Stress-strain state of the connection node of translucent structures with the load-bearing frame of the facade system

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Abstract. The article presents the results of studying the stress-strain state of the elements of the connection node of translucent modules with a load-bearing frame as part of a standard post-and-crossbar facade system. The research is aimed at studying the initial stresses and deformations of the system node elements in its design position without applying external loads. At the initial stage, experimental studies were conducted to determine the elastic modulus of rubber inserts, which are the main elements that transmit forces from translucent modules to the supporting frame of the system. Based on the results of the tests, an approximated graph of the dependence of stresses on deformations of rubber inserts was obtained, which was exported to the software package, for modeling their actual work when calculating by finite element methods. At the stage of numerical studies geometrically and physically nonlinear problems of contact interaction of elements were solved, the resulting picture of the stress-strain state of the node in position before the application of loads and impacts was created, the value of compression of the external pressure profile to the load-bearing frame was set.

Keywords: facade system, rubber inserts, translucent module, initial stress-strain state, contact interaction.

1 Introduction

Post-and-crossbar facade systems, including translucent modules, are widely used among the enclosing structures of buildings and structures. These systems are a load-bearing frame in the form of mutually perpendicular aluminum profiles, on which translucent modules (double-glazed windows) are installed by means of special external pressure profiles through rubber inserts that prevent the formation of stress concentrators in the areas of contact with the load-bearing frame of the system [1].

The vast majority of research in the field of structures of translucent facades is aimed at studying the energy efficiency of these systems [2-5], the impact of wind loads [6-9], as well as general review articles on various methods of manufacturing, mounting and application of facade systems [10-14]. However, the existing methods for calculating such facade systems with unified design schemes in the main current regulatory documents on the territory of the Russian Federation and albums of technical solutions of manufacturers do not take into account the features of operation of translucent modules (double-glazed windows) with a load-bearing frame and their joint interaction. Also, it is worth noting that in detailed numerical studies, many researchers do not take into account the initial stress-strain state of elements in the nodes of their interfaces, which can lead to significant errors and differences between the results of numerical calculations and field tests [15-17], especially for elements with nonlinear work schedules or anisotropic properties of materials.
Thus, to study the initial stress-strain state of a fragment of compounds of structural framing elements with a translucent module post-and-crossbar facade system, about conducting laboratory tests to determine elastic strength properties of rubber inserts and numerical calculations finite element methods [18-21] geometrically and physically nonlinear problems of contact interaction of elements of the system, taking into account the elastic strength properties of rubber inserts obtained from the experiment.

2 Materials and methods

2.1 Experimental determination of elastic strength properties of rubber inserts

Description of the object and method of testing. The main objects of the test are two rubber inserts that are part of the assembly for attaching a translucent module (double-glazed window) to the supporting frame (aluminum profile) using a pressure profile (figure 1).

The cross sections of the tested external and internal rubber inserts have different shapes in the specific area (figure 2a-b).

Figure 1. General view of the section of the studied node of the facade system. Figure 2. Sections of tested rubber inserts:

2a – external, 2b – internal.

The essence of the method for determining the elastic modulus of rubber is the following one: the test sample (using a lubricant or glued) is compressed at a speed of 10 mm/min until the deformation equal to 25% is reached. Then the deformation is removed at the same speed of 10 mm / min and the compression is repeated – cycle is deformed three more times. Four cycles of compression should be conducted. The curve of the dependence of stress from deformation should be determined.
**Preparation for testing.** The standard test sample is a cylinder with a diameter of \((17.80 \pm 0.15)\) mm and a height of \((25.00 \pm 0.25)\) mm. It is necessary to determine the elastic modulus for rubber inserts of a specific section, because of that standard samples cannot be used. To ensure that the tests are correct, we calculate the height of the new sample from the condition of equal flexibilities of the standard and tested samples. To do this, we set a condition:

\[
\frac{h_{st.s}}{i_{st.s}} = \frac{h_{test.s}}{i_{test.s}}
\]  

(1)

Radius of inertia of the standard sample:

\[
i_{st.s} = \sqrt{\frac{\pi D^4}{64} / A} = \sqrt{\frac{3.14 \cdot 17.8^4}{64}} / 248.84 = 4.45\text{mm}
\]  

(2)

Radiuses of inertia of the test samples:

\[
i_{test.s,1} = \sqrt{\frac{I_{min,1}}{A_1}} = \sqrt{\frac{430}{73.99}} = 2.41\text{mm}
\]  

