

CONCEPT FOR STUDENT GLASS PAVILION

Bojana Trajanoska, Elisaveta Dončeva, Daniela Pana, Hristijan Gjorgievski

*Faculty of Mechanical Engineering, “Ss. Cyril and Methodius” University in Skopje,
P.O. box 464, MK-1001, Skopje, Republic of North Macedonia
bojana.trajanoska@mf.edu.mk*

A b s t r a c t: Contemporary architecture and engineering are based on combining structural glass and steel, where glass is used for its transparency and steel for its strength. The intention behind this pavilion concept is decreasing the lack of modern glass structures in our surrounding. This article describes the FE modelling and analysis of a glass structure planned to be located in the technical campus of the Faculty of Mechanical Engineering in Skopje. The final exterior of the structure is consisted of five glass frames adhesively bonded and mechanically connected with bolts which give the support of the structure and hold the façade and roof panels. Different scenarios were presented regarding the stability and safety of the glass structure. The carried out FEM simulations are presented, based on predicted static loads, according to the pavilion's location and the climatic parameters. At the end of this article, visual representation of the CAD model within the campus space is given.

Key words: glass pavilion; steel connection; structural glass; state of the art; finite element analysis

КОНЦЕПТ ЗА СТУДЕНТСКИ СТАКЛЕН ПАВИЛЈОН

А п с т р а к т: Модерната архитектура и инженерство се темелат на комбинирањето на конструктивно стакло и челик, при што стаклото се користи поради провидноста, а челикот поради својата јакост. Овој концепт за студентски павилјон произлегува од недостигот на модерни стаклени конструкции во нашата околина. Трудот го опишува моделирањето и анализата со метод на конечни елементи на конструкција од стакло планирана да се постави во техничкиот кампус на Машинскиот факултет во Скопје. Крајниот надворешен изглед на конструкцијата се состои од пет стаклени рамки атактивно споени и механички зајакнати со завртки, кои го даваат скелетот на конструкцијата на која се поставуваат стаклените фасадни и покривни панели. Во поглед на стабилноста и безбедноста на стаклената конструкција, прикажани се различни конструктивни случаи. Презентирани се извршените симулации со примена на методот на конечни елементи, при што статичките оптоварувања се пресметани врз основа на локацијата и климатските услови. Визуелната репрезентација на моделот CAD е прикажана на крајот од трудот каде што се забележува хармоничното совпаѓање на конструкцијата со околината на техничкиот кампус.

Клучни зборови: стаклен павилјон; челични врски; конструктивно стакло; преглед на постојните трендови; метод на конечни елементи

1. INTRODUCTION

In the modern architecture and engineering, structural glass elements tend to replace the traditional structural materials, like steel or concrete. This dramatic change brought a new trend in glass roofs and external glass frames in home living. The two primary factors for using structural glass over any other building materials are innovative daylighting and transparency, which empower a sense

of unlimited space [2, 5]. Additionally these reasons are basic requirements when designing a student friendly environment for continuous learning or group working.

Although structural glass cannot be compared with steel in terms of durability and toughness, it is the only transparent material with high strength that can be used in many contemporary load-bearing structures. Strength values for structural glass design and its application are summarized in Table 1.

Table 1
Strength values of structural glass [4]
(MPa)

Compressive strength	880 – 930
Tensile strength	30 – 90
Bending strength	30 – 100

The high brittleness of the structural glass makes it risky to use in crowded locations because under tensile loads, any surface crack might cause failure of the glass element.

One of the common solutions regarding this problem is using treatment such as annealing, tempering and heat strengthening, as well as laminating in order to improve the mechanical properties and structural characteristics. Laminated glass has become extensively used as a safety glass in modern hybrid structures due to the polymeric interlayer that holds together the elements pieces when shattered. The interlayer, typically PVB or EVA, keeps the glass plies together even broken, constraining from breaking into large sharp pieces. Different types of glass breaking are shown in Figure 1.

