Evaluation of damping properties of structural glass panes under impact loading

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ABSTRACT: The latest technology and architectural trends have significantly improved the use of a large variety of glass products in construction which, in function of their own characteristics, allow to design and calculate structural glass elements under safety conditions. This paper presents the evaluation and analysis of the damping properties of rectangular laminated glass plates of 1.938 m x 0.876 m with different thickness depending on the number of PVB interlayers arranged. By means of numerical simulation and experimental verification, using modal analysis, natural frequencies and damping of the glass plates were calculated, both under free boundary conditions and operational conditions for the impact test equipment used in the experimental program, as the European standard UNE-EN 12600:2003 specifies.

1 INTRODUCTION

During the last decades the development of new production techniques of structural glass has permitted a large use of this material in construction. The laminated glass has a sandwich structure consisting of one or several layers of glass joined by intermediate layers of a polymeric material which confers better properties than the monolithic glass, so that monolithic glass is now replacing in various applications. Since the glass pieces remain attached to the polymer layer when the fracture occurs (Claramunt 2005), the security is one of the most significant properties of laminated glass, but also the acoustic and thermal insulation are other of its prominent characteristics.

Though the advantages of laminated glass are very attractive, the calculation and behaviour modelling are complex due to the combination of a rigid material, such as glass, with a flexible polymer material. The polyvinyl butyral (PVB) is commonly used as interlayer viscoelastic material, whose properties depend on the temperature and the frequency (or time) (Bennison 1999 & Pelayo 2011).

In this paper the dynamic response of laminated glass panes with different PVB thicknesses under impact testing is analysed according to the UNE-EN 12600:2003 standard.

2 LAMINATED GLASS BEHAVIOUR

While glass is generally considered a linear elastic material (Bennison 1999), the PVB presents a linear-viscoelastic behaviour. Although the thickness of the PVB layer is considerably less than the total thickness of the laminate, the influence of the polymer properties, like damping, can be significant as compared to a monolithic glass of equivalent thickness.

The viscoelastic behaviour can be easily understood if one considers that these materials have properties common to elastic solids and viscous fluids, typically represented by springs and dashpots, respectively (Ferry 1980). Factors such as temperature, pressure or the frequency (or time of application of the load) affect these materials so that, for example, at low temperatures or high frequency loads, the behaviour is more elastic than viscous, and vice versa (Lakes 1998).

A simple example of viscoelastic model is the Maxwell model given by a spring (elastic behaviour) and a dashpot (viscous behaviour) placed in series (see Figure 1).

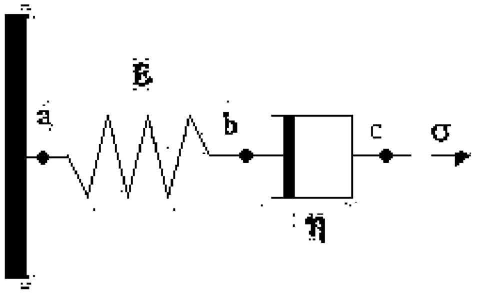

Figure 1. Maxwell Model

The response of the material under dynamic loads such as those due to impacts, is given by the complex modulus of the material E* (ω) which can be represented by the real part E' (ω), known as the storage modulus and related to the elastic capacity of the material and its imaginary part, E" (ω), known as the loss modulus and related to the dissipative capacity of the material.

In the Maxwell model both components are given by the following expressions (Tschoegl 1989):

$$E'(\omega) = \frac{\eta^2 \omega^2 E}{\eta^2 \omega^2 + E^2} \tag{1}$$

$$E''(\omega) = \frac{\eta\, \omega \mathrm{E}^2}{\eta^2 \omega^2 + E^2} \tag{2}$$

where ω is the frequency, E is the spring stiffness and η is the coefficient of viscosity of the material. The ratio between both components is known as the loss factor (or loss tangent tan δ):

$$\eta(\omega) = \frac{E''(\omega)}{E'(\omega)} \tag{3}$$

which can be associated with the modal damping ζ by the relation (Jones 2001):

$$\eta = 2 \cdot \zeta \tag{4}$$

For systems with relatively low damping this relationship provides good results, with errors less than 5% when $0 < \eta < 0.3$ (Jones 2001). Figure 2 shows the modulus values E' (ω) and E" (ω) depending on the PVB temperature. Figure 2 also shows how the capacity of PVB damping, represented by the loss factor (tan δ), depends strongly on the temperature.

