Vol. 11, 2022, 93-101

DOI: 10.17512/bozpe.2022.11.11

Construction of optimized energy potential

Budownictwo o zoptymalizowanym potencjale energetycznym

ISSN 2299-8535 e-ISSN 2544-963X

Gas interaction in insulating glass units in the case of elastic support of component glass panes

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Abstract: Insulating glass units (IGUs), commonly used for filling windows and glass facades, have in their construction a tight gas-filled gap. This determines the good thermal insulation of the IGU, but at the same time makes it sensitive to climatic loads (changes in atmospheric pressure, temperature, wind load etc.). In the IGU gas interaction calculation models, these loads are usually simply supported at the connection of the component panes with the edge spacer. Under real conditions, another type of connection is possible, which was the subject of interest by several researchers. In this article, on the basis of the general theory of plates, an analytical model of the resultant load and deflection of IGUs under climatic loads is proposed, taking into account elastic support of the component panes. The computational examples illustrates the influence of connection stiffness on the resultant climatic load and deflection in IGUs.

Keywords: glass in building, insulating glass units, elastic supported panes, climatic loads

Please, quote this article as follows:

Respondek Z., Gas interaction in insulating glass units in the case of elastic support of component glass panes, Construction of Optimized Energy Potential (CoOEP), Vol. 11, 2022, 93-101, DOI: 10.17512/bozpe.2022.11.11

Introduction

The idea behind the construction of insulating glass units (IGUs) was to increase the thermal insulation of external glass building envelopes (Pietrzak, 2014). An IGU consists of two or more glass panes joined at the edge by a double-sealed spacer (Van Den Bergh, 2013). The cavity between the component panes creates a tight gap filled with gas, most commonly argon. In practice, it has turned out that such a structure, giving the possibility of reducing heat loss, generates certain specific climatic loads. In the event of temporary or periodic changes in atmospheric pressure and

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temperature, a pressure difference is created between the gas in the gap and the environment, which causes loading, deflection and stress of the component panes.

This unfavorable phenomenon has been described in many studies, see the articles cited below. Visually, it can be observed by the deformation of the image reflected by the IGU – the unit takes a concave or convex form of deflection depending on the temporary parameters of atmospheric pressure and gas temperature in the gaps. The gas interaction is an important factor. For example, as atmospheric pressure increases, the IGU takes a concave form of deflection whereby, according to the ideal gas law, the gap volume decreases and the pressure increases, largely compensating for the primary pressure increase. It is different in the case of an asymmetric load – for example, a wind load. Here, the interaction of the gas causes the external load to be distributed to all of the component panes of the IGU, which is advantageous.

The static quantities (the resultant load on the component panes, their deflection and stress) result from the state of temporary equilibrium between the weather conditions and the operating pressure and gas volume in the IGU gaps.

The analytical models of static quantities in IGUs described in the literature (Curcija & Vidanovic, 2012; Feldmaier, 2006; Feldman et al., 2014; Respondek, 2017; Solvason, 1974) are mostly based on the classical theory of the linear Kirchhoff plate, assuming that a simply support at the connection of the glass pane with the spacer is sufficient. The article (Galuppi & Royer-Carfagi, 2020) presents a model for calculating multi-glazed IGUs using Green's function, also based on the assumption of a simply supported plate. The example of numerical analysis concerning the point supports of glass panes was presented in (Kuliński & Palacz, 2021).

In the literature, there are few descriptions of instrumental studies on the behavior of climate-loaded IGUs.

Hart et al. (2012) measured the actual deflections in operated IGUs at various locations in the US, mainly in the context of the impact of changing the thickness of the gap on the thermal transmittance of glazing. Similar studies, but with the IGU placed in a climatic chamber, were described in (Penkova et al., 2017).

Buddenberg et al. (2016), based on the measurement of pressure changes in IGU gaps placed in a climatic chamber subjected to cyclic temperature changes, drew conclusions about the changes in the connection stiffness of the glass pane with the spacer depending on the temperature and the number of load cycles. A numerical model based on FEM was used for the analysis.

