A numerical model for cold bending of laminated glass panels

Sophie PENNETIER, SHoP Construction
Frederic BINDJI-ODZILI, RFR

Abstract

Cold bending consists of deforming the glass elastically. The purpose of this study is the monitoring of the spring-back deflections and internal stresses in a cold bent laminate under several temperatures and geometries. A numerical model was built on the basis of material properties found in literature. It is currently being calibrated with results from tests.

Introduction

Cold bending consists of deforming the glass elastically. In architecture or transportation applications, the glass is laminated for security, impact and post-breakage. The cold bending of the constitutive glass panes of a laminate can either occur before or after lamination. The most common way is to deform the laminate by pushing a point out of plane and fixing it to the structure on site. This method has been used for the Avignon railway station and the Corp headquarters facades. Another approach consists of bending the flat panes of glass before lamination. The interest of this method is the fact it that takes less force to bend a thin layer of glass than a laminate. The present study focuses on this second method and its objective is to monitoring the behavior of the interlayer which prevents the glass from becoming flat again. For this purpose, a numerical model representing a two glass ply laminate was built. Two interlayer materials were modeled: butacite (PVB) and ionoplast (SGP). These products have been extensively tested; their mechanical properties are easily accessible and they are by far the most commonly used interlayers in the construction industry for such applications.

The visco-elastic behavior of the interlayer depends on time and temperature. The present study assumes an instantaneous loading and a constant temperature and the variable is the relaxation time.

Material properties

Sodocalcic glass is currently used in the construction industry. Its mechanical properties are defined by EN 572-1. The glass is modeled as an elastic isotropic material with E=70GPa, v=0.22 (thus G =28.7GPa).
The mechanical properties of the interlayer depend on the polymer itself and vary widely from one manufacturer to the other. The interlayers are modeled as an isotropic visco-elastic material with time-dependent properties at a given temperature. The properties of the butacite are derived from the following equation [1]:

G (T > 20°C) = 0.008 (100 – T) – 0.0011 (50 + T) log(t)
G (T < 10°C) = 2.0 – 0.2 log(t)
where T stands for the temperature and t stands for the time in seconds

The Poisson coefficient of the PVB is set at v=0.34 and the E values are deduced. The ionoplast properties are based on values provided in [2] and summarized in Figure 1.

	Butacite		Ionoplast		
Temperature	G (MPa)	υ	E (MPa)	G (MPa)	υ
0°C	1.50	0.20	/	/	/
10°C	1.40	0.22	651	225	0.446
20°C	1.34	0.23	567	195	0.453
24°C	/	/	505	173	0.458
30°C	0.75	0.33	324	110	0.473
40°C	0.46	0.39	91.6	30.7	0.492
50°C	0.29	0.43	33.8	11.3	0.497
60°C	0.21	0.45	10.9	3.64	0.499
70°C	/	/	5.64	1.88	0.500
80°C	0.05	0.49	2.49	0.83	0.500

Figure 1 - Material properties [2]

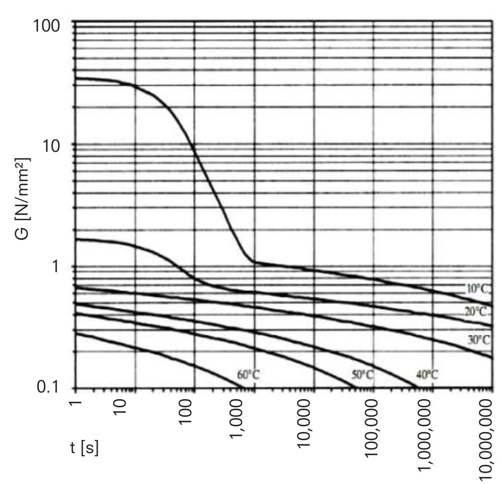


Figure 2 - PVB shear modulus in function of time and temperature [3]

Models construction

The model is made out of 2 glass plies measuring 2400x800x4mm bound together with a 2400x800x1.52mm interlayer. The size of panel was selected in order to compare the numerical results to that of cold bending experiments made by other teams. The target curvature for the initial shape corresponds to R=5m. The moment can be expressed as M=EI/R where I stands for the second moment of inertia.

