# Cold bending of laminated glass panels


Jan Belis

Laboratory for Research on Structural Models, Ghent University, Technologiepark-Zwijnaarde 904, 9052 Ghent, Belgium

Bart Inghelbrecht

CEI – De Meyer, Begoniastraat 30C, 9810 Nazareth, Belgium

Rudy Van Impe

Laboratory for Research on Structural Models, Ghent University, Technologiepark-Zwijnaarde 904, 9052 Ghent, Belgium

Dieter Callewaert

Laboratory for Research on Structural Models, Ghent University, Technologiepark-Zwijnaarde 904, 9052 Ghent, Belgium



**Curved glass can be applied in an interesting way in e.g. facades and canopies. Traditionally, curved glass is manufactured from float glass that is heated above the weakening point and formed in a heavy curving mould. Since this technique is time- and energy consuming and consequently relatively expensive. For this reason, a more affordable alternative has been developed. The technique is called a "cold bending process" because it is used to bend glass plates on the building site at room temperature. The process implies that toughened float glass laminates are gradually bent on a curved frame. Finally, the newly curved panel is mechanically fixed to the frame, which implies that the glass is continuously subjected to bending stresses during its lifetime. In this contribution, time dependent loading-deformation interaction during the bending process as well as relaxation after the bending process are closely examined. An experimental and a numerical research method have been used in a complementary way.**



***Key words: Curved glass, cold bending, visco-elasticity***


## 1 Introduction

Typical applications for curved glass are e.g. showroom facades and railway station canopies. The traditional manufacturing process for curved glass requires high operating temperatures: flat glass is heated beyond the weakening point and gradually curved in a heavy forming mould. After cooling down, the resulting glass element can maintain its new form without the need of extra boundary conditions. Disadvantages of this technique are the costs due to moulding, high energy consumption, a risk of optical distortions, impracticable transportation of the worked piece, and long delivery times (especially in case of later replacement). For this reason, valuable alternative techniques have been developed, which do not need treatments at elevated temperatures and which are therefore called "cold bending processes". These processes imply the on-site bending of toughened float glass laminates and their fixation to a curved frame. Several cold glass bending systems are already available on the market. In this contribution, two aspects are closely examined. The first aspect focuses on the mechanical behaviour of laminated glass panels and more precisely on the time dependent loading-deformation interaction during the bending process. The second aspect investigates the stress relaxation in the laminated glass due to the visco-elastic behaviour of the interlayer once it has been bent.

# 2 Material Properties

## *2.1 **Glass***

### *2.1.1 General*

The glass that is commonly used for building purposes is basic soda lime silicate glass. Typical values for some relevant characteristics are given in Table 1.

*Table 1: Relevant material properties of basic soda lime silicate glass according to CEN EN 572-1 2004*

| property | value | unit |
|---|---|---|
| density | 2500 | kg/m³ |
| Young's modulus | 70000 | N/mm² |
| Poisson's ratio | 0.2 | - |
| mean coefficient of expansion | $9 \times 10^{-6}$ | $K^{-1}$ |

For architectural applications, glass is generally considered to be a homogeneous and isotropic material. At temperatures below the deformation point (which is 520° C for basic soda lime silicate glass), it is generally accepted that glass can be assumed a linear elastic material. The linear path is abruptly ended when the failure strength is reached: glass is brittle.

### *2.1.2 Float glass*

Modern flat glass is produced by means of the so-called float process, a name which refers to the floating of molten glass on a tin-bath. Along the process, the glass is cooled down in a smooth and controlled way, so that residual stresses are in principle absent in the end product. The resulting glass is characterised by a very smooth, flat surface with excellent optical qualities. European standard float glass panel sizes measure 6.00 meters by 3.21 meters.

### 2.1.3 Toughened glass

For structural applications, however, well-controlled residual stresses can be very useful. They can cause an overall prestressing effect on the glass element, which increases its resistance against tensile (bending) stresses: it virtually becomes stronger. Most prestressed glass is made by means of a temperature treatment, but also chemical processes exist.
Depending on the level of prestress, the glass is called toughened (fully tempered) or heat-strengthened. The strength of glass is a very complex characteristic which is dependent of external factors like humidity (corrosion), ageing, surface flaws and scratches, loading history, loading speed, and so on. Strength values from literature should not be adopted without good knowledge of the corresponding conditions and assumptions. Nonetheless, some general values are mentioned here in order to give an estimation of the order of magnitude and to put the different glass types into the right perspective (Table 2).

*Table 2: Typical characteristic glass strengths for different types of glass, loaded perpendicular to its plane according to the indicated European standards*

| type | strength [N/mm²] | standard |
|---|---|---|
| annealed float | 45 | CEN EN 572-2 |
| Heat strengthened float | 70 | CEN EN 1863-2 |
| Toughened (clear/tinted/coated float) | 120 | CEN EN 12150-2 |

*These strength values should not be used without proper knowledge of the conditions of validity as described in the original standards.*

In comparison to the basic annealed float glass that it originates from, thermally treated glass types have quite a different failure behaviour. At the moment of crack propagation, the complete toughened glass area fractures into tiny dull cullets. Annealed float glass on the contrary, typically fractures in a limited number of large and sharp shards. The fracture pattern of heat strengthened glass is situated in between.

### 2.1.4 Laminated glass

Laminated glass is composed of minimum two panels, at least one of which in glass, which are completely surface to surface connected by means of an adhesive interlayer. Usually the interlayer consists of one or more transparent synthetic sheets, but sometimes resin is used as well. The main purpose of the laminate usually is to improve the glass performance by forcing the different layers to cooperate mechanically.

For structural applications, these performances are mainly focussed on safety aspects.

## *2.2 Interlayer*

The majority of glass laminates has an interlayer of polyvinylbutyral, shortly PVB. This translucent, soft, sheet-like copolymer can become transparent only after lamination, which requires the right pressure and temperature conditions in an autoclave. It is available in a standard thickness of (a multiple of) 0.38 millimetres. The order of magnitude for strength and maximum elongation of a typical PVB is 20 N/mm² and at least 250 % respectively.
Of major importance for cold bended glass laminates are the visco-elastic properties of PVB. Since both the shear modulus and the Poisson's ratio are dependent on temperature and load duration, the mechanical behaviour of glass-PVB laminates is relatively complex. In addition, several types of PVB are available with slightly different characteristics, dependent on their chemical constitution and manufacturer.
Van Duser et al. have proposed a material model for Butacite PVB, with which it is possible to determine the shear modulus of PVB at a certain reference temperature as a function of load duration [Van Duser, Jagota and Bennison, 1999]. The shear modulus drops to a dramatically low level after a relatively limited period of time and stabilises at a very low so-called plateau value, as can be seen in Figure 1.
The temperature effect can be taken into account by means of shift functions, which basically cause the shear modulus curve to shift in a horizontal way. Again, an important drop of the shear modulus results if the temperature is increased, as is illustrated in Figure 2. Hence PVB is close to disintegration if its temperature rises up to about 60° C.

