Inferring Shear Stiffness of Adhesive Bonds using SH Guided Ultrasonic Waves

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Inferring shear stiffness of adhesive bonds using SH guided ultrasonic waves

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Repairing of metallic structures using composite patches bonded with an adhesive layer is more and more common in the aeronautic field. Shear-horizontally polarized (SH) waves are investigated to infer the shear stiffness of the adhesive layer, which is necessarily linked to its shear resistance that is a critical parameter in bonded structures. Numerical simulations are run for selecting the most appropriate SH wave modes, i.e. with higher sensitivity to the shear stiffness of the bond than to other components properties. Experiments are also made for generating-detecting pre-selected SH wave modes and for measuring their phase velocities. An inverse problem is finally solved, consisting in the evaluation of the shear stiffness modulus of a bond layer between an aluminium plate and a carbon-epoxy composite patch, at different curing time of the adhesive.

1 Introduction

Bonded joints are often submitted to shearing loads, and breaking when occurring is often in the shearing mode, so designers are trying to make bonds so that they resist well to shearing. Shear resistance is then a critical parameter for adhesive bonds, and its non-destructive evaluation is of interest, especially in the Aeronautic or Aerospace context for safety reasons. For instance, the problem, which is investigated in this paper, concerns the repair of aeronautical metallic structures with adhesively bonded composite patches. As local disbonds or lack of glue in bonds may be routinely avoided with high-performance bonding processes, the need in bond testing is nowadays more oriented toward the characterization of the bond quality. Evidently, cohesive properties of the adhesive layer are of interest to check the curing state after the bonding is realized, but also to monitor eventual changes during the life of the bond. The evaluation of adhesive interfacial properties is also of interest. Ultrasonic guided waves can be good candidates for testing the cohesive properties of joints or the adhesion at each interface between the joint and the substrates, as they will integrate the bond properties while propagating along it. Shear-horizontally polarized guided waves are particularly interesting because they are sensitive to the shear stiffness of the bond [1], which is necessarily linked to its shear resistance that is a critical parameter for adhesive joints, as explained before.

In this paper, a one-dimensional semi-analytical finite element (SAFE) model is firstly used for predicting the dispersion curves of the three low-order shear-horizontally polarized (SH) guided waves propagating along a three-layered medium made of a composite patch, an adhesive layer and an aluminium plate, the aluminium / adhesive interface being supposed to be a possibly weak interface. Numerical simulations are made to select modes, which sensitivity is higher to the bond layer and/or to the interface between this bond and the metallic plate than to the metallic plate or composite patch. A laser-based technique is finally set-up for detecting SH guided wave modes, which are launched using a standard ultrasonic piezoelectric (PZT) transducer. It is used to measure velocities of SH-like modes for an aluminium / adhesive / patch assembly with different levels in the bond quality. A shear stiffness value corresponding to each of these levels is finally evaluated by comparing the measured and predicted velocities (inverse problem).

2 Materials

In this study, the structure of interest is made of three different material components: one elastic isotropic aluminium plate, one viscoelastic isotropic adhesive layer and one viscoelastic orthotropic composite patch. The aluminium plate is 3 *mm* thick and the composite patch is made of eight carbon epoxy plies with a $[0°/90°]_{2s}$ stacking sequence. It is 1.2 *mm* thick. Their complex viscoelastic *moduli*, the real parts representing the elasticity of the material and the imaginary parts its damping, have been measured using ultrasonic immersion techniques [2], [3]. Finally the adhesive is a two-component epoxy adhesive: a premium resin *Araldite GY-784* and an *Aradur 125* curing agent. To establish an initial set of the adhesive viscoelasticity, a specific assembly has been realized. This was made of two glass plates with very well known mechanical properties, bonded together using the studied adhesive. Its characterization has been realized using the ultrasonic plane-wave transmission technique presented in reference [3]. The results for these materials characterization are presented in Table 1.

