SCIENTIFIC CONFERENCE
PLANNING, DESIGN, CONSTRUCTION AND BUILDING RENEWAL

iNDiS 2018
NOVI SAD, 21-23 NOVEMBER, 2018

Tatjana KOSIĆ [1]
Igor SVETEL [2]
Dragana VASILSKI [3]
Zoran CEKIĆ [4]

TECHNOLOGIES FOR COMPLEX GLASS ENVELOPES DESIGN: PRODUCTION METHODS OVERVIEW

Abstract: Geometrically complex glass envelopes are an area of great engineering challenges which require developing of method of integrated design and construction process. The investigation is focused on different methods of curved glass fabrication to bring it into the right shape with a special focus on design and production process of different geometries that take into consideration different glass types. All these different methods are on the first view very easy but very complex in the detail and include the most used way of shaping glass in process with high temperature by sagging down, thermally pre-stressing, and cold bending by lamination and by assembling. The current paper gives a brief overview about the advantages and limitations of each production method in accordance with different geometries.

Key words: curved glass, complex form envelopes, hot bending, cold bending

TEHNOLOGIJE KOMPLEKSNIH STEKLENIH OMOTAČA: PREGLED PROIZVODNIH METODA

Rezime: Geometrijski kompleksni stakleni omotači su oblast velikih inženjerskih izazova koji zahtevaju razvijanje metode integrisanog procesa projektovanja i izgradnje. Istraživanje je fokusirano na različite metode izrade zakrivljenog stakla kako bi se isto dovelo u pravi oblik, sa posebnim fokusom na formu i proizvodnju različitih geometrija stakla uzimajući u obzir i različite vrste stakla. Sve ove različite metode su na prvi pogled vrlo jednostavne, ali vrlo složene u detaljima i uključuju najkorišćeniji način oblikovanja stakla uz pomoć kalupa u procesu pri visokim temperaturama, termičko prednaprezanje, i hladno savijanje laminiranjem i tokom montaže. Rad daje kratak pregled o prednostima i ograničenjima svake metode proizvodnje u skladu sa različitim geometrijama.

Ključne reči: zakrivljeno staklo, komleksna forma omotača, termičko savijanje, hladno savijanje

[1] Research Associate, IC Faculty of Mechanical Engineering, Belgrade University, tkosic@mas.bg.ac.rs
[2] Research Associate, IC Faculty of Mechanical Engineering, Belgrade University, isvetel@mas.bg.ac.rs
[3] Full Professor, University Union Nikola Tesla, Belgrade, dvasilski@fgm.edu.rs
[4] Full Professor, Faculty of Technical Science, University of Novi Sad, zoran.d.cekic@gmail.com

1. INTRODUCTION

Architectural practice continually followed the development of geometry, and many architectural directions were inspired by the latest achievements in this field. The construction of increasingly complex curved forms is interpreted from the architectural aspect as an expression of the freedom and dynamism of architectural forms and usually associated to the expression of modern tendencies at given historical moment. Today, the development of computer applications has made possible to generate complex geometric forms more easily thanks to the ability to quickly carry out a number of complex calculations, putting tools in the hands of architects that enable simple construction of these forms. However, in relation to geometric level, there are problems in the practical fabrication of geometrically complex forms, because unlike the abstract geometric forms, building elements have physical characteristics that prevent creation of any geometry in a particular material. This is particularly expressed in the case of glass which is a fragile and brittle material and therefore can not be produced in all shapes and sizes. Therefore, the modeling of geometrically complex forms of glass involves the process of '*panelization*' for which specialized computer programs are necessary.

However, in addition to the geometric aspects, the design and construction of curved building envelopes involves many aspects typical for the material itself particularly related to thermal properties of glass, as well as to production techniques, creating and finishing of the glass panels, and especially to effect that the glass as material brings into the completed architectural building.

The aim of the presented research is to collect data on the existing design technologies on curved glass structure cases. The investigation is focused on different methods of curved glass fabrication to bring it into the right shape with a special focus on production process of different geometries, also taking into consideration different glass types: monolithic glass, laminated safety glass or insulated glass.

