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Summary

Ever since Lucio Blandini developed a doubly curved synclastic shell with adhesively bonded glass components, the concept of building a self-supporting glass-only shell has almost become within reach. In the current contribution a small-scaled experimental concept is presented of a self-supporting anticlastic all-glass shell scale model, created by means of an adaptable mould.

First, different manufacturing parameters of relatively small shells are investigated, such as mould type, glass supporting system and dimensions, oven temperature and shell curvature.

Next, an adjustable mould for the bending of glass is developed, built and tested. With this mould it is possible to make glass panels synclastic and anticlastic in a great variety of forms. With this new moulding technique we were able to create different prototypes. They are forming the basis an intended larger shell, composed of smaller segments. The objective is to join the latter by using fusing techniques, which result in completely transparent monolithic all-glass shells. Therefore, additional experiments have been performed to explore different variants of glass fusion techniques to be applied for double curved glass shells.

Keywords: *Glass shell; structural glass; adjustable mould; glass fusing.*

1. Introduction

Research on self-supporting all-glass structures is mainly driven by architectural aspirations, in which high transparency and/or reflections are key objectives [1]. Following the developments of numerical tools, 3D CAD software and a trend towards freeform design structures, glass experts face an increasing demand for double curved glass creations. However, with respect to the latter only a very limited number of manufacturers is experienced and project costs are elevated. Consequently, continued research efforts or necessary to further develop easier and more affordable curved glass technologies.

Existing techniques to curve glass include cold bended glass [2],[3],[4],[5],[6], examples of which can be seen in railway canopies such as the canopy at ‘s Hertogenbosch (NL); cast glass, applied e.g. in the Dutch Institute for Image and Sound (NL); and hot bended glass, of which the Alpenzoo Station canopy of the Nordkettenbahn in Innsbruck (AT) is a striking example.

For the latter technique, probably the most straightforward production method makes use of custom made moulds (e.g. by cutting and milling) with a fixed geometry, of which several examples are reported on in literature [7][8]. However, usually related to construction materials other than glass, several authors have reported on different types of adjustable moulds, e.g. based on a bed of adjustable pins [9]; pressurised adjustable textiles [10]; or a bed of adjustable stainless steel rods [10],[12]. The latter molding technique has been successfully tested for double curved glass applications.

In the research presented below, the main objectives are 1) to experimentally investigate the influence of several production parameters, such as glass type, thermoforming temperature related to glass thickness and curvature, type of thermoforming emplacement, etc., and 2) to experimentally explore geometrical concepts and technologies to join several curved glass panels to form a larger unit on scale models.

2. Thermoforming experiments

Table 1: overview of small borosilicate test specimens used exploration of thermoforming parameters

Length [mm]	Width [mm]	Number of specimens
130	50	12
130	100	2
100	100	11
200	200	6

Figure 1: Schematic representation of preliminaryadjustable moulds used for exploration of thermoforming parameters

2.1 Exploration of thermoforming parameters

In a first step, the objective is to gain insight in the thermoforming process of glass at high temperature. Consequently, preliminary tests have been executed in a glass oven to identify and explore critical technological parameters.

2.1.1 Materials

Because the glass is subjected to significant temperature gradients during opening and closing of the oven, preliminary test specimens were made of borosilicate glass, which has a relatively high thermal shock resistance.
In this phase of the research, 31 preliminary test specimens in total have been made of three mm thick borosilicate glass, as listed in Table 1.

2.1.2 Methods

Using a preliminary adjustable mould, schematically represented in Figure 1, in a glass oven, the specimens were thermally deformed during a certain exposure time.
Subsequently, the specimens were removed from the oven to cool down to ambient temperature. During the experimental program, the main parameters to be systematically evaluated were the oven temperature and the exposure time in the oven, but also the diameter and distance of the supporting mould rods, visible in Figure 1, were varied. The resulting glass was evaluated according to geometry of the (single or double) curvature obtained and the smoothness of the surface, in particular the surface which was in direct contact with the mould.