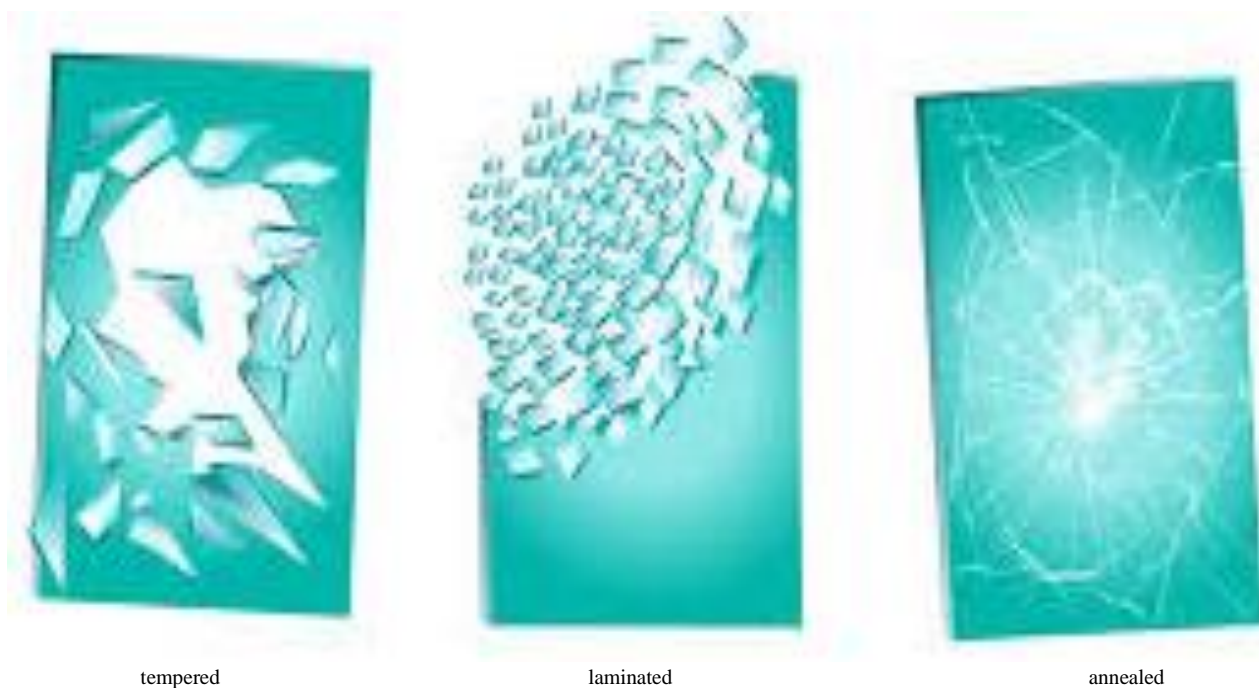


Fig. 1. Breaking of common glass types

The low ductility and the high compressive strength of the glass allows connections with greater strength and hardness, like the ones with stainless steel. Bolted connections (Figure 2) are used for connecting glass elements where stress concentrations may occur. Regarding the performance of the bolt, forces up to 30 kN can be transmitted per bolt [6]. In addition to prevent restraint forces, the number of bolts should be as minimal as possible in favor of greater bolt diameters.

Based on the above mentioned structural characteristic, the mechanical behavior the transparency and the innovative daylighting prospects of the structural safety glass as a laminated glass, it is chosen as the most adequate material for designing the stu-

dent pavilion accommodating new modern concepts with psychological benefits.

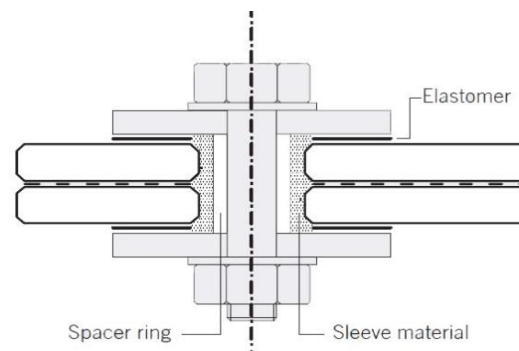


Fig. 2. Bolt connection [6]

2. CONCEPT

The student glass pavilion idea arose from the need of creative and innovative working space which students can use in their spare time at the technical campus of the Faculty of Mechanical Engineering in Skopje, and later the concept was introduced accordingly.

The glass pavilion is $5 \times 5 \times 2.5$ m, supported on a concrete fundament where steel groundwork is placed. The contact glass-steel is prevented with rubber installed inside the groundwork. The glass columns and beams are formed of tempered glass, joint with PVB, giving a high strength laminated panel (Figure 3).

