Paper 173

©Civil-Comp Press, 2012
Proceedings of the Eleventh International Conference
on Computational Structures Technology,
B.H.V. Topping, (Editor),
Civil-Comp Press, Stirlingshire, Scotland

Measurement and Prediction of the Dynamic Behaviour of Laminated Glass

L. Hermanns[1], J. Fernández[2], A. Fraile[1] and M.S. Gómez[2]
[1] Mechanical Engineering Centre CEMIM
Foundation for the Promotion of Industrial Innovations, Madrid, Spain
[2] Department of Structural Mechanics and Industrial Constructions
University of Technology Madrid, Spain

Abstract

This paper reviews the results obtained from measurements taken at different points of a window pane during ambient vibration testing. Accelerations have been measured at several locations of the window pane and air temperatures have been monitored. Several methods to estimate parameters such as the shear transfer coefficient and structural damping values are presented.

Keywords: laminated glass, polyvinyl butyral, viscoelastic behaviour, operational modal analysis, finite element method, system identification.

1 Introduction

Laminated glass is usually composed of two glass layers and an interlayer of polyvinyl butyral (PVB). The static behaviour of laminated glass is nowadays well understood and several design codes like [1] are available. However, due to its complex nature, the dynamic response of laminated glass is an important research topic. In modern cities the number of buildings including structural glazing systems is increasing and there is clearly a need to understand the dynamic behaviour of both the whole building and that of its components. Wind loads may cause important vibrations of window panes and the maximum amplitude of these vibrations is influenced by the amount of damping of the window pane. If shock loads are excluded from the analysis, glass can be considered as a linear elastic material whereas PVB is considered to behave viscoelastically. The mechanical behaviour of the PVB layer is heavily influenced by its temperature. The time dependent viscoelastic properties raise the need for transient dynamic analyses in order to represent stress relaxation and creep. As a consequence, it is very important to take into account the correlation between PVB temperature and wind loads in the framework of a probabilistic design approach [2].

The failure of a glass panel usually doesn't lead to the collapse of a building however, falling glass pieces may injure pedestrians that walk by [3].

The PVB layer is generally almost ten times thinner than the glass layers requiring finer meshes to obtain well-shaped elements. However, this level of mesh density is usually prohibitive in terms of calculation times as models become more intricate and the number of degrees of freedom increases notoriously.

In order to gather experimental data for the calibration of numerical models several tests under laboratory conditions were carried out.

The remainder of the paper is organized as follows: The test setups and the excitation methods used are described in section 2. In section 3 the post processing of the experimental data and the obtained results are described. The numerical model and the corresponding results are presented in section 4, and section 5 concludes with a comparison between experimental and numerical results which is followed by a brief discussion of the findings.

2 Description of the measurements

2.1 Description of the test structure

Two panes of laminated glass were bought at the beginning of the tests in order to study one of them under laboratory conditions whereas the second one was installed in a window of an office building. The tests that are described in the present section refer to the former one.
Each of the glass layers is 6 mm thick. Between them a 0.38 mm thick PVB layer is located. The dimensions of the pane are 1015 x 472 mm. A photograph of the window pane is shown in Figure 1.

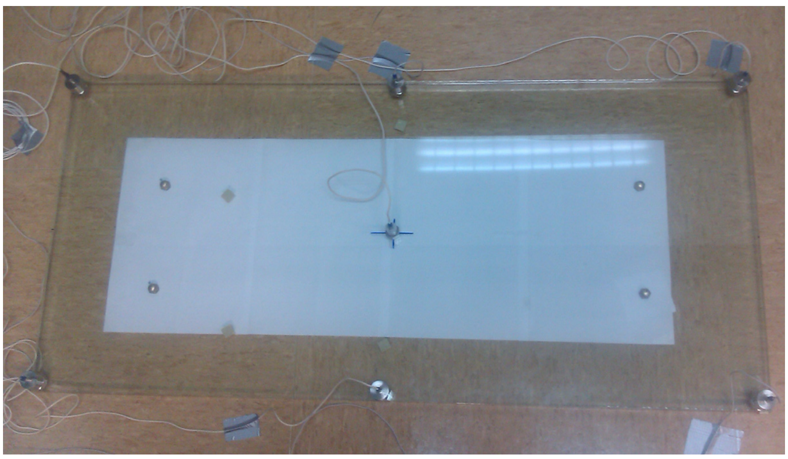

Figure 1: Photograph of the window pane.

