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PROVIDING OF THE VITALITY OF STEEL FRAMES OF HIGH-RISE BUILDINGS UNDER ACTION OF FIRE

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High-rise buildings are sensitive to progressive collapse – when the local destruction leads to the collapse of the entire building or disproportionately large part of it. Current Ukrainian norms are requiring the vitality of high-rise buildings under the action of unidentified factors and, since 2017, - under the action of fire, which is considered in this article.

Key words: high-rise buildings, progressive collapse, threat, vitality, column, fire, steel structures.

Actuality. The safety issue today is very relevant in various spheres of human life, including the sphere of exploitation of building structures. The development of society from the second half of the XX century has led to the creation of technical and organizational-technical systems in a global scale that provides activity in the political, economic, military, environmental and other areas.

The development of such systems increases their sensitivity to external actions as spontaneous - earthquakes, floods, solar activity, weather disasters, man-made disasters, and purposeful nature - hostilities, terrorism, etc.

Recently, the issue of the stability of high-rise buildings (with the height 73.5 m and higher) [1] to the so-called “progressive collapse” - the proliferation of local destruction, which leads to the collapse of the entire building or disproportionately large part of it.

Analysis of recent research and publications.In national norms [1], [2] there are noformalized methods of calculating buildings for vitality, there are only basic recommendations. In [1] it is recommended to calculate vitality with the simulation of a local destruction by removing one first floor column from the calculation scheme. However, in the simulation of local destruction in this way does not take into account the factor that causes the removal of the column from work and extraction parameters.

In [2] is a list of events that should be taken into account in a vitality calculation. The method for calculating vitality with a specific threat in national norms is not given. USA normative documents such as UFC 4-023-03 [9] set out the main provisions for the calculation of progressive collapse and methods of protection against it, as well as features and examples separately for metal, reinforced concrete, stone, wood, cold-rolled steel constructions. A European norm [3] providesmethods for calculating the vitality due to impact and internal explosion. In the review of selected normative documents, methods or recommendations regarding the calculation of vitality during the fire were not detected.

In scientific works [10-12]studiedmodern methods of progressive collapse simulation of building and structures and methods of analysis of steel frames high-rise buildings at single vitality.

A large number of scientific studies [13-19] is devoted to the research of the progressive collapse of steel frame in the removal of the first-floor column from the design scheme of the building. Also, in a many studies [21, 22] attention was paid to the work of the beam-to-column connection at the removal of the columns from the design scheme and the effect of the work of the connection on the progressive collapse of the floor plate. This doesn't take into account the factor that caused the local destruction of the column. In studies [20] the removal of a column is presented as a consequence of an explosion. But this approach doesn't take into account the process of removing the column from the work of the calculation scheme.

Studies [23-27] consider fire as a specific factor that can lead to the progressive collapse of a steel frame and simulating the effect of a fire on frame elements. However, the real mode of fire and then the cooling stage, which depend on the parameters of the fire compartment, and therefore the planning decisions of the building, as well as the fire protection of steel structures, are not taken into account. Also, there aren't ways to prevent progressive collapse or prevent local destruction.

In studies [28] it is proved that in the event of a fire, the beam is more exposed than the column, which is still working in the calculation scheme. From this it follows that by removing the first-floor column it is impossible to simulate local destruction as a result of a fire.

The scientific work[29] is devoted tobuckling of the flat form of bending of I-beams.The influence of heating and temperature loads on structural elements is given in publications [30-32].

Unsolved part of the problem. If the impact from a motor vehicle or an explosion can be simulated by removing the first-floor column, then the issue of simulating the effects of a fire with taking into account the real fire curves and fire proofing of steel structures is open to examination.

Tasks of the research. In this study the main task is to modeling the effect of a fire as a specific threat, and determining the possibility of designing a steel frame of a high-rise building in order to avoid the local destruction of elements of the design scheme.

Main material. As the initial model, the steel rigid frame of a high-rise building with a height of 75,6 m (18 floors) and 45x45m in size with a central core of rigidity in the plan of 15x15m, a 7,5m column in both directions, was adopted (Fig. 1). The structure of the building is designed in accordance with the building codes and regulatory loads. Steel for the bearing structures adopted S345.

