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Stress-strain state of Insulated Glass Unit in structural glazing systems

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Abstract. Article presents the analysis of classical and structural ways of fastening of the glass unit subjected to uniformly distributed wind load under the various conditions: modification of the fixing step in horizontal and vertical direction, change of gas-filled gap and glass panel thicknesses. Calculation is performed in FEM-based SJ Mepla software for three most common types of glass units of the size of 1200×1200 mm, 2400×1200 mm and 3600×1200 mm. On the basis of obtained results, it is possible to conclude that modification of the fixing step in horizontal direction and glass panel thickness have a significant influence on the stress and deformation values; in contradistinction, modification in vertical direction and gas filling thickness do not noticeably impact stress-strain state of a plate. Default fixing step between two adjacent supports, which is often adopted by manufactures of IGUs without preliminary calculation for actual applied load, has to be verified in each case in terms of deformation in order to satisfy the conditions of SLS. The table of recommended values of maximum distance between supports is presented.

1. Introduction

Glass facades are nowadays an indispensable part of modern structures [1–3]. However, besides numerous advantages of glass units' application the design of IGU may face challenges of both aesthetics and performance character [4–6]. Translucent facade structures are exposed to various combinations of mechanical and climatic loads throughout the whole lifecycle of the building [7]. Existing researches [8, 9] indicate an increased risk of glass damage and destruction due to the effect of "thermal shock". The experimental studies devoted to the analysis of the stress-strain state of glass panels under the climatic load, including those associated with extreme difference of temperature [10], are of a particular interest. However, conducting of such tests is technically complex and expensive [11]. It causes the necessity in other methods, such as computer modelling, which could produce sufficiently accurate results. The authors of [11] compare experimental and finite element modeling data obtained for similar facade systems in order to verify the use of Finite Element Method (FEM) for the calculation of systems subjected to thermally induced climatic load.

One of the main problems regarding aesthetics aspect is an appearance of optical distortion. Article [12] examines available engineering approaches and proposes a new way for mitigation of this effect. The new method is based on the partial rarefaction inside the IGU and performed by installation of additional pointed or linear support. The causes of optical distortion, also known as a «lens effect» in construction practice, are described in [13, 14].

Due to increased requirements for the reduction of thermal heat losses [15, 16] in buildings, parameters of IGUs are actively reconsidered what leads to change in their structural scheme . In order to minimize thermal transmittance, the thickness of gas-filled gaps tends to be increased, causing the higher weight of the structure, which can be partially eliminated by reducing the thickness of glass panes. The influence of IGU thickness on the values of deflections and stresses occurring in the glass panes is analyzed in [17]. The article presents a static calculation of the unit under various thicknesses of gas-filled gap and glass panes for 2-, 3- and 4-glazed IGUs.

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Article [18] contains the analysis of load sharing in IGUs by determination of the pressure of a cavity air. Cavity pressure is a complex function of different parameters including panel stiffness, which in its turn depends on edge sealant behavior among other factors. The research on edge seal spacers and their impact on overall performance of IGU is presented in [19]. The article covers an analysis of specific mechanical characteristics, which are not comprehensively stated in existing regulatory documents.

Among different factors which should be taken into account while designing the glazing system, the choice of fixing method of a significant importance [20]. Behavior of bolted and adhesive connections under static loads are investigated in [21]. Common IGUs are characterized by 4-side continuous supports (classical scheme), however novel methods such a point-fixings (structural scheme) and 2-side continuous supports are increasingly used in construction practice [22]. In [22], the specific case of IGUs with 2-side continuous supports subjected to both compression and combined action of compression and bending is investigated by Analytical and Finite Element (FE) numerical studies for the purpose of determining the IGUs' buckling resistance. Embedded laminated connections explored via FE modeling and validated towards past full-scale experimental test results are analyzed in [23].

Current research partially refers to the determination of an optimal option. Some of the optimization problems are defined and analyzed in [24]. The investigation of strategies which lead to the optimization though the use of generic algorithms is presented in [25]. These algorithms are characterized by providing exact satisfying of existing limitations with high stability and convergence rate.

The analysis carried out in this article shows difference between classic and structural ways of fixing under the various conditions. Ultimate Limit State (ULS) and Serviceability Limit State (SLS) define the requirements for considered IGUs. The application of different formulations in ULS in for glass elements and in particular IGUs are studied in [26].