The pane was manufactured by Saint-Gobain.

2.2 Description of the performed tests

Measurements were carried out subjecting the pane to different type of actions:

- Impulse force generated by the impact of a metallic marble.
- Ambient vibration test at different temperatures.
- Sound excitation generated by two loudspeakers.

The following measurement equipment was used in the tests: seven piezoelectric accelerometers (Endevco 7754-1000), three signal conditioners (Roga PA-3000), one acquisition system (NI DAQ-PAD 6015) and a laptop computer. The measurement setup is illustrated in Figure 2.

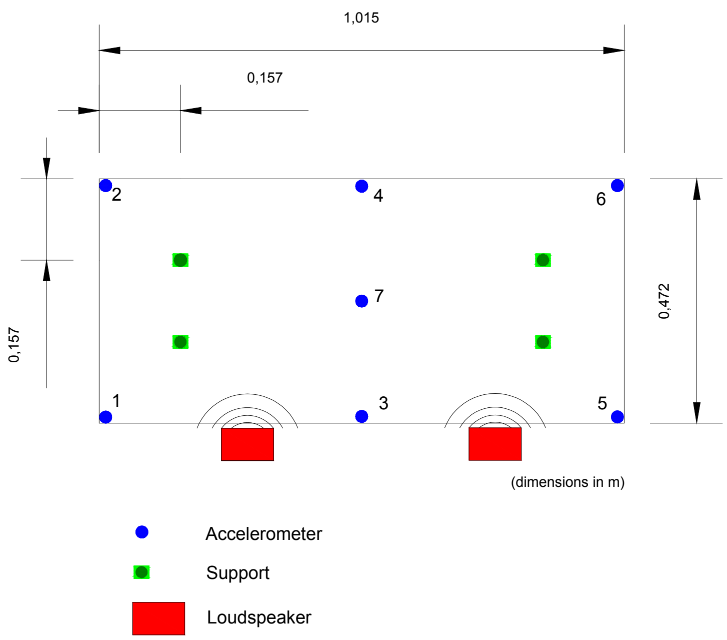

Figure 2: Measurement setup.

Four cap nuts were used as supports. A sampling frequency of 4096 Hz was used for all tests. The cutoff frequency of the anti-aliasing filter was set to 1 kHz.

3 Data treatment and results

The obtained acceleration time histories were first screened in order to identify abnormal incidents that could significantly influence the final results. Power spectral densities (PSD) were calculated in order to identify intermittent excitation sources like people walking by. The acceleration time histories corresponding to the ambient vibration test and the one with sound excitation were processed using the stochastic subspace identification method (SSI) and the enhanced frequency domain decomposition (EFDD) to estimate vibration mode shapes and damping values [4].

In stochastic subspace identification techniques a parametric model is fitted directly to the time series data measured by the accelerometers. The parameters of the model can be adjusted to change the way the model fits to the data. In general one looks for the set of parameters that minimizes the deviation between the predicted system response (predicted response) of the model and measured system response (measured response) [5].

The frequency domain decomposition method (FDD) is a technique where each mode is estimated as a decomposition of the system's response spectral densities into several single-degrees-of-freedom systems.

The enhanced frequency domain decomposition emerges as an improvement of the FDD method offering the possibility of estimating the damping ratio. The estimation of the eigenfrequencies and mode shapes is also improved [5].