Six expertly most likely and worst scenarios for the emergence and spread of fires in the building on the ground floor were considered in the plan (Fig. 2).

It was simplified that the plans on all floors are identical. The fire scenarios were expertly reviewed on the 1st, 4th, 7th, 11th, 15th floors (on each floor were modeledall 6 scenarios).

For each scenario, the parametric fire temperature-to-time ratios were determined according to Eurocode 1 [4]. Fire resistance of unprotected steel structures was determined according to Eurocode 3 [5]. At critical temperatures and fire protection of steel structures was designed in accordance with the Guide to EN 1993-1-2 [6], providing the fire resistance R180 [1] (as EN 1993-1-2:2005 [5] regulates a differentiated approach - taking into account the fire resistance of unprotected steel structures at projection of fire protection). The chosen fire-protection means - cement-vermiculite plates.

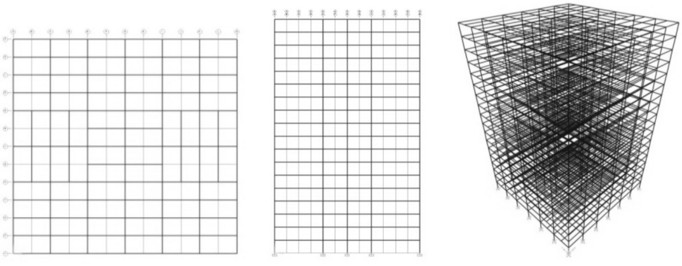
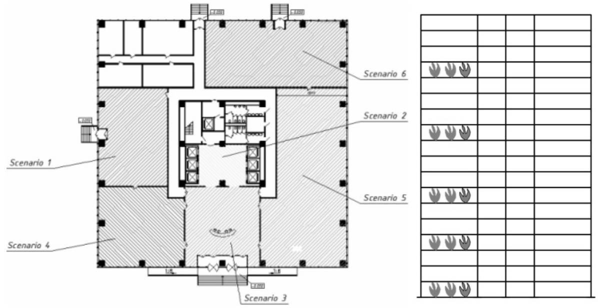

(a) (b) (c)

Fig. 1. General view of the calculation model:
(a) the plan of the building; (b) cross-section; (c) 3D view



(a) (b)

Fig. 2. Scenariosfortheemergenceandspreadofthefire:
(a) –within the floor, (b) –within a height of the building

The simulation of the fire effect on steel frame structures was carried out using the temperature loads, the values of which were equal to the steel temperatures of the protected steel structures, which were determined according to Eurocode 3 [5] for each scenario. After determining the values of temperature loads for each fire scenario, it was found that the strength characteristics of steel in the structural elements exposed to the fire are almost unchanged (with a maximum temperature load of 120,4 °C the value of the proportional limit is reduced by 3,9% and the value of the slope of the linear elastic range by 2%) when providing fireproof materials with a fire resistance limit R180.

Emergency loading is assumed to be dead and live with the value of load reliability factors equal to units [7], and the responsibility reliabilityfactor K_{fi}=1,05, which corresponds to the CC3 consequences class in the emergency calculation situation when verifying the elements for theultimatelimit state [7]. Factor of combination of loads are accepted as for an emergency calculation situation [7]. Emergency load in this case is the temperature load.

After calculating the effect of the fire, it was found that for any scenario, the strength of all structural elements of the framework is not ensured. It was decided to check the possibility of designing the framein such way as to prevent local destruction in the calculation, and in a case of the absence of such possibility - to analyze the local destruction and allow it to be calculated.

The first strategy of vitality was chosen to increase the areas of the frame elements cross-sections. Allsections and stresses determination was completed using SAP 2000.20. The calculation of steel structures wascompleted according to EN 1993-1-1:2005 [8].

