Viscoelastic vibration damping identification methods. Application to laminated glass.

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Abstract

Laminated glass is composed of two glass layers and a thin intermediate PVB layer, strongly influencing PVB's viscoelastic behaviour its dynamic response. While natural frequencies are relatively easily identified even with simplified FE models, damping ratios are not identified with such an ease. In order to determine to what extent external factors influence damping identification, different tests have been carried out. The external factors considered, apart from temperature, are accelerometers, connection cables and the effect of the glass layers. To analyse the influence of the accelerometers and their connection cables a laser measuring device was employed considering three possibilities: sample without instrumentation, sample with the accelerometers fixed and sample completely instrumented. When the sample is completely instrumented, accelerometer readings are also analysed. To take into consideration the effect of the glass layers, tests were realised both for laminated glass and monolithic samples. This paper presents in depth data analysis of the different configurations and establishes criteria for data acquisition when testing laminated glass.

Keywords: Viscoelasticity; laminated glass; damping identification

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1. Introduction.

Different laminated glass tests have been simulated with the FE method [1]. It has been shown that even quasi-static tests have to be simulated by means of transient analysis as the time dependency of the PVB layer is important. It is of primary importance to account for all environmental factors which affect the material properties during the tests like temperature variations.

To identify damping ratios a free-free test configuration has been used in [1]. Natural frequencies could be identified with reasonable accuracy. However, a quite big difference exists between experimentally and numerically obtained damping ratios.

This paper analyses the influence that external factors such as accelerometers and their connection cables exert over damping identification.

2. Material characterisation.

Glass may be considered a homogeneous, isotropic and linear elastic material within the range of time scales and temperatures considered throughout this paper.

PVB is both time and temperature dependent; thus, it is considered as a linear viscoelastic material. The time-dependent response is characterised by separated volumetric and deviatory terms, being the first characterised by the bulk modulus K whereas the shear modulus G reflects the deviatory behaviour. The shear modulus can be represented by a Prony series as shown in equation (1).

$$G(t) = G_0\left(\alpha_\infty + \sum_{i=1}^{n} \alpha_i e^{-\frac{t}{\tau_i}}\right) \quad (1)$$

The parameters of the Prony series have been obtained by means of testing PVB material. Since the bulk modulus is considered constant, the test has been carried out to determine the Prony series parameters of Young's modulus E and making the necessary transformations to determine the corresponding values of the shear modulus. The tests have been carried out at reference temperature of 20ºC. Material properties are presented in tables 1 and 2.

Table 1. Material properties.

Material	Young's modulus	Bulk modulus	Poisson's ratio	Density
PVB	E_0=1.19 GPa	K=2 GPa	ν=0.3908	ρ=1030 kg/m^3
Glass	E=72 GPa	-	ν=0.22	ρ=2500 kg/m^3

The temperature dependence has been characterized using one of the most commonly used shift functions: the WLF shift function [2]. WLF parameters are C_1=49.806; C_2=328.46 at reference temperature of 20ºC.

Table 2. Prony series parameters at a reference temperature of 20ºC.

α_i	$\tau_i(s)$	α_i	$\tau_i(s)$	α_i	$\tau_i(s)$
0.151	3.09 e-7	0.122	3.049 e-2	9.65 e-5	3007
0.191	3.08 e-6	0.054	0.304	2.75 e-4	3.00 e+4
0.141	3.07 e-5	0.0137	3.032	1.54 e-4	2.99 e+5
0.184	3.066 e-4	2.11 e-3	30.23		
0.139	3.057 e-3	9.46 e-4	301.5		

3. Experimental tests.

3.1. Test description.

To analyse the influence of the accelerometers and their connection cables a laser measuring device was employed considering three possibilities: sample without instrumentation, sample with the accelerometers fixed and sample completely instrumented. When the sample is completely instrumented, accelerometer readings are also analysed. To take into consideration the effect of the glass layers, tests were realised both for laminated glass and monolithic samples. Their dimensions appear in Table 3.

Table 3. Laminated and monolithic glass samples.

Sample	Length L (mm)	Width b (mm)	Thickness h (mm)
Monolithic glass	999	99	5.83
Laminated glass	996	99	2.8+0.38+2.8

Seven accelerometers were equidistantly spaced along each sample. The laser measuring device was situated in the centre of the beam, thus only symmetric modes will be identified. In order to eliminate supporting strings -another external factor- the free-free test configuration chosen in [1] was changed for a pinned-pinned configuration. Figure 1 shows this test configuration.