2. MODERN TECHNIQUES OF CURVED GLASS SHAPING

Since the use of curved glass has become more and more popular, allowing the creation of curved contours, organic forms, bold arches and dome structures, it is necessary to describe in detail various shaping techniques. These techniques which include glass bending can significantly affect the ability of getting desired form, the variability of the structural characteristics of glass, and consequently the design of glass envelopes, as well as the manufacturing constraints that compared to the flat glass differs considerably.

Two basic approaches / shaping techniques have been developed:

- The process of thermal bending of glass, and
- The process of cold bending of glass.

Each of these processes and their variants primarily affect the mechanical characteristics of the final product - the glass element, but also determine the minimum as well as the maximum production characteristics, the visual quality and the possibility of applying further processes and processing. In order to maximize the benefits of different glass bending technologies, architects and engineers should be familiar with all constraints regarding the form, strength, dimensions and possibilities of applying different treatments and finishing of the glass surface, which are imposed by different production processes. The following types of glass can be used for curved glass envelope:

- Float glass,

- Heat-strengthened glass,
- Toughened (safety) glass,
- Laminated glass (safety) glass,
- Toughened and laminated (safety) glass, and
- Thermal insulating glass (IGU panel),

as well as their combinations. From the aspect of geometry, the glass can be flat, single curved, double curved and complexly curved.

The inappropriate selection of shaping techniques or errors during the manufacturing process can very easily lead to damage or even glass breaking due to residual stresses caused by the force of straining on the glass surface. These stresses due to tensile force can lead to sudden breaking of glass even caused by the smallest scratch on the glass surface.

2.1. Process of thermal bending of glass

The process of thermal bending of glass is the oldest method of curved glass shaping. This process differs from new technique of cold bending, primarily because the process uses the property of the reversible phase transitions. By introducing heat, the glass can change the solid state of float glass, creating in the reverse direction a semi-liquid material that can be shaped into various forms. Until recently, the complex process of thermally shaped glass production has prevented its use in large scale projects. New automated production technologies have contributed to the fact that thermally shaped glass has become an increasingly available option by reducing the time and labor needed to produce one glass element. Depending on the project requirements and desired form, the manual process is still preferred.

Today, the most commonly used glass type in architectural buildings, is a float glass obtained by the most advanced manufacturing process producing flat glass of completely parallel and flat surfaces. During the production process, its basic components are mix and heat in a furnace to a temperature of 1,600°C. The liquid then flows from the furnace to the boiler of melted tin and appears as a continuous strip of glass, where going through the process of '*annealing*' is slowly cooled to the solid state. Thermally shaped glass is obtained by reversing the process of float glass fabrication, more precisely by re-introducing heat to an already formed flat glass panel. The bending process takes place as the glass is heated again to the temperature of about 600°C where again becomes semi-liquid viscous material and can be bent. To facilitate the shaping process, two different methods can be applied:

- Thermal bending by sagging (mold) (Figure 1a and b), and
- Thermal bending on the production line (Figure 1c).

a) b) c)

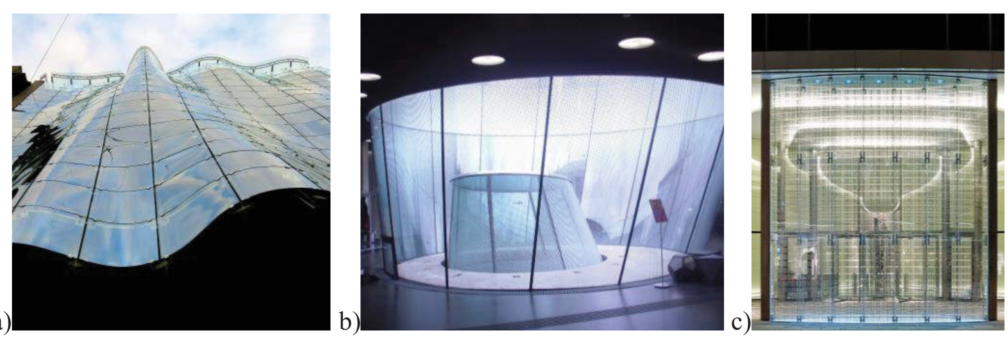

Figure 1 – Thermally bent glass applications: a) Infinity building, Belgrade and b) Joanneumsviertel Museum, Graz (bent by mold); c) Glass Lens, Park House, London (bent on production line)

These methods differ significantly, both in terms of the characteristics of the final product and different equipment used for their production. Thermal bending on the production line involves an automated process that bends the glass in few minutes, while thermal bending by mold is a process that requires time and labor. The defined procedures in process of thermal bending of glass, shown in Figure 2, are used in mapping of the entire process of design and construction of geometrically complex glass envelopes [1].