	Aluminium	Adhesive	Composite
Density (g/cm^3)	2.67	1.05	1.58
Thickness (mm)	3	0.2	1.2
C_{55} (GPa)	26	0.5+0.05I	6.6+0.1I
C_{44} (GPa)	25	0.5+0.05I	4.5+0.1I

Table 1- Density (±3%), thickness (±5% for the substrates and ±15% for the adhesive) and viscoelastic properties of the materials used in the study with measurement errors of about ±5% for the elastic *moduli* of aluminium, ±10% and ±15% for the real and imaginary parts, respectively, of the viscoelastic *moduli* of the others materials.

3 The 1D SAFE Model

3.1 Principle and equations

A semi analytical finite element (SAFE) model, more detailed in reference [4], is used to calculate the dispersion curves of the Shear Horizontal (SH) wave modes that may propagate along the waveguide made of a 3 *mm* thick aluminium plate, a 0.2 *mm* thick adhesive bond and a 1.2 *mm* thick composite patch. As illustrated in Figure 1, these three components are supposed to be of infinite extent along the x_3 direction, which is parallel to the surfaces of the guide and normal to the direction of propagation, i.e. to x_1. In these conditions a 1D-SAFE model can be defined.

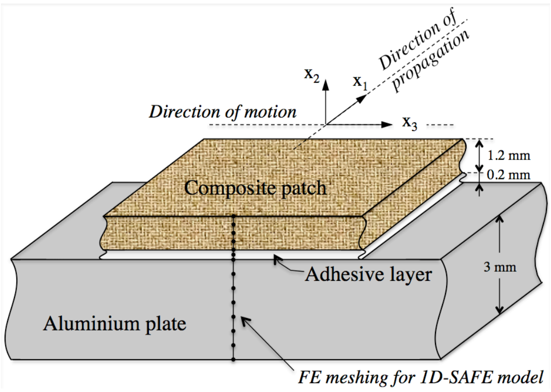

Figure 1 - 3D schematic of aluminium plate / bond line / composite patch structure, with 1D SAFE meshing shown as series of dots through thickness.

The eigen-value equation of motion is restricted to modelling SH-like guided wave modes only, i.e., displacement components in the direction of propagation and normally to the plate, as well as corresponding strains, are not permitted by this equation. Then, in the frequency domain it can be expressed as follows:

$$C_{44}\frac{\partial^2 u_3}{\partial x_2^2} - k^2 C_{55} u_3 + \rho\omega^2 u_3 = 0 \qquad (1)$$

where $\omega=2\pi f$ is the angular frequency, f being the frequency and k is the wave-number, where C_{55} and C_{44} are *moduli* representative of the mechanical properties of the material of interest, defined in the coordinate axis shown in Figure 1. At the outer or internal surfaces of the stacking, the unit outward vector $\boldsymbol{n}$ is defined along the x_2 direction so the stress vector, $\boldsymbol{T}=\boldsymbol{\sigma}.\boldsymbol{n}$, is reduced to:

$$T_3 = \sigma_{23} n = C_{44}\frac{\partial u_3}{\partial x_2} n \qquad (2)$$

where n is equal to ±1.

The outer boundaries of the system are free of stress, so T_3 is equal to zero. At the inner interface between the composite patch and the adhesive layer, the boundary conditions are defined to satisfy the continuity of displacements u_3 and also of stresses T_3. At the inner interface between the adhesive bond and the aluminium plate, a shear-spring model is defined as follow:

$$T_3 = k_T \Delta u_3 \qquad (3)$$

where k_T represents a uniform density of shear springs (N/m^3), and $\Delta u_3 = u_3^{adhesive} - u_3^{aluminium}$ is the displacement jump between the adhesive and the aluminium, the sign of the difference depending on the material this jump is considered from. It allows modelling the effect of bad adhesion at this known-to-be-critical interface on the propagation of SH-like wave modes.

