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Stress and deflection in multi-glazed IGUs of various dimensions

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ABSTRACT:
In the structure of insulating glass units (IGUs) there are gas-filled gaps. Therefore, changes in atmospheric pressure and temperature, as well as the action of wind, result in a load on the component glass panes. However, the deflection of the panes connected with climatic loads results in an interaction of the gas closed in the gaps, which partially reduces climatic influences. The aim of this article is to analyze the influence of IGUs dimensions on the maximum stresses and deflections in the component glass panes, also in the context of the use of multi-glazed IGUs. Three typical loads were analyzed. It was found that in the case of wind load, with increasing dimensions of the IGUs, the stresses and deflections increase. On the other hand, in the case of loads related to pressure and temperature changes, in large-size IGUs, the gas interaction in the gaps is significant, which reduces the resultant load on the panes. It has been shown that there are critical IGU dimensions here for which the stress and deformation ratio are greatest. It was also found that increasing the number of gaps in IGUs results in a significant increase in the stress and de-flection values due to climatic loads.

KEYWORDS:
glass in building; insulating glass units; climatic loads; stress and deflection of glass panes

1. Introduction

Insulating glass units (IGUs) are a specific construction element in the context of their static operation. The key factor here are the tightly closed gas gaps between the component glass panes. In the production process, certain initial values of pressure, temperature and gas volume are "closed" in the gaps of the IGUs. This generates certain types of operating loads that are not relevant for other building elements. First of all, any changes in atmospheric pressure and gas temperature in the gaps load the component glass panes (Fig. 1a,b).

In IGUs, however, we deal with a certain kind of feedback – the external load forces the deformation of the component panes, the deformation forces a change in the gap volume, the change in volume forces a pressure change in the gap, which causes a secondary load (interaction) with a return opposite to the primary load, which in turn, has an impact on the resultant load acting on each of the component glass panes. Thus, the system has a temporary equilibrium between the climatic conditions and the operating pressure of the gas in the gaps.

Gas interaction also works for external surface loads. For example, the wind pressure (Fig. 1c) acts directly only on the external pane (ex), but changes in gas pressure in the gaps partially relieve this pane and load the remaining panes. So the maximum load on the IGU is reduced.

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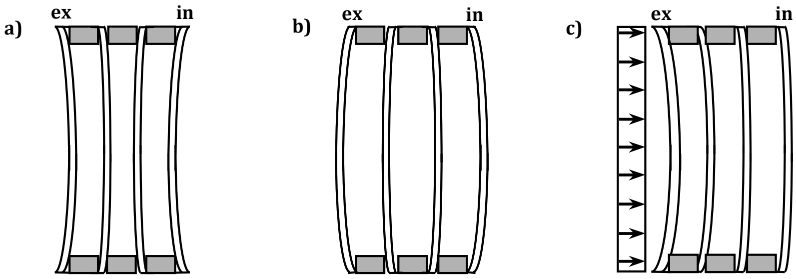

Fig. 1. Typical deformations of IGUs caused by: a) increase in atmospheric pressure or decrease in gas gap temperature, b) decrease in atmospheric pressure or increase in gas gap temperature, c) wind pressure

For the analytical modeling of static quantities, it is crucial to determine the operating gas pressure in the gaps, which allows the determination of the resultant load acting on each of the component panes, and then the deflection and stress.

There are several such models described in the literature. For example, analytical models provided by Solvason [1] (for double-glazed IGUs) Feldmaier [2-4] (for double and triple-glazed IGUs) Curcija and Vidanovic [5] provided assumptions for numerical determination of deflections in multi-glazed systems. Numerical analyses are also presented in articles [6, 7]. Experimental studies on deflection in IGUs under real conditions were also carried out [8], as well as studies in climate chambers [9, 10].