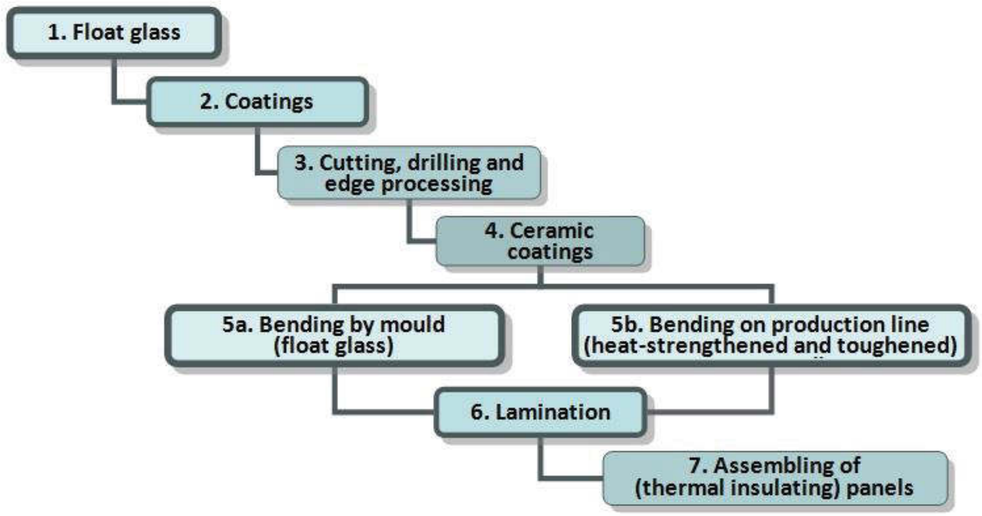

Figure 2 – Procedures (steps) in process of thermal bending of glass

Application of thermally bent glass in architectural buildings often involves the application of thermal treatments (tempering and heat-strenghtening) providing additional strength and safety. Since thermal bending and thermal treatments involve the introduction of heat, it is necessary to implement them at the same time in order to prevent mutual annulment. Thermal treatment that consider glass tempering is usually unavailable in the case of glass bending by mould, since this technique prevents the use of standardized annealing equipment. If bending by mould is required, laminating and chemical tempering processes provide options for achieving additional safety and strength. On the other hand, thermal bending on the production line allows thermal treatment (tempering and heat-strenghtening) which are carried out simultaneously with the production process.

Generally, by this technique it is possible to achieve a wide range of different shapes, such as spherical, double curved, as well as geometrically complex forms with large deflections, curves of small radius (the minimum radius of glass panel curvature produced in such way is 100 mm). However, this process is difficult to compare with the process of flat glass production, particularly in terms of reliability of glass tempering (prestressing). On the other hand, further finishing, which includes lamination and making of thermal insulating panels, is common. Also, the quality of thermally curved glass, in particular glass shaped by mould, is not quite comparable with the quality of flat glass, not only in terms of allowable (geometric) deviations, but also in terms of glass strength. From these reasons, greater quality control of the curved glass is necessary.

a) b)