(3)

\[
i_{test.s,2} = \sqrt{\frac{I_{min,2}}{A_2}} = \sqrt{\frac{208}{49.25}} = 2.06\text{mm}
\]  

(4)

The required height of the test samples:

\[
h_{test.s,1} = \frac{h_{st.s}}{i_{st.s}} \cdot i_{test.s,1} = \frac{25}{4.45} \cdot 2.41 = 13.54\text{mm}
\]  

(5)

\[
h_{test.s,2} = \frac{h_{st.s}}{i_{st.s}} \cdot i_{test.s,2} = \frac{25}{4.45} \cdot 2.06 = 11.57\text{mm}
\]  

(6)

**Testing.** Tests are performed under standard laboratory conditions on certified and verified equipment.

![Figure 3. The general view of the samples during the test: a) the process of compression of a sample in a tensile testing machine; b) a sample of the outer insert; c) a sample of the inner insert.](image)
The test method consists of cyclic loading and unloading of the sample and fixing the readings of forces and deformations:

1) The sample is installed on a fixed part of the machine;
2) The movable part of the machine is brought into contact with the sample;
3) The moving part compresses the sample at a speed of 10 mm/min until the sample reaches deformation level of 25%;
4) Lifting the moving part, the load is removed;
5) The loading-unloading cycle is repeated two more times, simulating fatigue when working with the material;
6) Then another, fourth, cycle of loading the sample is performed with compression to 20%;
7) The equipment registers its own movement and the resulting force;
8) The results are recorded in the form of a table of the dependence of forces on displacements.

The general view of the samples during the test is shown in figures 3a-3c.

Processing of test results. Absolute values of displacements and forces must be converted to elongation and stress, respectively. To do this, the resulting number of strain values must be divided by the total height of the samples, and the number of force values must be divided by the cross-sectional area of the samples.

It is important to note that the initial data in the form of a table obtained directly as a result of the experiment for different samples are not consistent with each other in time. You must agree on their movements for all samples. To do this, the values corresponding to 10% and 20% deformations of the samples are combined. After that, a graph of the stress dependence on the relative deformations is plotted for each of the samples. Figure 4 shows an averaged graph of the stress dependence on relative deformations based on the results of a series of tests of various samples.

Based on the results of the obtained force-deformations graphs, the compression modulus is determined at 10% and 20% of the strain; the strain is measured from the point where the graph intersects the strain axis in the last cycle. Elastic strength properties are determined by measuring the dependence of forces on deformation obtained during the last compression cycle. The median and individual values for 10% and 20% compression strain are recorded for all samples.

However, the obtained dependencies, although they most accurately represent the behavior of the sample when working under load, are not applicable for use in software packages, since they contain a high number of values. In this regard, further processing is performed in order to reduce the dependencies to a simplified form. To do this, the elastic modulus is calculated at 10% and 20% of the strain.
Modulus of elasticity at 10% strain:

\[ E_{0.1} = \frac{F_{0.1}}{A \cdot e_{0.1}} = \frac{0.023}{73.2 \cdot 0.1} = 3.142 \text{MPa} \quad (7) \]

Modulus of elasticity at 20% strain:

\[ E_{0.2} = \frac{F_{0.2}}{A \cdot e_{0.2}} = \frac{0.045}{73.2 \cdot 0.2} = 3.07 \text{MPa} \quad (8) \]

According to the results of data processing, we get a simplified (polyline) schedule of rubber inserts, the section of this graph of the stress dependence on relative strain in the deformation section up to 20% is shown in figure 5.

![Figure 5. Simplified graph of stress dependence (MPa) on relative deformations (%) based on the results of a series of tests of samples.](image)

2.2 Numerical studies of the facade system node

**Geometry creation.** To study the initial stress-strain state of a fragment of compounds of structural framing elements with a translucent module post-and-crossbar facade system, it is necessary to perform numerical studies of finite element methods geometrically and physically non-linear problems of contact interaction of elements of the system subject to the obtained from the experiment elastic strength properties of rubber inserts.