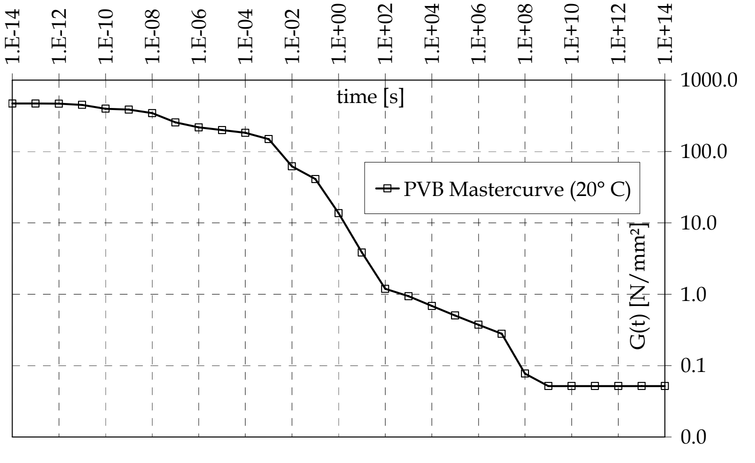



*Figure 1: Relaxation of the shear modulus (G) of Butacite PVB [Belis, 2005]*

## 3 Bending experiments

### *3.1 Aim*

The aim of the experimental research was to examine the time-dependent deformations in relation to the applied load during the "Freeform" cold bending process. Due to the visco-elastic properties of PVB, stress relaxation and creep effects are expected in the mechanical behaviour of the laminate. For this reason, economic use of the cold bending process requires a good compromise between load duration and bending loads: longer durations are more expensive because workers need to spend more time on the building site, while short loading durations are more expensive because more bending energy is needed.

The influence of different parameters such as the interlayer thickness, the speed of loading, etc. on the building process was examined.

### *3.2 Specimens and testing set-up*

The length and width of the laminated test specimens are 200 centimetres and 94 centimetres respectively. The specimens were composed of two toughened glass panes with a thickness of four millimetres each. Three different PVB-interlayers were used. The first series of specimens was composed with a 0.76 millimetres thick soft PVB, which is normally used for acoustic insulation. This series will be referred to as 'PVB.A' in this contribution. The second and third series were made with a standard PVB of 0.76 millimetres and 1.52 millimetres thickness respectively. In the following, the respective appellation for both series is 'PVB.2' and 'PVB.4'. An overview of the test specimens is given in Table 3.

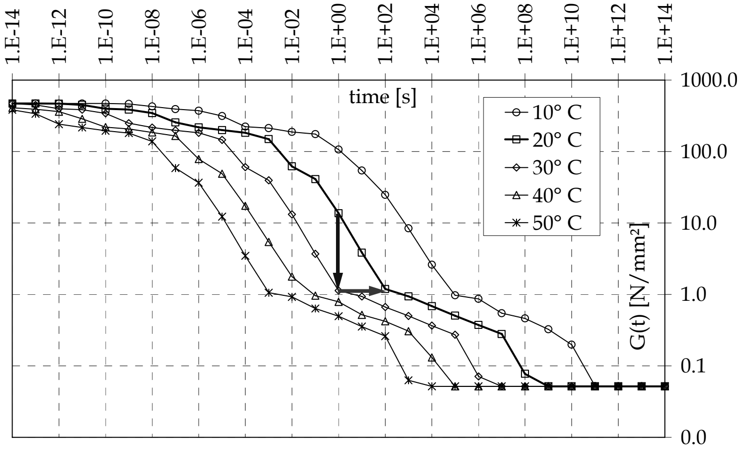



*Figure 2: Horizontal shift of the shear modulus curve (G) of Butacite PVB due to temperature increase [Belis, 2005]*

For the experimental part of the research, a plywood bending mould was made in order to bend glass plates into a circular shape. The mould acted as a substitute for a metal curved frame that would be used in reality. Although a typical radius for cold bending of laminated glass panels is situated in the range of four to ten meters, the mould's radius was only three metres. This rather small radius was applied since it was of interest to know the load-deflection behaviour of the given laminated glass specimens at a maximum curvature.

*Table 3: Overview of test specimens*

| series | PVB thickness [mm] | specimen number | overall thickness [mm] |
|---|---|---|---|
| PVB.A | 0.76 | 1 | 8.33 |
| | | 3 | 8.32 |
| | | 8 | 8.36 |
| | | 9 | 8.30 |
| PVB.2 | 0.76 | 2 | 8.42 |
| | | 4 | 8.45 |
| | | 10 | 8.52 |
| | | 11 | 8.46 |
| PVB.4 | 1.52 | 5 | 9.10 |
| | | 6 | 9.06 |
| | | 7 | 9.10 |
| | | 12 | 9.06 |

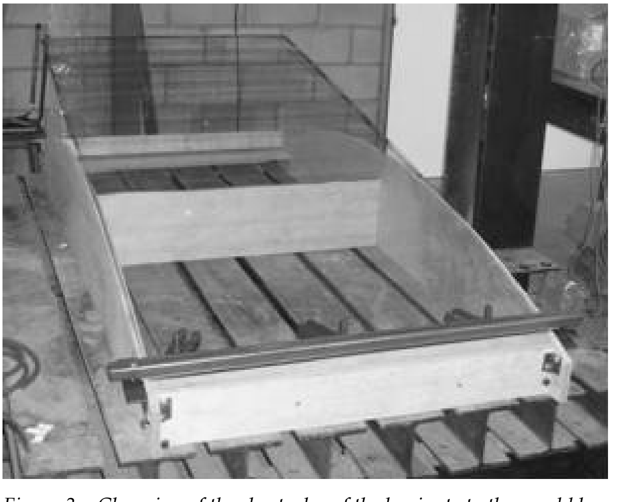


*Figure 3: Clamping of the short edge of the laminate to the mould by means of a steel hollow section*

The mould was fixed to the laboratory floor. For all lab tests, the unloaded test specimen was clamped to the mould along a short edge by means of a steel hollow section, as shown in Figure 3.

In order to avoid damage due to local stress concentrations, thin rubber strips were used as an interface between the glass and the steel parts.

A linear load was realised along the free short edge of the plate by means of mass elements of ten kilograms each. For safety reasons, a hollow section was provided in such a way that sliding of the mass elements was prevented during progressive deformations. The hollow section and its fixings equalled a weight of 37.5 N and were treated as own weight of the specimen.

The glass panels were always loaded in a symmetrical way. After the first element had been placed in the middle of the free edge, two additional mass elements were placed simultaneously and symmetrically with respect to the first element. The resulting loading sequence typically was 10 kg, 30 kg, 40 kg, 60 kg, 70 kg, 90 kg, … 210 kg.

During the bending tests, two electronic displacement devices, indicated in Figure 5, were used to register the progressive displacements as a function of the load and the load duration.