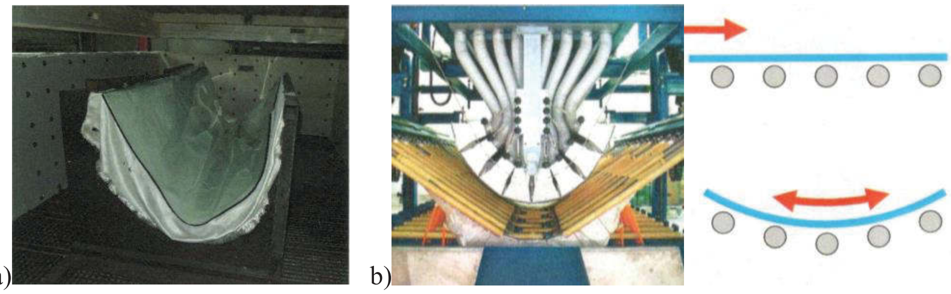

Figure 3 – Process of thermal bending of glass:
a) Bending by mould [2]; b) Bending on the production line [3]

2.1.1. Thermal bending by sagging (mould)

The basic process of thermal bending of glass has not changed since the 19th century when was first applied in architecture. This traditional process, known as '*slumping*' (Figure 3a) involves placing a flat glass plate over a mold and its warming up to the temperature between 550° and 620°C. At this high enough temperature, the change of viscosity related to reduced *Young's modulus* of elasticity is present [3]. This softened glass, by help of gravity force, falling over the mould (sometimes in the mold) placed below the glass. Since the glass is mould-shaped, this process provides great design options.

In this way, cylindrical, conical, spherical, parabolic and hyperparabolic forms of glass elements can be obtained, as well as large curvature or small radius of curvature. Nowadays, this process is mostly done manually and can last from 8-10 hours to get desired shape of panels in the furnace. It also includes individually customized moulds for different glass geometries that are handmade.

Also, an important feature of the thermal process of bending by mold implies that all next processing (application of coatings), carried out introducing heat, is practically unavailable since any following heating would contribute to original form to be changed. According to *Guidelines for European Structural Design of Glass Components* [4], curved float glass shows similar strength characteristics as well as flat float glass. Therefore, if panel shape requires a thermal bending by mould, then the options for obtaining a safety glass and its higher strength are as follows:

- Process of lamination, or
- Process of chemical tempering of glass.

2.1.2. Thermal bending on line

The economic and time constraints of large-scale projects and high-rise buildings imply a higher level of standardization in the application of curved glass than is possible through traditional technique by mould. The latest technological development of automated process of glass bending created a curved glass which is economically efficient and faster option if the panel shape can be adapted to the existing constraints. The process known as bending on a production line or by rollers in the bending machine uses the programmed pressure in order to quickly obtain the desired form (Figure 3b), simultaneously applying heat treatment – prestressing, in several minutes on the production line. The rollers are adapted to concave shape of glass panel whose axis is oriented parallel or diagonally in the direction of the rollers. An integral part of the machine press are the nozzles enabling the manufacturer to individually determine angle between the individual parts, in particular by increasing or reducing the bending radius of each glass panel. In order to avoid residual stresses in glass panel that may occur due to uneven cooling, constant moving of glass plate during cooling process is necessary since the tensile stresses on its surface can lead to sudden glass damage. By this simultaneously procedure, the problem of the tempering of glass bent by mould is overcomed.

Limitations of this bending process are production of only cylindrical forms, as well as individual glass plates for laminated safety glass which must be produced in separate phases. Thus, due to the allowable tolerances regarding form and dimensions of individual bent glass plates, thicker glass plates should be fabricated for creation of laminated glass.

Many regulations require the use of toughened or partially tempered (heat-strengthened) glass, which implies necessecity to meet the requirements for a certain strength of glass. Currently, in the market there are a large number of glass bending mascines equipped with a tool that allows glass bending both in one axis and in more complex geometry. However, the construction industry mainly uses machines that bend single curved glass, so far. Machines that produce double bent glass still indicate individual, manual making by mould. As a result, the technology of double curved glass production is not yet widespread, applying mainly in the automotive industry and industrial design, where the price is offset by cost-effectiveness of the production scope of curved glass.

