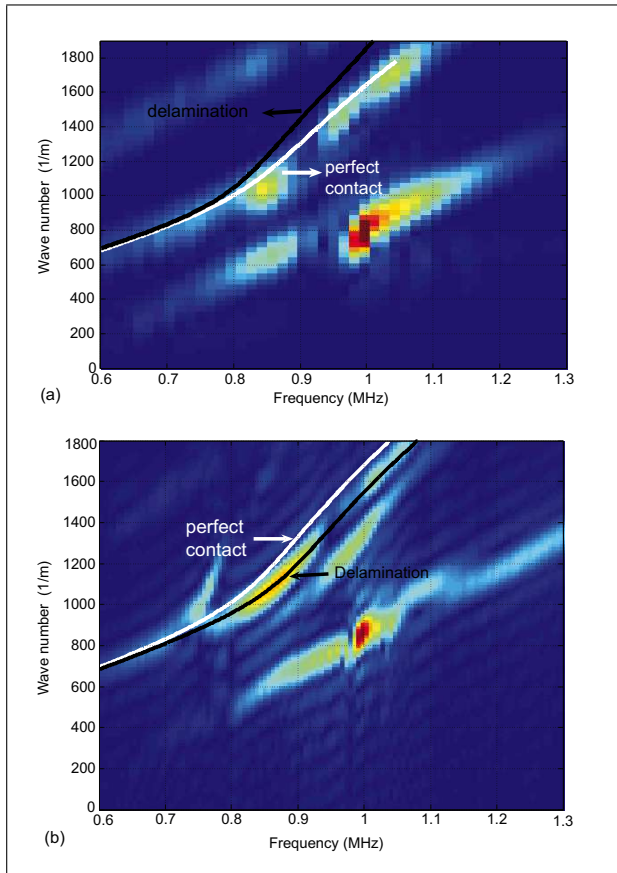


Figure 3. Dispersion curves for the S15 and S75 samples. (a): Experimental and theoretical dispersion curves for the transverse vertical mode, sample with 15% of grease. Model A (perfect contact): solid white line. Model B (delamination): solid black line. (b): Experimental and theoretical (solid line) dispersion curves for the transverse vertical mode, sample with 75% of grease. Model A (perfect contact): solid white line. Model B (delamination): solid black line.

3.1. Tri-layer model: perfect contact (model A)

The acoustic parameters of the glass and of the glue have been measured. The following values are obtained (ρ is the density and V_L and V_T are the longitudinal and shear velocities):

Glue:

$$V_{L\text{glue}} = 2590 \text{ m/s} \quad V_{T\text{glue}} = 1350 \text{ m/s} \quad \rho_{\text{glue}} = 1160 \text{ kg/m}^3.$$

Glass:

$$V_{L\text{glass}} = 5825 \text{ m/s} \quad V_{T\text{glass}} = 3485 \text{ m/s} \quad \rho_{\text{glass}} = 2490 \text{ kg/m}^3.$$

By using a classical procedure [6], the dispersion curves of the modes for the SRef sample are obtained and are reported in Figure 2. It can be concluded that the agreement is good and the sample has to be considered as well bonded.

When grease is added to the glue, the model can be used if the acoustic properties of the mixing are known. For this, one needs the density, the longitudinal and shear waves velocities in the grease. A block of grease is used to measure the velocities and the density. The following values are obtained:

$$V_{L\text{grease}} = 1117 \text{ m/s} \quad V_{T\text{grease}} = 506 \text{ m/s} \quad \rho_{\text{grease}} = 1197 \text{ kg/m}^3.$$

The density of the mixture is calculated as

$$\rho_{eq} = (1 - p)\rho_{\text{glue}} + p\rho_{\text{grease}}, \quad (1)$$

where p is the ratio of grease and ρ the density.