Moreover, viscoelastic behaviour also depends on the pressure to which is subjected the material (Ferry 1980). As more pressure is subjected to the material, there's greater stiffness, i.e., an increase of the actual component E' (ω) versus the imaginary E" (ω), which implies a lower loss factor (see equation 3) or what is the same, a reduced damping capacity of laminated glass. This pressure effect could be more pronounced in laminated glasses with smaller PVB thickness, for example, formed by a single layer of 0.38 mm, where the adhesive forces created between the two materials in the manufacturing process can subject the PVB layer to a compressive residual state. This effect can be reduced with laminated glasses with a thicker layer of PVB, where the relaxation of the material at points close to the central plane of the layer could be produced; points less influenced by forces of adhesion.

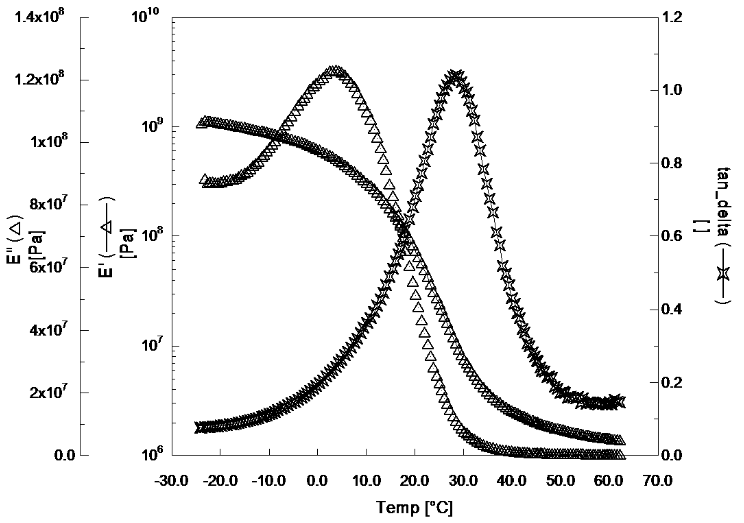

Figure 2. Storage modulus E ', loss modulus E" and tan δ of PVB.

3 EXPERIMENTAL METHODOLOGY

3.1 *Specimens*

Monolithic and laminated glass plates were used in the experimental programme. The plate dimensions were 1.938 m large and 0.876 m wide with 0.01 m thickness for monolithic glass, according to European Standard EN 12150-1:2000, and 5+0.38+5 mm and 5+1.52+5 mm for laminates called "Laminate 1" and "Laminate 2", respectively.

3.2 *Test Equipment*

The impact tests according to UNE-EN 12600:2003, which describes the testing methodology for classification of flat glass for building construction by pendulum tests, were carried on using an improved test equipment based on the guidelines described by the standard in order to achieve more accuracy, repeatability and versatility. The modified test equipment consisted of two separate structures, one held and moved the impact pendulum and the other one comprised a main frame and a clamping frame that held the glass sample during the test. In addition, an encoder angle measurement system was implemented that allowed fixing and positioning the pendulum to the desired height. Finally, an electromagnet was added to get an automatic pendulum release.

3.3 *Tests*

Tests were divided in two parts: a) modal analysis of the plate fixed under the clamping frame, and b) impact tests on the same position. The objective of both tests was, firstly, analyse the dynamic response of the plates (frequencies, modes shapes and damping ratios) and secondly, to facilitate the interpretation of the response of the plates under impacts.

Eight accelerometers of 100 mV/g (PCB-333B32) were used for modal analysis. In the experiments the acceleration signals were recorded with a cDAQ-9188 chassis equipped with two NI-9234 acceleration modules and using a sampling frequency of 2132 Hz. Artificial excitement on glass plates was used with two impact hammers of plastic head.

