Shaping ultra-thin glass

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Abstract

Ultra-thin glass is neither a new product nor new to the building environment. It is yet very little utilized in translucent facades for stiffness, detailing and cost reasons. This paper describes the elaboration of a cold bent ultra-thin glass sculpture, from concept to procurement, with explorations worth the eye of the façade designers. The design tools, FE analysis and testing procedure and fabrication of the glass elements are documented.

1 Introduction

In the building environment, transportation, household or artistic applications, glass is generally formed by slumping process, at temperatures exceeding 600 deg.C. The works described herein are based on the elastic deformation of the glass, which means that the glass is shaped without the use of heat but only by application of a sustained loading. This engages the glass structurally, not only as a rigid body transferring load like in the audacious Serres de la Villette by Peter Rice and RFR but where the glass compounds are subject to permanent internal bending forces like in other project RFR projects, such as the Avignon and Strasbourg railway stations.
The present work, of a much smaller scale, is a sculpture made of cold bent 200 μm glass strips, where the stability and the rigidity of the system is ensured by the internal bending forces of the glass, locked into the strips connected to one another. The sculpture measures 750mm by 750mm on plan and 700mm in height. This project demonstrates how an iterative analysis of the geometry and the internal forces can result into a rigid free form system, a process that is scalable to the built environment.
The use of thin glass in the built environment has many advantages. A stiff and thin glass façade system allows for the reduction of the glass weight supported by the superstructure, impacting transportation costs and energy demands as a result. The durability of glass in a chemical or corrosive environment and to UV is an asset, it is scratch resistant and hermetic, compared to other thin materials such as polycarbonate or ETFE, and ultimately the optical clarity of the glass is unequaled.
Until now, thin glass products such as Corning Gorilla and Willow glass are used in the building environment within a laminate compound, mainly for interior flat applications such as wall cladding (Corning Inc, 2016).
This article presents the fundamentals of glass cold bending, the properties of the thin glass product used for the project, the elaboration of the geometry, the structural analysis and the fabrication.

2 Cold bent glass

Cold bending a glass element consists of deforming it elastically, without the use of heat. Maintaining the bending force is required to keep the curvature of the glass element. The geometry resulting from the elastic deformation of flat elements is called a developable surface. This requires no distortion of the original flat element, as discussed in further detail in chapter 4.
Cold bending is particularly interesting in the built environment for the reason that it does not require any heating process. The bending process can occur in factory or on site, at virtually at any ambient temperature.
The façades of several architectural projects comport cold bent glass panels, such as the Avignon train station in France or the IAC Headquarters in New York (respectively Figure 1 and Figure 2). For these two projects, glass sheets were assembled in Insulated Glass Units (IGU) and the limiting component wasn't the glass itself but the shear of the primary seal of the IGU. This limitation lead to larger curvature radii than the one the glass sheets alone could sustain. Here the geometry allows to keep each strip in place and the structure stable only because of to the connection to the adjacent glass pieces.
Glass warm bending – also called two step bending, cold-lamination bending, lamination bending – consists of piling up sheets of glass and interlayer(s), bending the stack onto a support jig and then laminating it in autoclave. When the initial bending force is removed and the laminate removed from the jig, the shear in the interlayer prevents the assembly from completely flattening. The use of the term warm for this fabrication process derives from the fact that the lamination process requires to heat up the compound to ensure the adhesion of the interlayer to the glass. The lamination temperature, which depends on the interlayer material and pressure is approximately 80 to 140 deg.C which which is well below the softening temperature of glass, which exceeds 600 deg.C. Given the relative softness of certain interlayers, the glass laminate may partially

