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THE MULTI-STOREY BUILDINNGS STEEL FRAMES VITALITY IN THE FIRE INCREASING

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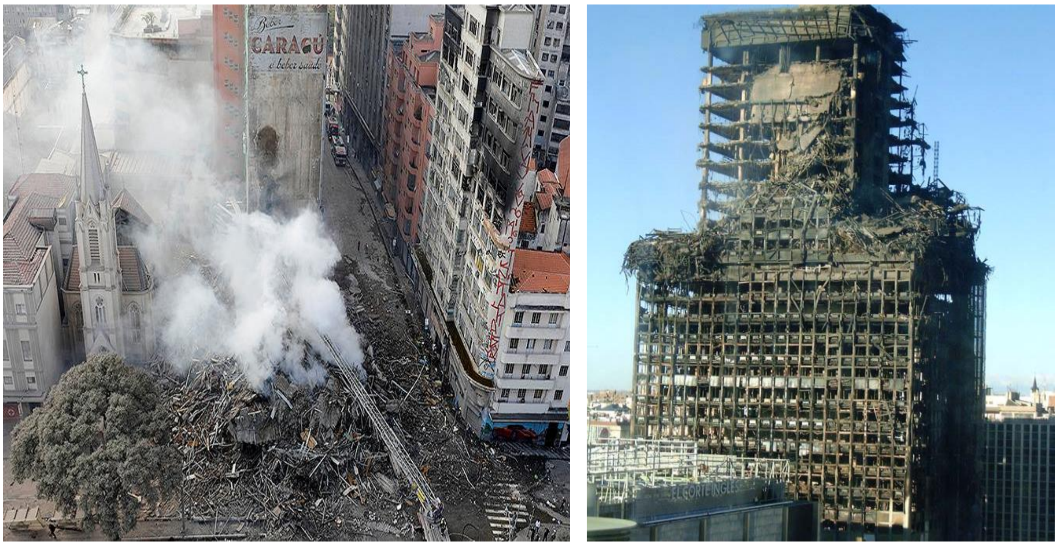
Abstract. In the article multi-story buildings steel frames in the fire before and after the first destruction is investigated, the frames vitality in the fire is investigated. It is emphasized on the relevance of the research during the war of the russian federation against Ukraine. An overview of previous domestic and foreign scientists' studies, devoted to the multi-story buildings steel frames vitality, in particular in a fire. The frame model for research was selected and simplifications was required in the study for the clarity of comparisons in research. There were compared different mechanisms of multi -story buildings steel frames collapse in a fire. It is proved that with the first destruction in the steel frame beam the vitality loss time will be longer than with the column first destruction.

Various measures vitality increasing frames are considered and investigated. Outrigger systems were investigated as a measure vitality increasing, and their impact on the forces distribution in the frame during heating of frame elements under the action of temperature loads from a fire. The dependence of various measures vitality increasing of multi-story buildings steel frames in the fire from the frame geometric sizes is established. It is established that the load - bearing capacity factor at the fire beginning in the most loaded column should be smaller than the most loaded beams. It is proved that the difference between the initial load-bearing capacity factor in the beam and column that necessary to increase the vitality loss time, is different for different ratios of beam span to the column height. It is revealed that the frame elements cross-sections shape affects its vitality in the fire. The importance of the limited plate deformations development in the frame elements cross-sections is emphasized. Recommendations for civil engineers to enhance the of multi-story buildings steel frames vitality in a fire are formed.

Keywords: vitality, fire, steel frame, multi-storey building, physical nonlinear, war, russian aggression.

Introduction. The lack of land plots in cities in dense construction conditions is increasingly leading to multi-storey construction. As the number of floors increases, the complexity of buildings as systems increases. Due to scientific and technical progress, the complexity of systems increases, but their reliability and vitality do not always increase accordingly. Various threats can cause complete or significant destruction of buildings: impact and explosion as a result of military operations, fire, earthquake, etc. It is impossible to design the load-bearing structures of the building in such a way that they withstand the effects of all threats. However, it is possible to investigate various ways of increasing the vitality of the building's load-bearing structures: so that local destruction does not lead to progressive collapse (or vitality loss). The fire in São Paulo (Brazil, 2018, Fig. 1, a) and Madrid (Spain, 2005, Fig. 1, b) are examples of the a multi-story building progressive collapse due to fire. After the beginning of the full-scale war of the russian federation against Ukraine, fires due to missile strikes or UAVs or falling debris after being shot down by air defense systems also became relevant. Such an example is the fire on June 27, 2022 in Kremenchug after a missile hit the shopping center building (Fig. 2).

