The object of this study is the processes of heating and destruction of glazing in translucent elements of fencing structures. The paper provides data on the computer simulation of a glass panel behavior when it is heated on one side under the conditions of exposure to the standard fire temperature regime. With the help of computer simulation of a glass panel under conditions of thermal influence, the process of heat transfer was reproduced based on the non-stationary heat conduction equation. The stress-strain state of the glass panel was considered using the finite element method. The thermal effect was combined with the mechanical load due to the excess pressure that can occur in the room where the fire originates and develops. To study the propagation of cracks in glass, the strength criterion according to the Johnson-Holmquist model was applied. As a result of computer simulation based on a mathematical model, data were obtained on the dynamics of the formation and propagation of cracks in a glass panel under conditions of heating according to the standard fire temperature regime. It is shown that the glass panel is destroyed through the formation of a system of branched cracks, which is confirmed by empirical experience. The destruction of the glass panel was associated with the onset of the limit state of loss of integrity, and its fire resistance limit was registered based on this attribute.

In the work, a comparative analysis of the obtained data with the findings from experimental studies has been carried out. As a result of the comparative analysis, it is shown that the results are adequate since their relative error is on average no more than 8 %, and the F-criterion of adequacy at the significance level of 0.05 does not exceed the tabular value. Based on the results, the possibility of its application for a reliable analysis of the fire resistance of enclosing elements in building structures has been proven

Keywords: heat resistance of glass, enclosing building structures, glass panels, fire resistance limit, calculation method

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DETERMINING THE BEHAVIOR OF A GLASS PANEL UNDER HEATING CONDITIONS DURING A FIRE

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1. Introduction

The use of structural elements of building enclosures with translucent glass elements is quite widespread in architecture as it allows to give buildings a modern and attractive appearance. At the same time, the large area of facade glazing contributes to the penetration of maximum external light into the premises of buildings, and thanks to this, they look more spacious and comfortable. In particular, the use of facade glazing prevails in the construction of commercial objects (offices, shopping centers and malls); administrative buildings (stations, state service facilities), medical centers, educational institutions, etc. The advantages of structural exterior and interior solutions with glazing are a prerequisite for their further spread to other construction objects.

Until recently, the requirements for the normative construction base regarding the fire resistance of glass structures, including the glazing of window and door openings, were not put forward in the general analysis of fire safety of a certain construction object. The reason for this was that the glazing area in the buildings was comparatively small, and it was believed that the spread of fire through window openings was of little importance. The situation changed when there was a noticeable trend towards more and more frequent and wider use of glass structures as facade and interior architectural elements. As an example of such structures, we can mention internal and external glass window and fencing systems, facade systems, and even load-bearing structures. Under such conditions, the issue of the need to ensure fire safety of glass constructions becomes relevant. It is known that glass is destroyed when it is heated to high temperatures. If the glazing is an element of the external or internal enclosure, when it is destroyed and openings in the room are opened, the risk of fire spreading through them increases [1–6]. In view of these circumstances, the necessary means for evaluating the fire resistance of glazing enclosures, including a calculation-based approach, must be established and implemented to ensure fire safety. For this purpose, the calculation approach must be devised in a required manner, scientifically substantiated, and verified experimentally.

Thus, the study of the behavior of glazing in enclosing structures under the conditions of the thermal effect of fire is relevant.

2. Literature review and problem statement

In many countries, there is an extensive system of regulatory documents containing instructions on methods of calculating fire resistance for any type of building structures [1, 2]. These methods are based on the theoretical basis of building mechanics and resistance of materials. However, taking into account the trend that existed until recently, there is a need to design a system of recommendations for the application of a calculation approach to the evaluation of fire resistance of enclosing structures with glazing. There are no such recommendations in works [1, 2]. This is explained by the insufficient theoretical justification of calculation methods, taking into account the latest theoretical and practical results of scientific research.

Existing regulatory documents [2, 3] recommend using two main approaches, which are based on the use of simplified and refined methods. Simplified methods for calculating the fire resistance of building structures are based on the known experience of experimental research and the experience of calculation practice, represented in the form of generalized reference tables or nomograms. Also, simplified methods for evaluating the fire resistance of building structures can be based on engineering calculation methods with simple mathematical models and algorithms when formulating a set of simplifying assumptions and hypotheses of building mechanics. The use of such techniques is productive. However, in works [2, 3], the limits of fire resistance of structures determined by this approach are significantly overestimated, and this is a prerequisite for the appearance of unnecessarily high fire resistance reserves in building structures. The guidelines in the norms [4], which establish recommendations for the use of calculation methods when ensuring the design fire resistance of certain structural elements, define such methods as basic. This is justified by the fact that they have high productivity and cost-effectiveness for use by specialists of various training levels. The disadvantage of the approach described in [4, 5] is the time-consuming preparation of calculation models and computations. Therefore, the advantage in the alternative use of various simplified calculation methods for the computational assessment of the fire resistance of building structures is given to methods based on the use of reference tables [6].

Refined methods are based on a universal theoretical approach, the fundamental laws of physics and thermomechanics are used to substantiate mathematical models. This means that differential equations should be used to describe mechanical processes inside building structures when they are heated under fire conditions. In the hierarchical system of calculation methods for assessing the fire resistance of building structures, the specified methods are the most difficult to implement, but they are considered the most accurate. The basic principles of using refined methods for calculating the fire resistance of building structures are well described in works [5, 6]. As a drawback, one should note the need for highly qualified specialists who perform these calculations and the increased requirements for calculation equipment.