Operational Modal Analysis (OMA) is an appropriate technique for modal identification over a wide range of practical applications [3]. The main difference from classic modal analysis is that applied forces need not to be measured in order to estimate modal parameters. Tests are carried out measuring the structure's response under service conditions such as wind or traffic loading. When testing is done in a laboratory, random artificial loads are employed in order to use this method.

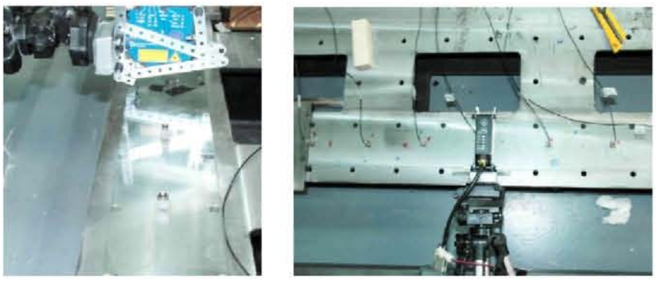

Fig. 1. Pinned-pinned test configuration: (a) sample with accelerometers fixed; (b) sample completely instrumented.

3.2. Data analysis.

Before ambient response data are used in an analysis, the data are usually preprocessed in order to bring the data into a form suitable for identification. Data from accelerometers (Figure 2(a)) were analysed using the stochastic subspace identification method (SSI). Individual responses from laser measurements are isolated (Figure 2(b)), evaluating the decay of motion with the logarithmic decrement.

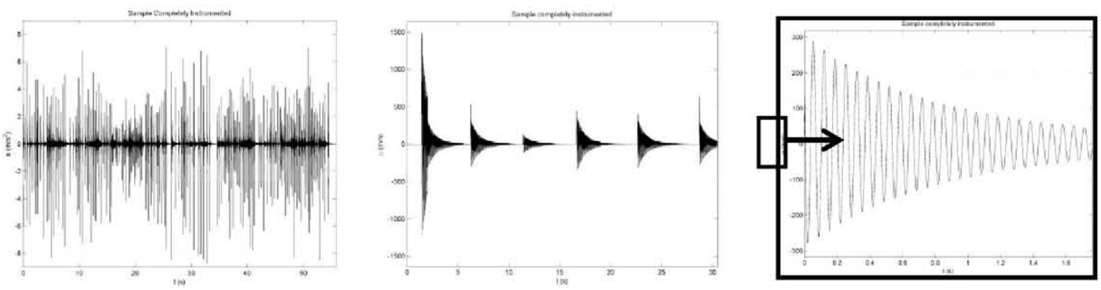

Fig. 2. Laminated glass completely instrumented: (a) acceleration signal used for OMA; (b) individual response isolated from laser measurements.

The power spectral density (PSD) of each isolated response is calculated, obtaining first mode natural frequencies. Decay of motion is evaluated then with the logarithmic decrement for each response. Figure 3 shows natural frequency and damping ratio identified for the isolated response from Figure 2. Each configuration has been analysed with this procedure.

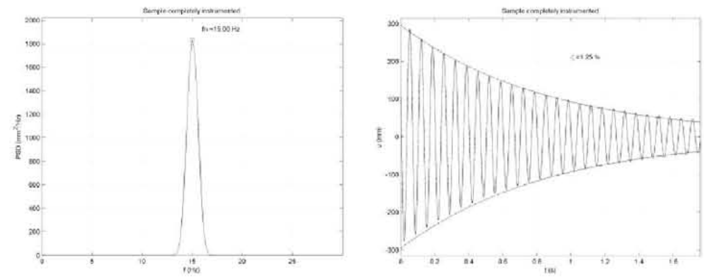

Fig. 3. Modal identification of the isolated individual response from Fig. 2: (a) natural frequency; (b) damping ratio.

4. FE model.

Two solid FE models have been developed to simulate the laminated glass sample without instrumentation and with accelerometers fixed. The glass elastic properties have been introduced in the model as well as the viscoelastic properties of PVB through the Prony series coefficients. Temperature dependence of PVB has also been introduced in the model through the WLF parameters.

PVB's slenderness strongly influences the model's mesh. In order to obtain well-shaped elements, three elements per glass layer and only one for PVB are selected (Figure 4). A high order three-dimensional 20-node solid element that exhibits quadratic displacement behaviour is chosen. Each node has three degrees of freedom: translations in the nodal directions x, y and z. Structural masses have been used to model accelerometers.

