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DETERMINATION OF THE TECHNICAL STATE OF BUILDINGS AND CONSTRUCTIONS AFTER FORCE AND TEMPERATURE INFLUENCES

Об'єктом дослідження є технічний стан і несуча здатність залізобетонних конструкцій будівель та споруд після силових і високотемпературних впливів. Методики розрахунку, які рекомендовано чинними нормативними документами України, не завжди дозволяють правильно прогнозувати зростання деформацій конструкцій і оцінити реальний запас несучої здатності. Одним з найбільш проблемних місць є розрахунок конструкцій, які працюють при вимушених зміщеннях опор та/або можливих високотемпературних впливах. Положення посилюється ще і тим, що розрахунки ведуться, як правило, із застосуванням недеформованих схем.

Показано, що підсилення конструкцій будівель, які отримали пошкодження після різних впливів, виконується, як правило, з використанням металевих елементів. При цьому основним залишається виконання розрахунку конструкцій для обґрунтованого призначення перерізів елементів підсилення. В ході дослідження використовувалися різні методи, в першу чергу моделювання роботи конструкцій з використанням методу скінченних елементів і сучасних обчислювальних комплексів. Це пов'язано з тією обставиною, що запропонований метод вирішення задачі має ряд особливостей, зокрема, дозволяє визначити розподіл зусиль в елементах будівлі після зміни характеристик жорсткості або введення в розрахункову схему додаткових стержневих елементів. В ході вирішення задачі моделюється поява і розвиток тріщин шляхом зміни характеристик жорсткості елементів.

Отримано зусилля, які могли б виникнути в елементах будівлі та підсилення. Завдяки цьому забезпечується можливість прийняття рішення про можливість подальшої експлуатації, підсилення або заміни конструкцій. Зміна умов закріплення розглядається як дія з боку основи. У порівнянні з аналогічними відомими методами розрахунку, такий підхід забезпечує можливість прогнозування зміни технічного стану в часі. Тобто врахування зміни умов закріплення та характеристик матеріалів конструкцій будівлі дозволить більш обґрунтовано підійти до оцінки напружено-деформованого стану і залишкового ресурсу конструкції або споруди в цілому.

Ключові слова: *залізобетонні елементи будівель та споруд, прогини слабоармованих елементів, розрахунок конструкцій, залишковий ресурс.*

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1. Introduction

Reinforced concrete elements of walls and floors were and remain the main components of buildings and structures for various purposes. Recently, in connection with a significant increase in the volume of construction of monolithic-frame buildings of increased number of storeys, the issue of ensuring comfortable and safe operation [1–3] remains relevant. This can't be achieved without taking into account geometric nonlinearity and the specifics of deformation of materials of structural elements, the construction of adequate design schemes, and the provision of regulatory documents for the strength and deformability of structures [4, 5].

When calculating steel-reinforced concrete slabs of modern structures, it is justified to use at least two CE variants (the abbreviation French Conformité Européenne is European compliance) for modeling steel-reinforced concrete flooring elements [6–8]. For effective adhesion of steel-reinforced concrete floor elements to each other, it is necessary to perform stamping in the corrugated board [9].

The operational experience of wall panels, columns, pylons, other compressed and bent elements indicates their sufficient supply of bearing capacity in the absence of unforeseen (non-design) impacts. One of the most significant causes of increased danger is considered uneven heating and a change in the strength and deformability of the material of structures during and after a fire [1–3]. Technical trends in the development of methods for thermotechnical calculation of reinforced concrete structures, the calculation of the heat loss of the base plate with uneven temperature profiles of the internal temperature are given in [10]. Determination of strength and deformability of steel-reinforced concrete beams with various anchor stops and types of fire protection during three-sided heating is shown in [11, 12].

In connection with the foregoing, it becomes necessary to carry out inspection work, determine controlled parameters (deflections, displacements, cracks, strength and deformability of structural materials, etc.) and assess the technical condition. Such work is carried out to determine the category of technical condition in accordance with the requirements of paragraph 5.2 of the current regulatory document [13]. Determining the category of technical condition allows you to decide on the possibility of further operation or on the restoration of the operational suitability of existing structures by reinforcement or replacement. In this case, it is necessary to take into account the requirements of the current regulatory document [14].