Classical (continuous) fixing of the facade filling the substructure is a system, which includes a decorative cover of any shape, installed in the grooves of the clamping bar, which is mechanically fixed by self-tapping screws to the mullion or transom façade [5].

Structural way is a type of glazing, in which the external filling element forms a single plane of the facade, hiding the fastening elements by means of a facade sealant. For this type of fixing, it is necessary to use special glass units with edge enameling and embedded profiles for hidden fixation from the end surface of the filling [5].

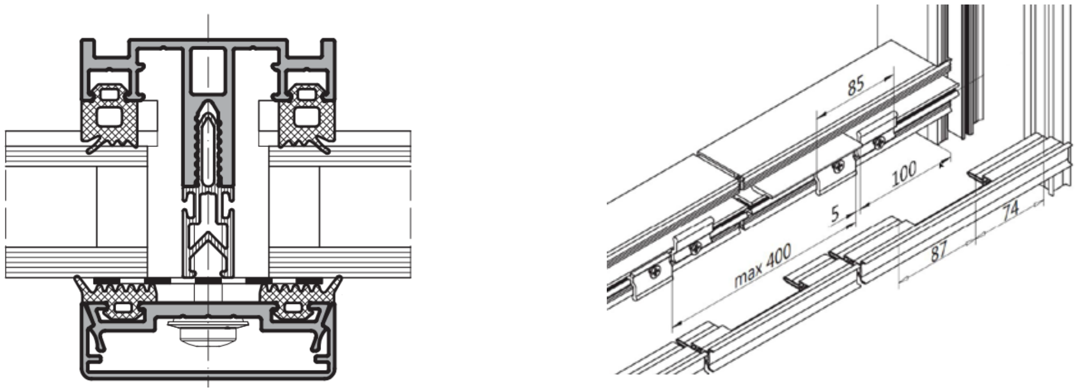


Figure 1. Left – classical scheme, right – structural scheme of IGU's fixing.

Nowadays design of both façade systems is based on the same technical algorithm without taking into account the discreteness of fixing placement. On the other hand, some manufacturers of the structural glass façades assume the distance between supports equal to 400 mm by default (Fig. 1, right). These factors lead to subsequent problems of the entire glazing system.

The object of the study is an insulating glass unit of the most common types: 1200×1200 mm, 2400×1200 mm, 3600×1200 mm, where first dimension is height of the fire barrier and second dimension is the width of the unit. Chosen values are justified on the one hand by the necessity of performing a study on the samples with different ratio of the vertical and horizontal dimensions, and on the other hand the equality of the vertical dimension to the height of interfloor fire belt.

Within this study, the authors intend to verify the correctness of fixing step value stated by manufacturers in case of structural scheme of façade and analyze the possibilities of usage of both structural and classical schemes.

Following tasks were carried out in order to find their influence on the stress-strain state of the glass plates under various boundary conditions:

1. Modification of the fixing step in horizontal direction

2. Modification of the fixing step in vertical direction
3. Change of gas filling thickness
4. Change of glass panel thickness

With the SJ MEPLA software, it is possible to perform a static calculation and determine which fixing scheme will work more efficiently.

2. Methods

Calculation of the stresses arising in the glass plate was based on the finite element method, which is widely used for analysis of glass elements under various conditions [4, 6, 25, 26], is realized within Mepla SJ software (version 4). The mesh of the plate was formed by a free meshing algorithm and controlled via the defined minimum value of an element size. Main concepts about the calculation and mathematic modeling for the complex systems containing polyvinyl chloride based profiles are considered in [29].

The methods described in [30] demonstrate the approach to the determination of a stress-strain state due to nonlinear distribution of a temperature field. Nonlinear problem of unsteady thermal conductivity and a problem of mechanical statics applied to the plane deformation are defined and solved. The general conclusions regarding the theoretical base of the performed calculations were as well adapted in the current research.

2.1. Element building

All considered glass unit were composed of three layers with determined parameters of Young's modulus, thickness and Poisson's ratio: two 6 (8) mm thick decking plates of toughened glass enclosing 20 mm thick gas volume filled with Argon in between them (Fig. 2, left).

