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DYNAMICAL ANALYSIS OF STEEL POINT CONNECTORS USED FOR FIXATION OF GLASS FAÇADES

This study presents the numerical comparative analysis of the point connector and its modification used for fixation of glass façades in terms of the obtained values of stresses and displacements. Since the most popular components of glass façades are square, rectangular or triangular, it was adopted that the load to the connectors is transferred from a rectangular façade component. Furthermore, the dynamic effect of wind gusts on façades was also assumed, with both wind pressure and wind suction. Adoption of the rectangular component of the glass façade leads to an unfavourable load distribution observed in the location of the connection, with the connector additionally twisted with respect to its own symmetry axis. ADINA software, based entirely on the finite elements method, was used for numerical analysis. The examinations allowed for evaluation of how the modifications introduced into the referential model reduce values of the obtained stresses and displacements.

Keywords: point connector, glass façades, dynamics, ADINA, wind load

1. Introduction

Nowadays, glass stairs, floors, roofs or façades are often used by designers and architects in the design of new buildings and structures. Glass components are mainly used due to their aesthetic values: standard glass is transparent, but a variety of glass components with any colour are manufactured. Apart from aesthetic values, these components allow the light to permeate, which in the case of façades is critical. Humans need sunlight for living. Therefore, glass façades, have a substantial advantage over the elevations made of other construction materials since in the case of other construction materials, the amount of sunlight that reaches the barriers is much limited. Furthermore, currently manufactured glass components offer higher thermal parameters inside the rooms, which are of key importance from the standpoint of energy efficiency of buildings.

Glass components in such façades and in other structural solutions such as stairs or floors represent exclusively finishing elements. The main function is performed by the load-bearing structure, with the load transferred loaded through the connectors from façade glass panes to the structure. In the case of the glass used in external building elevations, façade glass panes should resist the atmospheric load such as wind pressure and suction, snow load and temperature. Furthermore, glass façades should be resistant to the effect of UV radiation and should ensure adequate level of thermal insulation in the building. In the case of stairs and glass floors, glass has also to show enhanced load capacity, slip resistance, friction resistance and ensure safety in the case of cracking. Consequently, three different types of glass panes are used in the construction sector, such as non-tempered glass and laminated glass pane which ensure work safety in case of failure i.e. when glass pane is broken following excessive deformations. However, in such cases, continuity of this element is not damaged and the component of the glass pane may perform its role (for the limited time). The standard glass (non-tempered) is usually not used since the pieces of such a glass may cause serious threat. The most frequently used types of glass include tempered glass, which breaks into pieces in case of an accident and laminated glass. Apart from the construction sector, the tempered glass can be found in the automotive industry, where the rear and side vehicle windows are made of tempered glass and the windscreens are made of laminated glass with enhanced strength.

Laminated glass is preferred if holes should be drilled in a glass component as this type of glass is much stronger compared to other types of glass. Strength tests of the laminated glass pane supported on joints in the corners, concerning the stresses and displacements with respect to shear modulus of the foil used to integrate the glass were presented in the study [1]. The study demonstrated that even insignificant rigidity of foil has an essential effect on the results concerning glass pane deformations and distribution of stresses in the pane. Furthermore, it was found that ambient temperature is also critical to glass load capacity i.e. the higher temperature of the laminated glass pane, the lower range of transfer of shear stress in the glass. The details concerning dimensions of the layered glass pane were presented in the studies [2,3].

It is remarkable that in the production process, glass is not free from defects, with microscopic scratches observed at this

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stage. In order for these scratches not to develop into the noticeable cracks, the glass pane edges are chamfered or rounded through special rolls during the production process. These actions prevent from substantial edge stress which causes (visible) propagation of scratches. Crack and failure criteria for construction glass plates were discussed in [4]. Numerical study of glass shear walls with point mechanical connectors were studied in [5] and both the performance of connectors and safety evaluation of glass facades were studied in [6].

A factor which is similarly important in the design to adequate choice of the type of pane is the choice of the mechanical connector which is used to connect the façade glass pane with the supporting structure, allowing the load to be transferred safely.

2. Connectors: design solutions

Connectors are the components which ensure a safe transfer of the load safely from the façade glass pane onto the supporting structure. The study [7] discussed several types of connectors:
– due to the operation mode of the connector: joint-type with the ball, joint-type with the ring, rigid;
– due to the shape of the fixation: single ball-and-socket joints, sets of ball-and-socket joints ("spiders" with one, two, three or four arms) two-plane sets (joint-type, rigid).