As a result of the calculation, the weight of steel beams increased by 83.1% after the increase of cross sections areas, which is explained by the appearance of longitudinal forces in the beams, whose values reach - 3100kN.The weight of the steel columns has not increased. Total mass of steel frame increased by 49,2%.

In order to reduce the weight of the frame, two more strategies were considered.

The second strategy for providing vitality was to ensure the composite work of steel beams with ain-situ reinforced concrete slab on a profiled metal sheet, using stud-bolts. The weight of the steel columns has not increased. But the weight of steel beams increased by 129,4%, which is explained by the appearance of significant longitudinal forces in the beams, the values of which reach - 10225kN, which is much more than without the composite work of beams with a reinforced concrete slab. The total mass of the steel frame increased by 76,7%, which is more than with the increase of cross-sections.

The third strategy for providing vitality was to increase the thickness of the fireproof material in beams by 3 mm in order to reduce the weight of the frame compared to the variant with the increase in cross-section areas. At the same time, the weight of steel beams increased by 71,7%, which is 11,3% less than with the strategy of increasing cross-sections. The weight of the steel columns has not increased. The total weight of the steel frame was increased by 42,6%, which is 6,6% less than in the strategy with increasing cross sections, and by 34,1% less than in the strategy to ensure the composite work of steel beams with reinforced concrete slab.The economic costs of the considered strategies were compared in a Tab. 1.

Conclusions. The most economical strategy for providing vitality of a frame under action of fire is an increase in the thickness of the fireproof material in the beams.

Fire protection, which provides the fire resistance R180 in steel constructions of high-rise buildings, minimizes the temperature load and allowscalculating the frame of the building taking into account the fire. It was concluded that the steel frame of a high-rise building could be designed in such a way as to prevent the local destruction of elements of the design scheme due to the fire.

Table 1

Comparison of strategies for providing vitality of a frame under action of fire

Strategy №	Measures	Increasing the metal consumption, %	Extracash expense, mil. eur.*		
			The cost of metal	Costs or fire protection	Of all
1	Increasing cross sections	49,2	1,78	-	1,78
2	Ensuring the joint work of steel beams with a reinforced concrete slab	76,7	2,78	-	2,78
3	Increasing the thickness of the fireproof material in beams by 3 mm	42,9	1,54	0,036	1,576

* prices are provided by commercial mid-market experts for the city of Kyiv/7-2018

The best strategy for providing vitality under action of fire in this study was recognized increase in the thickness of fire protection. It was concluded that when calculating steel frames for vitality under action of fire, it is necessary to consider not only constructive measures, but also fire prevention measures.