The glass elements had following characteristics:

- Density:

$$\rho = 2500\,\frac{kg}{m^3}$$

- Young's modulus:

$$E = 70000\ MPa$$

- Poisson's ratio:

$$\nu = 0.2$$

- Thickness of glass panes:

$$t_1 = 6\ mm;\ t_2 = 8\ mm$$

- Argon-filled gap**:**

$$d = 20\ mm$$

The metal frame of the considered facade consisted of horizontal and vertical bars (transoms and mullions) with predetermined cross-sections shown in Fig. 2, right. Profiles were chosen due to necessity of accounting the geometrical characteristics of metal frame surrounding glass units for the purpose of investigation of its contribution to overall system performance.

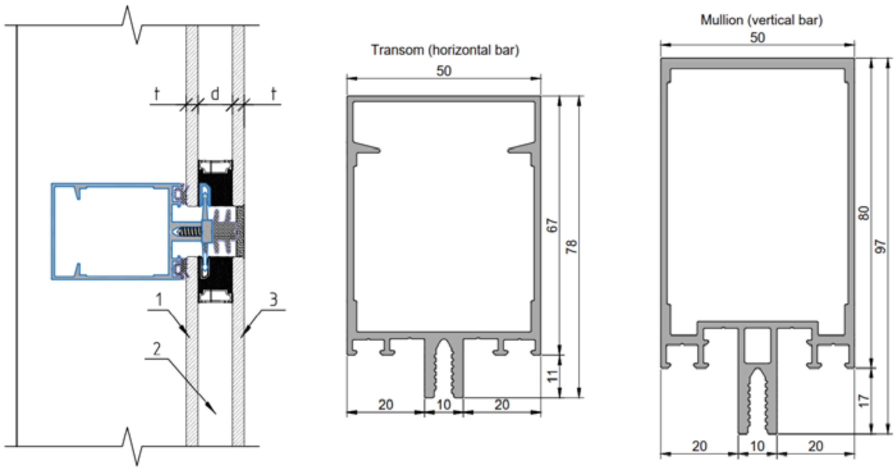


Figure 2. Left – glass unit composition (1, 3 – inner and outer glass panels respectively, 2 – gas-filled gap), right – cross-sections of the horizontal and vertical profiles of the metal frame.

2.2. Supports

Continuous way of fixing was implemented by edge hinged (pinned) supports, acting on the entire plate border and providing adequate stiffness with the defined number of freedom degrees:

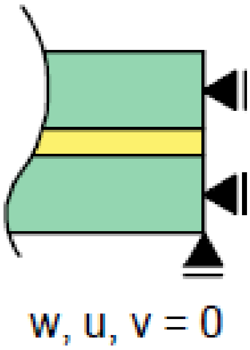


Figure 3. Scheme of the hinged support (SJ Mepla).

Structural variant of fixing was realized by using spring supports: each of them imitated a local embedded part. Each fixing limited linear movement along the z-axis (Fig. 4) and rotation about x- and y-axes. The bottom supports prevented the glass unit from moving in the plane of the facade under the action of gravity load (along the y-axis).

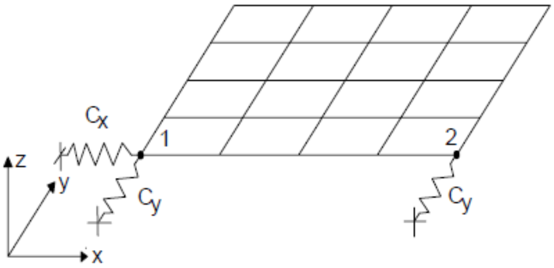


Figure 4. Scheme of the spring support.

The value of rigidity in x-direction refers to the characteristics of aluminum profiles (Fig. 2, right), which bound together create a frame of façade system. The total deflection of insulated glass unit within the system consists of deflections of both glass panes and profile (Fig. 8). Current regulations set the formulas for the maximum allowable deformations of the filling separately from the frame system, therefore two models were developed and analyzed in this study: in the first one spring rigidities c_z were taken as nearly infinite, so only deflection of panes itself was considered. In the second one rigidities c_z were calculated for each case in respect with the profile's structural response to the load distributed on the plate and further transferred to the horizontal and vertical profiles. The scheme of load distribution to the frame for each insulated glass unit is shown in Fig. 5, in accordance with [31]. The model consisted of two components, which allowed obtaining deflections in the location of embedded part and corresponding support reactions when embedded part was imitated. These values enabled the calculation of spring rigidity.