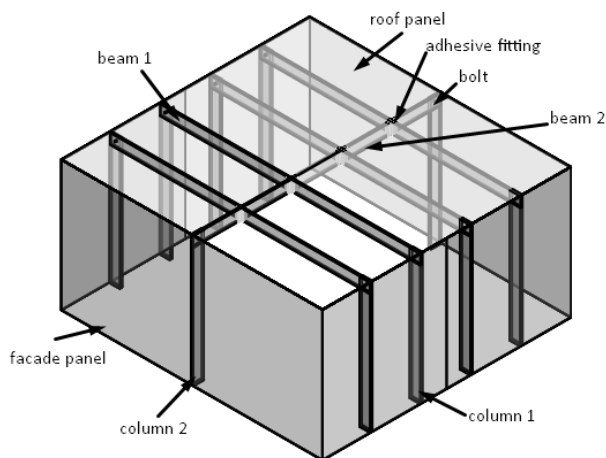


Fig. 3. Structural members

The lateral and horizontal glass panels that confine the structure consists of one fully tempered glass ply and heat-strengthened ply with inner PVB layer. Dimensions of the structural members are given in Table 2.

When designing, a previously detailed plan is required. Furthermore, a comprehensive research and calculations were carried out in order to realize the concept of glass pavilion. Finally, a flow diagram with various steps of work is presented (Figure 4).

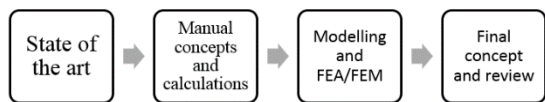


Fig. 4. Concept realization steps

A state of the art research has been done in the field of glass building construction. Wilson reviews the Glass Reading Room of the Arab Urban Development Institute in Riyadh, Saudi Arabia (Figure 5) [2]. The glass cube is

formed of laminated glass panels, connected with friction grip connections in order to provide stability through the frame that carries the applied loads.

Table 2

Dimensions of designed structural members

Structural member	Glass type, layer of glass (mm)	Dimensions L x W x H (mm)
Column 1	fully tempered, 2 x 10	200 x 20 x 2500
Inner column 1	fully tempered, 4 x 10	200 x 40 x 2300
Beam 1	fully tempered, 4 x 10	5000 x 40 x 200
Column 2	fully tempered, 2 x 10	200 x 20 x 2500
Inner column 2	fully tempered, 4 x 10	200 x 40 x 2300
Beam 2	fully tempered, 4 x 10	920 x 40 x 200
Roof pane	fully tempered 1 x 5 + heat strengthened 1 x 5	2500 x 1000 x 10
Façade pane	fully tempered 1 x 10 + heat strengthened 1 x 5	2500 x 2500 x 15



Fig. 5. Glass Reading Room in AUDI in Riyadh, Saudi Arabia [2]

In [10] the new pavilion located in Zurich, Switzerland (Figure 6) is analyzed). Matt-finished stainless-steel frame and colored but transparent glass, are the primary exterior details that give this polygonal-plan structure compliance with the environment and fulfill the illumination requirements.



Fig. 6. The color glass pavilion in Zurich, Switzerland [10]

All glass enclosure is discussed in [3, 7], built at the Leibniz Institute for Solid State and Material Research in Dresden, Germany (Figure 7). Their main goal is to describe the arrangement of the structural members, frame assembly and final installation. The fully glazed enclosure is made from laminated safety glass, bonded to the frame with a structural silicon adhesive as a joining technique. Hence, the glass corners are joint with acrylate adhesives, which give an exclusively transparent outlook.



Fig. 7. All glass enclosure at Leibniz Institute in Dresden, Germany [3]

Breakthrough in the application of structural glass was building the Apple Inc glass cube, the Fifth Avenue, store located in New York City, which was the first of a kind [1]. The structure itself shows functionality and simplicity. First glass cube (Figure 8) connected the engineering with the art; the second cube (Figure 9), further enhanced that connection. The limiting factors of the production technologies of glass resulted in a glass cube with 164 units joined, forming a standing art piece [1].



Fig. 8. Original glass cube – Apple store



Fig. 9. New glass cube- Apple store

The advancement in the production technology of structural glass was validated with constructing the second glass cube. Thirty-five units joined together proved that glass production has moved forward. Comparing the two of them (Table 3), it is inevitable not to see the difference in the roof design. Two spanning beams with secondary roof beams from sides and between the spanning beams holed with roof fins. The façade panes were able to be as large as $15\text{ m} \times 3.6\text{ m}$, which gave the final look of the second glass cube.

The reduction of the number of the glass structural members in the new Apple store, led to fewer glass-steel connections. One of the few reasons for rebuilding this glass cube was to establish the new developed connection that holds the glass panes together (Figure 10). Before it was completed, a numerical analysis was run with particular attention to the interaction between the glass, interlayers and fittings. The connection model (Figure 11) confirmed the expected behavior of the joined materials [1] and let to a unique challenge- rebuilding the glass cube.

