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Characterization of laminated glasses by means of an inversion method using Finite Elements

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The experimental determination of elastic modules and loss factor in laminated glass components is of great interest in Building acoustics since at present there are a lot of building systems using this type of devices. This makes necessary to predict the transmission losses in a partition. Even though described in regulation, the process is not exempt from serious difficulties. In this work we present a method in order to obtain the parameters mentioned above for a laminated glass composed of a sequence of isotropic layers by solving the model -based inverse problem for frequency admittance experimentally obtained. The parameter that best describes the mechanical constants of material of the layers is obtained by minimizing the discrepancy between the real numerically and numerically predicted results. This is done using an iterative optimization. A sensitivity study of the parameters uncertainty is performed in order to establishing the feasibility of this technique.

1 Introduction

The experimental determination of elastic modules and loss factor in laminated glass components is of great interest in Building Acoustics since at present, there are a lot of building systems using this type of devices. This makes necessary to predict the transmission losses in a partition. Even tough described in regulation, the process is not exempt of serious difficulties.

The need for precise predictions of acoustic isolation is increasingly growing due to the application of current regulations, focused on guaranteeing a certain comfort (or health) level for final users. This implies serious difficulties, one of which being the deviation from *in situ* measurements of experimental data obtained from laboratory measurements (in standardized transmission chamber). This is mainly due to contributions from indirect propagation and particular boundary conditions. The relatively large uncertainty of on site measurements has to be taken into account as well.

In addition to this, European (CEN) standards for glass in building do not consider any procedure for acoustic isolation predictions on multilayer glazing (laminated glass with polymeric films) and multiple glazing (several multilayer glazings separated by intermediate gas gaps).

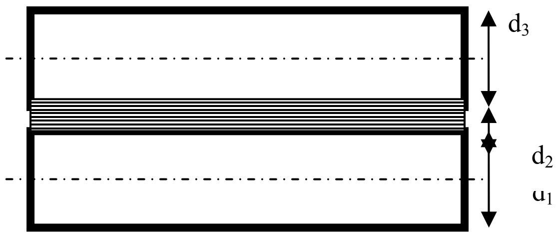
We are interested in partitions formed by several layers:

a) Monolithic glass, with standardised characteristics, which acoustically behaves as a impermeable layer.

b) Polymeric films, usually PVB (PolyVinyl Butiral), with organic components, or PMMA (PolyMetyl MetAcrilate), which derive from metacrilate resins. From an acoustic point of view, both of them attenuate vibration transmission (damping).

It should be noted that glass thickness is significantly larger than that of intermediate polymeric films, and that a large number of configurations include a three-layer structure with two glass panels of the same thickness (symmetric laminate).

The primary advantages of multi-layer configurations incorporating viscoelastic interlayers that act in shear are: (a) such configurations permit one to obtain very high loss factors by means of thin layers of appropriately chosen materials (as we show in next section, the thickness d_2 does not enter in the equation determining optimum loss factor), and b) the viscoelastic layer does not increase the stiffness of the composite. This latter effect implies that the damping obtained within a given distance along the plate is relatively high.



d_1=d_3

Figure1. Laminated Glass

ISO/PAS 16940:2004(E)[1], describes a method for the measurement of the loss factor and the equivalent bending rigidity modulus of laminated glass test pieces. The aim is to compare the properties of interlayer's. These two parameters (and others such as density and thicknesses of glass components) can be related to the sound transmission loss (STL) of the glazing itself. This provides a method for the calculation of transmission losses in this kind of partitions. So, TL=10log(1/τ(θ)) and:

$$\tau(\theta)=\frac{I_{tx}}{I_{inc}}=\left\{\left[1+\eta\cdot\left(\frac{\omega\cdot\rho_s}{2\cdot\rho\cdot c}\cdot\cos(\theta)\right)\cdot\left(\frac{\omega^2\cdot B}{c^4\cdot\rho_s}\cdot\sin^4(\theta)\right)\right]^2+\left[\left(\frac{\omega\cdot\rho_s}{2\cdot\rho\cdot c}\cdot\cos(\theta)\right)\cdot\left(1-\frac{\omega^2\cdot B}{c^4\cdot\rho_s}\cdot\sin^4(\theta)\right)\right]^2\right\}^{-1} \quad (1)$$

