Challenging Glass 7
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Thin Glass as a Tool for Architectural Design

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Glass with a thickness of less than 2.0 mm can be defined as a thin glass or with a thickness of less than 0.5 mm even as ultra-light. Thin glass requires for curved surfaces in order to gain structural stiffness in static use. The geometry is based on the known theory of developable surfaces. Such Façades may therefore be created from cold bent or curved laminated thin glass layers. In the past semester a seminar with architectural students were held and three projects of this seminar are worth to be presented to the public for demonstration of possibilities for use of thin glass. The definition of a seminar project for students was a connection of a big housing area with the nearby stop of the local tram which is separated by a railway line. Two possibilities for the pedestrian are given to pass the railroad. The first one is a passage underground below the railroad and the second one is a bridge above the railway line. This paper contents a study of architectural design made by students. Two projects which will be presented in this paper focuses on the design of the entrance building of a passage underground and the third project is a design of a pedestrian bridge above the railroad. Beside the architectural design a structural analysis was done to support the design process such as with ranges of possible bending radii for the curved thin glass elements and to guarantee the feasibility of the design.

Keywords: Thin glass, Developable surfaces, Cold bending

1. Introduction

The definition of a seminar project for students was to design a connection of a big housing area with the nearby railway station and a stop of the local tram which was separated by a railway line. Two possibilities for the pedestrian are given to pass the railroad. The first one is a passage underground below the railroad, marked with location A and the second one is a bridge above the railway line, marked with location B in Figure 1 below. This paper contents a study of architectural designs made by students. Two projects which will be presented focuses on the design of the entrance building of a passage underground and the third project is a design of a pedestrian bridge above the railroad. Beside the architectural design a structural analysis as a feasibility study was done to support the design process such as with ranges of possible bending radii for the curved thin glass elements.

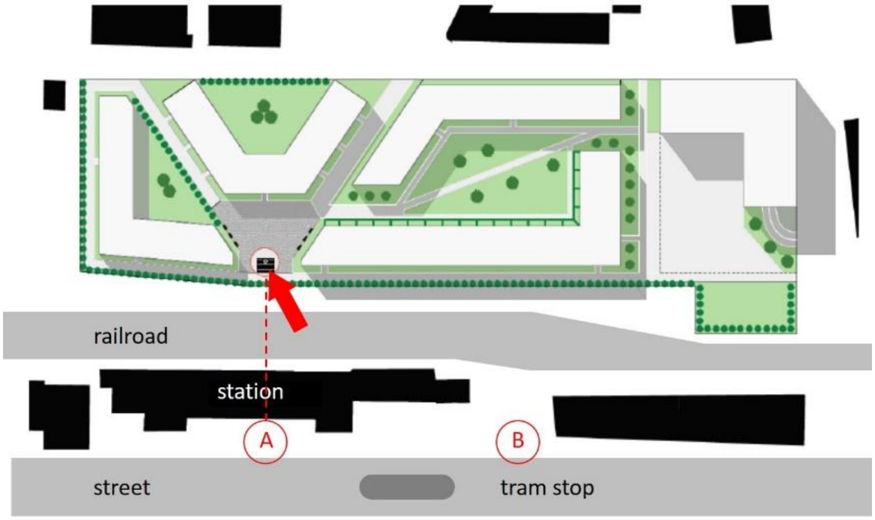


Fig. 1 Location plan of planning area.

2. Architectural Planning tools

The principle concept of the seminar was a kind experimental architectural design with paper or synthetic foils for the thin glass and small timber rods or laser cut paperboard for the substructure. After a short introduction about the possibilities and architectural design tools the students started their design process beginning from first sketches and small working models and ended by models in the scale of 1:50. The design tools such as developable surfaces, Gaussian curvature and minimum bending radii are explained in the following sub-chapters more in detail.

2.1. Developable surfaces

A developable surface is a smooth surface with zero Gaussian curvature, see chapter below. It is a surface that can be flattened onto a plane without distortion, which means without stretching or compressing the mid-surface of the glass. Conversely, it is a surface which can be made by transforming a plane by bending, also described in Silveira. et al (Silveira. et al).