Two sets of boundary conditions were considered for the model. In the first set the panes are simply supported at mid span and free at the ends, where the couple is applied. In the second set, the panes are supported at both ends and let free to slide away as the interlayer creeps. The couples are applied at the same location as in the first set. One technique used in the industry consists of forcing the plane glass panes onto a cylindrical jig by applying linear forces on the edges. The true deformation under a load applied onto the short edge only is not perfectly cylindrical but parabolic: f=p(l/2)^2/384EI. The difference between the parabolic deflection curve and the 5m radius circle is about 0.4% at ¼ of the span and does not exceed 1% close to the ends for the 2400x800x4mm panes used in this case. This discrepancy is acceptable for the purpose of this study.

The finite element mesh is made out of 50mm large hexahedron cells. Each one of the three layers is one element thick. Parabolic hexahedrons (HEXA20) are used in order to accurately represent the variation of the shear in the thickness of each component.
It was verified that meshing with HEXA20 elements is satisfactory by performing a comparative model of 4x4x4mm large elements versus the 50x50x4. Specific attention is drawn to the numerical error since the model involves elements with small thickness and where the stresses range from 1 to 1000 in the constitutive components.

The glass elements are assigned elastic isotropic properties.

The time-dependent properties of the interlayer were obtained by a step by step variation of E and v in time, for each sub step of the calculation. For each sub step, the interlayer is assigned different elastic isotropic properties. Each step is updated with the stress field, and deflection field of the previous one.

A non-linear static Newton Raphson type analysis is performed to model for the non-linearity of the time-dependent interlayer material. The overall computation is subdivided into 10 steps. At each step the mechanical properties of the interlayer are updated. The analysis also takes into account the variation of the deflection and stresses which are computed at each calculation step. Each step is a static analysis which reuses the deflection and stresses from the previous step.

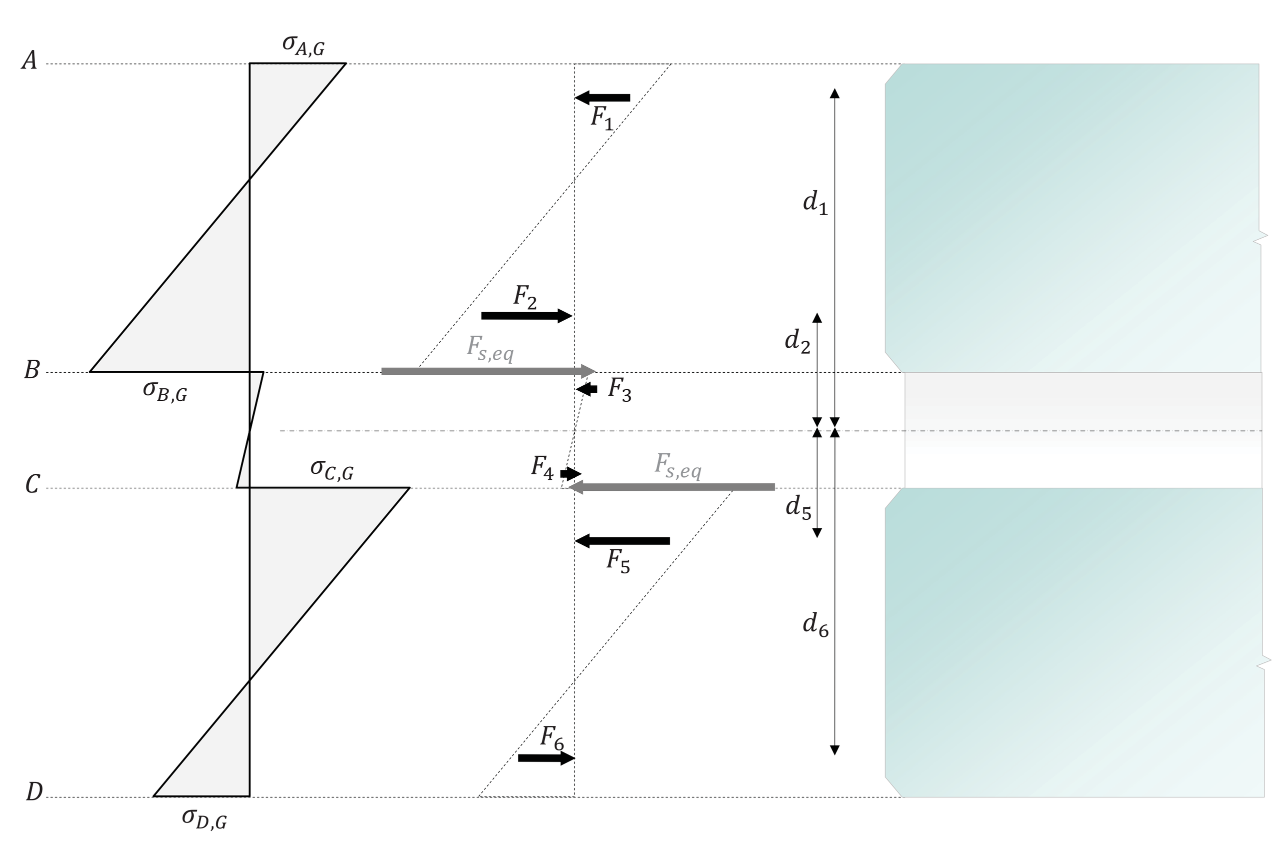
The Figure 3 provides the computation scenario for the non-linear static analysis. In the first step (statnl0), the glass is bent with the application of the couple at the short edges. In this case the interlayer properties are artificially set to low values in order not to bound the sheets of glass together. The deflection and stresses in each pane are exactly the same as for one single sheet of glass.

