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INVESTIGATION OF CHANGES IN STEEL FRAMES STRESS STATE IN FIRE AND INFLUENCE ON ITS VITALITY

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Modern studies of multi-storey buildings' load-bearing structures vitality are analyzed. The change of 2d steel frames various elements loading during a fire is investigated. The dependence of the frame loading on the location of the fire source on different floors and spans is analyzed. The influence of the frames' stress state change on their vitality is analyzed. The dependence of potential collapse mechanisms on fire source location in the frame is concluded.
Key words: vitality, fire, steel frame, multi-storey building, progressive collapse.

Actuality. In today's globalized world, there is a trend of urbanization. The population is growing in the cities and this leads to a decrease in the location of land plots for construction and increase a needsof multi-storey buildings. However, as the number of storeys of the building grows, so does its sensitivity to various threats, which can lead to the complete collapse of the building and a large number of human casualties. Many modern studies in the building construction field are devoted to the ability of a building to resist complete collapse after local destruction due to the threat - vitality. And if for the reinforced concrete frames of multi-storey buildings at the level of regulatory documents there are methods of calculation, for steel frames - there are only recommendations without methods of calculation [10]. One of the threats that can cause the collapse of a multi-storey building is a fire. One example of the progressive collapse of a multi-storey building due to a fire is the fire in Sao Paulo (Brazil, 2018, Fig. 1). In Ukraine, fire protection systems leave much to be desired, and at the same time in ukrainian norms, there is a requirement: the objects of the consequences class CC3 to rely on fire vitality [10].

Analysis of past research. Many studies of multi-storey buildings vitality are devoted to how to satisfy a "single vitality",which means the removal of one structural element from the scheme (usually the first-floor column), thus modeling the local destruction, which could potentially lead to much greater collapse [12-15, 18-19, 25-27]. This simulates the influence of a impact or explosion. But such a factor as fire can affect not only the column but also the beams and not one but several elements simultaneously. Studies on steel and reinforced concrete frames vitality in case of fire after the earthquake [16, 17] was conducted.Buckling was investigate in [28, 29].

Fig. 1. Multi-storey building collapse due to a fire in Sao Paulo, Brazil, 2018

The effect of destruction after local damage to the column and from the fire may differ [1, 4, 20], so multi-storey buildings should be calculated to vitality the fire. Studies [2-3, 5, 7, 8] show that during a fire, the floor of the frame can collapse first, not the column, as in the calculation of a “single”vitality from an uncertain factor. Therefore it is necessary to investigate various mechanisms of the collapse of frames at a fire for the purpose of definition less destructive.

Load capacity factor of steel frame elements and their influence on the frame vitality were studied [5-7]. In [1] it is emphasized that the load capacity factor in the columns should be 0.25 to prevent progressive collapse, which is economically impractical. Also in [13, 14] it is noted that only the increase in the frame elements load capacity does not guarantee increased vitality and it is necessary to take into account the peculiarities of the distribution of internal forces.

Studies [9] analyze the concept of "vitality" and propose to include the concept of "fire resistance". And it is expedient from the point of view that for studying vitality at a fire it is necessary to touch in one way or another a question of fire resistance.

In studies [11], calculations of the high-rise building steel frame for the fire were performed, taking into account fire protection and parametric fire regime depending on the building footrint. The possibility of designing a frame under the action of fire loads and preventing even local destruction was investigated. The maximum temperature load was 120^{o}C with fire protection R180. But after designing a frame, the frame steel weighthas increased by 50%.This indicates that the fire protection minimizes the temperature load on the frame elements from the fire but anyway constructive measures are needed to increase vitality. The large increase in metal consumption indicates that it is impractical to design the building frame in the case of a fire or other threat, which can lead to progressive collapse, completely eliminating the possibility of local destruction, as this probability always exists during an emergency. To enhance fire vitality and seismic resistance, it is recommended to use outrigger systems (superframes), combining vertical and horizontal outriggers along the contour of the frame frames [1].