2.1.3 Results and discussion

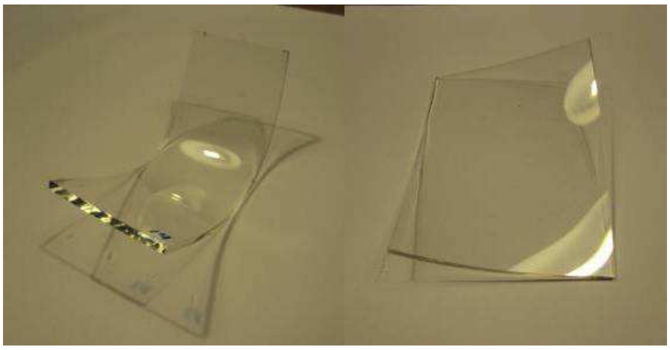

Figure 2: Typical results of preliminary tests: small-scale single and double curved glass shells

Best results were obtained at about 675° C and an exposure time of 15 minutes. In case an anticlastic double curvature was pursued, a smooth geometry was obtained by applying two immediately subsequent exposure cycles of 15 minutes each, and by turning the specimen upside-down in between two cycles. Following this procedure, a rise-to-span ratio between 1/10 and 1/8 could be obtained at either side of the resulting anticlastic shell. Typical examples are depicted in Figure 2 [13].

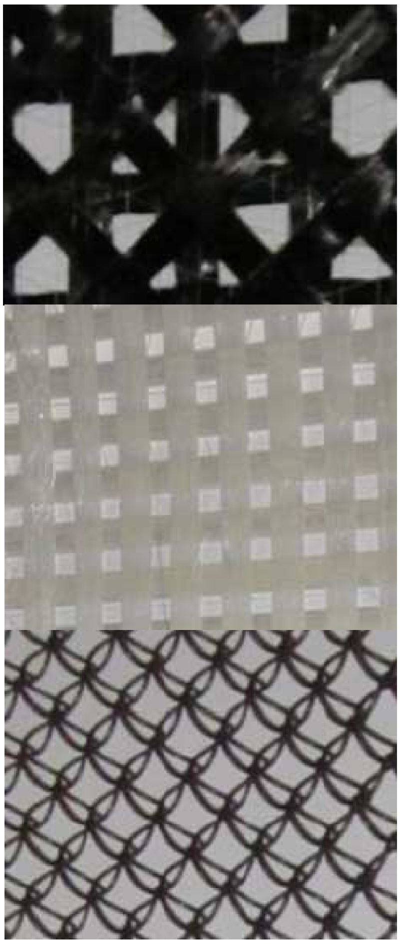

Figure 3: overview of membrane types tested for thermofolding at about 700° C. From top down: carbon fibre mesh, glass fibre mesh, and stainless steel mesh.

2.2 Adjustable mould experiments

In a next step, the mould was further developed to increase geometrical freedom, as the preliminary mould obviously was limited to ruled surfaces. Inspired by recent progress made in the development of flexible adjustable moulds for composites [14] several prototypes have been developed and tested for glass thermoforming. As depicted in Figure 3, three types of membranes, namely a carbon fibre mesh, a glass fibre mesh, and stainless steel meshes are tested [14]. An overview is presented below.

2.2.1 Carbon fibre mesh and glass fibre mesh

As expected, nor the carbon fibre mesh nor the glass fibre mesh were able to resist the high temperatures necessary during the glass thermoforming process: both materials simply disintegrated. Consequently, both options were rejected.

2.2.2 Stainless steel mesh

Subsequently, fifteen open stainless steel meshes with a varying weaving structure were experimentally tested for suitability during the glass forming process. Generally spoken, the open stainless steel structure was stretched and attached to an adjustable steel substructure illustrated in Figure 4 to obtain a double curved surface. The flexible adjustable moulds for composites fig 5 [14] were based on the elastic properties of a polyurethane foil. However, there are no materials with the same elastic properties at a temperature of about 680° C. To optimize the smoothness of the surface and adjustability of the mould further research was done to the sliding of strings in steel meshes. Another way to improve the adjustability of the steel mesh was to compare typological differences in the weaving of steel meshes.

