11th International Conference on Vibration Problems
Z. Dimitrovová *et al.* (eds.)
Lisbon, Portugal, 9-12 September 2013

TRANSIENT DYNAMIC ANALYSIS OF LAMINATED GLASS PANELS

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Keywords: Laminated glass, Viscoelasticity, Operational Modal Analysis, Finite Element Method, Transient dynamic analysis.

Abstract. *Commercial laminated glass is usually composed of two glass layers and an interlayer of polivinyl butiral (PVB). The modeling of laminated glass has attracted much attention [1] as the material's popularity is further increasing due to its multiple uses. While the static behaviour is well understood and several design codes like [2] are available, the dynamic response of laminated glass is an important research topic due to its complex nature.*

The viscoelastic behaviour of the PVB layer has to be taken into account when dealing with transient dynamic loads like wind however, the use of step-by-step time integration methods with 3d Finite Element models leads to very high computation times. An alternative approach would be to perform a mode superposition transient dynamic analysis which is computationally much cheaper. However, to follow this approach mode shapes as well as modal damping ratios have to be estimated. If experimental data is available these values can be estimated by means of modal data processing. However, the obtained damping values not only include the effects of material damping but also the contribution coming from the support conditions.

Different laminated glass tests have been simulated with Finite Element models in order to separate the different damping mechanisms.

Results are contrasted with data from different laboratory tests performed on glass beams.

1 INTRODUCTION

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. In some cases the wind induced vibrations can create a falling hazard as reported in [3]. Taking into consideration that the material's popularity is further increasing due to its multiple uses there is a clear need to study the dynamic behaviour of vibrating window panes during the design phase of a new construction project. As already mentioned damping plays an important role in the dynamic response of window panes and in the case of laminated glass the contribution of the polyvynil butiral (PVB) interlayer is very significant. A second source of damping comes from the support conditions of the glass panel. Obviously both sources have to be characterized adequately if good agreement between numerical predictions and experimental data is to be obtained.

2 OBJECTIVE

Finite element models are usually used to study the dynamic behaviour of laminated glass panels. The computer time needed to run 3D models that use solid elements is very large and consequently their use is normally limited to benchmark studies. For this reason these models are impractical for parametric studies even though they return reliable results that agree with those from different reference test cases.

Therefore, finite element shell models seem to be an attractive alternative to the time consuming solid element models. However, for the use of single layer elements an equivalent stiffness has to be estimated which is, due to the temperature and frequency dependent stiffness of the PVB layer, not trivial. In addition, the damping associated to the support conditions is a priori not known and has to be determined experimentally.

3 MATERIAL CHARACTERISATION

3.1 Glass

Even though there are many different types of glass, it may be considered a homogeneous, isotropic and linear elastic material within the range of time scales and temperatures considered throughout this paper. The most important properties of the particular type of plane glass used in the benchmark cases are listed in Table 1.

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

Table 1: Glass properties.

3.2 PVB

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. This is shown in Equation (1). Here ε_v and ε_d are, respectively, the volumetric and deviatory strain tensors.

$$\sigma(t) = \int_{-\infty}^{t} K(t-\tau)\frac{d\varepsilon_v(\tau)}{d\tau}d\tau + \int_{-\infty}^{t} 2G(t-\tau)\frac{d\varepsilon_d(\tau)}{d\tau}d\tau \tag{1}$$

The bulk modulus of PVB is considered to be constant throughout this study. The shear modulus can be represented by a Prony series as shown in equation (2).

$$G(\tau) = G_0\left[\alpha_\infty^G + \sum_{i=1}^{n_G}\alpha_i^G e^{-\frac{\tau}{\tau_i^G}}\right] \tag{2}$$

More information about the modelling of viscoelastic material behaviour can be found in standard text books like [4-8]. 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 the reference temperature of 20ºC. Results are shown in Table 2 and 3.

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

Table 2: PVB properties.