Previously studied measures to increase the steel frame’s vitality in case of fire (increased load capacity, increased fire protection, combined outrigger systems) significantly increase the metal consumption and cost of construction and need to be optimized. It is necessary to study in more depth the peculiarities of the forces distribution and the stress state of the building frame structures during a fire and to explore measures to increase vitality, which will be effective and economically feasible.

Unresolved part of the problem. In contrast to a impact or explosion, the effect of a fire is more extended in time.Therefore, studying the vitality of multi-storey buildings frames in case of fire, it is necessary to analyze not only the work of the frame after local destructionbut also the processes that precede it: initial load capacity factor, change of internal forces, change of steel mechanical characteristics when heated, change of stiffness, load capacity factor(strength, general and local buckling) in the frame before the first destruction due to fire and their impact on the framevitality.

Research objectives. The following tasks were performed in these studies:
- to investigate the changing load capacity factor of the 2d steel framevarious elements during the design fire;
- to analyze the dependence of the frame load capacity factor change on the location of the fire source on different floors and spans;
- to analyze the influence of changes in the frame`s stress state on their vitality.

The main text. A numerical study of the 2d steel frame when a fire acted in one of the spans on one of the floors was conducted. The object of the study is a 2d steel frame consisting of three spans (2 sidespans and one middle) and three floors (lower, middle, upper) without fire protection. Beam span accepted is 7.2 m. The height of the floor is accepted - 3.6 m. The columns are unfastened from the plane of the frame at the level of adjacency of the beams, the beams are unfastened from the plane with a step of 2.4 m. Frame step - 6m. The load on the beams and columns was assumed to be the same - 50% in order to make a clear comparison of load capacity factor changes during the fire. The base of the columns is taken with a rigid connection. The joints beam to column connection are rigid. There are 4 fire scenarios that were considered: lower floor - outside span, lower floor - middle span, middle floor - outside span, middle floor - middle span (Fig. 2).

Loads were calculated according to [21]. Design situation is accidental. The beams dead load were taken $1t/m^2x6m=6t/m$. 35% of the wind characteristic (according to UFC recommendations [23]) for Kyiv was accepted for the columns. The steel elements are S255. Steel construction designare performed according to [22]. The beam cross-section class is 1 (only elastic deformations according to [22]).The effect of the fire is simulated by the temperature loads determined according to [24].

The fire calculation is nonlinear static, as the fire has no instantaneous factors such as explosion, impact, etc. Step by step with an interval of 30 seconds in a nonlinear calculation (taking into account the geometric nonlinearity) was a set temperature increase. Change of steel strength and deformation characteristics depending on temperature according to DSTU-N B EN 1993-1-2: 2010 [24].

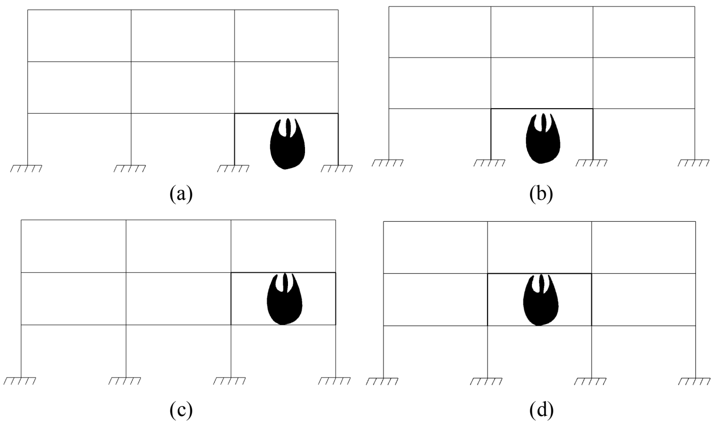

Fig. 2. Accepted scenarios of calculated fire: (a) - lower floor - outside span, (b) - lower floor - middle span, (c) - middle floor – outside span, (d) - middle floor - middle span

Simplification. The calculation assumes that the temperature is distributed evenly along the length of the element and the cross-section. It is also assumed that the elements of the frame do not perceive other temperatures than fire.

The calculation results are shown in the table. 1.