3.2 Finite element based commercial software and meshing

The used commercially-available finite element code [5] is particularly suitable for implementing such specific models. In this paper, it is used for solving the eigen-value equation (1) for the three domains (aluminium, adhesive and composite) joined together, and satisfying the various boundary conditions previously mentioned. The solution is a set of real, imaginary or complex wave-numbers, k, obtained for one angular frequency ω chosen within a frequency range of interest. By solving this problem at different frequencies, and by classifying properly the solutions, the dispersion curves of the SH-waves can be plotted. Considering that the size of FE elements should not vary too rapidly across the domain [6], and that a minimum of four quadratic elements are used across each layer, the dispersion curves calculated with the SAFE model perfectly agree (less than 2‰ difference) with curves predicted by the more classical surface impedance matrix method [3]. The interest of the SAFE model in comparison to classical methods such as matrix-based methods is that it allows easy implementation of the spring model to simulate variable adhesion at one interface of the medium, for example. Also, FE-based models are well known for being convenient for varying the material mechanical properties with space.

4 Numerical investigation of SH-waves sensitivity to material properties of assembly

The purpose of this preliminary numerical study is to establish frequency ranges within which properties of any of the three materials may cause trouble to the use of SH-like modes for quantifying the quality of the adhesive bond. The densities and thicknesses of the different materials are measured with accuracies of about ±3% and ±5%, respectively, except for the adhesive layer the thickness of which is estimated with ±15% accuracy. The stiffness of the substrates is measured with accuracies of about ±5% for the aluminium and ±10% for the composite. Numerical investigations are then realised to quantify the effect of changes of these parameters, within the intervals of confidence of their measurements, on the phase velocities of the SH_0, SH_1 and SH_2 modes propagating along the three-layered assembly, in the frequency range [0.01-1] *MHz*. The errors on the imaginary parts of the *moduli* are not investigated, since these have been checked to have no or negligible effects on the velocities.

4.1 Sensitivity to densities and thicknesses

Non-surprisingly, ±3% changes in the density of any of the three materials do not induce significant changes either in the phase velocities (≤1.5%) or in the frequencies cut-off (≤4%) of the guided SH modes (Figure 2.b, d, f). Similarly, ±15% changes in the thickness of the bond line have little effects on the dispersion curves (Figure 2.c). But, as shown in Figure 2.a, a particular attention should be paid to the thickness of the composite patch if the SH_2-like mode is selected between 0.7 *MHz* and 1 *MHz*. Indeed, ±5% changes in this parameter induce up to 15% changes in the phase velocity of this mode. Similarly, the accurate knowledge of the aluminium plate thickness is of importance if the SH_2-like mode is used at frequencies close to its cut-off. As shown in Figure 2.e, ±5% changes in the aluminium thickness cause up to 10% changes in the cut-off frequency of the SH_2-like mode. In the context of using SH-like modes for quantifying the cohesive or adhesive properties of the bond layer placed between a 3 *mm* thick aluminium plate and a 1.2 *mm* thick composite patch, it is therefore recommended to avoid the use of the SH_2 mode.