Glass is a fragile material and quickly breaks when heated to high temperatures without inelastic deformations. This makes it possible to use sufficiently simple mathematical models without significantly reducing the accuracy of the calculation [1, 7]. Such models can describe in detail all processes of deformation and destruction of glass for effective modeling of the behavior of glazing in enclosing building structures when they are heated under fire conditions. The disadvantage is the lack of a developed criterion base and the obtained published results with appropriate verification. Analysis of works [8, 9] revealed that the approach based on the assumption of independence of thermal and mechanical processes inside the glass is used to estimate the fire resistance of the enclosing elements of building structures with glazing. If we assume that this hypothesis is valid, then it is possible to divide the task of analyzing the fire resistance of glazing into two separate main tasks – a heat engineering problem and a task of researching the stress-strain state when glazing is heated.

When applying the above approach, while solving the thermal engineering problem, at the first stage of the calculation, temperature distributions in the thickness of the structure should be obtained at different moments of the time of the thermal effect of the fire. The obtained data on temperature indicators after solving the thermal engineering problem allow us to establish the onset of the limit state of loss of heat-insulating capacity for glazing.

At the second stage, the strength problem is analyzed, which is performed in order to evaluate the conditions for the appearance of the limit state of loss of fire resistance in terms of bearing capacity or integrity. With this statement of the problem of strength for glazing when it is heated, the effects of the formation and propagation of cracks and subsequent defragmentation of the glass, temperature deformations of the glass, noticeable degradation of its mechanical characteristics should be taken into account. Considering the presence of many factors that must be taken into account when making calculations using the described approach, the problem of the strength of glass when it is heated is difficult. The disadvantage is that the form of the differential equations, which are written for the implementation of the calculation, does not allow obtaining their analytical solutions [9, 10]. This is the reason that only approximate numerical methods of their integration are used to perform calculations using these differential equations. The finite difference method or the finite element method is widely used in works [11, 12] to estimate the fire resistance of glazing based on the loss of integrity, but these calculations do not have a proven practical implementation.

Therefore, the application of refined calculation methods is effective when conducting a calculation assessment of the fire resistance of structures in relation to the onset of the limit state based on the signs of loss of heat-insulating ability and loss of integrity. Therefore, it is logical to assume that they can also be used as a tool for calculating the fire resistance of enclosing structures with glazing, if hierarchically simpler methods do not make it possible to obtain the expected results.

An important point at the moment is that the existing regulatory framework in developed countries [8] does not provide recommendations for the calculated evaluation of the fire resistance of glazing according to the limit states of heat-insulating ability and integrity.

The problem of calculating the fire resistance of glazing based on the limit state of loss of integrity was considered in [9, 10]. However, the reported results do not make it possible to draw up a hierarchical structure of recommended methods for evaluating the fire resistance of glazing, which can be included in the system of regulatory documents and guidelines.

Therefore, our review of the literature showed that the properties of glass panels regarding their strength under the conditions of the thermal effect of fire have not been fully investigated. Calculation methods of research do not have consistently formed stages of fire resistance assessment of these structures and do not have a proven practical implementation. Also, the existing base of regulatory documents does not fully reflect indicators and permissible parameters of thermal impact on enclosing structures with glazing. All this gives reason to assert that it is expedient to conduct a study aimed at the substantiation and improvement of calculation methods for evaluating the fire resistance of glazing in enclosing structures.

3. The aim and objectives of the study

The purpose of our research is to establish the regularities of thermomechanical processes and the processes of glass destruction in translucent elements of enclosing structures under the conditions of thermal influence of the standard fire temperature regime. This will make it possible to evaluate the behavior of the glass panel under conditions of heating during a fire by means of computer simulation using the finite element method. The results could be used and implemented in the relevant normative documents, which would recommend this system of computational evaluation methods for the design of fire-resistant enclosing structures with translucent elements.

To achieve the goal, the following tasks were set:

– to carry out computer simulation of heating and destruction of glazing in transparent elements of fencing structures under the conditions of thermal influence of a standard temperature regime by means of mathematical modeling using the finite element method;

– to investigate the adequacy of the results.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our research is the processes of heating and destruction of glazing in transparent elements of enclosing structures under the conditions of thermal influence of a standard temperature regime. By studying these processes on the basis of mathematical modeling using the finite element method, the patterns of changes in the characteristics of these processes of the stress-strain state of glazing are investigated. The obtained regularities are used to improve the calculation method for evaluating the fire resistance of glazing in enclosing structures by substantiating mathematical models of deformation and destruction of glass under the conditions of thermal exposure during a fire based on the application of general laws of mechanics and heat transfer.

A set of hypotheses and assumptions was put forward to substantiate the mathematical models describing the behavior of glazing under the conditions of thermal influence of the standard fire temperature regime. The main assumption for substantiating mathematical models of glazing behavior under fire conditions is the independence of heat conduction processes in glass on indicators of its stress-strain state and could be considered separately from each other. The criteria for the destruction of glazing in translucent elements of enclosing structures under fire conditions are the fragmentation of finite elements, the avalanche-like build-up of current movements and velocities of the structural system of these elements. The current values of temperatures are determined through the non-stationary differential equation of thermal conductivity, taking into account the absorption of thermal radiation by introducing effective thermal characteristics. The stress-strain state in glazing panels is calculated using the explicit method of integration of the general differential equations of dynamics and the finite element method. The adequacy of the data obtained by mathematical modeling is investigated using statistical criteria calculated using the normal distribution of random variables.