Table 1

Calculation results

Scenario	Cell where the fire occurs	Time of the first destruction, s	Element	The temperature of the heated beam, ^{0}C	Within/outside the heated cell	The factor of load capacity
1	Lower floor - outside span	300	Outside column	229	Within	Buckling from the plane of bending
2	Lower floor - middle span	330	Outside beam	249	Outside*	Flange local buckling
3	Middle floor – outside span	240	Outside beam	188	Within	Flange local buckling
4	Middle floor - middle span	360	Outside beam	269	Outside*	Flange local buckling

* the destruction took place on the floor where was a fire

In scenario 1, the middle column was more loaded at the fire beginning, but due to the bending caused by the thermal expansion of the beam, the outside column is loaded and collapsed faster (Fig. 3). From fig. 4 it is possible to see that on the beam load capacity factor schedule there is a jump. On the beam load capacity factor change graph for various factors (Fig. 5) you can see that the jump occurs in the load capacity factor change for the flange local buckling. When the normal force in the beam increases due to the temperature load action,there is a transition from bending to compressed-bent stress state. The beam cross section was adopted in class 1 (according to [22] only elastic deformations are allowed in the cross-section), and the compressed-bent elements cross-sections according to [22] are considered to be those in which limited plastic deformations are allowed.Therefore, the reason for the graph jump is that the transition from the bending stress state to the compressed-bentstate is the transition from elastic to elastic-plastic analysis, which requires a greater load capacity reserve.

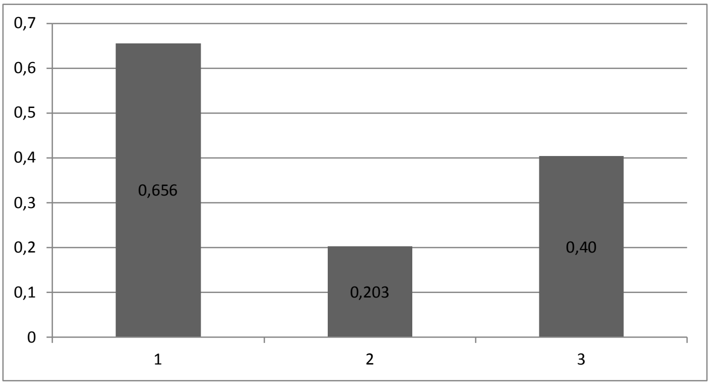

Fig. 3. Load capacity factor increase for scenario 1:
1 - outside column, 2 - middle column, 3 - beam

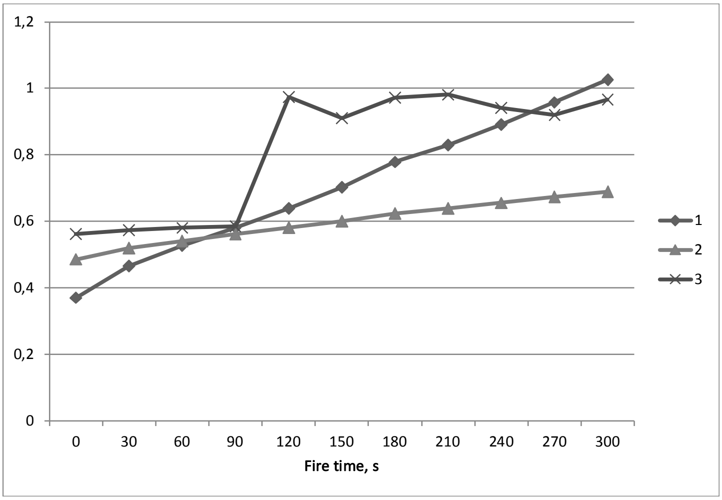

Fig. 4. Schedule of changes load capacity factor for scenario 1:
1 - outside column, 2 - middle column, 3 – beam (0-90s – elastic analysis, 120-300s – elastic-plastic analysis)

From Fig. 7 you can see that in the middle span on the ground floor (scenario 2), in contrast to the outside, the beam is loaded faster than the column. But the first is collapsed not the middle beam (heated), but the outside, although in it the jump in load capacity factor occurs later than in the middle (heated, Fig. 6). The earlier destruction of the outside beam, and not the middle, on which the fire acts, is explained by the smaller value of relative shift of the centroid m_{ef}, which is due to the smaller ratio of bending moment to normal force (Fig. 8).