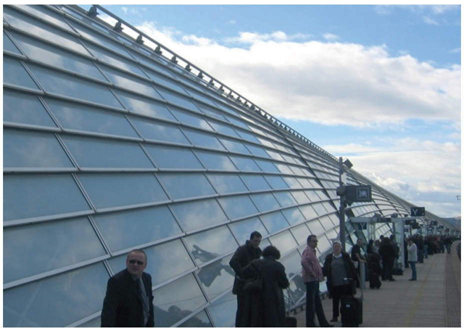
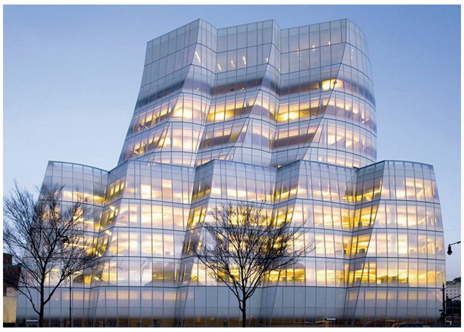


Figure 1,2,3 – Cold bent glass architectural projects precedents (left to right) : Strasbourg Railway station (2011, AREP+Dutilleul) IAC Headquarters (2007, Gehry architects) Strasbourg Railway station (2007, AREP+Dutilleul)

spring back. (Knippers, Filduth, Badassini, Pennetier, 2014) propose a time history study of warm bent laminates.
The glass panels of the Strasbourg train station have been curved using this process (Figure 3).

3 Ultra-thin glass

Architectural glass sheets in facades range in thicknesses between 2 and 22 mm. Thin glass refers to 2 to 6mm thickness and ultra-thin is proposed for smaller thicknesses, from of 25 µm to 2mm excluded.
Whereas most of the architectural glass for facades is soda-lime glass produced on a float line, thinner glass products such as Corning's Gorilla Glass and Willow Glass and AGC's Leoflex have a different chemical composition and different fabrication process.
Gorilla glass is composed of aluminosilicate. It is produced in thickness ranging from 0.2 to 0.7mm by a proprietary fusion-draw process. Gorilla is then chemically tempered in potassium chloride, which provides a surface compression stress preventing crack propagation.
Willow glass, used for the project discussed herein, is an alkali-free boroaluminosilicate glass (Corning Inc, 2016). It is fabricated by a proprietary overflow process (Corning Inc, 2016). In this process, the glass in fusion overflow out of a gutter on both sides down and fuses at the bottom point of the gutter (see Figure 4).
Unlike Gorilla glass, Willow glass is not chemically tempered and present a breakage pattern similar to the one of annealed glass, shattering in long thin pieces. Willow glass is named after the shape of the overflow used during the fabrication.
Willow glass is produced in sheets up to 1100 by 1200mm or spools of 1300mm wide, 300 meter long. The minimum bend radius, depending on handling and surface weathering, is 90mm for the 100 µm nominal thickness and 180mm for the 200 µm nominal thickness (Corning Inc, 2016).
Combining these bending radii to the bending charts provided by Corning (Corning inc, 2016) a design value of 40 MPa was extrapolated and retained for the design of the sculpture. In the built environment, material reduction factors should be used, concomitantly with reduction factors associated with (for example but not limited to) shape, size, load duration.



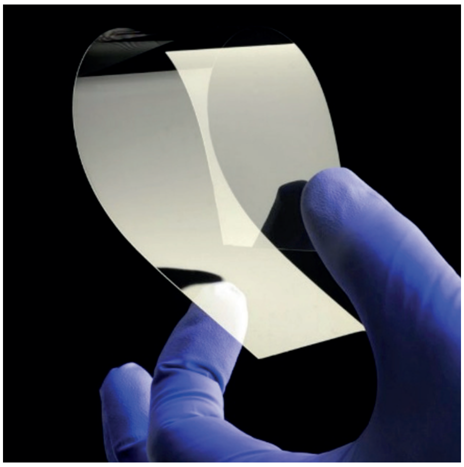

Figure 4,5,6 – Left to right: Corning proprietary fusion-draw process, Willow pattern and Willow glass

