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Complexity of Curved Glass Structures

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Abstract. Despite the increasing number of research on the architectural structures of curvilinear forms and technological and practical improvement of the glass production observed over recent years, there is still a lack of comprehensive codes and standards, recommendations and experience data linked to real-life curved glass structures applications regarding design, manufacture, use, performance and economy. However, more and more complex buildings and structures with the large areas of glass envelope geometrically complex shape are built every year. The aim of the presented research is to collect data on the existing design philosophy on curved glass structure cases. The investigation includes a survey about how architects and engineers deal with different design aspects of curved glass structures with a special focus on the design and construction process, glass types and structural and fixing systems. The current paper gives a brief overview of the survey findings.

1. Introduction

Increasing number of architectural structures of curvilinear forms set new requirements for application of curved glass as an element of geometrically complex envelope. At first glance, the application of curved glass provides an exceptional freedom in the design of modern wavy shape, but many constraints arises when it comes to the aspect of design, manufacture, use, performance and economy.

Development of computer applications enabled easier generating of geometrically complex forms, However there are problems in the practical fabrication of the geometrically complex shapes, because unlike the abstract geometric forms, construction elements have physical characteristics that prevent the creation of any geometry. This is especially emphasized in the case of glass that is brittle and easily breakable material and therefore unable to produce in all shapes and sizes. In addition to the geometric aspects, the design and construction of curved surfaces, involves many aspects typical for the material itself, which is particularly related to the thermal properties, production techniques, glass-shaping and finishing, as well as the effect that glass as material enters into completed building.

How the geometry represents theoretical assumption and defines the process of design and manufacture regarding the maximum and minimum dimensions, forms and curvature, physical and mechanical properties, the typology of the glass panels has been proposed according to their geometry curvature type and generating mode of the surface, as shown in figure 1.

The reference models, as well as variant models (geometric type or position) of the glass panels have been proposed. Other possible alternatives of proposed models relate to different curvature radii.



The purpose of the current study was to collect data on the existing design philosophy of curved glass structure to define and map the complex process of design and construction of geometrically complex form of building envelope.

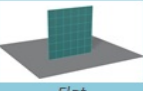
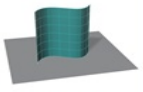
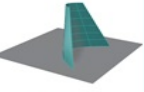

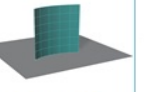

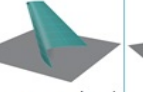
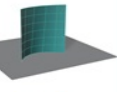
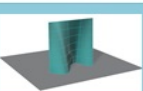
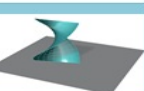
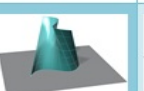
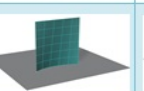
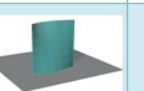
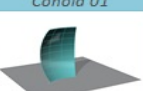



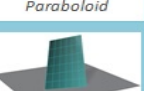
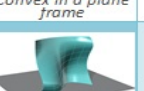

		Geometry of glass elements – panels						
Surface curvature	Developable surfaces	Reference models (surfaces)			Variants models (surfaces)			
		Flat The Gauss curve $K=0$ $r=\infty$						
								
		Flat						
		Single curved The Gauss curve $K \neq 0$, $H < 0$						
Non-developable surfaces	Double curved The Gauss curve $K > 0$							
		Cylinder 01	Cone 01	Torsion	Cylinder 02	Cylinder 02-inclined	Cone 01 - inclined	Cone 02
								
		Conoid 01	Helicoid	General Ruled	Conoid 02	Conoid 03		
								
		Sphera	Paraboloid	Convex in a plane frame				
								
		Gen. Translational	Hypar - HP	NURBS	One-Sheeted Hyperboloid			

Figure 1. Typology of the glass elements according to geometry and type of curvature [1].

2. Method

In the current study, the survey that includes 12 interviews with professionals was carried out. Interviews were conducted in person and in own arrangement.

2.1. Survey questions

It was made a proper balance between the number and kind of questions on one hand and the relevance and usefulness of the response on the other. This resulted in an eight question survey. The opening two questions inquiries about the general premises of the respondent with regard to different type of glass and curved glass structures. In the consecutive questions 3 through 5, the respondent is asked to list main considerations, challenges and opportunities for curved glass envelope engineering. Answers on questions 6 and 7 were supposed to show practical solutions of curved glass structures through the appropriate structural and glass fixing systems application. Finally, question eight gives comments on thermal performances of curved glass.