Most of the factors affecting the durability of buildings and structures are random in nature, so the reliability and durability of building structures are determined by the laws of probability theory.

2. The object of research and its technological audit

The object of research is the technical condition and bearing capacity of the structures of buildings and structures after power and high temperature influences.

The technical condition of the elements, depending on their ability to perform during the forecast period, all the functions provided for in the design and regulatory documentation can be classified as [13]:

– the technical condition of the structures is normal – the technical condition category «1»: the actual forces in the elements and sections of the structure do not exceed the allowable by calculation; there are no defects and damages that reduce the bearing capacity and durability or interfere with normal operation;

– the technical condition of the structure is satisfactory – category «2»: in terms of performance, the structure corresponds to the category of technical condition «1». There are partial deviations from the requirements of the project, defects or damage that can reduce the durability of the structure or partially violate the requirements of the second group of limit states. This circumstance in specific operating conditions of structures does not limit the use of the facility for a specific purpose. Necessary measures to protect the structure and compliance with the requirements for its use;

– technical condition of the structure – not suitable for normal operation – category «3»: the design does not correspond to the categories of technical condition «1», «2» in terms of bearing capacity or normal implementation of protective functions. The analysis of defects and damages with verification calculations reveals the possibility of ensuring the integrity of the structure for repair, reinforcement or replacement. It is necessary to repair, strengthen or replace the structure, and by the end of these measures, use the facility for a limited mode of operation, monitoring the condition of the structure, load and impact;

– technical state of the emergency structure – category «4»: the requirements of the first group of limit states are violated (or it is impossible to prevent these violations). The analysis of defects and damages with verification calculations shows the impossibility to guarantee the integrity of the structure to carry out its repair, reinforcement or replacement, if the possibility of the normal implementation of the protective functions of the structure is finally lost. This is especially true of the possible «fragile» nature of destruction. It is necessary to immediately exclude the presence of people in the area of possible collapse and/or take measures to exclude such collapse in order to repair, strengthen or replace the structure or to liquidate the facility.

It is assumed that structures throughout the entire life cycle due to aging and degradation can sequentially be in each of the four technical states. Establishing in which of the indicated technical conditions a given construction or building as a whole is located at a specific time is the task of a set of works to assess their technical condition.

In accordance with the requirements of design and regulatory documentation, criteria (quantitative and qualitative indicators) for assessing the state of structures and elements are established. These criteria are established on the basis of the analysis of available technical and current regulatory documentation.

The criteria are necessary to compare with them the actual values of the controlled and determining parameters that are obtained in the process of assessing the technical condition of structures.

3. The aim and objectives of research

The aim of research is development of the calculation methods taking into account the elastic-plastic properties of thermal effects to solve practical problems.

To achieve this aim, it is necessary to complete the following objectives:

1. To develop a set of interrelated measures to determine the parameters of the technical condition of structures after various influences.
2. To set the parameters and criteria of the technical condition, which would be suitable for calculating the stress-strain state and determine the technical condition of structures, buildings and structures in general.
3. To develop methods for determining the characteristics of strength and stiffness of the elements of buildings and structures after various influences.
4. To develop methods for calculating the stress-strain state, assessing the technical condition and the possibility of its regulation for the further operation of building structures after various influences.

4. Research of existing solutions of the problem

The development of building science and modern computer technology allows to take into account the specific features of the materials and structures used. Among such progressive structures can be noted steel reinforced concrete, pipe concrete structures, buildings with a monolithic frame and the like. At the same time, most objects for various purposes are built using structures and materials of the past. Such structures have been in operation for more than 30 years under the influence of various influences; it requires the determination of their technical condition [1, 2].

Among the main directions of solving this problem, which are found in the resources of world scientific periodicals, can be identified:

– taking into account temperature effects, including climatic ones [3];

– taking into account geometric non-linearity and non-linear operation of structures [4, 5], which allows the construction of adequate design schemes, reduce material consumption, ensure structural safety, resistance to progressive collapse;
– taking into account, when calculating the slab, two CE options for modeling elements of steel-reinforced concrete floors [6, 8], which makes it possible to determine the deflections and movements of structures.

