Progressive collapse evaluation in industrial building of existing production

Stanislav Pavlov[1,*] and *Olga* Tusnina[2]

[1]«Central Research Institute «Steel Construction Design» Ltd., 119607, Moscow, Michurinskiy avenue, 37, Russia
[2] Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

Abstract. The problem of analysis of the resistance to the progressive collapse of the bearing steel framework of industrial building of existing production with a complex structural form with a service life of about 50 years is considered in this article. The main goal was to determine the approaches to such analysis and to identify the degree of survivability of the building. Probable emergency situations associated with the actual condition of steel structures, as well as with new and existing technological processes occurring in the industrial workshop were defined. Under the identified scenarios of emergency situations, the possibility of local damage of steel structures and their individual elements was determined. The extent of the impact of emergency situations on bearing steel structures has been determined. The main provisions for the analysis are presented. As a result, the level of sustainability of the industrial building framework to progressive collapse was defined. As a conclusion, the suggested approaches for performing similar analyses of existing industrial buildings are presented. Also the use of measures to prevent possible damage of structures and accidents, as well as to reduce financial costs during technological renovations without reducing the level of reliability and survivability are justified.

1. Introduction

In the last fifty years, one of the most important stages in the design of the bearing frameworks of buildings and structures has been the analysis of resistance to progressive collapse caused by local damage of structural elements. There are quite a few examples of such catastrophes during this period: Ronan Point (London, 1968), Capitán Arenas (Barcelona, 1972), the U.S. Marine Barracks (Beirut, 1983), the Argentine Israelite Mutual Association (Buenos Aires, 1994), the A.P. Murrah Federal Building (Oklahoma, 1995), the Sampoong Department Store (Seoul, 1995), the buildings of the World Trade Center (New York, 2001), the Transvaal Park (Moscow, 2004), and the Achimota Melcom Shopping Centre (Acra, 2012) [1].

In the 21st century after the terrorist attack of September 11, 2001, scientific interest to the problem of progressive collapse has greatly increased. Nowadays the greatest amount of

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* Corresponding author: pavlov.st.a@gmail.com

research is carried out in China [2, 3], the United States, Britain [4, 5, 6], as well as in Italy and Singapore

The most important contribution in the researches of progressive collapse of buildings was made by Starossek [7, 8], Haberland [9], Baker [10], Brett and Lu [11].

In Russia researches in this area are made by P.G. Eremeev [12, 13], Y.I. Kudishin [14], O.V. Mkrtychev [15], A.G. Tamrazyan [16], A.R. Tusnin [17, 18].

The development of solutions to this issue has led to the appearance of common approaches to the analysis of resistance to progressive collapse into all national and international standards: Eurocodes, International Building Code in the United States, the National Building Code in Canada, Code of Rules in Russia.

But all these works and design standards address the issue of progressive collapse for new buildings and structures. There is a serious difficulty in carrying out the technological reconstruction of industrial buildings on the existing framework, especially which are 50 years old or more. On the one hand, it is necessary to fulfill the requirements of regulatory documents: understand exactly which emergencies can lead to local damage, and then determine whether they cause a progressive collapse. On the other hand, it is necessary to take into account the period of trouble-free operation of such buildings, the rationality of amending the initial design solutions of the framework, as this can lead to inappropriate financial costs or even to stop production

The general approach to the progressive collapse analysis of the industrial building of exiting production by the example of converter shop No. 2 at the production of Novolipetsk Steel (PJSC NLMK) is considered in this paper.

2. Materials and methods

The converter shop No. 2 of Novolipetsk Steel was built in Lipetsk in 1974. It is the existing steel production - there are three converters with a capacity of 300 tons operate in the converter shop.

The building of converter shop No. 2 has a complicated shape in plan with dimensions of 340x190 m. In accordance with the technology of converter steel production the building between grid lines A-G is formed by three main bays: ladle, slag and teeming bay. Between grid lines G-J there is the stack of bulk materials. Three gas cleaning rooms each 24m long and 12 m wide are adjoined to the building on the side of grid line J. The gas cleaning facilities are a stacks with floors on which gas cleaning equipment and working platforms are located. Also there are two charge bays located between grid lines J-U on two sides of the converter shop. The building is also uneven in height. The highest design level is 83.250 mm.