2.2. Process of cold bending of glass

Recent examples of the use of new technique – cold bending open up possibilities for the application of double curved, toughened and laminated, glass panel in order to create glass shell which optical and technical quality meet the requirements for a smoothly curved, transparent surfaces of the building envelopes (Figure 4).

a) b) c)

Figure 4 – Cold bent glass applications (by assembling): a) Victoria & Albert Museum, London; b) Train Station TGV, Strasbourg; c) Bus Station – Zuidpoort, Delft

RFR company from Paris was among the first to notice the possibilities of a new way of glass shaping since the early 1990s. Unlike traditional (thermal bending), the new technique can significantly improve aesthetic quality, reduce the total cost of curved glass application, but also enable the use of heat-strengthened and toughened (safety) glass of characteristical strength, as well as almost all coatings and films. The main advantage of cold bending techniques is elimination of visual distortions and unchanged physical properties of glass panels because, unlike thermal bending, there is no change in structure of glass but only in its shape. By this technique is possible to achieve a smooth, no distortion, curved glass surfaces. From the other side, safety of the application of structural characteristics of glass due to taking over the external load by primary membrane action even in the case of complex forms is present. However, the main limitation of this process is allowable curvature which have to be considered specially for each project. When complex geometry of glass building envelope involves the technology of cold bending, the decision on the design should be made at an early stage of the project in cooperation with the facade consultant and constructor, following the basic steps (Figure 5).

Cold bending technique uses advantages of the linear elastic deformation of the glass, thanks to the low modulus of elasticity (about 70.000 MPa) [4]. The process itself is based on the prestressed state of tempered glass. Stresses due to cold bending are superposed with residual stresses (prestressing state) and theoretically can compensate the tensile stresses of toughened glass completely.

Although in practice is difficult to apply a constant bending moment to a glass panel, it is possible to create a single curvature according to the static scheme of the console beam with a force at the end, or by creating two overhangs and applying force at both ends. Double curved shape can only be achieved by applying force simultaneously to as many points on both sides of the panel, as otherwise the glass panel tends to return to a single curved shape. Values of stresses and strains in relation to the variations of thickness and bending radius, as well as to ratio of length and width of panels, can be verified by combination of numerical and analytical analysis [5]. This implies that the curvature depends on glass thickness and possible tensile stress on the glass surface.

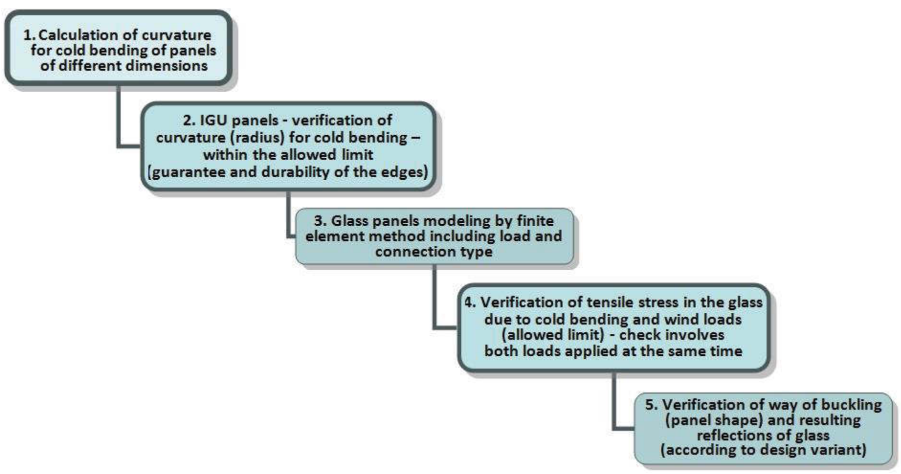

Figure 5 – Procedures (steps) in process of cold bending of glass

Double curved glass envelope can be created by joining of single curved elements along one of the two directions of main curves, while the glass is curved along other direction (‘*torsa*’ geometry). In this case, even small angular deviations can be seen due to the light reflection of the glass surface. Therefore, double curved panels provide optical quality to meets the requirements of a transparent double curved envelopes of modern buildings. On the other hand, the application of quadrilateral panels on a geometrically complex shape has aesthetic and economic advantages. This usually implies one of the four angles out of plane (geometry of negative Gaussian curve), causing a twisted deformation of the glass panel (‘*hypar*’ surface). Somewise, the panels can bear this type of deformation taking into account own load, as well as the load of wind and snow. This results in small, equal bending moments and significant forces through the glass showing characteristics of the membrane - tensile force along the edges and pressure force around the center of the curved panel.