3.1 Free vibration response

The free vibration response of a dynamic system may be used to estimate the fundamental frequency and the corresponding damping ratio. To this end the PSD of the acceleration signal is estimated and after that the frequency corresponding to the first peak is determined. In Figure 3 the acceleration time history and the PSD of the free vibration response are displayed. The first peak is located at 53.0 Hz.

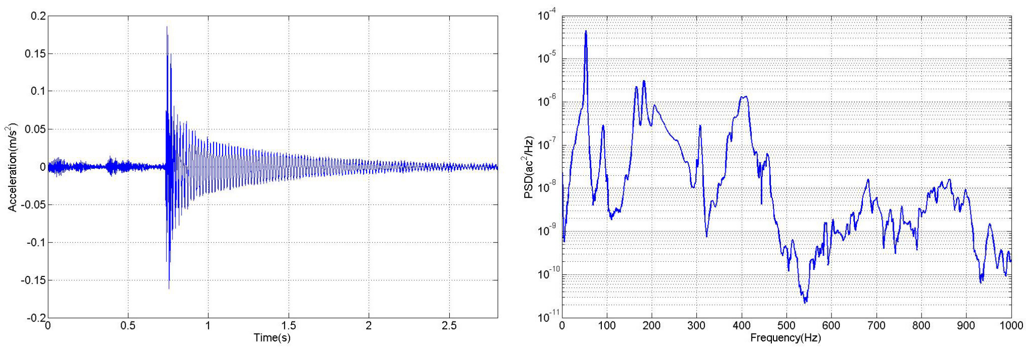

Figure 3: Acceleration time history and PSD of the free vibration response.

The additional peaks at higher frequencies correspond to higher modes. The damping ratio has been estimated using the logarithmic decrement method. The estimated value is 0.45%.

3.2 Ambient vibration excitation

Vibration data were collected during two days using the same measurement setup as before. In order to speed up processing, the data were decimated 4 times, i.e. lowpass filtered and resampled at 1024 Hz.

Figure 4 shows an acceleration time history and the corresponding PSD of ambient vibration data. The peaks that show up in the acceleration time history are caused by people working in the same building during the daytime.

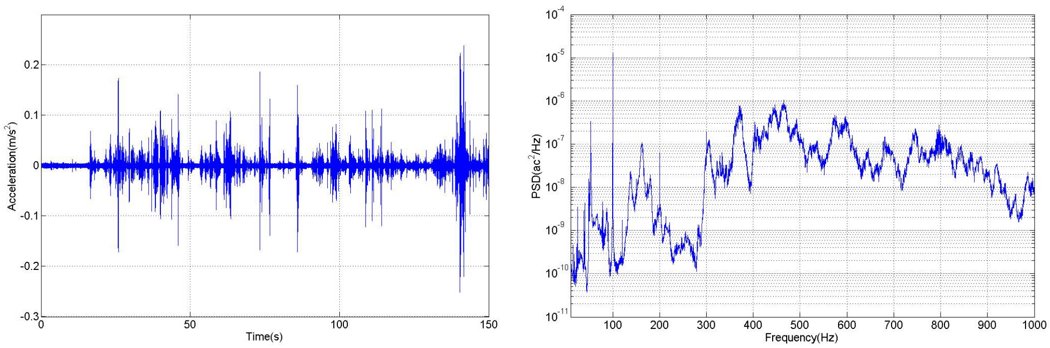

Figure 4: Acceleration time history and PSD of the ambient vibration response.

Figure 5 illustrates the Stabilization diagram of the estimated state space models obtained from the application of the SSI method.