REFERENCES

1. Derzhavni budivelni normy. Budynky i sporudy. Proektuvannya vysotnykh zhytlovykh i hromadskykh budynkiv (State building standards. Building sandstructures. Design of high-rise residentia land public buildings): DBN V.2.2-24:2009. – (Valid from 2009-09-01). – K.: Minrehionbud Ukrayiny (Kyiv: Ministry of Regional Development, Construction and Housing and Communal Services of Ukraine), 2009. – 133 p. – (Derzhavni budivelni normy).(in Ukrainian)
2. DBN V.1.2-14:20XX (project, second edition). Zahalni pryntsypy zabezpechennya nadiynosti ta konstruktyvnoyi bezpeky budivel, sporud, budivelnykh konstruktsiy ta osnov (General principles of maintenance of reliability and constructive safety of buildings, structures, building constructions and bases). – K.: Minrehiobud Ukrayiny(Kyiv: MinistryofRegionalDevelopment, ConstructionandHousingandCommunalServicesofUkraine), 2017. – 81 p. – (Derzhavni budivelni normy). (inUkrainian)
3. EN 1991-1-7. Eurocode 1: Actions on structures - Part 4: Part 1-7: General actions – Accidental actions: EN 1991-1. - Brussels: Management Centre, 2006. - 69 p. - (European Standard).
4. EN 1991-1-2:2002. Eurocode 1: Actions on structures –Part 1-2: General rules – Actions on structures exposed to fire: EN 1991-1. - Brussels: Management Centre, 2002. - 61 p. - (European Standard).
5. EN 1993-1-2:2005. Eurocode 3: Design of steel structures –Part 1-2: General rules – Structural fire design: EN 1991-1. - Brussels: Management Centre, 2005. - 81 p. - (European Standard).
6. Calculation Of Steel Constructions For Fire Resistance In Accordance With The Eurocode 3. Practical guide to DSTU-NEN 1993-1-2: 2010/ K.V. Kalafat // Ukrainian Center for Steel Construction. – 2016. – 83p.
7. EN 1990:2002. Eurocode 0: Basis of structural design: EN 1990. - Brussels: Management Centre, 2002. - 119 p. - (European Standard).
8. EN 1993-1-1:2005. Eurocode 3: Design of steel structures –Part 1-1: General rules and rules for buildings: EN 1991-1. - Brussels: Management Centre, 2005. - 93 p. - (European Standard).
9. UFC 4-023-03. United Facilities Criteria (UFC). «Design of Buildings to Resist Progressive Collapse». Department of Defense USA. 2009.
10. *Bilyk A.S., Kovalenko A.I.* Porivnyannya metodiv rozrakhunku metalevykh karkasiv vysotnykh budivel na odynychnu zhyvuchist (Comparison of methods of analysis of steel frames high-rise buildings at single vitality) // Zbirnyk naukovykh prats Ukrayinskoho instytutu stalevykh konstruktsiy imeni V.M. Shymanovskoho. – Vypusk 16. – Kyyiv, Vydavnytstvo «Stal», 2015. – S. 30-40. (inUkrainian)
11. *Bilyk A.S., Kovalenko A.I.* Suchasni metody modelyuvannya prohresuyuchoho ruynuvannya budivel I sporud (Modern methods of progressive collapse simulation of building and structures) // Stroytelstvo. Materyalovedenye. Mashynostroenye. Seryya: Sozdanye vysokotekhnolohycheskykh ékokompleksov v Ukrayne na osnove kontseptsyy sbalansyrovannoho (ustoychyvoho) razvytyya. - Dn-vsk., HVUZ«PHASA», 2016. - Vyp. 87. - S. 35-41. (inUkrainian)
12. *Bilyk A.S., Kovalenko A.I.* Dynamichni zusyllya v kolonakh stalevykh karkasiv bahatopoverkhovykh budivel pry rozrakhunku na odynychnu zhyvuchist (Dynamic forces in the columns of high-rise steel frame buildings at single vitality analysis) // Resursoekonomni materialy, konstruktsiyi, budivli ta sporudy. – Rivne, NUVHP, 2016. - Vyp. 32. - S. 304-309.(inUkrainian)
13. *Rinsha C, Biju Mathew*. Progressive collapse analysis of steel frame structures // International Research Journal of Engineering and Technology. - Volume 4 – Tamilnadu: IRJET, 2017. – p. 1653-1655.
14. *S. Jeyarajan, J.Y. Richard Liew, C.G. Koh*. Progressive Collapse Mitigation Approaches for Steel-Concrete Composite Buildings // International Journal of Steel Structures. – Basel: KSSC and Springer, 2015. – Volume 15, Issue 1 .- p. 175-191.
15. *Ru Liu, Buick Davison, Andrew Tyas*. A study of progressive collapse in multi-storey steel frames // Structures Congress. – Reston: ACSE, 2005. – p. 1-9.
16. *B.A. Izzuddin, A.G. Vlassis, A.Y. Elghazouli, D.A. Nethercot.* Progressive collapse of multi-storey buildings due to sudden column loss — Part I: Simplified assessment framework // Engineering Structures. - London: Elsevier, 2008.– Volume 30. – p. 1308-1318.
17. *A.G. Vlassis, B.A. Izzuddin, A.Y. Elghazouli, D.A. Nethercot.* Progressive collapse of multi-storey buildings due to sudden column loss—Part II: Application// Engineering Structures. - London: Elsevier, 2008.– Volume 34. – p. 1424-1438.
18. *A.G. Vlassis, B.A. Izzuddin, A.Y. Elghazouli, D.A. Nethercot.* Progressive collapse of multi-storey buildings due to failed floor impact // Engineering Structures. - London: Elsevier, 2008. – Volume 34. - p. 1522-1534.