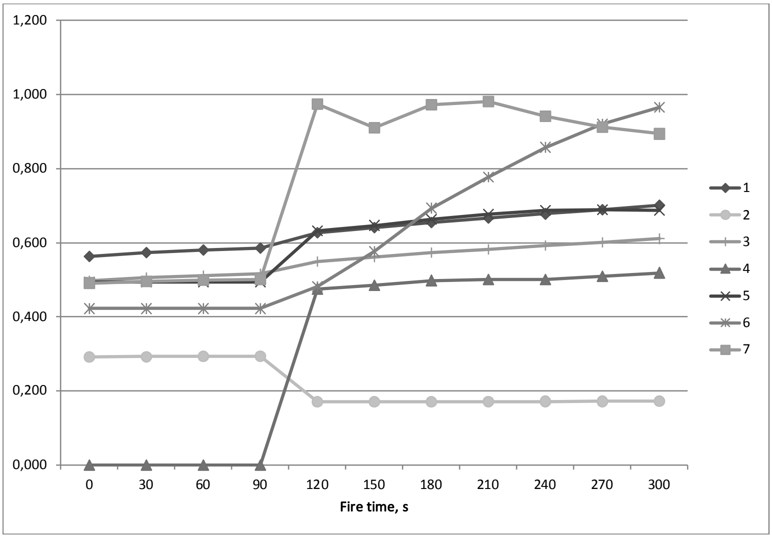

Fig. 5. Heated beam change load capacity factor for scenario 1: 1 - normal stress strength, 2- tangential stress strength, 3 - reduced stress strength, 4 - buckling in the plane of the bend, 5 - buckling from the plane of the bend, 6 - web local buckling, 7 - flange local buckling

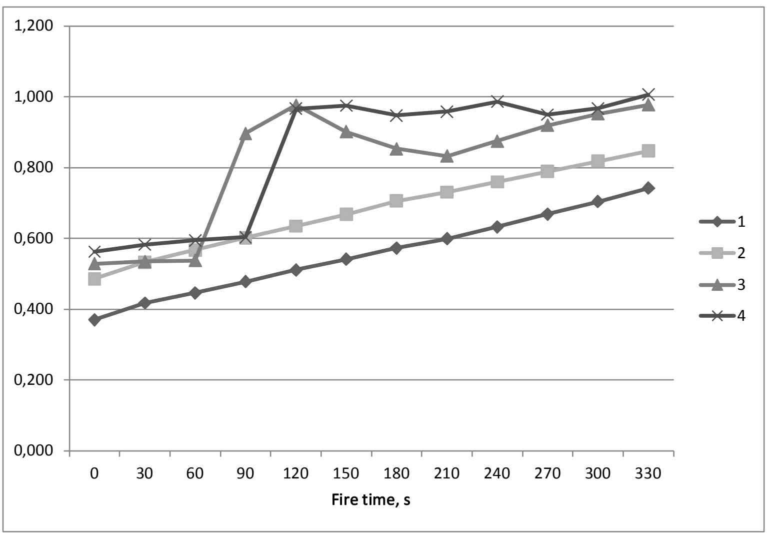

Fig. 6. Schedule of changes load capacity factor for scenario 2:
1 – outside column, 2 – middle column, 3 – middle beam (0-60s – elastic analysis, 90-330s – elastic-plastic analysis), 4 – outside beam (0-90s – elastic analysis, 120-330s – elastic-plastic analysis)

From Fig. 9 you can see that in the outside span on the intermediate floor (in scenario 3) in contrast to the lower (scenario 1) is loaded faster beam than the column. The fracture occurs in the outside beam, but in the middle beam due to adjacent beam thermal expansion, there is a significant increase in load capacity factor (Fig. 10).