α_i^G	τ_i^G (s)
0.151	3.09 e-07
0.191	3.08 e-06
0.141	3.07 e-05
0.184	0.0003066
0.139	0.003057
0.122	0.03049
0.054	0.304

α_i^G	τ_i^G (s)
0.0137	3.032
0.00211	30.23
0.000946	301.5
9.65 e-05	3007
0.000275	3.00 e+04
0.000154	2.99 e+05

Table 3: Prony series parameters at a reference temperature of 20ºC.

Temperature dependence has been characterised using one of the most commonly used shift functions: the Williams-Landel-Ferry shift function (WLF from now on), which is shown in Equation (3).

$$\log_{10}(A(T)) = -\frac{C_1\left(T - T_{ref}\right)}{C_2 + T - T_{ref}} \tag{3}$$

WLF constants C_1 and C_2 are given in Table 4.

C_1	C_2	T_{ref}
49.806	328.46	20ºC

Table 4: WLF shift function constants.

4 INFLUENCE OF SUPPORT CONDITIONS ON DAMPING

As already mentioned the amount of damping that comes from the support conditions has to be determined. To this end, a monolithic glass beam has been instrumented with 7 accelerometers as can be seen in Figure 1.

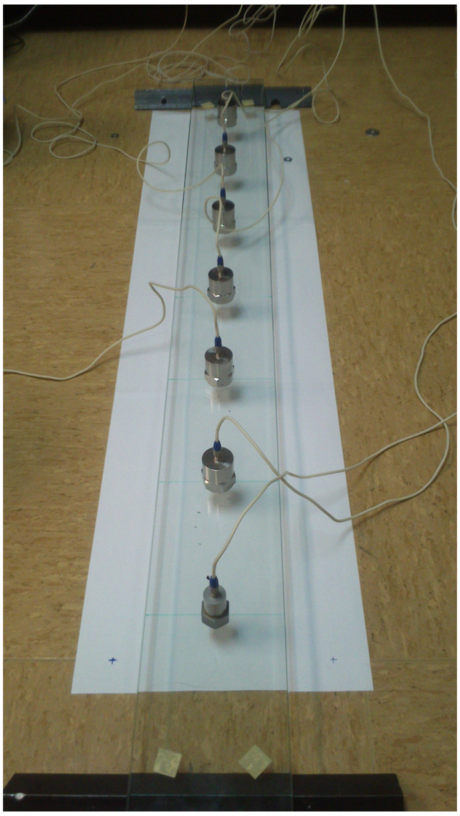

Figure 1: Monolithic glass beam instrumented with 7 accelerometers.

The modal frequencies and damping ratios have been estimated in two ways: Ambient vibration data has been analyzed by means of Artemis Extractor Software and free vibration data has been analyzed by traditional modal data processing techniques.

The mode shapes of the first two bending modes are displayed in Figure 2.

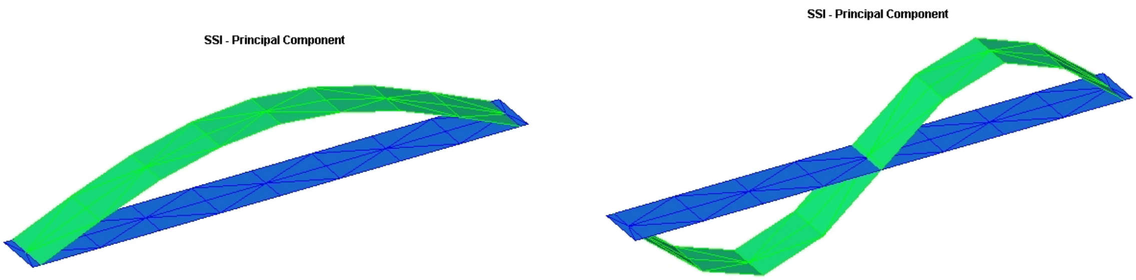

Figure 2: First two bending modes of the monolithic glass beam.

The corresponding frequencies and damping ratios are listed in Table 5.

	Frequency [Hz]	Damping ratio [%]
1^{st} mode	11.95	0.4075
2^{nd} mode	48.06	0.2140

Table 5: Frequencies and damping ratios of the first 2 bending modes estimated with SSI.

