Design Analysis of a Typical Steel Frame of a High-Rise Industrial Building After an Accident

O V Mkrtychev[1] and D S Sidorov[1]

[1] Research laboratory "Reliability and Earthquake Engineering", Institute of Fundamental Education, Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

E-mail: dimacolt@yandex.ru

Abstract. The article considers the high-rise industrial building with typical design solutions, which was severely damaged as a result of an emergency (fire).The main objective of the work is to perform a design analysis of the steel frame of the building, determine the stress-strain behaviour and assess the load-bearing capacity of the elements considered at all stages of the structural behaviour. Calculations were made taking into account the stress history, the contact between the model elements, and also taking into account geometric, physical and structural nonlinearities. The structural behaviour analysis was made with explicit and implicit schemes of forth integration of the equation of motion. The article presents a numerical solution of the problem for calculating the combined power and temperature effects for the model frame of the high-rise industrial building in accordance with the thermal behavior of "real" fire and gives assessment of stability of the initial structural layout to the progressive collapse. Based on the results of the analysis, conclusions were drawn and recommendations were given to increase the stability of load-bearing structures of such buildings to a chain, progressive collapse. The results of calculated analysis were used in the design phase of the project to strengthen the load-bearing elements, as part of support of construction and installation work to reconstruct the frame, as well as during structural monitoring.

1. Introduction and description of the facility

The facility under study is a steel-framed high-rise industrial building. In the transverse direction, the building consists of seven spans with a total width of 165 m. Block height is different, the maximum height is 130 m. The length in the longitudinal direction is 102 m. The building has overhead and underhung cranes with lifting capacity from 100 to 1500 kN. Equipment with a load equal to 300,000 kN is suspended on the frame structure at elev. +100,000.

The structural design of the building – braced frame. The steel frame elements, ensuring rigidity and stability in the transverse direction, are: transverse frames spaced at 6–12 m; vertical cross braced diaphragms located along the boundaries of expansion blocks; horizontal braced discs in two levels in height. The columns are rigidly restrained in the foundations. In longitudinal direction, the rigidity and stability of the building is provided by vertical longitudinal braces located in each longitudinal row of columns.

The emergency situation at the facility in question arose as a result of fire. The local effect of high temperatures led to the destruction of joints of load-bearing columns, which resulted in a disproportional progressive collapse of load-bearing elements of the building. Steel frame was

IOP Conf. Series: Materials Science and Engineering 463 (2018) 022080 doi:10.1088/1757-899X/463/2/022080

damaged, preventing its safe operation. The consequences of the failure were inadvertently not so significant in connection with the following factors: skew distortion of the massive equipment and its jamming in the frame elements, and involvement of nonstructural elements. To prevent further development of the emergency condition, the structures were reinforced.

2. Analysis of design solutions, compliance with standards and a brief review of literature

Most industrial structures of this kind were built 30–50 years ago. Due to deterioration and obsolescence of building structures, elements of equipment and utilities, the probability of an accident significantly increases. The accident can occur for various reasons: failure of the frame load-bearing elements, the soil mass distortion, the risk of fire or explosion, a terrorist attack. The most likely causes of emergencies can be: errors in the design and structural analysis, errors in installation and construction work, breakages and improper operation of equipment and utilities.

Today, the buildings with high level of responsibility of КС-3 [18] class, to which the facility belongs, is subject to increased requirements of mechanical, fire and anti-terrorist safety [20, 21]. Almost all standard documents have become tougher [16, 17, 19]. When designing such structures, the capabilities of the calculation complexes did not allow making full calculated analysis and some design situations were not even considered. In connection with the foregoing, most industrial buildings of this kind do not meet the requirements of the modern regulatory framework in terms of ensuring the frame stability with regard to a progressive collapse. This is due to the fact that during their design and construction this issue was not regulated by norms. Practical operation of these buildings and the accidents that have occurred indicate that it is necessary to increase the stability of these buildings to a progressive collapse. For this purpose, a detailed design analysis, inspection and reinforcement of building structures should be carried out.

Scientific novelty and practical relevance of the research is: development of a technique that realizes the numerical solution of the problem of analyzing combined force and temperature actions on the steel frame of a high-rise industrial building in an emergency condition, taking into account different types of nonlinearities and using explicit and implicit schemes of integration of the equations of motion; development of a mathematical model of temperature effects on the bearing elements of a given buildings in accordance with the temperature regime of a "real" fire by the [14] technique; application of the results of calculated analysis when supporting construction and installation work on the frame reconstruction and carrying out structural monitoring.

The reliability of the obtained results and the main conclusions is confirmed by comparing the calculated analysis with the data of survey and monitoring of building structures, as well as by carrying out independent analyses in various software systems, and a comparative analysis of the results showing a similar nature and a sufficiently good convergence of the values of the controlled parameters.