Survey questions:

1. What is your experience with the different type of glass (flat, single curved, double curved) and their characteristics (visual, physical, structural, manufacturing and economical)? Which do you find more challenging?
2. How has the design and construction process of curved glass structures in buildings evolved in recent years?
3. What are the main considerations when you design / specify a curved glass element?
4. How do these considerations differ from the design / specifications of a flat glass element?
5. What are the challenges and opportunities for curved glass envelope engineering?
6. Which structural systems are most appropriate / not appropriate (frames, simple trusses, mast trusses, strong-backs, glass fins, grid shells, tensegrity, cable trusses, cable nets, shell with cable) for curved glass panels and why?

7. Which glass fixing systems are most appropriate / not appropriate (framed systems - panel, veneer, unitized and frameless systems - point-fixed drilled and point-fixed clamped) for curved glass panels and why?

8. Do you consider the thermal performance when designing / specifying curve glass panels?

2.2. Distribution

The survey was distributed among architects, engineers and researchers known to have experience with the use of structural glass and glass facades, more specifically the members of several professional institutions, companies and glass manufacturers. They are: Foster + Partners, London; Glass Light and Special Structures, London; Eckersley O'Callaghan, London; Meinhardt Façade Technology, London; Malishev Wilson Engineers - Creative Engineering & Structural Glass Design, London; FH Joanneum University, Graz; Faculty of Architecture, University of Belgrade; Pavle Company, Belgrade; Concav Convex, Belgrade.

3. Results of survey

Survey is conducted during the period of one month, 12 responses were collected in that time period.

3.1. Respondents

The respondents are active in various professions within the field of glass structures. In this survey, distinction is made between A) engineers at consulting offices, B) engineers involved in facade construction, C) researchers at university and D) engineer at glass processing firm (table 1). The survey was held at an international level; exactly the respondents are active in three different countries, as shown in table 2. Although project and engineering skills, as well as experience would inevitably vary between respondents, all responses were valued equally.

Table 1. Respondent profession.		Table 2. Respondent's country of practice.	
Respondent profession	no. resp.	Country of practice	no. resp.
A) architects at consulting office	4	United Kingdom	8
B) engineers involved in facade construct.	4	Austria	1
C) researchers at university	2	Serbia	3
D) engineers at glass processing firm	2		
Total	12	Total	12

3.2. Analysis of responses

Not all questions were answered by each respondent. Therefore, Table 3 lists the number of responses per question.

Table 3. Number of responses per question.								
Question	1	2	3	4	5	6	7	8
no. of responses	9	9	9	8	7	8	8	10

3.2.1. Analysis of responses to Question 1. What is your experience with the different type of glass (flat, single curved, double curved) and their characteristics (visual, physical, structural, manufacturing and economical)? Which do you find more challenging?

The majority of respondents agreed that the application of curved glass presents a greater challenge. One respondent pointed out that the application of all types of glass represents an equal challenge. All respondents agreed that annealed glass presents more economical solution which does

not have an optical distortion. However, this type of glass is sensitive to thermal shock and can lead to easy cracking. Besides, due to the way it breaks, creating large pieces of very sharp edges, this type of glass does not provide the necessary security. Heat strengthened glass tolerated higher loads, but it breaks similarly to annealed glass. Thermally toughened glass has a higher degree of resistance and it breaks as safety glass. The process of lamination of glass also provides a high degree of safety since the glass does not scatter during fracture. Some respondents identified the thermal process of curved glass shaping as a technique during which additional problems arise due to its exposure to higher temperatures leading to its expansion, and thus to the appearance of optical distortions and changes in dimensions and edges of glass. Only three respondents recognized that new technique of cold bending of glass does not lead to such problems, but in this way it is not possible to create all geometry of double curved glass. One respondent indicated that complex curved forms can be achieved also by application of flat glass, so that the design process represents compromise between the wishes of the architect and the possibilities provided by the application of a particular type of glass in relation to economic cost. Curved glass panels are difficult to produce to be identical and ideally processed, which is particularly expressed in relation to available different technologies of production. The common comment is that should take into account that the glass always break, but it should be considered how this will happen. Regarding structural characteristics, by application of curved glass is possible to achieve more resistant structures, as all respondents agreed. Also, in the design stage, different ways of bearing glass panels have to be considered because hole drilling in the glass for point supported (bolted) structure contributes to additional concentrated stresses in glass creating opportunities for a break in the weakened areas. The general response is that there is still no systematized experience data for curved glass.