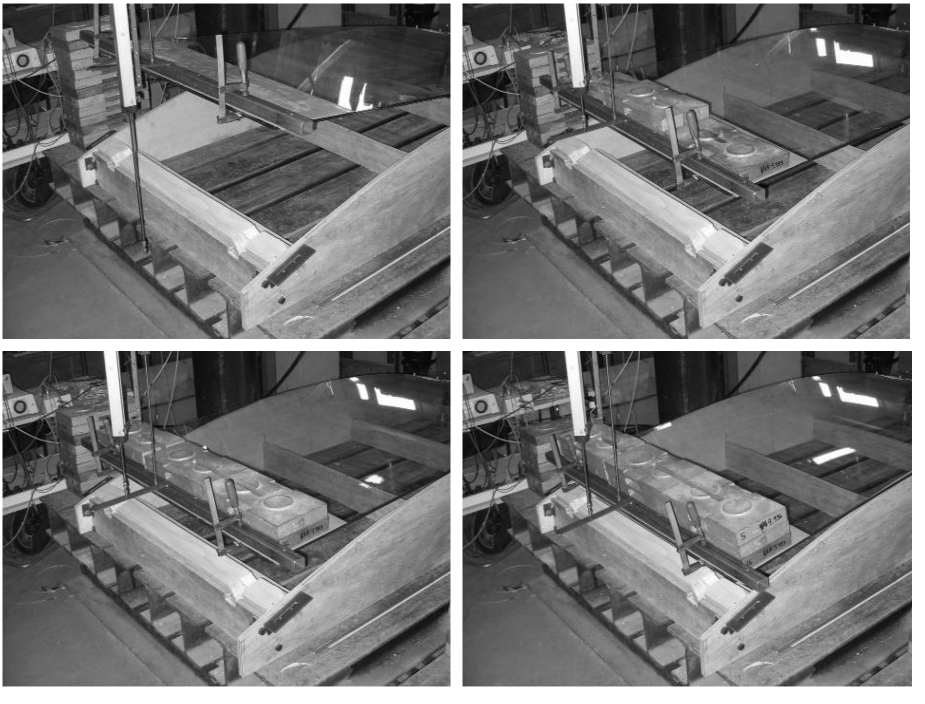


*Figure 4: Experimental loading cycle on specimen number 7 (PVB.4). Loading mass from top left to bottom right: 0 kg (own weight only), 40 kg, 60 kg and 90 kg*

### *3.3 Test overview*

The three different test series were subjected to several types of bending experiments.

In the first type, a standard mass of 90 kg is applied stepwise in a fixed period of time (2 min, 5 min, 10 min and 15 min; see Figure 4 above). This made it possible to compare relaxation and deformation for the different interlayers. This type of tests was used to examine the effect of multiple loading and unloading cycles as well. A schematic overview of the applied loading cycles is given in Figure 6.

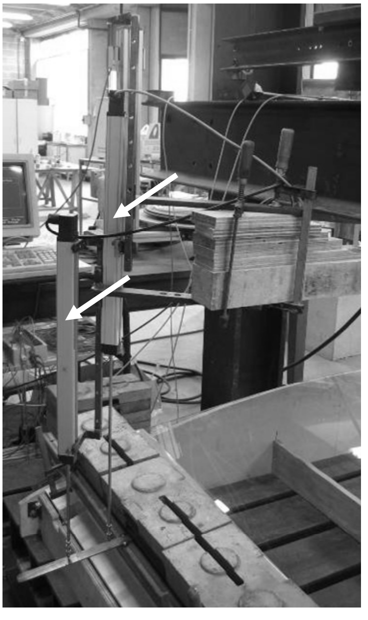


*Figure 5: Electronic displacement devices on a test specimen*

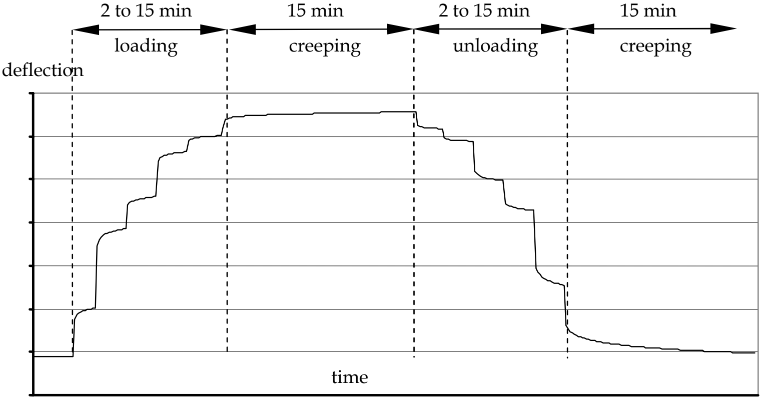



*Figure 6: Schematic overview of applied loading cycles*

During the second type, a limited number of experiments was conducted with a heater to see the effects of moderate local heating. For the third type the necessary load to bend the laminate completely on the mould was determined. This test made it possible to estimate whether the panel could bee bent or not without the need for special tools or machinery.

### *3.3.1 First test type: bending with a mass of 90 kg*

Test results for a certain loading time can be displayed in a graph where the displacement of the free edge is put as a function of the load duration. Results are shown for the PVB.2 series and for a loading time of five minutes in Figure 7. The effect of different time domains is visible in Figure 8.

Hence that the initial deflection differed from zero due to gravity forces on the unloaded laminate. After each loading or unloading step, a progressive nonlinear deformation was noticed

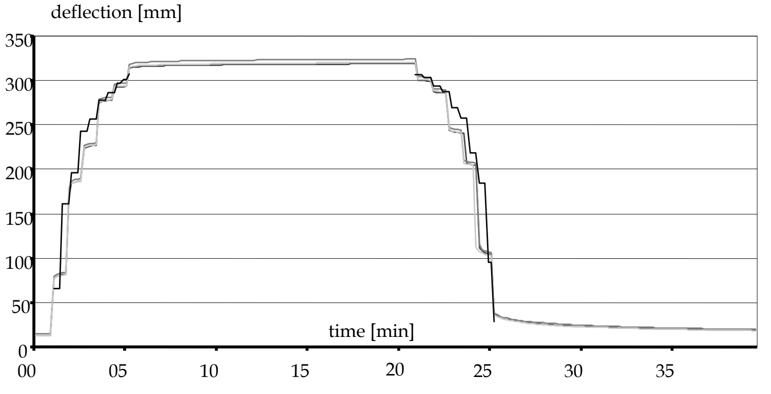



*Figure 7: Displacements of a PVB.2 laminate as a function of the load duration, for a loading time of five minutes*

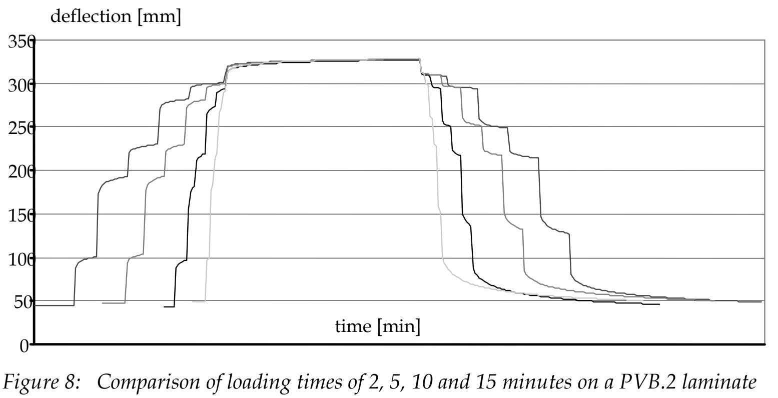



*Figure 8: Comparison of loading times of 2, 5, 10 and 15 minutes on a PVB.2 laminate*

due to creep of the interlayer. An example of creep curves after the last loading and unloading step respectively is shown in Figure 9 and Figure 10.
Based on our observations, a creeping time of 15 minutes between loading and unloading seemed suitable: it was short enough to be practicable in a busy laboratory environment, but long enough to register all significant measurements.
The basic response of the laminates was visco-elastic: when a plate was unloaded, it finally returned to its original shape. This process happened quickly in the beginning, but slowed down soon: the complete process lasted several hours. Since the time in between different loading cycles was typically only about 20 minutes, initial deflections had grown after each cycle (Table 4 column 2). The maximum absolute deflection after each loading cycle, however, stayed quite constant (Table 4. column 3). After a period of 15 minutes under a constant loading of 90 kg, PVB.A laminates typically showed an additional deflection of about 4 millimetres. The loading speed did not influence the value of the final deflection. It did have an effect, however, on the plate's relaxation: a high loading speed resulted in relatively larger additional deflections during the first moments after a constant loading was applied, as can be seen in Figure 11.