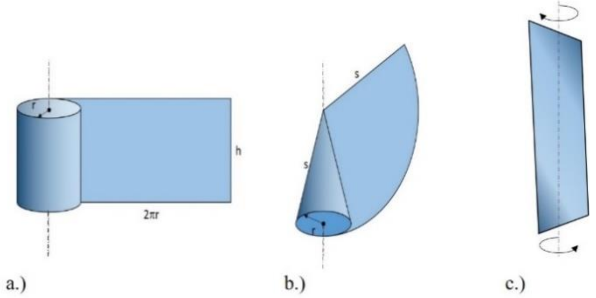


Fig. 2 Developable surfaces, a) cylinder, b.) cone, tangent developable surface c.).

2.2. Gaussian Curvature

At any point on a surface, we can find a normal vector that is at right angles to the surface, planes containing the normal vector are called normal planes. The intersection of a normal plane and the surface will form a curve called a normal section and the curvature of this curve is the normal curvature, as shown in Figure 3 a.) below. For most points on most surfaces, different normal sections will have different curvatures; the maximum and minimum values of these are called the principal curvatures and are designated with κ_1, κ_2. The Gaussian curvature K of a surface at a point is the product of the principal curvatures, κ_1 and κ_2, at the given point and can be determined with the following Equation (1).

$$K = \kappa_1 \cdot \kappa_2 \qquad (1)$$

For example, a sphere of radius r has Gaussian curvature of K=1/r2 everywhere on the surface. A flat plane, a cylinder or a cone has Gaussian curvature of $K = 0$ everywhere on the surface. The Gaussian curvature can also be negative, in the case of a hyperboloid. The sign of the Gaussian curvature can be used to characterize the surface. If both principal curvatures are of the same sign $K > 0$, then the Gaussian curvature at this point is positive, as can be seen in Figure 3 b.). At such points, the surface will be dome-like. All sectional curvatures will have the same sign. If the principal curvatures have different signs $K < 0$, as can be seen in Figure 3 c.), then the Gaussian curvature at this point is negative. At such points, the surface will be saddle-shaped, because one principal curvature is negative. If one of the principal curvatures is zero $K = 0$, as can be seen in Figure 3d.) the Gaussian curvature is zero and the surface is developable. The Gaussian curvature can be analyzed with programs such as Rhino, see in (Neugebauer 2019).

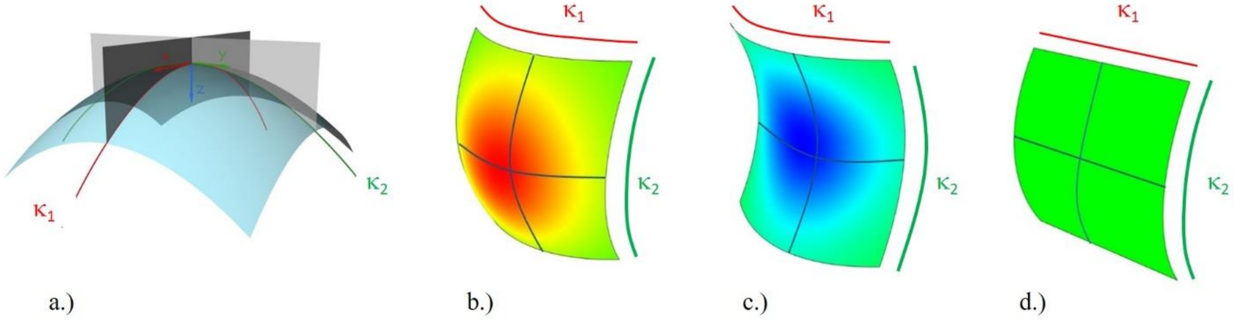


Fig. 3 Gaussian Curvature.

2.3. Bending radii

For such applications laminated safety glass is demanded for safety reasons. For architectural design minimum radii are helpful to find the balance between the radius and the required thickness of glass due to a structural design. In the following Table 1 minimal radii glass for different glass thicknesses are displayed with a full composite between the glass plies is assumed.

