Збірник наукових праць. Серія: Галузеве машинобудування, будівництво
Academic journal. Series: Industrial Machine Building, Civil Engineering

http://journals.pntu.edu.ua/znp
https://doi.org/10.26906/znp.2019.52.1682

UDC 624.042

Survivability and failure risks of steel frame structures: conceptual framework

Chichulina Kseniia[1]*, Chichulin Viktor[2]

[1] Poltava National Technical Yuri Kondratyuk University https://orcid.org/0000-0001-7448-0180
[2] Poltava National Technical Yuri Kondratyuk University https://orcid.org/0000-0003-1838-7269
*Corresponding author E-mail: chichulinak@ukr.net

The article considers the concept of "survivability" of steel frame structures and defines its features. In the design of steel frames there is a need to reserve the main load-bearing structures to prevent progressive destruction. With the possible destruction of any individual element, the entire object or its most critical part must remain operational. The degree of damage to the system in case of failure of an individual element is determined. The main prerequisites for prevention of destruction in emergency situations, in particular, the calculation of the increase in carrying capacity. The approaches to determining the risks of failure and strengthening of steel frame elements are considered.

Keywords: survivability, destruction, redundancy, risk, damage.

Живучість і ризики відмови сталевих рамних конструкцій: понятійний апарат

Чичуліна К.В.[1]*, Чичулін В.П.[2]

[1] Полтавський національний технічний університет імені Юрія Кондратюка
[2] Полтавський національний технічний університет імені Юрія Кондратюка
*Адреса для листування E-mail: chichulinak@ukr.net

У статті проводиться аналіз роботи сталевих статично невизначених рам використовуючи моделі з максимально наближеними до реальних конструкцій діючими за нормами навантаженнями при можливих відмовах окремих елементів. Розглядається визначення поняття «живучість» сталевих рамних конструкцій. При проектуванні сталевих рам існує необхідність резервування основних несучих конструкцій для запобігання прогресуючих руйнувань. При можливому руйнуванні будь-якого окремого елемента весь об’єкт або його найвідповідальніша частина повинна зберігати працездатність. Визначається ступінь пошкодження системи при відмові окремого елемента. Визначені головні передумови запобіганню руйнуванню при аварійних ситуаціях, зокрема, розрахунок величини збільшення несучої здатності. Представлені умови граничних станів при розрахунках живучості багатоповерхових будівель. Приводяться конструктивні заходи для забезпечення стійкості каркасів. Представлені системи діафрагм жорсткості висотних будівель. Проведені розрахунки ряду сталевих рам. Результати показують, що поодинокі відмови елементів конструкцій ведуть до руйнування ряду перетинів. Це унеможливлює розгляд лавиноподібного прогресуючого руйнування. Аналізуються підходи до визначення ризиків при відмовах і підсиленні елементів сталевих рам. Представлені межі нормативного ризику аварії. Розраховується гранично - допустимі ризики відмови конструкції. Визначається фактичний ризик аварії і рівень достатньої конструкційної безпеки об'єкта. Ресурс об’єкту можливо подовжувати підсиленням елементів що відмовили, але в межах гранично допустимого ризику. Підсилення виконується обмежену кількість разів з урахуванням амортизації. Вартість робіт по обстеженню та підсиленню визначають залежно від ризиків можливих втрат при відмові (аварії) та в порівнянні з вартістю об’єкту.

Ключові слова: живучість, руйнування, резервування, ризик, пошкодження.

Introduction

European and Ukrainian practices for solving survivability problems require detailed study and effective solutions. One of the reasons is the lack of a common calculation method in the design of buildings and as a consequence there is an imperfect regulatory framework. There are a number of documents in the regulatory framework of Ukraine. Some of these standards indicate the need to calculate the survivability [1, 2] and are used to perform most of the calculations in the design. These documents are advisory. The need to ensure survivability in technical systems requires the development of analysis and evaluation of mechanisms methods and means of its provision for each specific class of systems. In foreign norms as comparative characteristics for the calculation of the vertical element refusal such as columns or pylons, engineers-designers are offered a very specific restriction of the collapse - 70 m^2 or 15 % of the area of the floor.