Table 3

Comparison of the structural members of the two Apple glass cubes [1]

Building part	Cube 1	Cube 2
Columns	5 per elevation × 4 = 20	2 per elevation × 4 = 8
Facade panles (incl. doors)	72	12 + 2 doors + 2 side lights = 16
Roof beams	25 at 3.3 mm + 10 at 1.6 m = 35	2 at 10 mm + 7 at 3.3 m = 9
Roof panles	36	3
Entrance canopy	1	1
Subtotals	109 panels 20 fin columns 35 beams	20 panels 8 fin columns 7 beams
Total	164 glass units	35 glass units



Fig. 10. New developed fitting [1]

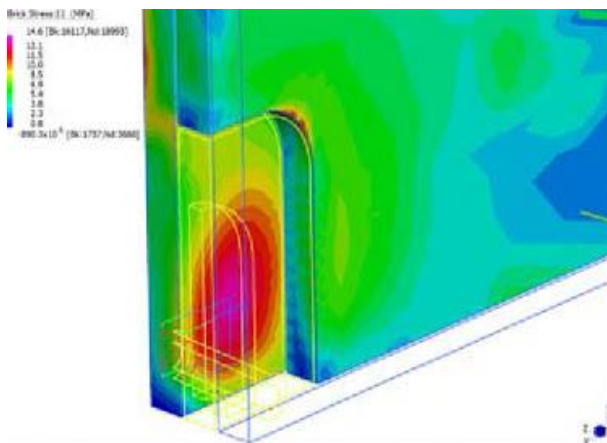


Fig. 11. Local connection model [1]

3. STRUCTURAL ANALYSIS

This paragraph shows the results of different analysis performed on these article subject concepts. Using laminated safety glass, all bearing elements were tested using FEM analysis, including the enclosed structure itself. The frame members, stated as glass beams and columns, are made of fully

tempered glass layers, each with thickness 10 mm. The glass frame were tested separately, as a primary bearing column-beam assembly. Mainly, it was expected a local stress to occur between the glass and the stainless-steel connection, because of the different behavior of the materials under loading conditions (Figure12).

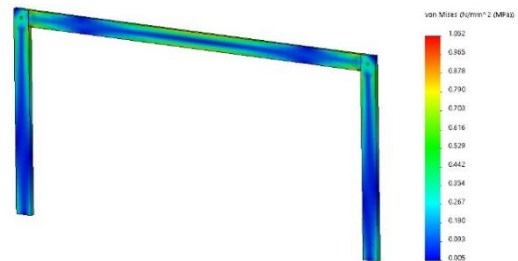


Fig. 12. Stress distribution of the structural frame

However, significant displacement was evaluated centrally on the glass beam, with maximum displacement of 0.182 mm (Figure 13).

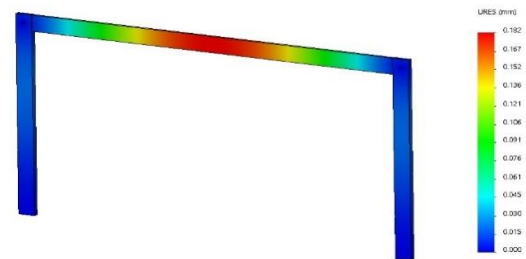


Fig. 13. Maximum displacement of the structural frame: column-beam

Regarding the above-analyzed factors, three different scenarios were examined under the same load conditions (Table 4).

Table 4

Scenarios for FEM analysis

Scenario No.	Description
Scenario 1	Structured without support beam and column 2, roof panel thickness 10 mm
Scenario 2	Structured with support beam and column 2, roof panel thickness 15 mm
Scenario 3	Structured with support beams and five cross beams with adhesive fittings, roof panel thickness 10 mm

A brief comparison of the FEM results is given in Table 5 and a significant explanation is summarized.

Table 5

Comparison of FEM results

Scenario	Max. stress (MPa)	Max. displacement (mm)
Scenario 1	13.80	26.39
Scenario 2	7.39	6.23
Scenario 3	7.96	7.57

The stress distribution is present for each scenario and remarkably lower stresses were observed on the front and back façade panes of Scenarios 2 and 3 (Figures 16 and 18, respectively), when compared to stress result from the Scenario 1, shown in Figure 14

The displacement analysis of Scenario 1 presented in Figure 15 shows considerably larger displacement of the front and back façade panes under buckling behavior, while the rest members of the structure are sufficiently substantial for the suggested scenario. On the other hand, the results obtained from both, Scenarios 2 and 3, illustrate smaller displacement gradient (Figures 17 and 19, respectively).