At present, the reconstruction of the production is carried out with the replacement of obsolete technological equipment with modern one. In order to determine the bearing capacity of the existing steel framework of the converter shop for new loads and impacts, the finite element analysis was made with the use of program SCAD Office 21.1. The finite element model of the converter shop framework is shown on figure 1.

The converter shop is a particularly dangerous production facility and in accordance with the Russian standard GOST 27751-2014 "Reliability for constructions and foundations. General principles" appertains to buildings with a higher level of responsibility (construction class KS3).

In accordance with Russian Federal Law dated December 30, 2009 N 384-FZ "Technical Regulations on Safety of Buildings and Structures", when designing a building or structure of a higher level of responsibility, an emergency design situation must be taken into account. The emergency situation has a low probability of occurrence and a short duration, but important from the point of view of the consequences of reaching the limiting

states that may arise in this situation (including the limiting states in a situation arising in connection with an explosion, a collision, an fire, as well as directly after the failure of one of the bearing framework elements (progressive collapse)).

Thus, the building of the converter shop should be analyzed on the resistance to the progressive collapse and on the emergency situations that may occur taking into account the peculiarities of production.
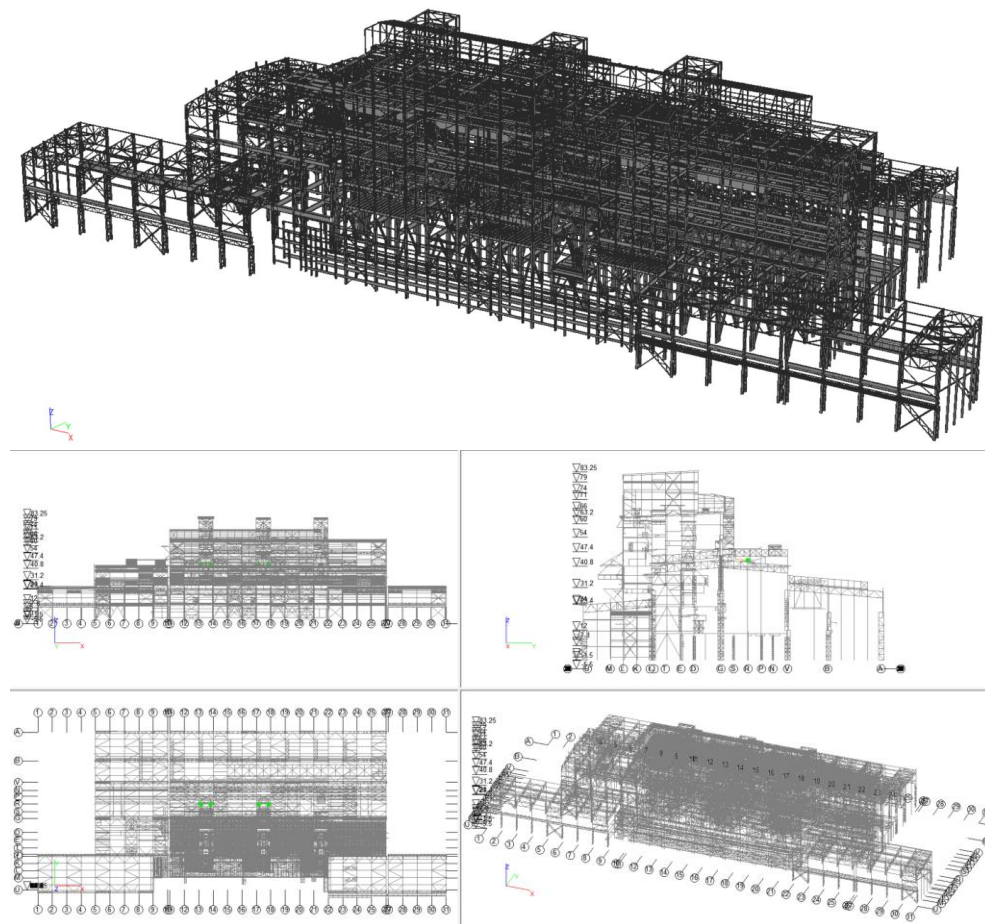

Fig. 1. Finite element model of convert shop No. 2 (NLMK)

Analyzing the main technological processes and loads in the converter shop, the following possible emergency situations affecting the framework were identified:

1. Explosion of cooling boiler.

Taking into account the simultaneous operation of two cooling boilers, there are two possible emergency loads acting during the explosion of the cooling boiler - taking into account the probability of an explosion at the same time, two cooling boilers of converters 1 and 2 and two cooling boilers of converters 2 and 3.