In the following step (statnl01) the interlayer is assigned its full mechanical properties. The model is not yet unloaded and the deflections are unchanged since the previous step.

In the following step (statnl1) the couple is removed and the instantaneous elastic spring-back is observed. A shear transfer occurs at the interface of the interlayer.
In the following steps (statnl2 to statnl10) the mechanical properties of the interlayer change. N corresponds to different steps in time for the computation of the visco-elastic behavior of the interlayer.

Step number		Description	Springback
statnl 0		Two separate sheets of glass are cold bent Interlayer: absent Boundary conditions: each sheet is has its own isostatic supports at the angles External load: bending torque at short edges Internal load: induced by torque in the glass	None
statnl 01		After lamination, before suppression of the torque Interlayer: present Boundary conditions: each sheet is has its own isostatic supports at the angles External load: bending torque at short edges Internal load: induced by torque in the glass, not instantly transferred through interlayer since no unloading	None
statnl 1		Removal of the torque, first stress transfer in the interlayer, creep of the interlayer Interlayer: present Boundary conditions: underside sheet has isostatic supports at the angles, no support on other sheets of the laminate External load: none Internal load: induced by previous stress field ivn the glass, instantly transferred through interlayer	Primary
statnl 2		Creep of the interlayer, under stress field Interlayer: present Boundary conditions: underside sheet has isostatic supports at the angles, no support on other sheets of the laminate External load: none Internal load: induced by previous stress field in the glass, instantly transferred through interlayer	Secondary
...			
statnl N		Creep of the interlayer, under stress field Interlayer: present Boundary conditions: underside sheet has isostatic supports at the angles, no support on other sheets of the laminate External load: none Internal load: induced by previous stress field in the glass, instantly transferred through interlayer	Secondary

Figure 3 - Calculation steps



$$F_1 = \frac{1}{2}\sigma_{A,G} \times B \times \left(\frac{\sigma_{A,G}}{\sigma_{A,G}+\sigma_{B,G}}\right) t_g$$

$$M_{res} = C_0 - \sum_i F_i d_i = F_{eq}\, t_{int}$$

Where:

$\sigma_{A,G}$: normal stress on extrados of the glass
$F_{i=1,2,5,6}$: equivalent normal force in the glass
$F_{s,eq}$: shear transfer at the interlayer
t_g : glass thickness
t_g : interlayer thickness
B : width of the laminate
M_{res} : resisting moment
C_0 : initial couple applied for cold bending

Figure 4 - Normal stresses at the face of glass and equivalent resisting moment in the interlayer

Results

We found that the internal stresses reduced with time, as expected, along with the reduction of the deflections.
Initially (at step statnl0) the deformation of the glass corresponds to the cold bending of two separate sheets of glass, since the sheets are freely moving before they are glued together.