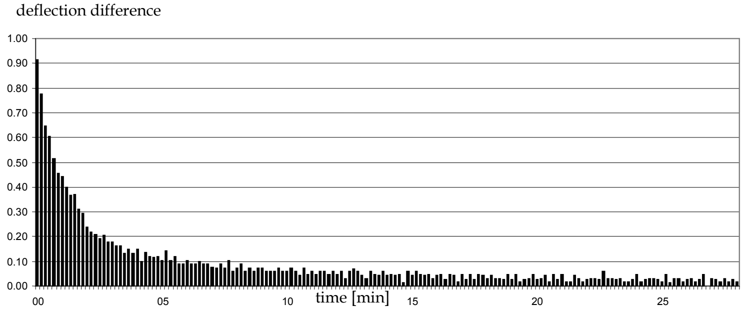



*Figure 9: Creep curves after last loading step*

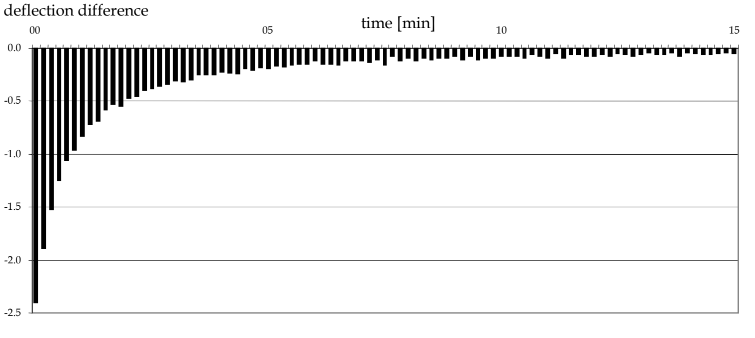



*Figure 10: Creep curves after last unloading step*

In correspondence to the increased initial deflection at the beginning of each loading cycle, also the remaining deflection after each unloading cycle increased (see above, Table 4, column 5). A similar behaviour was observed as well in case the glass panels were positioned upside down, or if a higher load was used.
Even if the basic behaviour of the PVB.4 test specimens was comparable to the PVB.A, there were some significant differences. First, in contrast to the PVB.A series, an important dispersion of the deflections was observed within the PVB.4 series, as can be noticed in Figure 12.
The second difference refers to the initial deflection caused by gravity forces on the unloaded cantilevered glass panel. The magnitude of this deflection was virtually constant within each test series. When the different test series were compared, however, initial deformations were larger for acoustic PVB and smaller for PVB.4 laminates, while PVB.2 specimens were situated in between. This is easily explained: for a given shear stiffness of the interlayer the overall second

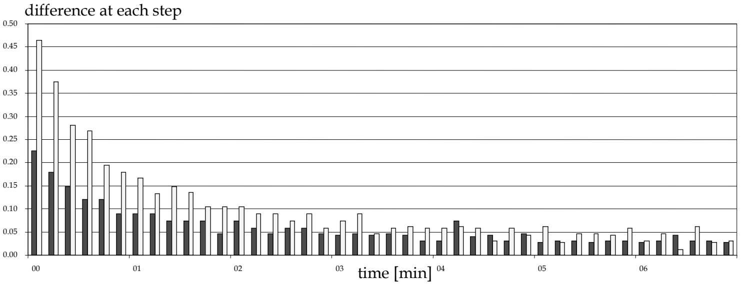



*Figure 11: Comparison of deflection growth for a PVB.A laminate at a loading speed of 15 minutes (dark grey) and 2 minutes (white)*

*Table 4: Experimental deflections of specimen number 9 during different loading cycles at room temperature (20 +/- 1° C)*

| loading | deflections [mm] | | | | |
|---|---|---|---|---|---|
| time [min] | initial | after loading | after relaxation | after unloading | after relaxation |
| 5 | 12.77 | 316.13 | 320.35 | 36.11 | 18.49 |
| 5 | 17.66 | 316.44 | 320.48 | 40.14 | 21.60 |
| 15 | 20.45 | 317.95 | 321.25 | 47.17 | 25.37 |
| 15 | 24.12 | 318.70 | 322.01 | 43.20 | 28.19 |
| 10 | 27.09 | 319.75 | 323.42 | 46.45 | 30.52 |
| 10 | 28.90 | 318.74 | 322.12 | 48.05 | 32.18 |
| 2 | 29.93 | 317.40 | 322.13 | 54.12 | 32.34 |
| 2 | 31.28 | 317.53 | 322.11 | 54.88 | 32.48 |

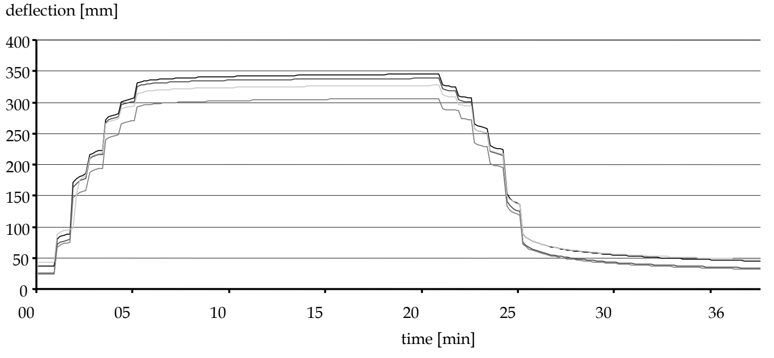



*Figure 12: Experimental deflections for PVB.4 laminates*

moment of area of PVB.4 laminates was larger because both glass plates were positioned at a larger distance from each other, so they reacted more rigidly than the other types.
As for PVB.A, which had the same thickness as PVB.2, the softer interlayer resulted in a lower bending stiffness of the laminate.
In the end, the PVB.2 laminates could not be compared to the other types. The limited thickness of the interlayer did not provide enough shear deformation at room temperature, as illustrated in Figure 13. During the tests on PVB.4, the relative shift of both glass blades could easily equal the interlayer thickness, as can be seen in Figure 14. As a result, high stresses appeared in the glass very early during the bending process: fracture occurred far before the complete 90 kg was applied, as shown in Figure 15. Fractures initiated in the same zone every time, namely at the long edge of the plate about 40 centimetres from the clamped edge, as illustrated in Figure 16. Close inspections of specimens and mould did not reveal any errors or imperfections. However, this position of crack initiation could be explained numerically (see also § 4.3.3).