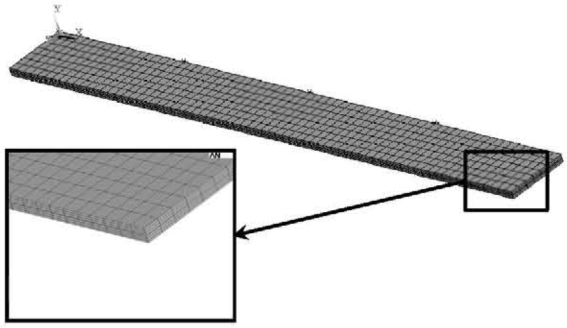

Fig. 5. FE model mesh.

A finite element modal analysis has been done to simulate monolithic glass with and without accelerometers, considering glass as a linear elastic material.

5. Results comparison.

Results obtained from the FE models for the first mode are presented together with test results in Tables 4 and 5. Theoretical results for laminated glass (RKU equations for composite beams with a viscoelastic layer [2], [4]) and monolithic glass are included. The same procedure that was used for laser measurements has been employed for FE models.

Table 4. Laminated and monolithic glass natural frequencies.

Sample	Configuration	Laser	Accelerometers	FE model	Beam theory
	Completely instrumented	14.98 Hz	15.04 Hz	-	-
Laminated glass	Accelerometers fixed	15.30 Hz	-	14.66 Hz	13.45 Hz
	No instrumentation	15.79 Hz	-	14.79 Hz	13.61 Hz
	Completely instrumented	14.72 Hz	14.69 Hz	-	-
Monolithic glass	Accelerometers fixed	14.84 Hz	-	14.03 Hz	14.06 Hz
	No instrumentation	15.20 Hz	-	14.22 Hz	14.22 Hz

Table 5. Laminated and monolithic glass damping ratios.

Sample	Configuration	Laser	Accelerometers	FE model	Beam theory
	Completely instrumented	1.20%	1.27%	-	-
Laminated glass	Accelerometers fixed	0.95%	-	0.18%	0.18%
	No instrumentation	0.86%	-	0.18%	0.18%
	Completely instrumented	0.53%	0.81%	-	-
Monolithic glass	Accelerometers fixed	0.35%	-	-	-
	No instrumentation	0.26%	-	-	-

6. Conclusions.

A pinned-pinned configuration has been chosen for testing the influence that accelerometers, connection cables and glass layers exert on modal identification of laminated glass samples. To this end three configurations were used: sample completely instrumented, sample with the accelerometers fixed and sample without instrumentation. Tests have been repeated for monolithic glass.

In order to measure displacements with a unique device for all configurations a laser measuring device has been placed in the centre of the sample, only identifying symmetric modes. Individual responses from laser measurements are isolated, evaluating the decay of motion by means of the logarithmic decrement. When accelerometer readings were available, they were also analysed employing the SSI method.

According to the laser measuring device, laminated glass is significantly influenced by the instrumentation. Removal of the connection cables leads to a 20.8% decrease of damping ratio and 2.1% increase of natural frequency. If all instrumentation is removed, damping ratio decreases 28.3% and frequency increases 5.4%. Monolithic glass is more influenced by the instrumentation. Removal of the connection cables leads to a 30.2% decrease of damping ratio and almost no variation of natural frequency. If all instrumentation is removed, damping ratio decreases 47.2% and frequency increases 3.1%.

Two 3d FE models have been developed to simulate the laminated glass sample in two of the configurations: without instrumentation and with accelerometers fixed. PVB's slenderness strongly influences the model's mesh. Removal of accelerometers has no effect on damping ratio and little effect on natural frequency (less than 1%). Theoretical results employing the RKU equations lead to the same damping ratios as those obtained with the FE model, but frequencies are not identified so precisely.

The 3d FE modal analysis employed to simulate the monolithic glass sample without instrumentation and with accelerometers fixed is not able to reproduce precisely test results, although frequency increases with the removal of accelerometers. This difference is thought to come from support conditions.

Acknowledgements

This work has been made under the sponsorship of the University State Secretary, belonging to Spanish Ministry of Science and Innovation, in its contract BIA2008-06816-C02-02. The presented results have been obtained in cooperation with Universidad de Oviedo.

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