Thermo-mechanical behaviour of laminated glass panes

Prof. Ing. Maurizio Froli, Dr. Ing. Leonardo Lani
Dipartimento di Ingegneria Strutturale, Università di Pisa, Via Diotisalvi 2, Pisa

Keywords

1=Laminated panes 2=Reinforced glass 3=Shear modulus 4=Prestress

Abstract

Tests on the mechanical behaviour of layered glass are traditionally performed on small specimens. This paper illustates the experimental results dealing with the mechanical and thermal behaviour of two full size layered glass plates (3000x2000mm) supported on the edge points and reinforced by pre-stressed stainless steel cables.

The two specimens, respectively thermally and chemically tempered, were submitted to three different stages of laboratory tests essentially in order to evidence how the Poly-Vinyl-Butyral (PVB) was able to transfer shear stress between the multiple layers under the action of thermo-mechanical load histories.

At a first stage it was studied the structural response of each plate under environmental temperature oscillations within a 70 hours time period.

In a second test step, different load patterns were applied to define both short and long time structural behaviour.

Finally, the failure modes of both plates were observed and analized.

The comparison between FEM predictions and experimental results allowed to estimate the actual PVB shear modulus in large layered glass plates submitted to 2D bending.

Introduction

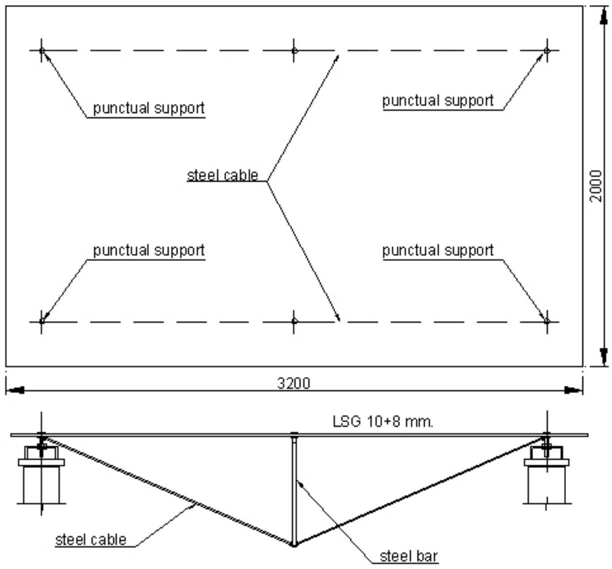
Until now glass was employed for structural applications mainly in form of slab shaped elements supported or reinforced by steel cables and subject in dominant measure to out of plane bending.

Such elements have already been used in Italy to rebuild the roof (about 200 m²) of the ruins of castle Schloß Juval in Südtirol [Schulte, D., 2005]. In this specific case the modules have been created from rectangular layered windowpanes, of about 3400x2000 mm, constituted by two thermally toughened 8 mm thick slabs.

Each element is punctually tied at the four edges by stud bindings and reinforced in its lower part with two longitudinal pre-stressed steel cables aiming at limiting out of plane displacements and at giving a further intermediate elastic support to the structure.

Figure 1

Specimens geometry .



In order to evaluate in advance the critical ultimate bearing ability of the standard element, some modules were tested at the University of Innsbruck under uniform loading [Böck, et Al.; 1998] actuated by the direct application of bags filled with sand on glass panels put in horizontal position and supported in the same way as those to be used in the construction.

Strains were monitored for long time periods by means of electric strain-gauges. This test campaign, although very significant, still doesn't explain many important aspects: indeed any comparison was performed between experimental results and numerical predictions. Furthermore, the determination of the PVB capacity to transfer shear actions, essential to calculate stresses in glass layered panels, appears to have been neglected, together with the evaluation of possible slow effects under long time loading [Behr, R.A.; 1986].

In this note we present the results of a research on the mechanical of a typical structural covering element, similar of those tested in Innsbruck, made of large rectangular laminated glass panes (3200x2000 mm) supported at the four edges by punctual devices and reinforced with a system of pre-stressed stainless steel cables (see Figure 1) .