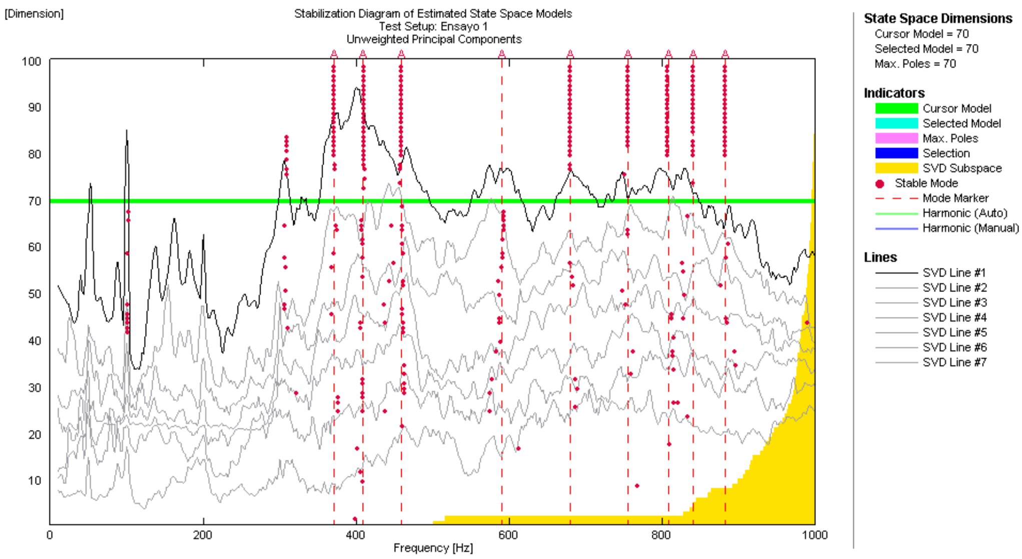

Figure 5: Ambient vibration. Stabilization diagram.

The results obtained using the SSI method and the EFDD are displayed in the modal assurance criterion (MAC) diagram, where the estimated frequencies are compared.

Furthermore, a comparison between results with and without decimation by a factor of 4 has been carried out i.e. using sampling frequencies f_s of 4096 Hz and 1024 Hz, respectively.

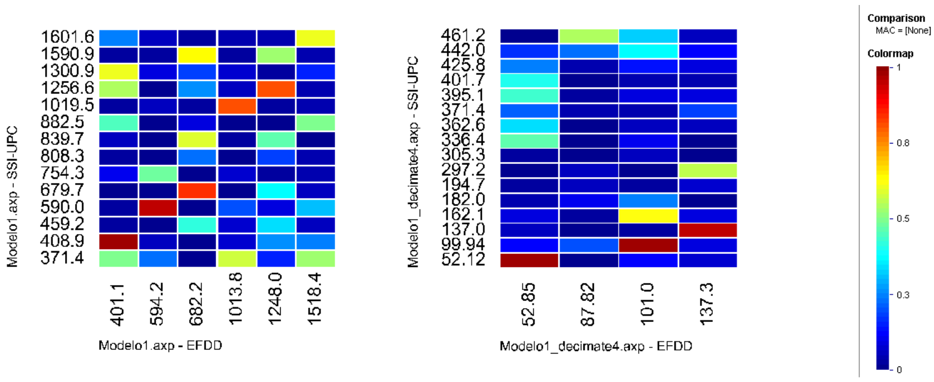

Figure 6: Ambient vibration. MAC: f_s= 4096 Hz (left), f_s=1024 Hz (right)

Deep red indicates that the two methods yield very similar results. It is important to note that neither of the methods is capable of identifying the fundamental mode if the raw acceleration time histories are used i.e. without decimation. Therefore it is recommended to vary the decimation factor progressively starting with a high value. Examination of the right diagram of Figure 6 confirms that the fundamental frequency is around 52 Hz. Both methods also identified modes at 100 Hz and 137 Hz.

3.3 Sound excitation

The sound excitation was generated by means of two loudspeakers of the same type that were placed next to the window pane (see Figure 2).