In the impact tests, the plates response was recorded by six accelerometers of 10 mV/g (PCB-352C15) fixed by glue to the glass samples. Furthermore, in these tests a configuration of three more accelerometers were placed, one accelerometer in the pendulum, one in the main frame and another one in the clamping frame. Additionally, a strain gauge rosette (0°-45°-90°) was located at the centre of the plate to measure the strains produced during impact. The registration of the signals was performed with the same equipment of modal analysis test adding a NI-9235 module for extensometry measurements. A sampling frequency of 10240 Hz was used in impact tests.

According to the UNE-EN 12600-2003, impacts were performed from three drop heights, considering the vertical position of the pendulum as a reference (190, 450 and 1200 mm), and additionally from intermediate heights of 25, 50, 75, 100, 200, 250, 300, 600, 750 and 1000 mm, providing the glass hadn't broken before. At each stage, a single impact and a double impact were carried out.

In each test, the maximum response of the accelerometer, time between impacts, time of response attenuation of the plates and the maximum strain of the gauge were recorded.

4 EXPERIMENTAL RESULTS

4.1 *Modal analysis of the plates placed into the clamping frame*

This section presents the results of the modal analysis of the plates placed into the clamping frame.

The modal analysis of the plates was performed using operational modal analysis, that is, only the responses of the plates were using in the modal parameters identification (natural frequencies, mode shapes and damping ratios). The modal identification of the plates was carried out using the Enhanced Frecuency Domain Decomposition (EFDD) technique (Brinker 2000), implemented in the ARTeMIS Extractor software.

In table 1 are shown the natural frequencies for the three plates. In a first analysis of results (see table 1) it was observed that the laminated plate presented lower frequencies than the monolithic plate, both of similar thickness. If we take into account that the high frequency response of a laminated glass can be assimilated to a monolithic glass with an equivalent thickness (sum of the 3 layers) (Ross 1959), the obtained results showed the opposite behaviour. A detailed measurement of the thicknesses of both plates revealed that the monolithic plate was 10.15 mm thickness while the overall thickness of the laminate glass, theoretically 5+0.38+5, was 9.86 mm. This difference in thickness justified, therefore, the obtained results. In the case of the laminated glass with PVB thickness of 1.52 mm, the natural frequencies were higher, compared with the other glasses, since the plate presented higher equivalent thickness and, therefore, greater effective rigidity (Ross 1959).

Table 1. Natural frequencies of the plates placed in the test frame.

Mode	Natural Frequency [Hz]		
	Monolithic	Laminate 1	Laminate 2
1	37.39	37.01	40.86
2	56.02	54.83	57.35
3	67.15	64.19	66.20
4	90.05	89.02	99.26

Comparing the damping values depending on whether there was or not the PVB layer (see table 2), the results showed an increase of damping with PVB thickness. Comparing the monolithic glass and the laminate of similar thickness (Laminate 1), the differences were apparently of the same order, however for the 1.52 mm PVB layer glass, the increase in the damping was significant (see Table 2).

In the analysis of damping with the frequency, it was observed that in both monolithic and laminated (Laminate 1) plates, the damping presented a tendency to decrease with frequency. In general this tendency in both cases should be inverse (Aenlle 2011), so it which suggested that some dissipation mechanism in the test frame support might be influencing the results. In preliminary tests on the monolithic plate for calibrating the test frame (Claramunt 2005 & UNE-EN 12600:2003), damping ratios of 0.3% or below under free-free boundary conditions were obtained, so the higher values obtained in the frame support tests couldn't due to the glass plate. This behaviour could be justified due to the rubber bands used in the clamping frame to hold the plates to the main frame support. Although the PVB layer in Laminate 1 produced an increment in the damping, not significance differences with monolithic plate and same tendency with frequency was observed. This could be an indicative that for this kind of clamping system the damping introduced in the plate when lower thickness PVB layers were used was of the same order that the damping introduced for the clamping device. In the case of the laminated glass Laminate 2, the damping increased with frequency. This different behaviour from the other two plates might be due to the higher dissipative capacity of the plate against the effect of the damping introduced by fastening rubber bands.