Since the plates undergo 2D out of plane bending, special aim of the research was to analyze the ability of the interlayered material to transfer the shear actions between the glass slabs. The experimental and theoretical investigations have been conduced in the laboratory of the Department of Structural Engineering of the University of Pisa on two identical real scale specimens, named TT and CT, differing from each other only for the temper treatments, respectively thermal for specimen TT and chemical for specimen CT. F.E.M numerical simulations were opportunely validated and calibrated on the basis of the experimental results thus allowing to precisely define the mechanical properties to be assigned to the different elements of the model in order to obtain a realistic description of the mechanical behaviour. Specimens like these have been tested for the first time in Italy, not only in reason of their large dimensions but also because of the type of supports, the presence of metallic ropes and the diversity of the temper treatment. Due to the relevant dimensions of the laminated glass it was particularly demanding for the producer to assure a uniform rate of ionic superficial exchange in the chemically tempered sample.

Test phase 1: Experimental analysis of the specimens submitted to cables prestress and environmental temperature variations

In this phase each specimen has been placed in a vertical frame and continuously supported at the basis by a Teflon sheet as shown in Figure 2.

Stresses induced by the own weight could therefore be calculated in closed form schematizing the body as an heavy elastic plate resting on a stiff ground.

With this test configuration the steel cables have been tensioned until a maximum horizontal displacement of 3 mm was obtained at middle span. Both specimens have been monitored along 3 days during which glass superficial strains, temperatures, displacements as well as air temperature, have been measured at time intervals of thirty minutes by means of rosettes, strain gauges, thermocouples and inductive displacement transducers. In consideration of the symmetry of the experimental set up, only a quarter of each specimen was equipped, at both sides, with measuring instruments (Figures 3, 4)

The knowledge of the correlations ($\mu\varepsilon$-T) between strain and temperature in the measuring points allowed, in the subsequent Phase II, that purely thermal components could be subtracted from the mechanical measured strains.

In both phases strain and movements measurement have been performed on short and on long time periods.

In figure 6 is reproduced as example the $\mu\varepsilon$-T correlation measured for strain-gauge n.8 in specimen TT compared with the corresponding one of specimen CT.

The analysis of graphs in figure 6 shows that the two specimens reacted differently to thermal variations and in particular it can be observed that the two $\mu\varepsilon$-T equations have almost the same slope but differ from each other mostly for in the constant term.

This result can be explained recalling that the interface material PVB has thermoplastic properties

Figure 2

Test set up for test phase 1

Figure 3

Strain gauges in the thermally tempered specimen glass plate TT

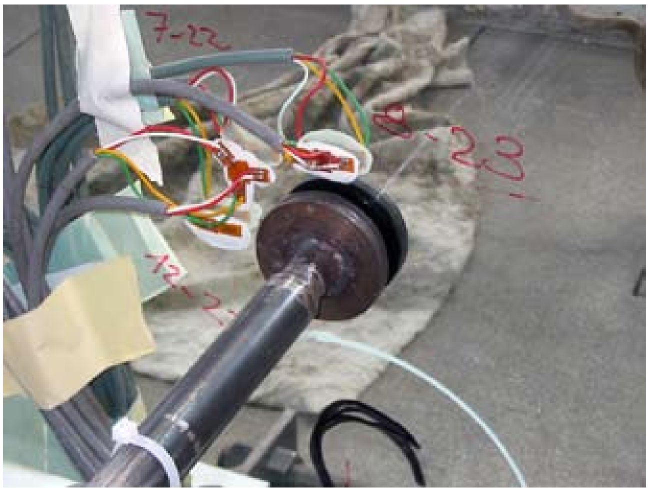
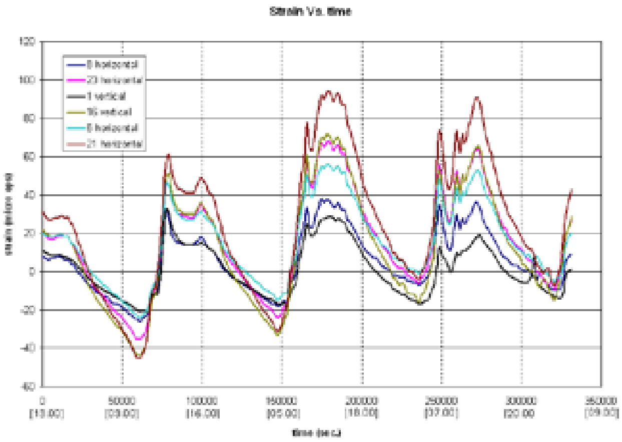


Figure 4

Strain versus time (sideral time) in thermally tempered specimen TT.