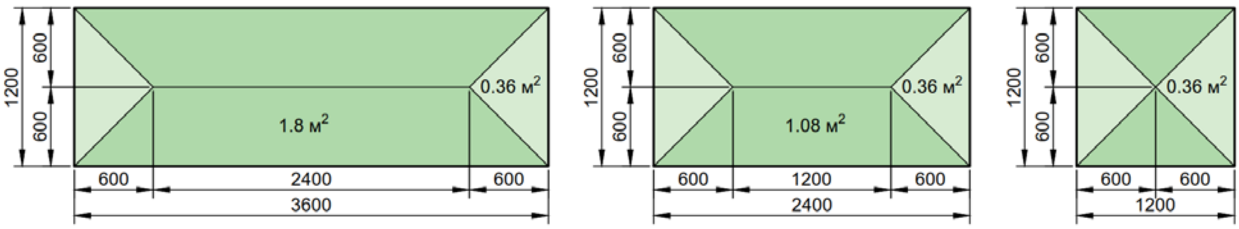


Figure 5. Area of the load transferred to the profiles of the systems for different glass unit sizes.

Two approaches are illustrated by Fig. 6, which contains the schemes of the horizontal profile with fixing step of 340 mm between supports and its rigidity assigned as nearly infinite in the first case and obtained through a static calculation by Finite Element Method (FEM) applied to continuous beam in the second case.

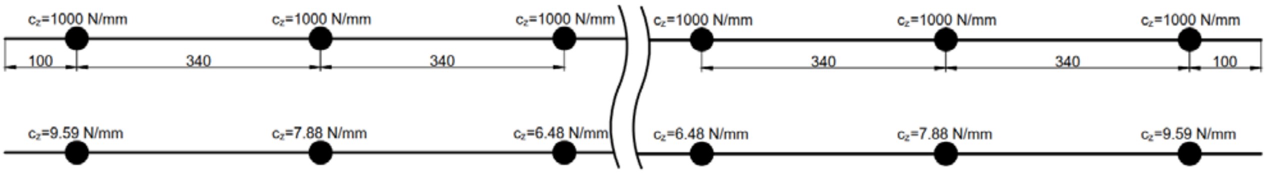


Figure 6. Spring rigidity assigned as nearly infinite and obtained through the calculation incorporating structural behavior of the profile.

2.3. Principal stresses

For each layer of stresses on the top and bottom surfaces σ_{xx}, σ_{yy}, σ_{xy} of each panel were calculated. The principal stresses were obtained through the following formulas:

Major principal stress

$$\sigma = \frac{\sigma_{xx} + \sigma_{yy}}{2} + \sqrt{\left(\frac{\sigma_{xx} - \sigma_{yy}}{2}\right)^2 + \sigma_{xy}^2}$$

Minor principal stress

$$\sigma = \frac{\sigma_{xx} + \sigma_{yy}}{2} - \sqrt{\left(\frac{\sigma_{xx} - \sigma_{yy}}{2}\right)^2 + \sigma_{xy}^2}$$

where σ_{xx} is a component of stress in x-direction; σ_{yy} is a component of stress in y-direction; σ_{xy} is a component of stress in shear stress plane.

The values of maximum principal stresses were used for structural analysis of glass plates.

2.4. Loading approach

Plates were studied under the action of uniformly distributed face load, which simulated an action of a peak wind load. The minimum value of the load applied was 0.45 kN/m^2, the maximum was 1.45 kN/m^2.

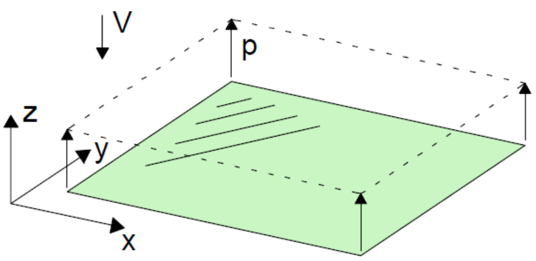


Figure 7. Scheme of load application.

2.5. Screening and selection of values

Obtained values of the principal stresses and deformations were compared for the same layer in case of each glass unit. For structural way of fixing maximum values of the stresses appeared around the springs, while for the classical way they arose in the corners of the plate. Character of horizontal deformation pattern remained same for both design schemes therefore values in the plate's center were taken.

2.6. Ultimate Limit State

Requirements for the maximum values of bearing capacity of the glass unit derived from the Ultimate Limit State specify the limit value equal to 120 MPa in case of toughened glass in accordance with Russian State Standard GOST 30698-2014 "Tempered glass".

