The transmission of Lamb waves across adhesively bonded lap joints to evaluate interfacial adhesive properties

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Abstract

The present work attempts to infer mechanical interfacial properties for lap joint like structures, using Lamb wave modes. A pair of air-coupled, ultrasonic transducers is used to generate and detect a desired Lamb mode. The Lamb waves are launched from one plate and propagate towards the other plate, via the joint. Signals are picked up by the receiving transducer, before and past the joint, and post-processed to obtain the experimental transmission coefficient versus frequency. In addition, a two-dimensional Finite Element-based model is developed and used to compare predicted transmission coefficients with experimental results. The FE model simulates the excitation produced by the transmitter takes into account the viscoelastic properties of the adhesive layer and distributions of longitudinal ($k_L$) and shear ($k_T$) springs at both interfaces between the adhesive and the substrates. Temporal responses of the receiving transducer are predicted before and past the joints, as well as the transmission coefficient versus frequency. This paper discusses preliminary results for aluminium substrates. Values for both $k_L$ and $k_T$ are optimized so that best fit is obtained between numerical and experimental transmission coefficients. These results demonstrate the potential of Lamb waves to infer mechanical properties at interfaces in adhesively bonded joints.

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1. Introduction

Adhesively bonded assemblies are increasingly used in the transport industries, such as automotive or aeronautics because of their numerous advantages: low-weight structure, high mechanical performance and relatively uniform repartition of stresses along the bonded area. Adhesively bonded assemblies however may contain two types of defects: cohesive defects such as poor curing, cracking or porosity of the glue, and/or weak adhesion, at the interfaces between the adhesive and the substrates. For safety reasons, it is critical to inspect adhesive joints, and the non-destructive evaluation of the adhesion at interfaces remains a big challenge as breaking, when it occurs, is often at this level, since it is more difficult to build a good and reliable interfacial adhesion than it is to make a strong cohesion of the bond. Interfacial adhesion is difficult to characterize with the non-destructive methods currently

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Among all existing NDT techniques used to inspect adhesive bonds, ultrasound-based methods seem to be the most suitable because they mechanically interrogate the bonds, contrary to electromagnetic wave-based methods, e.g., X-rays, thermography, etc. However, difficulties come from the very small thickness of interphases located between the adhesive and the adherents, which have little effects on wave propagation in some cases. Several works discuss the problem of controlling adhesively bonded joints using ultrasounds [2,3]. Recently, an assessment of the interfacial shear stiffness for single lap joint assembling two aluminium plates has been carried out using SH guided waves transmitted from one plate to the other [4]. The method was based on the comparison of experimental transmitted signals with predicted ones computed using a 2D FE model, in which mechanical interfacial properties of the lap joint were modeled using shear springs $k_T$ as proposed by Jones et al. [5]. SH guided waves were found to be sensitive to the lap joint adhesion quality. For example, for a sample made of sandblasted substrates, $k_T$ was found close to 1.5 PPa/m, while for a non-sandblasted sample, $k_T$ was optimized to a much lower value close to 0.03 PPa/m. In this paper, on the basis of this previous work, Lamb wave transmission through adhesively bonded lap joints is studied in order to assess both longitudinal and shear interfacial springs. Firstly, measured transmission coefficients are investigated to demonstrate the sensitivity of Lamb modes to interfacial changes caused by different treatments of the substrates surfaces. Then, a 2D FE model is used to mimic the experiments and both input data $k_L$ and $k_T$ are optimized so that best fit is obtained between numerical and experimental transmission coefficients. Finally, results and outlooks are discussed.

2. Experimental setup

Two samples are investigated. These are made of two 3 mm thick, 250 mm long and 200 mm wide aluminium plates. The overlap zone is 50 mm long, as shown in Fig. 1. The structural adhesive film AF3109 used for assembling the two pairs of aluminium plates is a thermosetting modified epoxy adhesive film. This layer has a well-calibrated thickness of 0.2 mm [4]. For each sample, the aluminium surfaces are prepared in a specific way before assembling the plates. For the first sample, sandblasting is applied to the aluminium, as well as careful cleaning and degreasing; this is a common industrial surface treatment method used prior to bonding [6]. Sandblasting makes the substrate surfaces rough, which is supposed to enhance the adhesive joint strength [7]. This sample is then considered as the reference sample (supposed to have a good adhesion) and is noted throughout the paper as SBI for Sand-Blasted Interface. For the second sample no sandblasting is applied to the aluminium surfaces, it is only carefully cleaned and degreased. This sample is then identified as NSBI for No Sand-Blasted Interface (supposed to have a poor adhesion).

The experimental setup used to generate and detect the Lamb waves ($A_0$ and $S_0$) is represented in Fig. 1. In order to generate a pure $A_0$ mode, an air-coupled capacitive transducer (diameter 50 mm) is used and excited by a 5-cycle Gaussian-windowed tone burst of 275 kHz central frequency. The incident angle $\theta_I = 8.5^\circ$ is set accordingly to the Snell’s Law and deduced from the $A_0$ mode phase velocity mean value within the frequency range of the excitation signal [8]. Since the displacement produced by the $S_0$ mode is mainly in plane, the use of a contact transducer, that is gel coupled to the edge of the plate is preferable, guaranteeing a high enough signal to noise ratio. In order to avoid an unwanted component of the $A_0$ mode to be sent by this source towards the lap joint, absorbing polymer blocks are coupled to each surface of the plate along the propagation path of the incident wave, very close to the transmitter (cf. Fig. 1). The receiver is an air-coupled transducer identical to the one used for the generation of $A_0$. For a given mode $m$, the incident ($I$) and transmitted ($T$) signals are measured by tuning the receiver angle appropriately ($\theta_T = 8.5^\circ$ for $A_0$ and $\theta_T = 3.5^\circ$ for $S_0$). Transmission coefficients are computed in the frequency domain as the ratio.
between the amplitudes (A) of the spectrum of the transmitted ($A_{Tm}$) and incident ($A_{Im}$) modes:

$$T_m(f) = \frac{A_{Tm}(f)}{A_{Im}(f)}$$  \hspace{1cm} (1)$$

Measured signals are picked up over 150 μs, which is chosen so that the contributions of modes reflected from the free edges of the plates are avoided.