Problems related to the efficiency of joining glass plates through the spacer were also the subject of experimental studies (shear and four-point bending tests) and numerical analyses presented in the articles (Bedon & Amadio, 2020a; 2020b).

Stratiy (2017) studied the deflections in the IGU model placed in the window frame. The climatic loads were simulated by forcing gas into the gap. It was found that the measured deflections are intermediate values between those calculated theoretically for a simply supported and rigidly fixed plate.

The aim of the article is to improve the analytical model for determining the resultant climatic load and IGUs deflection by taking into account the possibility of elastic connection of the component panes with the spacer. On the basis of the proposed model, examples of the influence of the connection stiffness on the resultant load and deflection in IGUs are presented.

1. Methodology of research

The conducted analysis refers to an own model of the behavior of climatically loaded IGUs with any number of gaps (Respondek, 2017; 2020; Respondek et al., 2022), hereinafter referred to as the base model. In that model, a linear dependence of the deflection w [m] in the center of the IGU component pane on the resultant load q [kN/m^2] acting on this pane was assumed. Glass dimensions (between supports): width a [m], length b [m]. For each component pane

$$w = \alpha_{\mathrm{w}} \cdot q = \alpha_{\mathrm{w}}^{'} \cdot \frac{q \cdot a^4}{D} \tag{1}$$

where:
α_{w} – proportionality factor for deflection (deflection under a unit load) [m^3/kN];
$\alpha_{\mathrm{w}}^{'}$ – dimensionless coefficient for deflection (depending on $e = b/a$) [–];
D – flexural rigidity of glass pane [kNm].

The change in the gap volume Δv [m^3] resulting from the deflection of one of its bounding panes is

$$\Delta v = \int_{\frac{-b}{2}}^{\frac{b}{2}} \int_{\frac{-a}{2}}^{\frac{a}{2}} w(x,y)\mathrm{dxdy} = \alpha_{\mathrm{v}} \cdot q = \alpha_{\mathrm{v}}^{'} \cdot \frac{q \cdot a^6}{D} \tag{2}$$

where:
$w(x,y)$ – function of deflection [m];
α_{v} – proportionality factor for the volume change [m^5/kN];
$\alpha_{\mathrm{v}}^{'}$ – dimensionless coefficient for the volume change (depending on $e = b/a$) [–].

On the basis of the function of the deflector for a simply supported plate and the ideal gas law, an equation (double-glazed IGU) or a system of quadratic equations (multi-glazed IGU) has been formulated, allowing the determination of the operating gas pressure in each IGU gap under any climatic load. This made it possible to calculate, on the basis of the pressure difference, the resultant load for each component pane, and then the maximum deflection and stress. The calculation has been based on dimensionless coefficients $\alpha_{\mathrm{v}}^{'}$ and $\alpha_{\mathrm{w}}^{'}$, the values of which in the articles cited earlier are given for simply supported glass panes.

Taking into account the possibility that elastic support comes down to the dependence of the above coefficients on the connection stiffness of the component panes with the spacer, this will supplement the base model. This aim is achieved by analyzing the deflection functions given in (Timoshenko & Woinowsky-Krieger, 1959) and applying appropriate boundary conditions.

2. Analysis of the case of elastic support

A system of two elastically supported plates on the edges, creating a gap with the thickness s [m] is assumed (Fig. 1). In order to determine the coefficients $\alpha_{\mathrm{v}}^{'}$ and $\alpha_{\mathrm{w}}^{'}$, we consider the change in the gap volume Δv caused by the deflection of one of these plates as a result of the load q. The symbol C [kNm/(m·rad)] denotes the rotational stiffness of the connection, defined as the bending moment of the elastic support beam, resulting in the unit angle of rotation. In boundary cases: C = 0 means simply support, $C \to \infty$ means clamped fixity.

