Challenging Glass 3 – Conference on Architectural and Structural Applications of Glass,
TU Delft Bos, Louter, Nijsse, Veer (Eds.), TU Delft, June 2012.

Cold-Bent Single Curved Glass; Opportunities and Challenges in Freeform Facades

ir. Mark Feijen
i-Saac, the Netherlands, mark@i-saac.nl
ir. Ivo Vrouwe
Sint-Lucas School of Architecture, Belgium, info@ivovrouwe.net
Peter Thun
BRS, the Netherlands, p.thun@brs.nl

The use of freeform geometry in architectural design necessitates a progressive building industry to be materialized. Great progress has been made in shaping materials into double curved surfaces by moulds and milling techniques. However, using these techniques in a material and energy efficient way proves to be a great challenge. Current solutions often result in less affordable techniques. In this paper the opportunities and challenges of cold-bent single curved glass are discussed. In comparison to most design industries, the architectural industry often constructs large surfaces with relatively little curvature. By subdividing these double-curved surfaces into single-curved parts, the initial design is translated into a specific material efficient geometry. After translation, the geometry can be materialized in Cold-Bent Glass. In most cases these techniques can compete well with preformed glass solutions.

Keywords: Cold-Bent, Glass, Geometry, Freeform

1. Introduction

In the contemporary building industry, an interesting dialogue is conducted. On the one hand, designing architects push the industry forward to develop techniques and materials to be able to materialize their progressive digitally driven designs. On the other hand, interesting materials and technologies are generated to assist forthcoming demand with sufficient techniques.

When, in design, material reflection takes place at the end of the process, one can speak of a top-down or non-deterministic [1] approach. In this case the design forms the start point of the engineering process, materialization comes second. In conventional architecture, this routine is quite common and successful. In more advanced geometries, the translation from the digital model to the physical one, often behaves less fluently. The top-down approach takes a broad-minded building and engineering partner as well as an experienced architect to provide an appropriate result. When one of these parties don’t line up, the end result can differ greatly from the initial form or idea.

The bottom-up or deterministic [1] development, requires an industry that is skilled in communicating design orientated information and an architect that is capable of working within material and geometrical parameters. In most cases, the success rate of a proper materialization is higher than in the first case.

In this paper technical information is presented to assist architects and designers in understanding the use of curved surfaces, materialized in glass. In the first part of the paper, the basic concept of freeform glass is discussed. In the middle part a parameter study of a specific case is described. In the last part of the paper a well managed top-down design approach for a double-curved glass façade is presented.

2. Cold-Bent Single Curved Glass

The concept of “cold” bending of flat panels is a well know concept in industry in general. Materialization can range from plastics to wood and metals as shown in fig.1.

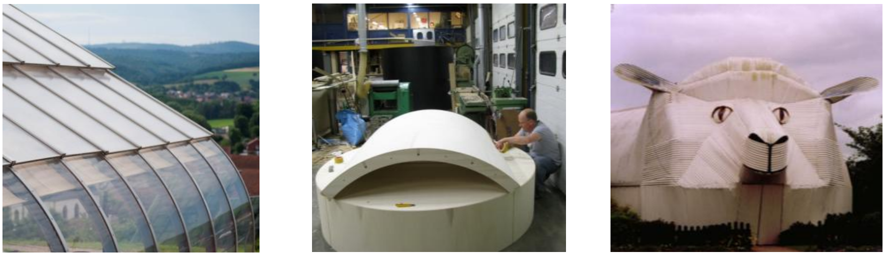

Figure 1a,b and c: “cold” bent Plexiglas in *Bio Solar Haus* in Germany; “cold” bent laminated wooden panels for stage setting of Barbara van Loon; “cold” bent corrugated steel panels (partly) in sheep shaped artwork in New Zealand

In cold bent materialization, glass does not seem to be the most obvious choice. The general perception of glass is still a brittle material with hardly any strength capabilities. The perception of glass as a brittle material is correct. The perception of glass having little strength is generally based on a misunderstanding. Over the last 20 years, an increasing amount of project and experiments were conducted with glass as main carrying component. To support this development, codes and standards [2] have been developed on maximum allowable tensile bending strength of glass.
Supported by FEM-Software and these well defined codes and standards at hand, investigation of material’s boundaries is more accessible. A study of cold bending of glass is one of the possibilities to support freeform architecture with a transparent materialization.

