A New Fire-Resistance Test Method for a Reinforced Concrete Truss

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Abstract. An innovative technology relates to the field of buildings and structures fire safety (hereinafter Buildings). In particular, we can use this technology to classify reinforced concrete trusses according to their resistance to fire. This provides an opportunity to reasonably use trusses with actual fire-resistance of buildings with various fire hazard classes. A summary of the innovative technology is to test tensile and compressive elements of a reinforced concrete truss under fire conditions without destruction according to a set of simple quality factors. The resistance procedure of load-carrying elements of the reinforced concrete truss to standard fire exposure is represented by mathematical dependences that take into account the integral heat engineering and design parameters, as well as the features of tensile and compressive elements reinforcement. The new method application makes it possible to determine the actual fire-resistance of tensile and compressive elements of the reinforced concrete truss without actual heat exposure; increases the reliability of non-destructive tests; makes test conditions of tensile and compressive elements closer to the actual operating conditions. The fire-resistance of the reinforced concrete truss determines the resistance limit to fire exposure of the weakest element.

1. Introduction
A need to determine the fire-resistance of reinforced concrete trusses arises during the reconstruction of a building, strengthening of its parts and elements [1-4], bringing the fire-resistance of the building into the condition with the requirements of modern building standards, during the examination and restoration of reinforced concrete trusses after a fire [6-20].

2. Materials and methods
The principle of this method is to increase the fire safety of a building, i.e. to establish reliable duration factors of tensile and compressive elements resistance of a reinforced concrete truss under fire conditions. These factors can be used when designing, building or operating buildings. Another principle is to use non-destructive test methods for fire-resistance of reinforced concrete trusses, which will reduce the testing time [5].

In the proposed method for evaluating the fire-resistance of a reinforced concrete truss, the main features are the following: the authors conduct the actual fire-resistance evaluation of truss elements without actual fire exposure and with non-destructive test methods, meanwhile evaluating the compressive truss elements of the building; the authors carry out a technical inspection and define groups of the same type tensile and compressive truss elements, assign a set of simple quality factors of tensile and compressive truss elements, determine the depth of occurrence, heating conditions and
concrete fire protection degree of tensile and compressive truss elements reinforcement, calculate the integral heat engineering and design parameters, and measure the actual fire-resistance rating of truss elements according to the thermal impact resistance duration until the bearing capacity loss of the less fire-resistant truss element; the resistance duration from the beginning of the standard fire exposure to the bearing capacity loss of the tensile and compressive truss elements $F_{u,n}$, min, is determined using the analytical equation (1):

$$ F_{u,n} = (2.15 \cdot J_{m})^{0.6/n} \cdot e^{c} \cdot K / (425/t_{c})^{0.6}, $$

where $J_{m}$ – a force stress intensity in the longitudinal working reinforcement in the critical section of the tensile truss element $(0,1 \div 1,0)$; $C$ – concrete fire protection degree of working reinforcement, cm; $K$ – integral safety factor of the tensile element; $n$ – empirical measure of reinforcement steel property change under fire conditions; $t_{c}$ – critical temperature for reinforcement steel, °C; force stress intensity in the longitudinal working reinforcement of the tensile truss element from the test load on the fire-resistance is determined using the equation (2):

$$ J_{m} = (A_{x,n}/A_{x}) \cdot (R_{x}/R_{n}) \cdot (N_{q}/N) \leq 1; $$

where $A_{x}$ and $A_{x,n}$ – areas of reinforcement installed in the critical section of the element and required by strength calculation, $mm^{2}$; $R_{x}$ and $R_{n}$ – design ultimate tensile strength of reinforcement, MPa; $R_{n} = R_{m} / 0.9$; $N$ and $N_{q}$ – a design axial force and force from fire-resistance test load, kN; the force from fire-resistance test load in the tensile truss element is determined using the equation (3):

$$ N_{p} = N_{a1} / \gamma \gamma m; $$

where $N_{a1}$ – a long part of the design load, kN; $\gamma \gamma m$ – a load effect factor; concrete fire protection degree of longitudinal working reinforcement of tensile truss element is determined using the power-law equation (4):

$$ C = 1.44 \cdot m_{0} \cdot a_{m} / D^{0.8} $$

where $m_{0}$ – a heating conditions factor of reinforcement in a critical section of truss elements $(0.25 \div 1.0)$; $a_{m}$ – a minimum depth of reinforcement occurrence, $mm$; $D$ – a concrete thermodiffusion factor, $mm^{2}/min$.

When there is an asymmetry in the arrangement of reinforcement bars about the angle bisector of a truss element rectangular cross-section, reinforcement heating conditions factor ($m_{0}$) in the case of two-sided heating (where $a_{x} \geq a_{y}$) is determined using the exponential function (5):

$$ m_{0} = 0.5 \cdot (a_{x} / a_{y})^{0.5}; $$

where $a_{x}$ and $a_{y}$ – respectively depth of reinforcement bars occurrence from the heated edges of the element along the axes of coordinates of the cross section, $mm$; (where $a_{x} > a_{y}$ in the exponent, the functions (5) take the inverse relation of axial distance values, i.e. $a_{y}/a_{x}$).