The study of the principles of cold twisting of glass panels, carried out during 2003, resulted in Staaks theory. In the *Octatube* lab, it was found that glass panels can be elastically twisted in a way to deform symmetrically creating a ‘*hypar*’ surface, as long as the deformation (deviation of one angle from the plane) is less than 16(x) thickness of the panel.

A larger twisting will cause deformations that will result in single curve bending along a shorter diagonal axis. Generally, deformation of 50-100 mm/m^2 of panel width is possible using toughned glass [6].

In adition to above mentioned, it should be taken into account that the glass is only part of the glazing system, since cold bending affects the stresses of various components. Although it is matter of cold bending of glass, silicone seals, window spacers, interlayers, frames and air also have to be considered. Therefore, it is necessary to perceive each component behaviour during the bending process.

In order to provide a unique aesthetics and savings enabled by this shaping process, two basic techniques of cold bending of glass are used:

- Cold bending by assembling (mechanically on site / in factory), and
- Cold bending by lamination (in autoclave / vacuum bag).

Figure 6 – Process of cold bending of glass (on the substructure, in the factory) [7]

2.2.1. Cold bending by assembling (mechanically)

Flat glass panels can be curved directly at the construction site during assembly process. Due to applied power and depending on the resistance, the glass is mechanically bent by external contact pressure, by pushing or pulling the edges or corners to achieve desired bulge or curvature (Figure 6). Holding the glass in desired shape can be achieved by mechanical fixing (clumping strips) for the substructure.

Two different types of curvature can be created:

- Bending into a cylindrical shape (single curvature – '*torsa*' geometry), when adjacent two edges are always parallel and two are curved (Figure 7a),
- Twisting into a double curved form ('*hypar*' geometry), when one corner is lift from the plane while the edges remain flat but not parallel (Figure 7б).

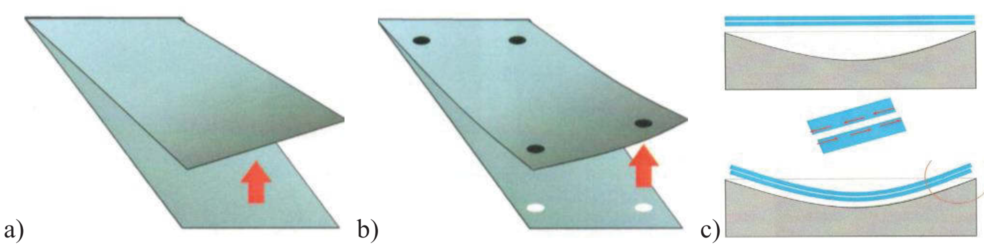

Figure 7 – Process of cold bending of glass:
a) Symmetric external contact pressure to achieve single curvature and b) Asymmetric external contact pressure to achieve double curvature - Bending by assembling [3]; c) Bending by lamination [3]

2.2.2. Cold bending by lamination

Another way of retaining the form can be achieved through simultaneous bending and lamination process of glass plates by a rigid interlayer (Figure 7c). *Seele Sedak* company has played a crucial role [3] in development of this new glass bending technology by the laminating process, which involves a rigid bond between glass and interlayer in order to produce extremely large, curved glass panels.

Cold bending, achieved by a lamination process which contributes to the stabilization of the form itself, comprising the following steps: putting together interlayers and flat glass, usually tempered; achieving the desired shape by physically pressing it onto the laminating substructure and clamping into place; laminating to achieve a high shear bond between the glass and the interlayer in autoclave (appropriate temperature and pressure of 12 bars, or 1.2 MPa) or in vacuum bag (appropriate pressure of 0.7-0.9 bars, i.e. 0.07-0.09 MPa) [3]; releasing from the substructure, hardening of intermediate layer and establishment of shear resistance, the viscoelastic effect of the interlayer, neccessity of high quality control and observance of stresses in the single plates due to'spring back' effect. The final state of deformation will be achieved depending on the properties of the shear resistance of the interlayer. Therefore, it is necessary to increase the curvature in the panel during the lamination process to get the exact shape after releasing the laminated panel from the substructure. Material having a high level of short-term and long-term shear resistance compared to the most commonly used - *PVB* foil is *SentryGlas®Plus 5000 (SGP)*. Also, the internal stresses (up to about 20-35 MPa) occurring at the interlayer due to cold bending, must be taken into account for dimensioning of the structure.