The following point connectors are used in the external glass elevations: multi-plane (single side), with the head over the glass surface (two-sided) and with the head between the panes.

Point connectors can be further divided in other groups, depending on whether the glass component has holes drilled during the production process. If the façade glass panes have the holes, the plate holders are used, whereas in the case of the lack of holes, the clamping boundary holders or glued fixations are used.

The joint-type connectors are typically used for external glass components which transfer short-time load such as wind in a manner that allows for an unrestricted deformation. The rigid connectors are used in locations where higher rigidity and stability of the structure are needed. Furthermore, ball-and-socket joints components are used as a single-point support for the glazing, whereas the single- or many-arm components ("spiders") allow for supporting of several glass panes. "Spiders" are often used in elevator window panes.

From the design point of view, it is safe to use point connectors for which holes are needed than clamping-type or glued connectors, and, unlike the glued connectors, the point connectors are easier to be fixed. Designing of the point connectors consists mainly in evaluation of the boundary load-bearing capacity. The stresses obtained in such cases cannot exceed the permissible stresses for the material from which the connectors are intended to be made. Furthermore, it is expected that the component should work in the elastic range since in the plastic range, deformations are likely to lead to lost integrity of the façade components or even to cracking of the glass panes. The displacements in the elastic range should be lowest possible in order not to lead to excessive deformations of the glass pane.

This study presents a comparative analysis of a numerical model of the single-arm "spider" and its two modifications in terms of the values of stresses and displacements. The numerical model involved the single-arm spider fixed to the supportive structure with one fourth of the pane through which the dynamic effect of wind gusts was transferred, including both pressure and sucking modes. It was assumed that the adopted glazing component is rectangular. In order to obtain the unfavourable load transfer to the connector, additional torsion of the section with respect to its symmetry axis was also assumed. The ADINA software based on finite elements method was employed to identify which of the modifications of the reference model allows for a reduction in the displacements and better utilization of stresses in the section.

A similar numerical analysis concerning the plate connector with joint-like support and rigid support using the ABAQUS software was presented in studies [8,9]. During modelling of the connector, the authors analysed the effect of the type of boundary conditions on the stresses and displacements in both the connector and the glass pane. Furthermore, the authors conducted an experiment of glass pane deflection for two different hole diameters under the plate connector and the results lead to the conclusion that even the smallest simplification of the model of plate connector causes a specific deviation (over-rigid model) compared to the real model. This study emphasized that the numerical analyses in the FEM software are idealized, whereas in experimental studies, the results are affected by additional parameters that include in particular: imperfect levelling of the glass pane, microscratches and microcracks, temperature, non-processed edges etc. Despite certain differences between the outcomes obtained in the software and the experimental analysis, it was demonstrated that the method to destroy the sample is nearly identical for both presented research methodologies. Also in [10] experimental and numerical investigations on bearing capacity of non-linear metallic spiders used in glass facades were presented. For numerical analysis authors used ANSYS software.

3. Numerical model

The author's structural solution discussed in this study for the single-arm point connector of "spider" type represents an adaptation to the external conditions of the connector used during fixation of the façade panes. The dimensions of the component are presented in Fig. 1, whereas the reference model represents a steel "spider" component without bolts (without components described with the letters "a" and "b"). The first modification was to add a single M8 bolt [11] to the reference model, more or less in the middle of the arm span (the "a" bolt). The second model modification consisted in verification whether the use of two bolts denoted as "b" in Fig. 1 leads to further unfavourable type of stresses in the model compared to the reference model.