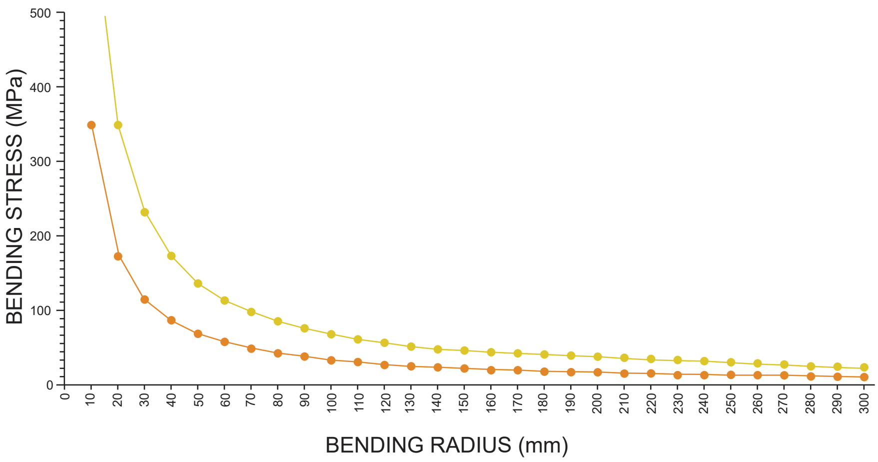

Figure 7 – Bending stress of Willow glass

4 Geometry

The deformation of inextensible flat sheets results in a developable surface. It is a specific case of ruled surface, which does not only apply to inextensible materials. For example, a hyperbolic paraboloid is a ruled surface which can be built from the translation in space of straight lines, it can be built with extensible nylon fabric but not from paper.
Developable surfaces comprise of cylinders, cones and tangent surfaces of spaces curves (Pottman and al) as shown in Figure 8. Conical shapes are ordinarily described by a planar curve and apex point. In the context of this sculpture, we used a variation of conical shapes defined by a space curve and apex point for each of the elements constituent of the geometry.

Figure 9 illustrates each step through the generation of the geometry for this project. At first, a set of helicoidal curves were created and distorted smoothly to create desired guide curves (Curve Set 1). The resulting curves are free form and do not comply with any geometrical rule, apart from the fact that they need to not overlap.
A first set of cones (Cone Set 1) was generated from each curve to an apex point P1 placed within the helicoidal set of curves (Curved Set 1). A second set of cones (Cone Set 2) was generated from each curve to an apex point P2 located above P1 so that every adjacent surface intersects each other. The Curve set 2 is defined by the intersection of the two sets of cones. Lastly, the two cone sets were trimmed by the Curve Set 2, creating the final developable surfaces used for the sculpture.
A parametric model allowed the fine tuning of the geometry in order to control the local radius of curvature.