One approach is to determine the stress using Equation (2). and (3). The bending moment can be calculated with Equation (2) based on the differential equation of bending theory and with the section modulus the stresses due to cold bending can be computed easily. With Equation (3) which includes the modulus of elasticity E the thickness of the glass h and the strength of used thin glass (f_k/γ_m) the minimum radius can be determined, but this approach neglects the influence of Poisson's ratio.

$$E \cdot I \cdot w'' = -M \,;\, E \cdot I \cdot \kappa = -M \qquad (2)$$

With the characteristic value for the strength given, for example for annealed glass f_k =45 MPa (EN 572-1), heat treated glass f_k=70 MPa (EN 1863) and chemically pre-stressed glass as f_k=150 MPa (EN 12337), the minimum radius depending on the thickness of the glass can be determined, as shown in Table 1 below.

$$r_{min} = \frac{E \cdot h}{2 \cdot \left(\frac{f_k}{\gamma m}\right)} \qquad (3)$$

Table 1: Minimum radii r_{min} of glass.

Thickness of one glass ply h [mm]	Annealed glass r_{min} [mm]	Chemically pre-stressed glass r_{min} [mm]
0.5	1167	350
1.0	2333	700
1.5	3500	1050
2.0	4667	1400

These architectural design tools, such as the developable surfaces with the analyzing tool of Gaussian Curvature and the approach of the minimal radii, were the basis to solve the task of the architectural design which was described in the introduction. The aim of architectural seminar was to make an experimental design started with the first sketches, followed be paper models and ended in a final model in the scale 1:50. Results of the seminar studies are presented in the following chapter.

3. Entrance portal "Umbrella"

3.1. Architectural idea

The idea of this architectural design of the entrance portal was to create an umbrella for covering the staircase which connects the different levels. Above the elevator this umbrella is located. To give a special design accent it was played with stripes made from thin glass with a width of 1 m. This glass stripes are the outer layer of the umbrella, as can be seen in the following Figure 4 below.

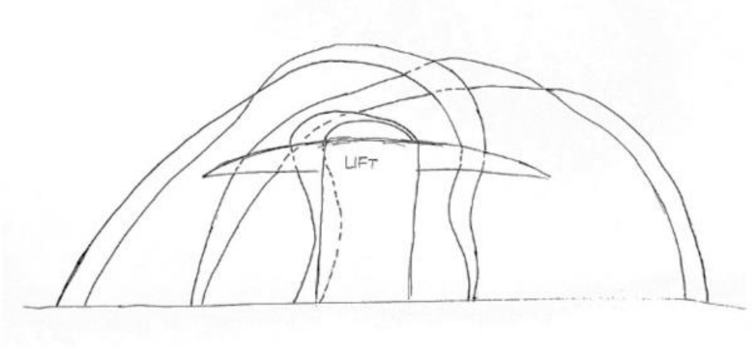


Fig. 4 First design sketch of the entrance portal "Umbrella".

3.2. Design concept

The strategy was to start with small stripes made from paper in the scale of 1:100. It was an analysis of possible geometries which can be made with such strips, as displayed in Figure 5 a.). The following step was to combine additional strips with the concept of strengthening the whole structure, as shown in Figure 5 b.). At the end of this second step a certain number of strips were arranged which resulted in a static stable structure. The whole model made from paper stripes in the scale of 1:100 is shown in Figure 5 c.) and d.).

