МОСТИ ТА ТУНЕЛІ: ТЕОРІЯ, ДОСЛІДЖЕННЯ, ПРАКТИКА

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THE PROBLEM OF FORECASTING THE ROD STRUCTURES SURVIVABILITY

Purpose. Methods of metal structures calculation which would take into account sudden changes of the design scheme and its elements destruction as a result, are not perfect enough and are often fragmentary. The research of survivability of multi-element bar structures affected by negative factors will improve the efficiency of the such structures calculation with the prospect of further expanding the possibilities of forecasting the survivability of metal structures depending on its operation conditions. As a research object three-dimensional metal bar structures are considered, which are characterized by a high degree of production significance and responsibility during the operation. **Methodology.** The considered normative documents do not have a single approach regarding the identification of the problem and technique of generating possible solutions, but they combine all the listed standards. Approaches and methods for assessing the degree of a structure damage or serviceability are somewhat different: in some documents the area of damaged floor structures is limited; in others, the state of structures that have not gone out of work is assessed; as well as the economic forecast of a new building construction or restoring an old one. If we group the normative documents' provisions of the different countries, we can single out two established approaches on "progressive destruction" protection. According to the first approach, it is necessary to use indirect protection measures, according to the second one, it is necessary to use the ability of key (bearing) elements to perceive damaging effects, the ability of structure to redistribute loads in case of some elements' failures. **Results.** To increase the stability of building structures to progressive destruction, metal ones particularly, it is necessary to consider the possibility of local destruction already at the stage of building design. Its increase is facilitated by a decrease in the number of hinged joints, in some cases the use of integral structural elements, the use of building materials affected by plastic deformation, as well as the identification of building structure elements which under normal operating conditions do not perform bearing functions, but perform them in the case of the local destruction appearance. **Scientific novelty.** The analyses of the regulatory base and the researchers' works in a number of countries including Ukraine regarding the progressive destruction is performed. The necessity to improve the concept of designing construction objects is justified. The basis of this concept should consist of both theoretical research and experimental confirmation of the accepted assumptions. **Practical value.** The necessity of forming a unified approach for determining the problem of survivability and durability of structures, redistribution of loads on undamaged structural elements is substantiated. Directions for the development of measures and design solutions regarding the prevention of the progressive destruction of multi-element bar structures are proposed.

Keywords: reliability; durability; survivability; multi-element rod structures; progressive destruction

Introduction

Reliability and durability of structural elements and technological equipment, operated under the conditions of the combined action of mechanical loads and aggressive environments, has always been and remains in the engineering practice focus.

Nowadays, the importance and relevance of this problem increases and it acquires new accents because of the modern technology trends: in particular, increasing the machines' unit power and increasing the operational parameters of the working environment. The last one is due to the fact that the progressive technological processes and new substances production often requires the use of various aggressive working environments that cause premature destruction of structural elements and equipment.

The operating conditions associated with the simultaneous actions of aggressive working environments and loads are typical for the actual operating conditions of metal equipment in the mining, oil-gas and chemical industries, metallurgy, of building structures, port facilities and others. That is why the problem of optimal designing structural elements used in such conditions is very relevant. Taking into account the high requirements for economic feasibility, reliability and durability at a minimum material consumption of structures, required by the current technological development level, their main parameters (under the relevant operating conditions) should be determined at the design stage. The basis for this, first of all, should be a set of measures applied at the design stage: the choice of rational structural schemes and materials; correct calculation, taking into account all the interactions that may appear during the structure operation. Therefore, in recent decades, the problem of optimal (according to various criteria) design of load bearing structures elements under the operating conditions connected with aggressive working environments, has been given quite a lot of attention.

Methods of structures calculation (metal structures, in particular) which would take into account sudden changes in the structure and, accordingly, in its design scheme due to its elements destruction, are not perfect enough and are often fragmentary.

Despite the great work of researchers from many countries, including Ukrainian scientists, there are still many tasks on developing measures and design solutions to prevent progressive destructions. At present, large-scale theoretical studies in this direction are needed, as well as experimental confirmation of the accepted initial assumptions in the calculation of buildings for progressive destruction.

Therefore, the aim of the work is studying the survivability of bar structures affected by negative factors in order to increase the efficiency of calculating such structures with the prospect of further expanding the possibilities of forecasting the metal structures survivability depending on its operating conditions.

Three-dimensional metal bar structures, characterized by a high degree of production significance and responsibility during the operation, are considered as a research object.

Purpose

A research subject is the of survivability property, which includes ensuring the reliability and durability of already built structures; ways to increase the degree of their protection from the aggressive environment impact.

Research methods include: stress-strain state research; general methods of structural mechanics; research and calculation of structures, taking into account the material defectiveness.

