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THE MULTI-STOREY BUILDINDS STEEL FRAMES PROGRESSIVE COLLAPSE MECHANISMS IN FIRE

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Abstract. An overview of previous studies, dedicated to the vitality of the multi-story building with a steel frame was carried out. Currently, measures are available to increase the multi-story buildings' steel frame vitality in fire, which affects the potential progressive collapse mechanism. The quantitative vitality indicators have been determined earlier. The model used to study a multi-story building steel frame is described. The way of modeling the fire action on steel structures is presented. The criterion for the steel frame elements destruction is determined.

The measures of increasing vitality for the multi-story building steel frame model are presented. The sequence of multi-story buildings' steel frames different elements destruction for a various measures of increasing vitality is determined. The collapse duration of each of the considered progressive collapse mechanisms is analyzed.

It is established that the initial destruction in the unheated frame element leads to a less projected and more unfavorable progressive collapse mechanism in the event of an accident evacuation. It is determined that to avoid the initial destruction in the unheated frame element, you need to use an attachment of the outriggers to the columns joint with the admission of vertical displacements. It is established that in the case of beam destruction earlier than the column, the progressive collapse mechanism will be longer than in the column's initial destruction case. Earlier internal column destruction leads to a longer progressive collapse mechanism than earlier external column destruction. It is established that the progressive collapse mechanism of the type "beam - the internal column - the external column – progressive collapse" is the longest and the most predictable. The gradation of the progressive collapse mechanisms of steel frames in the role of a qualitative vitality indicator is determined. The gradation presented can be used for the research of frames with a variety of spans and floors.

Keywords: finite element method, steel structures, vitality, fire, progressive collapse, collapse mechanism.

Introduction. The main purpose of a building's load-bearing structure design is to prevent the destruction of each element it consists of. As the load-bearing structures develop as systems, new threats can potentially destroy the building. Designing a building in such a way that the action of load from their weight, load from people and equipment, snow and wind, etc., possible and corresponding requirements are present in the current regulatory documents. However, for many buildings, a fire, explosion, impact, etc. is an extraordinary influence, and the design of a building's structures to prevent any destruction is impossible or economically inappropriate. In this regard, scientific studies of the vitality structures as a system - the ability to resist local destruction and prevent its spread. Fire as a threat has been relevant at all times but is becoming more widespread today because of the war russia against Ukraine.

Analysis of previous research. Today, research on the vitality of multi-story buildings load-bearing steel structures can be divided into vitality in modeling the explosion, fire, and earthquake. Numerous research has been conducted to invent measures for enhancing structures vitality. As a basic measure, when the column is destroyed, there are outrigger systems [1-4] were investigated, which redistribute forces from the destroyed column to other elements. In British studies, the steel frame joints load-bearing capacity in a fire was analyzed [5]. In Japanese studies [6], combined outrigger systems and the columns load capacity ratio were studied. It was determined that a ratio of 0.25 is sufficient to ensure vitality or fire. The study of the ensuring vitality of multi-story building's steel frames by preventing any destruction by increasing the cross sections of the elements and increasing fire protection showed that such an approach requires an increase in the metal intensity of the frame by 40-60% [7]. The feasibility of using the hinged joints of the adjoining beams to the columns to achieve a more projected numerical destruction was found in [8].

To enhance the vitality of multi-story building's steel frames, a technique was developed [9], which includes the following measures:

– regulation of the load capacity ratio difference in the beams and columns of the frame;

– taking into account the frame element's cross-section shape which affects the temperature in the frame element in fire and local buckling when heated;

– the nodes of the adjacent elements of the outriggers.

Different measures can have a different effect on the frame's vitality. Quantitative and qualitative indicators are required to evaluate this impact. In [9], the quantitative indicator of the steel frame vitality in the fire is "vitality time": the period from the destruction of one of the elements to the final collapse of the frame (vitality loss). Defining quality vitality is an open issue today.