3.3.1 White noise excitation

During 5 minutes a white noise signal was reproduced by the loudspeakers. The frequency response of the loudspeakers is not flat i.e. they are not capable of reproducing all the audible frequencies at the same volume at which they were recorded. Besides that, part of the excitation energy was transmitted through the supports as the loudspeakers were placed on the floor. This should be remembered when interpreting the acceleration time histories as, in general, different response levels were measured at different frequencies.

The acceleration time history and the corresponding PSD of one of these tests are shown in Figure 7.

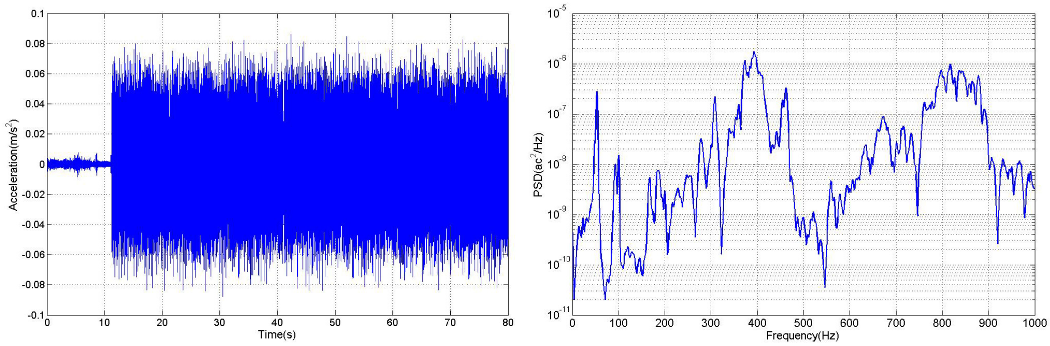

Figure 7: White noise excitation. Acceleration time history and PSD.

In terms of peak locations the PSD is similar to the one obtained from ambient vibration testing i.e. below 200 Hz there are peaks at 53 Hz, 86 Hz, 100 Hz, 166 Hz and 183 Hz.

In order to improve the identification of modes at lower frequencies the data were decimated 4 and 8 times, i.e. lowpass filtered and resampled at 1024 Hz and 512 Hz, respectively. Figure 8 illustrates the Stabilization diagram of the estimated state space models obtained from the application of the SSI method using the raw acceleration time histories i.e. without decimation.

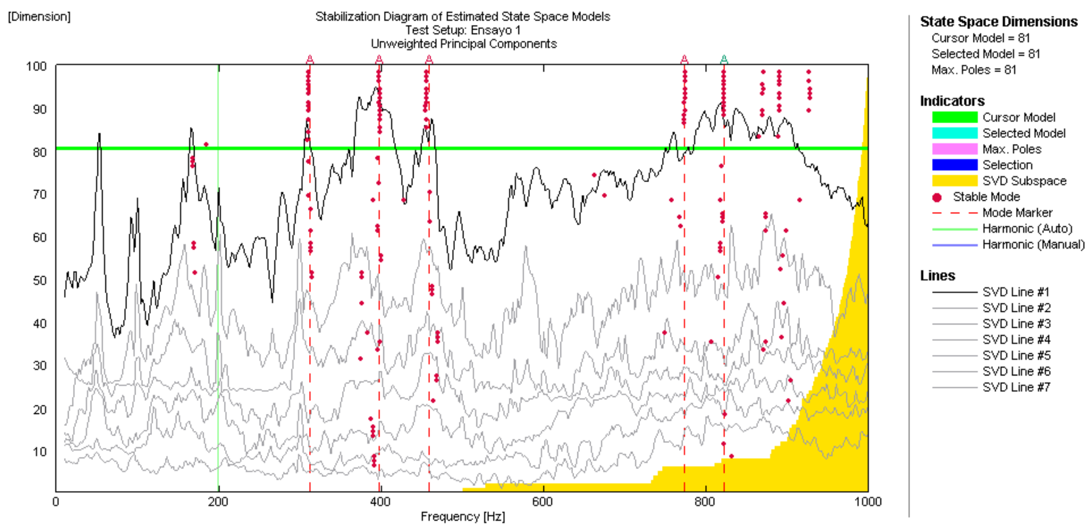

Figure 8: White noise excitation. Stabilization diagram.

