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Effects of Interlayer Weathering on the Structural Behaviour of Laminated Glass Structures

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Many studies reported in the literature are able to demonstrate significant influence of weathering on physical and mechanical properties of PVB. In this paper, the results of these researches are compared and discussed. The effects of rheological parameters modifications on the coupling capability of laminated glass structural elements and on the mechanical response to loads are then evaluated through numerical analysis. Real structures are often exposed to direct sunlight or to temperature or humidity levels that can induce damage phenomena in the interlayer; the modification of mechanical coupling capability and of adhesion properties of interlayer that effectively take place in laminated glass structures have to be taken into account in the design process as they probably affect the behavior of the structure not only in the serviceability state but especially in the ultimate limit state.

Keywords: Laminated glass, Poly-vinyl butyral, Weathering action.

1. Introduction

Laminated glass structures are commonly subjected to various load conditions, whose duration varies from few seconds to several years. The mechanical behaviour of laminated glass strongly depends on the coupling ability of interlayer and the response to long duration loads is evaluated taking into account the effects of interlayer viscosity, in the hypothesis that the polymer does not degrade over time. However, it is known that polymer interlayers are sensitive to weathering action and can modify their rheological parameters for example as a consequence of humidity and solar radiation. Many studies reported in the literature are able to demonstrate significant influence of weathering on physical and mechanical properties of PVB, extensively used as interlayer in laminated glass. Some authors studied the mechanisms of degradation of PVB from a physic-chemical point of view: for example Safy El-Din and Sabaa (1995), studied the influence of thermal treatments on the chemical structure of PVB in the range 50-200°C; the mechanisms of photo degradation were investigated by Saad et al. (1995); Liu et al. (2008) faced the problems of the thermal stability of PVB and its stabilization. Other authors are more interested on the influence of weathering on mechanical properties of laminated glass and on the overall behaviour of glass structures. Among these, Delincé et al. (2007) report some results of experiments carried out on PVB and SGP previously subjected to the action of moisture and UV radiation. Butchart and Overhand (2013) describe the results of an experimental campaign of peeling tests in which the degradation of adhesion between PVB and glass due to the presence of water is evaluated. Kothe and Weller (2014) carried out an articulated experimental campaign where various polymer interlayers were subjected to environmental actions like corrosion by saline fog, UV radiation and a combination of temperature and humidity via weathering cycles produced into environmental chamber. Serafinavicious et al. (2014) subjected glass beams laminated with SG, PVB, EVA to moisture, high temperature and UV radiation, and combinations of such actions; the effects were compared by means of the load path diagram produced by creep four point bending tests at different temperatures. Ensslen (2007) reports an extensive analysis of the behavior of laminated glass units subjected to weathering action: some specimens were subjected to UV radiation in a solarium, some underwent degradation cycles in temperature and humidity mixed conditions, some were simply exposed to the environmental outdoor weather for two years, in different climates. The comparison among the specimens artificially weathered and the ones exposed to the real weathering was made via monotonic shear tests. Finally, Louter et al. (2012) took care of evaluating the sensitivity of a new SG-laminated reinforced glass beam to environmental actions as thermal cycles and humidity.

Note that, although a large amount of experimental tests has been done and the results are available, these research works can hardly be compared, not only because the weathering procedures do not always follow the standards (EN ISO 12543-4), but mostly because the mechanical tests are usually performed in view of the comparison among the tests of every single campaign rather that in view of the determination of effective mechanical parameters. For this reason, the authors carried out an experimental campaign, already published in (Andreozzi et al. 2015), in which laminated glass specimens were subjected to artificial weathering and successively tested with dynamic mechanical analysis (DMA); in so doing, the complete thermo visco elastic characterization of interlayer was obtained before and after the degradation action.

In the following paragraph the attempt is made to draw some conclusions on the degradation phenomena of PVB interlayer on which all authors seem to agree. Then, we try to compare the results obtained by the Authors and already published in (Andreozzi et al 2015) with the results obtained by Ensslen (2007); in fact the complete thermo visco elastic characterization of PVB before and after the degradation took place, enables to simulate via FEM analysis the monotonic shear tests reported by Ensslen. Finally, some conclusions are drawn on the opportunity of further analysis on the weathering action on laminated glass interlayer.

2. Weathering consequences on PVB interlayer

Summarizing what various authors report in their papers, some conclusions can be drown on which researchers agree.