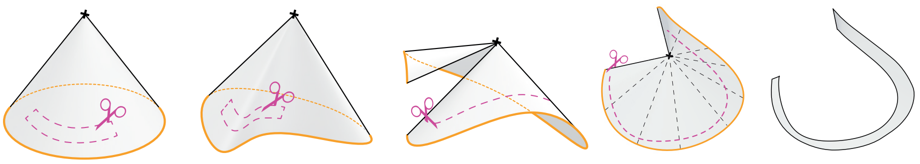

Figure 8 – Trims of developable surfaces

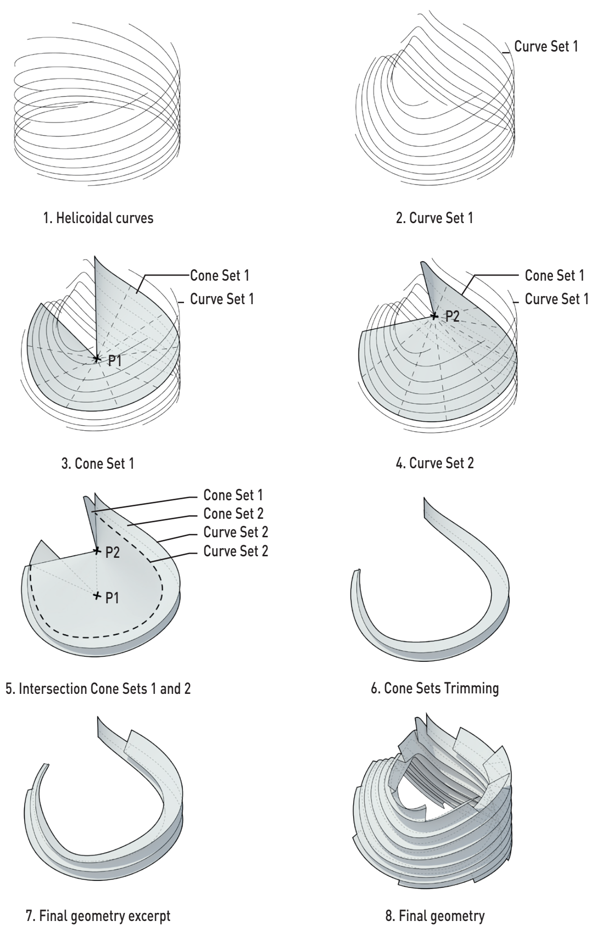

Figure 9 – Geometric principles

5 Analysis

This project being a sculpture, it was at firstly analyzed to sustain gravitational and bending forces.
An iterative process involving the round trip between maximum bending stresses assessment and the geometry adjustment was performed in a 3D modeling software packages (Rhino and Grasshopper). Since each strip is in pure bending, the principal curvature and bending stress can be derived from Eq. 1 and Eq. 2 below.
M = EI/R (Eq.1)
s = Et/2R (Eq.2)
With E : Young's modulus of elasticity (N/mm^2)
I : Moment of inertia (mm4)
R : Curvature radius (mm)
t: Glass thickness (mm)

Figure 10 shows a mapping of the principal curvature along one strip of glass.
When required, the construction points and generative curves of the strips geometry were adjusted in order to maintain a maximum stress of 35 MPa. This value, which is smaller than the allowable stress extrapolated in chapter 3, was arbitrarily set for the first iterative process, allowing additional reserve capacity for the effects gravity loading and potential buckling effects. Ultimately, the FE analysis proved that the effect of gravity was negligible for this specific geometry, scale and glass thickness.

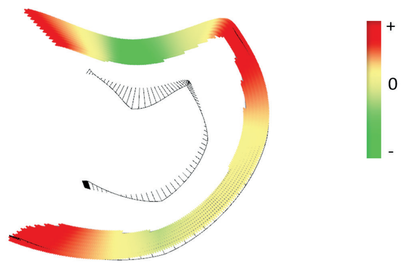

Figure 10 – Principal curvature mapping (only one strip shown for clarity)

After the parametric study has been performed, the strips were flattened and imported into a finite element analysis software (Strand7). For the analysis, a Young's modulus of elasticity of 75 GPa and a Poisson's ratio of 0.225 were used. Each strip was composed of approx. 200 plate elements of max. 20mm width. The thickness of the material was 200 µm. The model totaled 2560 plate elements. Each strip was initially flat and tied by links to the nodes of its final position (see Figure 11). A staged non-linear static analysis was then used to deform gradually the strips while the bending stress increase was monitored.

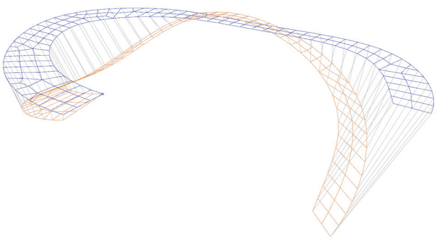

Figure 11 – Links used for imposing displacement on mesh nodes from flat (above) to bent (below)

Figure 12 shows the analysis steps. The glass strips are imported as flat geometry in the FE Analysis environment and shrink links pull them into position. At the last stage, when the glass strips are cold bent into position, adjacent nodes at the ridges are coupled together by stiff spring links and the load redistributes between the glass elements. The maximum stresses under bending case and after assigning gravity to the structure were below the maximum allowable stresses, with maximum at supports locations.