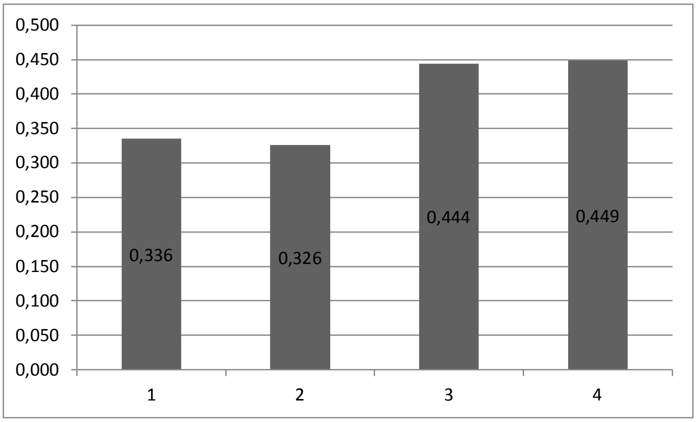

Fig. 7. Load capacity factor increase for scenario 2:
1 – outside column, 2 – middle column, 3 – outside beam, 4 –middle beam

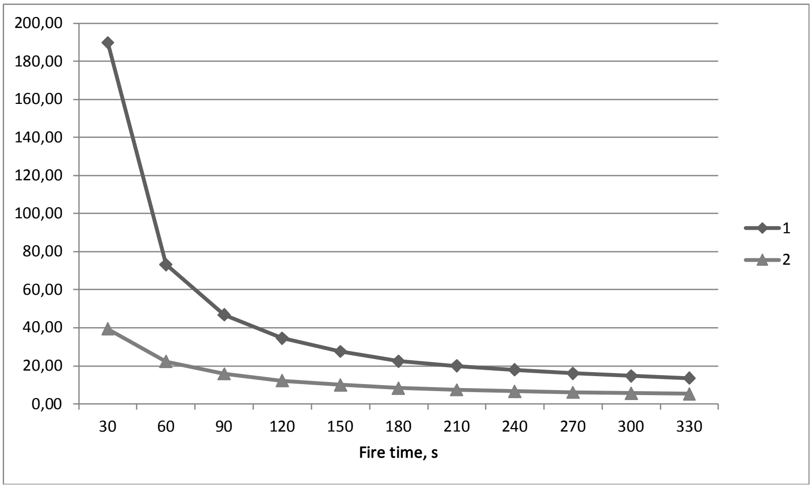

Fig. 8. Schedule of changes beam'srelative shift of the centroid m_{ef} for scenario 2: 1 – outside beam, 2 –middle beam

In the middle span on the intermediate floor (scenario 4) as well as in the lower (scenario 2) the failure occurs in the outside beam, which is outside the heated cell (Fig. 11).

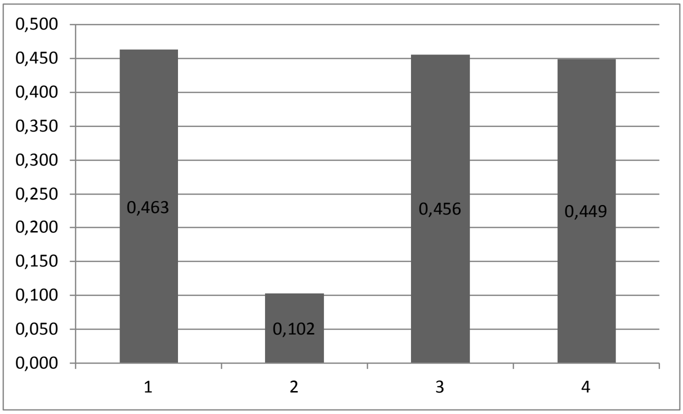

Fig. 9. Load capacity factor increase for scenario 3: 1 – outside column, 2 – middle column, 3 – outside beam, 4 –middle beam