The S235JR steel was used for a spider material, with the density of 7.860 kg/m^3, for which the Young's modulus is
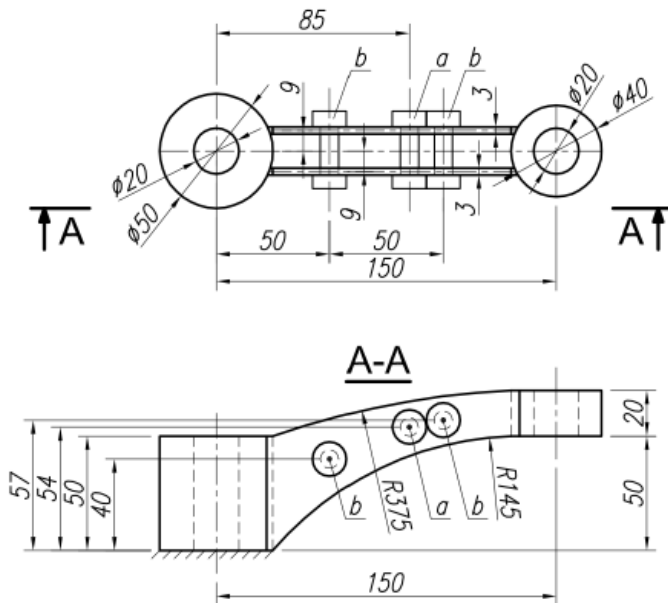
Fig. 1. The model of a single-arm spider

E = 210 GPa, and the Poisson's ratio is v = 0.30. It was assumed in the ADINA software that steel is a resilient isotropic material with above presented parameters. It was also assumed that the load to the connector is transferred through the glass pane for which the dimensions of 0.75×1.25 m was adopted. These dimensions represent one fourth of the actual size of the assumed glass pane since it was adopted that the glass façade model is symmetrical. Since the glass pane can be treated as a uniform isotropic material, it was modelled, for simplification purposes, in the ADINA software as a linear, elastic and isotropic material with the following parameters: E = 70 GPa, v = 0.23, ρ = 2.500 kg/m^3. Since this paper concerns numerical analysis of the connector, the stresses and displacements of the glass pane were not presented here.

Another simplification concerned the used bolts, washers and nuts. Steel bolt was modelled without division, that is, the bolt, washer and nut represented the compact wholeness. The inaccuracies resulting from welding of steel walls to the bushing walls were also neglected.

The following boundary conditions were assumed for the model: bushing with the diameter of Ø50 mm was fixed at the bottom and released of 6 degrees of freedom. The compliance of bushing connection with the supporting structure was not considered in this case. The top surface of the bushing with the diameter Ø40 mm is a place of connection between the connector and glass pane. In the presented type of connector, the glass pane is connected by means of the top plate, bottom plate, plate connecting bolt and special rubber dividers between the bolt, plates and glass pane. These dividers allow for reduction in stresses which would be generated in the case of sustainable, short-term dynamic effects at the contact of metal components with the glass pane. Furthermore, rubber dividers balance the stresses connected with assembly inaccuracy. Symmetrical boundary conditions were assumed on the side walls of the glass

pane: the constraint was added to the displacements on the X axis at one of the walls and rotations around the Y and Z axes, whereas on the other wall, to the displacements on the Y axis and rotations with respect to X and Z axes. The glass pane was fixed to the connector so that the symmetry axis for the connector is oriented at the angle of 45° with respect to the side wall of the glass pane, with the top projection on this pane.

The load was assumed on the upper part of the glass pane on the base [12], adopting the increased value of the load wind: it was assumed that the designed object is present in the second zone of wind load. It was also adopted that the analysed glass façade is of the height of 100 m and the fourth land category was also assumed. The coefficients for evaluation of the maximal wind pressure and suction were determined by assuming the wind effect on the A zone. The maximal value of wind pressure of 1.736 Pa was obtained, whereas the maximal wind suction was 1.240 Pa. In order to analyse the dynamic wind gust, the load curve with sinusoidal profile was used, with the maximal suction value occurring at the instant of t = 0.34 s and maximal pressure value at the instant of t = 0.78 s.

Discretization of the area of the connector and glass pane was based on 4-node 3D Solid elements. Density of the grid for the connector and the glass pane in the area of connection was assumed as ~0.005 m, whereas on the external edges of the glass pane, the density was limited to 0.05 m. The following number of nodes and finite elements was obtained:

– reference model without bolts: 3.867 nodes, 9.975 finite elements to describe the connector, 3.752 finite elements to describe the glass pane. 13.727 finite elements were obtained in total;

– modification of the reference model with one bolt: 3.959 nodes, 10.028 finite elements to describe the connector, 3.752 finite elements to describe glass pane and 293 elements to describe the bolt. 14.073 finite elements were obtained in total;

– modification of the reference model with two bolts bolt: 4.057 nodes, 10.065 finite elements to describe the connector, 3.752 finite elements to describe glass pane and 586 elements to describe the bolt. 14.403 finite elements were obtained in total.