The depth of the reinforcement bars occurrence along the axes of coordinates (axial distances $a_{x,y}$) is determined using the equation (6):

$$ a_{x,y} = u_{x,y} + 0.5 \cdot d; $$

where $a_{x,y}$ – the depth of reinforcement cover respectively along the axes $x$ or $y$, $mm$; $d$ – a nominal diameter of longitudinal reinforcement bars, $mm$. 

The concrete thermodiffusion factor $D_{cm}$, mm$^2$/min, at a temperature of 450°C is defined using the analytical equation (7):

$$D_{cm} = 60 \cdot 10^3 \cdot (\lambda_0 + 0,45 \cdot b) / p_c \cdot (C_0 + 0,45 \cdot d + \omega / 20),$$

where $\lambda_0$ and $C_0$ - concrete thermal conductivity factors, $Bm/(m^2°C)$, and thermal capacitance, $kJ/(kg \cdot °C)$, at a normal temperature (20±5°C); $b$ and $d$ - thermal factors of concrete heat conductivity and capacity; $P_c$ and $\omega$ - dry concrete density, kg/m$^3$, and its mass humidity %.

The integral safety value of the tensile truss element is determined using the equation (8):

$$K = \gamma_n \cdot m_{o\phi} \cdot k_{en} \cdot k_{\phi};$$

where $\gamma_n$ - truss reliability factor in relation to the type of a building; $m_{o\phi}$ - heating conditions factor of truss element section perimeter; $k_{en}$ - solidity factor of a truss element section; $k_{\phi}$ - a nominal diameter factor of the working reinforcement.

As simple quality factors of tensile truss elements affecting the fire-resistance rating, we take geometrical dimensions of critical section; the depth of occurrence, strength grade, nominal diameter, stress degree and yield strength of the working reinforcement; humidity and density of concrete, the cover depth and the concrete thermodiffusion factor.

The resistance duration of compressive truss elements $F_{\omega}$, min, from the beginning of the standard fire exposure to the loss of the bearing capacity is determined using the analytical equation (9):

$$F_{\omega} = 5 \cdot B^2 \cdot (1 - J_{\omega})^2 \cdot (1 - 0,6 \cdot \alpha_{\mu}) \cdot K_1 / (D_{cm} \cdot R_{cm}^{0,25}),$$

where $B$ – a rectangular cross-section minimum size of a compressive truss element, mm; $J_{\omega}$ - a force stress intensity in a critical section of a compressive element (0 – 1); $\alpha_{\mu}$ - reinforcement degree of a truss element; $K_1$ - an integral safety factor of a compressive element; $D_{cm}$ - a concrete thermodiffusion factor, mm$^2$/min; $R_{cm}$ – characteristic strength of concrete to axial compression resistance, MPa;

The force stress intensity in a critical section of a compressive element ($J_{\omega}$) from the fire-resistance test load is determined using the equation (10):

$$J_{\omega} = k_3 \cdot N_{\mu} / N_{\omega};$$

where $k_3$ - a fixing conditions factor of a truss compressive element (0,8 - 0,9); $N_{\omega}$ - a test load when determining the fire resistance of a compressive truss element, kN; $N_{\omega}$ - an axial force destroying a compressive element before the fire test starts, kN;

The reinforcement degree of a compressive truss element ($\alpha_{\mu}$) is determined using the equation (11):

$$\alpha_{\mu} = (A \cdot R_{cm}) / (R_{sc} / R_{cm});$$

where $A$ and $R_{sc}$, $R_{cm}$ and $R_{cm}$ - respectively the working reinforcement areas and concrete in the cross section of a truss element, mm$^2$; $R_{sc}$ and $R_{cm}$ - respectively design reinforcement resistance to compression and characteristic strength of concrete to axial compression, MPa;

An integral safety factor of a compressive truss element ($K_1$) is determined using the algebraic equation (12):
$$K_1 = \gamma_a \cdot m_{\omega_0} \cdot k_{cn} \cdot k_a \cdot \varphi_f$$  

(12)

where  $\gamma_a$ - truss reliability factor in relation to the type of a building;  
$m_{\omega_0}$ - heating conditions factor of truss element cross-sectional perimeter;  
$k_{cn}$ - solidity factor of a cross-sectional truss element;  
$k_a$ - the depth of working reinforcement occurrence;  
$\varphi_f$ - a buckling coefficient factor of a compressive truss element.

Replacement of fire tests with non-destructive tests reduces the complexity of assessing their fire resistance, expands the ways for applying the assessment method of truss elements fire resistance which have a different kind of stress state (compression) of truss building elements; makes test conditions of tensile and compressive elements closer to the actual operating conditions. The application of the proposed method allows us to assign a complex of thermal and structural parameters that affect their values. A mathematical description of the resistance process of tensile and compressive reinforced concrete truss elements to a standard fire test allows us to compose the corresponding analytical equations (1) and (9) to calculate their design fire resistance limits.

The innovative technology application reduces errors in determining the fire protection degree of the working reinforcement, evaluating its value depending on the depth of occurrence and heating conditions in case of fire.