After lamination the total stiffness is different and the deflection after the laminate is unloaded corresponds at first to the elastic spring-back. The elastic spring-back depends on the initial properties of the interlayer (E0, G0 and v0). The delayed
spring-back corresponds to the relaxation of the laminate in time. The deflections are given in Figure 9.

The observation of the axial stresses SXX shows that the maximum axial stress in the extrados and intrados of the laminate are approximately +/-30 MPa initially and decrease to +/-25 MPa at 160s. The axial stresses generally decrease as the deflection of the laminate reduces with time. The observation of SXX in one glass panel shows that the stress in the top surface is different from the stress in the bottom surface. The difference is due to the PVB opposing resistance to the glass from recovering a planar shape. This asymmetry corresponds to the displacement of the neutral axis in the thickness of the glass. It is verified that as long as the laminate remains curved, the residual elastic bending moment in both glass plies is balanced by shear forces occurring at the interface of the interlayer. The Figure 4 below shows the relationship between all the parameters. The shear force is obtained through integrating the actual shear stress over interface area.

The observation of the shear stresses in the glass/interlayer interface plane shows SXY stresses of about 1 MPa while the intrados and the extrados of the laminate show alternate symmetrical tension and compression. Figures 5 to 8 show the stress patterns observed in the PVB laminate.

The behavior of the SGP laminate is slightly different from that of the PVB laminate. Due to a higher elastic modulus, the instantaneous spring-back is much smaller and the overall creeping of the SentryGlas is slower. Transverse shear stresses are also higher and well distributed transversally.

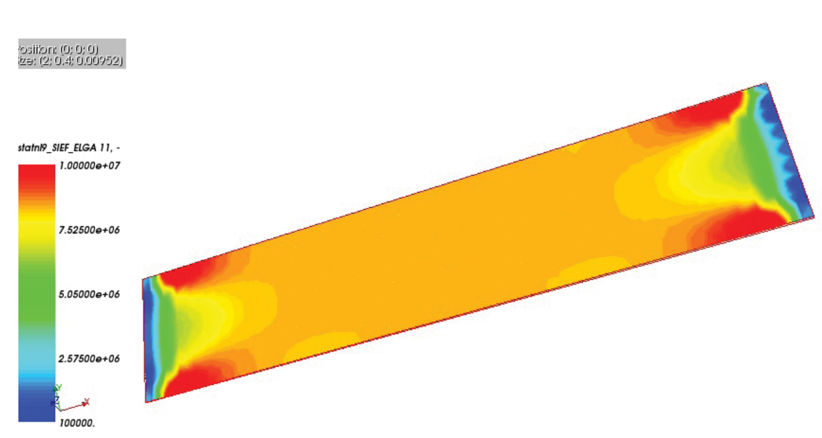


Figure 5 - PVB laminate, relaxation time 160s: Pattern of longitudinal axial SXX stresses

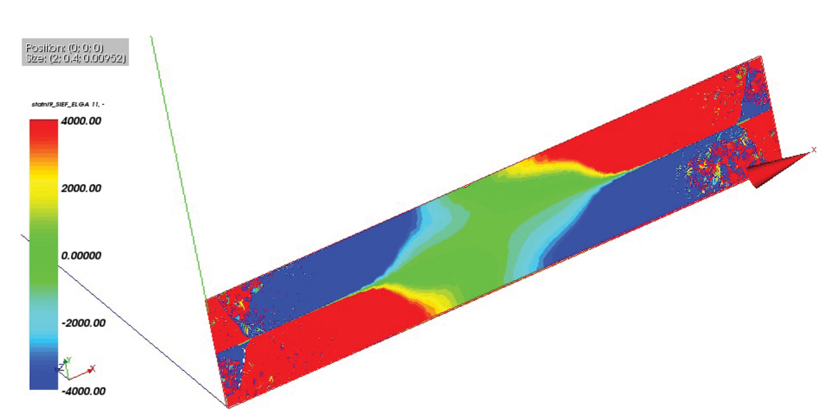


Figure 6 - PVB laminate, relaxation time 160s: Pattern of planar SXY shear stresses