4. 2. Research methodology

The task of calculating the fire resistance of glazing in translucent elements of enclosing structures, as for any structure, is divided into two separate subtasks – thermal engineering and durable sleep [10, 11]. According to the results reported in [10, 11], the heat engineering problem could be solved using a non-stationary differential equation of thermal conductivity written in the form:

$$C_p(t)\rho\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left(\lambda(t)\frac{\partial\theta}{\partial x}\right), \quad (1)$$

$\lambda(t)$ – temperature-dependent thermal conductivity coefficient of glass, W/(m·°C); $C_p(t)$ is the specific heat capacity of glass, which depends on temperature, J/(kg °C); ρ – glass density, kg/m^3; θ is the temperature of the glass at the point, °C; t is the current time, s.

For the numerical solution to equation (1), a boundary value problem must be stated, which could be represented geometrically in the form of an infinite plate of a certain thickness. Under such conditions, a fairly common approach could be used, which is based on establishing boundary conditions of the IIIrd kind at the edges of the calculation area [10].

Fig. 1 shows the calculation scheme of the calculation area for one layer of glazing.

According to the calculation scheme (Fig. 1), boundary conditions are set, which are written using the expressions:

$$-\lambda(\theta)\frac{\partial\theta}{\partial x}\bigg|_{x=0}=\alpha\left(\theta_P-\theta_W\right), \quad (2)$$

$$-\lambda(\theta)\frac{\partial\theta}{\partial x}\bigg|_{x=L}=\alpha_0\left(\theta_n-\theta_0\right), \quad (3)$$

$\alpha(t)$ – heat transfer coefficient for the glass surface and air from the side of the heated surface, W/(m^2°C); α_0=9 W/(m^2 °C) – heat transfer coefficient between the glass surface and the air from the side of the unheated surface, W/(m^2°C); θ_P – air temperature in the room with fire, °C; θ_W is the temperature of the glass surface of the heated glass panel in °C; θ_n is the temperature of the glass surface of the glass panel, which is not heated °C; θ_0=20 °C is the initial temperature.

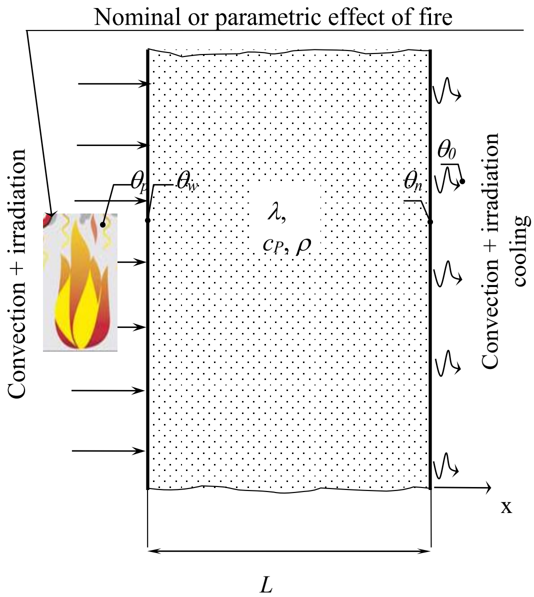


Fig. 1. The calculation scheme for the thermal engineering calculation of one layer of glazing of the enclosing structure

The temperature in the room where the fire occurs is calculated according to the standard temperature curve, which is calculated according to the formula given in works [1, 2]:

$$\theta_p(t) = 345 \cdot \lg(8t+1) + \theta_0. \quad (4)$$

The coefficient of heat exchange of the surface of the glass panel has two components that separately establish convective and radiant heat exchange. So, the heat transfer coefficient of the surface of the heated glass panel is determined as the sum:

$$\alpha = \alpha_k + \alpha_r. \quad (5)$$

The components of heat transfer coefficients, taking into account radiant heat exchange, are determined from the expressions:

$$\alpha_r = \varepsilon \cdot \sigma \left(\frac{(\theta_p + 273)^4}{\theta_P - \theta_W} - \frac{(\theta_W + 273)^4}{\theta_P - \theta_W} \right), \quad (6)$$

where ε=0.8 is the degree of blackness of the glass surface; σ=5.67·10^{-8} W/(m^2 °C^4) is the Stefan-Boltzmann constant.

The basic differential equations that are used for mathematical modeling of the stress-strain state of a solid as a dynamic system take the form of expressions that reproduce the fundamental conservative laws of dynamics, as shown in works [13, 14]. The principle of virtual displacements δ_{xi} for mathematical modeling of the movement of rigid deformed bodies with stresses arising in them under the action of external and internal forces allows us to write down an equation that reproduces the law of conservation of energy:

$$\int_\Omega \left[\rho \ddot{x}_i + \sigma_{ij,j} - \rho f_i \right] \delta x_i d\Omega + \int_{\Gamma_f} \left[\sigma_{ij} n_j - t_i \right] \delta x_i d\Gamma + \int_{\Gamma_c} \left(\mathrm{s}_{ij}^{+} - \sigma_{ij}^{-} \right) n_j \delta x_i d\Gamma = 0, \quad (7)$$

where $\sigma_{ij,j}$ is the Cauchy tensor, which is used to calculate the stresses at a certain point of the deformed solid body (Pa); ρ is the material density of the deformed solid body at its given point, (kg/m^3); $\rho \cdot f_i$ – external forces acting at given points of the deformed solid body under consideration (N·kg/m^3); $\ddot{x}_i$ – acceleration of a given point of a rigid deformed body at a given moment of time (m/s^2).