Fire is a rather complex factor from the point of view of taking it into account in the design of buildings load-bearing structures, as it depends on many components [1]. However, there is a requirement in domestic regulations: all objects of the CC3 consequence class should be expected to vitality, in particular, vitality in the event of a fire [2]. Modeling the effect of fire on the buildings load-bearing structures and multi-storey buildings steel frames vitality increasing is no longer an engineering, but a scientific task.



a) b)

Fig. 1. Buildings progressive collapse consequences from fire:
a – in Sao Paulo; b – in Madrid

Fig. 2. The result of building progressive collapse from a missile strike and fire in the shopping center in Kremenchug

Analysis of the latest research. Modeling of the fire effect on the multi-story building frame finite-element model was carried out in studies [1]. The steel structures fire protection, which was designed taking into account their load capacity ratio, was taken into account. Temperature loads were determined taking into account the premises layout (the fire compartments dimensions) and the corresponding parametric temperature-time dependences. The maximum temperature load was 120°C with fire protection R180. It was found that, even taking into account fire protection, in the case of static linear calculation, such large forces arise that after frame elements cross-sections design for the forces, the metal frame weight increased by 50%. This indicates that the calculation of fire action cannot be simulated with one maximum load (peak for the fire heating stage), and it is necessary to perform a nonlinear calculation taking into account geometric nonlinearity, which is a scientific problem.

In [2], a review of Ukrainian and foreign normative documents was carried out on measures to steel frames vitality increasing in case of fire. Neither methods nor recommendations for this were found in any documents.

In [3], the multi-story buildings steel frames stress-state before the first destruction was investigated in order to determine the most unacceptable location of the fire source. The multi-story buildings steel frames stress-state in case of fire was investigated for the fire source location in different frame spans on different floors. For the frame in question, it was established in particular that:

– in the event of a fire, the time to the first destruction under the fire scenario in the internal span is longer than in the external one;

– in case of fire on the upper floor, the destruction occurs later than on the lower one;

– on the lower floor, the columns are more likely to collapse earlier than the beam, than on the upper floor;

– in the internal span, the beams are more prone to collapse earlier than the column, than in the external one.

In [4], the steel frames stress-state during a fire under various initial conditions was analyzed, such as: types of joints connecting beams to columns, the initial load capacity ratio, allowing/not allowing the development of limited plastic deformations in the beams. In frames with hinged joints, the loss of the the first frame element load-bearing capacity takes longer than in frames with rigid joints.

British scientists in [5] investigated the fire resistance of steel frame joints and their effect on vitality. It was established that connections can be destroyed due to fire earlier than frame elements.

Japanese scientists in [6] determined that the load capacity ratio in the columns should be 0.25 to prevent progressive collapse in the fire, which significantly increases the frame metal weight. This factor should be specified for different frame geometry. The difference between beam and column load capacity ratios from the point of view of the potential mechanism of destruction also needs research.

To increase vitality in case of fire and earthquake resistance, it is recommended to use combined outrigger systems (super frame), which combine vertical and horizontal outriggers along the frame contour [6]. Such systems significantly increase the frame metal weight and limit architectural solutions.

In the studies of compatriots [7-10], the frames stress-state after the column removal in the frame was analyzed. Emphasis is placed on the importance of taking into account physical nonlinearity and the dynamic effect due to the column collapse when calculating the vitality.

Preliminary studies show that existing measures to the vitatiy increase of multi-story buildings steel frames require a more detailed study. It is necessary to investigate the frame after the first element destruction under the action of fire under the most unfavorable location of the fire source, taking into account the nonlinearity and dynamic effects of the destruction.

Research tasks. The following tasks were performed in these studies:

– to compare various multi-story buildings steel frames collapse mechanisms during a fire and to choose the most durable ones;

– investigate various measures to increase the vitality of multi-story buildings steel frames;

– check the dependence of measures to increase the vitality of multi-story buildings steel frames on their geometric dimensions.

Research materials and methodology. Based on [3], it was taken as a basis that the fire source location on the lower floor in the external span is the most unfavorable from the point of view that the most probable destruction of the column earlier than the beam will be in this case (Fig. 3).