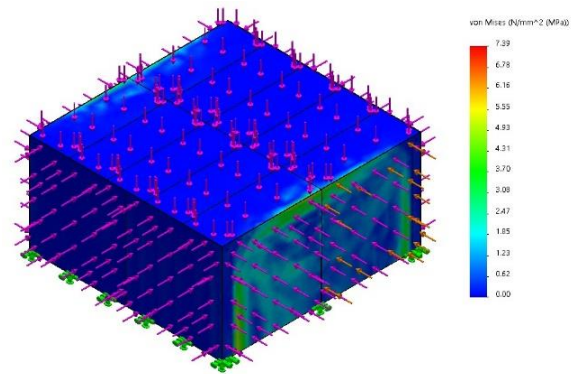


Fig. 16. Scenario 2 – Von Mises stress

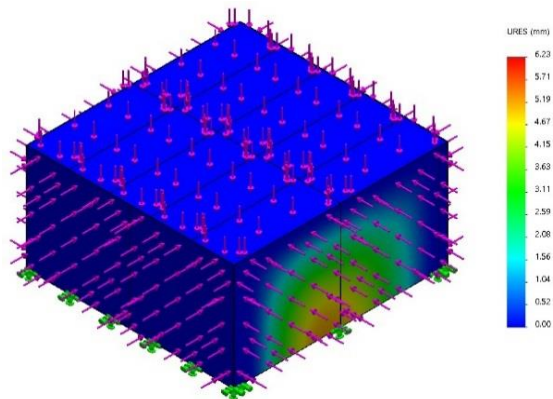


Fig. 17. Scenario 2 – Displacement

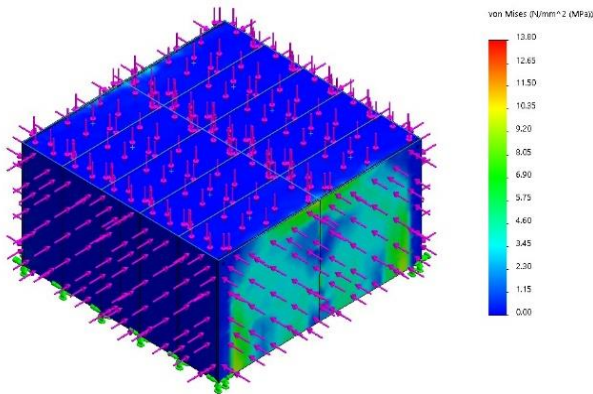


Fig. 14. Scenario 1 – Von Mises stress

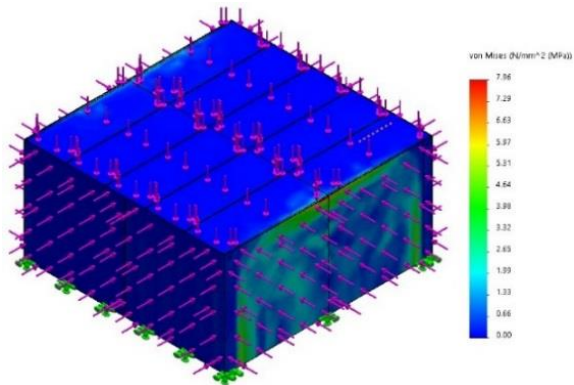


Fig. 18. Scenario 3 – Von Mises stress

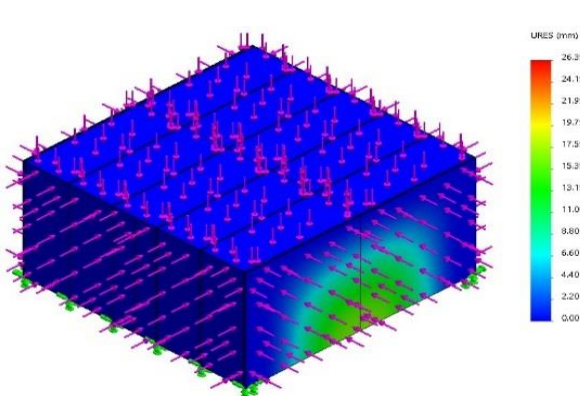


Fig. 15. Scenario 1 – Displacement

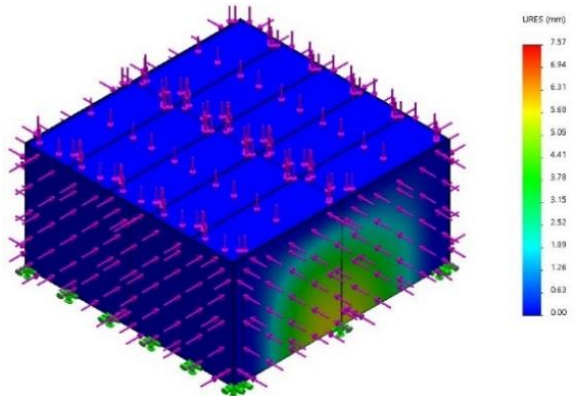


Fig. 19. Scenario 3 – Displacement

The exemplify results are due to the additional central support frame (*Scenario 1* is modeled without the support beams and columns).

Another conclusion can be outlined from the simulation analysis. As mentioned before, glass has high compressive strength, but it depends on the size of the glass panel [9]. The larger the size is the more chance of finding critical imperfections and defects in the glass element. The buckling phenomena in glass panels under compression is frequent problem in all glass structures [11]. Based on this knowledge, laminated glass columns are arranged on both, left and right side of the façade for support and preventing sudden failure. Considering these side columns arrangement, no significant stresses nor displacement were determined in none of the scenarios.

4. CONCLUSIONS

This comprehensive study on structural glass student pavilion opens the possibility for conversion of creative and innovative project. The mechanics and safety for this structure was proven by using FEM analysis on each scenario under static loads. Scenario 3 was chosen as an eventual structural solution for further detailed and accurate technical development (Figure 20).



Fig. 20. Visual representation of the student glass pavilion located in the technical campus in Skopje

Furthermore, the preceding results of the stress and deformation that occurred in Scenario 3 were

dependable and rational when choosing the final concept as well as the total weight of the glass structure.