In fact, all analytical models are based on the assumption that the gas in the gaps complies with the law of ideal gas

$$\frac{p_0 \cdot v_0}{T_0} = \frac{p_{\text{op}} \cdot v_{\text{op}}}{T_{\text{op}}} = \text{const} \tag{1}$$

where: p_0, T_0, v_0 – are the initial parameters of the gas in the chamber obtained in the production process: pressure [kPa], temperature [K], gap volume [m^3]; p_{op}, T_{op}, v_{op} – are the operating parameters, similarly.

The research results obtained in this article are based on the author's own model that allows the calculation of the resultant load of the component panes in IGUs with any number of gaps. The problem comes down to the numerical solution of the quadratic equation system described in the article [11]. The methodology of calculating deflection of glass panes is described in detail in [12].

Issues related to IGUs climatic loads are important both in the context of structure safety and performance parameters. Concave or convex forms of glass panes are noticeable and spoil the aesthetics of the facade, the image reflected from the glass is also distorted.

In recent years, double-glazed IGUs have been widely used. Stricter requirements for thermal protection of buildings forced the necessity of the common use of triple-glazed units. There are also units with more glass panes. In this context, the problem of climatic loads increases, because, as shown by calculation models, the greater total thickness of the gas in the gaps generates greater stresses and deflections from climatic loads.

The aim of this article is to analyze the influence of an IGU's dimensions on the maximum stresses and deflections in the component glass panes, this is also shown in the context of the use of multi-glazed IGUs. The problem is illustrated by the example of three typical climatic loads for which, if possible, critical IGU dimensions were determined, for which these static quantities are extreme.

2. Methodology of research

Three exemplary climatic loads were analyzed: wind pressure, decrease of the atmospheric pressure and decrease of the external air temperature.

The following parameters of the model IGUs were assumed: double-, triple- and quadruple-glass units, thickness of glass panes 4 mm, Young's modulus of glass 70 GPa, Poisson's ratio 0.20, gap width 16 mm, initial parameters of gas in the gaps – p_0 = 100 kPa (1000 hPa), T_0 = 20°C. Dimensions of IGUs are variable, but assume a constant length/width ratio of 1.5.

For each case, the resultant loads [kN/m^2], and deflections (in the center of the pane) [mm], were calculated for the glass panes in the analyzed IGUs according to the methodology described in [11] and [12], if it was possible, the indices were also determined describing the load reduction.

The values of the maximum deflection do not fully reflect the level of optical deformation of the image viewed in the reflected light. The same deflection values for different glass widths are more or less noticeable, therefore the deformation ratio [mm/m] was also calculated, defined as the ratio of maximum deflection to the IGU width.

In the glass panes, the maximum stresses have also been calculated, which are to be understood as stress in the center of the pane in a direction parallel to the shorter edge. The stresses were calculated using the dependencies known from the Kirchhoff-Love theory of plates according to [13].

3. Research results – static quantities in exemplary IGUs

Figure 2 shows the influence of IGU width on the static quantities in the case of a wind load of 0.5 kN/m^2, which corresponds to the dynamic wind pressure with a speed of about 100 km/h [14]. The presented values refer to the component glass pane ex as the most loaded one.

Figure 3 shows an analogous effect for the load with 5 kPa atmospheric pressure drop. This load is symmetrical, the maximum (in absolute value) static quantities in the extreme glass panes (ex and in). Such a load may occur, for example, when the IGU is installed in a building located at a much higher altitude above sea level than the production site. As is known, the atmospheric pressure given in weather forecasts is reduced to sea level, the real pressure decreasing with altitude.