The ultimate goal is to come as close as possible to the shape of a soap-film in force equilibrium. At the time of writing of this paper we have not come to a final conclusion.
Subsequently, flat square glass panels of 300 mm by 300 mm and 500 mm by 500 mm were positioned over the curved mesh at the start of the process, heated up to about 680° C for 15 minutes, and finally cooled down to ambient temperature again naturally in the closed oven.

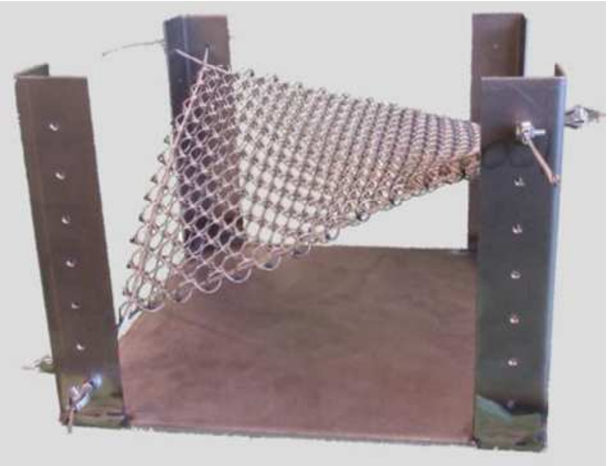

Figure 4: Open stainless steel mesh “Sierra papa 2”. Top: attached to a frame with adjustable plungers (in the oven); Bottom: attached at variable height to steel columns

2.2.3 Results and discussion

Figure 5: Double curved glass shell on “Sierra papa 2” stainless steel mesh

As stainless steel was able to resist the required operating temperature, the main criterion for evaluation of the different weaves was the quality of the resulting glass shell. More specifically, the smoothness of the final glass shell in terms of overall curvature and local surface imperfections were evaluated using soda lime silica float glass, for which a specific cooling down cycle was necessary to avoid thermal fracture.
Best results were obtained for the so-called “Sierra papa 2” mesh structure, illustrated in Figures 4 and 5. However, even for this mesh, global shape imperfections and local imprints in the glass at the contact points with the stainless steel supporting grid could not be completely avoided. Smoother results are expected when the two-phase technique, explained in §2.1.3, is applied here as well.

3. Joining experiments

A constraint of thermoformed curved glass panels is that their size is restricted to the size of the kiln used. Even for relatively large ovens, it will make sense of joining different curved segments to larger glass units. Consequently, in parallel to the investigation of the thermoforming technology, different joining options were experimentally explored. An overview is given below.

3.1 Adhesive bonding

Inspired by successful examples such as structural glazing in façades or Blandini’s self-supporting shell [7], the idea of structural bonding adhesives in the current study is attractive. However, a major concern and challenge is to select a suitable adhesive, which is resistant to all appropriate structural, constructional and esthetical requirements, such as gap-filling properties, suitable thickness to compensate for tolerances, sufficient strength, resistance to moisture and UV, etc. In near future the results of a broad screening of adhesives will be available, which will be very helpful to make a well-founded choice of adhesives possible [15].

3.2 All-glass solutions

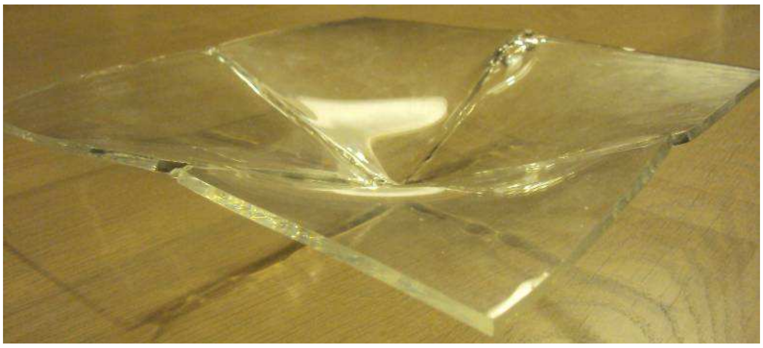

Figure 6: Initial fusion attempt of double curved glass panels

As an alternative to adhesive bonding, glass welding or fusing techniques, some of which had been explored on earlier occasions [16],[17], have been investigated for applications with double curved glass panels.
Figure 6 displays the result of the preliminary attempt: it was possible to join the separate shell segments, but clearly the technology needed to be finetuned. A short overview of the corresponding tests is given below.

