Adhesion and Viscoelasticity Properties of PVB in Laminated Safety Glass

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Summary

In Compression Shear Tests (CST) specimens of Laminated Safety Glass (LSG) are inserted in a special test device with an angle of 45° with respect of the loading force so that the compression and the shear components acting in the plane of the plastic interlayer have always the same magnitude.

The CST procedure has been adopted in the present research in order to assess the shear viscoelastic properties and the ultimate shear stresses of PVB interlayers of different kinds.

Critical values of shear and normal stresses have been taken as measures of the adhesion properties of PVB to be implemented in calculations to model interfacial adhesion.

Different sets of specimens were prepared under different bond process conditions and tested at the Laboratory for Testing Materials and Structures of the University of Pisa. During the tests, creep shear movements in PVB were also measured and compared with FEM predictions.

Keywords: Adhesion; Polyvinylbutyral (PVB); Laminated Safety Glass (LSG); Viscoelasticity; Compression Shear Test (CST); Rheological Models.

1. Introduction

It is well known that adhesion is a requisite of fundamental importance for the safety and the structural integrity of laminated glass.

The level of adhesion depends on many factors: type of materials, autoclave temperature, pressure and time of bonding process, cleaning process etc. Surprisingly any national or international standard requires minimum adhesion properties in spite of the importance to know and model bonding mechanisms between glass and polymers in order to get high quality LSG and to avoid delamination phenomena between glass and PVB.

Furthermore, the high adhesion of PVB to glass ensures, in the phase of post-breakage, that the fragments remain attached to the plastic film. On the other hand, a Laminated Safety Glass with low PVB adhesion guarantees a higher impact resistance, since more energy is absorbed by elastic deformation of the plastic material. Therefore, the control of the adhesion properties should be such to satisfy at the same time the capacity to absorb impacts and the need for a sufficient bond strength [1].

Adhesion proprieties of PVB to glass are usually measured with the Compression Shear Test (CST) [2] that allows to reach the ultimate shear stress of PVB before glass collapses as it often happens in single or double shear lap tests. As known, in a CST test a small specimen of LSG is inserted in the interface plane of two metallic units which is inclined of 45° with respect of the compression loading force so that the compression and the shear components acting in the plane of the plastic interlayer have at any instant the same intensity (see Fig. 2).

The adhesion strength if given by the minimum shear force that causes the collapse of PVB before the collapse of glass.

Moreover, using the same test device, some specimens were submitted to a constant force and the time development of relative slip displacement between the two glass sheet was recorded allowing the deduction of some properties of the creep behaviour in laminated PVB [3].

2. Experimental tests

2.1 Test description

Four rectangular LSG panes each composed by two 500x150x6mm rectangular glass panes have been prepared under different laminating conditions of autoclave temperature and pressure, as indicated in Table 1. The 0.76 mm thick PVB foils have been previously stored under two different humidity conditions: 45% for panes S1 and 60% for panes R1 and R2.

For each of the four panes, 30 50x50mm specimens have been cut and labelled as indicated in Figure 1 in order to exactly specify their original position in the pane.

Therefore the generated test population consists of 120 specimens subdivided in four homogeneous families: S1, S2, R1, R2. With reference to Fig.1, for example, label S1-5B indicates a specimen cut from the central part of pane S1.

Table 1- Lamination characteristics and storage conditions of the specimens

Family name	Number of samples	Thickness (mm)	Dimensions (mm)	Pressure (bar)	Temperature (°)	Storage Humidity (%)
S1	30	6+0.76+6	50x50	9.4	146	45
S2	30	6+0.76+6	50x50	12	140	45
R1	30	6+0.76+6	50x50	9.4	146	60
R2	30	6+0.76+6	50x50	12	140	60

CST tests were performed at room conditions of 18°C temperature and 55% relative humidity with a test velocity of 5 mm/min.