2.7. Serviceability Limit State

According to Russian State Standard GOST 30698-2014 "Tempered glass", maximum allowable deformation is determined by the following equation:

$$w_{\lim} = \frac{1}{250} \cdot a$$

where a is the shortest side of the element (1200 mm in the case of considered glass units). Therefore,

$$w_{\lim} = 4.8\ mm$$

3. Results and Discussion

Results of the static calculation performed on the glass units with two different approaches applied to the rigidity determination showed that for the purpose of estimation of the glass filling deflection the spring rigidity can be assumed as nearly infinite. Difference between deflection values of glass panes within glass units represents profile deformation, while regulations set the maximum allowable values for the deflection of the filling apart from the frame.

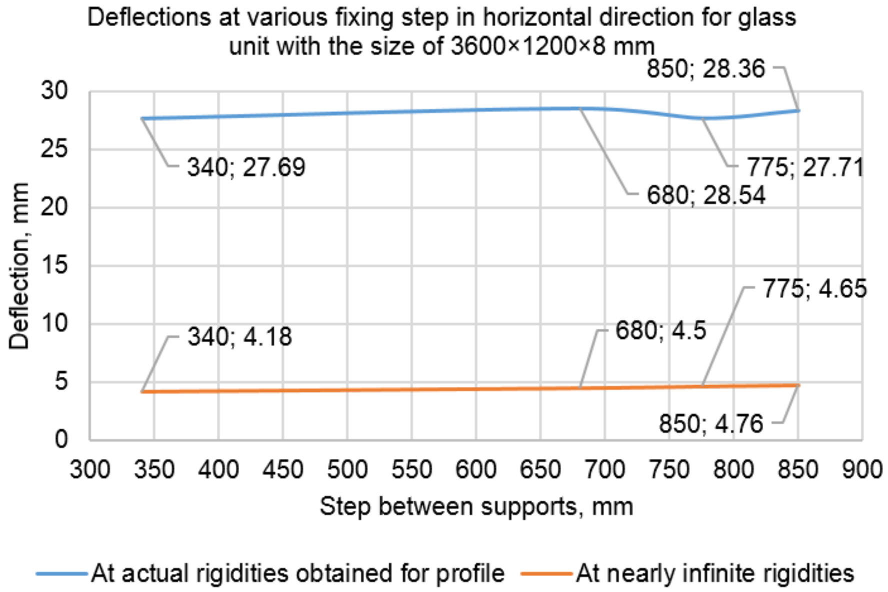


Figure 8. The deflections obtained at various boundary conditions.

The stresses arising in the glass pane of 3600×1200 mm were around 1.5 times higher when actual boundary conditions were accounted. The difference in character of stress distribution is shown in Fig. 9.

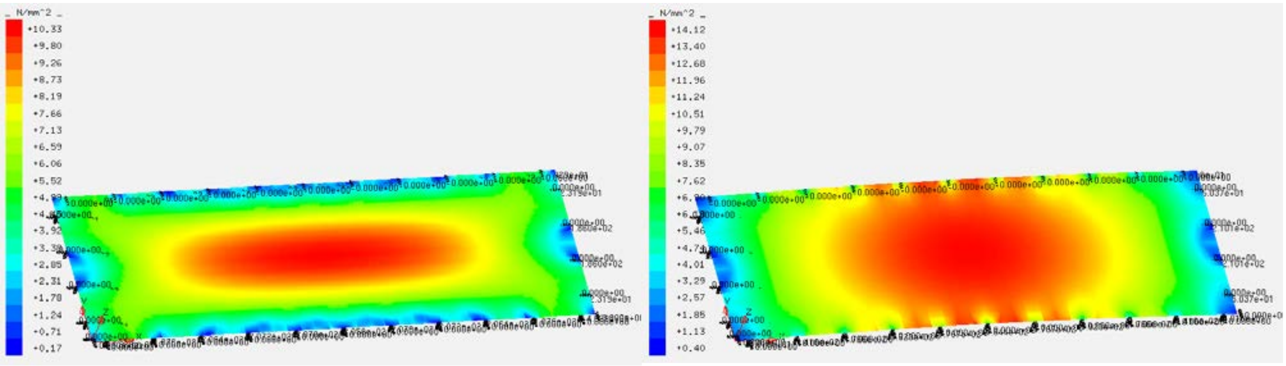


Figure 9. Stress distribution at various boundary conditions.
Left – nearly infinite rigidity, right – actual profile's rigidity.