This work is offered as a qualitative vitality "type of collapse mechanism" – a sequence of destruction of different frame elements. In [10], the impact of fire location on the potential collapse mechanism was previously investigated and the most unfavorable was determined. In [11-12] the next collapse mechanisms were investigated: vertically or lateral.

Research tasks. The following tasks are completed in this research:

– to analyze the existing measures of increasing the vitality of multi-story buildings' steel frames in fire, which affect the potential mechanism of their collapse;

– to determine the destruction sequence of different elements of multi-story buildings' steel frames for various measures of increasing the vitality;

– analyze the duration of the destruction of each of the mechanisms considered;

– to determine the gradation of destruction mechanism types of steel frames in the role of qualitative vitality.

Materials and research methods. Modeling the collapse of the multi-story building steel frame was made in the fire under different initial conditions. As the initial conditions were considered the measures of the frame vitality enhancement:

– the use of outrigger systems for redistribution of efforts due to the column destruction;

– different joints of attachment of outrigger systems;

– different differences in load capacity ratio in the elements of beams and columns;

– different shapes of elements cross sections of beams and columns.

The frame is modeled as rod finite elements. There are 3 spans, 3 floors. The beams span is 7.2m, floor height – 3.6m. For comparing the work of beams and columns of the frame, one cross-section of the beam was taken in different spans on different floors, and one cross-section of different floor columns. The rigid bases of columns and hinged beams to the column connections were adopted. On beams during the fire, there is a uniformly distributed load of 6 t/m, which simulates the effect of dead and live load in a residential or public multi-story building. The external columns are horizontally distributed load, which models the wind load, which adds a significant proportion to the load capacity ratio of columns in multi-story buildings. The steel of the frame elements is S255.

The action of the fire is modeled by temperature loads, which were determined by DSTU B EN 1993-1-2: 2010 [13]. The fire location is taken in the external span on the 1st floor (Fig. 1) as the most unacceptable in terms of the distribution of effort and potential collapse [10]. There is no fire protection for steel structures. The frame was calculated by [14-15].

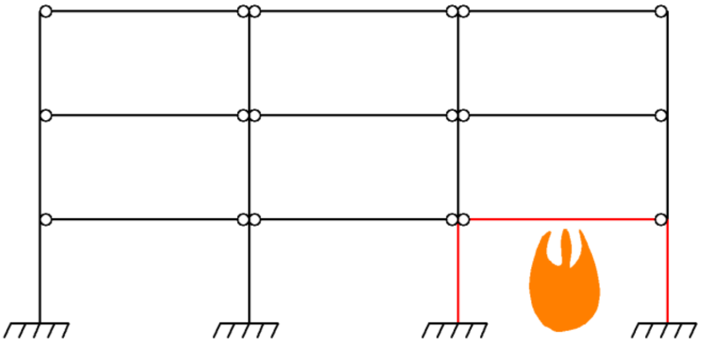


Fig. 1. The fire location in the frame

The frame elements are designed from a solid welded I-beam cross-section. It was accepted the plastic hinge occurs earlier than the local buckling. This allows modeling the frame collapse with rod finite elements.

The destruction criteria of a plastic hinge in the element. The element destruction was modeled with element removal from the calculation scheme with the reactions with the opposite sign. The dynamic factor value is accepted as 1 because the fire is not the factor that leads to instant destruction.

Research results. The first calculation was made for the frame, in which the load capacity ratio in the most loaded column and the most loaded beam was taken 0.5. Outrigger systems were used as a measure to increase vitality (Fig. 2).