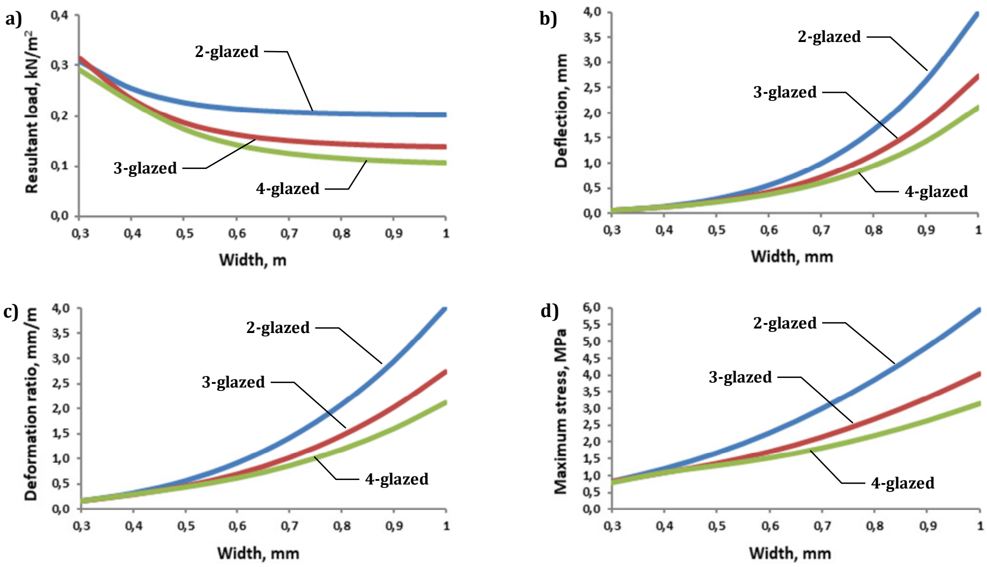

Fig. 2. Influence of model IGUs width loaded with wind (0.5 kN/m^2) on the static quantities in the glass pane ex: a) resultant load, b) deflection, c) deformation ratio, d) maximum stress

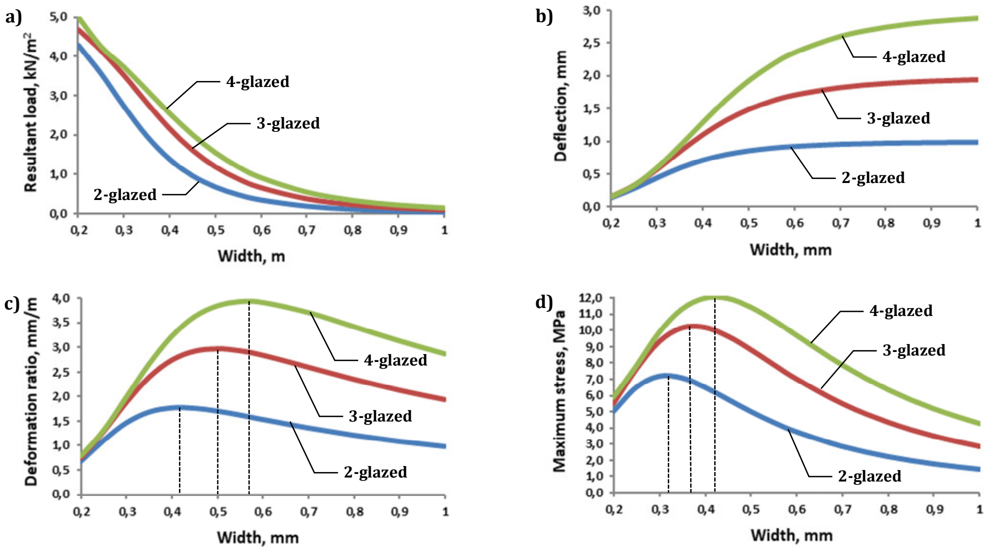

Fig. 3. Influence of model IGUs width loaded with decrease of the atmospheric pressure (5 kPa) on the static quantities in the glass panes ex and in: a) resultant load, b) deflection, c) deformation ratio, d) maximum stress