Also, in one of the analyzed works [7] it is shown that in heavy concrete structures at high loads the reinforcement deforms elastically, and plastic deformations occur in concrete. In this work, it is about the fact that a centrally compressed pipe-concrete element can't be destroyed in the full sense of the word. And this allows us to recommend such structures for wide consumption as columns of buildings.

In another work [9], the need is substantiated for performing extrusions in the profiled sheeting for effective adhesion of steel-reinforced concrete floor elements. And in [10], technical trends are presented in the development of methods for the thermotechnical calculation of reinforced concrete structures, as well as the calculation of the heat loss of the foundation slab with uneven temperature profiles of the internal temperature. The determination of the strength and deformability of steel-reinforced concrete beams with various anchor stops and types of fire protection during three-sided heating is shown in [11, 12].

All the above works, except for works [1–3], allow solving particular cases of structural analysis. But the methods for solving the problem of determining the parameters of the technical state of structures after various influences are absent in the literature available to the authors, which makes the study promising.

5. Methods of research

In the research, the following scientific methods are used:
– survey methods for building structures to determine controlled parameters using modern methods and instruments;
– mathematical modeling of the stress-strain state of structures of buildings and structures;
– methods of structural mechanics in the calculation of structures of buildings and structures under various influences;
– assessment of the technical condition on the basis of surveys and structural calculations.

Assessment (a set of interrelated measures) of the technical condition is carried out in the following sequence [1, 2, 13]:
– analysis of technical documentation;
– visual inspection of the state of structures;
– instrumental examination of the state of structures;
– analysis of the results of visual and instrumental examination;
– performance of verification calculations (if necessary);
– assessment of the technical condition;
– conclusions about the possibility of further operation and recommendations for bringing structures into serviceable condition;
– determination of residual life.

To assess the state of structures are used:
– criterion of conformity of the design (construction) of the working documentation (dimensions, reinforcement, design features);
– criterion for the conformity of the design (structure) to the determining parameters of the technical condition (the presence or absence of unacceptable defects, the conformity of the materials used to the requirements of the project, etc.) and to satisfy the calculation requirements for the limiting states of the first and second groups.

Based on the results of the analysis of technical documentation, visual and instrumental examination of structures, a decision is made on the need for verification calculation.

The following criteria are considered as criteria for making a decision on the need to perform verification calculations of structures and structures:
– presence of defects that reduce the bearing capacity of structures;
– decrease in the strength characteristics of materials compared to design ones (they are established by examining structures using destructive and non-destructive testing methods);
– reducing the area of the working section of the element;
– excess of actual operational loads of design values;
– technological impacts unforeseen by the project (including exposure to high temperature in case of fire);
– development of uneven deformations of the base.

In the course of performing verification calculations, it is provided for:
– mathematical modeling by the finite element method, taking into account the established deformed state [1–3];
– structural analysis and determination of forces and strains in the elements of the design scheme;
– comparison of the nature of the deformation of the real object and the mathematical model and refinement of the stiffness characteristics of the materials of the model elements;
– calculation of the refined model, determination of forces and displacements;
– verification of compliance with the conditions ensuring the bearing capacity and deformability of building structures, buildings and structures, assessment of their technical condition;
– adjustment of the design scheme of the building, taking into account the installation of reinforcement elements and the calculation of a new model;
– gain design.

Assessment of the technical condition of structures is carried out by comparing the controlled parameters, which are determined during visual and instrumental examinations, with the corresponding design parameters, as well as the results of verification calculations [1–3].

6. Research results

The application of the developed methodology in practice is illustrated by the following example of determining the technical condition of the structures of the building of the «Gagarin Cinema» on the Shchuseva 5 Street in the Shevchenko district of Kyiv in Ukraine (N 50°47′34.259″, E 30°44′67.098.15″). During the survey, engineering and geological studies of the base soils and studies are carried out to determine the physicomechanical characteristics of the structural materials and series of constructions. A feature of this construction is that a fire broke out in one of the rooms.

The building of the cinema «Gagarin Cinema» is a complex multi-storey structure in terms of construction, which was built in the 70s of the last century.