2.1. Basic concept

The concept of Cold bent glass is based on the pre-tensioned state of tempered glass. Simplified to a 2D problem, the bending stresses are superposed on the pretension state of the glass as presented in figure 2.

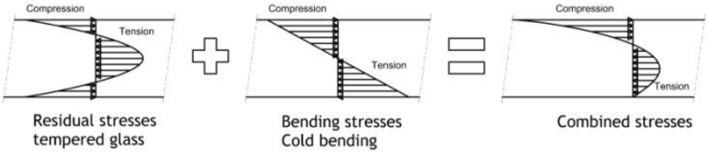

Figure 2: Superposing pretensions stresses and bending stresses

Theoretically the cold bending stresses can compensate the pretension stresses of the tempered glass entirely. However, bended to this limit won’t allow for additional loading as required by the codes and standards .

Due to cold bending, the stresses can be calculated by the formula:

$$\sigma = \frac{E \cdot t}{2 \cdot R} \tag{1}$$

Formula description: σ; bending stress, E; modulus of elasticity of glass, t; panel thickness, R; bending radius

Geometrically a perfect radius can be created by applying a constant bending moment on two opposite sides of the cold bent plate. The static scheme of this approach is shown in figure 3a.

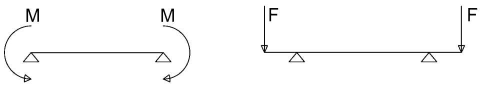

Figure 3a and b: left the static scheme for a perfect radius, right the approximation of a radius

In practice, it is difficult to apply a constant bending moment on a plate. By extending the plate on both sides of the supports first, creating a cantilever, and applying a force on both ends next, distance is introduced to apply the load (figure 3b). Doing so, the middle part of the plate will describe a perfect radius. Both ends will have deformed like a cantilevered beam with an end load.

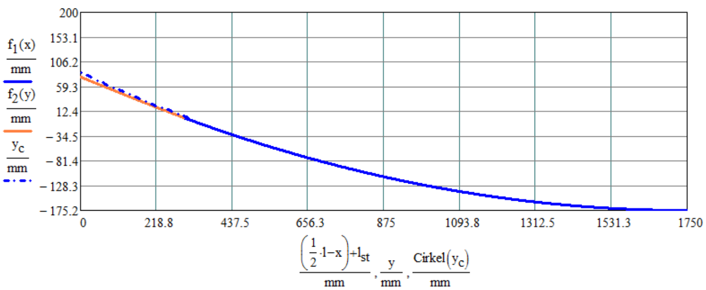

Figure 4: deviation of a circle (2D approzimation of a 3.0x1.5 m panel with thickness of 6 mm)

The approximated approach does not differ vastly from a perfect radius as presented in figure 4. The blue line represents a perfect radius. The orange line represents the deformation of both ends of the plate; cantilever deformation.

2.2. Parameter Study

The simplified structural approach, as described above, provides a sufficient description of the bending process. However, the study ignores the influence of the width of the cold bent glass panel. To obtain a better understanding and a solid exploration of the influence of the different parameters and limitations of cold bending, a parameter study has been performed. The study involves parameters like panel width, thickness and radius.

The study is based on a finite element analysis performed with the non linear FEM software ABAQUS. Cold bending of the glass panel is simulated by means of a contact simulation. This approach results in a better understanding of stress distribution in the panel during bending along a curved edges first, and the stress state after bending second. Sideways, the contact simulation produces contact stresses between the glass and the backing structure.

In figure 5a and b, the typical geometry of a model is presented. The model consists of a quarter of a glass panel, plotted in light blue, with symmetric boundary conditions. The curved backing structure , guiding the plate deformation, is a rigid part, plotted in green. The red curve element is a rigid element that assists deformation of the panel with the applied angle α (figure 5b; hoek α).