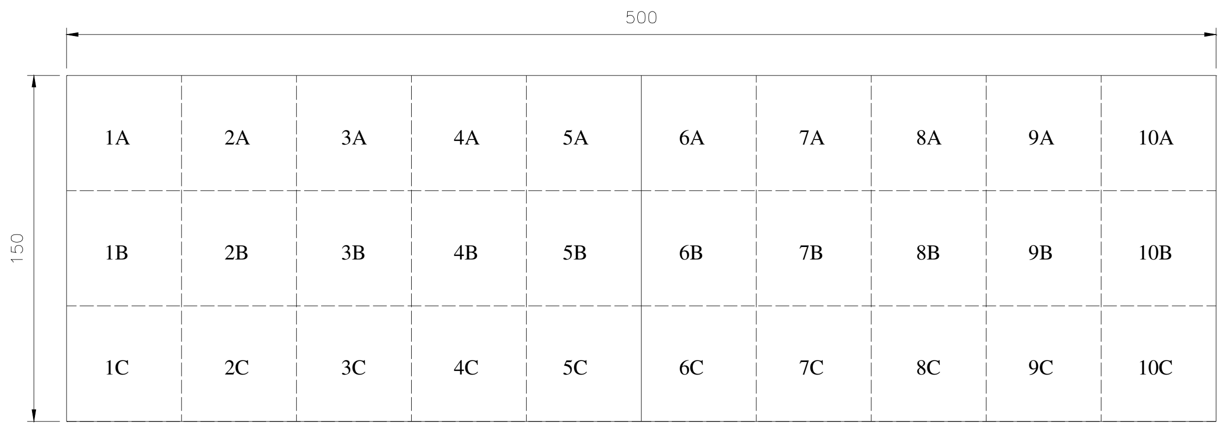

Fig. 1- Labelling and location of the specimens over the original LSG pane.

Fiogure 2 shows the test device where two inductive transducers measure the relative displacement between the two glass sheets from which the mean shear angle deformation γ can be estimated.

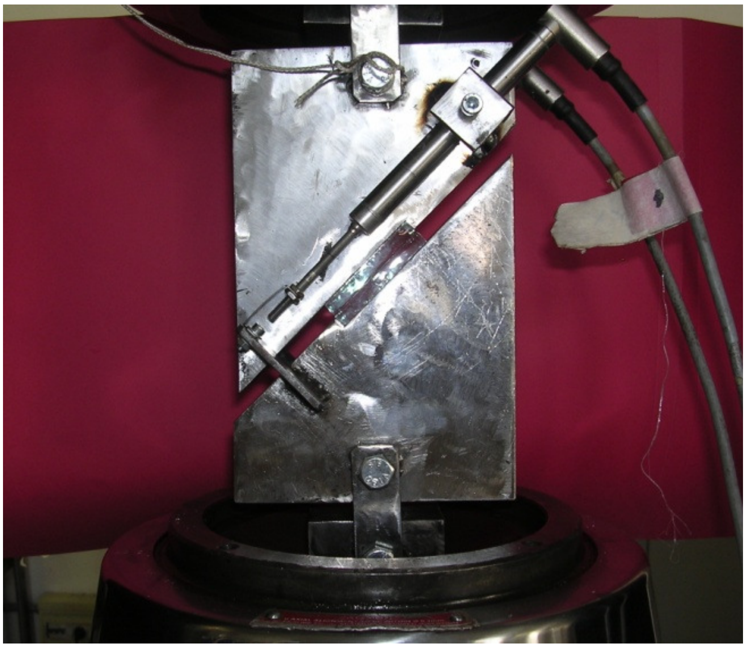

Fig. 2- CST test device

2.2 Preliminary results

For each of the tested specimen it was recorded the applied load and the relative displacement of the two steel units. Table 2 collects the test results obtained before 31/07/2010.

Figure 3 shows, for example, the results of test R1-5A, where each curve is referred to one of the two inductive transducers. The lack of coincidence between the curves indicates a imperfect parallelism between the two loaded edges of the specimen.

Table 2 - Adhesion stress (Θ=average)

Name	**Adhesion Shear Stress (MPa)**														**Θ**
	1A	2A	3A	4A	5A	6A	7A	8A	9A	10A	1B	2B	3B	4B	
R1	9.2	9.6	9.2	9.1	10.3	10.9	10.1	9.2	6.1	8.9	7.0	6.1	6.2	7.2	8.5
R2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
S1	12.5	12.1	14.9	10.8	-	-	-	-	-	-	-	-	-	-	12.6
S2	13.9	11.7	11.9	-	-	-	-	-	-	-	-	-	-	-	12.5

From the first test results of Table 2 it can be deduced that the most important parameter in the lamination process is the humidity storage of the PVB. Beside that these results show until now that the specimen's location on the main plate can be neglected.

The graph of Figure 3 indicates on the other hand that the stiffness in the ultimate limit state is constant with a linear behaviour of PVB and a shear modulus $G_{PVB} \cong 10$ MPa.