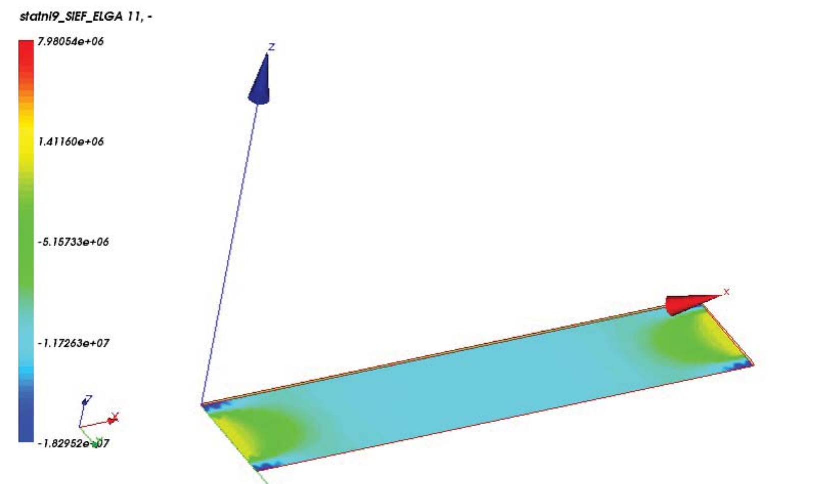


Figure 7 - PVB laminate, relaxation time 160s: Pattern of longitudinal axial SXX stresses in the intrados

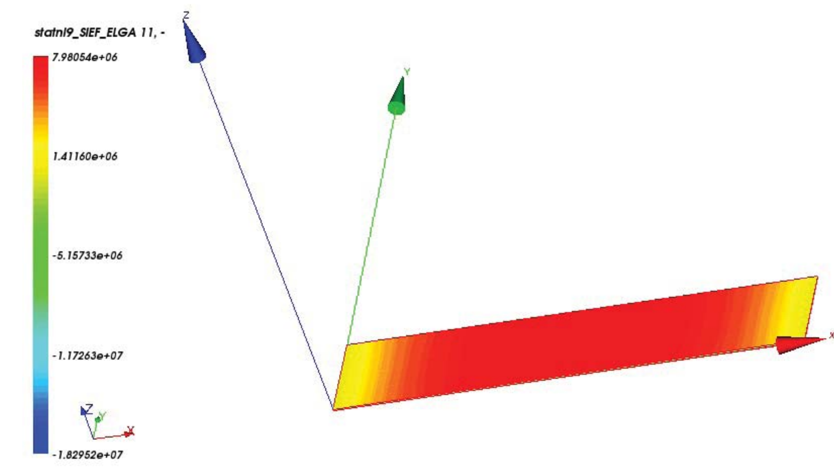


Figure 8 - PVB laminate, relaxation time 160s: Pattern of planar SXY shear stresses in the extrados

