Estimation of Fire Resistance of a Building Structure by the Criterion of Heat-Insulating Ability

N A Ilyin, D A Panfilov, E M Komov

1 Samara State Technical University, 194 Molodogvardeyska, Samara, 443001, Russia

E-mail: panda-w800i@yandex.ru

Abstract. Estimation of fire resistance of the building envelope (internal walls, slabs) is carried out without destruction, according to a set of single indicators of the quality of the building element. To do this, determine the geometric dimensions of the enclosing structure (slabs, walls), the scheme for heating the design section under fire conditions, the thermal diffusion coefficient of the structural building material, reveal the initial temperature of the body of the enclosing structure, the maximum permissible temperature and the critical heating temperature of the unheated surface of the structure, and, using the analytical equation (1), find the limit of fire resistance of the enclosing structure on the basis of loss of heat-insulating ability. The application of the proposed technical solution of the problem makes it possible to estimate the actual fire resistance of the enclosing structure without full-scale fire impact, improves the reliability of statistical quality control and non-destructive testing, reduces the required amount of computer memory for calculating fire resistance, and reduces economic costs.

1. Introduction

This new technical solution of the thermo-technical problem belongs to the area of fire safety of buildings and structures. In particular, it can be used for classification of building envelope (floor slab panels, interior walls) of buildings by their indicators of resistance to high temperatures in the conditions of fire. This justifies the use of existing constructions with real fire resistance limit in buildings of different functional classes by flammability classification.

The essence of the technical problem solution is to establish the fire safety indicators of building envelopes from any flame-resistant material, in the part of the guaranteed duration of resistance of the building envelope in the conditions of fire. This solution also determines reliable actual limit of building envelopes fire resistance; helps to increase efficiency and reduce economic expenses while assessing building envelopes fire resistance by the criterion of its heat-insulating ability.

2. Materials and methods

The technological result while using the proposed solution is achieved by the fact that the defects of the building envelope surface are determined, and the actual limit of the building envelope fire resistance is defined on the basis of loss of its heat-insulating abilities ($F_{ar} - min$). It is done by using the equation (1):

$$F_{ar} = \left( \frac{t_{cr}}{70} \right)^{1.85} \cdot \left( \frac{h_{min}}{D_{ar}} \right)^2$$

(1)
where $t_{cr}$ is the critical temperature of heating of the building envelope unheated surface, $^0C$; $h_{min}$ is the minimum thickness of the building envelope, mm; $D_{bm}$ is the indicator of the material diffusion, mm$^2$/min.

The critical heating temperature of the building envelope unheated surface ($t_{cr}, ^0C$) is calculated on the condition (2):

$$t_{cr} = t_{u,in} + t_e$$

(2)

where $t_{u,in}$ is the maximum permissible temperature of the building envelope unheated surface before the test, $^0C$; $t_e$ is the initial temperature of the building envelope body, $^0C$.

The value of the building envelope material diffusion ($D_{bm}, mm^2/min$) at the average temperature of 450$^0C$ is determined by the equation (3):

$$D_{bm} = \frac{60 \cdot 10^3 \cdot (\lambda_0 \pm 0.45 \cdot b)}{\rho_c \cdot (C_0 + 0.45 \cdot d + \omega / 20)}$$

(3)

where $\lambda_0$ and $b$ are empirical numbers for calculation of thermal conductivity coefficient of the heated material, (Vt/(m·$^0C$)); $C_0$ and $d$ are empirical numbers for calculation of specific heat capacity of the heated material, kJ/(kg·$^0C$); $\rho_c$ is the density of dry material, kg/m$^3$; $\omega$ is material moisture, mass, %. 

Figure 1. Here is the scheme to determine the critical temperature on the unheated surface of the concrete slab with thickness $h = 60$ mm made of heavy concrete on crushed limestone ($\rho_c = 2250 \, \text{kg/m}^3$; $\omega = 2\%$; $D_{bm} = 19.5 \, \text{mm}^2/\text{min}$), used to evaluate the building envelope fire resistance by the criterion of its heat-insulating ability ($J$): $t_{cr}$ – critical heating temperature of the unheated surface of the building envelope, $^0C$; $t_e$ – the initial temperature of the slab body, $^0C$; 1 – a reinforced concrete slab sample; 2 – temperature distribution curve on the section of the slab; 3 – graph of temperature rise on the unheated surface, $t_{in}, ^0C$; 4 – temperature on the heated surface of the plate, $t_{ext}, ^0C$; 5 – standard fire environment temperature ($v_{cm}, ^0C$) in time ($\tau_{cm}, \text{min}$): $v_{cm} = 345 \cdot \lg(8 \cdot \tau_{cm} + 1)$. 

\[ v_{cm} = 345 \cdot \lg(8 \cdot \tau_{cm} + 1) \]
To assess fire resistance, let us use a fragment of the building envelope surface with dimensions of $1000 \times 1000 \times h$. Here $h$ is the thickness of the building envelope, mm.