Review of research sources and publications

General concepts of risks and survivability of complex systems including building structures are presented in a number of scientific papers [3-6]. The work [3] presents a novel classification framework for severe global catastrophic risk scenarios. Extending beyond existing work that identifies individual risk scenarios, authors propose analyze global catastrophic risks along three dimensions: the critical systems affected, global spread mechanisms, and prevention and mitigation failures. The classification highlights areas of convergence between risk scenarios, which supports prioritization of particular research and of policy interventions. It also points to potential knowledge gaps regarding catastrophic risks, and provides an interdisciplinary structure for mapping and tracking the multitude of factors that could contribute to global catastrophic risks. The paper [4] is introduced the concept of system survivability under attack in analogy with system reliability. Authors limit consideration to the discrete case and define a component/system survivability to be the probability that the system/component continues functioning upon attack.

The differences between the suggested concept of system survivability and the traditional one of system reliability are defined. Most often, the survivability follows a Bernoulli distribution for which the survival probability is derived based on the system configuration. Authors develop results for series, parallel, series-parallel, parallel-series and k-out-of-n systems. It also provided the expected number of attacks for each system configuration based on the particular attack strategy both for single and multiple attacks. Scientists illustrate the process through a real application. According to [5] extreme events often cause local damage to building structures and pose a serious threat when one or more vertical load-bearing components fail, leading to the progressive collapse of the entire structure or a large part of it. Since the beginning of the 21st century there has been growing interest in the risks associated with extreme events. The accent is now on achieving resilient buildings that can remain operational after such an event, especially when they form part of critical infrastructures, being occupied by a large number of people, or are open to the public.

This paper [5] presents an ambitious review that describes all the main advances that have taken place since the beginning of the 21st century in the field of progressive collapse and robustness of buildings. Widely diverse aspects are dealt with, including: a collection of conceptual definitions, bibliometric details, the present situation and evolution of codes and design recommendations, quantification of robustness, assessing the risk of progressive collapse, experimental tests, numerical modeling, and research needs. The work [6] determines the strongest determinant of the destruction or endurance; some other factors such as inundation height, depth of the building parallel to the tsunami direction and opening ratio have also been considered as the factors supporting the survival. This paper investigates Sendai sewage purification center which survived the tsunami in the context of its endurance.

The issue of survivability and risks of steel frame structures devoted works [7-12]. The paper [7] presents a numerical model for analyzing steel frame structures subject to localized damage caused by blast load and subsequently investigating their survivability under fire attack. The proposed numerical method adopts a mixed-element approach for modeling large-scale framework and it is proven to be sufficiently accurate for capturing the detailed behaviour of member and frame instability associated with the effects of high-strain rate and fire temperature. Design implications related to the use of various numerical models for separate assessment of blast and fire resistance of steel structures and their components are discussed. Fire–blast interaction diagrams are generated to determine the fire resistance of columns considering the initial damage caused by the blast loads.

A multi-storey steel building frame is analyzed so that the complex interaction effects of blast and fire can be understood and quantified. The frame is found to be vulnerable, as it possesses little fire resistance due to the deformation of key structural elements caused by the high blast load. The paper [8] presents results of an investigation into the effect of span length on progressive collapse behaviour of seismically designed steel moment resisting frames which face losing one of their columns in the first story. Towards this aim, several nonlinear static and dynamic analyses were performed for three frames designed for a high seismic zone considering various span lengths. The analysis results revealed that beams and columns of the studied frames had adequate strength to survive one column loss in the first story. However, in order to determine the residual strength of the frame, a series of nonlinear static analyses called pushdown analyses were performed. It was shown that by decreasing the span length to half, the strength of the studied frames increases 1.91 times based on the performance-based analysis perspective. Besides, results of nonlinear static analyses revealed that by increasing the applied loads, the investigated structures are more susceptible to progressive collapse when they lose an internal column. Three frames have been analyzed in [9] with capacity design concepts taking into account shear capacity, flexural capacity and contribution from floor reinforcement to beams. Maximum inter-story drift ratios obtained from time-history analyses are plotted against ground motion intensities. Results are statistically interpreted to develop cumulative distribution functions for frames. Fragility curves are plotted for damage states of conventional structures. Fragility curves thus drawn are used to estimate the expected annual loss (EAL) of low rise RC frames using quadruple integral formula based on probabilistic financial risk assessment framework. Depending on the extent of damage, the fire resistance rating of the structure could be significantly reduced.