### *3.3.2 Second test type: bending with heater*

Since PVB.2 type laminates were clearly not suitable for bending at room temperature with a bending radius of three metres, a lightweight infrared heater was used to heat the laminate

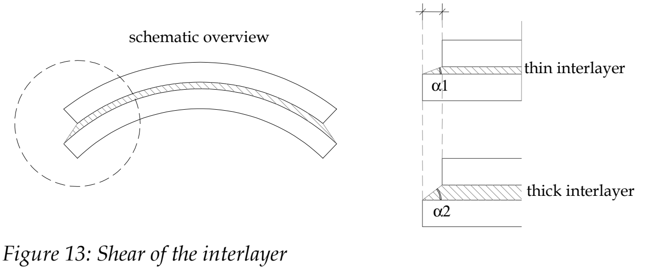



*Figure 13: Shear of the interlayer*

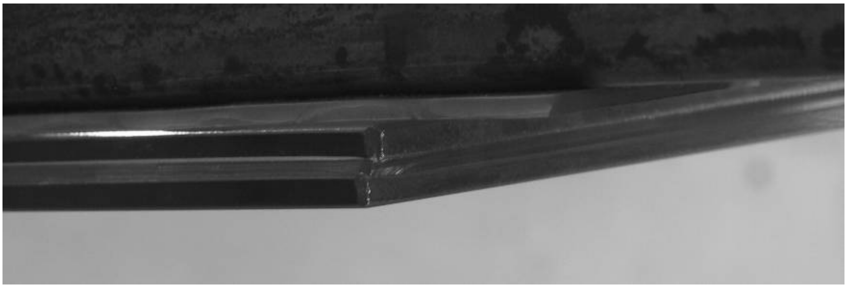


*Figure 14: Relative shift of glass plates during the bending process of PVB.4 laminates*

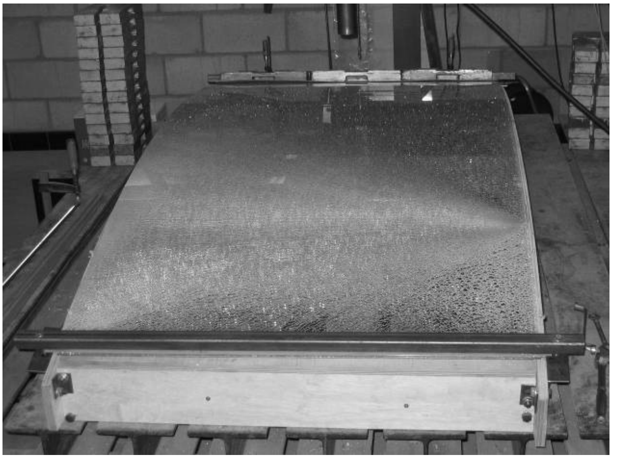


*Figure 15: Preliminary failure of a PVB.2 laminate*

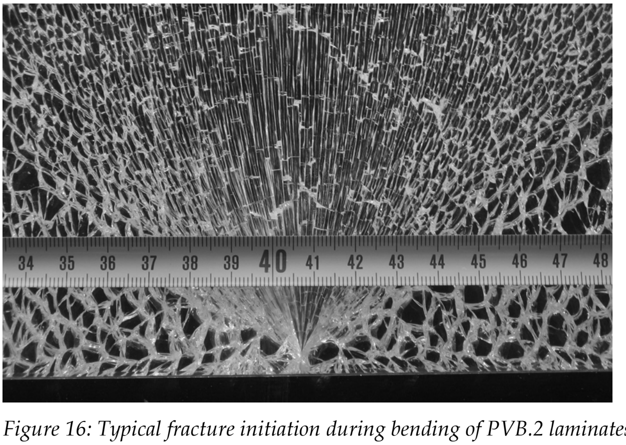



*Figure 16: Typical fracture initiation during bending of PVB.2 laminates*

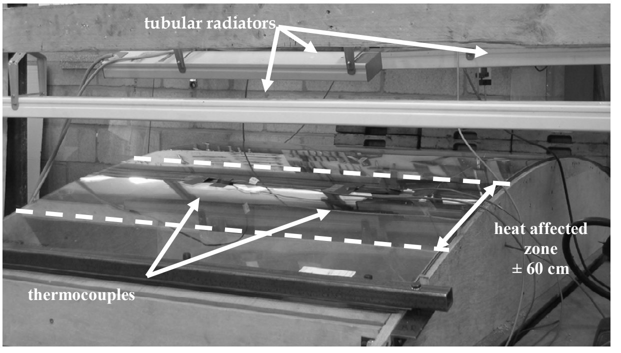



*Figure 17: Tubular lightweight heaters used to heat specimens locally up to 45° C during the bending process*

locally up to 45° C, see Figure 17. The temperature of the heated zone was controlled by thermocouples and could be kept constant with a precision of +/- 1° C. Bending results for a heated laminate are given in Table 5.

### 3.3.3 *Second test type: bending with heater*

Since PVB.2 type laminates were clearly not suitable for bending at room temperature with a bending radius of three metres, a lightweight infrared heater was used to heat the laminate locally up to 45° C, see Figure 17. The temperature of the heated zone was controlled by thermocouples and could be kept constant with a precision of +/- 1° C. Bending results for a heated laminate are given in Table 5.

*Table 5: Bending results for heated specimen number 2 (45° C) with a 0.76 millimetres thick standard PVB*

| cycle time | deflections [mm] | | | | |
|---|---|---|---|---|---|
| [min] | initial | after loading | after relaxation | after unloading | after relaxation |
| 3 | 43.22 | 312.11 | 320.30 | 103.55 | 73.93 |
| 3 | 72.49 | 315.33 | 322.61 | 119.26 | 86.27 |
| 3 | 85.87 | 316.80 | 323.59 | 127.56 | 95.47 |

A general effect of the heating was the large initial deformation of the unloaded specimen. The increased temperature clearly magnified the effects of creep. This is in perfect accordance with the theoretical models for the shear modulus of PVB, where a temperature increase corresponds with a horizontal shift of the shear modulus curve (see also § 2.2).

A plot of the unloaded plate deflection against the heater exposure time is put into relation with the temperature registration of two thermocouples on each side of the laminate in Figure 18. The initial undulation of the deflection line was caused by a differential thermal expansion between the two glass panes of the laminate. This changing effect was the consequence of the unilateral heating, which was only applied at the convex side of the glass [Vander Beken, 2006]. After 13 minutes of exposure time, initial deflections were only increasing, with a jump at 20° C. The jump corresponds with an average glass temperature of about 40° C. After half an hour exposure time, a uniform temperature of 45° C was established throughout the thickness of the affected zone.

### 3.3.4 *Third test type: necessary loads for complete bending*

In order to estimate practical consequences, the loads necessary to bend the different specimens completely on the mould have been determined. An overview of the mean loads is given in Table 6. The specimens with a soft acoustic interlayer could easily be bent manually. For PVB.4 specimens on the contrary, a mechanical device would be necessary to be able to bend and attach the glass panel completely to a curved frame.