The results obtained using the SSI method and the EFDD are displayed in the MAC diagram, where the estimated frequencies are compared. Furthermore, a comparison between results with and without decimation by factors of 8 and 4 has been carried out i.e. using sampling frequencies f_s of 4096 Hz, 1024 Hz and 512 Hz, respectively. The results are presented in Figure 9.

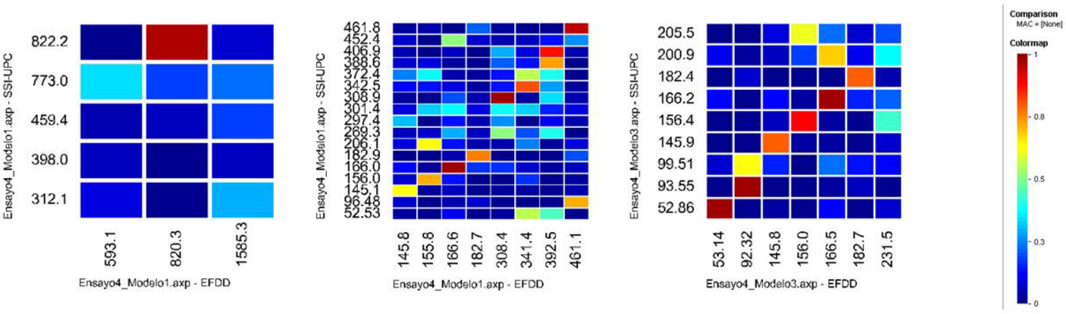

Figure 9: White noise excitation. MAC: f_s= 4096 Hz (left), f_s=1024 Hz (middle), f_s=512 Hz (right).

In this case a decimation factor of 4 is insufficient if the fundamental mode has to be identified.

3.3.2 Frequency sweep

During 10 minutes frequency sweeps were reproduced by the loudspeakers varying the excitation frequency from 20 Hz to 2000 Hz as indicated in Figure 10. At frequencies that are close to the modal frequencies of the window pane the response increases. In Figure 10 the results are displayed.

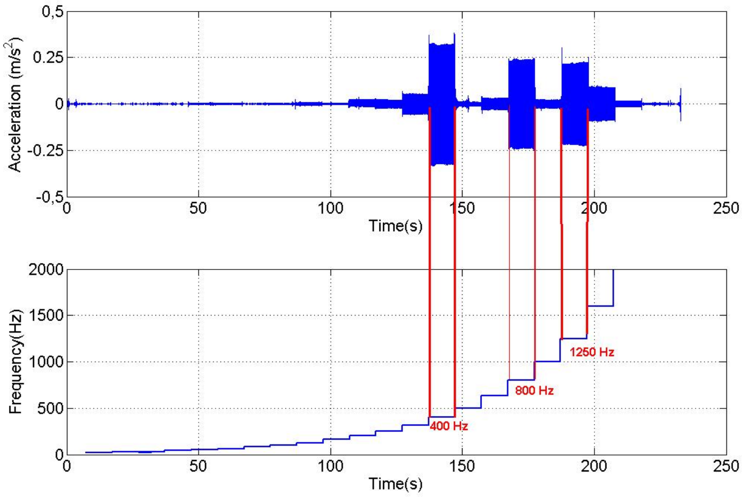

Figure 10: Frequency sweep. Acceleration time history (top) Variation of the excitation frequency with time (bottom).

Again, it should be reminded that the sound power level was not constant but varied with the excitation frequency. In particular at low frequencies the sound power level was quite small.