Table 2. Damping ratios of the plates placed in the test frame.

Mode	Damping ratios [%]		
	Monolithic	Laminate 1	Laminate 2
1	1.058	1.144	1.808
2	0.909	0.999	1.420
3	0.756	1.039	2.060
4	0.632	0.856	2.167

4.2 *Impact tests*

In case of single impact tests at different heights, the maximum acceleration values, the maximum acceleration registered produced upon impact by pendulum and, finally, the time it took to attenuate vibration at the plate was analysed. To calculate the attenuation time parameter, which provided an indirect measure of the damping capacity of the plate, the time between the maximum acceleration signal in the impact and the moment with the value of the signal was a 95% lower, was used. The results obtained in the three plates for a drop height of 100 mm are shown in Table 3. The results showed how the acceleration in the monolithic plate was higher than in the two laminated glass plates, and also in this latter case, the acceleration was lower with increasing thickness of the PVB. Although the response observed previously in the plates, see table 1, the higher the plate's equivalent thickness was, the higher its rigidity, here it looked that the opposite behaviour was obtained, however, we have to remark that the accelerations were measured in the opposite layer where the impacts were produced so the damping capacity of the PVB layer was clearly present in the results (table 3).

From the acceleration of the pendulum, at just the moment in which the impact occurred, it was observed how the value was higher at higher equivalent thickness, consistent with the values obtained in the natural frequencies of the plates.

The results of the attenuation time parameter were in line with the results obtained by operational modal analysis: the thicker the PVB was, the higher damping was shown on glass, and therefore the impact response took less time to be attenuated.

Table 3. Data obtained from simple impacts at 100 mm drop height.

	Monolithic	Laminate 1	Laminate 2
Maximum acceleration [g]	8.560	8.252	7.070
Pendulum acceleration[g]	7.002	7.103	7.241
Time of signal attenuation (95%) [s]	4.578	4.042	3.752

In double impact testing was noted that the time elapsed between the first and the second impact (see table 4) increased with the thickness of the layer of PVB. These results confirmed the behaviour of the laminated glass against impact loads could be likened to that of a monolithic glass of equivalent thickness, since a longer time between impacts occurred if the pendulum rebound was of greater height, produced by impact against a more rigid structure.

Table 4. Data obtained from double impacts at 100 mm drop height.

Frequency	Monolithic	Laminate 1	Laminate 2
	Hz	Hz	Hz
Mode 1	1.197	1.089	1.985

From the acceleration responses, obtained at impact tests, an estimation of the damping, using logarithmic decrement technique, was carried out, see figure 3. The values obtained for the three plates from a drop height of 100 mm are shown in Table 5.

When the responses of the plates were analysed in the frequency domain (see figure 4) two main contributions were observed, firstly at 38-40 Hz, and secondly at 90-100 Hz. These peaks corresponded with first and third modes of the plates (see table 1). This was due to that for this kind of testing, where the load was applied at the centre of the plate, both first and third mode shapes, which had a node (maximum) at this point, were mainly excited during the impact.

Table 5. Damping ratios obtained from the impacts tests

	Monolithic	Laminate 1	Laminate 2
Pendulum1 acceleration [g]	5.889	5.798	5.995
Pendulum2 acceleration[g]	4.890	4.777	4.922
Time between impacts [s]	1.372	1.389	1.405

Finally, from the complete test campaign at different drop heights, a linear tendency of the response of the laminated glass with height was observed, allowing to maintain the hypothesis of linear and linear-viscoelastic behaviours for glass and PVB, respectively, for this type of loading.