The vast field of application of the glass structures is evaluated by the state of the art, which are serving different functions. While being the driving factor, safety is the main concern when designing and constructing glass structure. Simplicity and the ability to comply with the environment is one of the benefits of an all-glass structure, which implies on the physiological state of the users.

REFERENCES

- [1] Bostick, C., O'Callaghan, J.: The Apple glass cube: Version 2.0, In book: *Challenging Glass 3 & Conference on Architectural and Structural Applications of Glass*, Technical University (TU) Delft, The Netherlands, 2012.
- [2] Wilson, P.: All-glass enclosures – Spaces for working and living, In book: *Challenging Glass 4 & COST Action TU0905 Final Conference*, pp. 641–647, 2014.
- [3] Weller, B, Nicklisch, F., Prautzsch, V. Döbbel, F., Rücker, S.: All glass enclosure with transparently bonded glass frames. In: *Challenging Glass 2 – Conference on Architectural and Structural Applications of Glass*, Bos, Louter, Veer (Eds.), TU Delft, May 2010.
- [4] Fröling, M.: *Strength design methods for glass structures*, Doctoral thesis, Lund, Sweeden, Division of Structural Mechanics, Lund University, 2003, pp. 9–15.
- [5] Louter, C., Bos, F., Belis, J., & Lebet, J. P. (Eds.): *Challenging Glass 4 & COST Action TU0905 Final Conference*. CRC Press, 2014.
- [6] Wurm, J.: *Glass Structures – Design and Construction of Self-supporting Skins*, Birkhäuser Verlag, 2007.
- [7] Weller, F., Nicklisch F.: Bonding of glass – Latest trends and research, In: *Structures Congress*, 2010 ASCE, Orlando, Florida, 2010.
- [8] Trajanoska, B., Gavriloski, V., Bogatinoski, Z., Gavriloski, M.: State of the art in research of reinforced structural glass elements, *Mechanical Engineering – Scientific Journal*, vol. **33**, 1, pp. 27–32 (2015).
- [9] Morgan, T.: *Aspects of Structural Glass*, Institute of Structural Engineers, SE Counties Branch, 2010.
- [10] Helzel, M., Taylor, I.: *Stainless Steel and Glass*, Euro Inox, The European Stainless Steel Development Association, Brussels, Belgium, 2008.
- [11] Bedon, C., Amadio, C.: Stability of flat glass panels under combined in-plane compression and shear, In book: *Challenging Glass 4 & COST Action TU0905 Final Conference*, Lausanne, Switzerland, 2014.