Methodology

The first event that gave rise to the term "progressive destruction" was the side facade destruction of the Ronan Point building in England in 1968. Since the structural scheme of the building did not have the multi-connectivity property and did not provide for the redistribution of the load, a chain of destruction occurred as a result of the fall of the overlying structures. The commission investigating the accident cause, used the term "progressive destruction" and formulated recommendations for protection for panel buildings.

At the moment, the main documents describing the current issue solutions are the following:

– Україна – ДБН В.2.2-41:2019 (2019). Висотні будівлі. Основні положення.

– Great Britain – B8 5950 2001, B8 8110 2005a, 2005b, B8 5628 2005;

– Canada – MBCC;

– USA regulations – UFC 4-023-03 (2016);

– Kazakhstan – Rekomendatsii po zaschite ot progressiruyuschego obrusheniya. Agentstvo Respubliki Kazahstan po delam stroitelstva zhilischno-kommunalnogo hozyaystva, Astana 2011.

The listed normative documents do not have a single approach regarding the identification of the problem and technique of generating possible solutions, but they combine all the listed standards.

Approaches and methods for assessing the degree of a structure damage or serviceability are somewhat different: in some documents the area of damaged floor structures is limited; in others, the state of structures that have not gone out of work is assessed; as well as the economic forecast of a new building construction or restoring an old one (Pustovoytova, Kamchatnaya, Orel, & Naboka, 2015).

If we group the normative documents' provisions of the different countries, we can single out

two established approaches on "progressive destruction" protection. According to the first approach, it is necessary to use indirect protection measures, according to the second one, it is necessary to use the ability of key (bearing) elements to perceive damaging effects, the ability of structure to redistribute loads in case of some elements' failures (Dusenberry, 2003; Ellingwood, Smilowitz, Dusenberry, et al., 2007).

Indirect measures include:

– prevention or reduction up to the a satisfactory level of the occurrence probability or intensity of a special impact through the use of preventive or organizational measures;

– ensuring the integral integrity, non-cutness, multi-connection of the system, plastic deformability.

Nowadays, there is no consensus concerning the definition of "progressive destruction" and the protection strategy in case of its occurrence (General Services Administration, 2003; Canisius, (2006). Its main feature is considered to be a disproportionately large scale of final buildings damages. Initially, the disproportionality was supposed to be determined in comparison with the value of the damaging effect, later in comparison with some normalized value of the allowable destruction (Ivanova, 2013).

Results

In the civil engineering industry a number of works and scientific publications regarding the survivability topic written by the following authors are known: Yu. Kudyshyn, G. Heniiev, A. Perelmuter, V. Bondarenko, V. Almazov.

Based on the mentioned categories, materials on the issues of survivability and «progressive destruction» can be grouped in the following way:

1) conceptual nature questions;
2) external structure impact (damaging impact);
3) structure reaction to damage;
4) assessment of the final structure state.

In questions of a conceptual nature, one of the first national scientists who raised the problem of survivability in civil engineering was N. Streletskyi. In their works V. Bolotin and G. Heniiev introduce the concept of survivability as the ability of an object to meet safety requirements despite failures or preliminary impacts (Ivanova, Hapieiev, Shapoval, Zhabchyk, & Zhylinska, 2021).

Currently, the survivability issues of building structures are considered in the works of A. Perelmuter, N. Abovskyi, V. Kolchunov, V. Bondarenko, Yu. Kudyshyn, S. Doronin.

V. Almazov analyzes the impact of various measures on the self-cost of reinforced concrete buildings to ensure survivability, as well as the results of calculations obtained under various assumptions and settings (quasi-static, dynamic setting; accounting and not accounting for plastic deformations; location and value of a test damages).

A. Perelmuter considers the problem of survivability, the relationship between the concepts of "survivability" and "reliability", as well as the issue of survivability in the framework of the limit states method. In (Perelmuter, 2004) the author notes: «With regard to construction objects, the concept of survivability began to develop much later, primarily in relation to earthquake-resistant construction, although the term "survivability" itself might not have been applied. In particular, there was an idea to single out the so-called main load-bearing structures, and their reliability ensures the building or structure from complete destruction during emergency impacts, even if its further use for its intended purpose turns out to be impossible without a capital renovation».

V. Roitman notes the need to consider the question of survivability of structures not only at "mechanical" damages, but also under combined effects.

In the materials on the external impact on the structure, the survivability of existing buildings and structures depends on the type and value of the test damaging impact and the load that occurs at the moment of failure. The values of test damages recorded in the national regulatory base are often borrowed from the foreign regulations.

D. Drobot showed a model for ensuring structure's stability, where the main factors affecting the durability are reliability and survivability (fig. 1).

Reliability is understood as the property of a building object to perform specified functions during the required period of time. Impact calculations refer to the first and the second groups of limit states. Survivability is considered as the ability of a damaged system to fulfill its functional purpose and it is refered to the third group of limit states as states with an unacceptable level of damage.