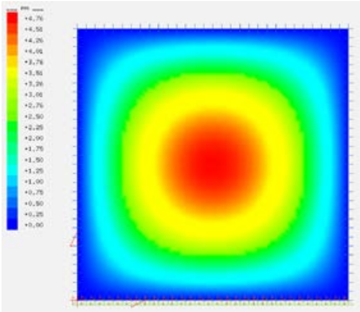
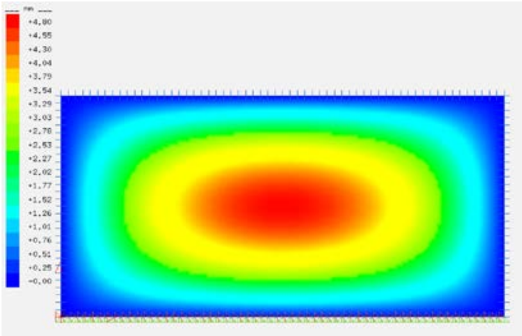
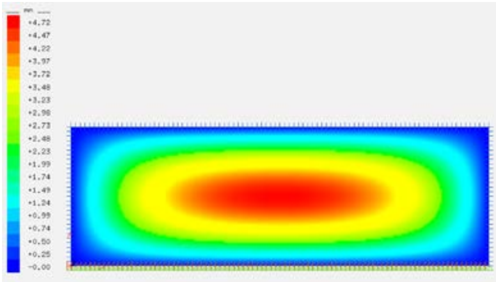
For the smaller glass units stress values as well as the distribution pattern did not differ significantly. For the further analysis of the structural response of the glass pane itself without taking into account profile's behavior spring rigidities in the direction out of the glass plane were assumed nearly infinite.

3.1. Classical scheme

Glass units with the dimensions of 1200×1200 mm, 2400×1200 mm, 3600×1200 mm were subjected to uniformly distributed load; glass unit formula:

Toughened glass 6 mm + Argon 20 mm + Toughened glass 6 mm.

Table 1. Values of the maximum load applied before reaching the limit deformation value.

Calculation scheme	Graphic surface	Load, kN/m^2	Max deformation, mm
1200×1200		1.45	4.76
2400×1200		0.6	4.8
3600×1200		0.5	4.72