4 Finite Element Model

A 3d model has been set up for the numerical simulation of the tests. The commercial FEA software ANSYS has been used for the simulations. For the glass panes as well as for the PVB layer 20 node structural solid elements of type SOLID186 have been used. As the PVB layer is much smaller than the glass layers a compromise has to be found between acceptable element aspect ratios and the number of degrees of freedom (dof) of the model. To limit the number of dof the PVB layer as well as both glass layers have been discretized with only one element along their height. In Figure 11 a top view and a section through the model are displayed; PVB is marked in purple.

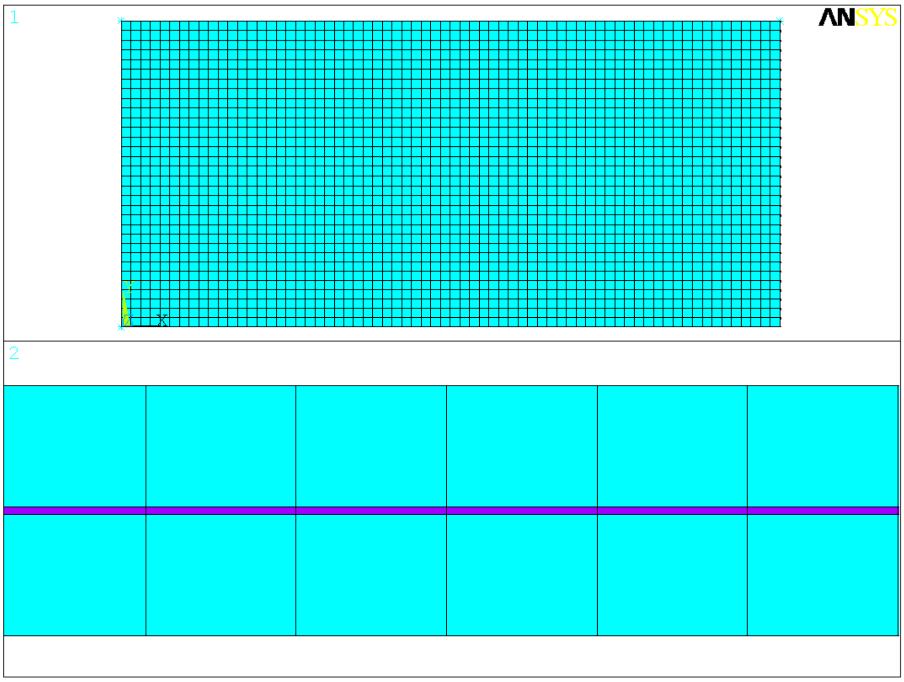

Figure 11: Top view and section through the model.

The material properties listed in Table 1 have been used for glass.

Young's modulus E	Poisson's ratio ν	Density ρ
72 GPa	0.22	2500 kg/m^3

Table 1: Material properties of glass

The viscoelastic behaviour of PVB has been defined by means of a Prony series as shown in equation (1).

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

The bulk modulus of PVB is considered to be constant. In the following tables the material properties are resumed.

Instantaneous shear modulus G_0	Bulk modulus K	Poisson's ratio ν	Density ρ
1.19 GPa	2 GPa	0.3908	1030 kg/m^3

Table 2: Material properties of PVB

α_i^G	τ_i^G [s]
2.342151953E-01	2.36600000000000E-07
2.137793134E-01	2.26430000000000E-06
1.745500419E-01	2.16668000000000E-05
1.195345045E-01	2.07327300000000E-04
1.362133454E-01	1.98389580000000E-03
6.840656310E-02	1.89837195000000E-02
4.143944180E-02	1.81653498300000E-01
7.251952800E-03	1.73822593210000E+00
2.825459600E-03	1.66329270788000E+01
2.712854000E-04	1.59158978189400E+02
4.293523000E-04	1.52297789909670E+03
9.804730000E-05	1.45732380763177E+04
5.274937000E-04	1.39449999999999E+05

Table 3: Prony series parameters (reference temperature 20ºC)

In order to estimate the fundamental vibration frequency and the corresponding damping ratio a transient dynamic analysis has been performed. The initially at rest window pane has been subjected to gravity loads. In Figure 3 the resulting displacement time history at the centre of the model and the estimated damping ratio are displayed. The estimated fundamental vibration frequency is 54.2 Hz. The agreement between experimental and predicted value is quite good.