3.2.2. Analysis of responses to Question 2. How has the design and construction process of curved glass structures in buildings evolved in recent years?

In total, seven respondents particularly emphasized that development of technology have contributed to the larger dimensions of glass panels, smaller optical distortions and economically more favorable characteristics. Besides, the development of technology has led to the emergence of ultrathin and ultrarigid Gorilla glass (0.7 – 1.5 mm) which shows excellent visual characteristics and can be further processed by cold or thermal bending for building application. Unfortunately, the limitation for its application in architecture is still small dimensions of the glass panel (max. 1.5 – 2.0 m). Two respondents commented that there are fewer questions concerning the possibility of fabrication of certain dimensions of curved glass panels, but rather questions of the functional and economic justification of their application. All respondents agreed that as the application of curved glass structures increasing, especially in the last ten years, the directions of development are the reduction of the economic cost, the rescission of optical distortion on the curved glass and the achievement of larger dimensions. The general response is that the best solutions are still achieved through the cooperation of designers with facade consultants, facade constructors and glass manufacturers.

3.2.3. Analysis of responses to Question 3. What are the main considerations when you design / specify a curved glass element?

The answers were more diverging in nature than previous questions. The main considerations are: dimension of glass panel; structural system; stress value in the glass; techniques of shaping (bending); residual capacity after fracture; visual quality of glass; glass performances; solar factor; glass shading; glazing type (single, double and triple glazing – insulated glass unites panels); possibility of application of laminated glass, as well as determined colour, ceramic frit, coatings and interlayers; visual distortion; rationalization of geometry; reduction of economic costs; the possibility of panel replacing after glass fracture without endangering the stability of the entire structure. The general response is that all aspects of the application of the curved glass are equally important, and from engineer itself depends the order in which he approaches to consideration of the aspects.

3.2.4. Analysis of responses to Question 4. How do these considerations differ from the design / specifications of a flat glass element?

The majority of the answers (7 of 8) claimed that the difference is primarily at an economic cost that is considerably higher for curved glass, while at the same time all technical characteristics and calculations are more complex.

Some particularly complex characteristics of curved glass are emphasized by respondents as follows:

- Using better structural characteristics of curved glass as a challenge.
- Requirements for greater visual quality inevitably influence in increasing costs.
- Greater sensitivity of curved glass as a material.
- Greater stiffness of curved glass can contribute to reduction of glass thickness.
- Drilling the holes in curved glass for bolted assembly.
- Only a few types of low-emission coatings (mostly hard) are applicable on curved glass.
- When applying curved insulated glass units (IGU) panels, it is necessary to take into account the existence of internal pressure, that is, the existence of a difference in climatic conditions in which the panel is manufactured and assembled in the factory from the climatic conditions that prevail at the site or place of assembly, and that can lead to breakage of glass elements.

3.2.5. Analysis of responses to Question 5. What are the challenges and opportunities for curved glass envelope engineering?

One respondent stated that the challenge could be, in addition to a little known technique of cold bending, a vision of use of traditional technique of glass blowing for shaping different forms from which the panels would be cut off. Nevertheless, the majority of the respondents (4 of 7) claimed that research on new materials is more challenging including new glass types (Dichroic glass) that improves design characteristics, as well as ultrathin Gorilla glass which application in architecture is in the research phase. Two respondents commented that improvements could be also achieved by the process of optimization of curved surface of glass structure which allows penalization by greater percentage of flat and single curved panels as opposed to a much smaller percentage of double curved panels or their avoidance. None of the respondents didn't take into consideration new developed 3D printing of glass which allows design and fabrication of geometrically complex and adaptable structures and which product - type of lens can reduce heat dispersion and thus reduce global warming on an urban scale [2]. The general response is that each curved glass application represents a new challenge, given that the architects' requests are still out of technical conditions of building construction. Manufacturers put an effort to bring the production technique closer to the architects' requirements, as well as to educate architects about technical production possibilities.