3.2.1 Fusion using joint filler on perpendicularly polished edges

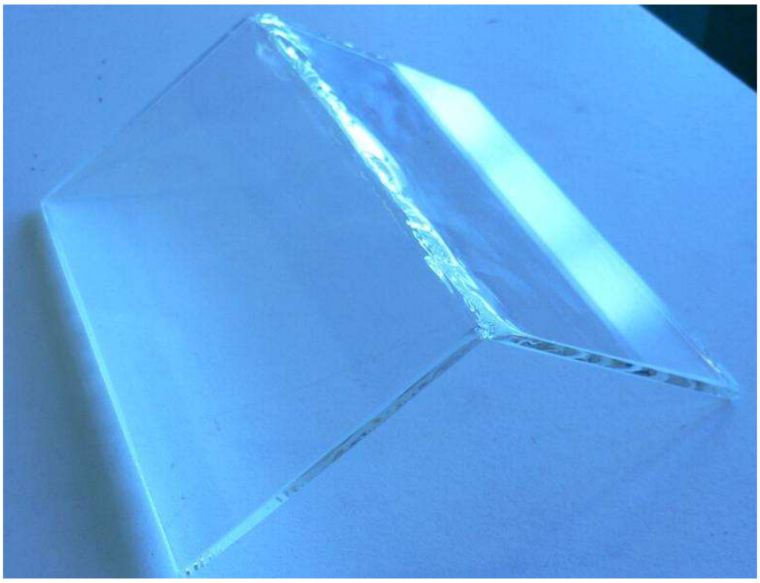

Figure 7: Sample with fused glass plates using joint filler on perpendicularly polished edges

To reduce the risk of thermal fracture, the glass edges which had to be joined were first polished at an angle of 90°. Subsequently, both glasses were joined by melting an additional glass rod in the butt contact area. Unfortunately, the resulting joint usually yielded an inferior resistance, probably caused by the local fusion area which is not evenly distributed along the thickness of the glass. In addition, the relatively large amount of heat introduced in the glass caused sagging and a consequent geometrically imperfect joint, as can be seen in Figure 7. In spite of the initial polishing, thermal cracks occurred relatively often.

3.2.2 Fusion using joint filler on inclined polished edges

In an attempt to significantly facilitate the addition of joint filling molten glass, the glass edges which had to be joined were polished at an angle smaller than 90°. However, a drawback was the expected vulnerability to thermal fracture of the sharp edges of the inclinations. In addition, imperfections and sags were still present due to the concentrated heat induction by the welding torch.

3.2.3 Direct fusion of perpendicularly polished edges

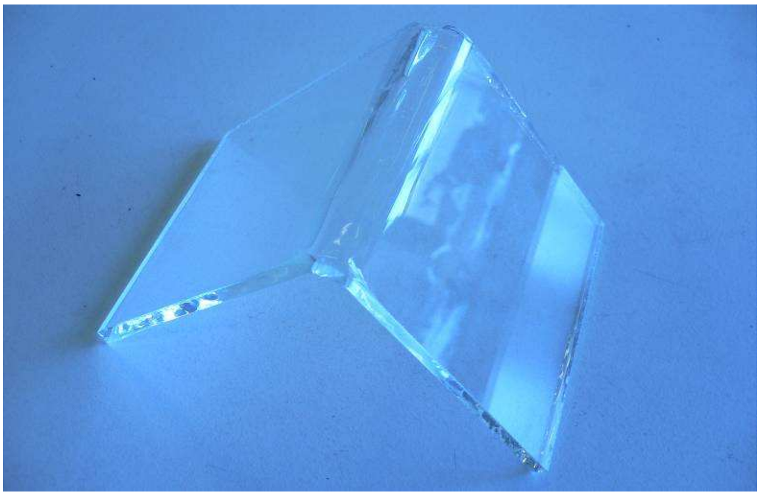

Figure 8: Sample with direct fused glass plates (i.e. without joint filler) on perpendicularly polished edges