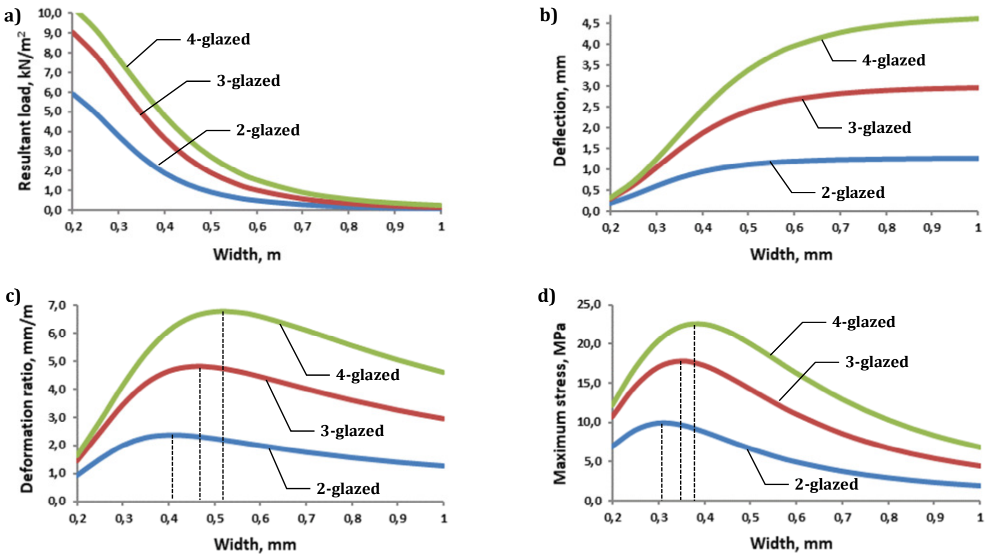

Fig. 4. Influence of model IGUs width loaded with a decrease of the external air temperature to −20°C on the static quantities in the glass pane ex: a) resultant load, b) deflection, c) deformation ratio, d) maximum stress

Figure 4 shows the effects of the load with a decrease of the external air temperature to −20°C. It was assumed that the average gas temperature in the gaps was then: 0°C for a double-glazed unit, −10°C and 10°C for a triple-glazed unit, −13,33°C, 0°C and 13,33°C for a quadruple-glazed unit. As the reference level is the initial conditions (20°C) for triple- and quadruple-glazed units, the load is not uniform. All the component panes are loaded, but the greatest static quantities are found in the pane ex.

4. Discussion of the results

In the case of wind pressure (Fig. 2), part of the load acting directly on the glass pane ex is transferred to the other panes of the IGU. The resultant load is therefore reduced. For a width of 30 cm, this reduction is approx. 40%, for larger widths the reduction increases, and for IGUs wider than 80 cm, the load is almost evenly distributed over all component panes and practically does not change. Thus, the stress and deflection increase as the IGU size increases. However, it can be seen that the use of multi-glazed IGUs is beneficial in terms of wind load – the external action is distributed over more glass panes.

In the case of a load with a decrease of atmospheric pressure (Fig. 3), the static quantities are strongly influenced by the interaction of gas in the gaps. If the component panes were perfectly stiff, we would deal with a load of 5 kPa acting symmetrically on the panes ex and in. The panes, however, are prone to deflection, which results interaction of gas in the gaps and reduction of the resultant load on this panes. This reduction strongly depends on the dimensions of the IGUs. For a width of 20 cm it is 14.3, 6.2, 0.015% (2-, 3- and 4-glazed IGUs), for a width of 100 cm it is 99, 98, 97.1% respectively. The load reduction decreases with the increase of the total thickness of the gas in the gaps (related to the increase in the number of gaps).