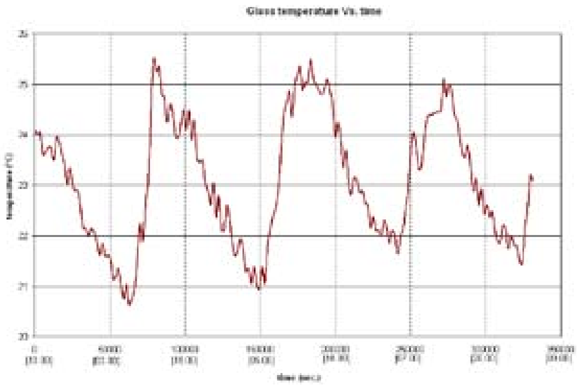


Figure 5

Glass Temperature versus time (sideral time) in thermally tempered specimen TT.

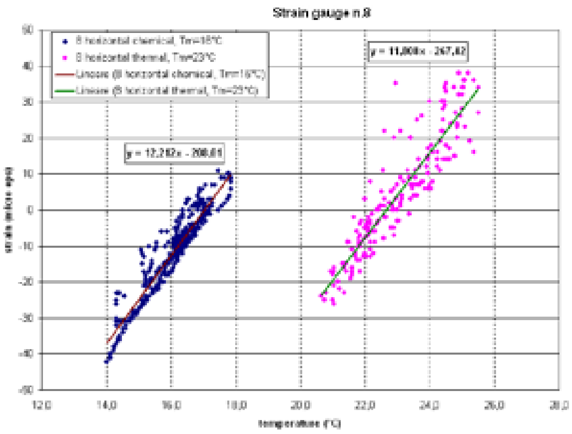


Figure 6

Correlations $\mu\varepsilon$-T found for the thermally (TT) and the chemically (CT) tempered specimen at the location of strain-gauge n.8.

[Albrecht, G., et Al; 2004] that is, its mechanical characteristics depend directly on the material temperature. Since the measures of the thermal deformations on the two specimens have been performed under different medium environmental temperatures (respectively equal to 23°C and 16°C), the PVB found itself, in the two cases, also in different states of mechanical and physical consistence and therefore also the $\mu\varepsilon$-T correlations resulted consequently defined by different equations.

Obviously found correlations could be used to correct Phase II experimental strains only within temperatures ranges not exceeding those of Figure 6.

Test phase 2: Horizontal positioning of the glass plates on 4 punctual supports and application of vertical loads

In this phase the two specimens have been placed in horizontal position on their punctual supports as shown in Figure 7 and submitted to load cycles through direct application of steel cylindrical weights (Figure 8) until collapse was reached.

Principal strains and strain directions have been deduced at the points where strain-gauge rosettes have been placed and correlated principal stresses have been calculated assuming the glass being a linear isotropic elastic material.

Punctual temperature measurements and the use of $\mu\varepsilon$-T correlations defined in Phase I permitted to separate the mechanical from the thermal deformations assuming, for the present ranges of strains and temperatures, the validity of the superposition principle:

$$\varepsilon_{tot} = \varepsilon^{T} + \varepsilon_{mec} \qquad (1)$$

being:
ε_{tot}=measured strain; ε^{T}= thermal strain;
ε_{mec}= mechanical strain;

Specimen TT was submitted to increasing loading steps. Each load level was maintained for about 1000 seconds in order to evidence delayed deformations.

At last the intensity of the distributed load reached the value of 350 daN/m^2 which induced a maximum tensile stress of about 50 MPa near the middle holes without causing any crack.

In order to bring to collapse TT specimen, two concentrated forces of 6.5 KN were applied symmetrically across one of the middle holes: the maximum tension stress measured by strain-gauge n°23 near the hole reached about 100 MPa before the specimen collapsed with a sudden and total lost of residual bearing capacity (Figure 10).

Chemically tempered specimen CT underwent a premature cracking during the long term charge programme. The evidenced cracking pattern was, as typically for chemically tempered glass, characterized by few isolated cracks that

Figure 7

Positioning of a specimen glass plate for Phase 2

Figure 8

Load application with cylindrical steel weights

Figure 9

Maximum principal tension stresses versus time in TT specimen.