19. *M. Krishna Chaitanya*. Progressive collapse of structures// International Journal of Mechanical Civil and Control Engineering. – Vengatapathy: International Institute of Scientific Research and technology, 2015. – p. 23-29.
20. North American steel contruction conference / Design of Steel Structures for Blast-Related Progressive Collapse Resistance. *Ronald Hamburger, S.E., Andrew Whittaker, S.E.* - Modern Steel Construction, 2004. – p. 1-4.
21. *Yuxin Liu, Lei Xu, Donald E. Grierson*. Influence of Semi-Rigid Connections and Local Joint Damage on Progressive Collapse of Steel Frameworks // Computer-Aided Civil and Infrastructure Engineering. – Ontario: Blackwell Publishing Inc., 2010. – p. 184-204.
22. Conference: XXIV Giornate italiane della Costruzione in Acciaio/ Ultimate Capacity Of Beam-To-Column Connections Under Bending And Axial Stresses. *Florea Dinu, Dan Dubina, Ioan Mircea Marginean, Ioan Petran*. – Torino: Research Gate, 2013. – p. 1-9.
23. Technical Contribution to the III International Seminaron The Use of Steel Structures in Civil Construction / The Ultimate Behaviour Of Composite Frames In Fire Conditions. *Zhaohui Huang, Ian W. Burgess, Roger J. Plank*. - Belo Horizonte: MG, Brazil, 2000. – p. 1-10.
24. *Ruirui Sun, Zhaohui Huang, Ian Burgess*. Progressive Collapse Analysis of Steel Structures under Fire Conditions // Engineering Structures. - London: Elsevier, 2012. – Volume 34. – p. 400-413.
25. *Vidyadhar Angadi, Dr. S. B. Vanakudre*. Fire Induced Progressive Collapse of Multi-storied Steel Structure // International Research Journal of Engineering and Technology. – Tamilnadu, IRJET, 2017. - Volume 4. - p. 1317-1323.
26. *Anil Agarwala, Amit H. Varma*. Fire induced progressive collapse of steel building structures: The role ofinterior gravity columns // Engineering Structures. - London: Elsevier, 2014. – Volume 58. – p. 129-140.
27. *Tavakoli, H.R., Kiakojouri F.* Threat-Independent Column Removal and Fire-Induced Progressive Collapse: Numerical Study and Comparison // Civil Engineering Infrastructures Journal. – Tehran: University of Tehran ,2015. - Volume 48 (1). - p. 121-131.
28. *Sun, R., Burgess , I.W., Huang, Z. And Dong, G.* Progressive faiuremodeling and ductility demand of steel beam-to-column connections in fire //Engineering Structures. – London: Elsevier, 2015.-Volume 89. - p. 66-78.
29. *Bilyk S.I.* Stiykist ploskoyi formy zhynu konsolnoyi dvotavrovoyi balky zi zminnoyu vysotoyu stinky za metodom Rittsa (Buckling of flatformbending of cantilever I-beam with variable height of a web by the method of Ritz) // Opirmaterialiv i teoriyasporud. – Kyiv, KNUBA, 2008. - Vyp. 82. - S. 146-153. (in Ukrainian)
30. *Kryvenko O.P.* Vplyv nahrivu na stiykist i vlasni kolyvannya sferychnoyi paneli pry zmini umov kombinovanoho zakriplennya konturu (The effect of heating on the stability and natural vibrations of a spherical panel with the changing combined fixation of the boundary) // Opir materialiv i teoriya sporud. – Kyiv, KNUBA, 2015. - Vyp. 96. - s. 48-65.(in Ukrainian)
31. *Shkryl O.O.* Vyznachennya koefitsiyentiv intensyvnosti napruzhen v dvovymirnykh tilakh pry temperaturnomu navantazhenni (Definition stress intensity coefficient two-dimensional bodies underthermal load) // Opirmaterialivtateoriyasporud. - Kyiv, KNUBA, 2014. - Vyp. 93. - s. 128-136. (in Ukrainian)
32. *Kryvenko O.P.* Vplyv poperednoho nahrivu ta zminy umov kombinovanoho zakriplennya konturu na stiykist i vlasni kolyvannya polohykh paneley pry diyi tysku (The effect of preliminary heating and combined fixation of theboundary on the stability and natural vibrations of panels underaction of pressure)// Opirmaterialiv i teoriyasporud. - Kyiv, KNUBA, 2016. - Vyp. 97. - s. 107-120. (in Ukrainian)