A frame finite element model of a 2d steel frame (without fire protection) with three floors and three spans was adopted as the research model. The dimensions are adopted in such a way that the span of the beam is 2 times greater than the height of the column: the span of the beam is 7.2 m, the height of the floor is 3.6 m. The columns are unfastened from the frame plane at the level of the abutment of the beams, the beams are unfastened from the frame plane with a step of 2.4 m. The load capacity ratio of beams and columns was assumed to be the same – 0.5 in order to make a visual comparison of the change in their load during the fire. Column bases are adopted with a rigid connection. Beam-to-column connections are hinged. The load on the frame was set vertically on the beams – 6t/m (simulating the effect of dead and live load) and horizontal on the columns (simulating the effect of wind load) according to [11]. Steel elements C255. The design and cheking of frame elements cross-sections is carried out according to [12]. The effect of fire is simulated by temperature loads determined according to [13]. The sections of all frame elements are designed in such a way that the hinge plastic occurs earlier than the local buckling.

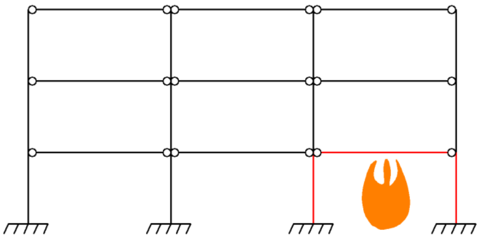


Fig. 3. The adopted calculated fire scenario for a frame with hinged beam-to-column connections

The effect of the fire was simulated by temperature loads. Step by step with an interval of 30 seconds in a non-linear calculation (taking into account geometric non-linearity) the temperature increase was set. The temperature loads values were determined according to [13] for the standard temperature-time fire dependence. It was accepted that the fire heats the column from 4 sides, and the beam – from 3. At each step, the change in strength and deformation steel characteristics depending on temperature was taken into account according to [13].

Simplifications are made. During the calculation, it is assumed that the temperature is distributed evenly along the length of the element and across the cross-section. It is also assumed that the frame elements do not perceive other temperature actions except fire. Connections have a greater bearing capacity reserve than frame elements.

The criterion for the frame element destruction is the occurrence of a hinge plastic in it. The very *process of element destruction* is modeled by removing it from the frame calculation scheme, and instead of it, forces equal to the reactions in this element, with the opposite sign, are applied to the joints (taking into account the dynamic effect). In the next step of nonlinear loading, these forces disappear. The phenomenon, when the frame upper floors fall on the lower ones, is proposed to be called *vitality loss*. The time from the first frame element destruction to the vitality loss is proposed to be called *vitality time*. The time from the fire start to the time of vitality loss is proposed to be called the *vitality loss time*.

Research results. As a measure to the frame vitality increase in the event of a fire, X-shaped outrigger systems on the upper floor were investigated, as recommended in [7-10] (Fig. 4).

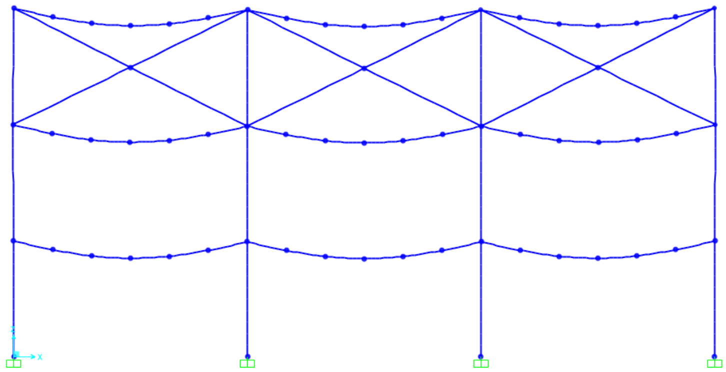


Fig. 4. The frame with outrigger systems

The first destruction occurs at 1080s=18min. The internal unheated column of the frame lower floor is collapsing (Fig. 5). The reason for the destruction is the increase in axial force. In the heated internal column, the axial force decreased from -130tf to -51tf, and in the destroyed one it increased from -130tf to -262tf. This frame forces distribution is due to the presence of outriggers, which redistribute forces from the heated (less stiff due to the decrease in the modulus of elasticity) to the stiffer unheated column.