2. Emergency pressure in flue gas ducts.

Taking into account the production technology, the emergency pressure in the flue gas ducts cannot act simultaneously with the explosions of the boiler-coolers.

3. Emergency filling of the wet gas cleaning system with water.

Possible emergency filling of the scrubber and quencher should be taken into account.

4. Emergency impact from the cart of the movable canopy of the converter.

The cart of the movable part of the caisson is designed to move the lower part of the cooling boiler while the converter is being repaired to a position that provides access to the converter's manhole. When a cart is located both in the position during converter operation and during repair, critical emergency loads may arise from it, which should be taken into account in analysis.

The emergencies associated with the accidental effects of equipment on structures and emergency loads are described above. The next step is the calculation of the framework of converter shop on the resistance to progressive (avalanche-like) collapse.

Analysis of the framework on the resistance to progressive collapse is made taking into account Russian building standards SP 385.1325800.2018 "Protection of buildings and structures against progressive collapse. Design code. Basic statements" and SP 296.1325800.2017 "Building and structures. Accidental actions".

The analysis on the resistance to the progressive collapse was made in accordance with following provisions:

1. Calculation of resistance to progressive collapse of the building of the converter shop No. 2 should be performed using the finite element method for special combinations of loads. The load safety factors for permanent, long-term and short-term loads, as well as the combination factors should be assigned as for special combinations of loads.

2. The combination factor for long-term loads is assumed to be 1 - for the main one long-term load according to the degree of its influence and 0.95 - for all other long-term loads

3. The combination factor for all short-term loads is assumed to be 0.8.

4. The load safety factor for all short-term loads is assumed to be 0.5.

5. The reliability factor of responsibility is assumed to be 1.

6. When performing calculations on the progressive collapse, emergency and special loads on the framework should not be taken into account.

7. The design strength and deformation characteristics of materials are assumed to be equal to their normative values in accordance with the current regulatory documents.

8. For steel structures made of ductile steel, if necessary, it is allowed to additionally use the structure behavior factor, taking into account the admissibility of steel work beyond the yield stress, the value of this factor is assumed to be 1.1.

9. To minimize the impact of possible errors in the design, manufacture, installation or improper exploitation of the structure, it is necessary to identify "key" elements, the failure of which entails an avalanche-like collapse of the entire framework.

10. Due to the fact that in this case, the main reasons for the destruction of the structures of the framework may be loss of stability of eccentric-compressed elements, exposure to elevated temperature, sediment of foundations, formation of plastic hinges and similar processes associated with the gradual failure of the elements, it is allowed to apply a load when a structural element is destroyed statically.

Based on the analysis of the stress-strain state of the framework and technological processes carried out in the building of converter shop the emergency shutdown of the following structural elements ("key" elements) of the framework was considered when progressive collapse calculation was performed:

- destruction of the most loaded branch of the most loaded column (1st case);
- destruction of the most loaded support brace of the truss (2nd case);
- destruction of the most loaded upper belt of the truss (3rd case);
- destruction of the most loaded lower belt of the truss (4th case);
- destruction of the most loaded element of horizontal braces along the belt of the trusses (5th case);
- destruction of the most loaded branch of the vertical braces (6th case);
- destruction of the main beam of the working platform (7th case);

All destroyed ("key") elements are located near the teeming bay (grid lines V-G). Taking into account the operation of the two most heavy cranes (filling crane 400 tons and scrap-charging valve 130 + 130 tons) of the most severe mode of operation (A8) in the span of V-G, as well as taking into account the location of the crane-subrafter trusses with a span of 36 m along the axis G the most dangerous for the frame will be emergency situations associated with the destruction of the most loaded structural elements along the G axis, and in the spans adjacent to it.

Calculations for the all cases of destructions of elements were carried out by finite element method with the use of program SCAD Office 21.1.