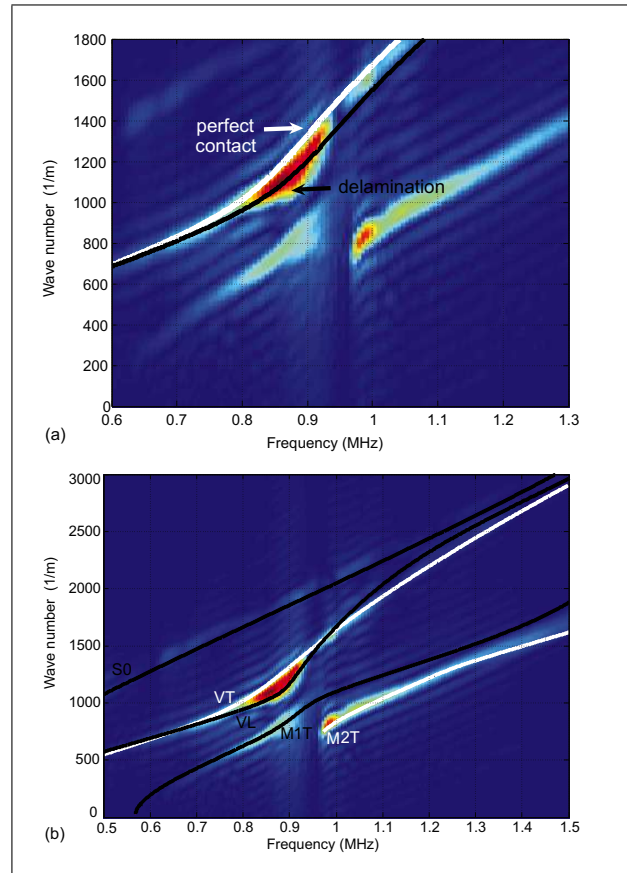


Figure 4. Dispersion curves for the S25 sample. (a): Experimental and theoretical dispersion curves for the transverse vertical mode sample with 25% of grease. Model A: solid white line. Model B: solid black line. (b): Experimental data and theoretical dispersion curves provided by the model of Jones (solid lines).

Table I. Characteristics of the different adhesive films.

	SRef	S5	S15	S25	S50	S75
Ratio p	0%	5%	15%	25%	50%	75%
ρ (kg/m ³)	1160	1157	1152	1146	1134	1120
V_T (m/s)	1350	1188	1004	836	664	568
V_L (m/s)	2590	2329	1992	1770	1439	1245

The longitudinal (v_L) and transverse (v_T) wave velocities are calculated assuming that the mixture of glue and grease behaves as a succession of springs in series or in parallel [11],

$$v_L = \sqrt{\frac{(\lambda + 2\mu)_{eq}}{\rho_{eq}}}, \quad (2)$$

$$v_T = \sqrt{\frac{\mu_{\text{glue}}\mu_{\text{grease}}}{(p\mu_{\text{glue}} + (1 - p)\mu_{\text{grease}})(p\rho_{\text{grease}} + (1 - p)\rho_{\text{glue}})}}, \quad (3)$$

with

$$(\lambda + 2\mu)_{eq} = \frac{(\lambda + 2\mu)_{\text{glue}}(\lambda + 2\mu)_{\text{grease}}}{p(\lambda + 2\mu)_{\text{glue}} + (1 - p)(\lambda + 2\mu)_{\text{grease}}}. \quad (4)$$

λ and μ are the Lamé coefficients.

Table I gathers the calculated density, longitudinal and shear waves velocities as a function of the grease ratio in the adhesive.

The case of the shear vertical mode is investigated, as in previous studies [12, 13]. In the case of a thin solid layer two vertical

Table II. Values of the constants of Jones versus the rate of grease in the adhesive film.

Grease ratio p	0%	5%	15%	25%	50%	75%
K_L (N/m ³)	$1.6 \cdot 10^{13}$	$1.4 \cdot 10^{13}$	$8.4 \cdot 10^{12}$	$4.6 \cdot 10^{12}$	$1.7 \cdot 10^{10}$	$4.3 \cdot 10^9$
K_T (N/m ³)	$1.4 \cdot 10^{13}$	$1.1 \cdot 10^{13}$	$9.2 \cdot 10^{12}$	$5.7 \cdot 10^{12}$	$1.4 \cdot 10^{10}$	$5.5 \cdot 10^9$

modes exist and are located in the lowest frequency range. The dispersion curve of the shear vertical mode, obtained considering the glass/adhesive/glass as a tri-layer with perfect adhesion assumption, is calculated for all the samples and compared to the experimental dispersion curve. Two representative examples, for the S15 and S75 samples, are given for illustration in Figures 3a and 3b. The results are in a good agreement for the S15 sample (it is also the case for the S5 sample but the figure is not shown for succinctness). As the perfect model agrees well with the experimental data it can be concluded that the bonding is good. The agreement is clearly not good enough for S75 (nor for the S50, but not presented) due to delamination. This is explained in the next section.

3.2. Tri-layer model: delamination (model B)

A slip condition is now imposed on the glass/adhesive interface for the same samples. The dispersion curve for the shear vertical mode is recalculated and superimposed on the experimentally obtained curve, as shown on Figures 3a and 3b. One can notice in Figure 3b that this condition significantly improves the agreement between the experimental and the theoretical curves for S75. As a verification, for S15 the computed modes assuming slip condition are not in a good agreement with the experimental data, as shown in Figure 3a. Models A and B are the limiting cases: either the bonding is excellent or the bonding is quite bad. In fact even for the case of S75 the structure seems integer and the two glass plates cannot be easily separated. Another possibility to describe the quality of the bonding is to use the model of Jones [5]. This approach has been often used in several works [13, 14].