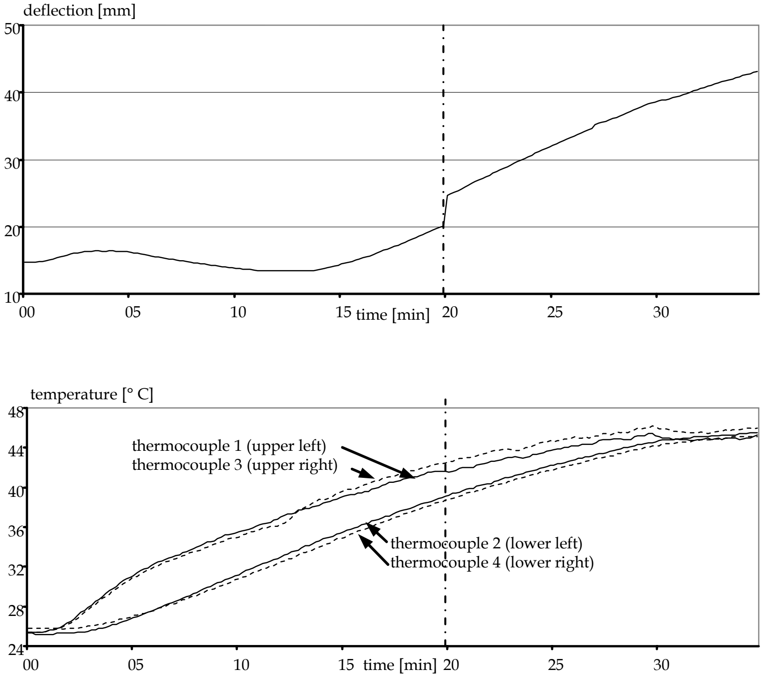



*Figure 18: Deflection of an unloaded PVB.2 specimen against heater exposure time (above) and glass temperature registration against heater exposure time (below)*

*Table 6: Mean bending loads for different experimental testing series in order to bend the laminates completely onto the mould*

| Series | mean load [N] | Remarks |
|---|---|---|
| PVB.A | 1275.3 | at room temperature |
| PVB.2 | 1471.5 | at room temperature ; only 1 specimen did not break |
| | 1373.4 | at 45° C |
| PVB.4 | 1765.8 | at room temperature |

For all series, the difference between the deflections of two consequent loading steps was the largest at the beginning of a loading cycle and at the end of an unloading cycle. Although this was not independent from the time effect on the shear of the interlayer, the main reason for this observation was the difference in cantilever distance. After each step of the bending process, a larger zone of the plate came into contact with the mould. As a consequence, the cantilever distance of the unclamped laminate part became shorter and a higher load was required in order to produce the required bending moment on the plate: the load increase was partly compensated by the shortening of the cantilever distance, as can be seen in Figure 19.

# 4 Numerical simulations

## *4.1 Aim*

The aim of the numerical simulations was to evaluate numerical models based on material characteristics from literature in comparison to the experimental results. In addition to the deflections, the mechanical stress distribution during the bending process has been examined numerically.

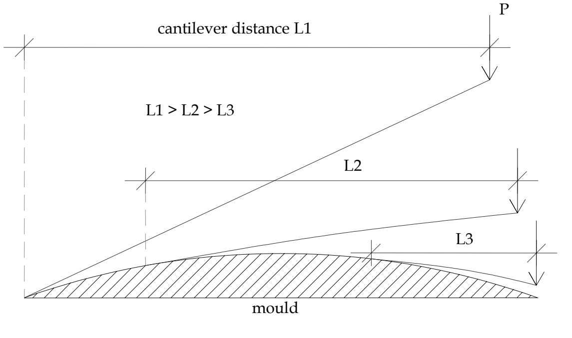



*Figure 19: Gradual shortening of the cantilever distance during the bending process*

### 4.2 *Models*

#### *4.2.1 General*

All nonlinear and visco-elastic numerical simulations have been conducted with the finite elements software Abaqus. 3D continuum elements have been used to model both glass and interlayer. The geometry of the laminates was based on nominal values: any production tolerances were not taken into account. Since deformations of the mould were not of interest during the analyses, it was modelled as a rigid body.

The reference temperature for all material properties of PVB is 20° C, which was in good agreement with experimental circumstances. The visco-elastic variation of the shear modulus of PVB was modelled according to Van Duser, Jagota and Bennison (see also §  2). Please note that the material model these authors proposed is basically valid for Butacite PVB and should be treated cautiously for other types of PVB. In the present contribution, it has been evaluated for a "standard" PVB. Due to a lack of experimental references of the 0.76 millimetres standard PVB, only specimens with a 1.52 millimetres thick standard PVB have been considered for numerical evaluation (see also § 3.3.1).

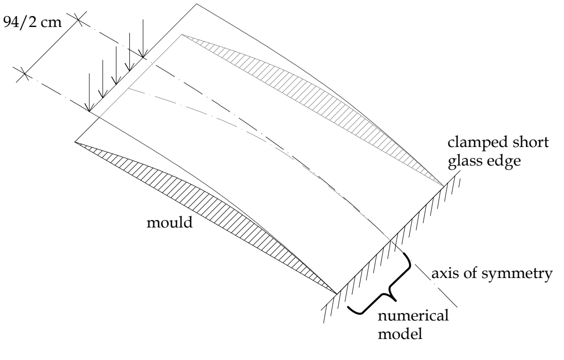



*Figure 20: Symmetry conditions for numerical modelling of the bending process*

Acoustic PVB has not been examined numerically since no proper material model was available for such a soft interlayer. Symmetry conditions have been applied on the model along the axis in the middle of the plate, perpendicularly to its short edges, as shown in Figure 20.

#### *4.2.2 Boundary conditions*

In the experimental tests, glass plates were clamped on the mould by means of a steel hollow section. This boundary condition provided -to a certain extent- a fixation of the clamped edge.

The real level of fixation was unknown and therefore hard to model. Therefore, two different boundary conditions have been evaluated: the first fixes the edges of both glass panels completely, whereas in the second the edge of only the lower glass panel was fixed, enabling the edge of the upper glass panel to move freely in the curved plane, as illustrated in Figure 21. The first option was believed to be too rigid, while the second was assumed to be too weak. The real boundary condition was expected to be situated somewhere in between.

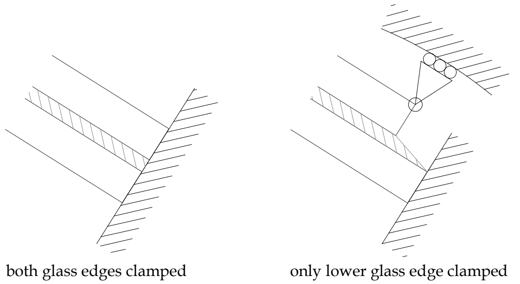



*Figure 21: Modelling boundary conditions: both glass plates fixed (left) and only the lower glass plate fixed (right)*

### 4.3 ***Analyses***

#### *4.3.1 Displacements*

All numerical analyses started from a perfectly straight laminate that was tangent to the mould. In reality, however, the laminate was not straight and a larger zone was in contact with the mould from the beginning onwards. Moreover, the initial deflection in the experiments could not be quantified. These factors caused difficulties for a correct interpretation of absolute deflections, which could only be evaluated quantitatively.
For this reason, the focus was mainly on the relative displacements, in particular due to creep action. The loading scheme is comparable to the experimental situation where the mass of 90 kg was applied in a time period of 15 minutes, as illustrated in Figure 22.