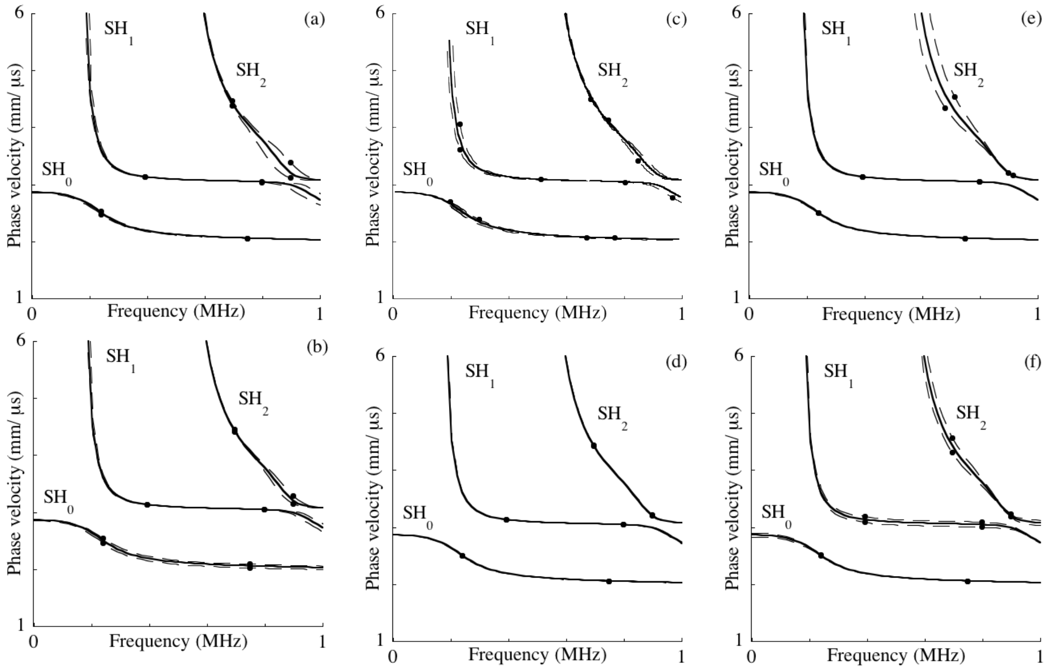

Figure 2 - Numerical predictions of SH_0, SH_1 and SH_2 phase velocity sensitivity to either ±p% changes in thickness (first line) or ±3% changes in density (second line) of (a, b) composite patch (p=5), (c, d) adhesive bond (p=15) and (e, f) aluminium (p=5); (——) are results for nominal properties (data presented in Table 1) and (— • —) for modified properties.

4.2 Sensitivity to shear properties of substrates, adhesive and interface

In the same way, taking into account the ±5% or ±10% errors related to the stiffness measurements of the aluminium or composite patch, respectively, allows showing that the SH_2-like mode is pretty sensitive to the properties of the assembled media. Figure 3.c and d show that up to 85% decay in the value of either the Coulomb *modulus* C_{44} of the adhesive or the shear stiffness k_T of the interface between the adhesive and the aluminium, would cause less or similar amount of changes in the dispersion curve of this SH_2-like mode, than the aluminium or patch stiffness do. This confirms the conclusion of section 4.1. Similarly, for frequencies greater than the frequency cut-off of SH_1, the SH_0 and SH_1-like modes are more sensitive to either the aluminium or patch properties than to the adhesive layer or to its adhesion with the aluminium, except if this later is set equal to 1% (almost no adhesion at all). To the contrary, in the low frequency regime, i.e. for frequencies below or around the SH_1 cut-off (≈ 0.2 *MHz*), both SH_0 and SH_1-like modes are more sensitive to the cohesive property C_{44} of the bond layer than to the aluminium or patch stiffness, or also to their thicknesses or densities. Indeed, the comparison between Figure 3.c, Figure 3.a-b and Figure 2 indicates that accurate measurements of the phase velocities of SH_0 and SH_1-like modes below and around the SH_1 cut-off should allow detecting about 40% (and even down to 30% according to simulations not all shown here) or more degradation in the shear *modulus* of the adhesive layer. Regarding the adhesion between the adhesive layer and the aluminium, Figure 3.d and its comparison with Figure 3.a-b and Figure 2 show that the SH_1-like mode may detect from about 85% degradation in this adhesion, if its phase velocity is very accurately measured around its cut-off. However, the sensitivity of this mode to the cohesive shear property of the adhesive layer is much larger than that to the interface shear stiffness, as seen by comparing Figure 3.c and Figure 3.d together. Therefore, any uncertainty in the cohesive property of the bond may prevent inferring the interface stiffness, but the reverse is not true. Consequently, accurate measurements of the phase velocity of the SH_1-like mode, around its cut-off, should provide a reasonably correct estimation of the shear *modulus* of the bond only, whether the adhesion between this bond and the aluminium layer is of good or average quality.