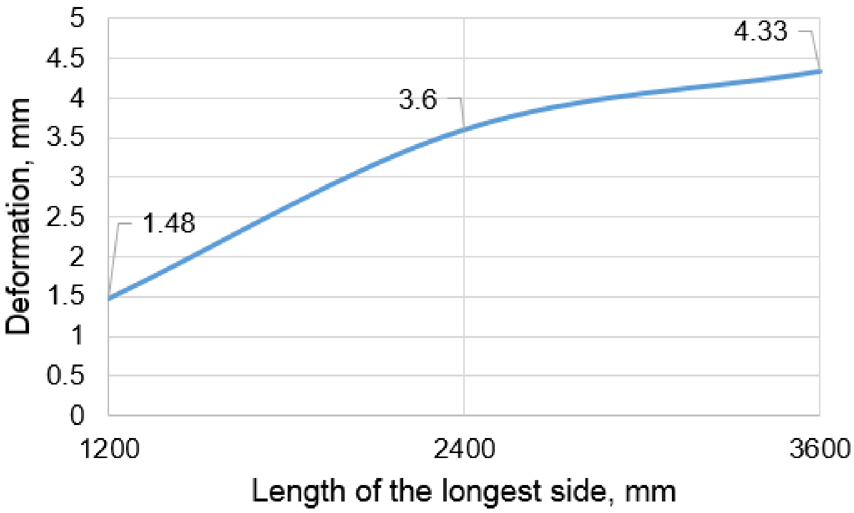


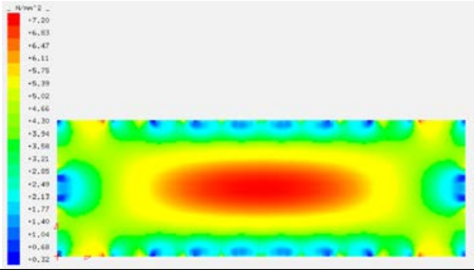
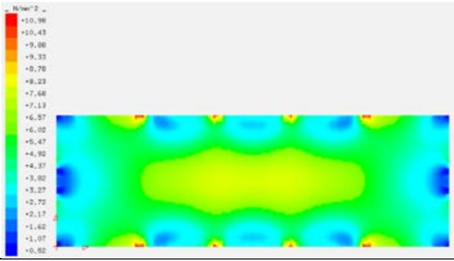
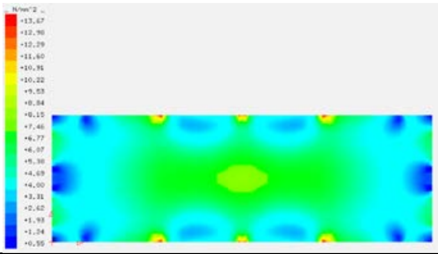
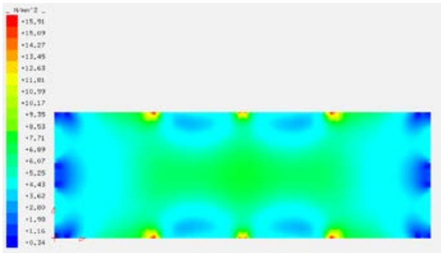
Figure 10. Deformations obtained under the uniform load P = 0.45 kN/m^2.

Glass units of all considered sizes with the formula *Toughened glass 6 mm* + *Argon 20 mm* + *Toughened glass 6 mm* fastened in the classical way satisfy conditions of ULS and SLS, therefore it can be concluded that this type of fixing is more rigid in comparison with point fixing. Structural behavior remains constant regardless the ratio between unit's sides: the center of the plate has a maximal deflection. Among three considered schemes the unit with the dimensions of 3600×1200 mm is characterized by maximal stresses and deformations under a similar face load. The size of the panel contributes to the overall unit stiffness as well as the fixing type.

3.2. Structural scheme

Glass unit with the dimensions of 3600×1200 mm was subjected to uniformly distributed load P = 0.5 kN/m^2; glass unit formula: *Toughened glass 8 mm + Argon 20 mm + Toughened glass 8 mm*.

Table 2. Dependence of the stress distribution on various support steps in horizontal direction.

Support step in horizontal direction, mm	Graphic surface	Max stress, MPa
340		7.2
680		10.98
775		13.67
850		15.91

Deformation values are obtained for different width between supports under the uniform load P = 0.5 kN/m^2 on the scheme 3600×1200 mm.

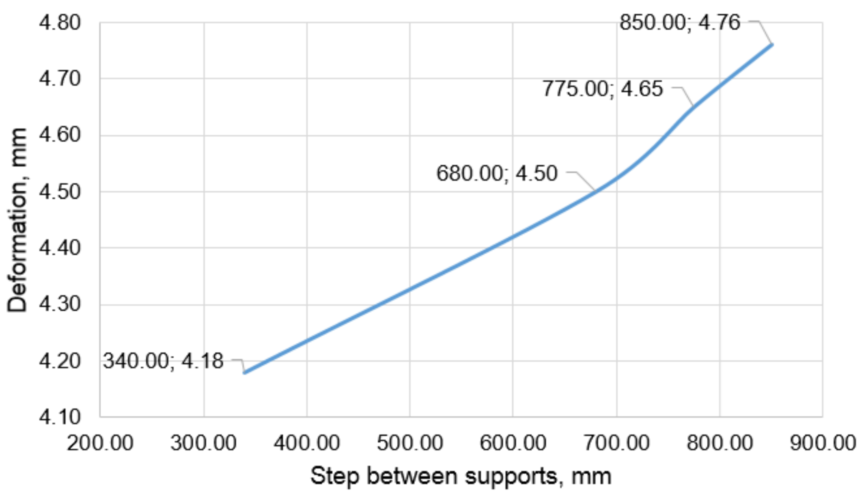


Figure 11. Dependence of the deformation values on various support steps.

As it can be seen from Fig. 12 and Fig. 13, value of the step between horizontal supports in structural scheme has a significant influence on the stress and deformation values, but not on their distribution character. Maximum value of deformation grows exponentially with the increase of the step in horizontal direction.

For a glass unit of the size 3600×1200 mm with the support step of 340 mm maximum value of deformation exceeds the limit value determined by SLS, therefore it can be concluded that step of 400 mm which is often adopted by manufactures without further checking has to be calculated in terms of deformation in order to satisfy the conditions of SLS.

