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Improvement of the estimation method of the possibility of progressive destruction of buildings caused by fire

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Abstract. With the progressive destruction of building structures, socioeconomic losses reach the biggest level, especially when the buildings have a high degree of responsibility. For such buildings there is a standardized requirement to carry out a calculated estimation of the possibility of progressive destruction. The article outlines the main provisions of the calculation method as to the estimation of the possibility of progressive destruction, with the failure of one or more compressed elements, that must be removed from the general structural system of the building frame consisting of steel beams, CFST and reinforced concrete columns. The basic principle of the method is the hypothesis about formation plastic joints in beams and columns. The possibility of progressive destruction is estimated according to the energy criterion based on comparison of the work of internal and external forces on the possible displacements of the system, which in such conditions is geometrically variable. The proposed method is productive and cost-effective compared to existing methods that involve complex mathematical models and software complexes.

1. Introduction

Statistics on fires and fatal accidents in fires shows that the destruction of load-bearing structures under fire remains one of the most dangerous factors, as shown in the works [1-6]. When the destruction of one or more structural elements leads to the successive destructions of other elements, then the socio-economic losses reach their maximum level, because of partial or complete collapse of the entire building. To prevent the progressive destruction of buildings, the standardized requirement [7] exists to estimate this possibility. When its result is negative, the investigated structures should be reinforced correspondingly. It is advisable to use modern calculation methods for predicting the possibility of

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progressive destruction. The methods should combine sufficient accuracy and theoretical validity with the relative simplicity of implementation and cost-effectiveness of calculation operations. Therefore, the development and improvement of such methods becomes a relevant task.

2. Literature review and purpose of research

According to the studies reported in [8, 9], the kinematic method can be distinguished among the methods of engineering evaluation of the possibility of progressive destruction of buildings and structures by its properties of sufficient accuracy, theoretical validity, simplicity of implementation and cost-effectiveness of computational operations. This method is applied to determine the work of internal forces (W) and external loads (U) on possible displacements of the considered mechanism, into which the static system is transformed, for each of the previously adopted mechanisms of progressive destruction. The condition for maintaining the resistance of static system to progressive destruction is solving the following inequation:

$$W \geq U \tag{1}$$

The mechanism of destruction of a building frame under conditions of thermal influence of fire suggests that the destroyed column is removed completely from the scheme of rigidity of the building, and is not considered a part of the mechanism, into which the building is transformed, with the existing plastic joints in it. However, this method has a disadvantage as it can not be applied to this type of frame. In addition, there is limited basis of the magnitudes of the moments, which are to be applied in the plastic joints of columns. Another approach to the computational prediction of progressive destruction was described and effectively applied in the studies [10 - 13]. This approach is based on application of the finite element method combined with the penalty function method under conditions of separation and collision of parts with finite elements, again formed during the calculation of a system in emergency. This approach requires labor-consuming and time-consuming calculations involving sophisticated software and skilled engineering staff. In view of the above, the purpose of the research was set. The purpose of the conducted research (its main results are presented herein) was developing a mathematical description of the work of external and internal forces in the kinematic scheme of the system, into which the structure of the building transforms, by introducing plastic joints in beams and columns that restrict the moving parts of the geometrically variable system as a basis for an advanced kinematic calculation method for predicting the progressive destruction of buildings with frames consisting of steel concrete composite and reinforced concrete columns, as well as steel beams.

3. Basic theoretical provisions for the calculation

To consider the progressive destruction under these assumptions, the calculated scheme of the failure mechanism of the first type was applied, Fig. 1, which shows the internal forces in the plastic joints that resist the failure under emergency conditions. The calculated scheme of the mechanism of progressive destruction of the second type is shown in fig. 2. These schemes correspond to the kinematic calculation of the part of a building with one element which is supposed to be destroyed as a result of fire.

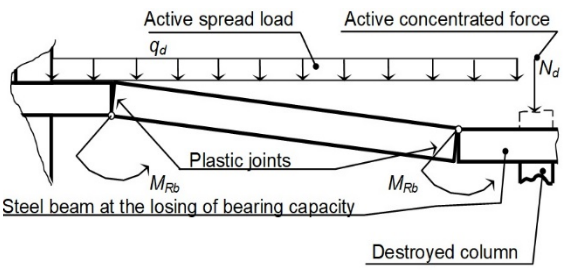

Figure 1. Calculated scheme of the work of internal forces for the mechanism of destruction of the first type.