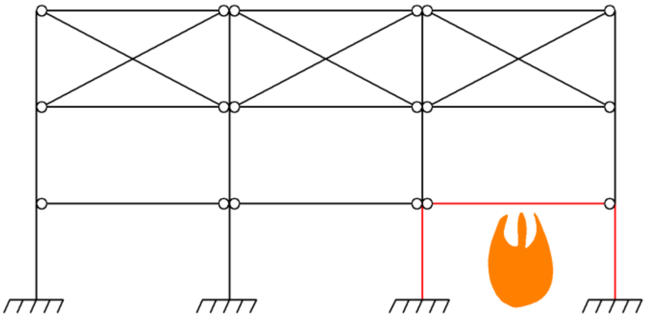


Fig. 2. Scheme of steel frame with outrigger systems

The first ruined element is the internal unripe column on the ground floor. The destruction time is 18 minutes. The deformed frame scheme is shown in Fig. 3, a.

In the next stage, as of 18.5 minutes the destruction of the middle heated column and the external unheated column (Fig. 3, b). The final destruction occurs because of the fall above-located floors below (Fig. 3, c).

It can be concluded that the mechanism of destruction of the type of "unheated middle column – heated internal column – final collapse" lasts 1 min (2 stages of calculation), is fast and dangerous in terms of people's ability to evacuate from the building in the event of an accident.

The second calculation was made for a similar frame, but with the attachment of the outrigger nodes, which allow vertical movement (Fig. 4). It is accepted that the elements of the outriggers are included in the calculation scheme only after the column is damaged.

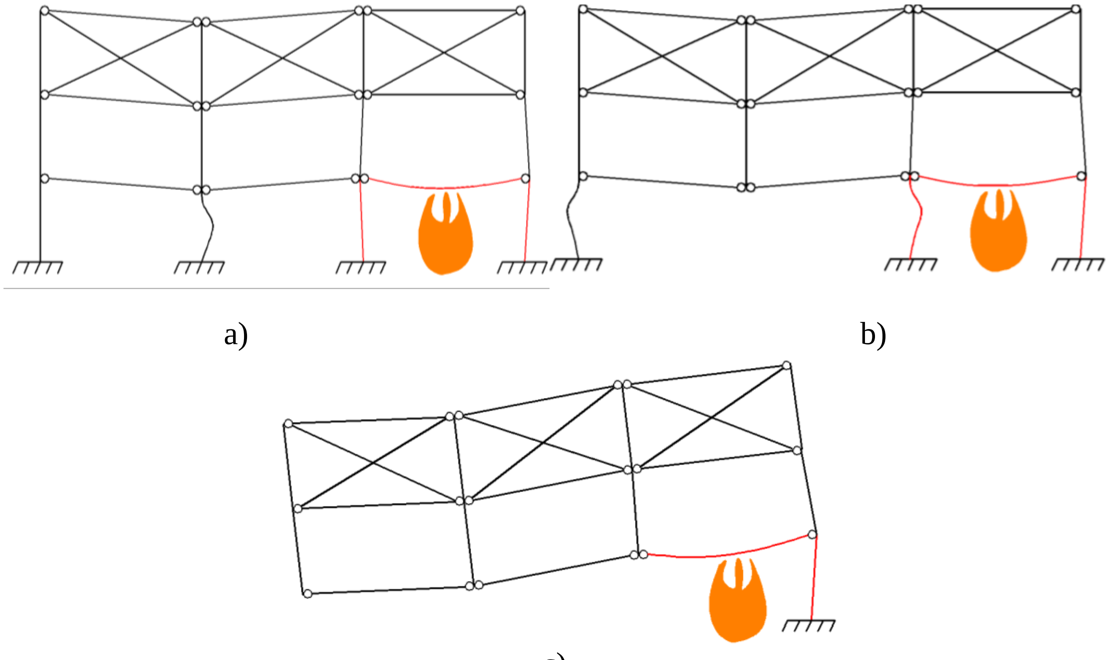


Fig. 3. The sequence of frame collapse for the first calculation:
a – destruction of the internal unheated column; b – destruction of the heated internal and external unheated column; c – final collapse