At present, a experimental programme is under execution to asses the creep properties of laminated PVB. For this purpose, specimens like those already described are loaded with the same test device of Figure 2 by means of a constant force of 280 N and the relative creep displacements between the two glass sheets were recorded along a sufficient time period.

The experimental results shall be later compared with those of the numerical model that contains literature available rheological constitutive laws of virgin PVB, in order to verify the correspondence between experimental data and numerical predictions.

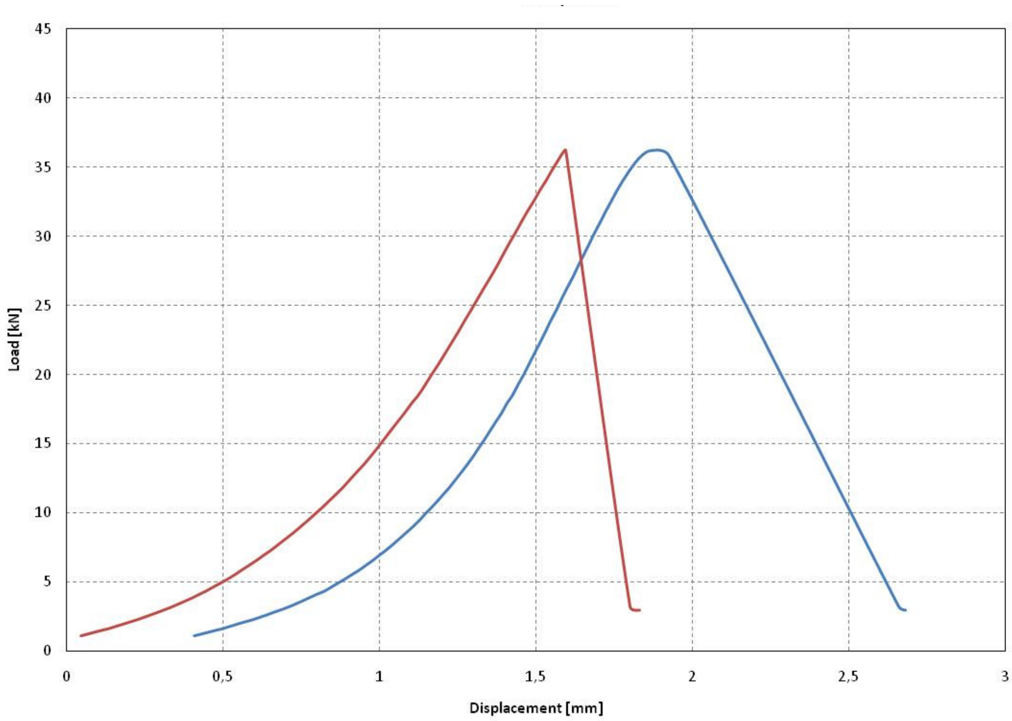

Fig. 3 - Load vs. Displacement for R1-5A specimen

3. Numerical model

3.1 Introduction

A numerical analysis was performed and compared with result of available creep tests of virgin PVB.

Soda–lime–silica float glass is modelled as a linear-elastic material with a Young's modulus of 70.000 MPa and Poisson ratio of 0.22.

In finite element method the rheological behaviour of PVB was taken into account by means of the shear relaxation modulus G(t) represented by a generalized Maxwell series:

$$G(t) = G_{\infty} + \sum_{i=1}^{n} G_i e^{-t/\tau_i} \qquad (1)$$

where G_{∞} is the long-time plateau modulus, G_i the moduli of individual terms in the generalized Maxwell series, and τ_i the associated relaxation times. The instantaneous or glassy modulus G_0 is given by:

$$G(0) = G_0 = G_\infty + \sum_{i=1}^{n} G_i \cong \sum_{i=1}^{n} G_i \qquad (2)$$

In particular, we have adopted the shear relaxation modulus published by two different PVB producers [4], [5] to study the sensibility of the FEM model when different G(t) properties of PVB are introduced.

Figure 4 shows that the two trends of the shear modulus versus time are quite similar and it could be concluded that apparently the differences are negligible.