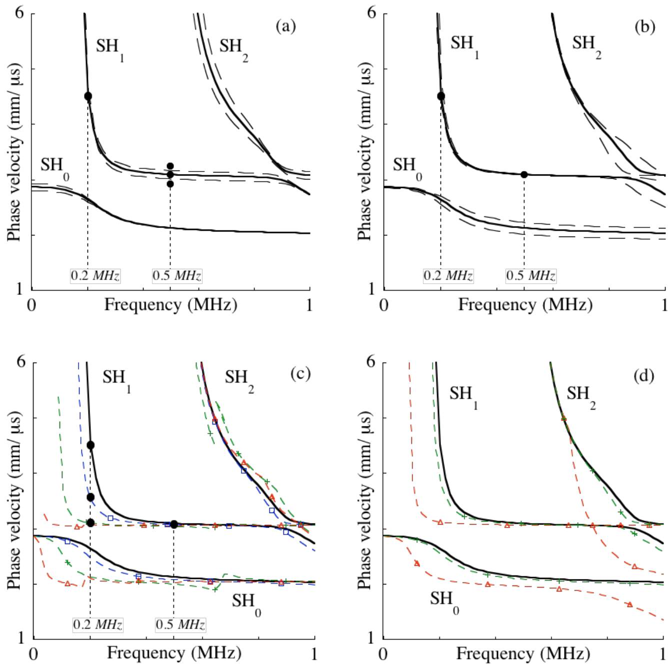

Figure 3 - Numerical predictions of SH_0, SH_1 and SH_2 phase velocity sensitivity to (a) ±5% changes in C_{44} (and C_{55}= C_{44}) of aluminium, (b) ±10% changes in C_{44} and C_{55} of composite patch, (c) -40% (–□–) or -85% (–+–) or -99% (–△–) drop in C_{44} of adhesive layer, and (d) -85% (–+–) or -99% (–△–) drop in k_T of interface between aluminium and adhesive; (——) are results for nominal properties (data presented in Table 1) and various dashes are for modified properties.

In Figure 3.c and d, parts of the dispersion curves plotted for 99% degradation of either the adhesive layer or the adhesion between this layer and the aluminium, respectively, tend towards those of the single aluminium or composite plates, or of the composite / adhesive bi-layer. Such solutions are sensible since these cases correspond to almost total mechanical disconnection between the materials. The sensitivity of ultrasonic wave modes to such level of degradation may be interesting for detecting large disbonds that could be present in a large structure.

The low-frequency regime identified as the domain of highest sensitivity of the SH_0 and SH_1 modes to the bond line is a bit unconventional and surprising, since ultrasounds usually should have small wavelengths to detect small defects or to be sensitive to small regions lost in large media. In order to understand this phenomenon, the distributions of displacements, stresses and power flow across the thickness of the assembly have been analysed at two frequencies: 0.2 and 0.5 *MHz*. These operating points, shown by dots in Figure 3, have been chosen so that they correspond to two cases of higher or lower sensitivity to the adhesive than to the aluminium and composite. It has shown that a 40% decay in the adhesive shear *modulus* produce much more changes in the mode shape of the SH_0 and SH_1-like modes around 0.2 *MHz* than any of the ±5% or ±10% variability in the aluminium or composite components. This can explain why the phase velocity of these modes is more sensitive to the bond layer stiffness than to the aluminium or composite ones, around or below the SH_1 cut-off. To the contrary, at a frequency equal to 0.5 *MHz* at which the SH_0 and SH_1-like modes are roughly as sensitive to the bond shear property as to the aluminium or composite ones, even up to 85% decay in the shear *modulus* of the adhesive layer does not cause more changes in the mode shapes, than ±5% or ±10% variability in the shear properties of the aluminium or composite components. So the low-frequency domain together with the SH_1-like mode cut-off region have been identified as the ranges of highest sensitivity