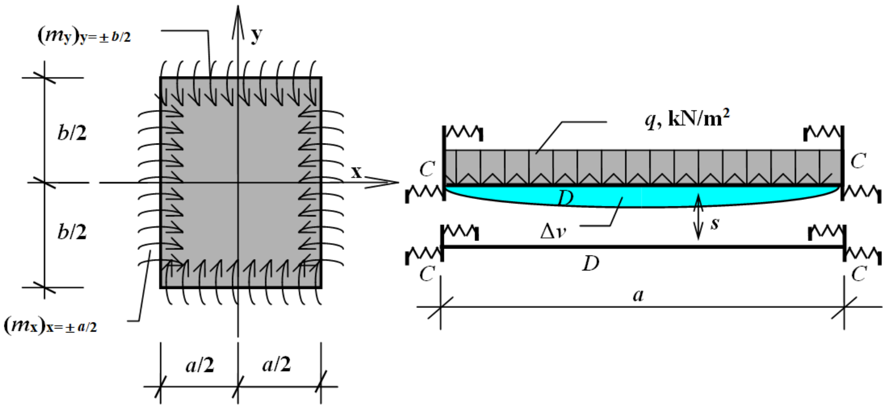

Fig. 1. Diagram of an elastically supported on the edges set of plates (*own research*)

Deflection of a single plate is the algebraic sum of the deflections of the simply supported plate loaded by q and loaded with edge moments $(m_y)_{y=\pm b/2}$ and $(m_x)_{x=\pm a/2}$.

$$w = w_{\mathrm{q}} + w_{\mathrm{my}} + w_{\mathrm{mx}} \tag{3}$$

According to the classical theory of plates (Timoshenko & Woinowsky-Krieger, 1959)

$$w_{\mathrm{q}} = \frac{4 \cdot q \cdot a^4}{\pi^5 \cdot D} \sum_{i=1,3,5....} \frac{(-1)^{(i-1)/2}}{i^5} \cdot \cos\frac{i\pi x}{a} \cdot \left(1 - \frac{\beta_i \cdot \mathrm{th}\beta_i + 2}{2 \cdot \mathrm{ch}\beta_i} \cdot \mathrm{ch}\frac{i\pi y}{a} + \frac{1}{2 \cdot \mathrm{ch}\beta_i} \cdot \frac{i\pi y}{a} \cdot sh\frac{i\pi y}{a}\right) \tag{4}$$

$$w_{\mathrm{my}} = -\frac{a^2}{2 \cdot \pi^2 \cdot D} \sum_{i=1,3,5....} F_i \cdot \frac{(-1)^{(i-1)/2}}{i^2 \cdot \mathrm{ch}\beta_i} \cdot \cos\frac{i\pi x}{a} \cdot \left(\frac{i\pi y}{a} \cdot \mathrm{sh}\frac{i\pi y}{a} - \beta_i \cdot \mathrm{th}\beta_i \cdot \mathrm{ch}\frac{i\boldsymbol{\pi} y}{a}\right) \tag{5}$$

$$w_{\mathrm{mx}} = -\frac{b^2}{2 \cdot \pi^2 \cdot D} \sum_{i=1,3,5....} G_i \cdot \frac{(-1)^{(i-1)/2}}{i^2 \cdot \mathrm{ch}\gamma_i} \cdot cos\frac{i\pi y}{b} \cdot \left(\frac{i\pi x}{b} \cdot \mathrm{sh}\frac{i\pi x}{b} - \gamma_i \cdot \mathrm{th}\gamma_i \cdot \mathrm{ch}\frac{i\pi x}{b}\right) \tag{6}$$

assuming that

$$(m_y)_{y=\pm b/2} = \sum_{i=1,3,5\ldots} (-1)^{(i-1)/2} \cdot F_i \cdot \cos\frac{i\pi x}{a} \tag{7}$$

$$(m_x)_{x=\pm a/2} = \sum_{i=1,3,5\ldots} (-1)^{(i-1)/2} \cdot G_i \cdot \cos\frac{i\pi y}{b} \tag{8}$$

In equations (5)-(6), auxiliary parameters $\beta_i = \frac{i \cdot \pi \cdot e}{2}$ and $\gamma_i = \frac{i \cdot \pi}{2 \cdot e}$ are used.