For example (for the 1st case of the emergency situation), the cross-section of the finite element model of the converter shop where the destroyed column branch is located is shown on the figure 2.
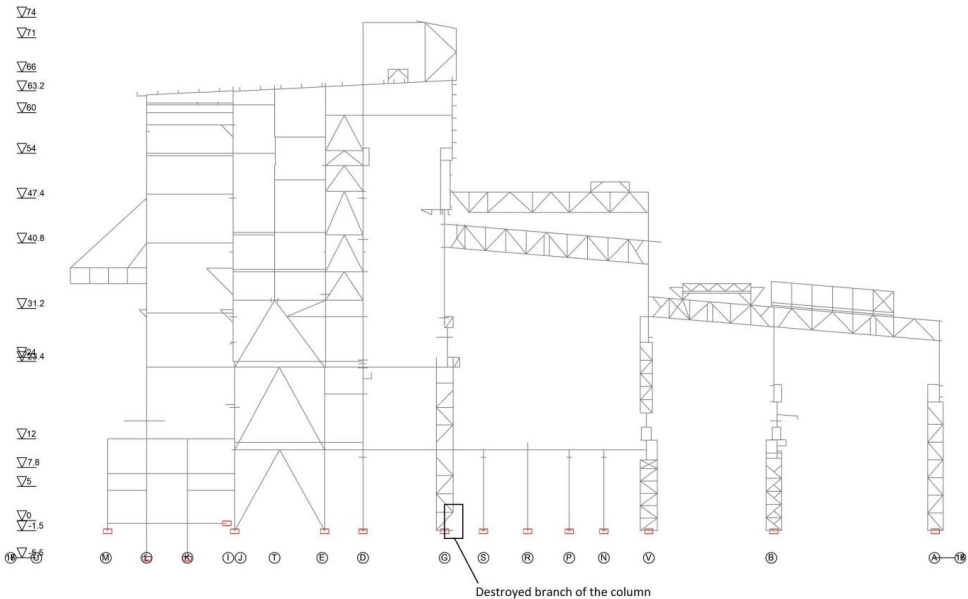

Destroyed branch of the column

Fig. 2. The 1st case of the progressive collapse calculation
(destruction of the most loaded branch of the most loaded column)

It's useful to note that analysis of the spatial framework with the use of finite element method allows to obtain quiet reliable results that is confirmed by the approaches described in [19] and [20].

3. Results

As a result of the calculations for the all cases of the destructions of elements, it was obtained that the bearing capacity of the other structures of the framework was ensured. Progressive (avalanche-like) collapse did not occur in any of the considered emergency situations.

The destruction of the element caused a redistribution of efforts in the framework elements, and taking into account the lower values of loads, additional efforts in the elements involved in the work did not exceed the normative characteristics of the material and their strength and stability were provided.

Besides, the inclusion in the work of enclosing structures (steel roof panels, attached to the trusses and roof beams by the welds in the corners and represented continuous shear

disk in the level of the roof, steel corrugated sheeting in the roof and walls) as well as work on the shear of the steel flooring of the working platforms was taken into account when performing progressive collapse calculation. These elements are also actively involved in the work and ensure the redistribution of efforts in the framework elements.

For example, the results of the analysis on the progressive collapse for the 1st case of the emergency situation are shown on figure 3.
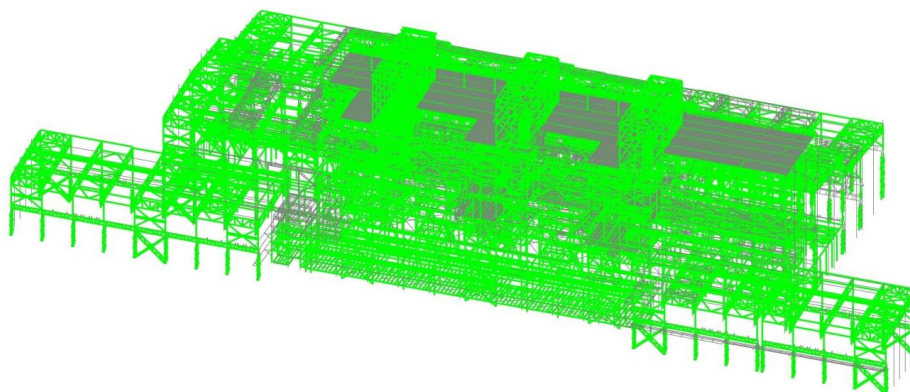

Fig. 3. The 1st case of the progressive collapse calculation (destruction of the most loaded branch of the most loaded column). Results

Thus, identifying the most possible emergency situations taking into account the existing and new technologies, as well as taking into account the actual state of the structures, determining the damaged elements and carrying out the appropriate calculation, we found an extremely high level of resistance to progressive collapse of such a complicated steel framework as in the converter shop No.2 in Lipetsk.