To conduct the analysis of the steel frame after the accident, a lot of preliminary preparatory work was carried out, including an analysis of the literature on this subject. The fundamentals of design and analysis of steel structures of industrial buildings are considered in [1-5,7,8]. Approaches to evaluation of the safety and reliability of buildings and structures and the calculation procedure, taking into account all types of nonlinearities in the time domain, by forth integration of the equations of motion according to explicit schemes are given in [10]. Problems and methods for structural analysis of combined force and temperature actions were given in [11, 14, 15]. The methodology and examples of simulating the temperature actions in accordance with different thermal behaviors of the fire are given in [6, 14].

3. Work procedure

To obtain reliable results, a design model of the building has been developed taking into account the loading history. The following stages of the structural behaviour were considered.

1. Development of the design model of the building, corresponding to the stage of normal operation and determination of the initial stress strain behavior (SSB) of the building structures. At this stage, the structures are in the elastic stage.

2. Based on the developed design model of the building in the normal operation stage, a spatial finite-element design model of the building frame in an emergency condition has been developed, taking into account the damage received.

Determination of the SSB of the building structures in an emergency condition and estimation of the bearing capacity were made by analysis of structure as a single system with combined force and temperature actions taking into account nonlinear behaviour.

Simulation of temperature actions was carried out in accordance with the thermal behavior of the "real" fire. A fire incident can be attributed to a three-dimensional fire, regulated by the load. When plotting a time-temperature curve, the actual magnitude of the fire load, the volume of premises and the area of openings in the fences were taken into account. Mathematical models of temperature actions in accordance with the thermal behavior of the "real" fire are given in [Roitman, Mkrtychev-Sidorov]. Fig. 1 shows the design temperature curve of a "real" fire for this building in comparison with the standard thermal behavior.

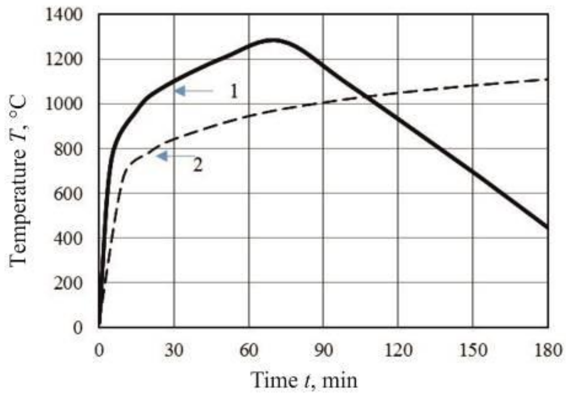

Figure 1. Thermal behavior of "real" fire (1) in comparison with the standard thermal behavior (2).

Based on the results of calculations, a comparative analysis of SSB of the structures during normal operation and in an emergency condition was performed, taking into account and without considering the loading history.

3. Based on the developed design model of the building in an emergency condition, taking into account the damage received, the design model of the building frame was updated, taking into account survey and geodetic monitoring data. At the same time, the coordinates of the model nodes in an emergency condition were refined and compared with the survey data. It should be noted that in a quality manner the pattern of the strain state of the building frame in reality corresponded to the pattern obtained in the design model.

4. Statement of the problem and the analysis sequence

Behaviour of typical steel frame structures of a high-rise industrial building was analyzed using PC Ansys,LS-Dyna. The mathematical formulations of the applied explicit and implicit schemes of integrating the equations of motion are presented in [10, 11].

Analysis of the building in an emergency condition was carried out for a special combination of loads and impacts, including the standard permanent and temporary loads. Strength characteristics of materials were assumed to be equal to their standard values. The analysis was performed taking into account geometric, physical and structural nonlinearities in a dynamic formulation, and also taking into account the contact interaction between the contacting elements.

The analysis sequence for the simulation of an emergency situation and the subsequent reinforcement:

- static vertical loads with corresponding combination factors [17] are step-by-step applied to the structure corresponding to the normal operation stage (load parameter from 0.0 to 1.0, i.e. from 0% to the full value of 100% of the loads). The rate of load application is selected by the criterion of the lack of significant oscillations in the dynamic analysis. Total analysis time is 15 secs. Time of static load application 1,5 secs;
- after attenuation of all dynamic effects caused by the application of a static load (2 secs), a temperature action is applied to the key element of the column along the axis 18/D. For this element, changes in the physicomechanical properties as a function of temperature are taken into account;
- further structural damages have a "mechanical" nature;
- when the frame strains specified in the survey report are reached, the analysis is suspended;
- coordinates of the nodes of the design model of the building in an emergency condition are specified, taking into account the survey data;
- the reinforcement structures are simulated in accordance with the developed work production plan;
- after mounting the reinforcement, the wind load is applied to the building structures (7–9 seconds);
- the steel elements are excluded when the limiting yield strains are reached in the process of analysis.