The paper [10] is devoted to obtaining some quantitative information about this topic, with reference to steel moment-resisting frames, even if the adopted methodology could also be extended to either different structural types or structural materials. As a first step, a simplified modeling of earthquake-induced structural damage, based on the superposition of geometrical and mechanical effects, is proposed. Then, a wide numerical analysis is performed with reference to a single-bay single-storey frame structure, allowing the main parameters affecting the problem to be identified. Finally, two multi-storey plane frames, designed in accordance with methods specified by Eurocodes, are analyzed as a case study.

In [11] a numerical procedure has been developed to model the sequences of failure which can occur within steel beam-to-column connections under fire conditions. In this procedure two recent developments, a static–dynamic solution process and a general component-based connection element, have been combined within the software in order to track the sequence of local failures of the connections which lead to structural progressive collapse in fire. In particular the procedure developed can be used to investigate the structural behaviour in fire, particularly the ductility and fracture of different parts of the steel-to-steel connections, and the influence of the connections on the progressive collapse resistance of steel frames in fire.

In the component-based connection model, a connection is represented as an assembly of “bolt-rows” composed of components representing different zones of mechanical behaviour whose stiffness, strength, ductility and fracture under changing temperatures can be adequately represented for global modelling. The potential numerical instabilities induced by fractures of individual connection’s components can be overcome by the use of alternate static and dynamic analyses. The transfer of data between the static and dynamic analyses enables a seamless alternation between these two procedures to take place. Accuracy and stability of the calculations can be ensured in the dynamic phase, provided that the time steps are set sufficiently small. This procedure has the capacity of tracking the local failures sequence (fractures of connection components, detachment and motion of disengaging beams, etc.) which lead to final collapse.

Following an illustrative case study of a two-bay by two-storey frame, the effect of ductility of connections on the collapse resistance of steel frames in fire is demonstrated in two case studies of a generic multi-storey frame. It is shown that the analytical process is an effective tool in tackling the numerical problems associated with the complex structural interactions and discontinuous failures which can affect a steel or composite frame in fire, potentially leading to progressive collapse. It can be seen that both tensile and compressive ductility in the connections make a contribution to the fire resistance of the beams. Preventing the detachment of steel beams in fire can be achieved by inducing greater ductility into their connections. Combined with appropriate component-based connection models, this procedure can be adopted in performance-based fire-resistant design to assess the ductility requirements of steel connections. Detailed finite element modelling of key elements is necessary to improve the robustness assessment of structures subjected to a coupled effect of fire and blast loads.

The paper [12] presents a method for a realistic multi-hazard approach by studying the residual load bearing capacity of steel columns under fire conditions and followed by an explosion. The approach adopts the use of a material constitutive law able to take into account both the strain rate sensitivity and the thermal softening. Explicit nonlinear dynamic analyses are performed using the explicit commercial code. Results show that the residual load bearing capacity is influenced by the stand-off distance. The time of fire loading at which an explosion is triggered is a critical parameter as well. High strain rates in the typical blast range are numerically obtained as a consequence of explosions in the close proximity. A comparison with the Eurocode approach is also reported. The results can be of great interest to establish the initial conditions that could potentially lead to the onset of progressive collapse in steel framed structures subjected to a combined effect of fire and blast loadings.

A static push-down analysis [13] is conducted experimentally using a 1/3 scale one-story bare steel moment frame substructure in this study. The objectives of this test include: investigating the behavior of bare steel moment frame under column loss scenario; validating the computational models developed for the purpose of investigating progressive collapse of steel frame structures. The contributions of collapse resisting mechanisms including flexural action and catenary action to the robustness of the system as the increase of the vertical displacement of the center column are quantified. The test results reveal that flexural action plays an important role in resisting progressive collapse along the entire loading process. However, the catenary action becomes the primary collapse resisting mechanism in the final stage of loading. Dynamic responses of the test specimen are estimated using energy-based method. It is shown the test specimen behaves elastically subjected to sudden loss of the center column and therefore progressive collapse will not occur. The dynamic increase factor is also estimated on the basis of the testing results. The analysis results suggest that catenary action has a great impact on the value of the dynamic increase factor under large deformation conditions.

At the same time, the problem of ensuring the survivability of structures in emergency situations has been studied for a long time [14]. Substantial research, conducted since about 1990, So, in [15] gives a General analysis of this problem. As a result of these studies, certain recommendations have been made for certain types of structures concerning the establishment of emergency parameters and constructive measures to prevent "progressive" destruction.