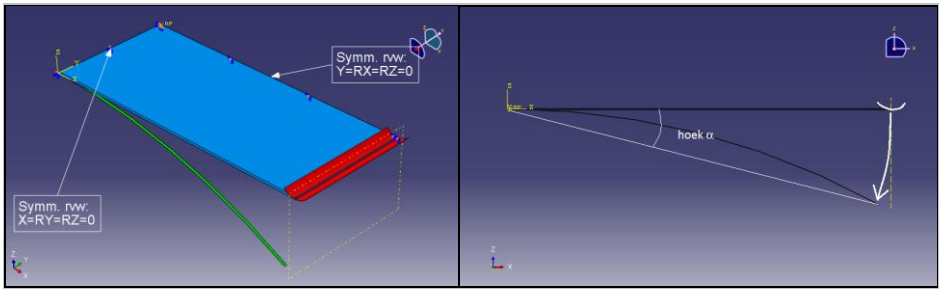

Figure 5a and b: typical geometry of model for contact simulation and applied deformation.

To simplify the first simulation step in this study, a model of a monolithic panel is used. By doing so, the complexity of the non-linear problem, as present in double layered panels, is reduced. The simulation is a step-by-step approach. In a later stage the research project will be supplemented with bending models for laminated glass and insulated glass.

The start dimension of the model is a panel of 3500 x 1500 x 6 mm. The model is based on the panel dimension of a realized case study. This case is not presented in this paper. In the parameter study the radius varies from 3.5 to 6, 9 and 12 meters, the thickness varies from 4, 6, 8 to 10 mm and the width is varies from 500 to 3500 mm in steps of 500 mm. For this case, the length of the plate was a fixed value.

A characteristic result of bending stresses in the plate model is presented in figure 6. A colour contour of the stresses in tangential direction is plotted (top fiber stresses). A stress peak in the plate occurs near the described structural contact egde.

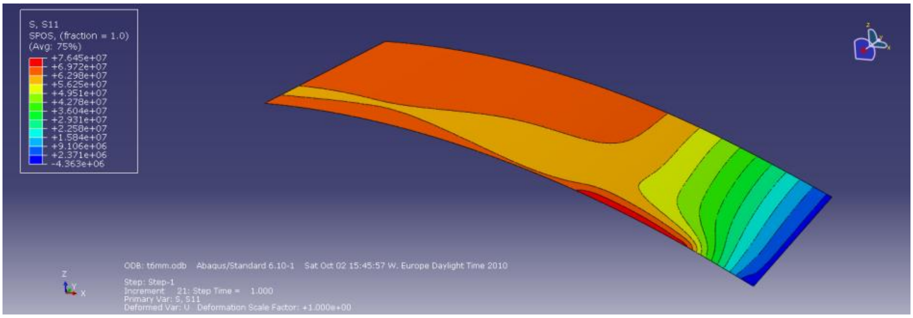

Figure 6: Typical bending stress (stresses in tangential direction) of a cold bent panel in end situation. Panel size: 3000x1500x6 mm, bending radius 3.5 meter

The variation of the radius and thickness results in relatively easily scalable stress results. The results follow the standard stress and strain relations between bending radius and thickness as expected acoording to formula (1).

Less predictable are the results of the variation of width. The panel is only kept in shape along the two longitudinal edges. In between these two edges the panel is unconstrainted and will tend to flatten out. Over a certain length to width ratio this effect will be visible in the reflection of the glass. This flattening effect is clearly visible when one compares the stress results in different longitudinal panel sections of two separate panels with a different width (graphs in figure 7 and 8).

The panel in the graph in figure 7 is 3500x 500 x 6 mm, the panel in the graph in figure 8 is 3500 x 3500 x 6 mm. The bending radius is 3.5 meter. In both graphs the smooth line represents the section along the symmetry line of the panel (the exact middle) and the section line with the"peak" stress along the edge of the panel.