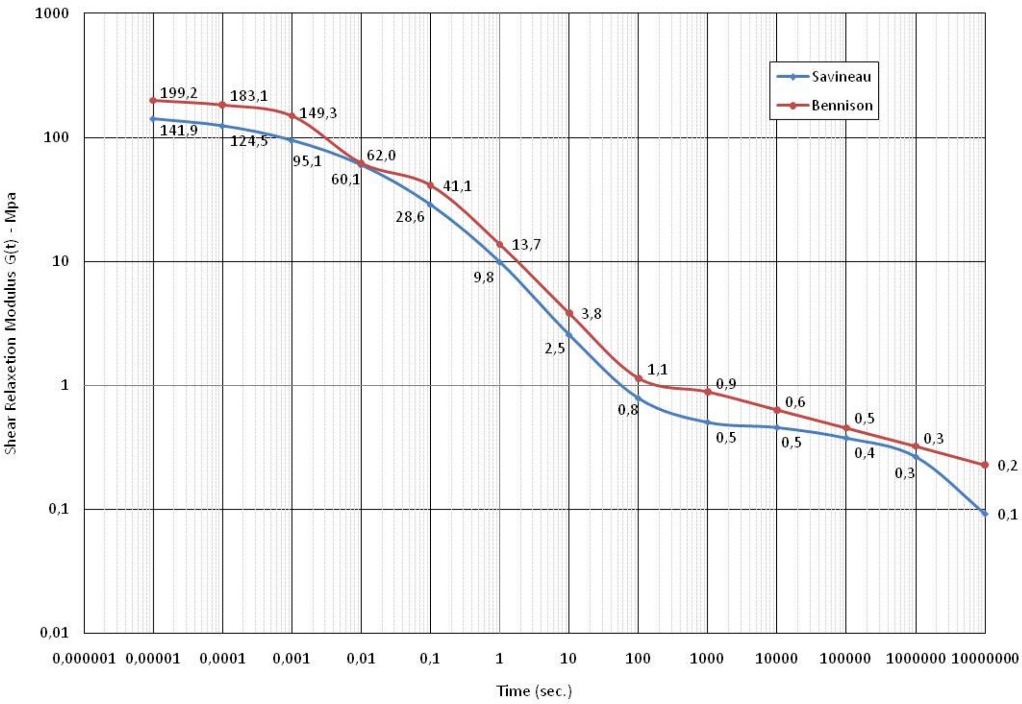

Fig. 4 – PVB shear relaxation modula G(t) vs. time

3.2 Numerical results

Figure 5 shows the finite element model of a specimen. In the numerical simulation, a constant shear force of 200 N was applied and than removed after 5 seconds. A linear quasi-static analysis was performed to include the creep behaviour of PVB.

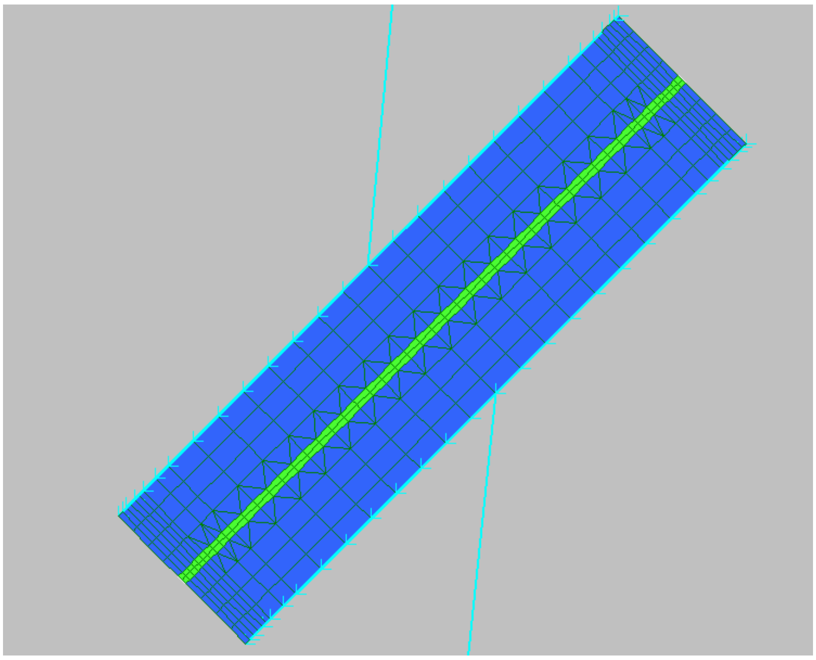

Fig. 5 - Finite Element Model

Figure 6 shows the time developments of the shear deformation obtained in the numerical simulation. The graph indicates that, in spite of the apparent coincidence of the two PVB constitutive curves, the two *γ(t)* curves are rather different from each other thus denouncing that the numerical model is very sensitive to the constitutive relaxation curve *G(t)*, and that it is very difficult to identify a unique, generally valid constitutive law for PVB.