By this method is possible to create double curved forms whose radius range from 17 m to 40 m, depending on the dimensions of the panel, the form and the applied technique. Smaller dimensions allow for greater curvature. The maximum dimensions of the panels are 14.00 m x 2.80 m [5].

Finally, the production of quality glass curved envelopes obtained by a cold bending must include communication and collaboration among all participants (engineers, manufacturers and assemblers). Also, cold bending will not completely replace thermal bending, since only a small curvature/large radius is possible.

3. TECHNOLOGICAL PARAMETERS - INDICATORS OF POSSIBILITIES AND CONSTRAINTS FOR THE CURVED GLASS MANUFACTURE

In order to maximize the benefits of the applied process of curved glass shaping, it is necessary to consider different technological parameters - indicators related to possibilities and limitations in terms of form, dimensions, strength of glass, possibilities of applying different coatings, as well as the appearance of visual defects on the glass surface such as: optical distortion, anisotropy, distortion due to reflection. Those indicators (Table 1) have to be considered in assessment of buildability of designed systems, during development phase of detailed project design [1].

The German *Guidelines for thermally-curved glass in the building industry* [8] lists a number of different production tolerances of the final product in relation to form and dimensions, which vary according to project type, radius of curvature and selected shaping technique. In Table 1, in addition to previosly mentioned, production tolerances are also defined in relation to selected glass manufacturers. (*Cricursa*, Spain; *Concav Convex*, Dobanovci; *Beokom* and *Pavle*, Pančevo).

Table 1-Technological parameters-indicators of possibilities and constraints for curved glass production

Technological parameters – indicators of possibilites and constraints for curved glass production (in terms of form, dimensions, strength, coatings and visual difects)									
	Shaping technique	**Thermal bending**						**Cold bending**	
	Manufacturer	***Beokom*, Serbia**		***Concav Convex*, Serbia**	***Pavle*, Serbia**	***Cricursa*, Spain**			
	Process	**On line**	**By mould**	**By mould**	**By mould**	**On line**	**By mould**	**By assembling (mechanically)**	**By lamination**
FORM AND DIMENSIONS	**Single curved glass**	+	+	+	+	+	+	+	+
FORM AND DIMENSIONS	**Double (complex) curved glass**	–	+	+	+	–	+	+ (except surface with a negative curve and curved edges)	+ (Research in progress)
FORM AND DIMENSIONS	**Panel max. dimensions (cm) (width x length x deflection)**	146 x 232	195 x 300 x 50	200 x 350 x 70	190 x 290 x 50 220 x 380 x 50	244 x 450	320 x 1.000 x 100	330 x 1.500	330 x 1.500
FORM AND DIMENSIONS	**Max. radius of curvature (cm)**	800 (tickness 4,5,6,8 и 10 mm)	/	/	/	/	/		
FORM AND DIMENSIONS	**Min. radius of curvature (cm)**	80 (tickness 4,5,6, и 8 mm) 100 (tickness 10 mm)	/	small radius is not possible	small radius is not possible	200 (tickness 19 mm) 150 (tickness 15 mm) 120 (tick. 8, 10, 12 mm) 100 (tickness 5, 6 mm)	300 (tickness >10 mm) 250 (tickness 8-10 mm) 150 (tickness 6-8 mm) 100 (tickness 4-6 mm)	500 (tickness 3 mm) 900 (1.000) (tickn. 6 mm) $r_{allow} = E \cdot z / \sigma_{allow}$	500 (tickness 3 mm) 900 (1.000) (tickn. 6 mm) $r_{allow} = E \cdot z / \sigma_{allow}$
FORM AND DIMENSIONS	**Max. deviation from the plane (cm)**							< 16,8x glass tickness	< 16,8x glass tickness
FORM AND DIMENSIONS	**Tolerances (mm) (in terms of width, lenght and form)**	/	/	±1-2 mm (width and length)	±3 mm (width and length)	±0,2 mm (dim<2 m, t<12 mm) ±0,3 mm (dim $\gtrless$ 2 m, t $\lessgtr$ 12 mm) ±0,4 mm (dim>2 m, t>12 mm) ±5 mm (form)	±0,2 mm (dim<2 m, t<12 mm) ±0,3 mm (dim $\gtrless$ 2 m, t $\lessgtr$ 12 mm) ±0,4 mm (dim>2 m, t>12 mm) ±5 mm (form)	/	/
TYPE / STRENGTH OF GLASS	**Float glass**	+	+	+	+	+	+	+	+
TYPE / STRENGTH OF GLASS	**Heat-strengthened glass**	–	–	–	–	+	–	+	+
TYPE / STRENGTH OF GLASS	**Toughened glass**	+	–	–	–	+	–	+	+
TYPE / STRENGTH OF GLASS – further processing	**Laminated glass**	+	+	+	+	+	+	+	+
TYPE / STRENGTH OF GLASS – further processing	**Termo insulating glass**	+	+	+	+	+	+	+	+
COATINGS AND FILMS	**Soft coatings**	+ (on a particular position)	–	–	–	+ (on a particular position)	+ (A new generation of soft coatings - *Magnetronic*, but on smaller panels)	+	+
COATINGS AND FILMS	**Hard coatings**	+	+	+	+	+	+	+	+
COATINGS AND FILMS	**Ceramic coatings (colour)**	–	–	–	–	+	–	+	+
DISADVANTAGE	**Anisotropy**	+	–	–	–	–	–	+	+
DISADVANTAGE	**Optical distortion**	+	+	+	+	–	+	–	–

