Study of Deflection in Insulating Glass Units Under Climatic Loads Simulation

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Abstract. Insulating glass unit (IGU) is a commonly used filling element in transparent building partitions. The component glass panes in the unit are connected to each other on the edges by a spacer in such a way, that the space between them forms a tight gap filled with gas. The state of the gas in the gap can be described, with sufficient accuracy, by the law of ideal gases. Periodic changes in external climatic factors, above all atmospheric pressure and temperature, result in deflection of the component glass panes, which generates secondary loads associated with the change of gas pressure in the gap. The static quantities in the glass panes (deflection, stress) are therefore the result of the state of temporary equilibrium between the gas pressure in the gap and the external pressure. Measuring the deflection of component glass panes in operating conditions is time-consuming, because it requires waiting for changes in weather factors – these changes are often unpredictable. The aim of this article is to develop the concept of a test stand allowing the measurement of the deflection of the IGU models under the conditions of climatic loads changes simulation, where these changes can be controlled over time and generated in an orderly manner. The presented project meets these requirements. The stand is built from a massive main frame, which is the basis for the placement of deflection sensors, which is accompanied by a supporting frame, that allows placing glass panes with different thicknesses. The tested model of IGU is equipped with threaded elements, thanks to which it is possible to regulate the gas pressure inside the gap and monitor its temperature. An additional function of the stand is the ability to assess the tightness of the connection of component glass panes with the spacer, which may be an alternative to the standard way of testing this parameter.

1. Introduction
Insulating glass unit (IGU) is a commonly used building element, primarily as a filling of transparent partitions: windows, glass façades, glass roof-ceilings, etc.

A characteristic feature in the IGUs structure is the tight gas gap – the component glass panes are connected at the edge with a spacer and the connection is sealed with polysulphide, polyurethane or silicone [1]. Because the component panes are not perfectly rigid, they deflect in operating conditions due to climatic loads: first of all, changes in atmospheric pressure and temperature. In some cases (high buildings, open terrain) wind pressure and suction are also important. A noticeable symptom of this phenomenon is the distortion of the image viewed in reflected light. Figure 1 presents examples of IGUs with a visible reflection of a neighboring building from both component glass panes. Images
show that the glass can take concave (usually in winter) or convex (summer period) form of deflection.

Figure 1. Visible distorted reflection of the image of the neighboring buildings from both component glass panes indicates: a) the concave, b) the convex form of deflection of the IGU.

Currently, many typical structures and elements used in construction are modeled using the finite element method (FEM). This method is mainly used to carry out analyses of mechanical and thermal actions on structures [2]. With FEM it is possible to model both connectors [3] as well as structural elements in the form of plates, profiles [4], as well as layered elements [5]. However, an IGU is an example of an unusual layer construction. The result of the variability of the gas pressure in the sealed gap of the unit is the mutual transfer of external loads between the component glass panes (gas coupling of the panes) and partial compensation of adverse external influences (gas interaction) [6]. Taking into account these phenomena requires the use of special algorithms in the FEM analysis [7, 8]. Another difficult factor to determine is the susceptibility of the glass-spacer connection. Therefore, experimental studies are necessary to verify analytical and numerical models.

2. Deflection in insulating glass units – theoretical basis

The theoretical basis for determining static quantities (deflection, stress etc.) in double-glazed insulating glass units is presented in many studies, among others [6, 8, 9, 10, 11]. The article [12] gives the method of calculating static quantities of IGUs of any number of gaps (multi-glazed IGUs).

In these computational models, it is assumed that gas in a sealed gap (most often argon) meets, with sufficient accuracy for technical purposes, the equation of ideal gas

\[ \frac{p_0 \cdot v_0}{T_0} = \frac{p_e \cdot v_e}{T_e} = n \cdot R \]

where:
- \( p_0, T_0, v_0 \) – initial gap gas parameters: pressure [kPa], temperature [K], volume [m\(^3\)]; it is assumed that in these conditions the component glass panes are unformed,
- \( p_e, T_e, v_e \) – operating parameters – analogously; these values change in time to the cycle of changes in weather factors,
- \( n \) – the number of moles of gas enclosed in the gap, which is a measure of its mass [–],
- \( R \) – ideal gas constant 0.00831446 kJ·m/(mol·K).