4. Discussion of the obtained results

In order to read the results of stresses and displacements, the zones of data reading were defined as presented in Fig. 2. Global displacements at wind were read from the lower point of the upper bushing with the diameter of Ø40 mm, whereas during suction, the reading occurred from the upper point. The vertical displacement along the Z axis are read from the point 1 and the point 1T being the mirror reflection of the point 1 with respect to the XZ plane that runs through the symmetry axis of the model. The maximal stresses are read at the connection of the bushing with the steel wall. Furthermore, the compressive and tensile stresses were read at the lower surface in the middle

of the span of the steel walls. Triangles near the point 2 present finite elements from which the stress was read as a mean value from these three elements. Additional 2T point was assumed, being the mirror reflection of the point 2 with respect to the XZ plane that runs through the symmetry axis of the model.
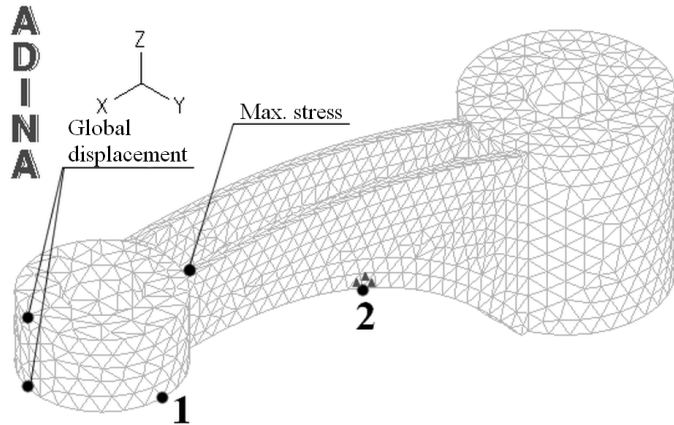

Fig. 2. Numerical model with measurement points

Firstly, the maximal stresses in each model were read. The stresses for wind pressure are presented in Fig. 3, whereas the maximal stresses for wind suction are presented in Fig. 4.

Figs. 3 and 4 clearly show that the use of the individual and double bolt leads to the reduction in maximal stresses. In the case of a single bolt, stresses at wind pressure are reduced by 7.3 MPa, whereas for two bolts, the maximal pressure is reduced by 11.6 MPa. Similar pattern occurs at wind suction, with stresses in the case of the use of a single bolt reduced by 5.43 MPa and by 8.60 MPa for two bolts.
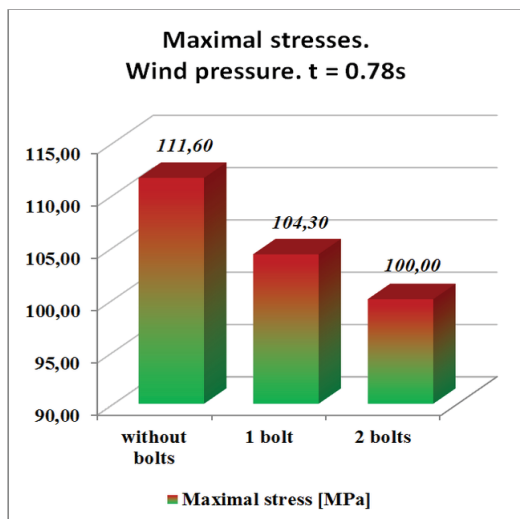

Fig. 3. Maximal effective stresses for wind pressure in three different numerical models $t = 0.78$ s

Values of displacements in point 1/1T, global displacements and stresses in point 2/2T for wind pressure were presented in Table 1, whereas the same values for wind suction are contained in Table 2.
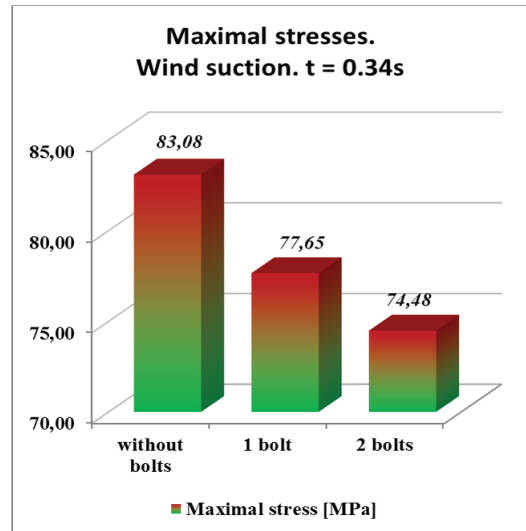