#### *4.3.2 Loads*

The bending loads that are necessary to bend the laminate on the mould to such an extent that the free edge can be fixed to the frame were compared, as can be seen in Figure 23.
Table 7 shows that both boundary conditions resulted in a model that was too flexible; the necessary load lied below the experimental value. The numerically obtained bending load on a laminate with two fixed glass edges was closer to the experimental value, but was still about five

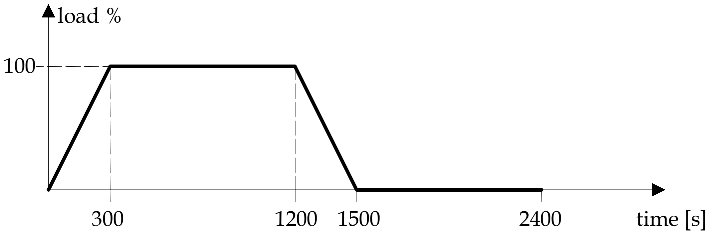



*Figure 22: Typical loading cycle in numerical simulations (in the example shown a loading time of 15 cm is applied)*

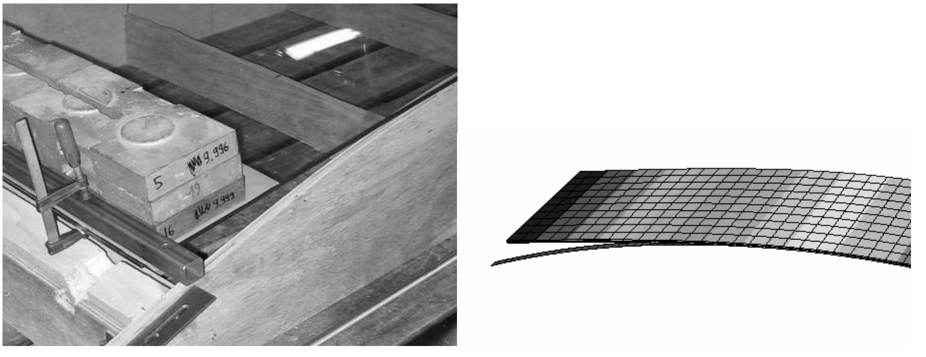


*Figure 23: The end of the bending process: the cantilever edge of the laminate could be attached to the mould (left: experimental test, right: numerical simulation of vertical displacements)*

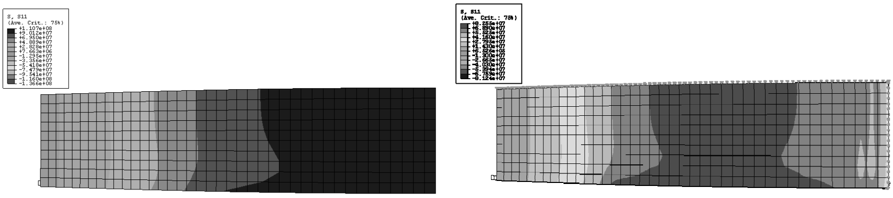
*Table 7: Necessary loads for complete bending on the mould, for numerical and experimental boundary conditions*

| Boundary conditions | bending load [N] |
|---|---|
| Numerical, one glass plate fixed | 1408.4 |
| Numerical, both glass plates fixed | 1676.2 |
| experimental | 1765.8 |

percent too small. A possible explanation could be the difference between real and assumed material properties.

#### *4.3.3 Stresses*

Both types of boundary conditions have been used to evaluate stress distributions during the cold bending process. The focus was on the migration of stresses with respect to loading durations, and not on the detailed quantitative approach, which would probably require a finer element mesh. The difference in stress patterns for both situations is illustrated for a step time of five minutes, immediately after the 900 N load has been applied, in Figure 24. Stress levels are different as well: in case both glass panels were fixed along the short edge, maximum bending stresses appeared near the clamped edge, with maximum stress values close to the conventional breaking stress of toughened glass. This did not correspond well to the experiments.



*Stress values are given in N/mm². The clamped edge is situated on the right hand side.*

*Figure 24: Birdseye view on the stress patterns on the upper glass plate in case both plates are fixed at the right edge (figure on the left) and in case only the lower glass plate is fixed at the right edge (figure on the right)*

An argument in favour of the other modelling conditions (only the lower glass panel fixed along the clamped edge), was the good geometrical correspondence of the shifting edges during the bending process. The correspondence between the shift in the numerical model and in the experiments is illustrated in Figure 25. For these reasons the model with only one glass panel fixed was considered to be more appropriate. The evolution of the stress distributions during a loading cycle are illustrated in Figure 26. Numerical simulations of the PVB.2 series revealed a qualitatively completely similar stress distribution as shown above. The reduced interlayer thickness, however, resulted in a significant increase of the stress level. The location of the maximum stresses corresponded reasonably well with the experimental observations of failure. Taking into account that the protective layer of residual compressive stresses due to the toughening process had a reduced thickness in the neighbourhood of the glass edges, the edges

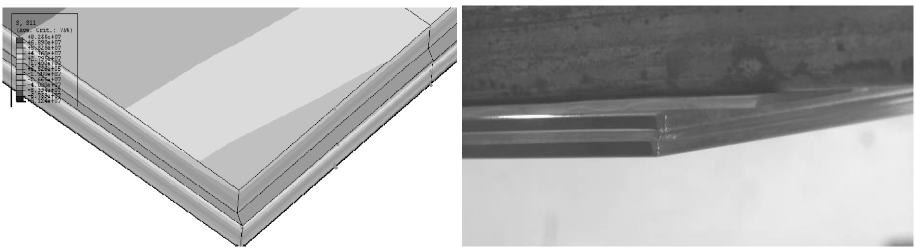
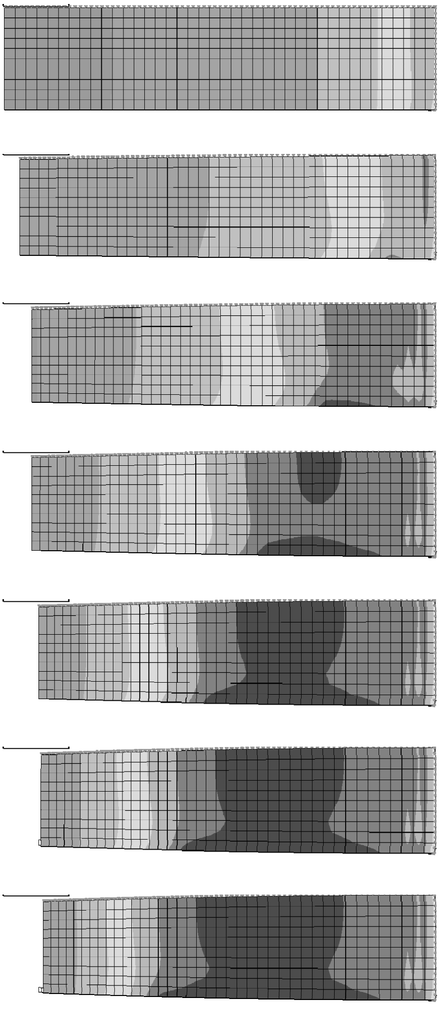