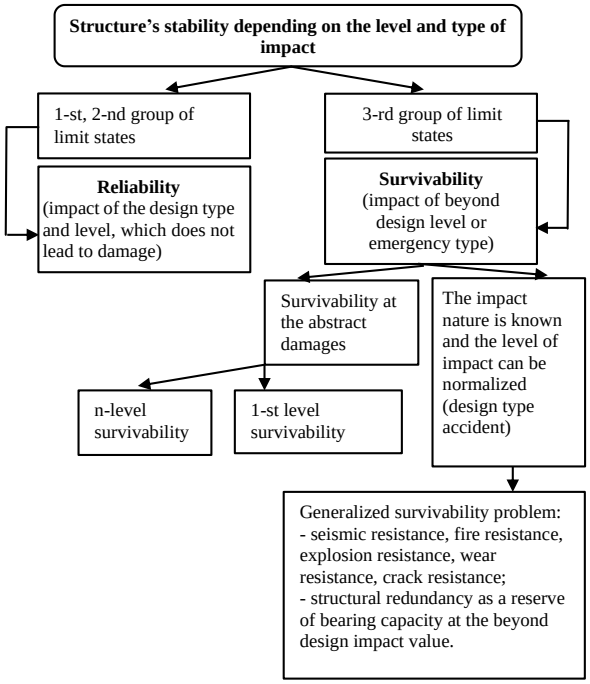

Fig. 1. Providing the structure stability

The problems of generalized survivability are all accidental actions and the corresponding problems of resistance to damaging effects:

– emergency type (seismic resistance, fire resistance, explosion resistance, wear resistance, crack resistance);

– emergency value of the design type impacts in the context of the structural redundancy issue at searching a bearing capacity reserve. The problem of modeling the failure of a structure's part is quite important. The main methods are the following;

– gradual rigidity drop of the failed part (because of elasticity modulus drop) or internal forces replacing the failed part (Barabash, 2014);

– the structure is calculated for an external non-emergency impact with the failed part already removed in advance, thus, neither the phasing of the process nor the dynamic effect is taken into account.

The previous methods replace the following, which is the most capacious, when the failure of a structure's part is achieved by loading it (Ivanova, Hapieiev, Shapoval, Zhabchyk, & Zhylinska, 2021).

Most of the works that consider the response of structures to damage, have local experimental and applied nature, but there are no system works.

Systems of failures which are caused by corrosion damage and sudden beyond design basis impact are investigated in a list of works. As a result, a technique of theoretical analysis of the processes of deformation, crack formation and destruction of physically and structurally nonlinear beam and rod reinforced concrete failure systems has been developed. The external action is given by simple loading, and the force in the damaged structure is calculated as in a system with previously removed elements. All technique's results are compared with the data of experimental studies on samples.

T. Pavlova described mathematical models of the stress-strain state of rods and membranes, affected by sudden structural changes such as reinforcement breakage, delamination or bonds disconnection. Wedge-shaped rods are given a different shapes intersections. With an instantaneous disconnection of the bonds on the supports the fiber normal stresses are analyzed in these rods.

Regarding the question of assessing the structure final state, N. Streletskyi demonstrated the problem of survivability on the example of a two-span metal continuous bridge and used a static connectivity as a numerical characteristic. As the survivability criterion the possibility of structure's further operation is considered. Its loss occurs at the moment of loss of bearing capacity.

In a number of works, the condition of non-destruction of elements on which the load is redistributed after failure is used as a criterion for ensuring survivability More rarely, the criterion of survivability is the condition when system maintains geometric invariability or the condition of maintaining a certain size of the rigid core. In these examples, to assess the survivability of the considered statically indeterminate systems, as well as to assess the contribution of individual elements for ensuring survivability, logical-probabilistic models are used (Ivanova, Hapieiev, Shapoval, Zhabchyk, & Zhylinska, 2021).

The fundamental document of the European design system is EN 1990 (EN 1994-1-1, 2004). The Eurocodes system of normative documents (EN 1994-1-1, 2004; ДБН В.1.2-14:2018, 2019) is based on a deterministic way using experience-based checks, but it allows to do probabilistic tests and calculations. The designing structures in emergency situations according to involves performing emergency calculations for extreme impacts, as described in EN 1990, EN 1991-1-7 and EN 1992-

1-1. The requirements for performing calculations for special effects are established by the document EN 1991-1-7. The document does not consider cases of explosions outside the building from terrorist acts and military operations. Particularly, there is no concept of progressive destruction, it is necessary to perform the calculation for the main design situations, including the emergency situation in accordance with EN 1990 (EN 1994-1-1, 2004).