The symbols F_i [kN] and G_i [kN] denote unknowns, the elements of decreasing sequences should be determined from the boundary conditions, in this case

$$\frac{\partial w}{\partial y} = \frac{m_y}{C} \quad \text{for } y = \pm b/2, \qquad \frac{\partial w}{\partial x} = \frac{m_x}{C} \quad \text{for } x = \pm a/2 \tag{9}$$

After calculating the derivatives on the basis of equations (4)-(6), substituting equations (7)-(8), and then appropriate ordering, we obtain two infinite systems of linear equations

$$\frac{F_j}{j}\left[\operatorname{th}(\delta_j e) + \frac{\delta_j \cdot e}{\operatorname{ch}^2(\delta_j e)}\right] + r_C \cdot F_j + \frac{8j}{\pi \cdot e} \sum_{i=1,3,5\ldots} \frac{G_i}{i^3} \frac{1}{\left(\frac{1}{e^2} + \frac{j^2}{i^2}\right)^2} = \frac{r_q}{j^4} \cdot \left[\frac{\delta_j \cdot e}{\operatorname{ch}^2(\delta_j \cdot e)} - \operatorname{th}(\delta_j \cdot e)\right] \tag{10}$$

$$\frac{G_j}{j}\left[\operatorname{th}\frac{\delta_j}{e} + \frac{\frac{\delta_j}{e}}{\operatorname{ch}^2\left(\frac{\delta_j}{e}\right)}\right] + \frac{r_C}{e} \cdot G_j + \frac{8 \cdot j \cdot e}{\pi} \sum_{i=1,3,5\ldots} \frac{F_i}{i^3} \frac{1}{\left(e^2 + \frac{j^2}{i^2}\right)^2} = \frac{r_q \cdot e^2}{j^4} \cdot \left[\frac{\frac{\delta_j}{e}}{\operatorname{ch}^2\left(\frac{\delta_j}{e}\right)} - \operatorname{th}\left(\frac{\delta_j}{e}\right)\right] \tag{11}$$

where: $j = 1, 3, 5 \ldots$, $e = b/a$, $\delta_j = j\pi/2$, $r_q = \frac{4 \cdot q \cdot a^2}{\pi^3}$, $r_c = \frac{2\pi \cdot D}{a \cdot C}$.

The dimensionless parameter r_c is called the connection flexibility index, where $r_c \to \infty$ means simply supported, $r_c = 0$ means clamped fixity.

In practice, in equations (5)-(8) and (10)-(11), instead of F and G (with the appropriate index), it is preferable to substitute

$$F = F' \cdot q \cdot a^2, \;\; G = G' \cdot q \cdot a^2 \tag{12}$$

In this way, the searched sequence elements are dimensionless, and the solutions depend only on the dimension index e and the connection flexibility index r_c.

Equations (10)-(11) are solved taking into account the first 5 elements of both sequences: F'_1-F'_9 and G'_1-G'_9. In this way, a system of ten linear equations with ten unknowns are obtained. The solution is performed using the determinant method after constructing an appropriate spreadsheet.

Then, from equations (4)-(6), the coefficients $\alpha_{\mathrm{w}}^{'}$ are determined, and after integration, the coefficients $\alpha_{\mathrm{v}}^{'}$. The results of the calculations for the exemplary values of e and r_c are presented in Tables 1 and 2. Thus, the base model is extended with coefficients allowing the analysis of IGUs with elastically supported glass panes. By using the above, it is possible to analyze many examples of climatic loads, including boundary cases of static quantities in operating IGUs.