6 Models

For the fabrication, the 3D geometry was flattened and laid out on sheets. Two study models were built prior to the final construction of the sculpture. A desk model and a full-scale model. Figure 13 shows the fabrication steps of a scaled model made of 0.5mm thick PETG plastic strips and assembled by hand with tape. The first plastic scaled model, an assembly 130 x 130 in plan by 100mm high assembly of 20mm large strips, served as communication tool and a first proof of the fabrication sequence.
The second full scale model was fabricated with 1mm PETG foils. It was used as a template for the adjustment of the supports and jigs used for the glass sculpture. The full scale fabrication sequence was validated with this model. The connection detailing and assembly are not discussed herein.

7 Glass cutting process

The glass elements were provided and CNC cut by Coresix Inc, based in Virginia (USA). The fabrication pictures show in order: unrolling the Willow glass spool, the CNC cutting operation, strips cuts for testing and calibration of the tooling (the microscopic evaluation is not pictured), the breaking out of the final pieces, the final C shaped pieces and one piece bent by an operator.
The cutting process used to cut the glass pieces is called scribe and break. It is a similar process to standard glass cutting, despite the

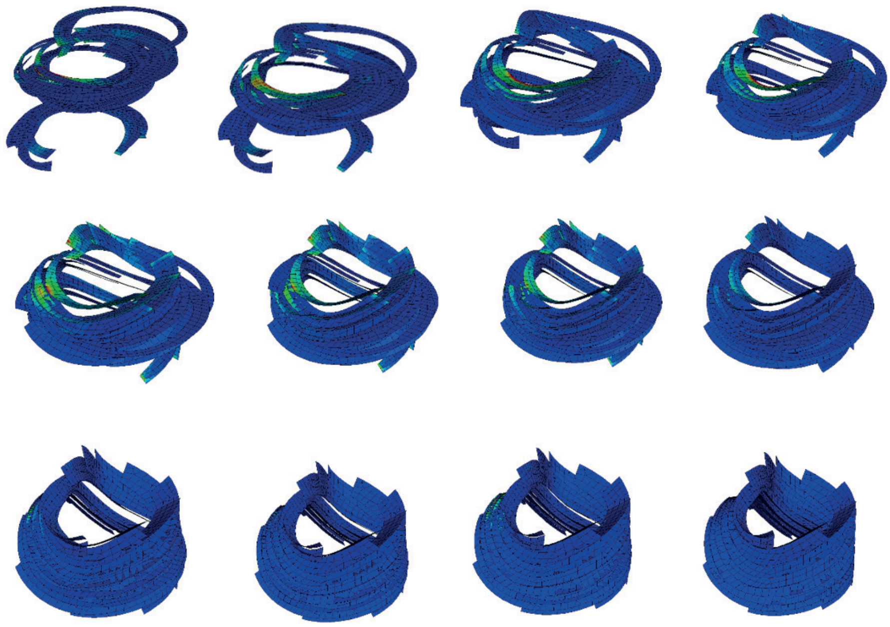

Figure 12 – Staged analysis

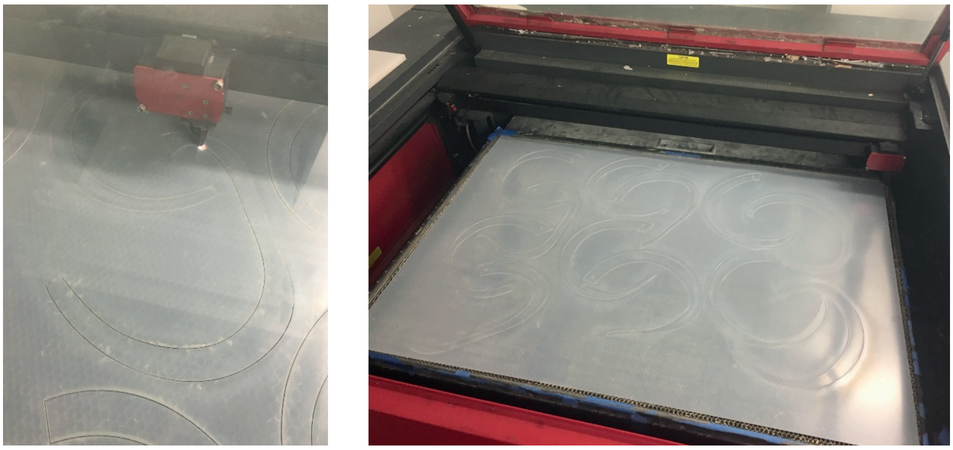

Figure 13 – PETG model fabrication

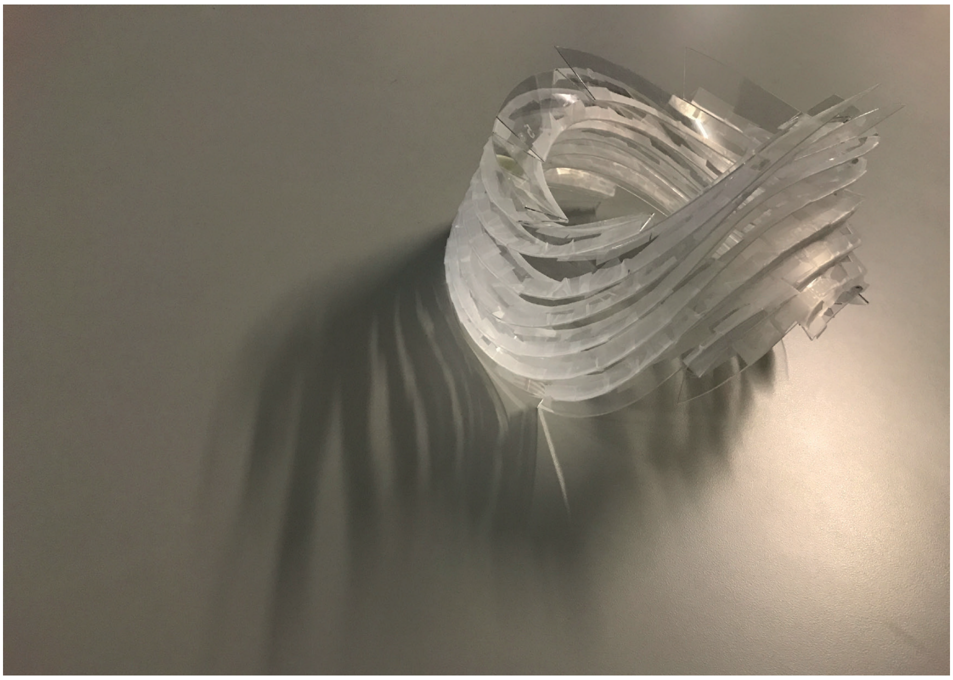

Figure 14 – PETG model