3. 2D finite element model

The schematic description of the developed 2D finite element model (FEM) is presented in Fig. 2. Comsol multiphysics software is used in the general Partial Differential Equation (PDE) mode, so that the equations of dynamic equilibrium, boundary conditions, absorbing regions and excitation are implemented according to procedures already described in other papers [8,9].

![Fig. 2: Schematic diagram of FEM used for predicting the transmission coefficients of Lamb modes across adhesively bonded lap joints.](image)

The overlap zone is modeled by 3 layers: both aluminium plates and the adhesive layer. As computations are carried out in the frequency domain, the model takes into account the viscoelasticity of the adhesive layer, and absorbing regions (AR) are easily implemented. In order to model the interfacial variations induced by the different surface treatments of the samples, surface distributions of longitudinal and transverse springs, $k_L$ and $k_T$ are implemented [3-5]. The incident mode is launched from the excitation zone towards the overlap zone. Out-of-plane displacements are monitored at the surface of the aluminium plates, on each side of the overlapping zone and over a length equal to the diameter of the experimental receiver. Phase shift is then applied to these monitored displacements to account with the propagation paths in air, from the monitored points to points located at the surface of the receiving transducer (collimated beam model as in [10]). This receiving surface is oriented at specific angles according to the mode (A0 or S0), which is to be selected. Then phase-shifted displacements are applied a Gaussian appodization window to simulate the sensitivity of the receiver surface, and summed up together. Finally, the transmission coefficients are obtained using Eq. 1. Using all known material properties given in Table 1 as input data, the optimization of both $k_L$ and $k_T$ is made in order to obtain the best fit between the numerical and experimental transmission coefficients.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Thickness (mm)</th>
<th>$C_{11}$ (GPa)</th>
<th>$C_{16}$ (GPa)</th>
</tr>
</thead>
<tbody>
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<td>Adhesive AF3109</td>
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<td>3.7</td>
<td>1.02</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2780</td>
<td>3</td>
<td>112</td>
<td>27</td>
</tr>
</tbody>
</table>

4. Results and discussions

Transmission coefficients of the S0 Lamb mode are measured along each of the three lanes shown in Fig. 1. These are shown in Fig. 3 for both samples. Average variations of measurements are equal to 15% (except for certain frequencies where they reach 35%), which enables to validate the constancy of the method and the acceptable spatial uniformity of the adhesive bonds. Fig. 4 compares measured and predicted transmission coefficients. Good agreement is obtained except at frequencies below 0.27 MHz in the case of both modes for the SBI sample and in the case of A0 mode for the NSBI sample. The optimized interfacial spring values in the case of SBI sample are $k_L = 3.75 \text{ PPa/m}$ and $k_T = 1.5 \text{ PPa/m} \pm 20\%$, whether the A0 or S0 mode is used for the optimization process. These values correspond to a level of adhesion, which is supposed to be high, and are then
called nominal values. The optimized nominal value of $k_T$ is in agreement with that from the literature [4]. In the case of the NSBI sample, optimized interfacial stiffnesses are not the same depending on the Lamb mode, which is used: $k_L = 0.25 \text{ PPa/m}$ and $k_T = 0.015 \text{ PPa/m}$ ($\pm 3\%$) for the $A_0$ mode, while $k_L = 0.075 \text{ PPa/m}$ and $k_T = 0.03 \text{ PPa/m}$ ($\pm 2\%$) for the $S_0$ mode. However, values obtained for $k_L$ and $k_T$ of that NSBI sample, when using the $A_0$ or $S_0$ mode, are in a ratio of 3 and 2, respectively, which is an order of magnitude smaller than ratios between the set of $k_L$ and $k_T$ obtained for the SBI sample and that obtained for the NSBI sample. This means that even if uncertainties are found for the estimated values of these stiffness’s for the NSBI sample, their values are clearly smaller than those measured for the SBI sample, thus indicating a relatively good sensitivity of the $A_0$ and $S_0$ modes to these parameters, which quantify the state of the interfacial adhesion. Work in progress concerns the investigation of modes conversion ($A_0$ to $S_0$ modes and *vice versa*) in the purpose of assessing more information about the adhesion state and of improving the quantitative estimation of the sought stiffness’s.

Fig. 3: Measured transmission coefficients for $S_0$ mode along 3 different paths of propagation:
($\times \times \times$) path 1, ($\bullet \bullet \bullet$) path 2 and ($\bigcirc \bigcirc \bigcirc$) path 3; (a) SBI sample and (b) NSBI sample

Fig. 4: Comparison between measured (dots) and predicted (lines) transmission coefficients for: (a) $A_0$ mode and (b) $S_0$ mode; (—)& ($\times \times \times$) SBI sample and (—)—& ($\bullet \bullet \bullet$) NSBI sample

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References