UV radiation produces on PVB the most important consequences. Saad et al. (1995) give some interpretation of the physical mechanisms of such degradation. In general, different researchers seem to agree on the fact that a stiffer material is produced. Andreozzi et al. (2015) highlight how the action of UV radiation modifies the mechanical behaviour of PVB leading to a different material; in fact it does not exhibit any more thermo reological simplicity, so that it can hardly be mechanically described in view of numerical simulations or mechanical analysis.
Humidity produces two different effects: high water content in the interlayer foils acts as a plasticizer (Ensslen 2007) and gives softer bulk properties; once the original water content is recovered, damage produced by the previous presence of moisture in the polymer seems to produce an increase in material stiffness (Andreozzi et al. 2015).

Temperature effects need more investigations, as the thermal variations can induce very different effects on different kind of PVB productions, depending on the glass transition temperature of each material. The results obtained by different researchers seem to be not representative of the phenomenon.

The influence of weathering action on adhesion properties deserves a specific attention [Andreozzi et al. 2015, Ensslen 2007, Delincé et al. 2007]. Butcharth et al. (2013) report the results of peeling tests in presence of water; these results highlight that adhesion may decay heavily as a consequence of ageing phenomena, as it is demonstrated by the occurrence of bubbling and delamination phenomena on laminated glass (see also UNI EN 12543-4). Specific analysis is necessary to evaluate these influences.

Particular attention has to be devoted to the pattern of damage phenomena: while temperature variations regard the whole bulk of laminated glass, solar radiation acts on the glass surfaces of the structural element exposed to the daylight. On the contrary, humidity penetrates the PVB foil into laminated glass from the boundary towards the centre. According to Ennsslen (2007), humidity penetrates for a maximum of 10 cm and produces an increase of water content in PVB foil from the initial value of 0.4-0.5% (water content of the foil as it comes out from the lamination cycle) to a maximum of 1.4%. In this case also the damage of polymer due to the past presence of moisture will be confined to the boundary portion of a large panel. It is important to note that the sealing of the boundary is a straightforward remedy to this problem when designing laminated glass structures that have to stand in a moist condition, provided a compatible sealant is chosen.

In the following paragraph a comparison is attempted between the results obtained by Andreozzi et al. (2015) and Ensslen (2007) on PVB specimens subjected to UV radiation.

3. Comparison among results

The weathering action produced in the research studies reported in the former paragraph are not always comparable as they have been produced with different procedures and often superimposing different ageing actions. Moreover, when mechanical tests were performed, the aim was often the comparison among specimens subjected to various intensity and kind of weathering actions, not to determine some effective properties. For this reason, the comparison among results obtained by different authors is quite complicated.

Delincé et al. (2007) describe the results of creep tests and of CST tests. While the former are not completely described, so that the load level is not reported and the comparison cannot be made on the basis of the only maximum displacement, CST tests are very useful as they represent simultaneously both shear behaviour and adhesion capacity. Unfortunately, the stress state is not a simple one and the parameters of the material are not easily evaluable.

As far as the Authors know, peeling tests have been performed only by Butchard et al (2013). The extensive analysis of Kothe and Weller (2014) gives back only the glass transition temperature of reference and damaged materials. Also Serafinavicious et al. (2014) report experimental diagrams of the specimens before and after the weathering treatment, but the values of maximum displacements cannot be compared as the load level of creep tests is not reported.

Among the results, the possibility was observed to compare the difference in rheological behaviour of PBV subjected to UV radiation tested by the Authors in (Andreozzi et al. 2015) with the specimens subjected to UV by Ensslen. In fact, being known the stress state and the load rate of Ensslen (2007) experiments, it was possible to reproduce via FEM analysis the monotonic shear tests, using the visco-elastic parameters determined by the dynamic torsion tests by Andreozzi et al. (2015).

3.1. Numerical simulations

The series of specimens subjected to solar radiation by the Authors (Andreozzi et al. 2015) and by Ensslen were all exposed to UV action with the intensity recommended in EN ISO 12543-4. For this reason, it can be assumed that equal exposure times correspond to equal UV actions in the two campaigns. In both cases, Trosifol interlayer was investigated, namely Trosifol MB and Trosifol BG R20. However, the weathering actions produced on the specimens differ in some extent: in the first case the temperature did not exceed 35°C (while humidity was not recorded), while in the second, temperature reached 70-80°C and humidity was about 10%; moreover the exposition times did not equal in the two cases. In tab. 1 exposition time (expressed in hours) is reported for the series and the specimens of the two campaigns.