The building consists of three volumes. The main volume (part) of the building is a hall for spectators. It is a one-story building with a height difference. The technological part, which is a three-story building, is attached to the hall.

The structural system of the main part of the building is frameless with load-bearing brick walls. Two monolithic reinforced concrete belts are placed in the masonry of the walls. According to the results of the studies, it was found that the density of the masonry is classified as «conditionally effective», the compressive strength and bending corresponds to the brand M100. The masonry of the building has significant damage: cracks, destruction of the surface layers and the like.

According to the results of laboratory tests of cement-sand mortar, it is found that in terms of compressive strength, the solution corresponds to grade M25 (in the room where there was a fire) and minimum grade M50 (in other rooms).

As the supporting horizontal elements in the hall parts, rafters of prefabricated reinforced concrete gable beams with a span of 18 m are used. According to the results of the studies, the beams correspond to the marking 1B4-18-2 in the PK-01-06 series.

On the upper belt of the rafters, ribbed cover plates are supported. According to the results of the studies, ribbed plates correspond to the PNS-12 marking according to the PK-01-111 series with a bearing capacity of 650 kg/m^2 (excluding dead weight). This corresponds to a payload of 380 kg/m^2.

The spatial rigidity of the main part of the building is ensured by the joint work of 510 mm thick brick walls, horizontal reinforced concrete belts and a reinforced concrete horizontal coating disk.

The results obtained during the surveys are used to calculate the stress-strain state of the building. Building calculations are based on a mathematical model developed for joint calculation of the BASIS-FOUNDATION-BUILDING system. The spatial calculation model, as the only structural system, consists of two substructures:

– substructure No. 1 – calculated finite-element model of the structural system of the building;
– substructure No. 2 – design model of the base.

The purpose of the complex calculation is obtaining the stress-strain state of the building structures and the base, as a system that works together.

The calculation of the building (substructure No. 1) is performed using the LIRA CAD software package, which is based on the finite element method in displacements. To develop the model, the following finite elements are used, which make it possible to fully take into account the properties of materials, structures, their compounds and base soils:

– type 10 – universal spatial bar finite element;
– types 41, 42 and 43 – a quadrangular shell element, a triangular shell element;
– type 51 – an element that allows to simulate the vertical movement of the soil of the base.

The foundation sheet piles were modeled using the GRUNT system (substructure No. 2), a program for automated creation of a soil model and calculation of elastic foundation parameters (base stiffness factors C_1, C_2). The GRUNT system provides an interface for the exchange of data between LIRA CAD software package, a unit for determining precipitation and stiffness factors of the base, and also takes into account the bearing capacity of the foundations when determining stiffness coefficients with significant loads on the base. This allows to determine the stress in the soil mass from the circular load area by numerical integration for the entire array of elementary layers of all foundation plates, taking into account the mutual influence. This increases the accuracy of determining the settlement of foundation slabs in comparison with a rectangular load area.

The following program functions are used:

– creating a soil model based on given wells;
– calculation of the parameters of the elastic base;
– calculation of the stiffness factors of the base C_1, C_2 for CE, which are transmitted from the LIR-VISOR system.

The soil model contains geology information at every point on the construction site. Each composite EGE (engineering-geological element) is described by the following soil characteristics:

– deformation modulus E;
– Poisson's ratio ν;
– specific gravity γ.

The loads that were imported from LIR-VISOR are considered. A computational scheme in the form of a half-space (Boussinesq problem) is used, it is linearly deformed.

The calculation is performed in an iterative way, in which at the first stage of the LIRA CAD software package workloads are collected in the form of reactions at the level of the soles of the foundations, taking into account the structural rigidity of the object, constant values of the stiffness coefficients of the base were also calculated. The obtained values of the reactions of the base are transferred as the magnitude of the pressure loads on the calculated model of the base with its subsequent calculation of the deformations (sediments), which are used to determine the new (redistributed) stiffness coefficients of the base.