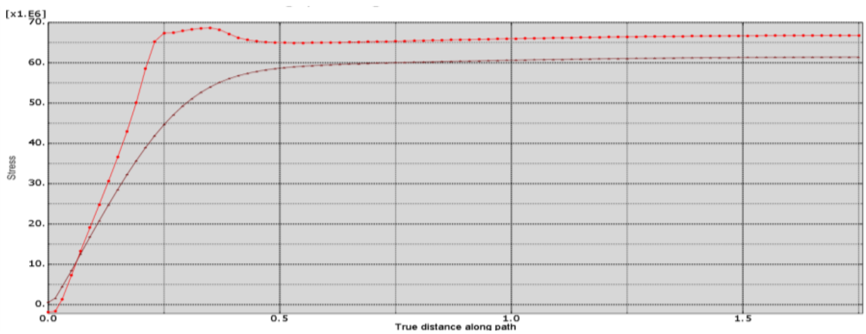

Figure 7: Bending along longitudinal edge of the model at the contact edge (with the peak stress) and along symmetry axis side (smooth curve). Panel size: 3000 x 500 x 6 mm

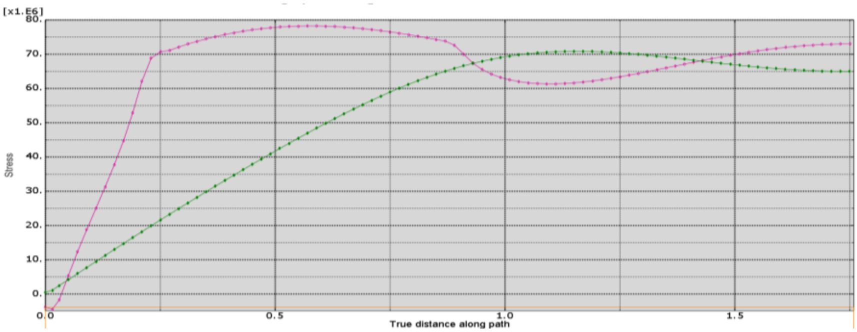

Figure 8: Bending along longitudinal edge of the model at the contact edge (with the peak stress) and along symmetry axis side (smooth curve). Panel size: 3000x3500x6 mm

In figure 7, the stress in both section lines behave much alike, whereas the behaviour of the lines in figure 8 differs significantly. This large difference in the stresses is clearly visible in the deformation plots.
The exact boundary between acceptable and inacceptable deformation difference is difficult to determin. A practical guideline is width/length ratio of 1/2.

The peak stresses in the longitudinal edge sections occurs nearby the contact area between the glass and the backing structure. The contact location indicates a similar “cantilever” effect as described in section 2.1 (figure 2 and 3).

The expected cold bending stress based on formula (1) for these panels is 60 N/mm^2. If the peak stresses found in the finite element results are related to the expected cold bending stress in a graph as presented in figure 9, the peak stress values can be predicted for a given panel width. This assumption creates a procedure to determine the maximum stress in the panel due to cold bending.

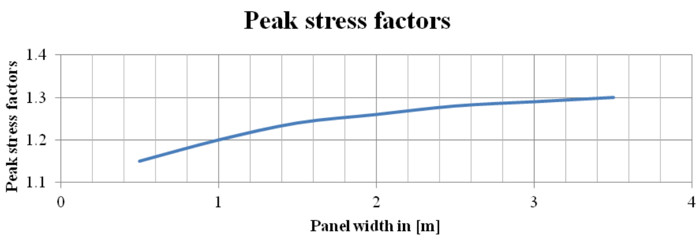

Figure 9: Peak stress factor in relation to the width of the panel (Length 3.5 m, radius 3.5 m)

3. New Headquarters of the Council of the European Union

The study for the new headquarters of the Council of the European Union in Brussels, a design by Samyn and Partners, is an example of a non-deterministic colt bent glass materialization. The initial design was made by double curved glass panels. By describing alternatives in cold-bent glass, different options were compared.

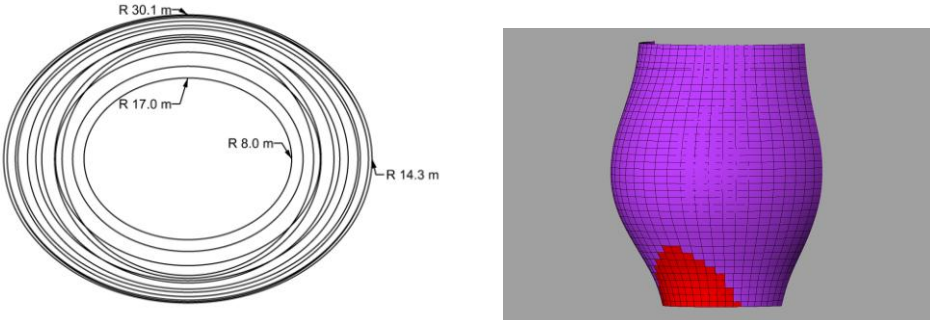

Figure 10a and b: Design Geometry and Surface Curve Analysis

The geometry of the initial design is described by connecting thirteen elliptic forms. The ratio of length to width varied per segment. Every ellipse was elevated by 1.18 meter per segment. Next, every elevation was filled in with three horizontal lines of curved glass segments.