4. Discussion

The main reasons for the high level of resistance to the avalanche-like collapse of the frame of the converter shop No. 2 is the complexity of this building, both from a constructive and technological point of view, because of which the various sections of the shop "insure" each other, respectively, the redistribution of efforts is as efficient as possible. Initially, with the design, it seems that engineers comprehensively sought to minimize any risks.

However, there remains a huge number of industrial buildings and structures of similar age, but with simpler structural forms, the resistance to the progressive collapse of which remains questionable.

5. Conclusions

Based on the analysis of emergency situations, their probabilities, the results of the calculations performed, the following conclusions can be made:

1. For existing industrial buildings and structures when carrying out technological renovations in accordance with existing regulatory documents, the calculation of resistance to progressive collapse is mandatory.

2. In determining possible emergency situations, it is necessary to take into account the probabilities of their occurrence, as well as history and experience throughout the operation of such industrial buildings and structures.

3. In the process of analyzing of the design scheme and calculations, it is necessary to eliminate progressive collapse by preventive measures as much as possible, for example, to consider the possibility of changing technological processes in such a way that the survivability of the building increases, while the costs of business owners are reduced to the minimum possible.

References

1. L.M. Adam, F. Paris, J. Sagaseta, X. Lu, Engineering Structures, **173**, 122–149 (2018)
2. P. Ren, X. Lu, H. Guan, Y. Zhou, Engineering Structures, **118**, 28–40 (2016)
3. H. Wang, A. Zhang, Y. Li, W. Yan, The Open Civil Engineering Journal, **8**, 183-192 (2014)
4. B. A. Izzuddin, A. G. Vlassis, A. Y. Elghazouli, D. A. Nethercot, Engineering Structures, **30**, 1308–1318 (2008)
5. B. A. Izzuddin, A. G. Vlassis, A. Y. Elghazouli, D. A. Nethercot, Engineering Structures, **30**, 1424–1438 (2008)
6. R. Sun, Z. Huang, I. Burgess, Engineering Structures, **34**, 400–413 (2012)
7. U. Starossek Progressive collapse of structures. 2nd ed. Thomas Telford Limited (2018)
8. U. Starossek Engineering Structures, **29**, 2302–2307 (2007)
9. U. Starossek, M. Haberland, Structure and Infrastructure Engineering, **7**, 625–631 (2011)
10. J. W. Baker , M. Schubert, M. H. Faber, Structural Safety, **30 (3)**, 253–267 (2008)
11. C. Brett, Y. Lu, Front Struct Civ Eng **7 (4)**, 356–368 (2013)
12. I. I. Vedyakov, P. G. Eremeev, D. V. Solovyev, Industrial and Civil Engineering, **12**, 14-19 (2018)
13. P. G. Eremeev, Modern Industrial And Civil Construction, **4 (3)**, 129-134 (2008)
14. Y. I. Kudishin, D. Y. Drobot, Metal Constructions, **15 (1)**, 59-71 (2009)
15. V. L. Mondrus, O. V. Mkrtychev, A. E. Mkrtychev, Proceedings of Moscow State University of Civil Engineering, **5**, 56-61 (2012)
16. A. G. Tamrazyan, Zhilishchnoe Stroitel`stvo Journal, **1**, 15-19 (2010)
17. A. R. Tusnin, Magazine of Civil Engineering, **78**, 47-64 (2018)
18. M. P. Berger, A. R. Tusnin, IOP Conference Series: Materials Science and Engineering. **365**. 052020 (2018)
19. B. I. Song, K. A. Giriunas, H. Sezenb, Journal of Constructional Steel Research, **94**, 76–83 (2014)
20. B. I. Song, H. Sezenb 2013 Engineering Structures, **56**, 664–672 (2013)