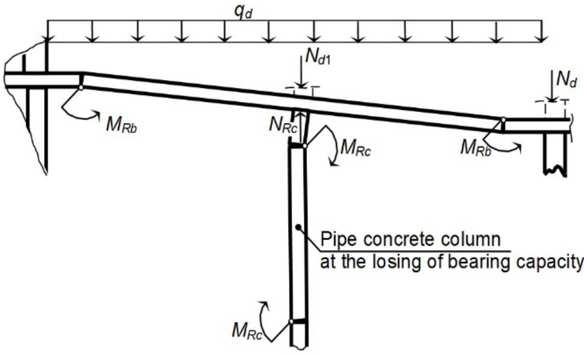

Figure 2. Calculated scheme of the work of internal forces for the mechanism of destruction of the second type.

Fig. 3 and Fig. 4 show the calculation schemes for determining the virtual displacement to determine the virtual works of interior forces in kinematic schemes of the structures, according to Fig. 1 and Fig. 2.

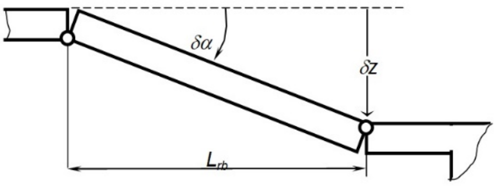

Figure 3. Calculation scheme for determining the virtual displacement for the mechanism of destruction of the first type.

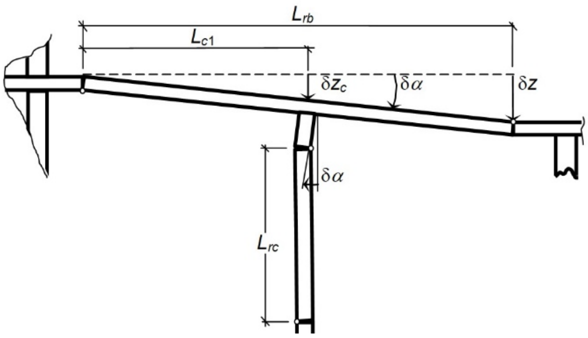

Figure 4. Calculation scheme for determining the virtual displacement for the mechanism of destruction of the second type.

The following calculation schemes determine the work of internal forces on the possible displacement δz for the first calculation scheme (see Fig. 1 and Fig. 3) using the following expression:

$$W = \frac{2M_{Rb}}{L_{rb}}\delta z, \tag{2}$$

where M_{Rb} is a boundary moment under plastic boundary deformation of a steel beam, determined by the method of boundary deformations; L_{rb} is length of the beam between plastic joints. The work of internal forces on possible displacement of δz for another calculation scheme (see Fig. 2 and Fig. 4) using the following expression:

$$W = \frac{2M_{Rb} + M_{Rc}}{L_{rb}}\delta z + \frac{M_{Rc}L_J}{L_{rc}L_{rb}}\delta z + N_{Rc}\frac{L_{c1}}{L_{rb}}\delta z, \tag{3}$$

where M_{Rc} is a boundary moment under plastic boundary deformation of a CFST or reinforced concrete column, determined by the method of boundary deformations; L_{rc} is the length of the column between the plastic joints; L_{rc} = 0.5 m - the shortest distance from the plastic joint of the element to its junction with another element.

The following calculation schemes determine the work of external forces on the possible displacement δz for the first kinematic failure scheme of structure (see Fig. 1 and Fig. 3) using the following expression:

$$U = 0.5q_d L_{rb}\delta z + N_d \delta z \,. \tag{4}$$

The work of external forces on the possible displacement of δz for the second kinematic failure scheme (see Fig. 2 and Fig. 4) using the following expression:

$$U = 0.5q_d L_{rb}\delta z + N_d \delta z + N_{d1}\frac{L_{c1}}{L_{rb}}\delta z \,. \tag{5}$$

For the calculation of boundary moments and boundary forces in columns, the boundary state method [8] is applied, which is schematically shown in Fig. 5.

The calculation is performed using the special schemes of deformation of the fragment under the gradual displacement of the neutral axis along the dangerous section of the investigated column fragment [14]. Fig. 5 shows the positions of the neutral axis and the epures of deformations, corresponding to this position.