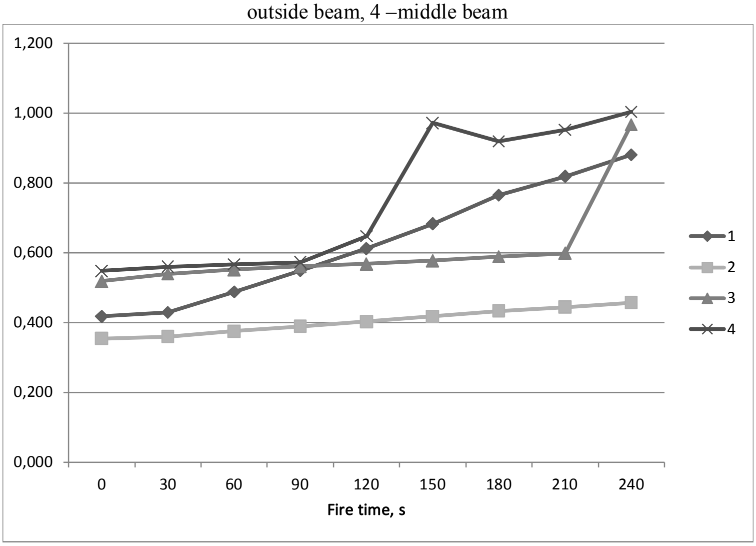

Fig. 10. Schedule of changes load capacity factor for scenario 3: 1 – outside column, 2 – middle column, 3 – middle beam (0-210s – elastic analysis, 240s – elastic-plastic analysis), 4 – outside beam (0-120s – elastic analysis, 150-240s – elastic-plastic analysis)

Conclusions. In the case of a fire, the time to the considered frame first destruction in the fire scenario in the middle span is greater than in the outside. In case of fire on the upper floor, the destruction occurs later than on the lower floor. On the lower floor, the columns are more likely to collapse earlier than the beam than on the upper floor. In the middle span, the beams are more prone to collapse earlier than the column than in the outside. As you can see, depending on the fire source location on different floors and spans, both the beam and the column of the frame may be the first to collapseand the potential frame collapse mechanisms may be different. This should be taken into account when analysis the multi-storey steel frames vitality in case of fire.

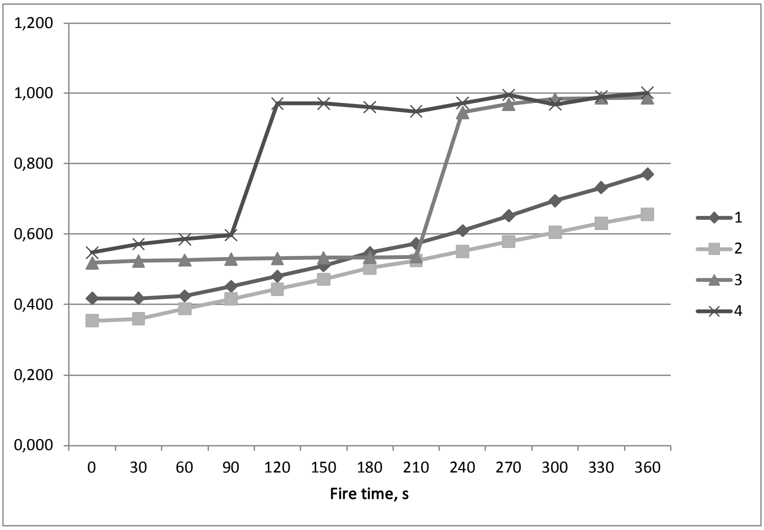

Fig. 11. Schedule of changes load capacity factor for scenario 4: 1 – outside column, 2 – middle column, 3 – middle beam (0-210s – elastic analysis, 240-360s – elastic-plastic analysis), 4 – outside beam (0-90s – elastic analysis, 120-360s – elastic-plastic analysis)

When studying steel frames for fire, it is necessary to take into account not only the decrease in the characteristics of steel from temperaturebut also the distribution of forces, changes in the load capasity of the elements by various factors. In the event of a fire, the steel multi-storey frame’sbeam can change from a bending stress state to a compressed-bent state, which allows the development of limited plastic deformations. Therefore, analysingmulti-storey steel frames for vitality and fire resistanse, it is necessary to design them taking into account the development of limited plastic deformations, which requires an additional load capacity reserve.