Under the condition that the total amount of possible work should be equal to zero, performing the appropriate transformations of equation (7), it could be written in the form:

$$\sum_{e=1}^{en} \begin{bmatrix} \int_{\Omega_e} \rho \mathbf{N}^{\mathrm{T}} \mathbf{N} \mathbf{a}_e d\Omega + \int_{\Omega_e} \mathbf{B}^{\mathrm{T}} \sigma d\Omega - \\ - \int_{\Omega_e} \rho \mathbf{N}^{\mathrm{T}} \mathbf{b} d\Omega - \int_{\Gamma_e} \mathbf{N}^{\mathrm{T}} \mathbf{t} d\Gamma \end{bmatrix} = 0, \quad (8)$$

where N is the matrix of interpolation of values in finite elements using parametric functions of the form; σ is the stress vector; B – stiffness matrix; a_e – acceleration vector of nodes of finite elements; b – load vector; t is a vector of traction forces.

To carry out calculations of the structural system, which is a glass panel under the conditions of thermal influence of the standard fire temperature regime, planar elements of the Belychka-Tsai shell type are used as finite elements [14]. This type of planar finite elements is based on the mathematical description of the current state by the sum of the rotational and translational movements of nodes under deformation conditions.

The rate of deformation of finite elements is calculated using the Cauchy stress tensor. This makes it possible to prevent an increase in the volume of calculations during the disclosure of the physical nonlinearity of the deformation equations.

The Johnson-Holmquist damage model [14] is used to model the defragmentation of glass under the conditions. It is assumed that the equivalent stress under these conditions is calculated from the expression:

$$\sigma^* = a(p^* + t^*)^n (1 + c \ln \dot{\varepsilon}^*) - -D\left[a(p^* + t^*)^n (1 + c \ln \dot{\varepsilon}^*) - b(p^*)^m (1 + c \ln \dot{\varepsilon}^*) \right], \quad (9)$$

$$p^* = \sigma_t / p_h, \; t^* = \sigma_p / p_h,$$

$$D = \sum \Delta\varepsilon^p / \varepsilon_f^p, \; \varepsilon_f^p = d_1 (p^* + t^*)^{d_2}, \quad (10)$$

where a is the strength parameter of the intact material, (Pa); c is a parameter depending on the rate of deformation of the material; $\dot{\varepsilon}^*$ – normalized rate of deformation, (s^{-1}); n, m, d_1, d_2 – dimensionless empirical parameters of the model; σ_t and σ_p are tensile and compressive strength limits, respectively, (Pa); $\Delta\varepsilon^p$ – increment of plastic deformation; p_h is the coefficient of reduction during destruction.

4. 3. Methodology for determining the strength properties of a glass panel under the conditions of thermal exposure of the standard fire temperature regime

To study the behavior of a glass panel under the conditions of thermal exposure of the standard fire temperature regime, a single-layer glass panel is considered, the structural scheme of which is shown in Fig. 2.

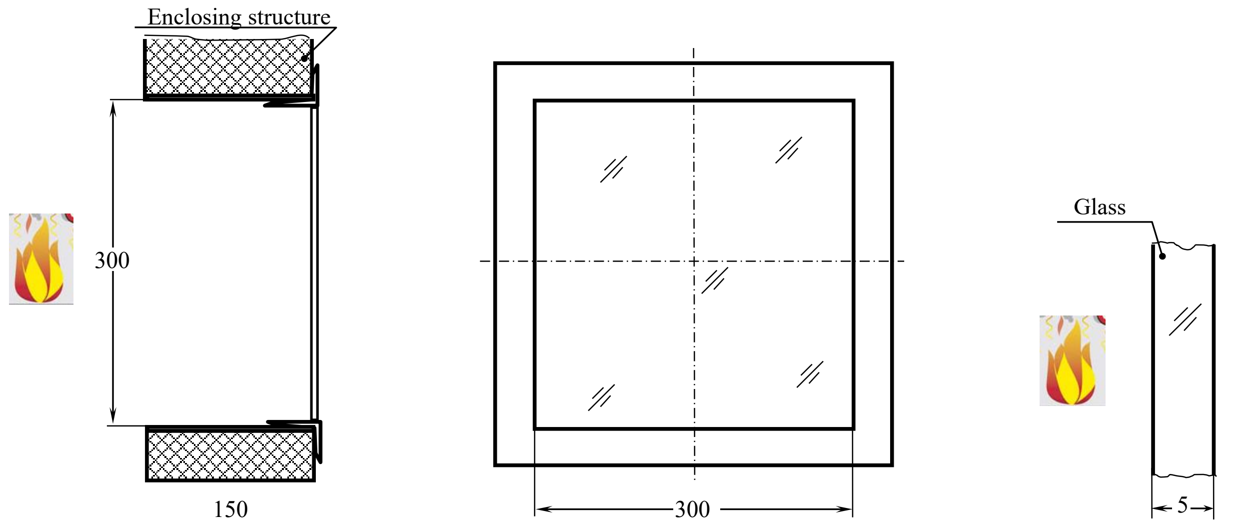


Fig. 2. Structural scheme of the glass panel

To solve the thermal engineering problem of the thermal calculation of the glazing panel under the conditions of thermal influence of the standard fire temperature regime, it is enough to consider the heat exchange in its cross-section, as shown in the calculation scheme displayed in Fig. 1. The equation of heat conduction in quasi-linear notation, taking into account convection and radiation heat exchange at the boundaries of the calculation area with the fire environment under boundary conditions (BCs) of type III, is written in the one-dimensional statement (1) to (3). The temperature regime in the environment of a room with a fire is described by a standard fire temperature curve. Modeling of the behavior of the glass panel takes place during the sequential solution of the heat engineering problem and the strength problem. The results of solving the thermal engineering problem are used to solve the strength problem when using the calculated nodal temperatures as a load.