This is especially true for widths less than 70 cm. As a result, the deflection and stress are significantly greater for 3- and 4- glazed IGUs. Figure 3b shows that in each case the maximum deflections in IGUs, after reaching a certain value, hardly increase with the increase in IGUs dimensions. However, the deformation ratio and stress reach their maximum values for certain critical IGUs width values – furthermore, with increasing dimensions, these values decrease significantly. For the analyzed type of load, the critical widths for the deformation ratio are 42, 50, 57 cm (2- 3- and 4-glazed IGUs), for stresses respectively 32, 37, 42 cm. Obviously, these results were obtained for IGUs with a dimension ratio of 1.5. With regard to the double-glazed IGUs, the maximum stresses for the critical widths were 41.3% higher in the triple-glazed and 65.8% higher in the 4-glazed ones. The load with a uniform increase/decrease in gas temperature in the gaps works in a similar way.

The analysis of the load with the decrease of external temperature showed that the shape of the resulting graphs (Fig. 4) is similar to the previous example. Critical widths for the deformation ratio are 41, 47, 52 cm, for stresses 31, 35, 38 cm. It should be pointed out that the values of static quantities are significantly greater than when loaded with a large (5 kPa) change in atmospheric pressure. It is especially visible for 3- and 4- glazed units – in relation to double-glazed ones the maximum stress is 79 and 126.8% higher. As shown by additional calculations, this is related to the unevenness of the load (the gas temperature is different in each gap), so that the load is not evenly distributed over the component panes and is disproportionately large in the most loaded glass pane ex.

5. Conclusions

The analysis of static quantities in climatic loaded IGUs is a complex problem. As shown in the article, in the case of loads related to changes of atmospheric pressure and air temperature, there are critical IGUs dimensions for which the stresses in the component glass panes and the deformation of the image when viewed in reflected light are the greatest. These critical IGU dimensions depend on both the load type and the IGU design. For the cases analyzed in the article, the critical widths (with a dimension ratio of 1.5) for the maximum stress range from 31 cm to 42 cm.

The IGU works differently when it is loaded with the wind, at which there are no critical widths and the static quantities increase with the increase of the dimensions of the unit.

It can therefore be concluded that in structures not exposed to strong winds, the use of large-size IGUs is usually safe, rather the dimensions close to the critical should be avoided.

Another problem is the significant increase in the stress in the IGUs with increasing the number of glass panes and consequently increasing the total thickness of the gaps in the unit. The problem intensifies in the case of unevenly acting loads, e.g. gas temperature change is different in individual gaps. Excessive stress can be minimized by reducing the gap thickness between the panes, but it is associated with a deterioration of the IGU thermal performance.

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Naprężenia i ugięcia w wielokomorowych szybach zespolonych o różnych wymiarach

STRESZCZENIE:
W konstrukcji szyb zespolonych (IGUs) istnieją szczelne szczeliny wypełnione gazem. W związku z tym zmiany ciśnienia atmosferycznego i temperatury, a także działanie wiatru skutkują obciążeniem składowych płyt szklanych. Jednak związane z obciążeniami klimatycznymi ugięcie płyt skutkuje interakcją gazu zamkniętego w szczelinach, która częściowo redukuje te wpływy klimatyczne. Celem artykułu jest analiza wpływu wymiarów IGUs na maksymalne naprężenia i ugięcia w szybach składowych, również w kontekście stosowania szyb wielokomorowych. Analizowano trzy typowe obciążenia. Stwierdzono, że w przypadku obciążenia wiatrem przy zwiększaniu wymiarów IGUs naprężenia i ugięcia rosną, natomiast w przypadku obciążeń związanych ze zmianami ciśnienia i temperatury w szybach wielkowymiarowych interakcja gazu w szczelinach jest znacząca, przez co maleje wypadkowe obciążenie szyb. Pokazano, że istnieją tutaj krytyczne wymiary IGUs, dla których naprężenie i wskaźnik deformacji są największe. Stwierdzono również, że zwiększenie liczby szczelin w IGUs skutkuje znaczącym zwiększeniem wartości naprężenia i ugięcia spowodowanego obciążeniami klimatycznymi.

SŁOWA KLUCZOWE:
szkło w budownictwie; szyby zespolone; obciążenia klimatyczne; naprężenie i ugięcie szyb