GUIDED SHEAR WAVES ATTENUATION IN BONDED METAL-COMPOSITE STRUCTURES

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Abstract: *Composites are extensively used in modern structures such as those used in aeronautics. Joining these light and strong structures to the metallic frame is done by bonding, due to the advantage of relative uniform distribution of stresses over the entire bonded surface. The quality inspection of bonded assemblies by non-destructive methods is of highest importance. Among these techniques, the guided ultrasonic waves have proven to be very efficient in inspecting relatively long domains from a single transducer position. The length of the inspection domain depends on the attenuation of guided waves. The present work is focused on computing attenuation of ultrasonic shear waves, for all guided modes, in a frequency range of practical interest. Recently published results on guided waves propagation in bonded structures, coming from a long lasting collaboration between the Universities of Le Havre and Politehnica of Bucharest, are also briefly presented.*

Keywords (TNR 9 pt Bold): *guided waves, attenuation, shear waves, composites structures.*

1. INTRODUCTION

In the last decades, many industries required strong and light structures, like for example the aeronautical industry. Bonded structures are widely used in recent years in such industries, due to their advantages of lightness and distribution of stresses over the entire bonded surface. The adhesive homogeneity, adhesion to the bonded structure, and strength are of critical importance for the safety of the structure. Ultrasonic testing techniques are well proven in structural quality assessment, but the classical pulse-echo method is time consuming and less efficient. Guided ultrasonic waves are a potential alternative, due to their relatively long range propagation, allowing for a more rapid inspection of wider areas. From the existing guided waves in planar structure, the Shear Horizontal (SH) polarized ultrasonic waves were preferred for their advantage of being less dispersive: in a planar elastic layer the fundamental SH0 mode is totally nondispersive. The investigation of these waves began more than 50 years ago. Among the more recent researches applied to bond quality, are mentioned here the works of Yew and Weng [1], Adams and Drinkwater [2], Guyott and Cawley [3]. After 2000, the works of Barros et al. [4], Le Crom and Castaings [5], Castaings [7], Potel et al. [10], introduced analytical or semi-analytical models for the SH modes propagation in multilayers. Plate thickness variation influence on guided modes propagation was studied by Nurmalia [6] and Belanger [8]. The distinction between the influence of adhesion quality and thickness variation was investigated by Predoi et al. [9]. The energy flux of guided waves was numerically determined by Predoi et al. [11]. Adhesive properties, surface roughness influence on the guided waves propagation were investigated by Leduc et al. [12], El Kettani et al. [13] Gauthier et al. [14].
The length of the inspection domain depends on the attenuation of guided waves. The present work is focused on computing the attenuation of ultrasonic SH waves, for all guided modes, in a frequency range of practical interest.

2. THORETICAL BACKGROUND

The main hypothesis concerning the SH waves is the modal displacement field (U=V=0 , W(y)) shown on Figure 1. The motion is defined by $w(x,y,t)=W(y)\exp\left[i(kx-\omega t)\right]$, but the harmonic factor $\exp\left[i(kx-\omega t)\right]$ will be omitted in the following. The usual notations are used: k for the wavenumber of the SH waves, and

$\omega=2\pi f$ is the angular frequency, corresponding to the frequency f. The dynamic elasticity equations concerning the SH guided waves can be deduced for orthotropic materials:

$$-k^2 C_{55} W + \frac{\partial}{\partial y}\left[C_{44}\frac{\partial W}{\partial y}\right] = -\rho\omega^2 W \ . \qquad (1)$$

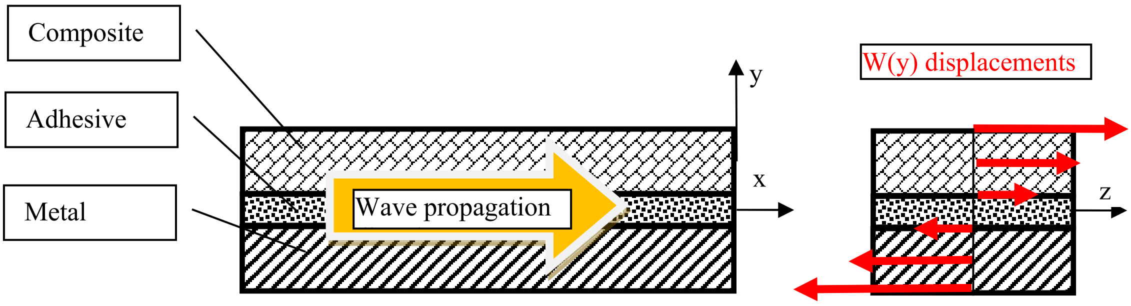

Figure 1 The planar layers geometry (left) and SH wave displacements (right).