Definition of unsolved aspects of the problem

In the literature, not enough disclosed questions on the formulation of the term "survivability", not presented a single algorithm for calculating the survivability of building structures. Also, the literature does not take into account the dynamic components of the load on steel redundant frame.

Problem statement

The main problem in the work is the use of analytical methods in the study of approaches to determining the survivability of steel statically indeterminate frames in case of failure of individual elements. One of the tasks is to consider common approaches to assessing the risks of failure of structures and their corresponding strengthening.

Basic material and results

In the course of the study, the concept of "survivability" was defined. This property of the object to maintain limited working capacity under influences not provided for by the operating conditions, in the presence of some defects and damages, as well as the failure of some components of the object. As a rule, all parts of the object and the object as a whole should be calculated taking into account the limit States of the first and second groups. When considering emergency design situations, it is allowed to calculate only the main load-bearing structures of category A1 according to the limit States of the first group.

The technical system has the ability of survivability thanks to the built-in internal and external means of ensuring survivability (means of performance control, means of emergency protection). Survivability as an internal property of the system can be manifested in large external influences that are not provided for by the conditions of normal operation and under normal operating conditions, when there are failures of elements caused by operational defects, aging and other factors.

The main bearing structures of the objects of the classes of consequences (responsibility) CC3 and CC2 should be designed so that in an emergency the probability of avalanche (progressive) destruction, incomparably greater than the initial structural damage, is sufficiently small.

According to the source, the survivability of building structures is defined as the preservation of the bearing capacity or performance of structures in case of failure of one or more elements. Under the survivability of the building is understood to exclude the collapse of the entire building or its part with the sudden destruction of individual elements of the carrier system from the action of explosive waves or strikes when hitting vehicles, falling aircraft and other similar cases. There are two types of collapse: progressive collapse of the building and the loss of the overall stability of the building. Safety of building structures has led to the study of the properties of survivability - ensuring the stability of buildings and structures to emergency actions, to progressive collapse [16].

The most common is the definition of survivability properties as the system ability to adapt to emergency situations, to resist harmful effects, while performing its target function by changing the structure and behavior of the system. Depending on the degree of complexity of the organization and the class of systems, as well as the level of analysis, the property of survivability can be manifested (and, accordingly, quantified) by the same indicators that characterize the stability, strength, reliability, adaptability and others. According to the main positions of the theory of systems at the solution of a question in probabilistic statement the level of its survivability raises. This is done by improving the reliability of the system.

Survivability models can be stochastic, within the framework of the modern mathematical theory of reliability, or deterministic, within the framework of catastrophe mechanics. The probabilistic model describing the survivability of the system is called "load-strength" ("load - bearing capacity", strength model). Under the influence of an external load, the "strength" of the system gradually decreases until the system fails. External loads are described by a random function. For the rational justification of the damage magnitude which the construction is steady to the last, the necessary theory of risk, this enables to associate a probability of damage certain value occurrence and damage which may cause failure.

It is considered the survivability of building structures with possible destruction. According to [17], survivability is understood as the property of an object, which consists in its ability to resist the development of critical failures from defects and damages in the installed system of maintenance and repair, or the property of an object to maintain limited performance under influences not provided for by the operating conditions, or the property of an object to maintain limited performance in the presence of defects or damages of a certain type, as well as in the failure of some components."

There is no generally accepted term "structural survivability". Under the "survivability of the structure" is proposed to understand its property to maintain the overall bearing capacity at local destruction caused by natural and man-made impacts, at least for some time. This problem is directly related to ensuring the stability of structures of buildings and structures of "progressive" collapse in beyond design basis emergency damage and local structural damage. When designing critical structures, it is necessary to develop a system of preventive safety measures that reduce the emergency impacts risks. In addition, it is necessary to identify the "key" elements of the supporting structure which failure inevitably entails avalanche-like structure destruction, and to ensure the ability of such elements to perceive emergency effects without destruction.

Justification of the structures ability to withstand "progressive" destruction is carried out on the basis of calculation. The most accurate nonlinear calculation of structures considers the actual operation of the material and the system as a whole. Calculation of structures for resistance to "progressive" destruction is proposed as follows. At the first stage, the design is calculated at the operational stage (or in several installation and operational stages, considering the physical and geometric nonlinearity. At the second stage, the scheme is calculated with the elements removed from work. The calculation is also carried out considering the physical and geometric nonlinearity. If it turns out that some elements of the model do not meet the condition of strength (that is, they are destroyed), the calculation continues in the same way in the next stage without such elements. The calculation is completed by complete destruction of the carrier system.