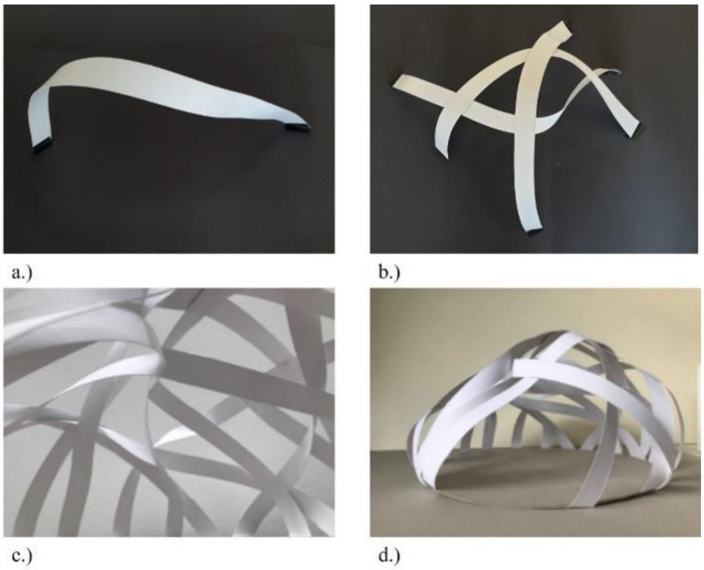


Fig. 5 Design concept as paper model.

The last step of this special architectural design process was to build a model made from paper board or timber board and synthetic foils which should represent the glass in this model in the scale of 1:50.

In the process between the working model and the final model the group had to solve structural issues. In this case one point was the length of the strips. The stripes were subdivided into laminated safety glass elements and connected with stainless steel profile, which are as tiny as possible, as shown in Figure 6. The solution with this steel profiles has another benefit. It gives the possibility to connect the glass stripes at certain point. This concept lead to a static stable system of the architectural design. The curved thin glass elements between the stainless profiles act as a membrane surface for shear forces.

Fig. 6 Final Model of entrance portal "Umbrella", side view a.), top view b.), interior view c.).

4. Entrance portal - "Wings"

4.1. Architectural idea

The idea of this architectural design of the entrance portal was to cover the staircase like a bird with its wings. This design shows a clear portal through which the people can enter the passage underground below the railroad, as displayed in Figure 7 below.

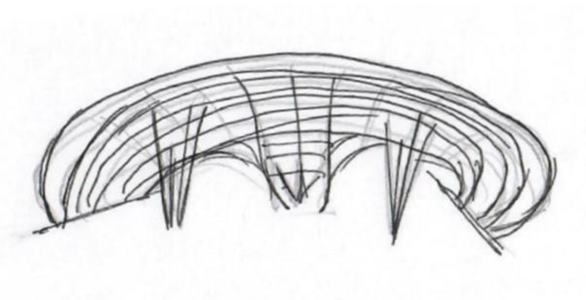


Fig. 7 First design sketch of the entrance portal “Wings”.

4.2. Design concept

The concept was to play with a certain cut paper in scale 1:100, as shown in the flat geometry in Figure 8 a.) below. With this paper a curved geometry was created. This process followed very clear the principle of developable surfaces, displayed in figure 8 b.) and c.).

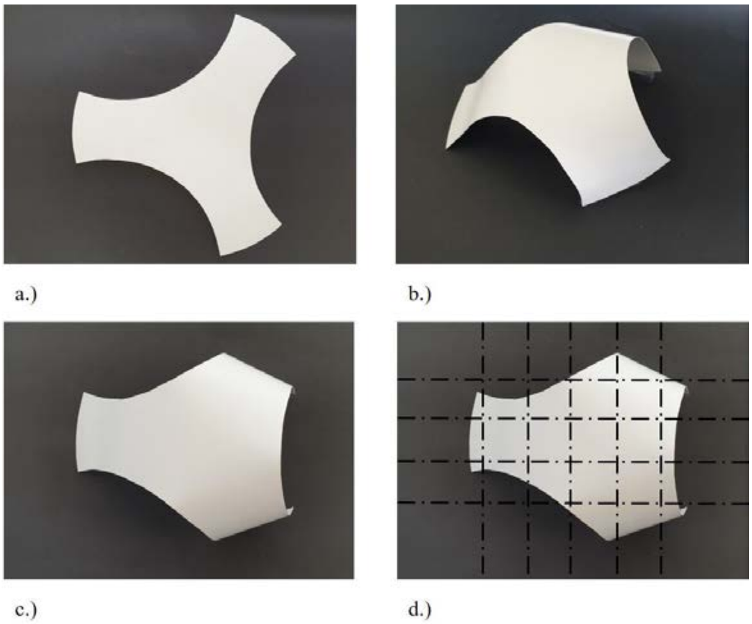


Fig. 8 Design concept as paper model.