The damping ratio has been estimated using the logarithmic decrement method. At the beginning the transient part of the response causes a variation of the estimated damping ratio however, after three tens of a second the estimated damping ratio converges to 0.4 % of critical damping. Taking into account that the model only accounts for the damping of the PVB layer, the agreement between experimental and predicted value is acceptable.

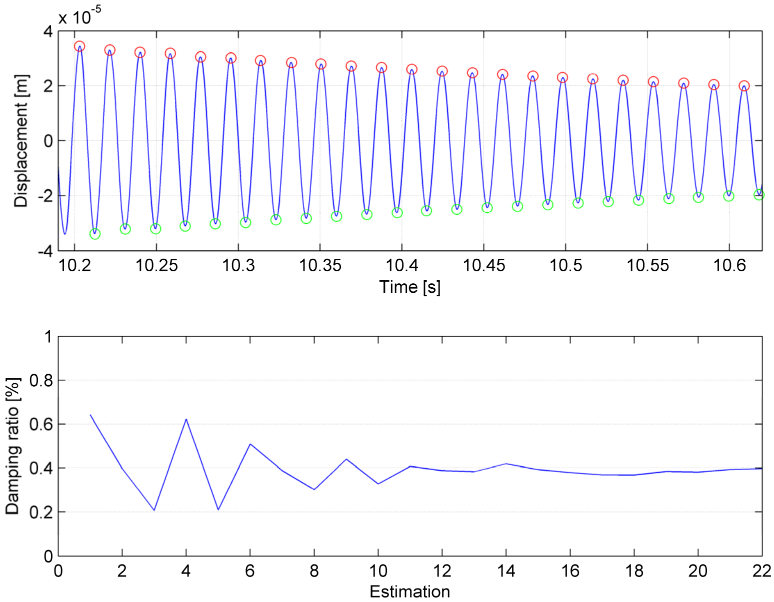

Figure 12: Displacement time history and estimated damping ratio.

5 Conclusions

In this paper experimental results and numerical predictions for the response of a window pane composed of laminated glass have been compared.
Measurements were carried out subjecting the pane to different type of actions. The test data were processed using the stochastic identification method and the enhanced frequency domain decomposition method to estimate vibration mode shapes and damping values.

A three-dimensional model has been set up for the numerical simulation of the tests. The agreement between experimental and predicted fundamental vibration frequency is reasonably good. In the future smaller elements will be used in order to reduce the difference between experimental and predicted values. The agreement between predicted and measured damping ratios is acceptable and can be improved taking into account the damping of the glass and the supports in the model.

Acknowledgements

The work described in this paper is funded by the Ministerio de Ciencia y Tecnología under contracts BIA 2008-06816-C02-02 and BIA 2011-28380-C02-02.

References

[1] ASTM E1300 - 09a Standard Practice for Determining Load Resistance of Glass in Buildings.

[2] Sedlacek, G., Wellershoff, F., Düster, H.: Bemessungsschubmodul für PVB Folien in Verbundsicherheitsglas unter Klimalasten in Deutschland – Bericht G 2003/10-06. RWTH Aachen, 2003.

[3] Byrnes, E. Falling glass injures pedestrian, Aug 15, 2011, Toronto National Post

[4] Brinker R., Ventura C., Andersen P., Damping Estimation by Frequency Domain Decomposition, IMAC XIX, 2001.

[5] Artemis Extractor Pro 2011. Structural Vibration Solutions A/S. Denmark