+ possible
-- limited (not possible)

4. CONCLUSIONS

The following conclusions can be listed:

- The complex process of thermally shaped glass production has prevented its use in large scale projects. However, new automated production technologies have contributed to the fact that thermally shaped glass has become an available option by reducing time and labor needed to produce one element.
- The modern technique of curved glass shaping by the cold bending process, which has not been applied in Serbia so far, is a solution in according to the physical characteristics of glass, while contributing significantly to economic efficiency, prevention of visual problems of glass surface caused by thermal bending and possibility of applying most coatings and films. By cold bending is possible to design models of a glass envelope whose geometry is represented by a '*hypar'* (hyperbolic paraboloid) and a '*torsa'* (single curved) surfaces of individual glass panels.
- Defined technological parameters - indicators of possibilities and limitations for the production of curved glass can be used as a basis for determination of the form, dimensions, strength, possible coatings and visual characteristics of curved glass in relation to the particular shaping technique.

5. LITERATURE

[1] Kosić, Tatjana (2016): *Application of Glass in Materialization of Geometrically Complex Forms of Architectural Building Envelope, Doctoral Dissertation*. Belgrade: Faculty of Architecture, University of Belgrade.

[2] Timm, C. and Chase, J. (2014): Thermally curved glass for the building envelope. In: *Proceedings of Challenging Glass 4 & COST Action TU0905 Final Conference*. London: Taylor & Francis Group, pp.141-149.

[3] Neugebauer, J., Penkova, N., Iliev V. (2013): Insulated Glass and Curved Glass. In: *Proceedings Structural Glass Cost Training School*. Darmstadt: Technische Universitat Darmstadt, COST European Cooperation in Science and Technology, pp. 71-104.

[4] Feldmann, M., Kasper, R., ... (2014): *Guidelines for European Structural Design of Glass Components*. Luxembourg: Publications Office of the EU.

[5] Fildhuth, T. and Knippers, J. (2009): Double Curved Glass Shells from Cold Bent Glass Laminates. In: *Proceedings of Glass Performance Days Conference*, pp.316-321.

[6] Eekhout, M. and Staaks, D. (2012): Cold twisted glass panels in Engineered transparency. In: *Proceedings of Engineered transparency International Conference*, pp.213-222.

[7] Molter, F. and Wolf, T. (2011): Glass-shaping Techniques in Building, *Detail- Glass Construction*, 1/2, pp.80-86.

[8] *Guidelines for thermally-curved glass in the building industry*. (2011). Troisdorf: Bundesverband Flachglas.