5. Building analysis results

As a result of the analysis, the SSB of the load-bearing frame elements was determined at each stage of the structural behaviour. The following are some of the results obtained.

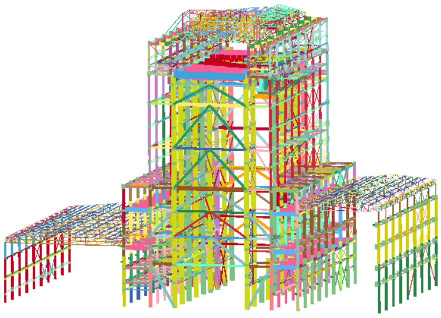

Figure 2. General view of the design model of the building at the stage of reinforcement mounting.

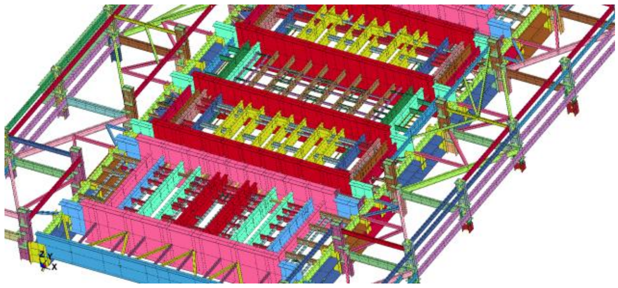

Figure 3. Part of the general design model, which shows the structures for fastening the main equipment.

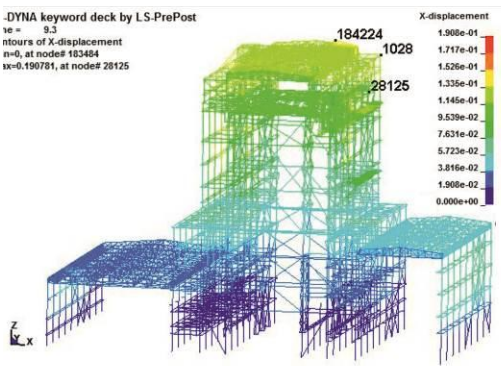

Figure 4. X axis displacement at time t = 9.3 secs (m)

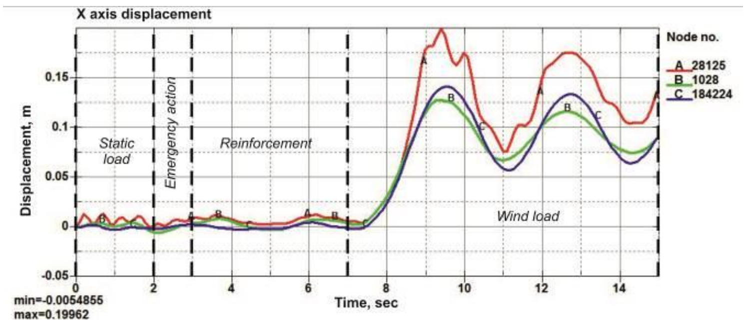

Figure 5. Curves of the structural frame nodes displacement.

IOP Conf. Series: Materials Science and Engineering 463 (2018) 022080 doi:10.1088/1757-899X/463/2/022080

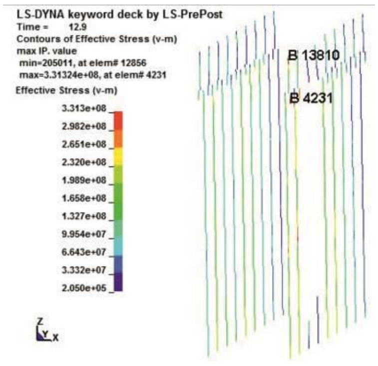

Figure 6. Stress intensity in columns at time $t = 9.4$ secs. (Pa)

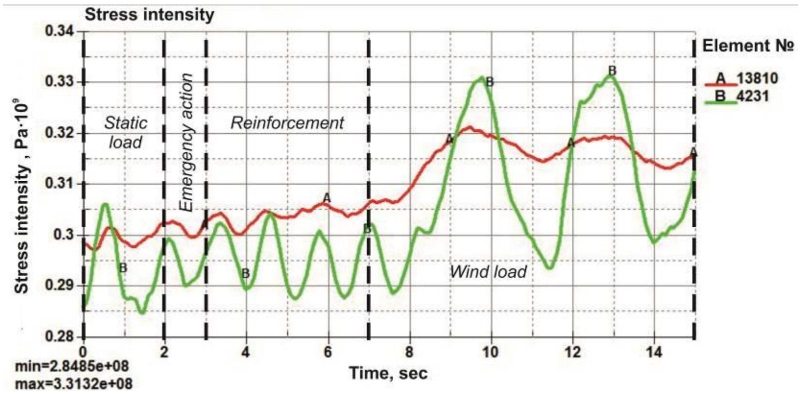

Figure 7. Curves of stress intensity in (Pa)

6. Conclusion

In accordance with the design analysis of the steel frame of a high-rise industrial building, the following results were obtained at all the stages of work under consideration.