Fig. 4. Maximal effective stress for wind suction in three different numerical models $t = 0.34$ s

TABLE 1

Displacements and effective stresses. Wind pressure

Wind pressure, $t = 0.78$ s				
		Without bolts	1 bolt	2 bolts
The displacement "Z" of the free end [mm]		–0.09547	–0.09357	–0.09218
Global displacement [mm]		–0.09715	–0.09524	–0.09384
The displacement "Z" of the point [mm]	1	–0.08316	–0.08133	–0.08000
	1T	–0.08070	–0.07887	–0.07756
Stress in the point [MPa]	2	80.25	74.49	79.91
	2T	70.66	71.27	77.22

TABLE 2

Displacements and effective stresses. Wind suction

Wind suction, $t = 0.34$ s				
		Without bolts	1 bolt	2 bolts
The displacement "Z" of the free end [mm]		0.07108	0.06966	0.06863
Global displacement [mm]		0.07233	0.0709	0.06986
The displacement "Z" of the point [mm]	1	0.06191	0.06055	0.05956
	1T	0.06008	0.05872	0.05774
Stress in the point [MPa]	2	59.75	55.45	59.49
	2T	52.61	53.06	57.49

The results presented in Table 1 and Table 2 show that application of a single bolt or two bolts in the numerical model leads to the reduction of both vertical displacements and stresses in the measurement point No. 2. Since each model uses the linear-elastic isotropic material, percentage differences in results of both for wind pressure and suction are nearly identical. The comparison of the displacement on the Z axis for the free end of the model (place of reading of global displacements, see Fig. 2) for pressure and one bolt used with respect to the reference model reveals a reduction in the vertical displacements by 1.990%, whereas for two bolts, the displacements are reduced by 3.446%. In the case of suction, the displacements are reduced by 1.998%

for a single bolt and by 3.447% for two bolts. The comparison of the values of vertical displacements in point 1 compared to point 1T, shows that the displacements are not identical: distribution of load transferred by the glass pane causes a torsion of the section with respect to the symmetry axis. Similar to the free end, the use of a single bolt leads to a reduction in the displacements at wind pressure and suction. In point 1, the displacements are lower by 2.201% for pressure and a single bolt, whereas in point 1T, by 2.268%. In the case of two bolts, these values are 3.8% in point 1 and 3.891% in point 1T, respectively.

Comparison of the results obtained for the distribution of reduced stresses for three different numerical models on the wall with the measurement point 2T for wind pressure are presented in Fig. 5.
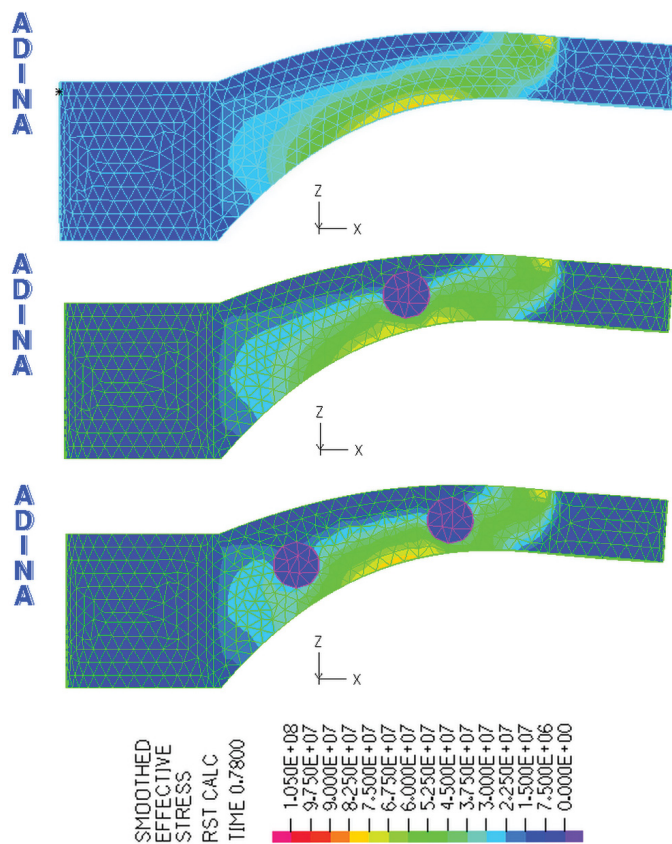