The thermo-viscoelastic behaviour of PVB is generally described via the generalized Maxwell model, which usually applies to polymers exhibiting analogous properties; that is, a remarkable viscous deformation, isotropy of mechanical response in the initial state, globally incompressible behaviour, so that the viscous share of deformation can be attributed only to the deviatoric part of deformation. Since the viscoelastic behavior of PVB strongly depends on the temperature, time-temperature superposition principle is generally applied, and the William Landel Ferry equation is accepted (Andreozzi et al. 2014).

For this reason, the mechanical tests which load path is reported by Ensslen in fig 6 could be easily reproduced via FEM analysis using commercial FEM code; in particular, the numerical simulations described in this paper have been performed using the code ADINA. The shear tests described in Ensslen (2007) were carried out on cylindrical specimens 31 mm in diameter made of laminated glass 4-0.76-4 mm. Constant relative displacement rate was applied on the glass plies in a direction parallel to the interlayer plane; as it is known, due to the different stiffness of glass and PVB (about three decades) the deformation can be reasonably considered only in the PVB interlayer and glass can be assumed as rigid. For this reason, only the interlayer was meshed using quadratic 27 nodes brick elements. In view of the symmetry of the problem, only a half of the specimen was simulated. The thickness was divided in three finite elements. The mesh was composed by 8304 elements and 78337 nodes. As usual, PVB interlayer was schematized using the generalized Maxwell constitutive model. In particular, the parameters reported in Andreozzi et al. 2014 (Table 4) were used to simulate the behaviour of the reference non exposed specimen (C_1); the relaxation times were recalculated for the reference temperature of 20°C according to WLF parameters reported in Andreozzi et al. 2014. Displacement controlled shear tests were simulated applying a constant displacement rate on the PVB nodes corresponding to the interface with glass; the displacement rate was 0.1 mm/min (slow test) and 1 mm/min (fast test) respectively, in order to fit to the tests which diagrams are reported in Ensslen (2007); the corresponding stress was calculated as the average of nodal reaction forces on the constrained surface. Due to the relatively large values of the shear deformation obtained in the Ensslen tests, the analysis was performed with nonlinear kinematic assumption.

Table 1. Exposition times for the specimens of Ensslen (2007) and of Andreozzi et al. (2015)

Exposition time [h]	Ensslen Series	Andreozzi et al. Specimens
0	C1	PVB@0.76
672	C2	-
912	-	I8A
1344	C3	-
3360	C4	-
7968	-	I1A
11209	-	I2A

Table 2. Alteration parameter computed on specimens I8A and I1A, extrapolated for specimen C2 and interpolated for specimens C3 and C4 (italics)

	UV exp. time		G/G0	
	[h]	0-71 s	0-710 s	full range
C2	672	*0.95754*	*0.95013*	*0.94728*
I8A	912	1.00256	0.98758	0.97660
C3	1334	*1.08173*	*1.05343*	*1.02815*
C4	3360	*1.46181*	*1.36957*	*1.27564*
I1A	7968	2.32627	2.08862	1.83853

In order to reproduce the mechanical tests reported by Ensslen (2007) on series C_2, C_3 and C_4, it was necessary to determine an alteration parameter to be used as an input to describe the constitutive behaviour of the interlayer, corresponding to the exposition times of 672, 1344 and 3360 h. As the tests reported by Andreozzi (2015) did not investigate the very same exposition times, it was necessary to assume the time linearity of UV alteration. In particular, the hypothesis was made that the modifications in the mechanical response of PVB due to UV exposition was linearly distributed in time between 912 and 7968 hours (corresponding to specimens I8A and I1A in Andreozzi (2015)). The average increase of G(t) corresponding to the given exposure times (specimens I8A and I1A) with respect to G(t) of the blank specimen (specimen PVB@0.76) was divided by exposure time and used as an alteration parameter. The corresponding alteration parameters were then calculated for specimens C_3 and C_4 interpolating the results of I8A and I1A; the alteration parameter for specimen C_2 was calculated extrapolating the results of I8A and I1A.