I is the sound intensity (W/m^2), ρs the surface density of the plate (kg/m^2), and the rest of the parameters have been previously defined. The standard also includes an experimental procedure which permits to obtain the equivalent stiffness modulus of a laminated glass, dependent on the frequency B=B(fi) and the loss factor of the whole system. In order to obtain the diffuse field transmission coefficient, the standard proposes a limit angle of 75º. However, this standardised expression has less utility (and a lower quality) as a predictive model than the models based on impedance coupling, such as RKU model (Ross- Kerwin-Ungar, 1959 [6]) analysis or Ookura-Saito, 1978 [2]) and others [4,5,7,13].

On the other hand, ASTM/C 623–92 [10] describes a method covers the determination of the elastic properties of glass and glass-ceramic materials. Specimens of these materials possess specific mechanical resonance frequencies which are defined by the elastic moduli, density, and geometry of the test specimen. Therefore the elastic properties of a material can be computed if the geometry, density, and mechanical resonance frequencies of a suitable test specimen of that material can be measured. Young's modulus is determined using the resonance frequency in the flexural mode of vibration. The shear modulus, or modulus of rigidity, is found using torsional resonance vibrations. All glass and glass-ceramic materials that are elastic, homogeneous, and isotropic may be tested by this test method. The test method is not suitable for specimens that have cracks or voids that represent inhomogeneities in the material; neither is it satisfactory when these materials cannot be prepared in an adequate geometry.

ATSM/ E 756 – 98 [9] covers the description of method measures the vibration-damping properties of materials: the loss factor, h, and Young's modulus, *E*, or the shear modulus, *G*. Accurate over a frequency range of 50 to 5000 Hz and over the useful temperature range of the material, this method is useful in testing materials that have application in structural vibration, building acoustics, and the control of audible noise. Such materials include metals, enamels, ceramics, rubbers, plastics, reinforced epoxy matrices, and woods that can be formed to cantilever beam test specimen configurations.

The uncertainty in the determination of transmission loss (TL) of sandwich panel-like structures - laminated glass- is partly due to the uncertainties on the vibrational and mechanical properties of their components coming from the fact that, in particular, polymeric films do not co-exist with identical properties independently from the multilayer structure. Essentially, the parameters defining acoustic behaviour are bending stiffness and loss factor.

2 Concepts

2.1 Bending waves in monolithic beam: Euler Model

One can find the analytical transfert function for a flexural vibration experiment on a uniform beam composed of a linear, homogeneous and isotropic viscoelastic material without axial loads as shown in figure 2, in [8].

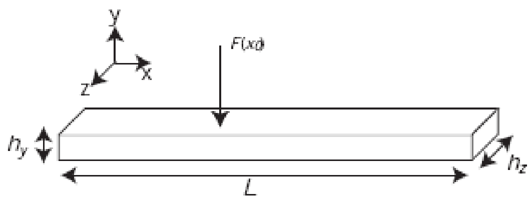


Figure 2

As is well know, the resonances of the frequency response function provides the necessary information to determine Young´s modulus from modal response measurements**.**

2.2 Constitutive models for the material

The first analytic approximation to this problem is found in Cremer-Heckl (1973) [3], where for the case of a three-layer laminated structure, with viscoelastic nucleus of smaller width, it is shown that:

$$\eta_{eq} = \eta_2 \frac{2E_3 d_3 a^2}{B} \frac{g_i}{\left|1+\left(1+j\eta_2\right)g_i\right|^2} \qquad (2)$$

$$B = 2B_1\left[1+\frac{E_3 d_3 a^2 g_i}{B_1}\frac{1+g_i\left(1+\eta_2^2\right)}{\left|1+\left(1+j\eta_2\right)g_i\right|^2}\right] \approx \approx 2B_1\left(1+\frac{3g_i}{1+g_i}\right) \qquad (3)$$

where E_3 is the Young modulus for the glass (N/m^2) and hi is the thickness of the i-th layer (m). The shear parameter, gi, explicitly depends on the shear modulus of the intermediate film, G_2, through the expression,

$$g_i = \frac{2G_2}{E_3 d_3 d_2 k^2} \qquad k = \sqrt[4]{\omega^2 m' / B_{eq}} \qquad (4)$$