The factor of the working reinforcement heating condition is determined using the mathematical relationship (5) taking into account the number of heat supply directions and the location of its bars about the angle bisector of the heated section.

We have simplified the design features that need to be taken into account: the reinforcement degree of the critical section, the force stress intensity of concrete and reinforcement strength, diameters of reinforcement bars, the section heating conditions, the depth of reinforcement occurrence, the element flexibility and the cross section solidity by the fire resistance value.

Figure 1 shows the diagrams of the reinforced concrete truss elements to calculate its fire resistance: geometry of a segmental truss with a 24 m span with a polygonal top chord (figure 1); a diagram of stresses in the elements of a segmental truss with a 24 m span (load ± N, kN) (Fig. 2); a design model for determining the strength of a tensile truss element (section 1-1) (Fig. 3); a design model for determining the fire resistance of a tensile element (four-sided section heating, section 2-2) (Fig. 4); a design model for determining the strength of a compressive truss element (Fig. 5); a design model for determining the fire resistance of a compressive truss element (four-sided section heating) (Fig. 6).

Figures 1-6 show: 1–working reinforcement; 2–web bars; 3– concrete; $t_{cm}^0C$ – the direction of high temperature.

The critical temperature value ($t_{cr}^0C$) of steel and smoothing function factor ($n$) are as follows depending on the reinforcement class (Table 1):
Table 1. Critical temperature values of steel and smoothing function factors.

| Quality class | A 400 (A–III) | A 300,A 600 (A–II,A-IV) | A 800 (A-V) | A1000 (A-VI) | K1500 | Bp1200-1500 (B-II, Bp-II) |
|---------------|---------------|--------------------------|-------------|--------------|-------|--------------------------|
| \( t_{cr} \), \(^0\) C | 550           | 525                      | 500         | 450          | 365   | 360                      |
| n            | 4.4           | 3.6                      | 4.2         | 3.85         | 2.48  | 2.65                     |

Concrete thermodiffusion factor can be taken from Table 2.

Table 2. Concrete thermodiffusion factor.

| Material (type of concrete) | Density \( p_e \), kg/m\(^3\) | Moisture \( \omega \),% | Parameters of Thermal Conductivity \( \lambda_o \), W/m\(^0\)C and Heat Capacity \( C_o \), J/kg\(^0\) C | Thermodiffusion Factor \( D_{num} \), mm\(^2\)/min |
|----------------------------|-------------------------------|------------------------|------------------------------------------------|---------------------------------|
| 1. Expanded-Clay Concrete  | 750                           | 6                      | 0.18, 0.8, 0.92                              | 12,1                            |
| 2. Perlite Concrete        | 1090                          | 3                      | 0.3, 0.11, 0.85                              | 13.2                           |
| 3. Heavy-Weight Limestone Aggregate Concrete | 2250                  | 3                      | 1.15, -5.5, 0.71                              | 19.4                           |
| 4. Heavy-Weight Granite Aggregate Concrete | 2400                  | 3                      | 1.2, -3, 0.72                                 | 22.2                           |
| 5. Sand Concrete           | 1930                          | 2.5                    | 1.03, 4.4, 0.75                               | 23.2                           |

Heating conditions factor of the truss element section perimeter is determined using the equation:

\[
m_{ob} = \left( \frac{P}{P_0} \right)^{1.2};
\]  

(13)

here \( P \) and \( P_0 \) - respectively the perimeter and the heated part of the element section perimeter, mm; 

\( k_{cn} \) - the solidity factor of the truss element cross-section: for the solid cross-section \( k_{cn} = 1.0 \); for the hollow cross-section \( k_{cn} = 0.8 \); 

The nominal diameter factor of the working reinforcement is determined using the equation \((d, mm)\):

\[
k_{\phi} = (0.1 \cdot d)^{0.05}.
\]  

(14)

The buckling coefficient of the compressive truss element is determined using the equation:
Figure 1. In addition to the fire-resistance calculation of reinforced concrete truss elements.
\[
\varphi = 0.9 - 7 \cdot 10^{-3} \cdot ((\ell_a / B_{mn}) - 10)
\]

(15)

Here, \(\ell_a\) - the effective length of the compressive element, \(mm\); \(m_{06}\) - the heating conditions factor of the truss element section perimeter determined using the equation (14); \(k_{cn}\) - the solidity factor of the truss element cross-section;

The depth factor of the working reinforcement occurrence is determined using the equation:

\[
k_n = 1 - 0.1 \cdot (a_n - a) / a_n
\]

(16)

Here, \(a_n\) and \(a\) - respectively standard and true depth of reinforcement occurrence, \(mm\).

3. Conclusion

1. The innovative technology was developed to determine the fire-resistance of a reinforced concrete truss in a building [5];
2. The mathematical description of tensile and compressive truss elements resistance in case of fire was given: equations (1) and (9);
3. The design values of truss elements were set particularly concerning their actual fire-resistance by bearing capacity loss in case of fire;
4. A creative result was obtained to improve the fire resistance theory of reinforced concrete trusses.

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