4. Model of Jones

4.1. Presentation of the results

In the model of Jones, the displacements at the boundary of two solids in contact are not continuous and at the bonding interface the stresses are proportional to the jump of displacements. The coefficients of proportionality are called the parameters of Jones K_L and K_T . The adhesive layer is then modelled as a uniform and linear distribution of springs with two stiffness constants K_L and K_T .

Figure 4a shows the experimental data for the sample S25. It is shown that neither the theoretical results obtained assuming the perfect contact nor those obtained assuming the slip condition agree with the experimental data. The model of Jones allows a quantitative evaluation of the bonding quality. From the experimental values of the wavenumber-frequency pairs, it is possible to deduce the values of K_L and K_T by solving an inverse problem. The algorithm used [9] is summarized in the following. First, a wide range of variation of the Jones parameters is assumed. Then for each experimental pair (k_x, f) of a given Lamb mode, a double loop for the two parameters of Jones is performed. A new narrower range minimizing the characteristic equation is obtained. The minimization of the dispersion equation is performed using a classical Newton-Raphson method. At each step, the mean value $\hat{p}$ and the standard deviation $\hat{\sigma}_p$ are

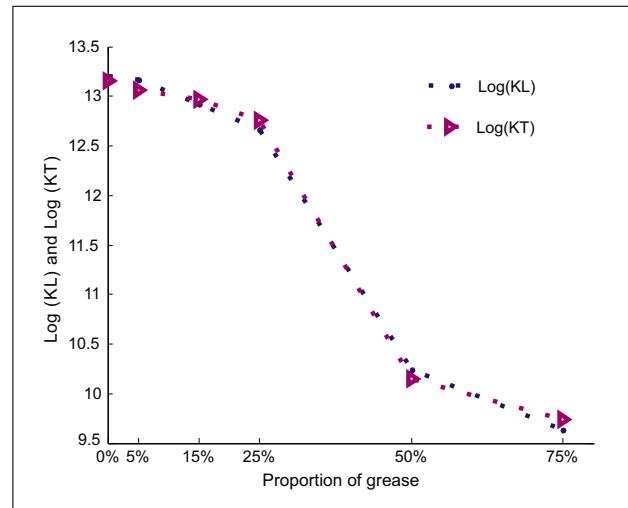


Figure 5. Variations of the parameters of Jones versus the grease ratio.

calculated for each parameter. The following criterion is then introduced: if $\hat{\sigma}_p/\hat{p} \leq 3\%$ then parameter deduction is assumed to be precise enough. The experimental data for the two vertical modes have been used in the parameter deduction procedure.

The values obtained for the parameters of Jones are summarised in Table II. As it can be seen, the parameters are close to each other. Indeed, the shear and the compressive strains are of the same order of magnitude due to Lamé's coefficients being the same order of magnitude. This is also the case for the shear and longitudinal displacements. Thanks to the boundary conditions that link stress to displacements, the parameters of Jones are consequently of the same magnitude order.

For S25, the dispersion curves are recalculated, using the determined Jones coefficients, and superimposed on the experimental ones, as shown in Figure 4b (continuous lines). One can see a good agreement between experimental and theoretical results for all the modes in the experimental frequency range, even for those not used for the determination of the Jones coefficients in the inverse problem.

From Table II one can see that the values of the Jones parameters increase when the ratio of grease decreases. Their variations are small for ratio of grease varying between 0% and 25% (for SRef to S25, the constants are divided at the maximum by 3). Indeed, for SRef, S5 and S15, the experimental dispersion curves have been successfully compared in the previous section to the ones obtained from a tri-layer model with the perfect contact hypothesis. The variations of the parameters of Jones versus the grease ratio are plotted in Figure 5. If the ratio of grease is greater than 25%, the parameters are divided by a factor of about 10^3 . They vary logarithmically indicating a progressive and high degraded quality bonding. To the author's knowledge, such variation has not been previously reported for the gradually damaged structures. The lowest value of the parameters correspond to delamination condition between the glue and the glass: in this case the bonding is not effective.

5. Conclusion

In this paper we proposed an experimental evaluation of the bonding quality of a tri-layer glass/adhesive/glass structure when the quality of the glue is changed. This is performed by the estimation of the Jones parameters obtained from experimental dispersion curves of Lamb modes by solving an inverse problem. Two limiting cases have been considered: the case of welded layers and the case of delamination. A link between the Jones model and tri-layer models has been made. A logarithmic variation of the parameters of Jones is measured when the interfaces inside the structure evolves from perfect contact to delamination condition.

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