Table 1. Coefficients $\alpha_{\mathrm{w}}^{'}$ used to calculate the deflection in the center of the glass pane (*own research*)

e	Connection flexibility index $r_{\mathrm{c}} = 2\pi \cdot D/(a \cdot C)$							
	0	0.1	0.5	1	5	10	100	$\to\infty$
1.0	0.001265	0.001417	0.001883	0.002273	0.003326	0.003638	0.004013	0.004062
1.1	0.001508	0.001682	0.002223	0.002684	0.003953	0.004339	0.004807	0.004869
1.2	0.001725	0.00192	0.002533	0.003061	0.004549	0.005009	0.005575	0.005651
1.3	0.001912	0.002127	0.002808	0.003400	0.005101	0.005637	0.006303	0.006392
1.4	0.002068	0.002301	0.003044	0.003697	0.005604	0.006216	0.006982	0.007085
1.5	0.002197	0.002445	0.003245	0.003954	0.006057	0.006742	0.007607	0.007724
1.6	0.002300	0.002563	0.003412	0.004173	0.006461	0.007215	0.008177	0.008308
1.7	0.002382	0.002657	0.003551	0.004357	0.006817	0.007639	0.008694	0.008838
1.8	0.002446	0.002731	0.003663	0.004511	0.007129	0.008015	0.009159	0.009316
1.9	0.002496	0.002789	0.003755	0.004639	0.007402	0.008347	0.009576	0.009745
2.0	0.002533	0.002833	0.003827	0.004744	0.007639	0.008639	0.009948	0.010129
3.0	0.002617	0.002941	0.004049	0.005117	0.008764	0.010121	0.011970	0.012233

Table 2. Coefficients $\alpha_{\mathrm{w}}^{'}$ used to calculate the change in gap volume (*own research*)

e	Connection flexibility index $r_{\mathrm{c}} = 2\pi \cdot D/(a \cdot C)$							
	0	0.1	0.5	1	5	10	100	$\to\infty$
1.0	0.000389	0.000459	0.000677	0.000860	0.001355	0.001502	0.001679	0.001703
1.1	0.000511	0.000600	0.000877	0.001114	0.001771	0.001971	0.002214	0.002246
1.2	0.000642	0.000750	0.001092	0.001388	0.002226	0.002486	0.002805	0.002848
1.3	0.000777	0.000905	0.001315	0.001674	0.002710	0.003038	0.003444	0.003499
1.4	0.000915	0.001064	0.001545	0.001970	0.003218	0.003619	0.004122	0.004189
1.5	0.001054	0.001225	0.001778	0.002271	0.003742	0.004222	0.004830	0.004912
1.6	0.001194	0.001387	0.002012	0.002575	0.004279	0.004843	0.005562	0.005659
1.7	0.001334	0.001548	0.002248	0.002882	0.004824	0.005476	0.006312	0.006427
1.8	0.001474	0.001709	0.002483	0.003189	0.005377	0.006118	0.007078	0.007210
1.9	0.001614	0.001871	0.002719	0.003497	0.005933	0.006768	0.007855	0.008004
2.0	0.001753	0.002032	0.002954	0.003804	0.006493	0.007423	0.008640	0.008808
3.0	0.003143	0.003636	0.005299	0.006874	0.012138	0.014068	0.016685	0.017055

3. Calculation example and discussion

The example concerns double-glazed IGUs, with glass panes 4 or 6 mm thick, and a gap of 16 mm. Typical glass parameters are assumed as: Young's modulus 70 GPa and Poisson's ratio 0.2, respectively. Initial conditions of gas in the gap (assumed conditions without deformation and stress of the panes): pressure 100 kPa, temperature 20°C. Two typical types of climatic load are considered: a decrease in atmospheric pressure by 5 kPa (symmetrical load) and a wind pressure of 0.3 kN/m^2 (asymmetric load).

Tables 3 and 4 show the results of calculations of the resultant climatic load q and the maximum deflection w in IGUs, for the boundary cases and two intermediate values of the r_c index. Various dimensions of glass panes are considered with the same $e = b/a$ = 1.5.