However, it should be noted that in most cases, to prevent "progressive" destruction of the structure, it is necessary to provide the carrying capacity of all its elements in the initial emergency damage. In these cases, the calculation is stopped at the calculation first stage and the calculation second stage and "progressive" destruction process modeling is not necessary. The proposed method of calculation, in fact, is a computer simulation of a critical situation and enables to trace the adaptation of the structure to the new situation on the basis of changes in the design scheme. The designer on the basis of this calculation is able to identify a number of constructive measures to prevent this type of destruction.

The example of calculation of a high-rise building at local destruction caused by removal of an average column is given. This calculation enables to ensure the stability of the building structure to "progressive" destruction in case of emergency failure of building frame one of the columns. This can be done by a small increase in the percentage of reinforcement. According to the linear-elastic calculation, the number of longitudinal reinforcement of crossbars required for the perception of emergency action and the loads applied to its moment is about 3.5 times higher than the number of reinforcement necessary to ensure the bearing capacity of crossbars at design loads and impacts.

As a result of the two-stage calculation of the frame, taking into account the geometric and physical nonlinearity of the necessary reinforcement of the crossbars, it turned out to be 29% less. One-stage nonlinear calculation showed results similar to the results of two-stage calculation, but the required number of reinforcement bars was 10% more. Thus, a careful calculation analysis of the load-bearing system of the building allows to reveal additional reserves of its load-bearing capacity and with certain structural measures that require some increase in material consumption, it is possible to ensure the stability of the building to "progressive" destruction. In addition, it is possible to reduce the material intensity of the bearing structures of the building by taking into account the beyond-design emergency effects of those structures that in the design state of the building, with minor deformations, are not load-bearing, and with significant deformations of the bearing system due to emergency exposure, can be included in the work on the perception of the existing loads on the building.

Therefore, the sustainability of the constructions to the "progressive" destruction is part of the General problem of survivability of the structure. The problem of fire resistance of load-bearing structures, as well as the problem of meeting the requirements of seismic resistance, even in the case of construction of critical structures in areas with weak seismic activity, adjoins here. Consider the concept of" survivability " for high-rise buildings. High-rise buildings are buildings with an increased level of responsibility, so ensuring their reliable survivability is a priority. The survivability of a high-rise building is provided by a number of factors: the right choice of the design scheme, measures against progressive collapse, special techniques, fire resistance, seismicity, the use of appropriate materials and structures.

In high-rise construction, both traditional structural systems (frame, frame, cross-wall) and special ones used only in the construction of high-rise buildings (trunk, box, "pipe in pipe" and their combination) are used. The highest survivability of a high-rise building is provided by the cross-wall system. In addition, this system allows to achieve significant savings in materials of load-bearing structures [20]. This does not mean that only the above-mentioned structural systems should be used for all high-rise buildings. This problem should be solved individually in each case, depending on the whole complex of architectural, structural, installation and operational tasks.

To ensure the necessary survivability of a high-rise building, it is necessary to take into account the probability of local destruction of its supporting structures, which should not lead to a progressive collapse of the building. The calculation of the stability of the building must be made on a special combination of loads, taking into account the following schemes of local destruction: the destruction of two intersecting walls of one floor in a circle of 80 m2; failure of columns (pylons) with the walls adjacent to them, on the same area of local destruction; the collapse of the overlap of one floor on the above area. In some cases other schemes of local destructions can be accepted. In high-rise buildings are dominated by monolithic and precast-monolithic reinforced concrete floors, which are connected with other load-bearing structures should provide for the perception of the weight of half the span of the overlap.

Consider the concept of "survivability" of buildings and structures. There are measures to ensure survivability in emergency situations that should be recorded in the project documentation and known to the personnel responsible for the operation of the facility, as well as provided with appropriate instructions for supervision and maintenance of structures.

The building structure and substrate should meet the following requirements: to accept without damages and deformations unacceptable impacts arising during construction and within the prescribed period of operation; have sufficient capacity to perform under conditions of normal use during the entire installed life, namely, their operational parameters (displacements, vibrations, etc.) with a given probability should not exceed the established regulatory or project documentation limits, and their durability should be such that deterioration of materials and structures as a result of rot, corrosion, abrasion and other forms of physical deterioration did not lead to an unacceptably high probability of failure; to have sufficient survivability against local destruction and in compliance with the standards of emergency situations (fires, explosions and the like), excluding the progressive collapse phenomenon, when the overall damage is much larger than the initial perturbation that caused them.