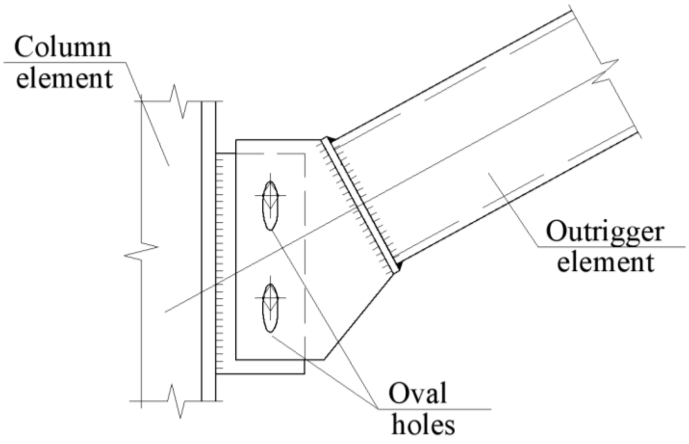


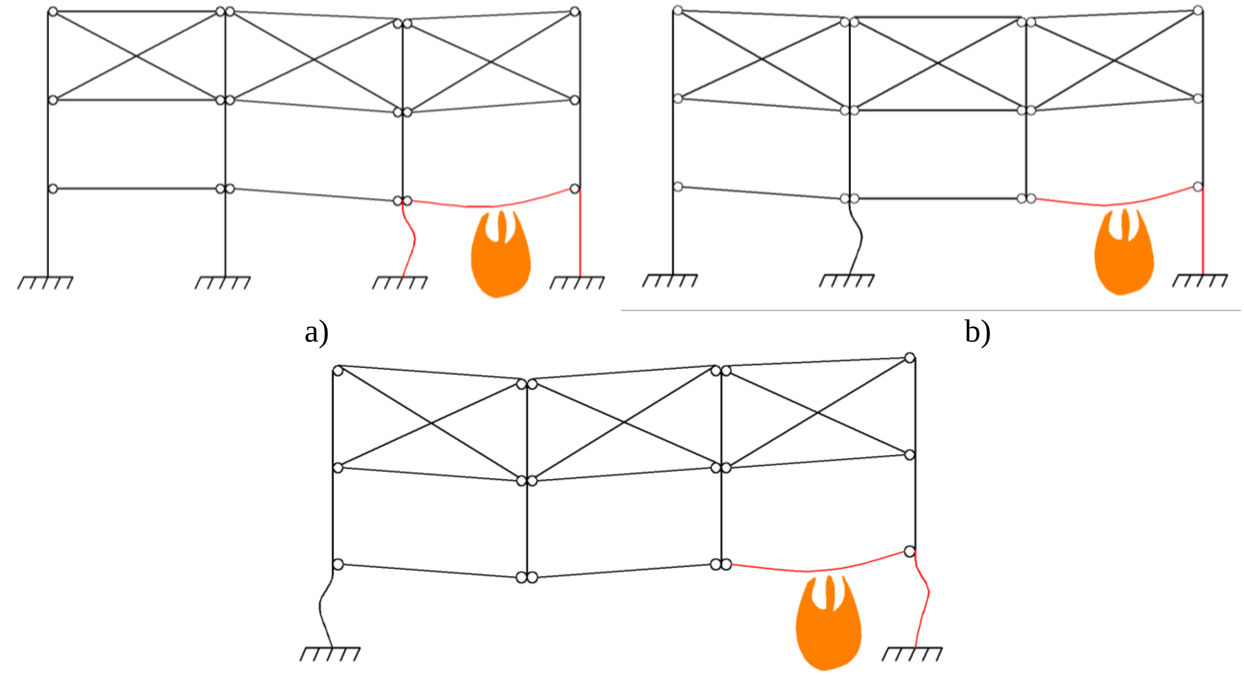
Fig. 4. Typical outrigger element to column connection

As of 21 minutes, the first collapsed element was the heated internal column on the 1st floor (Fig. 5, a). After removing the collapsed column in the calculation scheme in the next stage (21.5 minutes), the unheated internal column (Fig. 5, b) is immediately collapsed. As of 22 minutes, the final collapse of the frame was due to the destruction of the external columns (Fig. 5, c).