Scientific novelty

The analyses of the regulatory base and the researchers' works in a number of countries including Ukraine regarding the progressive destruction is performed. The necessity to improve the concept of designing construction objects is justified. The basis of this concept should consist of both theoretical research and experimental confirmation of the accepted assumptions. There is a need of forming a unified approach for the determination of the problem of survivability and progressive destruction and the formation of possible solutions to this problem for multi-element structures.

To increase the stability of building structures to progressive destruction, metal ones particularly, it is necessary to consider the possibility of local destruction already at the stage of building design. Its increase is facilitated by a decrease in the number of hinged joints, in some cases the use of integral structural elements, the use of building materials affected by plastic deformation, as well as the identification of building structure elements which under normal operating conditions do not perform bearing functions, but perform them in the case of the local destruction appearance.

Conclusions

Despite the importance of the survivability problem, there are currently no appropriate methods and targeted calculations of the survivability of structures. This problem is directly related to ensuring the stability of buildings' structures to progressive destruction in case of beyond-design emergency damages and local destructions.

Within the framework of this paper, an attempt to formalize the problem of survivability was made. At the structure design stage, elements are calculated according to the allowable loads, which are determined based on normal operating conditions as a rule. Also, calculations of the technical systems reliability are performed, which means the probability of their failure-free operation. However, during the structure operation, an overnormal (extreme, emergency, beyond design) increase of loads or an extremely rapid damage increase is possible. Under these conditions, the structure's operational features are determined by its survivability, what means the ability to resist external forces when system's several elements fail.

High survivability buildings are destroyed gradually, while maintaining limited workability. Therefore, there is always time for their repair.

Low survivability structures are destroyed catastrophically, which is often accompanied by large material losses and even death of people.

Consequently, designing structures, it is necessary to take into account extreme situations and make a forecast of the survivability of systems, then finding structural solutions to increase their survivability in order to avoid catastrophic destruction.

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ПРОБЛЕМА ПРОГНОЗУВАННЯ ЖИВУЧОСТІ СТРИЖНЕВИХ КОНСТРУКЦІЙ

Мета. Методи розрахунку металевих конструкцій, які б враховували раптові зміни розрахункової схеми, і як наслідок руйнування її елементів, недостатньо досконалі та мають найчастіше фрагментарний характер. Вивчення живучості багатоелементних стрижневих конструкцій, що зазнають впливу негативних факторів, дозволить підвищити ефективність розрахунку таких конструкцій з перспективою подальшого розширення можливостей прогнозування живучості металевих конструкцій залежно від умов її експлуатації. Як об'єкт дослідження розглядаються просторові металеві стрижневі конструкції, яким відповідає високий рівень виробничої значимості та відповідальності під час експлуатації. **Методика**. У розглянутих нормативних документах немає єдиного підходу для визначення проблеми та методики можливих шляхів вирішення, але в них поєднано всі перелічені стандарти. Способи та методи оцінки ступеня пошкодження або експлуатаційної придатності споруди дещо відрізняються: в одних документах обмежується площа пошкоджень конструкцій перекриття; в інших – оцінюється стан конструкцій, які не вийшли з роботи; а також економічний прогноз будівництва нової або відновлення старої будівлі. Якщо згрупувати положення нормативних документів різних країн, то можна виділити два підходи, що склалися до захисту від прогресуючого обвалення. Згідно з першим підходом необхідно використовувати непрямі заходи захисту, згідно з другим – здатність несучих елементів сприймати шкідливі впливи та здатність конструкції перерозподіляти навантаження при відмові деяких елементів. **Результати**. Для підвищення стійкості будівельних багатоелементних металевих конструкцій, зокрема металевих, до прогресуючого обвалення вже на стадії проектування споруди необхідно розглядати можливості локальних руйнувань. Її підвищенню сприяють зменшення кількості шарнірних з'єднань, у ряді випадків – використання цілісних конструкційних елементів, застосування будівельних матеріалів, що сприймають пластичні деформації, а також визначення у конструкції споруди елементів, які за нормальних умов експлуатації не виконують несучих функцій, але

виконують їх у разі появи локальних руйнувань. **Наукова новизна.** Виконано аналіз нормативної бази та робіт дослідників низки країн, включаючи Україну щодо прогресуючого обвалення споруд з металевими стрижневими конструкціями. Обґрунтовано необхідність удосконалення концепції проектування будівельних об'єктів. Основа цієї концепції повинна складатися як з теоретичних досліджень, так і з експериментальних підтверджень, прийнятих на основі вихідних передумов. **Практична значимість.** Обґрунтовано необхідність формування єдиного підходу до визначення проблеми живучості та довговічності споруд, перерозподілу навантажень на не пошкоджені елементи конструкцій. Запропоновано напрями щодо розробки заходів та проектних рішень щодо запобігання прогресуючого обвалення багатоелементних стрижневих конструкцій.

Ключові слова: надійність; довговічність; живучість; багатоелементні металеві стрижневі конструкції; прогресуюче обвалення

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