The free vibration response of a dynamic system may be used to estimate the fundamental frequency and the corresponding damping ratio. In Figure 3 several estimates of the damping ratio are displayed that have been obtained by means of the logarithmic decrement method.

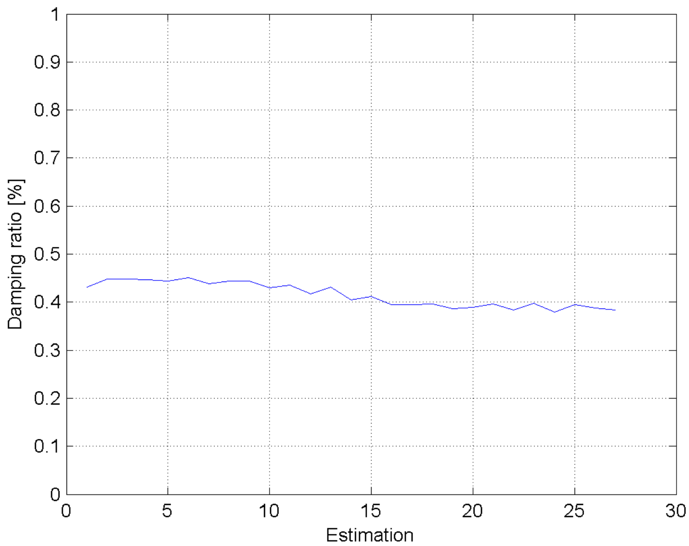

Figure 3: Estimated damping ratio of the fundamental mode; monolithic glass beam.

There is a slight amplitude dependence of the damping ratio observable. The values obtained by both methods are in good agreement. In order to study the damping contribution of a PVB layer the test was repeated with a laminated glass beam. The additional glass layer increases significantly the fundamental frequency and adds more damping. The results are listed in Table 6.

	Frequency [Hz]	Damping ratio [%]
1^{st} mode	27.62	0.5016

Table 6: Estimated damping ratio of the first mode; laminated glass beam with single PVB layer (0.38 mm).

The test was repeated with a laminated glass beam with two PVB layers. The additional PVB layer slightly increases the fundamental frequency as well as the damping ratio. The results obtained are listed in Table 7.

	Frequency [Hz]	Damping ratio [%]
1^{st} mode	28.78	0.5722

Table 7: Estimated damping ratio of the first mode; laminated glass beam with two PVB layers (0.76 mm).

As the mode shapes of all three tested beams are practically identical, it seems reasonable to think that the damping that comes from the support conditions is also practically identical. This is confirmed by numerical results obtained with Finite Element models. 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. The mass-loading effect of the accelerometers has been taken into account adding the corresponding point masses to the model.

The results obtained corresponding to both types of laminated glass beams are presented in Table 8.

	Frequency [Hz]	Damping ratio [%]
One PVB layer (0.38 mm)	28.13	0.128
Two PVB layers (0.76 mm)	29.19	0.251

Table 8: Frequencies and damping ratios of the fundamental mode; FE model results.

Taking into account that the FE model does not account for damping coming from the support conditions the agreement between numerically predicted and experimentally estimated damping values is acceptable.

The viscosity of the PVB layer is strongly temperature dependent. An increase of 3 ºC increases the damping value corresponding to the model with one PVB layer from 0.128 % to 0.2 %. It is therefore very important to monitor the temperature before and during the tests.

The influence of the support conditions on the damping values changes with mode number i.e. it has to be estimated for each mode that is thought to contribute significantly to the overall solution and will be used in the modal superposition.

5 CONCLUSIONS

In the present study experimental results and numerical predictions for the response of laminated glass beams have been compared in order to identify the contribution of the support conditions to the overall damping of the system.

Measurements have been carried out subjecting the beams to different type of actions. The test data has been processed using the Stochastic Subspace Identification Method to estimate vibration mode shapes and damping values.

A 3d model has been set up for the numerical simulation of the tests. The agreement between numerically predicted and experimentally estimated damping values is acceptable taking into account that the FE model does not account for damping that comes from the support conditions.

If mode superposition analysis is to be used, it is very important to consider the contribution of the support conditions to the overall damping of the system. In general, this amount changes with mode number.

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