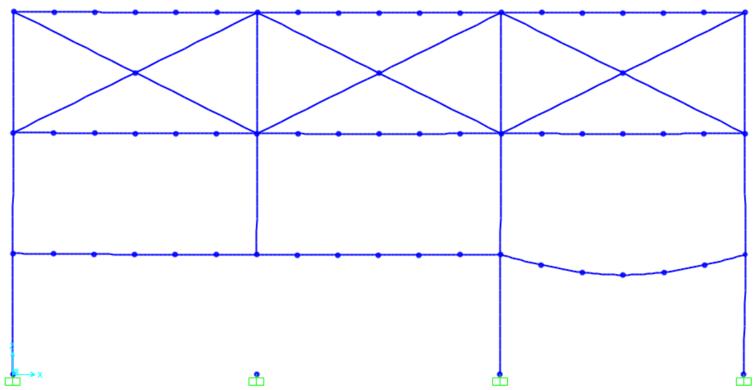


Fig. 5. Frame calculation scheme after the destruction of the unheated internal column

The frame vitality loss occurs at 1110s=18.5min due to the destruction of the external unheated column of the lower floor, the internal heated column of the lower floor, the beams of the upper and intermediate floors above the destroyed column. The reason for this is the change in the lateral force in the beams reaches from -40tf to -202tf (beam of the upper floor), from -40tf to 196tf (beam of the middle floor), and in the columns of the lower floor from -16tf to -270tf (external unheated column), with -50tf to -338tf (average heated column).

Destruction beyond the location of the fire source is undesirable from the point of view of evacuating people from the building. However, outrigger systems are necessary to redistribute efforts from the destroyed column to others. Therefore, the option of including the outrigger elements in the work of the frame only after the column destruction was considered (Fig. 6). Practically, such work can be achieved by attaching outriggers to the frame on connections with oval holes for bolts in the vertical direction.

The first destruction occurs at 1260s=21min. The internal heated column is destruction. The destruction occurred due to the buckling from the bending plane. The reason for the decrease in the column bearing capacity is a decrease in the steel yield strength due to heating, as well as a decrease in the steel modulus of elasticity and, accordingly, an increase in slenderness. In this case, the first destruction occurs within the fire source location, so not including the outrigger in the frame work before the column collapse is a justified measure.

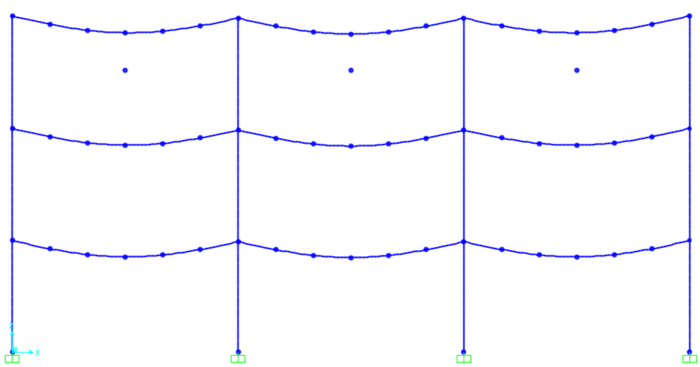


Fig. 6. The frame scheme at the fire beginning

At the next stage (1290s=21.5min), outriggers are introduced into the frame work and the destroyed column is removed from the calculation scheme (Fig. 7). Effort increases from -138tf to -312tf. The external heated column cannot withstand the dynamic effect and collapses. After that (1320s=22min), the frame beams collapse and the vitality loss occurs.

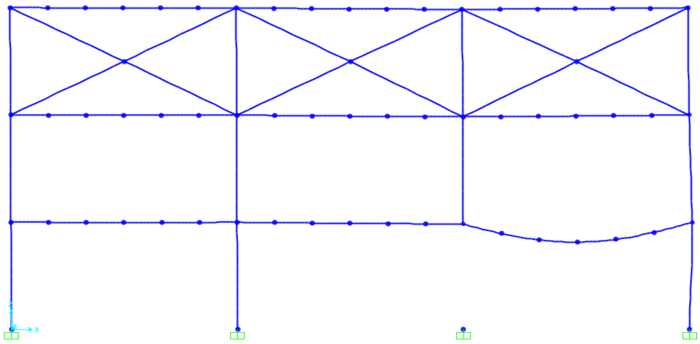


Fig. 7. Frame scheme of the after the column collapse

To increase the vitality time, it was decided to design the frame in such a way that the first failure occurs in the beam, not in the column, and that all frame elements withstand the dynamic effect of the column failure. Calculations were made for this frame, where the column has a lower load capacity ratio (herein after LCR) than the beam, with a gradual increase in the difference and calculation of the frame for fire vitality. The following results were obtained in the frame, in which the difference in the LCR of the beam and column is 20%.