Mathematical models were used for the calculation, the parameters of which are given in Table 1.

A hexahedral finite element of the Lagrangian type was used to solve the heat engineering problem using the finite element method [15].

The finite-element scheme of the glazing panel in accordance with Fig. 1, 2, as well as the scheme of application of boundary conditions (BCs) when stating the boundary value problem is shown in Fig. 3.

Table 1

Basic methods for numerical investigation of glazing in translucent elements of enclosing structures

Component of a mathematical model	Calculation methods used
Thermal engineering problem	
Thermal conductivity	Differential unsteady heat conduction equation, approximated by the finite element method [5, 14]
Boundary conditions	Boundary conditions of the IIIrd kind, taking into account convection and radiant heat exchange [5, 14]
Physical nonlinearity	Newton-Raphson method [14]
Structural problem	
Stressed and deformed state	Finite element method in nonlinear implementation [5, 14]
Criterion of destruction	Johnson-Holmqvist model [13]
Physical and geometric nonlinearity	Explicit method of integration of dynamics equations [13, 14]

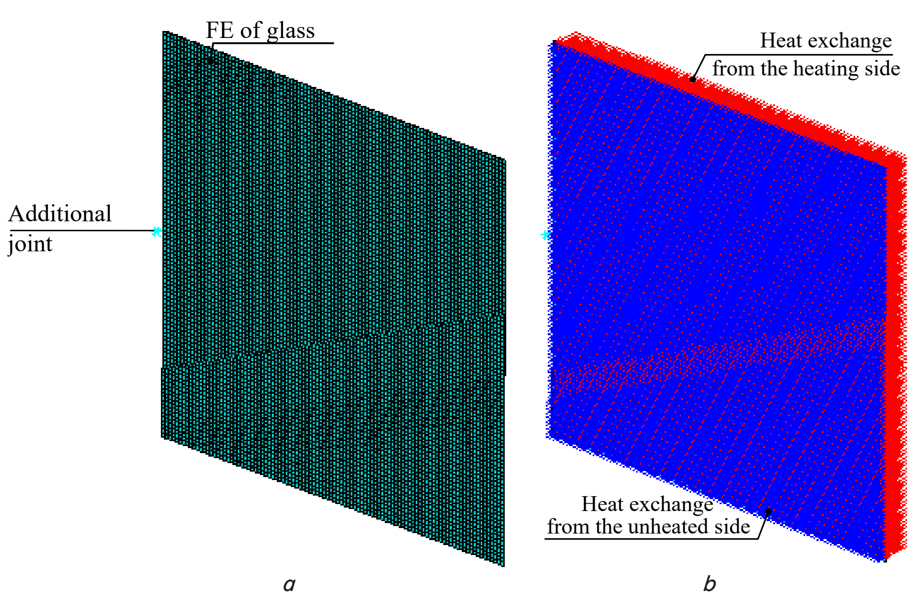
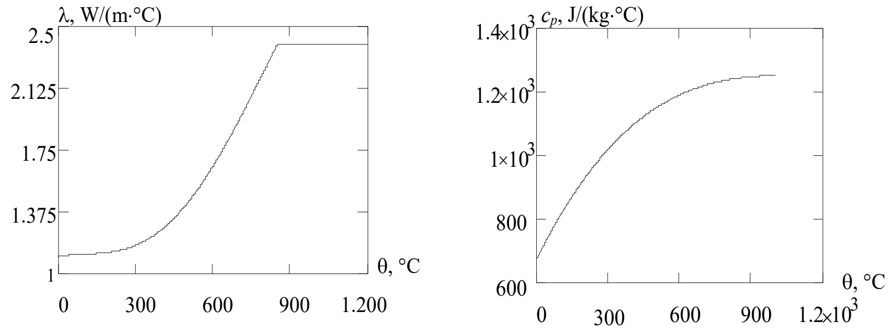


Fig. 3. Finite-element diagram of a single-layer glazing panel: *a* – for solving the thermal engineering problem of thermal calculation; *b* – scheme of application of boundary conditions

After the calculations, the temperature data in the inner layers of the glazing panel were obtained. These data are used as initial data for mathematical modeling of the behavior of the investigated glazing panel under the thermal influence of the standard fire temperature regime.

For mathematical modeling, a system of general differential equations of dynamics and stress-strain state is used, which is solved numerically applying the explicit method in combination with the finite element method.