![Figure 6. Geometric model of the facade system node in the design position with undeformed elements: 1 – translucent module (double-glazed window); 2 – external pressure profile; 3 – element imitating the screw of the pressure profile; 4 – external rubber insert; 5 – internal rubber insert; 6 – profile of the supporting frame of the system; 7 – "dowel".](image)
To solve these problems, we select the Ansys software package, which is a universal software system for finite element analysis (FEA). At the initial stage, the geometry of the studied node is constructed in the assembled design position, but with undeformed component elements, this model can be performed in any CAD-complex, including the Ansys itself (figure 6).

*Design model and material characteristics.* After creating the geometry of the node under study, a "library" of materials with the appropriate characteristics into the calculation complex is then entered. For all other elements of the studied node, except for the tested rubber inserts, our own Ansys "Engineering Data" material base with the appropriate characteristics is used. For rubber inserts, the material deformation diagram obtained in the course of experimental studies is used (figure 7).

![Figure 7. Simplified graph of stress dependence (Pa) on relative deformations (%) based on the results of a series of tests of samples.](image)

This diagram is transferred to the "Engineering Data" material database. Then the "Mooney-Rivlin" function is used to create an automatically approximated deformation graph of a non-linearly deformable body (figure 8).

![Figure 8. Approximated graph of stress dependence (PA) on relative deformations (%) of elastic elements of rubber inserts.](image)
After creating the materials library, the design scheme is then created in the "Static Structural" block. Each of the model elements is set to the appropriate materials, fixing conditions, friction coefficients between the contacting elements, and so on.

Next, a mesh of finite elements of the model is created, and the contact zones and zones of the most probable stresses are divided into a smaller mesh of finite elements (figure 9).

![Figure 9](image)

**Figure 9.** Calculation scheme of the node under study with a split finite element mesh.

Since the elements of the facade system node were set in an undeformed state, there are areas of their intersection in the design scheme, using the "Contact Tool" and the "Penetration" option, the areas and values of the penetration of the contact surfaces of the elements are determined, an example of one of the penetration contacts is shown in figure 10.

![Figure 10](image)

**Figure 10.** Certain values of penetration at the intersection of the contact surfaces of the external rubber insert and the translucent module (double-glazed window).
3 Results

After setting all the necessary conditions in the design model, a calculation is performed, which results in the initial stress-strain state of the elements of the facade system node in the design position without external loads.

According to the calculation results, the greatest deformations in the design position of the facade system node are observed in the elements of external and internal elastic inserts, the maximum deformations of external inserts reach 3.8553 mm. The deformed scheme of the node is shown in figure 11.

![Deformed scheme of the node](image)

**Figure 11.** Initial deformations of elements of the facade system node in the design position.

The values of initial stresses of external and internal rubber inserts in the design position are obtained, equal to 0.0035 MPa and 0.0025 MPa, respectively. The initial stresses that occur in the rubber inserts are shown in figure 12a-b.

![Initial stresses of rubber gaskets](image)

**Figure 12.** Initial stresses of the rubber gaskets of the facade system node in the design position: a) external; b) internal.
In the process of solving the contact problem, the values of the tension of the screw connecting the translucent module to the load-bearing frame through an external pressure profile with an insert and a "dowel" are additionally obtained. The obtained values equal to 19.418 N indicate the minimum screw tension force required to bring the elements of the facade system during assembly to the design position without taking into account the perception of external loads. The results of calculating the reaction of a plate simulating a pressure screw are shown in figure 13.

![Figure 13. Reaction of the plate simulating a pressure screw, necessary to bring the elements of the facade system node to the design position without taking into account the perception of external loads.](image)

4 Discussions

Thus, based on the results of the work performed, experimental methods have determined the elastic-strength properties of external and internal elastic inserts that are part of the attachment unit of translucent modules (double-glazed windows) to the supporting frame of the facade system. The data obtained in the form of an approximated function of stresses from relative deformations are entered in the database of materials of the computational software package. Based on the results of numerical studies, geometrically and physically nonlinear problems of contact interaction of system elements were solved, a picture of the stress-strain state of the node in the design position was obtained before loads and impacts were applied, the most dangerous zones were identified, and maximum deformations were observed in the external rubber inserts. Additionally, the values of the tension of the screw connecting the translucent module to the supporting frame through an external pressure profile with an insert and a "dowel" are obtained. The obtained values indicate the minimum screw tension force required to bring the elements of the facade system during assembly to the correct position without taking into account the perception of external loads.

Further research is aimed at studying the operation of the translucent modules themselves, depending on their size and cross-sections, both individually and as part of the frame of the facade system under the action of design loads.
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