small thickness of the glass. The scribing is performed by rolling a small diamond wheel on the glass creating a small crack, or vent. Then the sheet of glass is handled by an operator which breaks it at the location of the vent. This process can be used for pieces of a couple millimeter overall size.

7 Conclusion

At the time of the publication of this article, the connection detail connecting the glass pieces is still under testing consideration. The design, fabrication and manipulation of the glass elements for the sculpture is a proof of concept of the design process for ultra-thin cold bending to form a small structure with tight curvature for both base flat shape cuts and bending radii. Given its relatively small size and the fact that, as a sculpture, it is not designed to resist climatic or seismic loads, the current design comports assumptions which does not make it directly scalable. The final geometry, the thickness of the glass, the connections between strips and to the ground will need to be re-evaluated.

However, it is obvious to the practitioners that the geometrical rules, the geometry to finite element analysis workflow and curved cuts fabrication knowledge capitalized on this project can be used for larger scale.

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Figure 15 – Glass sculpture fabrication images

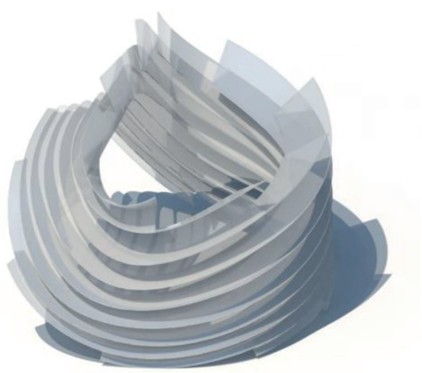

Figure 16 – Final sculpture rendering image

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Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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