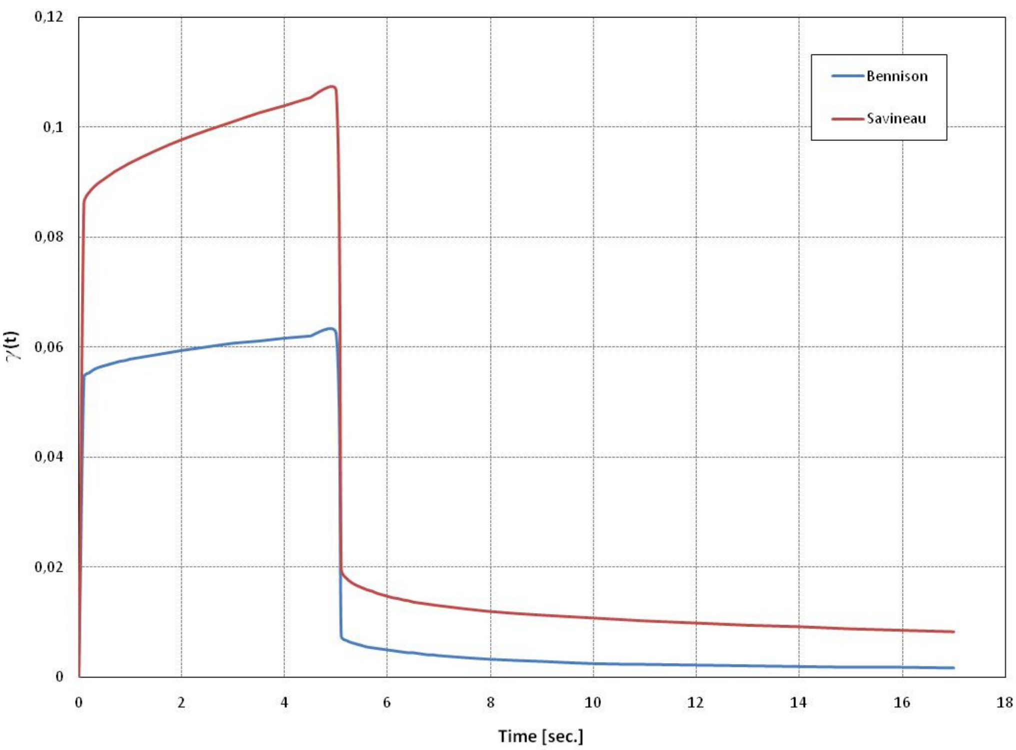

Fig. 6 – Shear deformation $\gamma(t)$ vs. time in numerical creep analysis

4. Conclusions

A Compression Shear Test (CST) programme is presently running at the University of Pisa over a population of 120 LSG specimens divided in 4 groups characterized by different lamination conditions.

The variable parameters are : autoclave temperature and pressure, storage humidity of the PVB. The first tests confirmed the importance of the influence of storage humidity on the adhesion property of PVB.

A numerical analysis was also performed to evaluate how sensitive numerical simulations are with respect to the implemented relaxation shear modulus *G(T,t)* law of PVB.

First numerical results indicate that this sensitivity is rather high and that it is difficult to assess a generally valid *G(T,t)* law to be implemented in numerical models of laminated safety glass panes.

5. References

[1] KELLER U., MORTELMANS H., "Adhesion in Laminated Safety Glass – What Makes it Work", *Glass Processing Days 1999*, Tampere, Finland.

[2] SCHNEIDER K., LAUKE B., BECKERT W., "Compression Shear Test (CST) – A Convenient Apparatus for the Estimation of Apparent Shear Strength of Composite Materials", *Applied Composite Materials*, 43-46, 2001

[3] FERRY J. D., *Viscoelastic Properties of Polymers,* 3rd ed. Wiley, New York, 1980.

[4] D'HAENE, P., SAVIENAU, G., Mechanical properties of laminated safety glass – FEM study, *Glass Performance Days 2007*, Tampere, FI.

[5] BENNISON, S., J., JAGOTA, A., SMITH, A., Fracture of Glass/Poly(vinyl butyral)(Butacite) Laminates in Biaxial Flexure, *Journal of American Society,* 1761-70, 1999.