$(B_1 = E_1 \frac{d_1^3}{12}$ y $a \approx d_1/2.)$

One may note that at high frequencies, $g_i \to 0, B \to 2B_1$. At low frequencies, $g_i \to \infty, B \to 8B_1$, and thus corresponds to that of a plate with trice the thickness of one of the single plates.

If one introduces the notation $h_i = \frac{E_3 d_3 a^2}{B_1} \approx 3,$ into Eq. (3) one finds alter some manipulations that

$$\eta = \frac{\eta_2 h_i g_i}{1+(2+h_i)g_i+(1+h_i)(1+\eta_2^2)g_i^2} \approx \approx \frac{3\eta_2 g_i}{1+5g_i+4(1+\eta_2^2)g_i^2} \qquad (5)$$

That wich maximum damping accurs here obeys

$$g_i = 1/2\sqrt{1+\eta_2^2}\ ,$$

and correspond to

$$f_{\max} \approx \frac{2}{\pi}\frac{G_2}{E_3 d_3 d_2}\sqrt{\frac{B}{m}} \approx \frac{'2}{11}\frac{G_2}{E_3}\frac{c_{L1}}{d_2} \qquad (6)$$

Where the value $B \approx 4B_1$ (which is appropriate in the vicinity of f_{max}), was used for the flexural stiffness. At the optimum frequency, the loss factor is

$$\eta_{opt} \approx \frac{3\eta_2}{5g_i + 4\sqrt{(1+\eta_2^2)}} \qquad (7)$$

However, a more detailed studied can be found in Ross-Kerwin-Ungar (1959) [6] for the construction of a homogeneous bending stiffness for the three layer system, Beq. This model is based on similar hypothesis for the bending wave as in the previous model, but with a more refined geometric construction.

2.3 Measuring Vibration-Damping Properties of material

The test method measures the resonance frequencies of test bars of suitable geometry by exciting them at continuously variable frequencies. Mechanical excitation of the specimen is provided through use of a transducer that transforms an initial electrical signal into a mechanical vibration. Another transducer senses the resulting mechanical vibrations of the specimen and transforms them into an electrical signal that can be displayed on the screen of an oscilloscope or an analyzer to detect resonances. The resonance frequencies, the dimensions, and the mass of the specimen are used to calculate Young's modulus and the shear modulus. The loss factor and the equivalent bending rigidity modulus are determined from the measurement of the mechanical impedance of the glass beam sample.

Resonance frequencies for a given specimen are functions of the bar dimensions as well as its density and modulus; therefore, dimension should be selected taking into account this relationship . When the transfer function corresponding to the input impedance is measured, resonance frequencies $f_{res,i}$. are determined . Loss factor is then calculated using the relationship resonance).

The configuration of the cantilever beam test specimen is selected depending on the type of damping material to be tested and the desired damping properties. Two transducers are used. A transducer applies the excitation force, and the other measures the response of the beam. Because of the necessity of minimizing all sources of damping except that of the material to be investigated, it is preferable to use noncontacting transducers.

3 Methodology

We are ultimatelly interested in obtaining the mechanical parameter of the interlayer. To succesfully acomplish this objective a first step is an independent study of monolithic glass. In this study we obtain both numerically predicted and experimentally obtained movility and we define a Discrepancy function,

$$D_M = \sum_i \left(M_{mi} 1 - M_{Pi} \right)^2 \qquad (8)$$

This function is, in fact, a distance and measures the difference between of set of values. We seek the values that make this distance minimum.

This (pair of) values that have been obtained are a start point in our study of laminated glass. As done previously we obtain numerically predicted and experimental movility for laminated glass, defining now a new Discrepancy function

$$D_L = \sum_i \left(M_{mi} 1 - M_{Pi} \right)^2 \qquad (9)$$

The minimization of this function provides the values for the parameters of the interlayer.