*Figure 25: Relative shift of both glass plates of a laminate during the bending process (left: numerical simulation, right: experimental observation)*



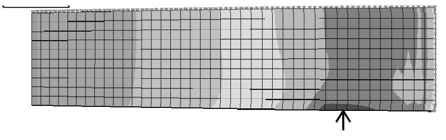
*The clamped edge is situated on the right hand side.*

*Figure 26: Stress distributions on the upper glass plate of a PVB.4 laminate during a loading cycle o 5 minutes – only the lower glass plate was clamped. (Loading time progress from top to bottom: 0 s, 45 s, 101 s, 143 s, 200 s, 257 s, 314 s).*

were more vulnerable to tensile stresses than the rest of the glass plate [Laufs, 2000], [Redner and Hoffman, 2001]. As a consequence of the appearing stress pattern, the stress level and the weakened glass edges, the position of crack initiation during the experiments could be explained -see also § 3.3.1 and Figure 27.

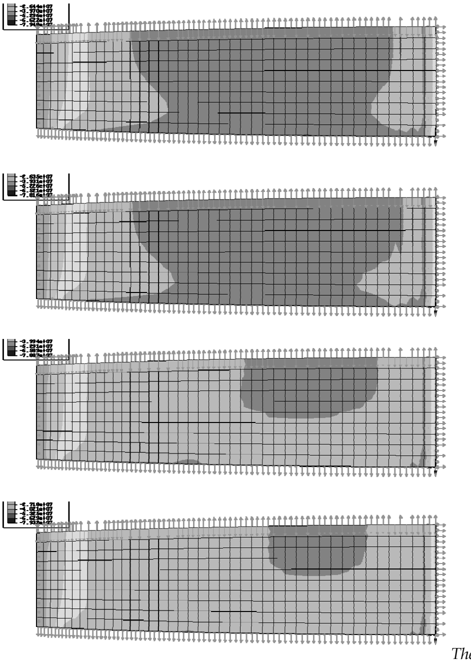
### 4.3.4 *Relaxation*

From the analysis of destructive experimental tests on cold bent laminated glass panels it is known that the failure load is influenced by the relaxation time before loading [Belis, Inghelbrecht, Van Impe and Callewaert, 2007]. For this reason, the numerical models that are discussed above have been used to examine the stress relaxation after the cold bending process, starting from the moment the plate is completely positioned in its curved frame. The overview of



*The clamped edge is situated on the right hand side.*

*Figure 27: Numerical stress pattern in the upper glass plate after a bending process of 101 seconds on a laminate with a 0.76 mm thick standard PVB interlayer, at 20° C. Maximal stress locations (indicated in dark grey) correspond well to experimental observations of crack initiation (see also § 3.3.1)*



*The clamped edge is situated on the right hand side.*

*Figure 28: Stress relaxation in upper glass plate after complete bending of a PVB.4 series laminate. (Top to bottom: immediately after bending, after 30 minutes, after 57 hours, and after 5 days)*

stress distributions in the upper glass plate (Figure 28) demonstrates that a major stress relief has happened after five days of relaxation.

# 5 Conclusions

In the present research of a cold bending process on a circular bending mould with a radius of three metres, the major influencing factors have been determined. The most important are the type of the interlayer, the loading speed and the operating temperature. More specifically, the following conclusions can be drawn:

- Glass laminates composed of two four millimetres thick toughened glass panes and an interlayer of acoustic PVB (0.76 millimetres) or a standard PVB with sufficient thickness (1.52 millimetres) are suitable for a cold bending process with a radius of only three metres. Hence in this contribution only the bending process is evaluated, and not the load-bearing capacity of the bent laminates.
- A thickness of 0.76 millimetres is not sufficient to redistribute the shear stresses in a standard PVB interlayer without transferring too many stresses between both glass panels. At 20° C, such laminates are very likely to break at a low bending load.
- Experimental failure of laminates with a 0.76 millimetres standard PVB interlayer can be explained numerically. Numerical failure stresses appear at the same locations where experimental crack initiation was observed.
- The examined PVB.A laminates could be bent on the mould manually by one man. The PVB.4 laminates, however required a bending load for which a supplementary operator or mechanical device is necessary.
- All laminates show a visco-elastic load-deflection behaviour: deformations will grow even under a constant load. The deflection growth loses significance quickly as loading time passes.
- Numerical results are qualitatively in good agreement with experimental results, but generally overestimate deflections.
- More bending forces are needed as the contact area between the laminate and the circular mould grows during the process, since the cantilever distance for the bending moment diminishes.
- Unloading cycles reveal a visco-elastic effect as well. A small remaining deformation was noticed after complete unloading, probably because the duration of the experiments was smaller than the period of time necessary for full shape recovery.
- For numerical stress analysis purposes, boundary conditions in which the edge of only the lower glass panel is clamped are more reliable.

- Local heating of the laminates decreases the overall bending stiffness visibly.
- A lightweight tubular heater made it possible to bend a laminate with a 0.76 millimetres standard PVB interlayer. Since the heating was local, could be applied on the building site and was limited to 45° C, the procedure is still considered to be a "cold bending process".

***Acknowledgements***
The authors wish to thank BRS (Moerkapelle, The Netherlands) for the laminated glass test specimens. Dennis Elias, Eric Vonck, Wouter Praet and Jeroen Vander Beken are acknowledged for their support during the laboratory experiments.

## References

Abaqus, Inc. (2004) Manuals, USA.

Belis, J. (2005) *Kipsterkte van monolithische en gelamineerde glazen liggers*, Ghent: Ghent University.

Belis, J, B. Inghelbrecht, R. Van Impe and D. Callewaert (2007) 'Experimental Assessment of Cold-bent Glass Panels', in Proceedings of *Glass Performance Days*, pp. 115-117.

BRS freeformglass, http://www.freeformglass.nl.

CEN European Standard EN 572-1 (2004) *Glass in buildings: Basic soda lime silicate glass products – Part 1: Definitions and general physical and mechanical properties*.

Laufs, W. (2000) *Ein Bemessungskonzept zur Festigkeit thermisch vorgespannter Gläser*, Aachen: Shaker Verlag.

Redner, A. S and B. R. Hoffman (2001) 'Detection of Tensile Stresses Near Edges of Laminated and TEmered Glass' in Proceedings of *Glass Processing Days*, pp. 589-591.

Vákár, L. and H. van Doorn (2000) 'Nieuw type gelaagd glas in situ koud buigbaar' in *Detail in architectuur*, april 2000, pp. 32-34.

Vákár, L. and M. Gaal (2004) 'Cold Bendable, Laminated Glass – New Possibilities in Design' in *Structural Engineering International*, 2/2004, pp. 95-97.

Van der Beken, J. (2006) Temperatuursafhankelijk gedrag van gelamineerd glas met een ionoplast tussenlaag, Ghent: not published.

Van Duser, A, A. Jagota and S.J. Bennison (1999) 'Analysis of Glass/Polyvinyl Butyral Laminates Subjected to Uniform Pressure' in *Journal of Engineering Mechanics*, April 2004, pp. 435-442.