As G(t) is a time dependent function, it was necessary to compare the values of G(t) of the exposed specimens with the G(t) of the blank specimen, via a time average; rather than considering the whole time domain available from the mechanical experimental analysis, it was decided to focus the attention on the specific range of time in which the experiments had to be simulated. So it was decided to perform the time average on different time domains depending on the displacement rate of the simulated test: in Table 2 the values of the alteration parameters are reported calculated via a time average on the domain of 0-71 sec (corresponding to the time necessary to simulate the load of the fast tests), via a time average on the domain of 0-710 sec (corresponding to the slow tests) and via a time average on the full range of experimental available times. The values of the alteration parameters calculated via interpolation or extrapolation are reported in italics.

The alteration parameters were applied as multiplicative factors to the generalized Maxwell constitutive parameters G_i reported in Table 4 in Andreozzi et al 2014. The corresponding relaxation times were not modified in this case.

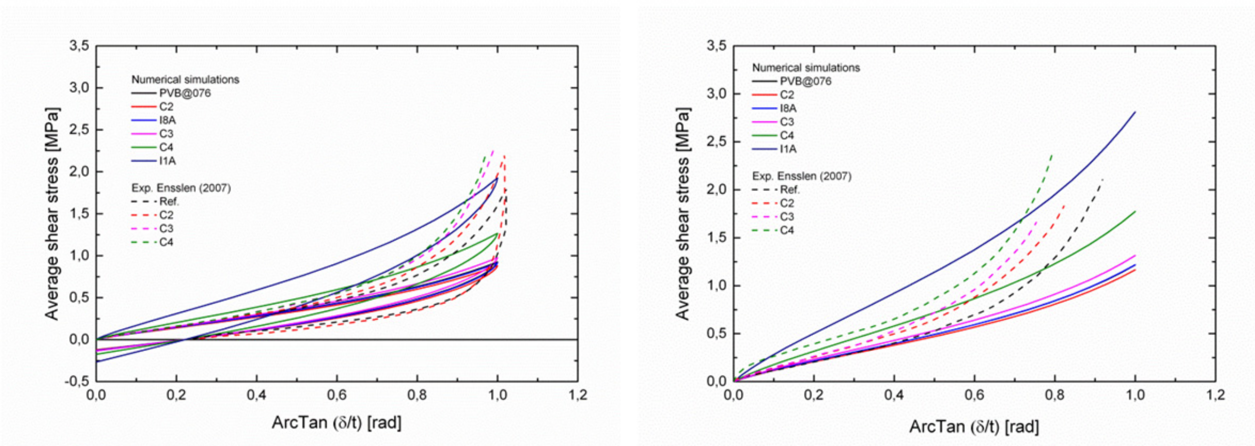

Fig. 1 Test diagrams obtained with the slow tests (left) and with the fast tests (right) by Ensslen (dashed lines) and with the numerical simulations by the authors (solid lines).

3.2. Comparison among results

In fig. 1 the results of the FEM simulations of the shear tests (solid lines) performed using the visco elastic parameters and the alteration parameters determined by the Authors are compared with the experimental diagrams reported by Ensslen (dashed lines). In abscissa, δ/t is the ratio of the relative displacement between the glass cylinders and the interlayer thickness. As it can be seen, the numerical simulations are quite similar to the experimental diagrams for relatively small values of the deformation (up to 0.5) while for higher values of the shear strain the experiments seem to report a stiffer behaviour than the numerical description. This can be explained observing that values of arctg(δ/t) higher than 0.5 represents quite large deformations. A more complex model for the description of the mechanical response of PVB is needed than the linear viscoelastic description; the elastic part of deformation could be described with a large strain hyperelastic mechanical model. On the contrary, the residual deformation obtained in the slow tests seems to have been well caught, meaning that the viscous share of deformation has been properly described.

Specimens subjected to fast displacement rate show lower curves in the stress-deformation diagram numerically simulated; this means that the numerical description highlights a less stiff material, as if the alteration produced by UV radiation was less emphatic. It must be noted that the alteration parameters were calculated as linear interpolation of the experimental ones, as it is shown in Table 2. It is possible that the progressive stiffening of PVB was not linear but characterized by a stronger growth in the first times, so that the evaluation of the parameter was underestimated.

4. Conclusions

Many authors carried out experimental programs in order to simulate the weathering action on PVB interlayers and to determine the modification of interlayer response. The problem has been faced of comparing the results of such simulations and the consequences that they produce on laminated glass. It has been shown that UV radiation produces the stiffening of interlayer polymer and the intensity of such effect as determined by Ensslen (2007) and by Andreozzi et al. (2015) was compared.