By using custom scripts, every panel within the geometry is measured in radius. Panels with a bending radius of 12 meters and more, displayed in figure 10b in purple, were assumed to be realized in cold-bent glass. Panels curved in a radius of 12 meters or less, plotted in red, were assumed to be critical for cold bent insulated glass and had to be realized in an alternative way.

Figure 11a, b and c: Design Geometry and Surface Curve Analysis

Due to the limited curve differences and a small horizontal shift from one ellipse to the next, every horizontal section strip was conceived as a straight tubular cut. Unrolling the section provided a flat single curved panel in projected view. By subdividing the unrolled section, the individual panels were generated.

To be able to cut cutting costs, several panels within the geometry were compared to elements with straight instead of curved outlines. Deviations of 5 millimeter or less could be assimilated within the connection detail. A small selection of parts behaved within the parameters of this group.

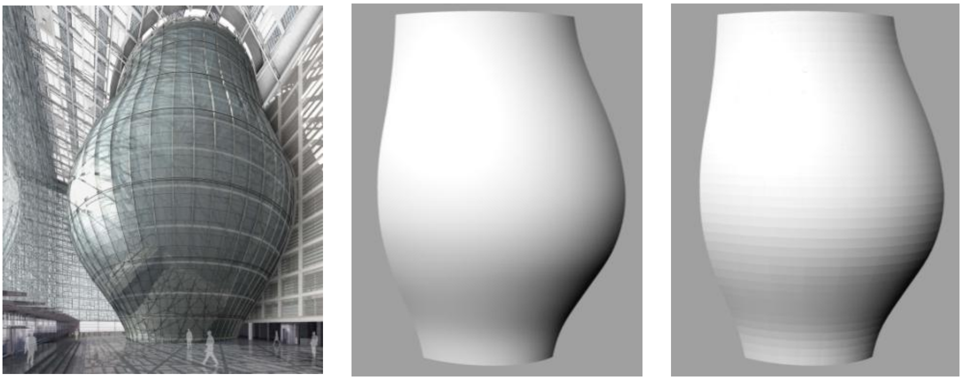

Figure 12a, b and c: The initial design, a quarter of the surface geometry and the section described by single curved panels. (3a Computer rendering polygon graphics 2008 by Philippe Samyn and Parners architects & engineers,Lead and Design Partners)

4. Conclusion and Further Research

Using single curved cold bent glass for double curved architectural envelopes shows great potential. Evolving double curved surfaces to material efficient, single curved geometries, proves to be a less expensive alternative. Due to large surfaces used in architecture, visual distortion due to faceted construction is reduced to a minimum. Architecturally, further research is needed in material connection in various angles. In further studies, mockups will be used to explore different connection types and principles.

Structurally, determining the limitations of cold bent glass is a work in progress. The scope of the study for the near future will be a further investigating of the behavior of layer panels of glass (laminated and insulate). The aim of these upcoming research steps is to develop practical and time efficient calculation methods for cold bent laminated and insulated glass. Mockups will be use to explore boundary conditions of cold bent glass curvature. Hereby, different techniques of curving the glass will be tested.

5. References

[1] Hanafin, Stuart; Pitts, Greg, *Non-Deterministic Exploration through Parametric Design,* international journal of architectural computing, issue 4, volume 7, 2009.

[2] NEN 2608, 2nd design code januari 2011; Glass in building – Requirements and determination method.

[3] Belis,J. , B.Inghelbrecht, R. Van Impe, D.Callewaert ‘Cold Bending of Laminated Glass panels; HERON Vol. 52 2007 No,1/2