3.2.6. Analysis of responses to Question 6. Which structural systems are most appropriate / not appropriate (frames, simple trusses, mast trusses, strong-backs, glass fins, grid shells, tensegrity, cable trusses, cable nets, shell with cable) for curved glass panels and why?

According to the majority of interviewees (5 of 8), a significant feature of the application of curved glass is use of its geometric stiffness in order to achieve greater spans and to reduce the number of elements of supporting structure. However, according to one interviewee, complete glass structure which implies glass columns, beams and ribs or spatial structures of a large span can not be applied in the case of large curvature of glass surface. As well, the smallest limitations for curved glass application is set up by frame systems, while for application of cable nets it is necessary to predict the possibility and to determine the maximum deflection. Glass is a material that does not tolerate large deformations, as four respondents emphasized. More precisely, it has its structural performance and maximally allowed stress values in relation to different static influences. As the engineer usually determines a primary structure by guiding other requirements, on the parts of the building where glazing is provided, the structure is subsequently verified and possibly corrected, while inversely it is much rarer. General response is that considering a number of different constructive systems, according

to which the structural glass facades are classified [3], it could be concluded that there is no system that would be comprehensively the best for application on curved glass envelopes.

3.2.7. Analysis of responses to Question 7. Which glass fixing systems are most appropriate / not appropriate (framed systems - panel, veneer, unitized and frameless systems - point-fixed drilled and point-fixed clamped) for curved glass panels and why?

According to most interviewees, the framed system still stands out as the most appropriate considering curved and freely shaped glass which remains attached along the edge on substructure. On the other hand, architect's requirements for increasing transparency of the envelope surface remain a particular challenge for facade contractors. All respondents agreed that in case of curved glass panels that are point fixed on the substructure, it is important to take into account the order of the activity: 1. hole drilling; 2. glass bending using one of the shaping techniques (hot and cold bending); 3. curved glass tempering - prestressing. According to some respondents (3 of 8), one of the options is a linearly or dotted glued glass on a substructure, especially placed on a frame in the factory and such mounted on a construction site. General response is that connections and fixing methods for the application of curved glass must be analysed and numerically verified, since the curved shape of glass panel contributes to the load distribution in different ways, acting as a glass shell.

3.2.8. Analysis of responses to Question 8. Do you consider the thermal performance when designing / specifying curve glass panels?

Thermal performances must be analysed in order to avoid thermal shock effect in the glass [4]. However, as four interviewees emphasized, it is possible to apply only a small number of low-emission coatings in thermal bending and therefore the possibility to achieve a good solar factor (g-value) is to be considered. Almost all the respondents agreed that thermal performance is taken into account without possibility of obtaining the correct results. The general response is that is necessary to explore the methods for a precise calculation of thermal characteristics of curved glass, respectively to create a mathematical model of heat transfer in a curved insulated glass panels that would give a link between geometry, type of insulated glass panels and thermal characteristics in order to evaluate the energy efficiency of buildings with geometrically complex glass envelope.

4. Conclusion

The analysis of collected data during survey clearly showed that there is a need for more research, comprehensive design aids and recommendation for engineering of curved glass structures. During the interviews, different data and answers were obtained indicating that it was not possible to get determined elements and their order in the process of design and construction, but the process especially adapts to each project. Taking into account the need to clarify all mutual influences and dependences of the process elements, the mapping of the process of design and construction of geometrically complex form of glass building envelopes have seen as a necessary. From that reason, the survey enabled development and verification of the process map which represents help and support for further research of curved glass applications in the materialization of building envelope.

Finally it should be claimed that curved glass is a material that implies many complex considerations in the early stages of the design process involving glass surfaces concept, geometry, aesthetics, structural and thermal characteristics, selection of geometry of glass elements and glass-shaping (bending) techniques, as well as the compatibility of all the treatments with the bending process. The reasons of selection of particular type of glass geometry and construction methods should always be analysed, discussed and well understood in order to maximize the utilization of potentials of curved glass application and to provide safe and well geometrically complex forms of glass structure.

Acknowledgments

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