In this case, the collapse mechanism was like a sequence "heated internal column – the external column – the final collapse". The first destruction occurs in a heated element, which is more predicted in the scientific study of this phenomenon. Destruction occurs 3 minutes later than in the first calculation. Such a mechanism as the previous one is also fast and dangerous.

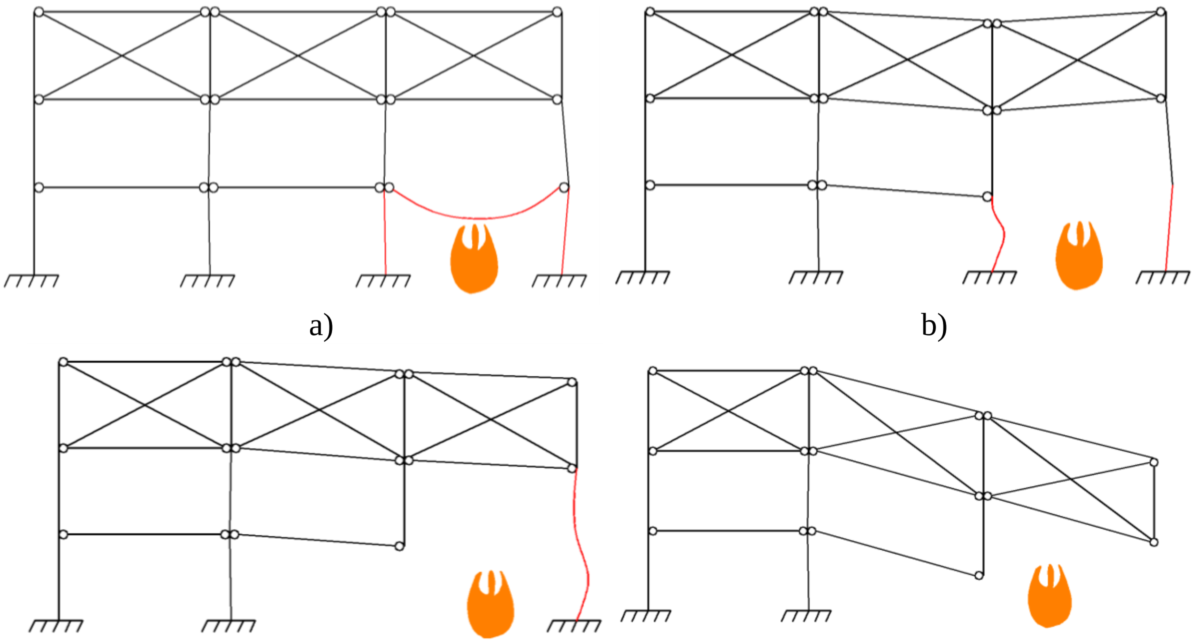
The third calculation was made for the frame in which the joints of the attachment of the outriggers according to Fig. 4 and the load capacity ratio in the most loaded column is 20% higher than in the most loaded beam. The collapse mechanism occurred with the following sequence:

– as of 22 minutes the heated beam collapsed (Fig. 6, a);
– as of 27 minutes the internal heated column collapsed (Fig. 6, b);
– as of 27.5 minutes the destruction of the externally heated column (Fig. 6, c);
– as of 28 minutes the final collapse of the frame (Fig. 6, d).



a) b) c)

Fig. 5. The sequence of frame collapse for the second calculation:
a – destruction of the heated internal column; b – destruction of the unheated internal column;
c – final collapse



a) b) c) d)

Fig. 6. The sequence of frame collapse after the third calculation:
a – destruction of the beam; b – destruction of the heated internal column; c – destruction of the heated external column; d – is the final collapse

The comparison of the third calculation with the two preliminary calculations for the frame collapse in the fire was established:

– the collapse mechanism of the type "beam-internal column-external column-final collapse" begins later in time (22 minutes compared to 18 minutes for "unheated internal column-heated internal column-final collapse" and 21 minutes "heated internal column-external column-final collapse");

– collapse mechanism of the type "beam-internal column-external column-final collapse" is longer (6 min compared to 1 min for "unheated internal column-heated internal column-final collapse" and 1 min "heated internal column-external column-final collapse").