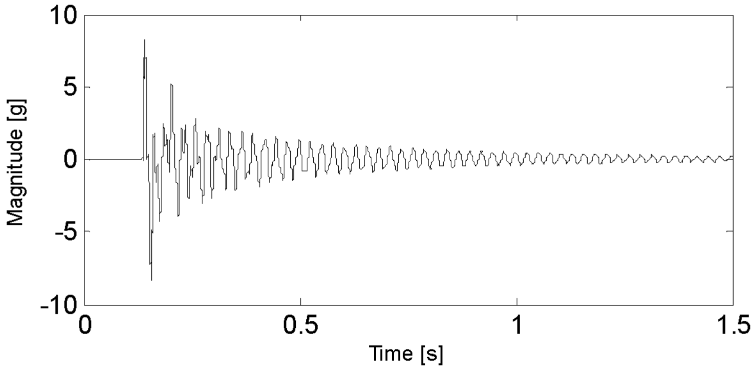

Figure 3. Example of response in an impact test

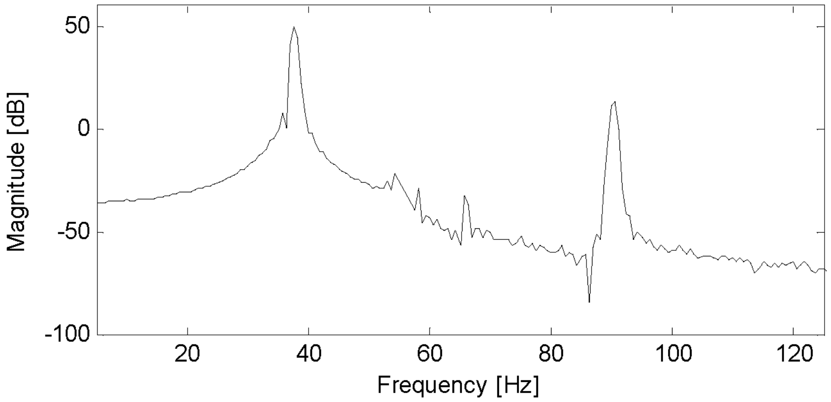

Figure 4. Example of spectral density of the plates' response in an impact test

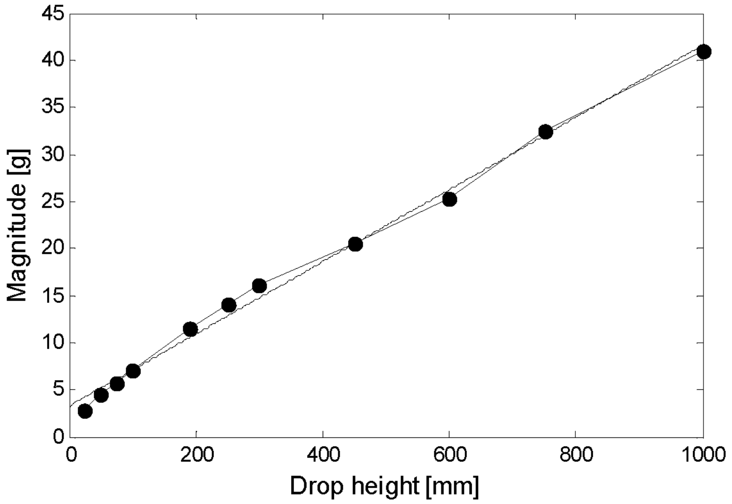

Figure 5. Relation between drop height and response of laminated glass (0.38 mm layer of PVB)

5 CONCLUSIONS

By using the modal parameters of the plates in operating conditions, one can estimate their performance against impact loads, thus facilitating the calibration of a numerical model for this type of testing.

The results of this paper demonstrate the influence of the thickness of the PVB interlayer to the glass damping capacity. However in laminated glasses with low PVB's thicknesses, this influence may be of the same order as the entered by the flexible elements to fix the plate.

In the study of stress, strain and displacement of glass plates subjected to impact loading is necessary to consider not only the collaboration of first mode shape but also the third, due to the type of excitation performed.

In impact tests on laminated glass was obtained a linear relation between the response of the plate and the magnitude of impact. This permits use of the hypothesis of linear and linear-viscoelastic behaviour for glass and PVB, respectively.

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