1. Comparative analysis of SSB of the structures during normal operation and in an emergency condition was carried out. Forces and displacements of structures in an emergency condition taking into account the loading history differ from the results obtained by simultaneous application of loads and the removal of collapsed structures. For example, vertical displacements of structures above the failure zone, taking into account the loading history, are 70 cm (2 seconds after the elements are excluded), and 52 cm without taking into account the loading history. The results obtained were taken into account when carrying out design works and when supporting construction and installation works.

2. The strength and stability of the structure were verified according to a special limiting state with respect to the non-collapse criterion in accordance with 5.1.1 [18], taking into account the dynamic effect, loading sequence, physical, geometric and constructive nonlinearities, as well as contact interactions between the bearing elements in the collapse process.

3. The results show that the adopted and implemented initial structural design of the frame structure under accidental exposure has inadequate resistance to progressive (chain, avalanche-like) collapse caused by local destruction and loss of stability of individual structural elements.

4. Industrial buildings with these standard design solutions do not meet the requirements of the modern regulatory framework. Such facilities have insufficient resistance to progressive collapse. For them, it is necessary to increase the stability of the framework to a progressive collapse by reinforcing structures, introducing additional links, increasing the degree of static indeterminacy and coupling of the bearing elements.

7. References

[1] Belenya E I 1986 *Metal constructions* (Moscow: Stroiizdat)
[2] Gorev V V 2004 *Metal constructions* (Moscow: High School)
[3] Kudishin Yu I 2007 *Metal constructions* (Moscow: Academia)
[4] Kuznetsov N N 1998 *Metal constructions* (Moscow: ASV)
[5] Mel'nikov N P 1980 *Metal constructions* Designer’s handbook (Moscow: Stroiizdat)
[6] Molchadsky I S 2005 *Fire in rooms* (Moscow: VNIIPO)
[7] Streletskii N S 1961 *Metal constructions* (Moscow: Gosstroiizdat)
[8] Vedenikov G S 1998 *Metal constructions* (Moscow: Stroiizdat)
[9] Mkrtychev O V 2000 *Reliability of multi-element rod systems of engineering structures* The dissertation author's abstract on competition of a scientific degree of the doctor of technical sciences (Moscow)
[10] Mkrtychev O V 2010 *Safety of buildings and structures under seismic and emergency actions*

Monograph (Moscow)
[11] Mkrtychev O V Dorozhinsky V B and Sidorov D S 2016 *Reliability of building structures in explosions and fires* Monograph (Moscow)
[12] Mondrus V L Mkrtychev O V, Mkrtychev A E 2011 Probabilistic calculation of a large-span structure for operational loads *Industrial and civil construction* (Moscow) **3** 21-22
[13] Mondrus V L Mkrtychev O V, Mkrtychev A E 2011Evaluation of the reliability of a large-span structure according to the second limiting state *Collection of scientific papers on the materials of the international scientific and technical conference "Industrial and civil construction in modern conditions."* (Moscow: MSSU) 11-13.
[14] Roitman V M 2001 *Engineering solutions on the assessment of the fire resistance of the designed and reconstructed buildings*. (Moscow: Association "Fire safety and science")
[15] Fedorov V S Levitsky V E, Molchadsky I S and Aleksandrov A V 2009 *Fire resistance and fire hazard of building structures* (Moscow: ASV Publishing)
[16] 2011 *SP 16.13330.2011. Steel structures. Updated version of SNiP II-23-81** (Moscow)
[17] 2011 *SP 20.13330.2011. Loads and impacts. Updated version of SNiP 2.01.07-85**(Moscow)
[18] 2014 *GOST 27751-2014. Reliability of building structures and foundations. Basic provisions* (Moscow)
[19] 2017 *SP 294.1325800.2017. Steel structures. Design rules. The updated manual to SNiP II-23-81** (Moscow)
[20] Federal Law No.384. Technical regulations for safety of buildings and structures.
[21] Federal Law No.123. Technical Regulation on Fire Safety Requirements.

Acknowledgments
This study was performed with the support of the RF Ministry of Education and Science, grant №7.1524.2017/Project Part.