The elastic constants C_{44} and C_{55} are involved in the shear stress produced during the wave propagation:

$$\sigma_{23} = C_{44}\frac{\partial W}{\partial y};\ \sigma_{13} = C_{55}\frac{\partial W}{\partial x} \ , \qquad (2)$$

and the σ_{23} stress cancel along the two free boundary surfaces.

The dispersion curves, representing the variation of the modal wavenumbers with the frequency, can be obtained by solving the eigenvalue problem associated to the differential equation (1), with stress-free boundary conditions for the σ_{23} stress defined by eq. (2). It is also assumed a prefect contact between the three layers depicted on Figure 1, meaning continuity of displacements and stresses. The method used to solve the eigenvalue characteristic equation is commonly known as Semi-Analitical Finite Elements Method (SAFEM), which is described in ref. [9].

The purpose of the present investigation is to evaluate the influence of the adhesive and composite layers viscoelastic properties, on the dispersion curves. The imaginary parts of the wavenumbers, will be present at all frequencies and a plot of these imaginary parts and the corresponding attenuations will be determined as functions of frequency.

3. NUMERICAL RESULTS

The numerical parameters used in this analysis are close to measured values of a specimen which is currently tested. In the next table are presented the relevant parameters used in the SAFEM model implemented in Comsol version 5.1 [15].

Table 1: SAFEM model parameters

Layer	Thickness (mm)	Mass density (kg/m^3)	C44 (GPa)	C55 (GPa)
Aluminum	4	2800	26.91	26.91
Adhesive	0.5	1160	1.46	1.46
Composite	1.72	1700	4.87	4.87

The frequency range selected for the numerical analysis is 0 - 2 MHz in steps of 10 kHz. The SAFEM model consists in three colinear segments perpendicular on the free surfaces of the three-layer, divided into 69 unidimensional quadratic finite elements. One SAFEM analysis lasts about 25 minutes on a Laptop and has the advantage of computing the chosen number of 28 complex conjugate eigenvalues representing the wave-numbers at each frequency. The modal displacements and strains are also computed for each mode at every frequency, providing important information concerning the modal detectability in practice, but these results will be included in following research. Modal labeling uses the classical single layer labels: SH_0, SH_1, etc. even if the modal displacements are quite different from those of the classical case.

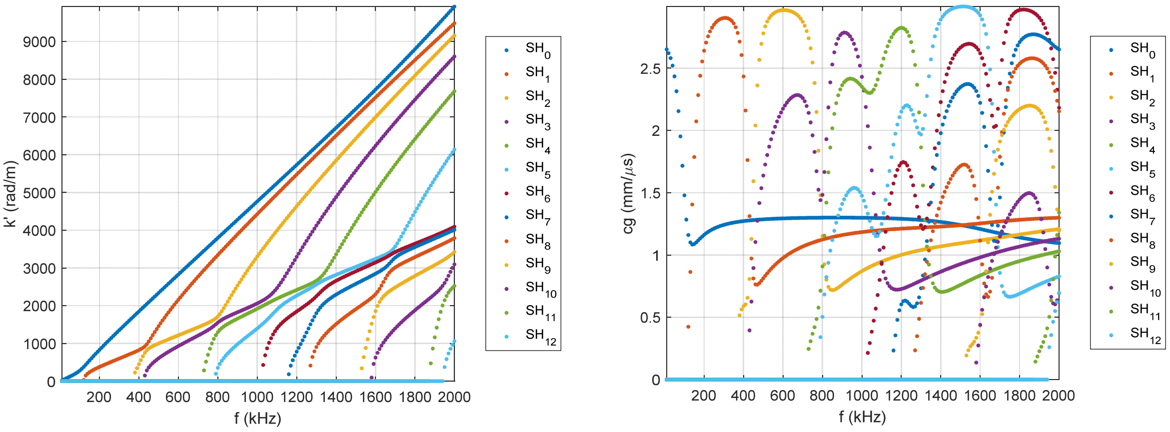

Figure 2: Wavenumbers (left) and group velocities (right) for perfectly elastic materials