Fig. 5. Comparison of distribution of reduced stresses on the wall with the measurement point 2T for wind pressure in three different numerical models $t = 0.78$ s

The values of stresses presented in Tables 1 and 2 reveal an increase in stresses in point 2T in numerical models with a bolt compared to the referential model and a noticeable reduction in stress in point 2. The increase in the value of stresses in point 2T is attributable to better use of the transfer of load to both sides of the connector. A single bolt located in the central parts of the walls helps absorb a certain amount of stresses near the lower surface of the central part of the wall compared to the reference model and the model with two bolts (see Fig. 5). It is remarkable that the reference model shows a substantial asymmetry of the values of stresses between one wall and the other of over 9.5 MPa

(see Table 1). If the bolts are used, the distributions of stresses on both walls are more symmetrical. Percentage symmetry of the distribution of stresses for both wind pressure and suction between measurement points 2 and 2T is presented in Fig. 6.
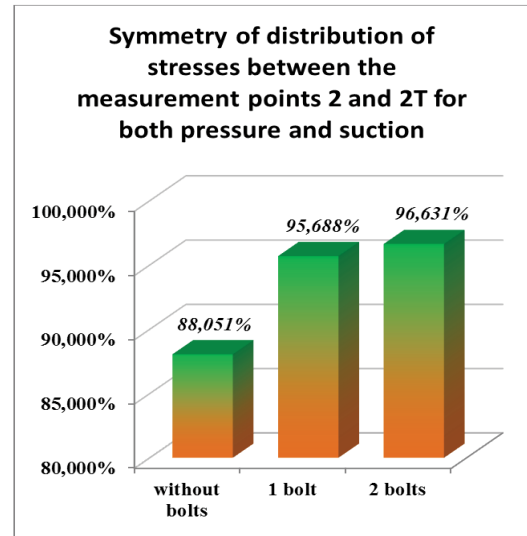

Fig. 6. Symmetry of distribution of reduced stress expressed in percentage terms between the measurement points 2 and 2T for both wind pressure and wind suction

Analysis of the results presented in Fig. 6 reveals that the use of a single bolt in the reference model allows for obtaining a substantially better work of both walls during transfer of load from the glass pane. Furthermore, it is also noteworthy that a single bolt does not only allow for improved symmetry of load transfer but also, compared to the model with two bolts, lower values of stresses are obtained in the steel walls. Although maximal stresses obtained in the model with a single bolt were higher than in the case of the numerical model with two bolts, the model with the single bolt would be probably better from the economic standpoint. The number of operations to be performed in both phase of production and in the assembly cycle is slightly lower than in the case of the connector with two bolts, whereas differences in the symmetry of the distribution of stresses in the walls between models and in maximal stresses are negligible.

5. Conclusion

This study discussed the types of the glass used in the construction sectors, types of glass components and types of connectors used to connect these components. The problems of design of point connectors that allow for integration of the glass façades with the supporting structure were analysed. The numerical analysis was also conducted for one type of the single-arm "spider" connector in terms of the transfer of dynamic load caused by wind pressure and wind suction. Two modifications of this connector were proposed. The modifications were aimed to reduce the current vertical displacements of the reference

connector as well as to balance its torsion around the symmetry axis as a result of the transfer of load from the fixed rectangular glass pane.

The comparative analysis in terms of the vertical displacements and stresses allowed for finding a model with adequate rigidity and most symmetrical distribution of stresses over the connector profile which would be justified by manufacturing and assembly-related aspects. The analysis demonstrated that the use of a single mechanical connector in the form of the bolt that connects the walls of the point connector leads to a substantial reduction in maximal stresses compared to the reference model and better redistribution of forces by both walls of the connector, thus balancing the negative effect of torsion. The use of bolts for connecting both walls of the connectors does not lead to significant changes in global displacements in the model since reduction was nearly from 2 to 4% for both wind pressure and wind suction.

This study presents only one of many possible variants of point connectors used for fixation of glass façades. The modifications of the analysed connector are only of demonstrative character and, in the case of planning the use of the modified connectors in the real structure it is recommended to perform adequate experimental tests. Optimization and parametric analysis for bolted connections between glass panels and connectors were conducted in [13] moreover, the optimization of the shape of glass facade single-armed spider was carried out in [14].

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