The last step of the architectural design was to build a model made from laser cut paper board and small timber rods for the substructure. Synthetic foils should represent the thin glass in this model in the scale of 1:50. For this reason an analysis of the geometry was done in the way that the curved surface was described along orthogonal orientated axis, as shown in Figure 8 d.) above. After an optimizing process of these geometry data a system of arches were defined and used for laser cut. The final model is shown in Figure 9 below.

Fig. 9 Final model of the entrance portal “Wings”, front view a.), back view b.), interior view.

5. Bridge - "Wrapping"

5.1. Architectural idea

The architectural design idea was to connect the residential area and local infrastructure such as the tram stop or the railway station with a bridge above the railroad. This structural concept of the bridge with intermediate supports via inclined cables fixed at a big building of the residential area, as shown in the sketches in Figure 10 below.

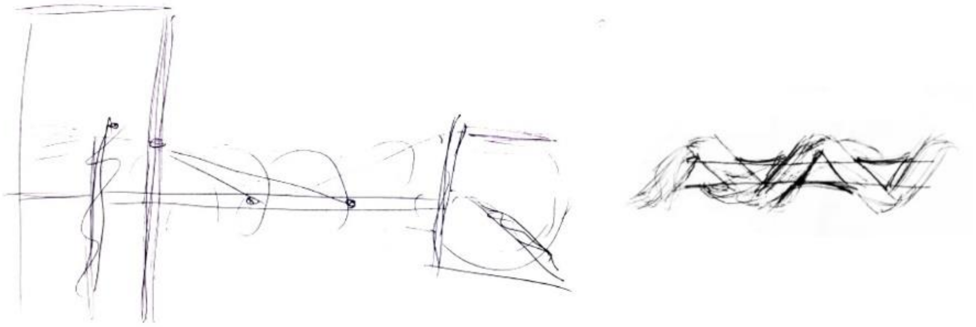
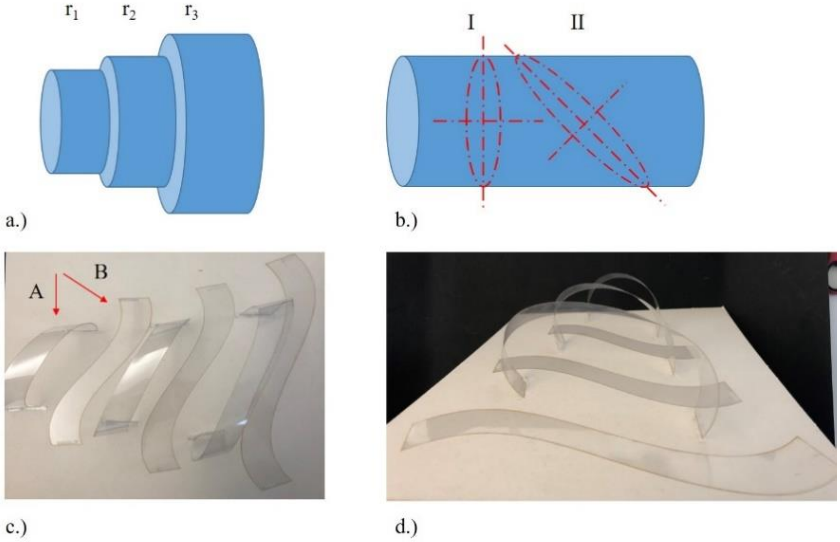


Fig. 10 First design sketch of the bridge "Wrapping".

5.2. Design concept

The design concept for the cladding or "Wrapping" of the bridge was to play with three cylinders with different radii ($r_1 = 3500$ mm, $r_2 = 4000$ mm and $r_3 = 4500$ mm), as displayed in Figure 11 a.). A special idea was to cut the cylinder not perpendicular to the longitudinal axis of the bridge, as shown with situation I in Figure 11 b.). Rather the cylinders were cut inclined around a vertical axis, as shown with situation II. This concept leads to elliptical arches instead of round arches circles. In addition, the different special cut cylinders were arranged with an alternated change of radii, as displayed in Figure 12.



a.) b.) c.) d.)