In the comparison it was highlighted as the general results are in good agreement for small values of imposed shear deformation and for slow tests, while the numerical description of the mechanical behaviour is not accurate enough to describe large deformations as those obtained by the tests. It seems appropriate to use a more refined description of the constitutive behaviour of material in order to catch the full mechanical response of laminated glass structures, in which interlayer is often subjected to large deformation.

Moreover, more systematic analysis are necessary to add information about the laws of accumulation of the consequences of weathering actions; in order to do that, the procedures employed both for the laboratory artificial reproduction of the alterations produced by weathering, and for the mechanical tests need to be shared in the scientific community.

Some authors suggest that weathering action is not to be considered as a problem in case it produces an increase in stiffness. However it is worth noting that stiffness of plastics is often accompanied by brittleness and by lower adhesion; moreover the low modulus of PVB, together with the extremely good adhesion, is the key mechanism that gives the good rupture behaviour of laminated glass as the interlayer is able to produce the bridge ligament among glass fragments in virtue of a good mixture of deformability and adhesion. Due to great deformability and to strong Poisson effect, interlayer delaminates steadily from fractured glass and forms the ligament among fragments avoiding their fall. For this reason, the real behaviour both of interlayer and of adhesion has to be investigated and taken into account in order to demonstrate the safety of laminated glass structures at rupture over time.

Acknowledgements

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References

Andreozzi, L., Briccoli Bati, S., Fagone, M., Ranocchiai, G., Zulli, F.: Weathering action on thermo-viscoelastic properties of polymer interlayers for laminated glass, Construction and Building Materials. 2015; 98: 757-766.

Andreozzi, L., Briccoli Bati, S., Fagone, M., Ranocchiai, G., Zulli, F.: Dynamic torsion tests to characterize the thermo-viscoelastic properties of polymeric interlayers for laminated glass, Construction and Building Materials. 2014; 65: 1-13. DOI: 10.1016/j.conbuildmat.2014.04.003

Butchart, C., Overend, M.: Influence of Moisture on the Post-fracture Performance of Laminated Glass. Glass Performance Days 2013, Tampere, Finland, 13-15 June 2013, 59-61, Glaston Finland, (2013)

Delincé, D., Belis, J., Zarmati, G., Parmentier, B.: Structural behaviour of laminated glass elements – a step towards standardization. Glass Performance Days 2007, Tampere, Finland, 15-18 June 2007, 658-663, Glaston Finland, (2007)

EN ISO 12543-4. Glass in building - Laminated glass and laminated safety glass - Part 4: Test methods for durability. European Committee for Normalization; 2011.

Ensslen, F.; Tragverhalten von bewitterten Verbund-Sicherheitsglas-Scheiben. Stahlbau 76, 582-590 (2007)

Kothe, M., Weller, B.: Influence of environmental stresses to the ageing behaviour of interlayer. Challenging Glass 4 & COST Action TU0905 Fineal Conference, Louter, Bos, Belis & Lebet (Eds), 439-446 Taylor & Francis Group, London (2014).

Liu, R., He, B., Chen, X.: Degradation of poly(vinyl butyral) and its stabilization by bases. Polymer Degradation and Stability 93, 846-853 (2008).

Luter, C., Belis, J., Veer, F., Lebet, J-P.: Durability of SG-laminated reinforced glass beams: Effects of temperature, thermal cycling, humidity and load-duration, Construction and Building Materials 27 280–292 (2012).

Saad, G.R., El-Shafee, E., Sabaa, M.W.: Dielectric and mechanical properties in the photodegradation of poly(viny1 butyral) films. Polymer Degradation and Stability 47, 209-215 (1995)

Safy El-Din, N.M., Sabaa, P.M.W.: Thermal degradation of poly(viny1 butyral) laminated safety glass. Polymer Degradation and Stabilily 41, 283-288 (1995).

Serafinavicious, T., Lebet, J-P., Louter, C., Kuranovas, A., Lenkimas, T.: The effects of environmental impacts on durability of laminated glass plates with interlayers (SG, EVA, PVB). Challenging Glass 4 & COST Action TU0905 Final Conference, Louter, Bos, Belis & Lebet (Eds), 455-462, Taylor & Francis Group, London (2014).