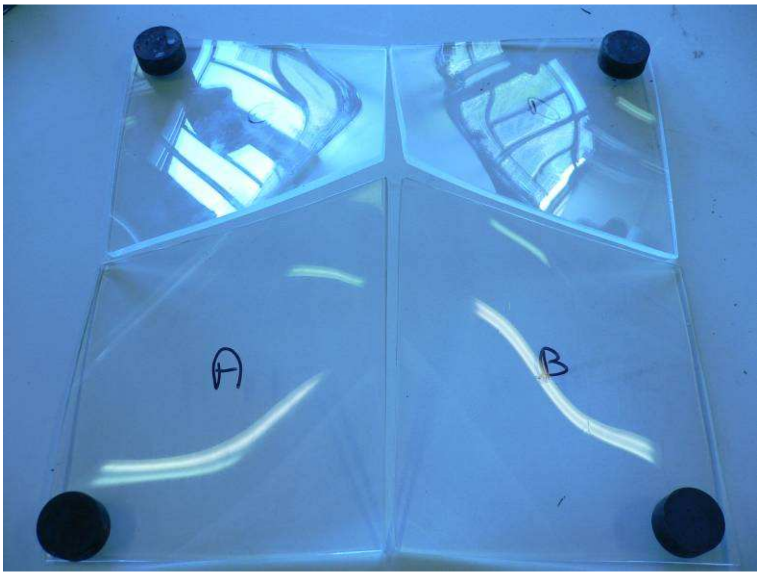

Figure 9: Sample with direct fused glass plates (i.e. without joint filler) on perpendicularly polished edges

Finally, a fusion technique was used without the addition of supplementary joint filling molten glass. Therefore, the edges of the glass panels which had to be joined were heated separately by means of a welding torch. Because the latter could move faster along the edges compared to the previous techniques, it was less difficult to avoid sagging of the panels. Subsequently, the hot edges were pressed one to the other, resulting in a direct fusion of both glass panels. The resulting joint is by far yielding the best optical quality and strength compared to the previous techniques, as illustrated in Figure 8.

In spite of the polishing, thermal fracture could not always be avoided, resulting in a loss of samples. However, by thermally working the glass edges locally, the number and size of edge flaws – and consequently also the risk of thermal fracture - could be further reduced. At the time of writing, the latter technique is being used to join four quadrants of a hypar shell, depicted in Figure 9.

4. Conclusions

The current paper describes the progress made in the technology to create doubly curved all-glass shells by means of technological experiments on scale models. Several aspects have been investigated, and the most important conclusions are summarised below.

4.1 Thermoforming parameters

The complete temperature cycle during thermoforming is of major importance; in particular the maximum temperature, the exposure time in the oven, and the cooling down process. Best results have been obtained for borosilicate glass at 675° C and 15 minutes exposure time, and a very slow cooling-down phase. In a later phase, successes have been obtained for soda-lime silica glass as well.

4.2 Adaptable moulds:

Several adaptable moulds have been experimentally tested, such as moulds with carbon fibre meshes, glass fibre meshes and stainless steel meshes. Only the latter withstood the required temperatures. Of the fifteen open structure stainless steel meshes tested, type "Sierra papa 2" yielded best results in terms of supporting the glass to obtain the desired curvature. However, minor imprints of the mould in the glass could not be completely avoided at the contact points.

4.3 Joining by fusion

Three different glass fusion techniques have been tested to create butt-jointed all-transparent glass "welds". Clearly the most promising result was obtained using a direct glass fusion technique, i.e. without adding additional molten glass. The resulting joint, however not thoroughly tested yet, preliminary seemed to yield optically and mechanically high quality results.

5. Acknowledgements

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