The operating conditions components corresponding to the normal operation of the object effect depending on the equipment operation, atmospheric influences and others. Hazardous impacts should be considered throughout the construction and operation of the facility. The spatial unevenness and frequency of these impacts should be considered in the assessment of impacts. If hazards cannot be accurately predicted, it is advisable to consider them for safety reasons [16].

The structural safety position of a construction object imposes restrictions on the amount of the actual risk of the buildings, structures and structures accident. To the main part of the situation applies to the area of admissible values, the accident risk which boundaries are regulatory and limits the risk of accidents (Fig. 1). As long as the object accident actual risk remains within that area, the level of structural safety is considered sufficient.

The main purpose of the provisions introduction on the accident risk magnitude is to ensure the construction projects maximum possible safe resource and service life. The Figure 1 shows the whole set of standard accident risk values (R_n, R_{ma} i R_m). Therefore, if the risk of accident inherent in the object before its commissioning, normative (R_n), prevention of gross errors in the operation of the object, the safe resource (T_S) and service life (T_L) of this object is the greatest possible values, depending on the building structural type. In the presence of the provision, a principal opportunity is provided through planned examinations, during which the actual risk (R_a) is measured and changes associated with aging and wear are detected, and through preventive measures (strengthening, repair, etc.) that reduce the accumulated risk amount and cyclically increase the object safe resource (Fig. 1).

The object durability most significant indicators are its safe resource. If at the end of a safe resource, repair and restoration measures to reduce the risk of an accident at the facility are not carried out, then the value (T_L-T_S) is the time of the dangerous existence of the facility. However, during this period of life, the resistance of the object overload is reduced and (T_L-T_S) resource use can lead to an accident, and hence to losses that are disproportionately higher than the cost of preventive measures. Position on the accident actual risk magnitude plays the role of the regulatory framework in the implementation procedures of technical regulation the accident risk for the purpose of extending the safe service life of building objects. At the same time, the greatest effect is achieved through the regulation of the accident risk at the early stages of the object life cycle - the design and construction stages - designated in the law on technical regulation as declaration and certification.

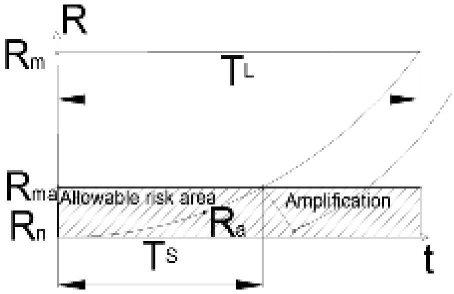

Figure 1 – Possible risk of accident and the resource object

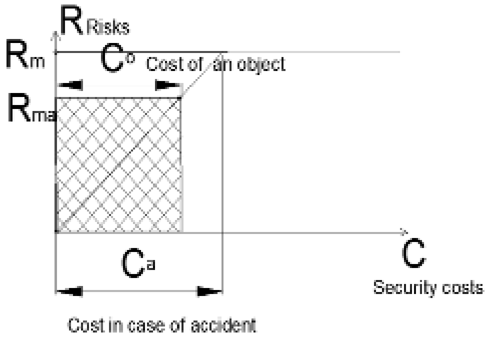

Figure 2 – Definition of safe risk taking into account the cost of the object in conventional units

Based on the economic feasibility, when deciding on the implementation of strengthening structures, cost in case of accident C_a (loss) and cost of an object C_o should be analyzed. Therefore, the inequality should be fulfilled

$$C_a \leq C_o \,. \qquad (1)$$

In case of structures failure (accident), the risk of loss should not exceed the failure

$$R \leq R_{ma} \approx C_o \,, \qquad (2)$$

where R – the potential risk of failure of the structure; R_{ma} – maximum allowable risk.

Conclusions

As a result of the study, it has been found that the survivability of steel statically indeterminate frames can be increased by improving the reliability of both individual elements and the system as a whole. The resource of the object can be extended by strengthening the failed elements. But it can be done within the maximum permissible risk. It has been proved that the cost of inspection and strengthening is determined depending on the possible losses risk in case of failure (accident) and in comparison with the object cost.