The first destruction occurred in the heated beam at 1320s=22min The destruction occurs according to the bending strength inside the span. The reason for the destruction is a decrease in the steel strength characteristics by 60% (from 255MPa to 103.3MPa). At the next stage, the beam was removed from the calculation scheme and reactions from it with the opposite sign were applied instead. The internal heated column at 1350s=22.5 min has a LCR of 0.746, the heated external column – 0.708 (Fig. 8). The reason for the jump in the LCR of the external column is an increase in the buckling length in the frame plane by two times, since the beam was the anchorage for the column.

As of 1620s=27min, the heated internal column collapses due to the buckling from the frame plane. LCR of the external column is 0.601.

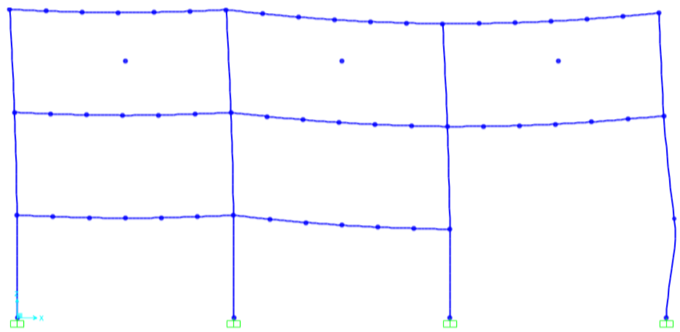


Fig. 8. Frame calculation scheme with a destroyed beam

After removing the internal column (Fig. 9) at 1650s=27.5 min and applying reactions with the opposite sign to it, the heated external column collapses due to the buckling from the bending plane. The reason for the destruction is an increase in axial force (from -47tf to -142tf) transmitted from the destroyed internal column through the outriggers. The internal unheated column is not destroyed (LCR 0.718). The external heated column cannot withstand the dynamic effect of the destruction of the internal heated column, but it is worth paying attention to the fact that the steel yield strength at this moment in the column is 63.5 MPa, that is, 25% of the initial value of 255 MPa. As of 1680s=28min, the frame vitality loss occurs due to the beams on different floors destruction.

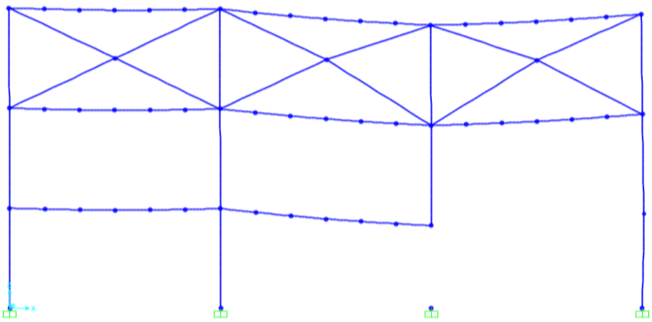


Fig. 9. Frame scheme of the after the column collapse

The calculation results of this frame (with the ratio of the span beam to the column height the l/h = 2) with different vitality increasing measures are given in Table. 1.

From Table 1 it is possible to see that the considered vitality increasing measures in the fire of multi-story buildings steel frames make it possible to increase the vitality loss time by 40%, and the time frame work after the 1st destruction by 12 times. Also, the reserve material strength when it decreases during heating is used 2.34 times (149.1MPa/63.5MPa) more.

Table 1 – Calculation results for the frame

Increasing vitality measures	1st destruction time	Vitality loss time	Vitality time	Percentage of use of material strength
Outrigger systems on the upper floor	1080s=18min	1110s =18.5 min	30s =0.5 min	43
Outrigger systems on the upper floor with connections with oval holes for bolts	1260s =21 min	1290s =21.5 min	30s =0.5 min	53
Outrigger systems on the upper floor with connections with oval holes for bolts; LCR in the beam is 20% larger than in the column	1320s =22 min	1680s =28 min	360s =60 min	75

Similar calculations were carried out for the ratio l/h=1, 3, 4. Based on the calculation results (Table 2), the relationship between the required difference in the LCR of the beam and the column to increase the vitality time was established from the ratio of the beam span to the column height.