It is also assumed that the volume of the gas gap is related to the deflection of the component glass panes of the unit. This affects the operating pressure and generates a secondary load on these panes. Therefore, static quantities in IGU component panes are the result of a state of temporary equilibrium between the pressure of gas in the gap and atmospheric pressure. The analytical solution of the problem consists in solving the appropriate non-linear equation (for double-glazed IGUs) or a system
of equations (for multi-glazed IGUs), determining the resultant load acting on each of the glass panes, and then calculating the static quantities based on the adopted theoretical plate model.

3. New stand for testing of deflection in IGUs – concept
Studies of the deflection of IGUs in operating conditions pose many difficulties. Above all, they are time-consuming and require waiting for changes in weather conditions. These changes are often unpredictable.

For example, the article [12] describes tests for deflection of IGUs installed in windows of buildings in the US. To obtain reliable results, the measurements had to be carried out twice: in summer and winter conditions. The article [13] describes laboratory tests of deflection of composite glass loaded with temperature changes. The tested window model was a divider of a large climate chamber. It was necessary to maintain different temperatures on both sides of this glazing.

Another example of deflection measurement is described in monograph [6]. The tests were carried out on a test stand where the IGU model was situated horizontally. The wind load was modeled using a water column, but there was no possibility of controlled modeling of atmospheric pressure and temperature changes.

In the context of the above-described difficulties, the aim of the project described in this article was to develop the concept of a testing stand allowing measurement of the deflection of the IGU models under the conditions of simulation of climatic load changes, which can be controlled over time and generated in an orderly manner.

The above requirements can be met by allowing the controlled change of gas pressure in the gap $p_0$ during the test. Forced increase of gas pressure in the gap, for example by 1 kPa, causes similar effects as a natural reduction of atmospheric pressure by a certain value, which can be calculated using mathematical models presented in the literature e.g. [6, 12]. It is possible for specific conditions (IGU dimensions, rigidity of component panes, current weather conditions) to plan the experiment so that it is possible to simulate cyclical changes in external pressure. It is also possible to simulate gas temperature changes in the gap using appropriate equivalent loads. For example, on the basis of equation (1) we can calculate that a temperature drop of 1 K causes similar effects as an increase in atmospheric pressure of 0.341 kPa (for $p_0 = 100$ kPa).

It should be added that the dimensions of the tested models should not be too large – their width should not exceed 60 cm. As shown in [6] in the case of large IGU sizes, the gas interaction in the gap is large, i.e. even significant changes in external pressure cause slight changes in pressure in the gap, which may make analysis of the test results difficult.

4. New stand for testing of deflection in IGUs – description
For the proper performance of the test, it is necessary to adequately prepare the model of the IGU.

First of all, the dimensions of the IGU (width × length) must be adapted to the dimensions of the stand. It is also necessary to insert several connecting elements into the edge-spacer of the model, as shown in Figure 2. These elements have the form of tubes inserted through drilled holes – it is advantageous to install these elements in the factory before assembling the unit. The ends of elements protruding beyond the outline of the model are threaded from the outside and inside, as in a car tire valve. The non-threaded ends of the connecting elements are inserted into the inter-pane gas space. The contact of the connecting element with the hole should be properly sealed – the tightness of the gap must be ensured. The threaded ends of the elements are used to connect the devices necessary to force changes in the gas pressure in the gap and control of the gas parameters. These can be, for example:

- a device for introducing gas into the gap (inducing hypertension),
- a device for expressing gas from the gap (evoking underpressure),
- temperature sensors,
- a manometer or a device for measuring the absolute pressure.
Figure 2. A threaded connecting element mounted in the edge-spacer.