4 Results

4.1 Monolithic Glass

We have studied different monolithic (4, 5 , 6 mm thickness and 38 cm length) and laminated (4+4, 5+5, 6+6 acoustic and normal types) glass samples. Due to space limitations, we only show some results. In table I can be seen the results of previously made modal Analysis, corresponding to the figure 3 (below)

Type	Freq. 1	Freq. 2	Freq.3	Freq.4
Monolithic 4 mm	24.6	150.7	421.7	825.7
Monolithic 5 mm	30.07	188.3	526.72	-
Monolithic 6 mm	36.08	225.9	631.4	-

Tabla 1 Numerical Results

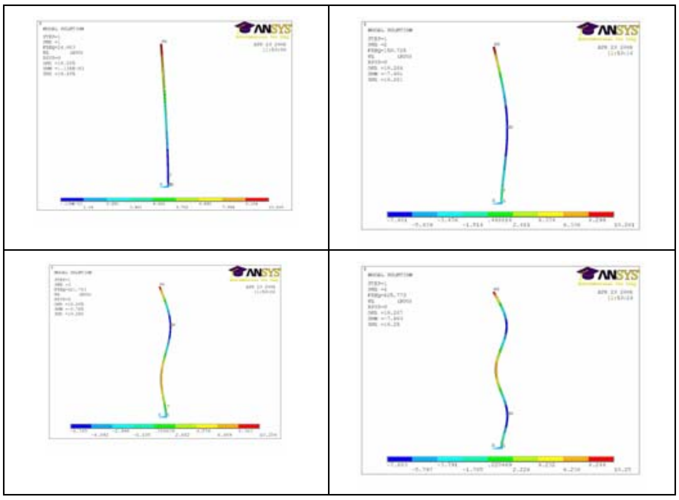


Figure 3 : 4 mm monolithic first four modes

Next figure (4) shows experimental results and theoretical simulation of the modal response of a 4 mm monolithic, and in Table II the experimental results for Young Modulus and Loss Factor. In figure 5 we can observe these values obtained for each frequency.

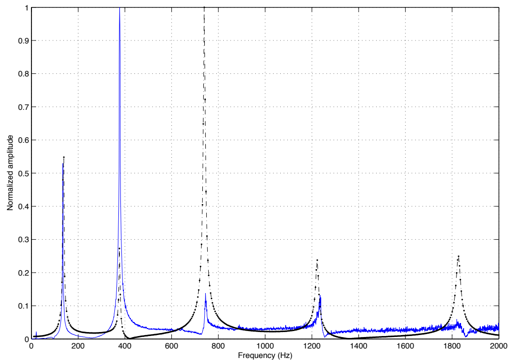


Figure 4 Experimental results and theoretical simulation of the modal response of a 4 mm monolithic

Type	Young Modulus (Pa)	Loss Factor
Monolithic	$5.49*10^{10}$	0.01

Table II Experimental results for Young Modulus and Loss Factor

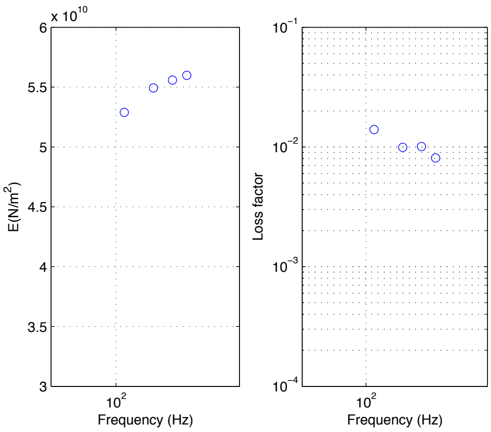


Figure 5 Values obtained for each frequency

4.2 Laminated Glass

Normal Laminated

In figure 6 we show modal analysis experimental results compared with a simulation of a monolithic of equal density