Using the assumptions stated above, the finite-element scheme of the glazing panel and the scheme of application of boundary conditions were developed, shown in Fig. 4. It could be seen that this scheme is built on the basis of planar finite elements of the Belychko-Tsai shell type. When establishing the boundary conditions, a simplified hypothesis was adopted that the edges of the glass panel are fixed by introducing hinged and movable beams in each node along the edges of the glass panel.



a *b*

Fig. 5. Thermophysical characteristics of silicate glass: *a* — thermal conductivity coefficient; *b* — specific heat capacity [13]

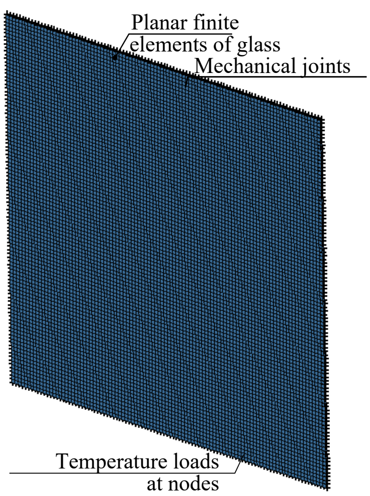


Fig. 4. Finite-element diagram of a single-layer glazing panel for solving a structural problem and a diagram of applying boundary conditions

As a load, the temperatures at the nodal points are applied, and it is assumed that the temperature is distributed evenly over the surface of the panel on both sides. Planar finite elements of the Belychko-Tsai shell type are considered to have a finite thickness. This allows two sets of temperature data from both panel surfaces to be specified at each node.

With the generalized theoretical approach to solving the thermal engineering problem, when the internal heating of the glass due to thermal radiation is taken into account by determining the thermophysical characteristics of the glass, the thermophysical characteristics [13] shown in Fig. 5 should be used.

When determining the numerical values of the thermal characteristics, one could use the numerical regression formulas given in Table 2 [13].

When stating the problem of the strength of a glass panel under the conditions of thermal exposure of the standard fire temperature regime, the temperature dependence of mechanical and thermomechanical properties on temperature should be taken into account [14]. These dependences are shown in Fig. 6 and given in Table 3.

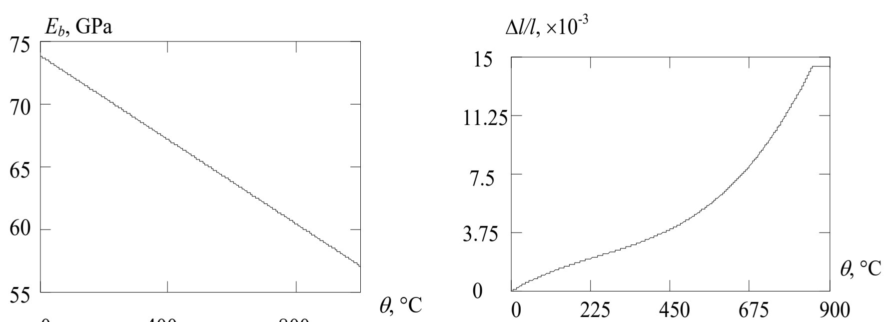
To implement the specified methods, it is necessary to take into account the brittle fracture of glass, applying the appropriate theory of strength, which is implemented according to the Johnson-Holquist model [13].

Recommended values of mechanical characteristics are given in Table 4 [13].

Table 2

Temperature dependence of thermophysical characteristics of structural building glass

Thermal conductivity coefficient, λ(θ), W/(m °C)	Specific volumetric heat capacity, c_p(θ), J/(m³ °C)
at 20 °C ≤ θ ≤ 850 °C $1.116-5.603\cdot10^{-2}\cdot(\theta/100)+$ $+2.438\cdot10^{-2}\cdot(\theta/100)^2$	$682.18+1.298\theta-7.371\cdot10^{-4}\theta^2$



a *b*

Fig. 6. Thermomechanical characteristics of silicate glass: *a* — modulus of elasticity; *b* — temperature deformation [14]

Table 3

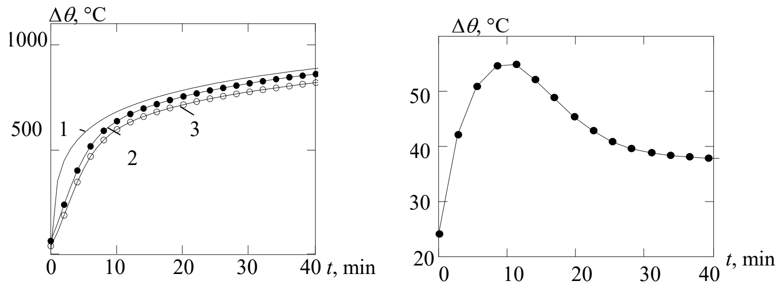
Temperature dependence of thermomechanical characteristics of structural building glass [14]

Modulus of elasticity, GPa	Temperature deformation
$73.864–0.017·10^{-2}θ$	$-2.996·10^{-3}+5.597·10^{-6}θ–$ $–7.155·10^{-9}θ^2$

Table 4

Generalized mechanical characteristics of structural building glass

Glass strength, f_b, MPa	Poisson's ratio, m	Heat resistance, $Δθ_b$, °C
40	0.23	48.219



a *b*

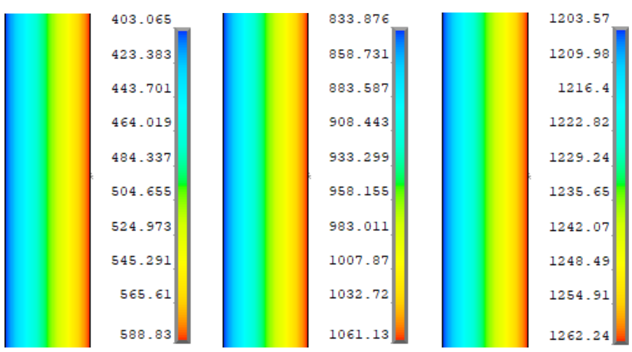
Fig. 8. Plots of the heating temperature:
a – plot of the temperature difference of the heated and unheated surfaces of the glass panel; 1 – standard fire temperature regime; 2 – temperature of the unheated surface; 3 – temperature of the heating surface;
b – plots of heating of different points

It is possible to use generalized characteristics that determine the lowest strength and the highest stiffness.