5 Experiments

5.1 Set-up

The experimental set-up is shown in Figure 4. A 25 *mm*-in-diameter, circular PZT transducer (*Panametrics V152*) is placed into contact with the edge of a plate sample, and coupled using honey. This element is a shear transducer oriented so that it produces horizontal motion. An arbitrary function generator (*Agilent 33120A*) and a power amplifier (*Ritec GA 2500A*) are used to produce the desired excitation, with an amplitude of about 400 V peak-to-peak.

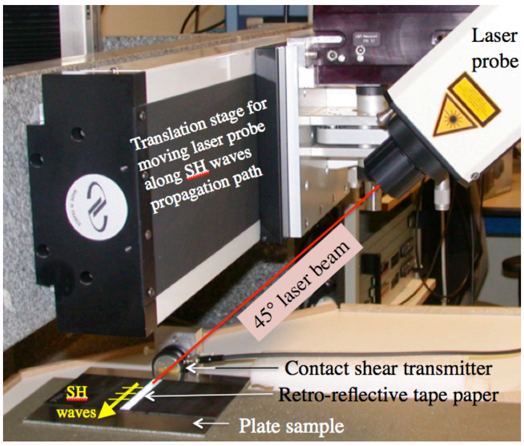

Figure 4 - Photo of experimental setup used for launching-detecting SH guided wave modes and for measuring their phase velocities.

The displacements produced by the SH guided waves are measured using a *Polytec* Doppler velocimeter of 0.005 $m.s^{-1}/V$ in sensitivity. Only the x_3-component of the displacement is to be measured since this is either the only non-zero component (standard SH waves) or the dominant one. To pick-up this horizontal u_3 displacement, the laser probe is oriented at 45°, an angle which insures sufficient high level of the detected u_3 displacements, as well as good stability of the apparatus when being moved along the path of propagation. In order to retro-reflect the optical beam of the laser probe, a specific retro-diffusive taper is bonded on the top of the plate sample, along the propagation path. The signal-to-noise ratios obtained when measuring real-time waveforms on a 5 *mm* thick Carbon Epoxy plate at two distances equal to 50 and 80 *mm* remote from the PZT transmitter, are equal to 5 and 3.8, respectively, which is good enough to identify the guided modes. Of course, filtering and averaging are applied to such data in order to reduce the noise and to allow optimum signal processing. The laser probe is then moved away along the propagation path using a motorized translation stage, and over a distance of about once or twice the expected maximum wavelength (λ_{max}), with steps equal to about a quarter of the expected smallest wavelength (λ_{min}), in the whole frequency range. A two-dimensional Fourier transform (2D-FFT) is then applied to the series of measured waveforms to quantify the phase velocities of each mode propagating in the tested sample [7].

To validate the laser-based technique, phase velocities are first measured for both fundamental SH modes propagating along a free 3 *mm* thick aluminium plate and a free 5 *mm* thick composite plate. These measurements have allowed slight adjustment of both C_{44} and C_{55} *moduli* from their initial values given in Table 1 in order to obtain very good correlation between the experimental and numerical phase velocities. These quantities are shown to be equal to 26.5 *GPa* and 27.5 *GPa,* respectively, for the aluminium plate and to 4.75 $\times$ (1+I 3%) *GPa* and 6.2 $\times$ (1+I 3%) *GPa*, respectively, for the composite plate. These new estimations are very close to the initial ones made with the immersion technique, if the ±5% measurement errors due to each technique are considered.