Table 3. The resultant load and deflection in IGUs loaded with decrease in atmospheric pressure by 5 kPa (*own research*)

a [cm]	simply supported		r_c = 10		r_c = 1		clamped fixity	
	q [kN/m^2]	w [mm]	q [kN/m^2]	w [mm]	q [kN/m^2]	w [mm]	q [kN/m^2]	w [mm]
IGUs 4-16-4								
40	1.390	0.707	1.545	0.686	2.261	0.588	3.189	0.461
60	0.357	0.919	0.410	0.922	0.711	0.936	1.309	0.959
80	0.119	0.968	0.138	0.979	0.250	1.042	0.508	1.176
100	0.049	0.983	0.057	0.996	0.106	1.075	0.222	1.255
IGUs 6-16-6								
40	2.808	0.423	2.990	0.393	3.665	0.283	4.273	0.183
60	1.024	0.781	1.152	0.767	1.780	0.695	2.707	0.587
80	0.379	0.914	0.436	0.916	0.751	0.927	1.373	0.941
100	0.163	0.959	0.189	0.969	0.339	1.021	0.675	1.131

Table 4. The resultant load and deflection in IGUs loaded with wind pressure 0.3 kN/m^2 (*own research*)

a [cm]	simply supported		r_c = 10		r_c = 1		clamped fixity	
	q [kN/m^2]	w [mm]	q [kN/m^2]	w [mm]	q [kN/m^2]	w [mm]	q [kN/m^2]	w [mm]
IGUs 4-16-4								
40	0.191	0.097	0.195	0.087	0.217	0.056	0.245	0.035
60	0.160	0.412	0.162	0.363	0.171	0.225	0.188	0.138
80	0.153	1.248	0.154	1.093	0.157	0.654	0.165	0.381
100	0.151	3.007	0.152	2.629	0.153	1.556	0.156	0.883
IGUs 6-16-6								
40	0.233	0.035	0.239	0.031	0.260	0.020	0.278	0.012
60	0.180	0.137	0.183	0.122	0.202	0.079	0.230	0.050
80	0.161	0.388	0.163	0.342	0.172	0.212	0.190	0.130
100	0.155	0.910	0.155	0.798	0.160	0.481	0.169	0.284

In the case of a symmetrical load, it should be noted that the more susceptible to deflection the component panes are (thinner panes, large IGU dimensions), the gas interaction in the gap increases and the smaller the resultant load than in IGUs with panes of lower deflection susceptibility. Thus, a feedback takes place here, so that e.g. the resulting deflections do not increase significantly for large IGUs dimensions.

It is similar in the case of stiffening the connection of the glass pane with the spacer. The stiffer the connection, the less susceptible the glass pane is to deflection, which results in an increased resultant load. Since two opposing factors are active, the effect of stiffening on the resulting maximum deflection may be different. As shown in Table 3, for small IGU dimensions, the stiffening reduces the maximum deflections – with an IGU width of 40 cm and a glass thickness of 4 mm, the deflection at clamping is 35% smaller than for A simply supported system, and with a glass thickness of 6 mm it is 57% smaller. On the other hand, for large IGU dimensions, the resulting deflections increase together with stiffening (28% greater for 4 mm and 18% greater for 6 mm, respectively).

Discussed behavior is different for an asymmetrically loaded IGU. Here, for large IGUs dimensions, the external load is distributed over both component panes nearly equally, and the increase in dimensions causes an exponential increase in deflection. By making the connection stiffer, this results in a significant reduction in the resulting deflection. The value of deflection for a clamped system is around 29-36% of the deflection obtained for simply supported one.

Additionally, even large reductions in the deflection in IGUs with the connection stiffening of the glass pane with the spacer do not prove that such a connection is beneficial. In this case, edge stresses arise in the panes, which must be taken into account in the static analysis of the IGU. This issue will be the subject of a separate study.

Conclusions

Most of the known models of IGUs behavior under climatic loads assume simple support between the component panes and the rigid edge spacer. In fact, there may be elastic support at this point, as evidenced by the experimental studies described in the literature. The stiffening of the panes on the edges may be due to two reasons: the properties of the adhesive-sealing materials forming the connection and the operation of the window frame, which, due to the pressure of the gaskets, may partially limit the freedom of rotation of the glass pane on the support.