To calculate the base absorbing at each settlement point in contact with the foundations, the method of summing the deformations of elementary layers along a given vertical line without taking into account lateral expansion was used. In this case, the stress from the self-weight of the soil is calculated by the generally accepted method, and the distributed stresses are calculated on the basis of closed solutions for the half-space model, it is linearly deformed. Distributed stresses are calculated taking into account the mutual influence of the sections of this foundation. The calculated values of the stiffness coefficients of the base, taking into account the operation of soils in the linear stage, were substituted into the initial data for calculating the model on the LIRA CAD software package in the second step. Based on the results of this calculation, an analysis of the stress-strain state of the calculation scheme is performed.

The calculations are performed and it is found that the greatest deformation of the base soil is 22.19 mm under the walls of the hall part of the building (Fig. 1). According to the requirements of current regulatory documents, for multi-storey frameless buildings with load-bearing brick walls with reinforced concrete belts, average precipitation should not exceed 18 cm, that is, the design precipitation of the building does not exceed the limit values.

According to the requirements set forth in clause 5.2 [13], the condition of the external walls of the building is assessed as unsuitable for operation. To ensure continued reliable operation of the walls of the building, it is necessary

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to repair the masonry, grease the joints, clean the facade, and repair the blind area. It is recommended to carry out activities that will make it impossible to soak the masonry walls – organized drainage from the roof and the construction area, as well as wall insulation in accordance with the requirements of current regulatory documents.

The developed model allows to determine the forces and movements in all CEs with which the building is modeled. As an example, Fig. 2 shows the results of calculating the walls of the first floor.

Thus, on the basis of the complex of studies, the stress-strain and technical condition of the building structures are determined and measures for restoration of structures are developed.

7. SWOT analysis of research results

Strengths. A positive effect of the application of the proposed methodology for assessing the technical condition of both individual structures and buildings and structures as a whole can be considered the possibility of extending the service life or performing reinforcement or replacing structures. Since the reliability and durability of buildings during the construction process is ensured through the use of high-quality materials, compliance with the technology of work and full compliance with their design. Most of the factors affecting the durability of buildings and structures are random in nature, so the reliability and durability of building structures are determined by the laws of probability theory.