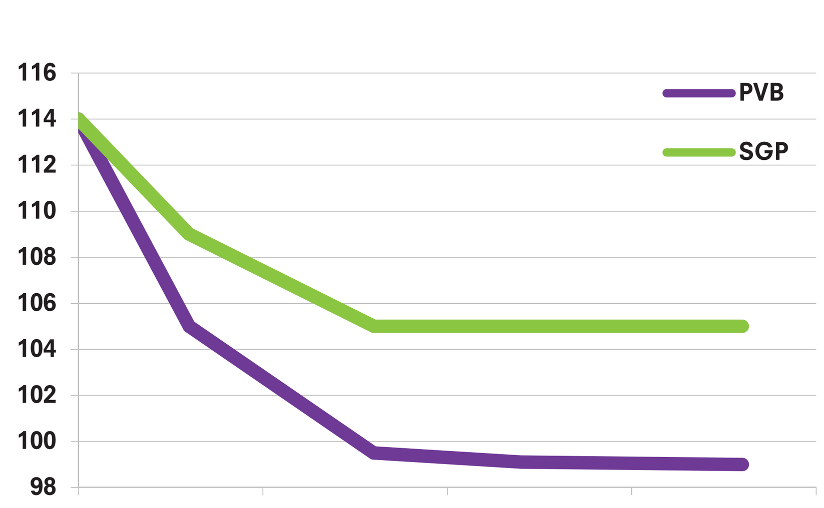


Figure 9 - Evolution of spring back in time for PVB and SGP

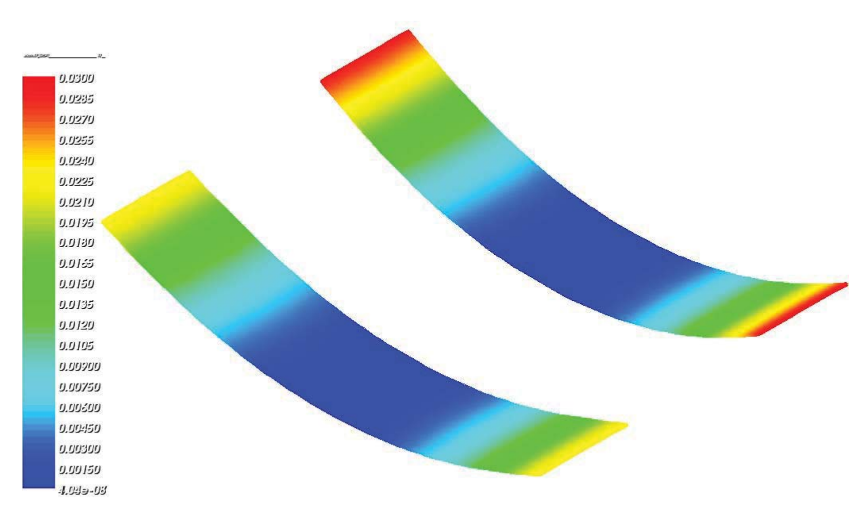


Figure 10 - Spring back after 0s (right) 60s (left)

Conclusions

This numerical model gives out results corresponding to our expectations about the behavior of the creeping of the interlayers in laminated panels. The outputs of the model corroborate the level of resisting shear stress at the interface of the interlayer. The numerical model acknowledges that cylindrically cold bent laminates are able to keep their shape for a long time. We have noticed a stabilization of the variation of out-of-plane deflections (DZ) after 360 seconds. This behavior happened for both PVB and SentryGlas samples.

Our study depends on a precise description of the evolution of the shear modulus with respect to time and temperature. This numerical study raises the following questions, which are still under investigation and shall be supported by further experimentation on actual samples:
- How does the system react under an additional stresses?
- How does the system react under external loading, such as permanent load, dynamic wind load or construction loads?
- What about cyclic variation of temperature?

Summary

This study consisted of modeling the relaxation of a laminated cold bent glass sample. The model shows the variation in time of the deflections, the effective shear transfer at the interlayer and residual stresses in the components of the laminate. It has been verified by calculation on the basis of material properties found in the literature and shall be confirmed with experimental results.

Acknowledgements

This research was supported by the European Community's 7th Framework Program under grant agreement 230520 (ARC).

References

[1] Kutterer 2002 - Verbundglasplatten – Näherungslösungen zur Berücksichtigung von Schubverbund und Membratrag-wirkung
[2] DuPont SentryGlas Elastic Properties (SGP5000)
[3] C. Schuler, O. Bucak, G. Albrecht, V. Sackmann, and H. Gräf. Time and temperature dependent mechanical behaviour and durability of laminated safety glass. Structural Engineering International, 14(2):80–83, 2004.