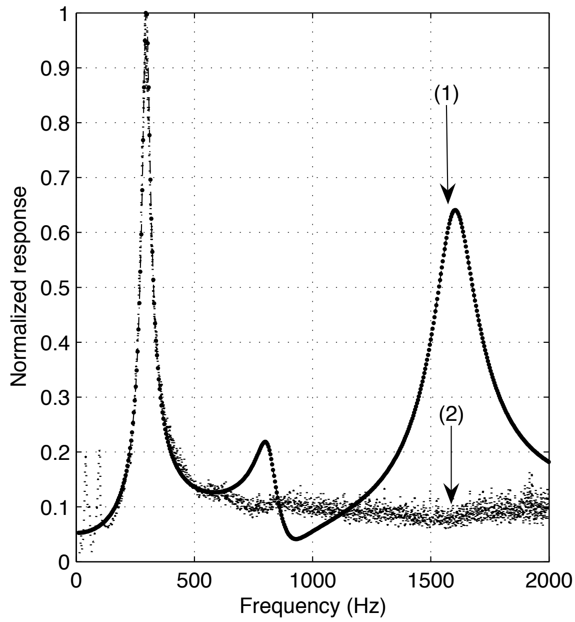


Figure 6. (2) Modal response of a 5+5 mm laminated glass (normal). (1) Theoretical response for a monolithic of same density.

Type	Young Modulus (Pa)	Loss Factor
Laminated-Nornal (4+0.76+4)	$3.9*10^{10}$	0.1
Laminated-Nornal (5+0.76+5)	$3.6*10^{10}$	0.11
Laminated-Nornal (6+0.76+6)	$3.5*10^{10}$	0.11

Table III Experimental results for normal laminated glass

.Acoustics Laminate Glass

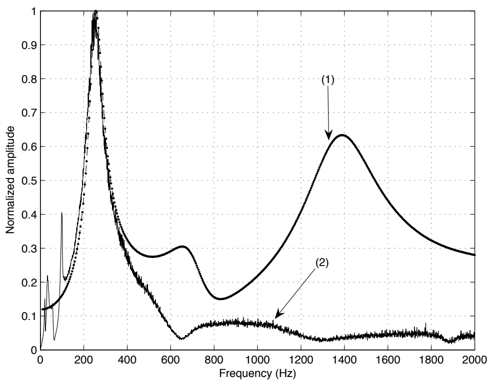


Figure 7. (2) Modal response of a 5+5 mm laminated glass (acoustic). (1) Theoretical response for a monolithic of same density.

Type	Young Modulus (Pa)	Loss Factor
Laminated-Acoustic (4+0.76+4)	$2.8*10^{10}$	0.25
Laminated-Acoustic (5+0.76+5)	$2.5*10^{10}$	0.25
Laminated-Acoustic (6+0.76+6)	$2.4*10^{10}$	0.27

Table IV. Experimental results for acoustic laminated glass

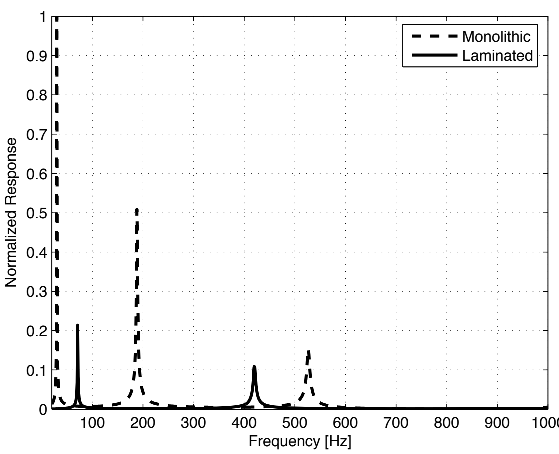


Figure 8. Results of a numerical simulation after a first approximation.

5 Conclusion

A technique is proposed to determine Shear Modulus and Loss Factor properties, of interlayer in multilayered partitions being applied for laminated glasses. This technique uses as input data the experimental obtained from a modal analysis of a sample beam and is proved experimentally consistent

Acknowledgments

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