The article proposed an analytical model for determining the resultant climatic load and deflection of IGU component panes with the assumption of elastic support on the edges, which is an improvement of the known model assuming simply supported systems. The example calculations show that in the case of external symmetrical loads, the stiffening at the connection reduces the gas gap interaction, which in different ways translates into the maximum deflection in IGUs. In small size IGUs, the stiffening of the connection reduces the resulting deflection. In large size IGUs the deflection increases. In the case of asymmetrical loads, e.g. the action of wind, stiffening the connection significantly reduces the deflection.

The proposed analytical model can be used for the validation of numerical models and for the interpretation of the experimental studies conducted under various conditions taking into account real supporting.

Bibliography

Bedon, C. & Amadio, C. (2020a) Mechanical analysis and characterization of IGUs with different silicone sealed spacer connections – Part 1: Experiments. *Glass Structures & Engineering*, 5, 301-325.

Bedon, C. & Amadio, C. (2020b) Mechanical analysis and characterization of IGUs with different silicone sealed spacer connections – Part 2: Modelling. *Glass Structures & Engineering*, 5, 327-346.

Buddenberg, S., Hof, P. & Oechsner, M. (2016) Climate loads in insulating glass units: Comparison of theory and experimental results. *Glass Struct. Eng.*, 1, 301-313.

Curcija, C. & Vidanovic, S. (2012) *Predicting Thermal Transmittance of IGU Subject to Deflection.* Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division: Berkeley, CA, USA.

Feldman, M. et al. (2014) *Guidance for European Structural Design of Glass Components; Support to the Implementation, Harmonization and Further Development of the Eurocodes.* Luxembourg, Luxembourg Publications Office of the European Union.

Feldmeier, F. (2006) Klimabelastung und Lastverteilung bei Mehrscheiben-Isolierglas. *Stahlbau*, 6(75), 467-478.

Galuppi, L. & Royer-Carfagi, G. (2020) Green's functions for the load sharing in multiple insulating glazing units. *International Journal of Solids and Structures*, 206, 412-425.

Hart, R., Goudey, H., Arasteh D. & Curcija, DC. (2012) Thermal performance impacts of center-of--glass deflections in installed insulating glazing units. *Energy and Buildings*, 54, 453-460.

Kuliński, K. & Palacz, P. (2021) C*omparison of internal forces redistribution and displacements subjected to the dynamic wind gusts depending of point fixed glass connector model shape.* Periodica Polytechnica-Civil Engineering, 65, 1008-1014.

Penkova, N., Krumov, K., Zashkova, L. & Kassabov, I. (2017) Heat transfer and climatic loads at insulating glass units in window systems. *International Journal of Advances in Science Engineering and Technology*, 5, 22-28.

Pietrzak, A. (2014) Koncepcja „szklanych domów" w budownictwie energooszczędnym. *Construction of Optimized Energy Potential*, 2(14), 60-66.

Respondek, Z. (2017) Rozkład obciążeń środowiskowych w wielokomorowej szybie zespolonej. *Construction of Optimized Energy Potential*, 1(19), 105-110.

Respondek, Z. (2020) Heat transfer through insulating glass units subjected to climatic loads. *Materials*, 13, 286.

Respondek, Z., Kozłowski, M. & Wiśniowski, M. (2022) Deflections and stresses in rectangular, circular and elliptical insulating glass units. *Materials*, 15, 2427.

Solvason, K.R. (1974) *Pressures and stresses in sealed double glazing units*. Technical Paper No. 423, Division of Building Research, National Research Council Canada, Ottawa.

Stratiy, P. (2017) *Numerical-and-analytical method of estimation insulated glass unit deformations caused by climate loads*. Advances in Intelligent Systems and Computing, 692, 970-979.

Timoshenko, S. & Woinowsky-Krieger, S. (1959) *Theory of Plates and Shells*. New York – Toronto – London, McGraw-Hill Book Company. Inc.

Van Den Bergh, S., Hart, R., Jelle, B.P. & Gustavsen, A. (2013) Window spacers and edge seals in insulating glass units: A state-of-the-art review and future perspectives. *Energy and Buildings*, 58, 263-280.