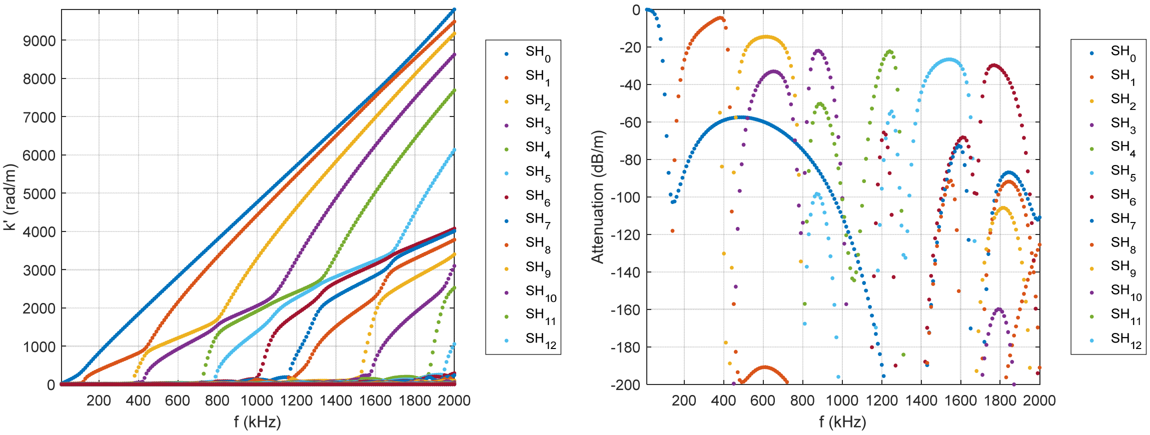

Figure 3: Wavenumbers: real part (left) and modal attenuation (right) for a viscoelastic adhesive

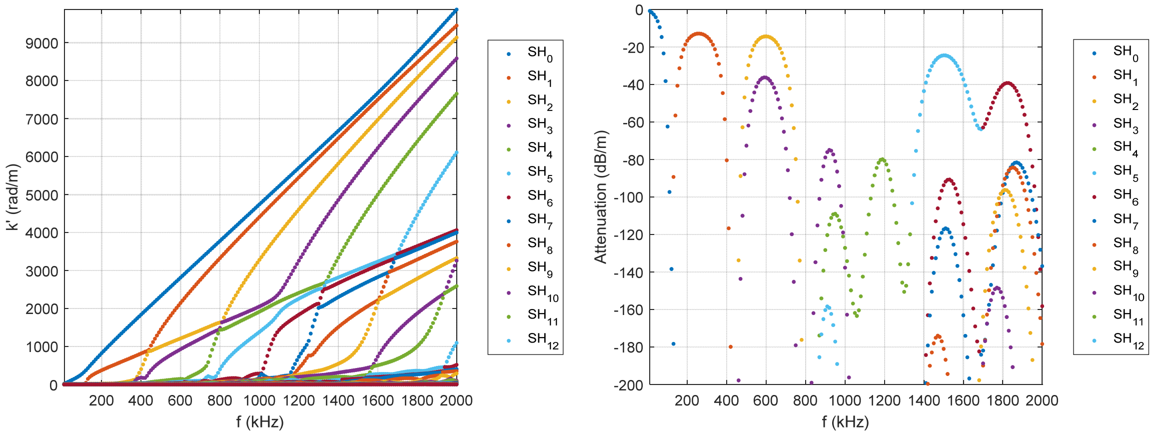

Figure 4: Wavenumbers: real part (left) and modal attenuation (right) for a viscoelastic composite

On Figure 2 are shown the wavenumbers for the first 13 modes, all real numbers. Also the group velocities for each mode are plotted. These velocities indicate which mode reaches first a receiver, as function of frequency, an important aspect especially if more than one mode is sent in the bonded three-layer. On Figure 3 are shown the real part of the wavenumbers and the attenuation in dB/m in case the adhesive is considered viscoelastic with C_{44}=C_{55}=(1.46+0.14i) GPa in which *i* is the imaginary unit. All modes have higher attenuation with increasing frequency. The same plots on Figure 4 correspond to the case of a non-viscoelastic adhesive but a viscoelastic composite plate, with C_{44}=C_{55}=(4.87+0.49i) GPa. The wavenumbers show crossing curves and the plotting function has difficulties in following the modes with the same label. Only higher order modes are different from the previous case. The modal attenuation remains high, but in the 800-1300 kHz interval the viscoelastic composite induces a much larger attenuation that the viscoelastic adhesive. This remark can help in identifying the layers contribution to attenuation.