5.2 Inferring shear stiffness of bond

The experimental set-up has then been used for an assembly made of a 1.2 *mm* thick composite patch coupled to a 3 *mm* thick aluminium plate by a 0.1±0.05 *mm* thick adhesive bond line having a particularly slow curing process. This approach represents a useful and easy way to monitor changes in the ultrasonic wave propagation for various states of the bonding agent. The incident wave is the SH_0 mode launched from the PZT transmitter along the aluminium plate. This propagates along the free aluminium plate before reaching the area where the patch is deposited. Then it propagates along the assembly over a 100 *mm* long path, which corresponds to the width of the patch sample. In this region, mode conversion occurs and modes corresponding to the three-layered system are produced. Then, past the patch, these modes will be converted back to the SH_0 mode along the aluminium plate. No SH_1 mode is produced along the single-aluminium regions because the frequency in these experiments do not exceed 0.4 *MHz*, which is below the frequency cut-off of the SH_1 mode in the 3 *mm* thick aluminium plate. In fact, the excitation is a 5-cycle toneburst with 0.25 *MHz* centre frequency, so that the frequency range is [0.15-0.35] *MHz*, down to -15 *dB*. Modes produced along the three-layered system are monitored by picking-up u_3 displacements at the surface of the composite patch. The probe is moved along an 80 *mm* long propagation path, and temporal signals are stored every 0.8 *mm*. Figure 5 shows results obtained at five different times during the curing process of the adhesive going from forty-five minutes to few days after the bonding is realized. Measured phase velocities (various symbols) are compared to those predicted (various lines) after C_{44} *modulus* of the adhesive is optimized.

Real quantities have been obtained although C_{44} should be a complex quantity, its imaginary part representing the viscosity of the epoxy-based adhesive. This imaginary component is weakly connected to phase velocities of the SH modes, so no information about it is obtained when measuring these velocities. However, the initial characterization of this adhesive has revealed imaginary parts equal to about 10% of the real parts (Table 1). This seems to be a standard estimation for imaginary parts of viscoelastic *moduli* for epoxy-like materials [3], so it could reasonably be used if complex *moduli* of the adhesive layer are required.

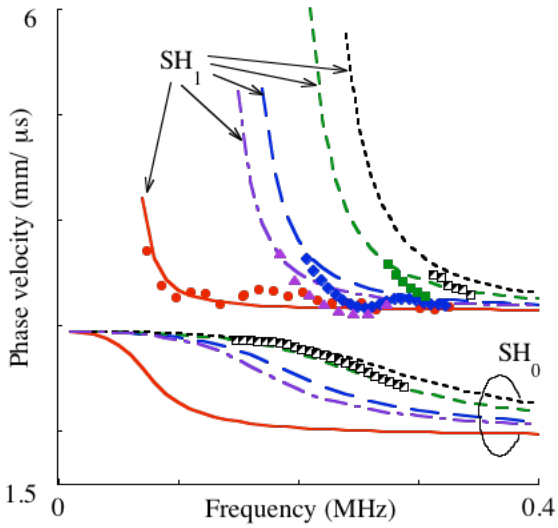

Figure 5 — Phase velocities of SH_0 and/or SH_1 modes along 3 *mm* aluminium plate / 0.1 *mm* adhesive bond / 1.2 *mm* carbon epoxy patch assembly; Numerical predictions with optimized C_{44} of adhesive (lines) and experiments (symbols) made at different curing time of adhesive: 45 min (——, ●), 4h (— – —, ▲), 8h30 (—— ——, ♦), 35h (— —, ■) and infinite time (- - -, ◩).

This process consists in fact of solving an inverse problem the purpose of which is to non-destructively characterize the shear stiffness of the bond line. Numerical values obtained for the C_{44} of the adhesive, at the various times, are summarized in Table 2.

Curing time	Optimized C_{44} (*GPa*)
45 *min*	0.02
4*h*	0.13
8*h*30	0.18
35*h*	0.35
Few days	0.53

Table 2 - Optimized real parts of C_{44} of the adhesive joint obtained from the SH phase velocities measured during the curing of the adhesive of an aluminium / adhesive / carbon epoxy assembly.