The fourth calculation was made for a similar frame with a span of 9.6m (Fig. 7). Measures to enhance vitality are similar to the preliminary calculation.

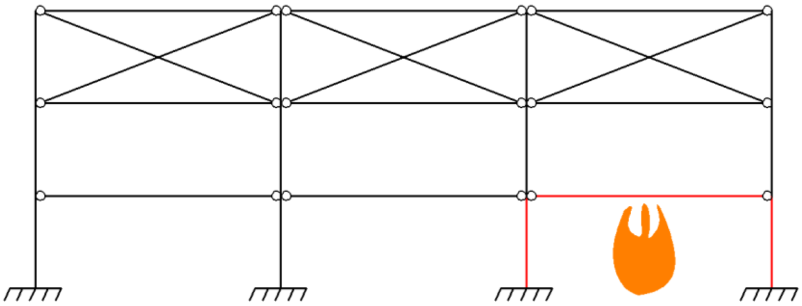
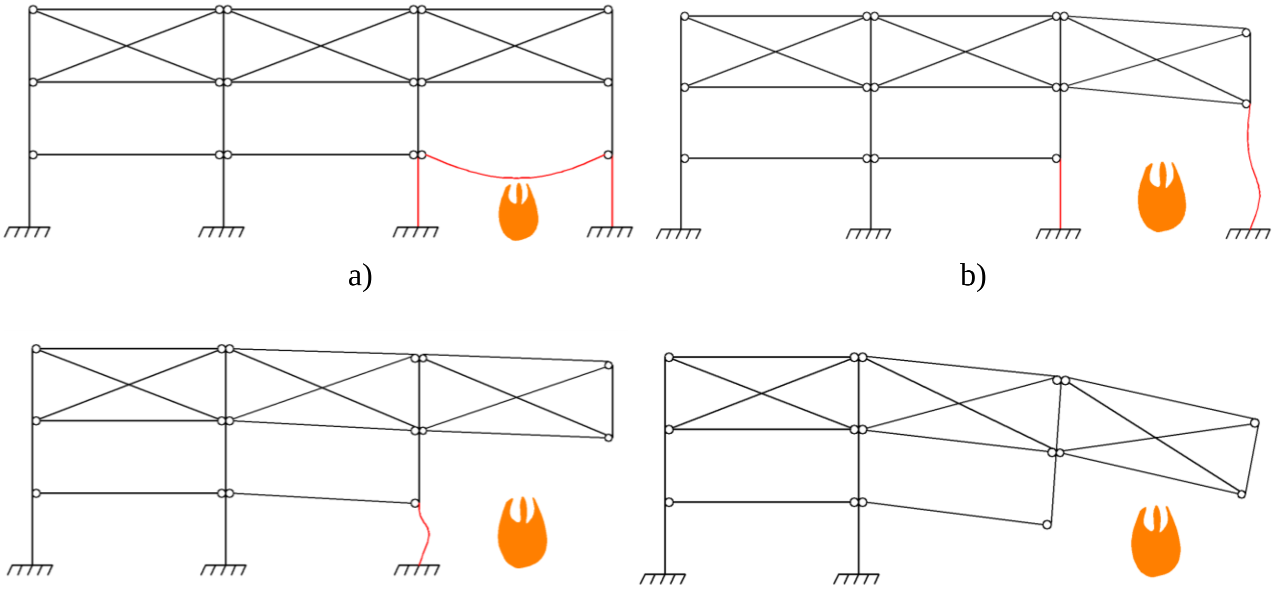


Fig. 7. A frame with a span of 9.6m

The collapse mechanism occurred with the following sequence:

– as of 25.5 minutes the heated beam collapsed (Fig. 8, a);
– as of 26 minutes was the destruction of the externally heated column (Fig. 8, b);
– as of 26.5 minutes the destruction of the internal heated column (Fig. 8, c);
– as of 27 minutes the final collapse of the frame (Fig. 8, d).