Glass unit with the dimensions of 2400×1200 mm was subjected to uniformly distributed load P = 0.3 kN/m^2; glass unit formula: *Toughened glass 6 mm + Argon 20 mm + Toughened glass 6 mm*.

Table 3. Dependence of the deformation values on various support steps vertical direction.

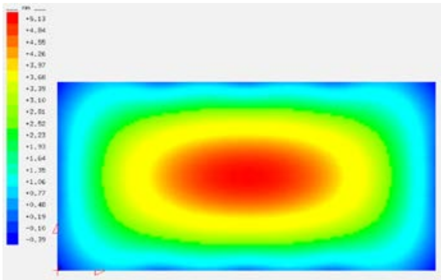
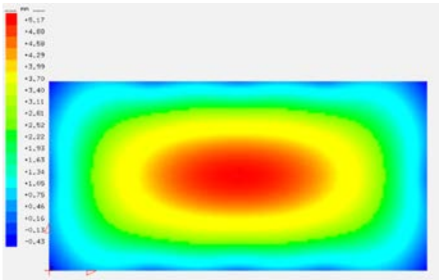
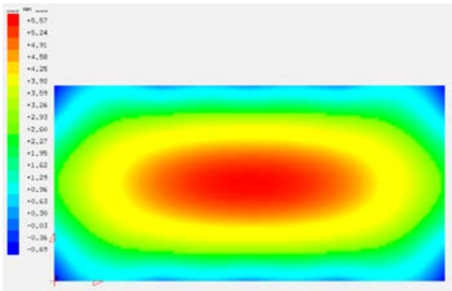
Support step in vertical direction, mm	Graphic surface	Max deformation, mm
293		5.13
440		5.17
880		5.57

Fig. 14 shows that increase of number of the supports placed on the short side (in vertical direction) do not essentially influence the maximum values of the deformations; however, increase of number of the supports placed on the long side and increase of glass thickness provide pursuance of the conditions stated by SLS.

Thickness of glass panel has a significant influence on the deformation values. Glass unit of the size of 3600×1200 mm requires increase of the thickness from 6 mm to 8 mm for all the variations of structural way of fixing, and glass unit of the size of 2400×1200 mm requires increase of the thickness from 6 mm to 8 mm for some variations of structural way.

Calculations carried out for different values of the gas filling shows that its modification does not significantly impact the values of stresses and deformation, therefore its influence on the maximum stresses and deformations can be neglected.

Recommended values of the maximum distance between supports and glass unit composition in order to fulfil the conditions of SLS are presented in Fig. 15.

Figure 15. Dependence of distances between supports on the value of face load and unit composition.

Glass unit size; panel thickness, mm	Maximum value of support step, mm		
	Face load, kN/m2		
	0.4	0.5	0.6
1200×1200; 6	880	440	290
2400×1200; 8	950	770	475
3600×1200; 8	850	680	340

Existing researches, which were found and analyzed by authors within this study, did not have comprehensive information regarding stress-strain state of considered element under consimilar parameters and therefore final results could not be compared, however the methods and main principles of calculation in accordance with Limit State design remain analogous.

4. Conclusions

Within this study, three types of IGUs representing different ratios of width height were modelled in order to verify correctness of a default fixing step value given by manufacturers of structural glazing and find out the dependence of the main changeable parameters of IGU on its overall performance.

The model incorporating profile's contribution to the total deflections and stresses of system through rigidity characteristics was developed, and its influence on glass unit's performance under the action of uniformly distributed load was described. Evaluation of pane's stress-strain state was performed separately from the frame in accordance with current regulations.

On the basis of obtained results, it is possible to make the following conclusions:

1. Modification of the fixing step in horizontal direction (along larger side) and glass panel thickness have a significant influence on the stress and deformation values;

2. In contradistinction, modification in vertical direction (along shorter side) and gas filling thickness do not noticeably impact stress-strain state of a plate;

3. Default fixing step between two adjacent supports, which is often adopted by manufactures of IGUs without preliminary calculation for actual applied load, has to be verified in each case in terms of deformation in order to satisfy the conditions of SLS.

Recommended maximum values of support steps and glass unit composition are proposed in accordance with the value of the face load acting on the plate surface and parameters of IGUs.

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