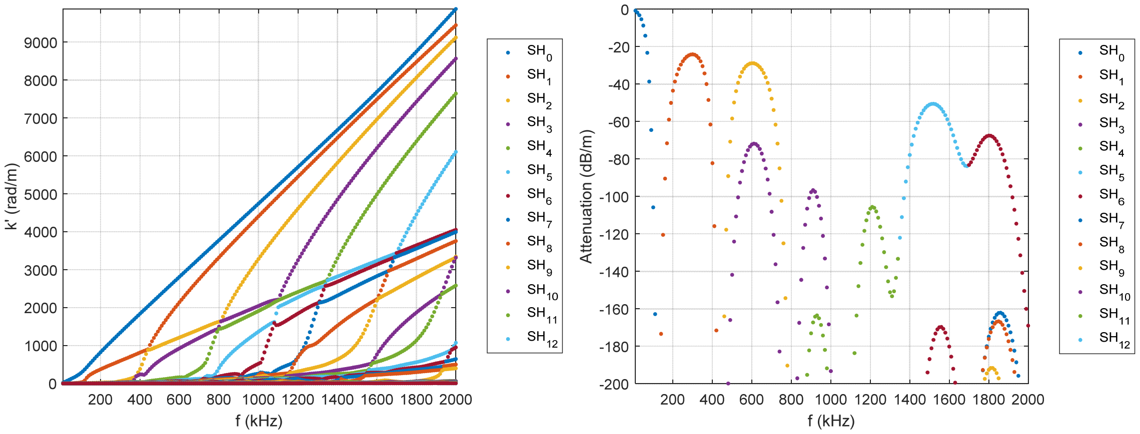

Figure 5: Wavenumbers: real part (left) and modal attenuation (right) for viscoelastic adhesive and composite

On Figure 5 are shown the real parts of the wavenumbers and attenuation if both the adhesive and composite are considered viscoelastic materials. A first remark is that the wavenumbers are close to those of the first two cases. There are visible differences for the higher order modes at high frequencies, but their detectability is less obvious. The crossing of modes can be attributed to the composite viscoelasticity, by comparing with the previous case. The modal attenuations are higher if both the composite plate and adhesive are viscoelastic. However, the viscoelasticity of the adhesive has a considerable influence on the SH_3 mode between 500 kHz and 700 kHz, making possible the characterization of the adhesive.

4. CONCLUSIONS

The influence of viscoelastic properties of the adhesive and of the composite on the SH wavenumbers imaginary part is investigated. The SAFE method was used to solve the dispersion equation. Four cases have been studied. The first case considers all materials as ideal, without dissipation. The second case considers only the adhesive as viscoelastic, by adding 10% of the elastic constant as its imaginary part. This is in general a strongly dissipating material and can be considered as a limit case. The third case considers only the composite plate as viscoelastic, by adding also an imaginary part which is 10% of the real part. The last case considers these high levels of material dissipation for both the adhesive and the composite plate.

In all investigated cases, the real parts of the wavenumbers are almost unchanged at least in the so-called “subsonic” domain of higher wavenumbers. Only close to the cutoff frequencies of higher order modes (the “supersonic” domain), there are differences in the dispersion curves, but these variations are hard to detect.

The study of the attenuations bring important information for the practical applications. The fundamental mode SH_0 is nondetectable at all frequencies due to the attenuation. Remain detectable the modes SH_1, SH_2 and SH_3 but each mode has its frequency interval of low attenuation. The attenuation of modes SH_3 and SH_4 in the 800 kHz -1300 kHz range is strongly affected by the attenuation of the composite, making measurable this attenuation in this frequency range. An interesting aspect is the attenuation of modes SH_5 and SH_6, labeled as such for the second analysis case. For frequencies between 1400 kHz – 2000 kHz, these modes which seem to join in cases three and four, have a lower attenuation than other modes, making them detectable.

These results, obtained in frame of a long duration collaboration between the two laboratories of the authors, will be developed in subsequent publications, considering the importance of the bond quality in many modern structures.

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