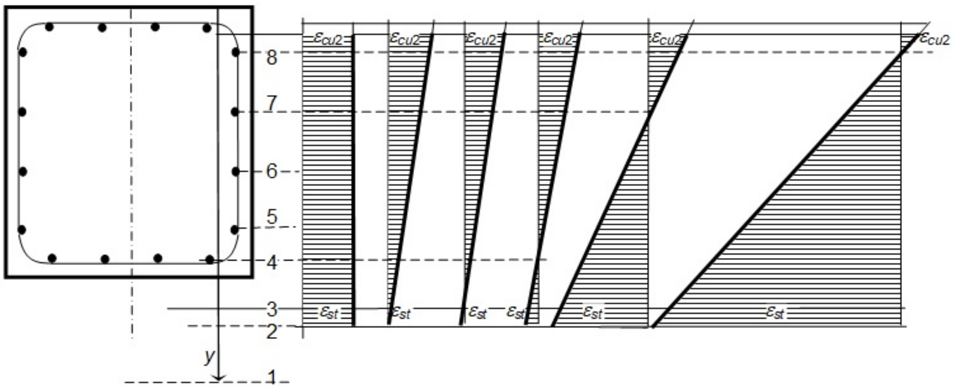

Figure 5. Positions of the neutral axis and the corresponding epures of deformation in the dangerous section of the column.

Using the scheme for determining the boundary force, shown in Fig. 5, the graphs should be plotted in the coordinates: longitudinal force – the bending moment so that to describe all the possible boundary states of the columns in case of losing their bearing capacity when plastic deformation increases and plastic joints are formed. These graphs are shown in Fig. 6 and Fig. 7.

Boundary moments of steel beams are determined by the following formula [15]:

$$M_{Rb} = \frac{f_y W_x}{\gamma_{M,0}}, \tag{6}$$

where W_x is the moment of resistance of the cross section of the beam; γ_{M0} is reliability coefficient of the corresponding properties of the material in case of fire (according to [15], it should be taken as equal to 1.0).

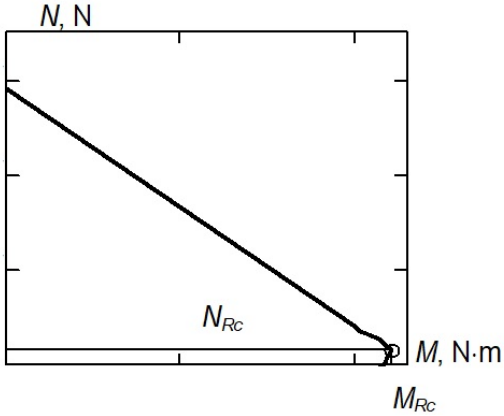

Figure 6. Diagram “boundary moment - boundary force” for CFST.

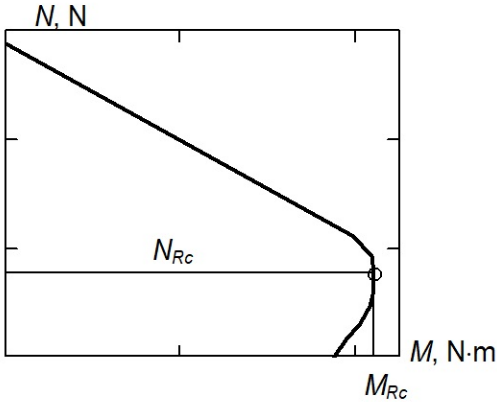

Figure 7. Diagram “boundary moment - boundary force” for reinforced concrete columns.

4. The method of calculated estimation of the possibility of progressive destruction

The following procedures should be followed to calculate the possibility of progressive destruction of a building in case of fire.

1. There is determined a column or a group of columns (diaphragms), which is removed from the rigidity scheme of a building as destroyed by fire. 2. The positions of the plastic joints are determined. They must be located at points 0.5 m from the groups of non-destroyed columns and rigidity diaphragms. The necessary geometric parameters of the kinematic schemes for the first and second mechanisms of progressive destruction are determined. 3. There are determined the boundary stresses in steel beams, reinforced concrete columns and CFST columns at normal temperatures. 4. Using formulas (2) and (3), there is determined the possible work of internal forces in each of the parts, into which the kinematic scheme around the removed columns was divided. Total possible work is defined as the sum of all obtained components. 5. Using formulas (4) and (5), the total possible work of external forces is determined. 6. Compliance with the condition (1) is checked and the conclusion is drawn on the possibility of progressive destruction of the building in case of fire.

5. Conclusions

As a result of the conducted research we can draw the following conclusions:

- there was developed a mathematical apparatus for determining virtual works for the external and internal forces of kinematic systems, into which transforms the structural systems of buildings and structures in emergency condition as a result of fire which acts on the frames of buildings erected on the basis of steel beams, reinforced concrete and CFST columns;

- based on the proposed mathematical apparatus, the kinematic design method for predicting the possibility of progressive destruction for the frames of buildings based on steel beams, reinforced concrete and CFST columns was improved.

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