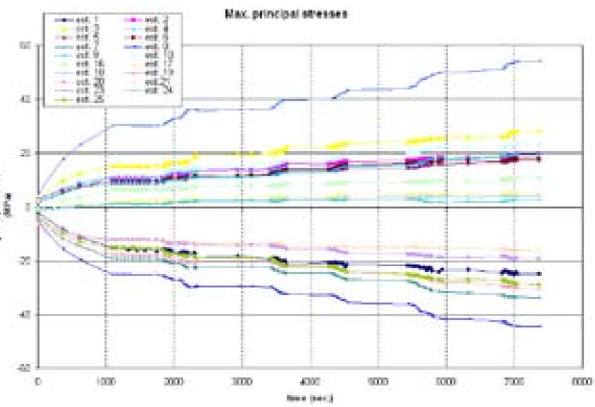
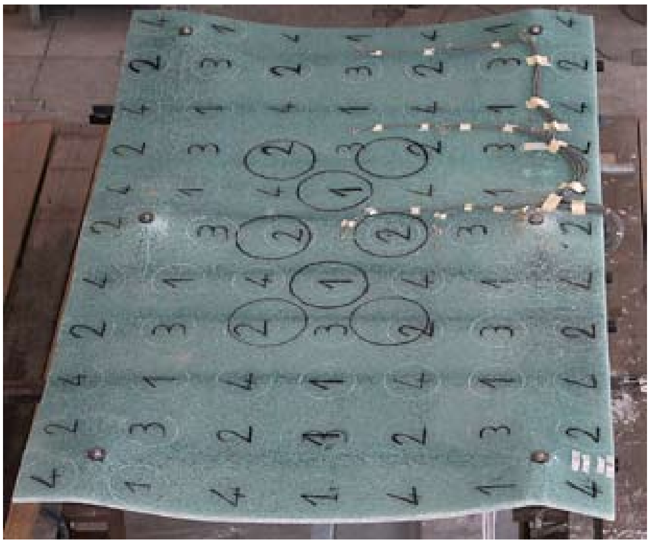


Figure 10

Specimen TT after collapse.



not compromised the residual bearing capacity of the structure thanks to the action of mutual connection performed by PVB. Despite the premature damage we still submitted it to the same final load sequence applied to the specimen TT with the aim to test the post cracking structural behaviour of the plate [Kott, A., Vogel, T., 2003].

During the application of the load, strain measurements have been performed with a scanning of 4 seconds and at the same time the vertical displacement of the centre of the plate was measured by a inductive movement transducer.

Figure 11 shows the time progressions of the applied load together with the strains measured at both sides in the centre of the plate. Figure 12 contains the time distributions of principal strains at all the measuring points.

The peaks that can be observed in the strain-time curves of these two figures correspond to the elastic impulses induced by the starting of new cracks and the propagation of already initiated cracks.

The diagrams also demonstrate that the presence of numerous cracks in the 8 mm thick slab, where strain-gauge n°10 was glued, does not compromise significantly the capacity of this layer to transfer loads.

The final uniform charge of 350 daN/m^2 was kept steady until the total collapse was reached. This happened in a gradual way after about 15 minutes during which the number of new cracks increased and old cracks propagated finally drawing a pattern similar to a spider web. This experiment enlightened the fact that, due to the different form of breaking, chemically tempered layered glass structures have a better overall apparent “ductility” than thermally tempered glass structures.

The photo of Figure 13 shows the collapsed specimen CT where it can be observed that the cracks reproduce with a good approximation the typical distribution of the isostatic lines.

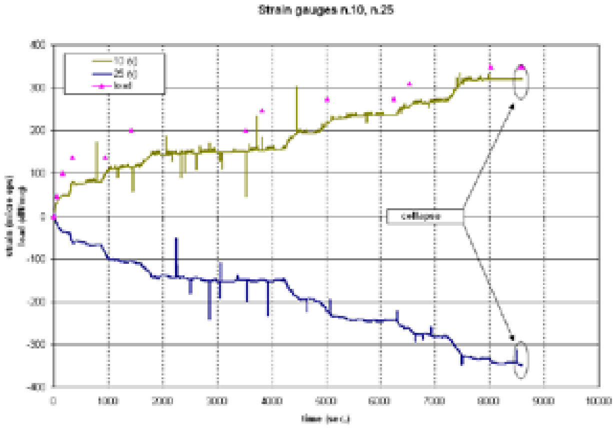


Figure 11

Strains versus time measured by strain-gauges n°10(v) and n°25(v) and loading history in specimen CT.