Fig. 11 Design concept.

A cylinder is a developable surface, as described in a previous chapter. The concept of developable surfaces with the cylindrically curved geometry is marked with A and the developed "flat" surface is marked with B, as displayed in Figure 11c.). One can see that the developed glass edges got a curved geometry, which can be laser cut. Figure 11 d.) shows a different view of the same concept.

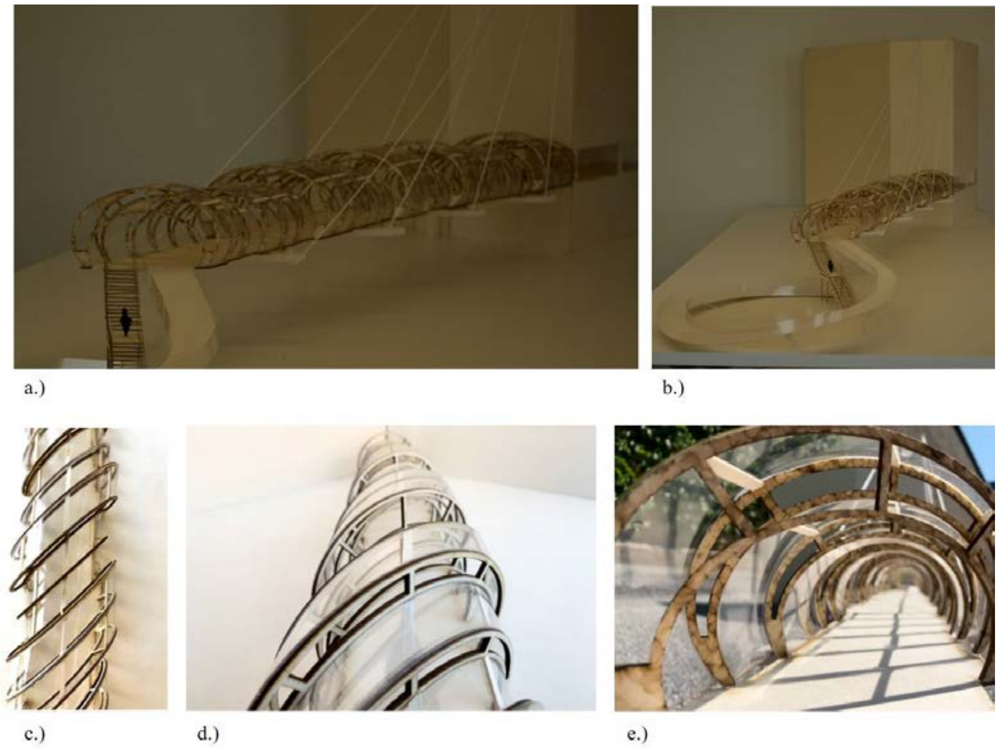

a.) b.) c.) d.) e.)

Fig. 12 Final model of the bridge "Wrapping".

5.3. Structural analysis

For the feasibility study of the bridge a structural analysis was made. The project site for the architectural design is located in the center of Graz, Austria.The span of the elliptical arches is given with s = 6960 mm and the height is given with h = 4000 mm, as displayed in Figure 13 below. The radii of curvature of the elliptical arches were determined with r_{side} = 2121 mm for the smaller side radii and r_{top} = 5998 mm for the bigger radius on the top. The distance between the arches are given with 2000 mm in direction longitudinal to the axis of the bridge.