It is interesting to note that while the SH_0 mode is launched from the PZT transmitter in the aluminium component, only the SH_1-like mode is measured along the aluminium / adhesive / composite assembly for all states of the adhesive, except when this is fully cured. This very interesting phenomenon may be useful for detecting little weaknesses in shear properties of adhesive bonds due to either bad curing or to small degradation occurring in time. As show in [4], this mode conversion phenomenon can be explained by the in-plane power-flow distributions through the aluminium / adhesive / composite assembly, for two extreme states of the adhesive: a weak one and a strong one (the C_{44} *moduli* of the bond is set equal to 0.02 and 0.53 *Gpa*), at a frequency where both SH_0 and SH_1-like modes may coexist. In fact, the SH_0-like mode produces no power-flow across the aluminium if the bond is weak, while the SH_1-like mode does. This explains why the SH_0 mode incident from the aluminium plate is not coupled to the SH_0-like mode but to the SH_1 one, until the adhesive curing is not fully finished. Moreover, the modes attenuation was checked to be contributing to the detection of SH_0 and SH_1-like modes, at different levels of the adhesive curing [4].

The second interesting result to note in Figure 5 is the gradual change in the position of the SH_1-like mode cut-off (from about less than 0.1 *MHz* to about 0.28 *MHz*) as the adhesive cures. Such results is very complementary to the previous one, since it allows different levels of a bad adhesive to be distinguished each others and eventually the corresponding shear *modulus* to be inferred (see Table 2).

Conclusion

The three low-order shear-horizontally polarized guided wave modes have been considered to quantitatively characterize the shear properties of an adhesive bond layer between an aluminium plate and a carbon epoxy composite patch. Numerical predictions have been made using a one-dimensional, semi-analytical finite element (SAFE) model, with specifically implemented shear-spring boundary conditions to consider variable adhesion at the interface between the bond layer and the metallic plate. Phase velocity dispersion curves have been plotted for various states of the bond (cohesive or adhesive properties) and also considering the material variability of either the aluminium or composite components. The SH_2-like mode has shown to be unsuitable for testing the cohesive properties of the bond because of its high sensitivity to other components (aluminium, composite) or parameters (thickness). However, both SH_0 and SH_1-like modes have revealed higher sensitivities to about 40% and 30% changes, respectively, in the cohesive shear property (shear *modulus*) of the adhesive layer than in small changes (10% or less) in either the aluminium or composite shear *moduli*. This phenomenon was particularly visible in the low frequency regime, around or below the SH_1-like mode frequency cut-off.

A laser-based technique has been set-up for detecting SH guided wave modes launched by a PZT contact shear transducer. This experimental process has been used to measure velocities of SH-like modes propagating along an aluminium / adhesive / patch zone, the incident mode being the pure SH_0 mode produced along the aluminium component, which was much larger than the patch. The adhesive has been selected to have a particularly slow curing process, and phase velocities have been measured at various times running from right after the bonding was realized to few days after that, to ensure the adhesive curing was finished. Strong mode conversion from the incident SH_0 mode in the aluminium to the SH_1-like mode in the three-layered zone has been clearly observed at all times before the adhesive curing was complete, and no or negligible-in-amplitude SH_0-like mode was detected. Then, after the curing was over, no or very little SH_1-like mode was detected and strong SH_0-like mode was measured along the assembly. This mode conversion phenomenon may be used to monitor changes, due to ageing for example, in initially well-made adhesive bonds. The strong sensitivity to the bond of the SH_1-like mode phase velocity, close to its frequency cut-off, allowed the shear *moduli* of the adhesive layer to be successfully inferred by comparing velocities measured at the various curing times to those predicted using the SAFE model. All these results demonstrate a strong potential of the low-order SH_0 and SH_1 –like guided modes to quantify the shear stiffness of adhesive bond layers.

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