The minimum thickness ($h_{\text{min}}, \text{mm}$) of the building envelope is calculated (under $\delta_g \geq \delta_z$) on the condition (4):

$$h_{\text{min}} = h - \delta_g,$$

with $\delta_z > \delta_g$, in the condition (5):

$$h_{\text{min}} = h - \delta_z,$$

where $h$ is the design thickness of the building envelope, mm; $\delta_g$ is a permissible deviation from the design size (± 5 mm); $\delta_z$ a deviation from the building envelope surface nonlinearity, mm.

All protective structures selected for the assessment of fire resistance are subjected to a technical inspection, which consists in checking the sizes of structures and their sections. After that, a thorough inspection of the surface of the structure to detect cracks, shells, concrete splits and of the surface nonlinearity is conducted.

The degree of the building envelope surface nonlinearity (undulation) is determined by the measurement of the greatest gap ($\delta_z, \text{mm}$) between the edge of the metal control rod with length of 1 ÷ 1.5 m and the surface of the inspected building envelope (see Fig. 3, a), or by the measurement of distances $\delta_1$ and $\delta_2$ from the ends of the control rod, located on the top of the bulge, to the inspected surface of the building envelope. It is equal to Figure 3, b. The dimensions of the building envelope are checked with accuracy up to 1 mm; the width of cracks – with accuracy up to 0.05 mm.

3. Results

Example. The following characteristics of a reinforced concrete ribbed slab beam are given: dimensions in terms of $1.4 \times 6.0 \text{ m}$; thickness $h = 60 \text{ mm}$; heavy concrete $D_{bt} = 19.5 \text{ mm}^2/\text{min}$; initial temperature of the slab body: $t_e = 20^\circ \text{C}$; maximum-permissible (normative) degree of heating of the unheated surface $C_{t_{in,u}} = 140^\circ \text{C}$ [4]. It is requityed to determine the fire resistance limit of the slab.

Solution: 1) The critical heating temperature of the unheated surface is determined by the condition (2):

$$t_{cr} = t_{u,in} + t_e = 140 + 20 = 160^\circ \text{C}$$

2) The limit of fire resistance of reinforced concrete ribbed slab on loss of its heat-insulating ability ($J$) is calculated by the equation (1):

$$F_{U(J)} = \left( \frac{t_{cr}}{70} \right)^{1.85} \left( \frac{h_{\text{min}}}{D_{bt}} \right)^2 = \left( \frac{160}{70} \right)^{1.85} \left( \frac{650}{19.5} \right)^2 = 4.615 \cdot 9.467 \approx 45 \text{ min}$$

The proposed method is applied in the field inspection of concrete structures of the warehouse block roofing with an area of 2160 $\text{m}^2$ of an industrial building in the city of Samara.

4. Conclusion

The technological result is obtained by:

- reduction of labour intensity and simplification of the assessment method of the building envelope fire resistance by the criterion of its heat-insulating ability;
- the possibility to determine building envelopes fire resistance without disrupting the functional process in the building;
• improving the accuracy of fire resistance indicators and reducing the economic costs of the test; simplification of conditions and reduction of building envelopes fire resistance assessment time;
• simplification of the mathematical description of the process of structure thermal resistance;
• reduction of the required amount of computer main memory capacity to calculate the building envelope fire resistance by the criterion of its heat-insulating ability.

Figure 2. Calculation scheme of the wall heating:
1 – sample of a concrete wall; 2 – temperature distribution curve along the section; \( V_{cm} \) – temperature of the standard fire environment over time, \(^\circ\mathrm{C}\); \( t_{ex} \) – heating temperature of the heated surface of the wall, \(^\circ\mathrm{C}\); \( t_{in} \) – temperature on the unheated surface of the wall, \(^\circ\mathrm{C}\); \( t_{ez} \) – critical temperature on the wall unheated surface, \(^\circ\mathrm{C}\); \( t_e \) – initial temperature of the body of the wall, \(^\circ\mathrm{C}\).

Figure 3. Measurements of the building envelope surface nonlinearity: (a undulation; b) bulge; 1 – real surface profile; 2 – control rod; 3 – the greatest deviation from straightness – \( \delta_2 \), mm; 4 – minimum thickness of the building envelope – \( h_{min} \), mm.

5. References
[1] N A Ilyin 2013 Fire protection design of buildings and structures: Textbook p 48
[2] Ilyin N A and Panfilov D A 2017 Assessment of fire resistance of designed reinforced concrete structures. Monograph. p 186.
[3] Borodachev N A 2015 Course design of reinforced concrete structures in the dialogue with the computer Coursebook p 256
[4] Application for an invention № 2015 147 135 (072 566) MPC G 01 № 25/50. Method of reinforced concrete beam structure fire resistance assessment. Ilyin N A, Panfilov DA, SGASU, 2015.
[5] Determining fire resistance of reinforced concrete structures of buildings. Methodology STO SGASU 21.13.35–15 ed N A Ilyin and D.A Panfilov p 82.
[6] The manual on calculation of fire resistance and fire durability of reinforced heavy concrete structure (to 100 35 554 501 – 006 – 2006) 2008 p 80.