References

1. ДБН В.1.2-14:2018. (2018). *Система забезпечення надійності та безпеки будівельних об'єктів. Загальні принципи забезпечення надійності та конструктивної безпеки будівель і споруд*. Київ: Мінрегіонбуд України, Укрархбудінформ.

2. ДБН В.2.2-24:2009. (2009). *Проектування висотних житлових і громадських будинків*. Київ: Мінрегіонбуд України, Укрархбудінформ.

3. Avin, S., Wintle, C.B., Weitzdörfer, J., ÓhÉigeartaigh, S.S., Sutherland, W.J. & Rees, M.J. (2018). Classifying global catastrophic risks. *Futures,* 102, 20-26. https://doi.org/10.1016/j.futures.2018.02.001

4. Yaghlanea, A.B. & Azaiezb, M.N. (2017). Systems under attack-survivability rather than reliability: Concept, results, and applications. *European Journal of Operational Research, 258, 3,* 1156-1164. https://doi.org/10.1016/j.ejor.2016.09.041

5. Adama, J.M., Parisib, F., Sagasetac, J. & Lud, X. (2018). Research and practice on progressive collapse and robustness of building structures in the 21st century. *Engineering Structures,* 173, 122-149. https://doi.org/10.1016/j.engstruct.2018.06.082

6. Pushpalala, D. & Ogatab, K. (2014). The Role of Buildings in Disaster Risk Reduction: Focusing on the Great East Japan Earthquake. *Procedia Economics and Finance*, 18, 483-488. https://doi.org/10.1016/S2212-5671(14)00966-6

7. Liew, J.Y.R. (2008). Survivability of steel frame structures subject to blast and fire. *Journal of Constructional Steel Research*, 64, 7-8, 854-866. https://doi.org/10.1016/j.jcsr.2007.12.013

8. Rezvani, F.H., Yousefi, A.M. & Ronagh, H.R. (2015). Effect of span length on progressive collapse behaviour of steel moment resisting frames. *Structures*, 3, 81-89. https://doi.org/10.1016/j.istruc.2015.03.004

9. Melani, A., Khare, R.K., Dhakal, R.P. & Mander, J.B. (2016). Seismic risk assessment of low rise RC frame structure. *Structures*, 5, 13-22. https://doi.org/10.1016/j.istruc.2015.07.003

10. Corte, G.D., Landolfo, R. & Mazzolani, F.M. (2003). Post-earthquake fire resistance of moment resisting steel frames. *Fire Safety Journal,* 38, 7, 593-612. https://doi.org/10.1016/S0379-7112(03)00047-X

11. Sun, R., Burgess, I.W., Huang, Z. & Dong, G. (2015). Progressive failure modelling and ductility demand of steel beam-to-column connections in fire. *Engineering Structures,* 89, 66-78. https://doi.org/10.1016/j.engstruct.2015.01.053

12. Forni, D., Chiaia, B. & Cadoni, E. (2017). Blast effects on steel columns under fire conditions. *Journal of Constructional Steel Research*, 136, 1-10. https://doi.org/10.1016/j.jcsr.2017.04.012

1. DBN V.1.2-14:2018. (2018). *System to ensure the reliability and safety of construction sites. General principles for ensuring the reliability and structural safety of buildings and structures.* Kiev: Ministry of Regional Development of Ukraine, Ukrarhbudinform.

2. DBN V. 2.2-24:2009. (2009). *Design of high-rise residential and public buildings.* Kiev: Ministry of Regional Development of Ukraine, Ukrarhbudinform.

3. Avin, S., Wintle, C.B., Weitzdörfer, J., ÓhÉigeartaigh, S.S., Sutherland, W.J. & Rees, M.J. (2018). Classifying global catastrophic risks. *Futures,* 102, 20-26. https://doi.org/10.1016/j.futures.2018.02.001

4. Yaghlanea, A.B. & Azaiezb, M.N. (2017). Systems under attack-survivability rather than reliability: Concept, results, and applications. *European Journal of Operational Research, 258, 3,* 1156-1164. https://doi.org/10.1016/j.ejor.2016.09.041

5. Adama, J.M., Parisib, F., Sagasetac, J. & Lud, X. (2018). Research and practice on progressive collapse and robustness of building structures in the 21st century. *Engineering Structures,* 173, 122-149. https://doi.org/10.1016/j.engstruct.2018.06.082

6. Pushpalala, D. & Ogatab, K. (2014). The Role of Buildings in Disaster Risk Reduction: Focusing on the Great East Japan Earthquake. *Procedia Economics and Finance*, 18, 483-488. https://doi.org/10.1016/S2212-5671(14)00966-6