As you can see from the values of the time, the collapse mechanism is the type of "beam – the externally heated column – the internal heated column – the final collapse" less than the duration (1.5 min) by the mechanism type of "beam – the internal column – the external column", but longer than the mechanisms where the first column is collapsed. The results of all calculations are listed in Table. 1.



a)

b)

c)

d)

Fig. 8. The sequence of frame collapse for the fourth calculation:
a – destruction of the beam; b – destruction of the heated external column; c – destruction of the heated internal column; d – the final collapse

Table 1 – Calculations results

Collapse mechanism type	The time of the onset of collapse, min	Duration of destruction, min
«unheated internal column –heated internal column – final collapse»	18	1
«heated internal column –external column – final collapse»	21	1
«beam – internal column –external column – final column»	22	6
«beam – external heated column – internal heated column – final column»	25.5	1.5

Conclusions. The above calculations revealed various collapse mechanisms of multi-story buildings' steel frames. The collapse mechanism will be longer and predictable if:

– the first will collapse the heated element of the frame;

– the first element to be collapsed should be a beam, not a column that prevents loading of other columns;

– the internal column should be collapsed earlier than the external, which prevents the console from "hanging" above the floors.

Based on the above gradation, it is possible to qualitatively evaluate the vitality of steel frames as a result of a fire and other factors. The stated provisions can be taken as a basis for the study of the vitality of steel frames with different numbers of spans and floors.

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МЕХАНІЗМИ РУЙНУВАННЯ СТАЛЕВИХ КАРКАСІВ БАГАТОПОВЕРХОВИХ БУДІВЕЛЬ ПРИ ПОЖЕЖІ

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Анотація. Проведено огляд попередніх досліджень присвячених питанню живучості багатоповерхових будівель зі сталевим каркасом. Проаналізовано наявні на сьогодні заходи посилення живучості сталевих каркасів багатоповерхових будівель при пожежі, які впливають на потенційний механізм їх руйнування. Визначені кількісні показники живучості, досліджені раніше. Описано використану в дослідженні модель сталевого каркасу багатоповерхової будівлі. Представлено спосіб моделювання дії пожежі на сталеві конструкції. Визначено критерій руйнування елементів сталевого каркасу.

Представлено використані заходи посилення живучості для моделі сталевого каркасу багатоповерхової будівлі. Визначено послідовність руйнування різних елементів сталевих каркасів багатоповерхових будівель за різних заходів посилення живучості. Проаналізовано тривалість руйнування кожного з розглянутих механізмів.

Встановлено, що початкове руйнування в ненагрітому елементі призводить до менш прогнозованого і більш несприятливого механізму руйнування з точки зору евакуації в разі аварії. Визначено, що для уникнення початкового руйнування в ненагрітому елементі потрібно використовувати вузол кріплення аутригерів до колон з допущенням вертикальних переміщень. Встановлено, що у випадку руйнування балки раніше за колону, механізм буде тривалішим, ніж у випадку початкового руйнування колони. Більш раннє руйнування середньої колони призводить до тривалішого механізму, ніж більш раннє руйнування крайньої колони. Встановлено, що механізм руйнування типу «балка-середня колона-крайня колона-остаточне руйнування» найбільш тривалий та найбільш передбачуваний. Визначено градацію типів механізму руйнування сталевих каркасів в ролі якісного показника живучості. Представлена градація може бути використана для досліджень каркасів різної прольотності та поверховості.

Ключові слова: метод скінченних елементів, сталеві конструкції, живучість, пожежа, прогресуюче руйнування, механізм руйнування.

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