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ДОСЛІДЖЕННЯ ЗМІНИ НАПРУЖЕНОГО СТАНУ СТАЛЕВИХ КАРКАСІВ ПРИ ПОЖЕЖІ ТА ЇЇ ВПЛИВУ НА ЖИВУЧІСТЬ

Проаналізовано сучасні дослідження живучості несучих конструкцій багатоповерхових будівель. Визначено недоліки досліджених раніше заходів посилення живучості сталевих багатоповерхових каркасів. Встановлено необхідність дослідження більш ефективних та економічно доцільних заходів. Досліджено зміну завантаженості різних елементів сталевого плоского каркасу під час пожежі. Проаналізовано залежність завантаженості рами від розташування джерела вогню на різних поверхах та прольотах. Розглянуто 4 сценарії розташування джерела пожежі в плоскому багатоповерховому каркасі.Проаналізовано вплив розподілу внутрішніх зусиль в балках при нагріванні на напружений стан каркасу, зокрема на місцеву стійкість поясу та стінки двотаврової балки.

Виявлено, що від температурних розширень внаслідок пожежі першими в каркасі руйнуватися можуть не лише ті елементи, які нагріваються. Встановлено, що під час пожежі перше руйнування швидше відбувається в крайньому прольоті каркасу, ніж у середньому. При порівнянні сценаріїв пожежі на нижньому та верхньому поверхах каркасу визначено, що на нижчому поверсі колони більш схильні до того, щоб зруйнуватися раніше за балку, ніж на верхньому. При порівнянні сценаріїв пожежі в середньому та верхньому прольотах каркасу визначено, що в середньому прольоті балки більш схильні до того, щоб зруйнуватися раніше за колону, ніж у крайньому. Підтверджено, що залежно від розташування пожежі на різних поверхах та прольотах першими можуть руйнуватися як балка, так і колона каркасу. Встановлено, що залежно від розташування джерела пожежі можуть бути різні механізми руйнування багатоповерхового каркасу. Встановлено, що на напружений стан конструкцій каркасів суттєво впливає розподіл внутрішніх зусиль при температурних навантаженнях, а не лише вогнезахист та вогнестійкість сталевих конструкцій.

Ключові слова: живучість, пожежа, сталевий каркас, багатоповерхова будівля, прогресуюче руйнування.

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INVESTIGATION OF CHANGES IN STEEL FRAMES STRESS STATE IN FIRE AND INFLUENCE ON ITS VITALITY

Modern studies of the multi-storey buildings load-bearing structures vitality are analyzed. The shortcomings of the previously studied measures to increase the steel multi-storey frames vitality are identified. The need to study more effective and cost-effective measures have been identified.

The change of 2d steel frame various elements loading during a fire is investigated. The dependence of the frame load-bearing capacity on the location of the fire source on different floors and spans is analyzed. 4 scenarios of fire source location in 2d multi-storey frame are considered. The influence of the distribution of the internal forces in the heated beams on the frame stress state, in particular on the local buckling of the I-beam flange and the web is analyzed. It was found that due to temperature expansions due to fire, not only heated elements are can be the first to be damaged in the frame. It is established that during a fire the first destruction occurs faster in the outside span of the frame than in the middle. When comparing the fire scenarios on the lower and upper frame floors, it was determined that on the lower floor the columns are more prone to damage earlier than the beam on the upper floor. When comparing the fire scenarios in the middle and outside frame spans, it was determined that in the middle span the beams are more prone to collapse earlier than the column than in the outside. It has been confirmed that, depending on the fire source location on different floors and spans, both the beam and the column of the frame may be the first to collapse. It is established that depending on the fire source location there may be different mechanisms of multi-storey frame collapse. It is established that the frame structures' stress state is significantly influenced by the distribution of internal forces at temperature loads, and not only fire protection and steel structures fire resistance.

Key words: vitality, fire, steel frame, multi-storey building, progressive collapse.

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The influence of multi - storey buildings steel frames stress state in case of fire on their vitality is analyzed.

Tabl. 1. Fig. 11. Ref. 24.

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Дауров М.К., Білик А.С. **Дослідження зміни напруженого стану сталевих каркасів при пожежі та її впливу на живучість**//Опір матеріалів і теорія споруд: наук.-тех збірник. – К.:КНУБА, 2021. – Вип. 108. – С. 325-336.

Проаналізовано вплив напруженого стану сталевих каркасів багатоповерхових будівель при пожежі на їх живучість.

Табл.1. Рис. 11. Бібліогр. 24 назв.

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