Table 2 – The necessary difference of LCR depending on the frame geometry

l/h (the ratio of the beam span to the column height)	4	3	2	1
Difference in the LCR of the beam and the column, %	30	25	20	15

It was also found that the frame element cross-section shape plays an important role in the vitality increasing of multi-story buildings steel frames. The section factor (fire protection characteristic $(A/V)_{sh}$) depends on the cross-section section shape, which in turn depends on the element steel temperature. A frames were compared, where the column cross-section steel temperature is higher than that of the beams and vice versa. The calculation results are given in Table. 3.

As can be seen from the Table. 3, the steel frame element cross-sectional shape is no less important from the point of view of the frame's vitality in case of fire.

Table 3 – Comparison of the calculation with and without taking into account the shape of the section

Increasing vitality in the fire measures	Outrigger systems on the upper floor with connections with oval holes for bolts; LCR in the beam is 30% larger than in the column	Outrigger systems on the upper floor with connections with oval holes for bolts; LCR in the beam is 30% larger than in the column; the section factor in the beam are greater than in the column
1st destruction time	1530s=25.5min	1380s=23min
Vitality loss time	1590s=26.5min	2040s=34min
Vitality time	60s=1min	660s=11min
Percentage of use of material strength	60	77

Conclusions. On the basis of the above calculations, a technique was developed to multi-story buildings steel frames vitality increasing of in the fire event:

– the minimum difference in the LCR in beams and columns must be taken depending on the ratio of the beams span and the column height according to Table 2;

– the frame element fire-resistant cross-section shape must be taken in such a way that the cross-section factor of the beam must be greater than that of the column in order for the beam temperature to be higher:

$$(\frac{A}{V})_{sh,б} > (\frac{A}{V})_{sh,к}$$

– elements cross-sections must be design as such, in which the plastic hinge is formed earlier than local buckling occurs (1 class cross-section according to Euro code [14]);

– in the frame on the upper floor, it is necessary to provide X-shaped outrigger systems with their fastening on connections with oval holes for bolts so that they perceive vertical forces only in case of column destruction.

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ЗБІЛЬШЕННЯ ЖИВУЧОСТІ СТАЛЕВИХ КАРКАСІВ БАГАТОПОВЕРХОВИХ БУДІВЕЛЬ ВНАСЛІДОК ПОЖЕЖІ

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Анотація. В статті досліджено роботу сталевих каркасів багатоповерхових будівель при пожежі до і після першого руйнування, досліджено живучість каркасів при пожежі. Акцентовано на актуальності теми дослідження в час війни рф проти України. Виконано огляд попередніх досліджень вітчизняних і закордонних вчених, що присвячені живучості сталевих каркасів багатоповерхових будівель, зокрема при пожежі. Обрано модель каркасу для дослідження та введено спрощення задля наочності потрібних в дослідженні порівнянь. Було порівняно різні механізми руйнування сталевих каркасів багатоповерхових будівель при пожежі. Доведено, що за першого руйнування балки сталевого каркасу час втрати живучості буде довшим, ніж за першого руйнування колони.

Розглянуто та досліджено різні заходи посилення живучості каркасів. Досліджено аутригерні системи, як захід посилення живучості, та виявлено їх вплив на розподіл зусиль у каркасі під час нагрівання окремих елементів при дії температурних навантажень від пожежі. Встановлено залежність різних заходів посилення живучості сталевих каркасів багатоповерхових будівель при пожежі від геометричних розмірів каркасу. Встановлено, що коефіцієнт використання несучої здатності на початку дії пожежі в найбільш завантаженій колоні має бути меншим, ніж в балки найбільш завантаженій балці. Доведено, що різниця початкових коефіцієнтів використання несучої здатності в балці та колоні, необхідна для збільшення часу втрати живучості, різна для різних співвідношень прольоту балки до висоти колони. Виявлено, що форма перерізів каркасу впливає на його живучість при пожежі. Наголошується на важливості допущення розвитку обмежених пластиних деформацій в перерізах елементів каркасу. Сформовано рекомендації для інженерів-конструкторів щодо посилення живучості сталевих каркасів багатоповерхових будівель при пожежі.

Ключові слова: живучість, пожежа, сталевий каркас, багатоповерхова будівля, фізична нелінійність, війна, агресія рф.

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