7. Liew, J.Y.R. (2008). Survivability of steel frame structures subject to blast and fire. *Journal of Constructional Steel Research*, 64, 7-8, 854-866. https://doi.org/10.1016/j.jcsr.2007.12.013

8. Rezvani, F.H., Yousefi, A.M. & Ronagh, H.R. (2015). Effect of span length on progressive collapse behaviour of steel moment resisting frames. *Structures*, 3, 81-89. https://doi.org/10.1016/j.istruc.2015.03.004

9. Melani, A., Khare, R.K., Dhakal, R.P. & Mander, J.B. (2016). Seismic risk assessment of low rise RC frame structure. *Structures*, 5, 13-22. https://doi.org/10.1016/j.istruc.2015.07.003

10. Corte, G.D., Landolfo, R. & Mazzolani, F.M. (2003). Post-earthquake fire resistance of moment resisting steel frames. *Fire Safety Journal,* 38, 7, 593-612. https://doi.org/10.1016/S0379-7112(03)00047-X

11. Sun R., Burgess I.W., Huang Z. & Dong G. (2015). Progressive failure modelling and ductility demand of steel beam-to-column connections in fire. *Engineering Structures,* 89, 66-78. https://doi.org/10.1016/j.engstruct.2015.01.053

12. Forni, D., Chiaia, B. & Cadoni, E. (2017). Blast effects on steel columns under fire conditions. *Journal of Constructional Steel Research*, 136, 1-10. https://doi.org/10.1016/j.jcsr.2017.04.012

13. Li, H., Cai, X., Zhang, L., Zhang, B., & Wang, W. Progressive collapse of steel moment-resisting frame subjected to loss of interior column: Experimental tests. *Engineering Structures,* 150, 203-220. https://doi.org/10.1016/j.engstruct.2017.07.051

14. Pugsley, A. & Saunders, O. (1968) *Report of the Inquiry into the Collapse of Flats at Ronan Point, Caning Town.* London: MSO.

15. Marchand, K.A. & Alfawakhive, F. (2005). *Blast and Progressive Collapse*. USA: AISC.

16. Кудишин, Ю. И. & Дробот, Д. Ю. (2009). Живучість будівельних конструкцій - важливий фактор зниження втрат в умовах аварійних ситуацій. *Металеві конструкції,* 1(15), 59-71.

17. Назаров, Ю.П., Городецкий, А.С. & Назаров, Ю.П., Симбиркин, В.Н. (2009). К проблеме обеспечения живучести строительных конструкцій при аварийных воздействиях. *Строительная механика и расчет сооружений*, 4, 5-9.

18. Городецький, А.С., Батрак, Л.Г., Городецкий, Д.А., Лазнюк, М.В. & Юсипенко, С.В. (2004). *Расчет и проектирование конструкций высотных зданий из монолитного железобетона (проблемы, опыт, возможные решения и рекомендации, компьютерные модели, информационные технологии)*. Киев: «Факт».

13. Li, H., Cai, X., Zhang, L., Zhang, B., & Wang, W. Progressive collapse of steel moment-resisting frame subjected to loss of interior column: Experimental tests. *Engineering Structures,* 150, 203-220. https://doi.org/10.1016/j.engstruct.2017.07.051

14. Pugsley, A. & Saunders, O. (1968) *Report of the Inquiry into the Collapse of Flats at Ronan Point, Caning Town.* London: MSO.

15. Marchand, K.A. & Alfawakhive, F. (2005). *Blast and Progressive Collapse*. USA: AISC.

16. Kudishin, Y. I. & Drobot, D. Y. (2009). The survivability of building structures is an important factor in reducing losses in an emergency. *Metal structures*, 1(15), 59-71.

17. Nazarov, Yu.P., Gorodetsky, A.S. & Nazarov, Yu.P., Simbirkin, VN (2009). To the problem of ensuring the survivability of building structures during emergency influences. *Construction mechanics and construction calculation,* 4, 5-9.

18. Gorodetsky, A.S., Batrak, L.G., Gorodetsky, D.A., Laznyuk, M.V. & Yusipenko, S.V. (2004). *Calculation and design of structures of high-rise buildings of monolithic reinforced concrete (problems, experience, possible solutions and recommendations, computer models, information technologies)*. Kiev: Fact.