5. Results of investigating the properties of the behavior of a glass panel under conditions of heating during a fire

5. 1. Results of simulating the heating and destruction of a glass panel under fire conditions

After the calculations, the temperature data in the inner layers of the glass panel were obtained. Fig. 7 shows temperature distributions across the cross-section of the glass panel at different times.



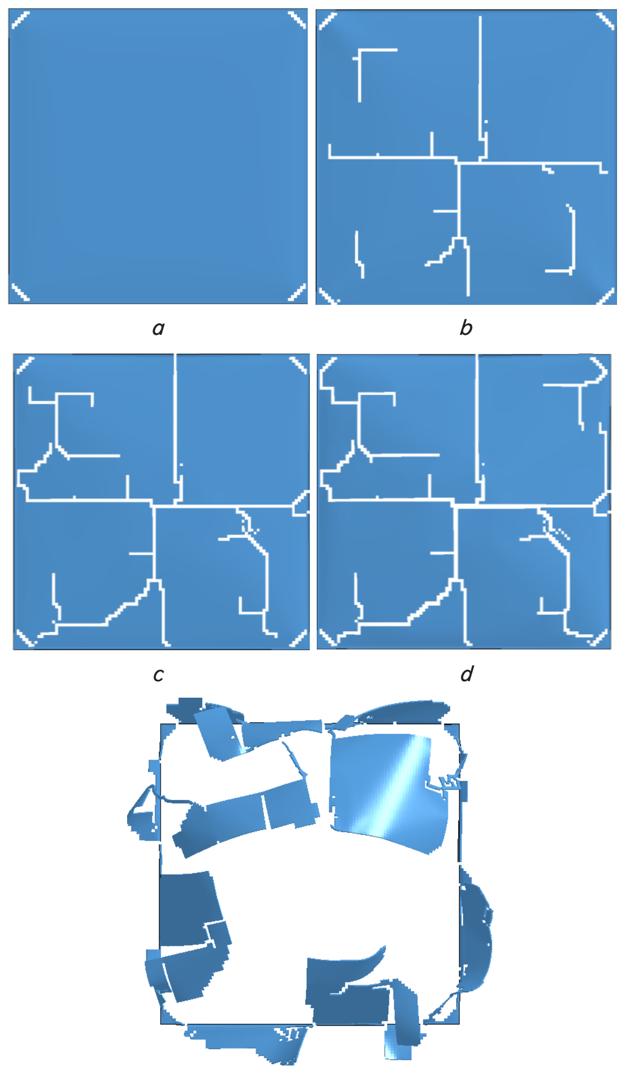
a *b* *c*

Fig. 7. Temperature distributions across the cross-section of the glass panel at different times of exposure to the standard fire temperature regime (°C):
a – 5 min; *b* – 10 min; *c* – 20 min

Fig. 8 shows plots of the heating temperature of a glass panel at different points under the thermal influence of the standard fire temperature regime and the plot of dependence of the temperature difference of heated and unheated surfaces depending on time.

The temperature data shown in Fig. 8 could be used for calculation when solving the strength problem.

The results of solving the thermal engineering problem were applied to solve the strength problem. According to the initial data and calculation schemes described above, the calculations were performed shown in Fig. 9 in the form of images of a glass panel. They show the dynamics of the formation of cracks during the heating of glass under the influence of the standard fire temperature regime.



a *b* *c* *d* *e*

Fig. 9. Images of the formation of cracks at different moments of exposure to the standard fire temperature regime: *a* – 4.51 min; *b* – 4.64 min; *c* – 4.71 min; *d* – 4.92 min; *e* – 5.11 min

Thus, the evaluation of the fire resistance of these elements based on the results of computer simulation allows us to reproduce the temperature distribution along the cross-section of the glass panel at different times of the test. And the dynamics of the formation of cracks allow us to assume that the complete destruction of the glass panel occurs in approximately 5 minutes of exposure to the standard fire temperature regime.

5. 2. Investigating the adequacy of results related to identifying the strength properties of a glass panel under fire conditions

According to our results, the fire resistance of glazing in the translucent elements of the enclosing structures was evaluated under the conditions of heating under the influence of the standard fire temperature regime. Evaluation of the fire resistance of glazing is carried out using a simplified method based on the analysis of the ultimate thermal resistance of glazing, which occurs when checking the condition [13]:

$$\theta_w - \theta_c \leq \Delta\theta_b = \frac{f_b\left(1-\mu\right)}{\beta E_b}, \tag{11}$$

f_b – glass strength, Pa; E_b – modulus of elasticity of glass, Pa; μ – Poisson's ratio of glass; β is the coefficient of thermal expansion of glass, °C^{-1}.

Fig. 10 shows a plot of the change in temperature difference, on which the point of onset of the glass panel's destruction is marked when it is heated under the influence of the standard fire temperature regime.