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ЗАБЕЗПЕЧЕННЯ ЖИВУЧОСТІ СТАЛЕВИХ КАРКАСІВ ВИСОТНИХ БУДІВЕЛЬ ПРИ ДІЇ ПОЖЕЖІ

Висотні будівлі чутливі до прогресуючого руйнування – поширення локального руйнування, що призводить руйнування всієї будівлі або непропорційно великої її частини. Чинні вітчизняні норми вимагають забезпечення живучості для висотних будівель при дії невстановлених факторів і, віднедавна, - при дії пожежі, що розглядається в даній статті.

В даній статті змодельовано вплив пожежі як конкретного фактору, що може спричинити прогресуюче руйнування, на елементи сталевого каркасу висотної будівлі. Було розглянуто різні сценарії виникнення пожежі на різних поверхах та в різних протипожежних відсіках на поверсі. При моделюванні було враховано: вогнезахист сталевих конструкцій та параметричні температурно-часові залежності для різних протипожежних відсіків. Дію пожежі було змодельовано через температурні навантаження, виконано перевірку міцності перерізів сталевого каркасу. Після розрахунку було визначено характер змін міцнісних характеристик сталі при пожежі і проаналізовано зміну внутрішніх зусиль в елементах каркасу.Перевірена можливість та доцільність запроектувати сталевий каркас висотної будівлі таким чином, щоб не допускати локальне руйнування при дії пожежі. Було розглянуто три стратегії забезпечення опору елементів сталевого каркасу дії пожежі. Такими стратегіями були: збільшення перерізів елементів сталевого каркасу, забезпечення сумісної роботи сталевих балок із залізобетонною плитою перекриття та збільшення товщини вогнезахисного матеріалу в балках. Дані стратегії були порівняні з точки зору металоємності та економічних витрат і визначена найбільш економічна стратегія. Для найбільш економічної стратегії було виконано розрахунок із урахуванням фізичної та геометричної нелінійності.

Ключові слова: висотні будівлі, прогресуюче руйнування, загроза, живучість, колона, пожежа.

Дауров М.К., Билык А.С.

ОБЕСПЕЧЕНИЕ ЖИВУЧЕСТИ СТАЛЬНЫХ КАРКАСОВ ВЫСОТНЫХ ЗДАНИЙ ПРИ ВОЗДЕЙСТВИИ ПОЖАРА

Высотные здания чуствительны к прогрессирующему разрушению – распространение локального разрушения, которое приводит к разрушению всего здания или непропорционально большой его части. Отечественные нормы требуют обеспечения живучести для высотных зданий при действии неустановленных факторов и, с 2017 года, - при воздействии пожара, что рассматривается в статье.

Ключевые слова: высотные здания, прогрессирующее разрушение, угроза, живучесть, колонна, пожар.

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The issue of simulating the effects of a fire on elements of a steel frame and providing of the vitality of steel frames of high-rise buildings under action of fire is being studied.

Fig. 5.Ref. 32

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Вивчається питання моделювання впливу пожежі на елементи сталевого каркасу та забезпечення живучості при дії пожежі для сталевих каркасів висотних будівель.

Іл. 5. Бібліог. 32 назв.

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Изучается вопрос моделирования влияния пожара на элементы стального каркаса и обеспечения живучести при действии пожара для стальных каркасов высотных зданий.

Ил. 5. Библиог. 32 назв.

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