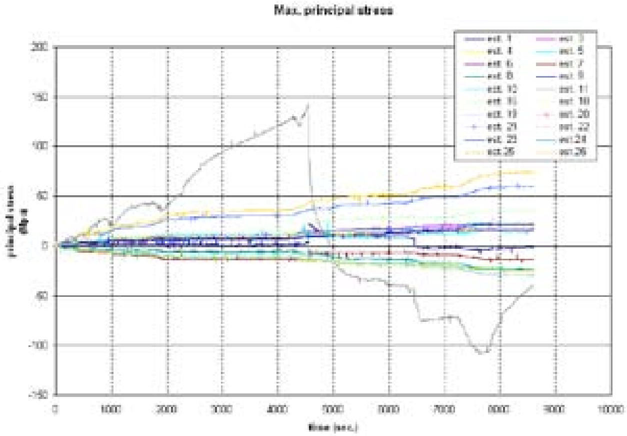


Figure 12

Principal stresses-time curves in specimen CT.

Figure 13

View of the collapsed specimen CT.

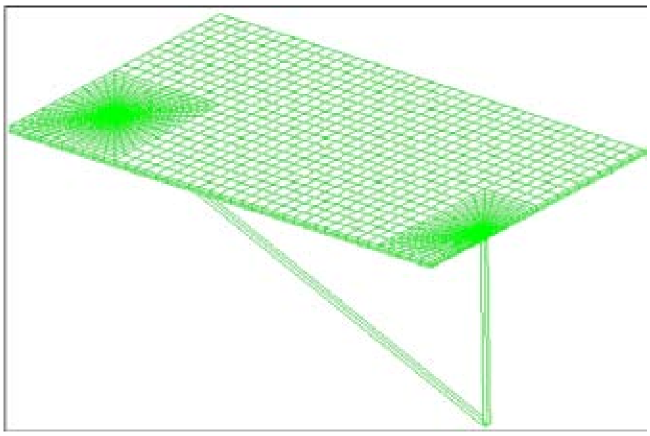


Figure 14

F.E. Model of the layered glass specimens.

Finite Elements modelling and assessment of the in situ PVB mechanical characteristics

Presently, the Finite Elements arrangement mostly able to reproduce the many physical aspects of layered glass structures is that to use *solid* elements to describe single layers of glass and *interfaces* elements to simulate the behaviour of the plastic interlayer material. Assigning convenient values of shear modulus G to the interface elements it is possible to gather the range of behaviours that characterises layered glass, including temperature dependant phenomena and long time loading effects.

This kind of modelling can describe the whole 3D behaviour of the structure and therefore also the important aspect of the stress distributions over the thickness of the glass elements that cannot be performed with other simplified models. Figure 14 reproduces the F.E. meshing adopted for the two specimens where solid elements and interface elements can be distinguished.

The number of mesh knots in each layered plate resulted about 35000 and the number of elements round 7500.

The estimation of the in situ mechanical properties of the interlayer material can be performed in a layered glass by comparing the numerical results of the modelled structure with the experimental data obtained from laboratory experiences [Schuler, C. et Al. ; 2004]. This kind of approach does not represent a direct method to measure the shear modulus of the interface material, but it allows a estimation of it sufficiently accurate for use in current structural analysis and design.

By means of the numerical model we can calculate movements, stresses and deformations that depend on the characteristics assigned to the shear modulus G of the PVB; on the other hand, from experiments we obtain corresponding quantities that depend on actual temperature and on test duration. A process of structural identification can be performed by calibrating conveniently the numerical model until the output data are optimally close to the experimental results. When the model is sufficiently sound, it permits good estimations of the in situ values of G [Vallabhan, C.V.G. e Al.; 1993].

In our case the first calibration was performed by balancing the maximum principal tension stress measured by strain –gauge n° 23 under load condition LC5 (200 daN/m^2) on the upper surface near a middle hole.

Figure 15 illustrate a comparison between calculated and measured stresses.

Load condition LC5 was maintained constant for ten minutes without that any slow deflection due to the viscosity of the interface material was noticed. The estimated in situ shear modulus of PVB resulted then just function of the glass temperature and G=0,912 MPa provided the best fit between predictions and measurements. In order to verify if the estimated G could be assumed uniform all over the layered glass plate, comparisons were performed between theoretical and experimental stresses also for the other measurement points. Figure 16 reproduces the result of such comparison for strain-gauges n° 10 and n° 25 placed at the centre of the plate. The hypothesis of uniformity for G appeared to be completely validated by the experimental data. It obviously represents a remarkable exemplification that appears important, under a practice point of view, since it would be extremely complex to assign G values also in dependence of the location of the point over the domain of the layered glass plate.