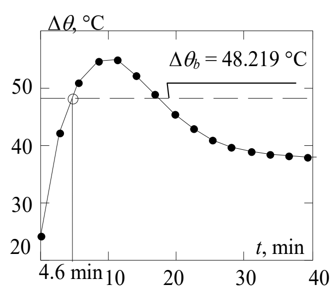


Fig. 10. Plot of temperature difference between heated and unheated surfaces of a glass panel with the limit value of heat resistance

When comparing data on the fire resistance limit of glazing by refined and simplified methods, a difference in indicators was obtained, which does not exceed 8 %. This confirms that the results obtained by the refined calculation method of fire resistance assessment are adequate.

In order to determine the adequacy of the results of mathematical modeling when using a refined calculation method, a comparative analysis was conducted. Table 5 gives data from the comparative analysis.

Analysis of the statistical data given in Table 5 confirms the adequacy of our results based on investigating fire resistance of glazing in translucent elements of enclosing structures.

6. Discussion of results based on evaluating the fire resistance of a glass panel under fire conditions

Based on the results of our studies, the behavior of glazing under the conditions of the thermal effect of a fire has been shown when considering a single-layer glass panel, the structural scheme of which is given in Fig. 2. To calculate the temperature field in a glass panel under the conditions of the thermal effect of a fire, a solution to the thermal engineering problem was proposed, which was based on the use of the non-stationary differential equation of thermal conductivity (1).

For the numerical calculation, mathematical models were used in accordance with the methods of numerical research, which are given in Table 1. After conducting calculations based on the finite element method using planar elements of the Belychko-Tsai shell type, temperature distributions along the cross-section of the glass panel at different time points were obtained. Based on the results of the temperature distribution, plots of the dependence of temperature difference of the heated and unheated surfaces as a function of time were constructed, which are shown in Fig. 8. The obtained temperature distributions were used as initial data for solving the strength problem. The results of investigating the strength properties of glazing shown in Fig. 9 demonstrated that the destruction of the glass panel occurs due to the formation of a system of branched cracks. The time of onset of the limit state of loss of fire resistance in terms of integrity is 5 min 11 s.

Based on our results, a comparative analysis of the results of mathematical modeling was carried out using a refined calculation method for evaluating the fire resistance of a glass panel under fire conditions. Using the value of the temperature difference between the heated and unheated surfaces of the glass panel with the limit value of heat resistance (Table 4), the time of destruction of the glass panel was obtained, which is shown in the form of a plot in Fig. 10. The results of investigating the limit of fire resistance of glazing according to the refined and simplified methods differ by 8 %.

As shown by the comparative analysis given in Table 5, the data obtained using a refined calculation method for evaluating the fire resistance of glazing in translucent elements of enclosing structures are adequate. In particular, the relative error of the temperature indicators does not exceed 13.8 %, the root mean square deviation of the temperature does not exceed 15.3 °C, and the F-criterion of adequacy at the significance level of 0.05 does not exceed the table value. This makes it possible to apply the obtained results of computer simulation as a component of a hierarchical system of methods for calculating these elements. In contrast to work [6], in which the study of thermal effects was carried out using simulation of fire load with software packages, the results of our study were verified using a simplified method based on the analysis of the ultimate thermal resistance of glazing. The limitation of this study is the thickness of the glazing since the mathematical modeling of the thermal effect of the fire was carried out only for glass with a thickness of 5 mm.

Table 5

Statistical parameters obtained while investigating the adequacy of results from calculating the temperature of the unheated surface in the studied samples

The number of degrees of freedom of the numerator, ν_1	The number of degrees of freedom of the denominator, ν_2	Number of computational experiments, d	The number of measurements in the computational experiment, n	Reproducibility variance	Adequacy variance	Estimated value of the F-criterion	Tabular value of the F-criterion	Average relative deviation, %	RMS deviation, °C
2	124	2	62	0.63	0.598	0.949	1.01	13.8	15.3

The results regarding the evaluation of the behavior of the glass panel under conditions of heating during a fire could be used and implemented in the relevant regulatory documents, which would recommend this system of calculation evaluation methods for the design of fire-resistant enclosing structures with translucent elements.

The next step, which will make it possible to expand scientific knowledge about the behavior of translucent elements under fire conditions, is to conduct similar studies for panels with other structural data and types of glass, to determine the real patterns of reduction of the strength properties of glass in enclosing structures.

7. Conclusions

1. Computer simulation has been carried out to simulate the behavior of the glass panel of building enclosing structures with translucent elements based on the application of the explicit method of integration of differential equations of mechanics and the method of finite elements. Based on the calculations, the temperature indicators at the control points of the cross-section and the picture of the distribution of defects in the glass panel were obtained. The obtained indicators are necessary for the implementation of the method for calculating the fire resistance of elements of building enclosing structures with translucent elements. It is shown that the fire resistance is lost if the glass panel is destroyed for 5 minutes under the influence of the standard fire temperature regime. This result is explained by the nature of deformation of glass during heating and its fragile destruction. The results of our research allow the use of the proposed mathematical models in the development of relevant regulatory documents.

2. The adequacy of results from the calculated evaluation of fire resistance of the glass panel was analyzed. As a result of the analysis, it is shown that the obtained results are adequate since the relative error is 13.8 %, and the Fisher criterion does not exceed the tabular value. This result is explained by the high requirements for the composition and properties of glass, which determines the reproducibility of the experimental data and the good adequacy of the calculation data.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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