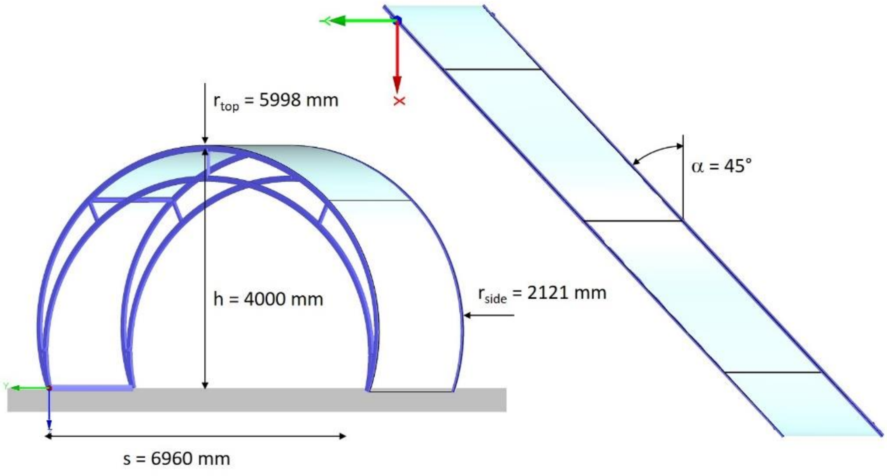


Fig. 13 Geometry of Finite model of the bridge "Wrapping".

The loads on the structural analysis were given beside the deadload with the characteristic snow load on the ground with s_k = 1.65 kPa and basic pressure for wind is given with q_b = 0.26 kPa. The thin glass as the cladding of the elliptical arches was modeled with the help of a finite element program.

For the determination of the stresses of the thin glass due to the curvatures the radius of the cylinder r_{cyl} = 4000 mm had to be taken. The stresses resulted due to the Equation (3) for the laminated safety glass consists of 2 x 2 mm chemically strengthened glass with $\sigma_{cur} = \pm 35$ MPa. Full connectivity between the glass plies without relaxation effects was assumed. These stresses are tension stresses for the outer glass surface and compressive stresses for the inner glass surface.

The maximum tension stress for the inner surface of the thin glass for the load combination due to the dead and snow load was determined with $\sigma_{ED,g+s} = 73.8$ MPa and the maximum tension stress for the load combination due to dead load and wind load was determined $\sigma_{ED,g+w} = 49.3$ MPa on the outer surface, as displayed in Figure 14 below.

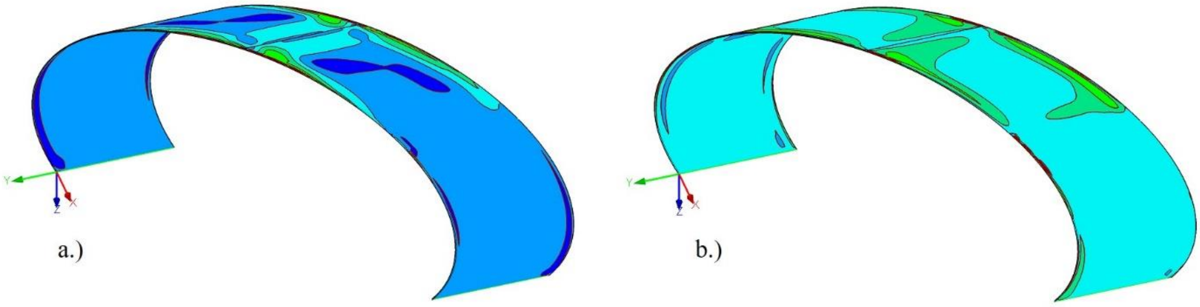

a.) b.)

Fig. 14 Results of Finite model of the bridge "Wrapping" a.) load combination with snow, b.) load combination with wind.

The load combination of the loads dead load and snow load and curvature of the thin glass resulted in the maximum tension stress of $\sigma_{Ed} = 38.8$ MPa for the inner glass surface and the load combination of the loads dead load and wind load and curvature of thin glass resulted in the maximum tension stress of $\sigma_{Ed} = 96.6$ MPa for the outer glass surface. Which is less than the design value for chemically strengthened glass $f_d = 100$ MPa. The maximum deflection was determined with 11.5 mm which is less than the allowable deformation. With these results that feasibility of such a structure can be validated.

6. Conclusion

The described examples which were designed with the described architectural tools demonstrates the high potential which is given with a flexible thin glass. This potential of realization was validated with a feasibility study. Another benefit is the reduction of dead loads and consequently a reduction also a reduction of environmental impact. Additionally, the concept of cold bending instead of hot bending helps to reduce the energy consumption in the production process.

7. Acknowledgements

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