In spite of this result, the shear connection performances of the PVB interlayer are very different depending on weather the point is situated. Near the contour, where relative tangential displacements are maximum, the two glass slabs almost reacted as just layered with a very poor inter-connection degree. Near the central part of the plate the behaviour was on the contrary almost monolithic.

Figure 15

Calculated stresses compared with measured stresses at strain-gauges n° 8 and n° 23.

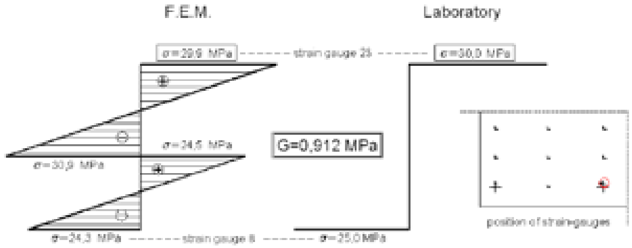
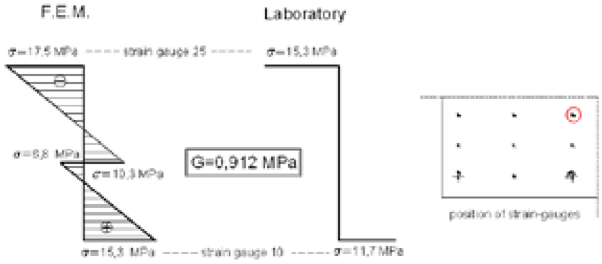


Figure 16

Calculated stresses compared with measured stresses at strain-gauges n° 10 and n° 25.



Conclusions

Objective of the present research was the analysis of the thermo-mechanical behaviour of two rectangular, layered glass roofing plates respectively made by thermally and chemically tempered glass panes laminated by means of PVB and reinforced with pre-stressed metallic cables.

Of particular interest was to investigate the real in situ connection performances exerted by the interface material and to evaluate long term effects.

The plates were punctually supported on four fix bearings and on two elastic bearings fixed at the plate through cylindrical holes of 30mm diameter and a system of steel struts and pretensioned steel cables

Although the examined type of layered plate is under many aspects non conventional, the results of this specific research can be generally used and extended to analyze more usual structures of similar shape subjected to out of plane bending loads.

Together with the experimental approach, the problem of numerical modelling the layered have been also faced and solved. Numerous numerical analyses performed have shown how the connection grade between the two layers of the glass depends on the position of the investigated area, in particular it was detected how nearby the holes or the borders of the plate the interlayer material is poorly able to transfer the shear efforts also for high values of its shear modulus. This implies that the general assumption of monolithic behaviour for layered glass subjected to short term loads, can be accepted just in the central parts of a plate.

Structural identification and calibration procedures based on best fit comparisons between theoretical and experimental results allowed to estimate the in situ mechanical characteristics of the plastic material that confirmed to be highly dependant on temperature but fairly uniform all over the plate surface.

Special thanks

The authors want to express their best thanks to the Society Roberglass s.r.l. (Pisa) that supplied, tempered and stratified the specimens. The research was conducted with the financial support of the Italian Ministry of University and Research (MIUR).

References

Behr, R.A., Minor, J., Linden, M., (1986), *Load Duration and Interlayer Thickness Effects on Laminated Glass*, Journal of Structural Engineering, ASCE, Vol. 112, No. 6.

Böck, H., Unterweger, R., Bergmeister, K., (1998), *Experimentelle Untersuchungen an Glasplatten,* Proceedings of Darmstädter Statik Seminar. Glas im Bauwesen.

Kott, A., Vogel, T.,(2003), *Remaining Structural Capacity of Broken Laminated Safety Glass*, Glass Processing Days, Tampere (Finland).

Schuler, C., (2003), *Einfluss des Materialverhaltens von Polyvinylbutyral auf das Tragverhalten von Verbundsicherheitsglas in Abhängigkeit von Temperatur und Belastung*, TU München.

Schuler, C., Sackmann,V., Gräf, H., Bucak,Ö., Albrecht, G., (2004), *Time and Temperature Dependent Mechanical and Durability of Laminated Safety Glass*, Structural Engineering International,Vol.14, n°2, IABSE.

Schulter, D., 2005, *Point supported bottom and or rear trussed glass panes*, Glass Processing Days 2005, Tampere (Finland).

Vallabhan, C.V.G., Das, Y.C., Magdi, M., Asik, M., Bailey, J.R., (1993), *Analysis of Laminated Glass Units*, Journal of Structural Engineering, ASCE, Vol. 199, No. 5.