Figure 3. Stand for testing deflections in an IGU: a) view, b) detail of the model’s support
1 – IGU model, 2 – main frame, 3 – fixed part of supporting frame, 4 – movable part of supporting frame, 5 – bolt, 6 – supporting rods, 7 – gusset plate.

The main element of the stand is a massive frame (Figure 3a), made of square steel shapes, e.g. 100 × 100 mm, whose fronts can be considered stationary – these planes are the basis for placing devices for measuring deflections. It is advantageous if the frame is anchored in a concrete pavement. The IGU model is placed in a supporting frame made of steel shapes as shown in Figure 3b. The frame consists of a fixed part and a movable part. Both parts are bolted together, which gives the chance to test models of IGUs of different thickness. The model is supported in the frame from below and from the sides on elastic washers, as in window glazing. In the orthogonal plane, the model is supported linearly on flexible supporting rods, for example silicon or teflon rods. The supporting rods can not be too tight to the model – glass near the edge is particularly sensitive to cracks.

5. Measuring the deflection of component glass panes
To measure the deflection of component glass panes, dial gauges (Figure 4) or laser devices are used.

As was already mentioned, the simulation of changes in weather conditions will occur by changing the mass of gas in the gap, which forces changes in its pressure. The exemplary calculations (double-
glazing IGU with dimensions of 60×90 cm, thickness of component panes 4 mm, thickness of gas gap 16 mm, $p_0 = 100$ kPa, $T_0 = 20^\circ$C) carried out according to the methodology presented in [6] and formula (1) showed that:

- when the external pressure drops by 1 kPa, the pressure inside the gap is 99.0689 kPa, so the pressure difference between the IGU and the environment is 0.0689 kPa,
- the maximum deflection in the pane centre is 0.178 mm, and the gap increases its volume by 81.324 cm$^2$,
- to simulate the above conditions, the pressure in the gap should be increased to 100.0689 kPa,
- this can be achieved by introducing 0.0358 moles of gas, which in the conditions described corresponds to 87.34 cm$^3$ (0.104 g of air or 0.143 g of argon).

It can therefore be concluded that the mass of gas needed to simulate changes in climatic conditions is low.

**Figure 4.** Scheme of deflection measurement

1 – IGU model, 2 – main frame, 3 – magnetic base, 4 – dial gauge.

The described stand can also be used for other tests, for example:

- an alternative method of testing the tightness of the connection between the pane and the frame; according to the standard [15], the tightness is assessed by subjecting the IGU to climate cycles (heating and cooling), and then determining the gas leakage rate; climate cycles can be simulated by changes in the gas pressure in the gap,
- destructive tests of the strength of the connection between the glass pane and the edge-spacer,
- by forcing pressure change in one of the gaps of the multi-glazed IGU, it may be possible to simulate the pressure and suction of the wind.

6. **Conclusions**

The stands and methods of testing the deflection of IGU component glass panes loaded with climatic factors, described in the literature, are long-term (research in operating conditions) or generate the need to build large-scale research standings (simulation of climatic conditions in the laboratory).

The project of a new type of test stand, currently implemented at the Faculty of Civil Engineering, Czestochowa University of Technology, described in the article allows simulation of possible climate loads by changing the gas pressure in a sealed gap. In this way, the IGU model can be loaded in an orderly manner, which facilitates proper planning of the experiment. The article shows that a small mass of gas added to the gap or out of it allows simulation of large loads. By applying appropriate equivalent loads, it is also possible to simulate operational temperature changes, and by loading the model in a suitable way to simulate the pressure or sucking of the wind.

Thanks to the described stand, another problem is also solved. The initial conditions of gas pressure and temperature in the gap result from the real production conditions and are not sufficiently controlled. IGUs, even from the same production batch, may have different initial conditions "closed
in the gaps”, which makes interpretation of the test results difficult. The possibility of equalizing the pressure before the test is an important advantage of the new stand.

The stand can also be used to carry out other types of tests, for example testing the tightness of the connection of glass pane with the edge-spacer, which may be an alternative to the standard method of testing this parameter.

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