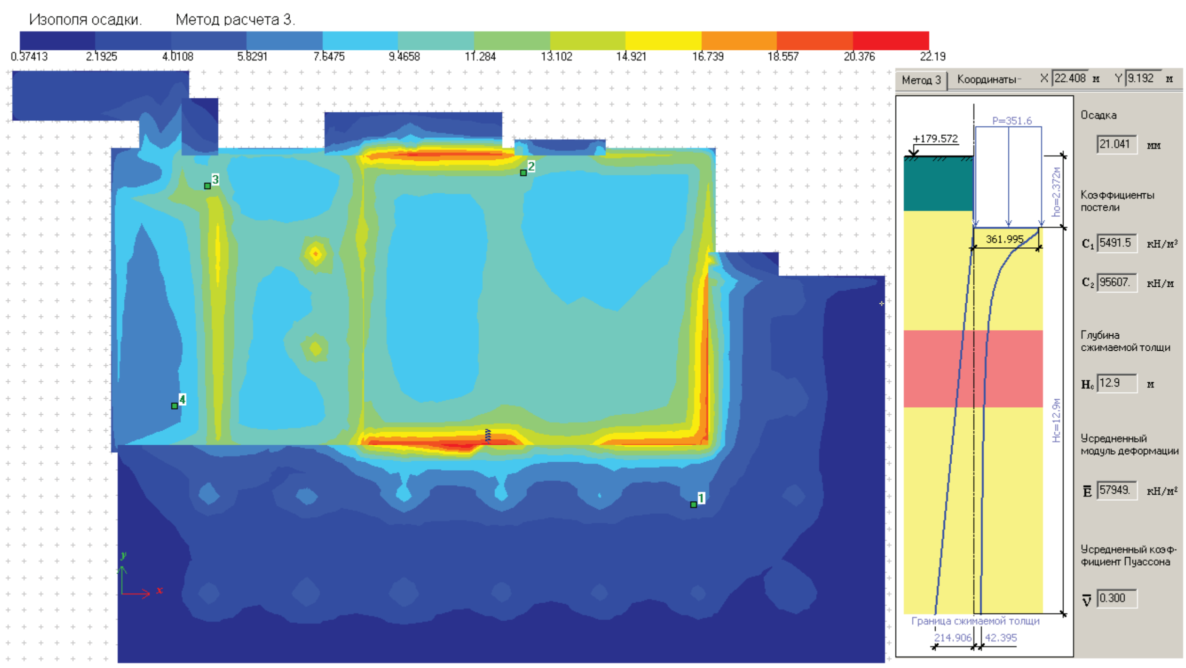

Fig. 1. Absorbing isopoles, mm

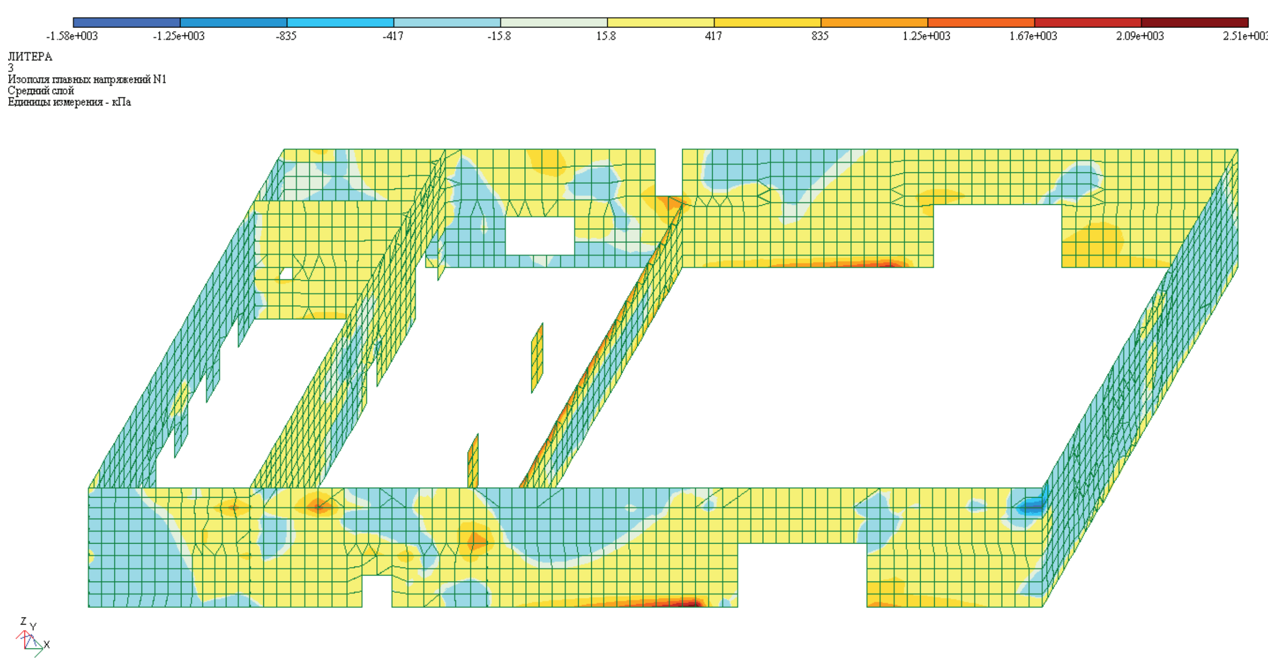

Fig. 2. The distribution of the main stresses N_1 in the walls of the first floor

Weaknesses. The weakness of the developed methodology for determining the technical condition of structures is the significant dependence of the results of diagnostics of structures and soil of the base on the instruments used and design features.

It is necessary to carry out regular monitoring of the technical condition of building structures, buildings and structures at various stages of their life cycle: design, construction, operation, conservation, re-conservation, liquidation.

Opportunities. The forecast of changes in the parameters of the technical condition will make it possible to predict current and overhaul repairs of structures, to exclude losses from accidental destruction of structures. Because the basis of the organization of monitoring to ensure the operational safety of buildings and structures is to monitor changes in indicators of controlled parameters of the technical condition and assess certain changes. And the number and types of monitored parameters are determined by the results of the previous survey, the requirements of regulatory and design documentation, and the conditions for maintaining the operational properties of an object during its life cycle.

The proposed methodology for determining the technical condition of structures of buildings and structures can be applied in the elimination of non-design impacts on structures (natural disasters, industrial accidents, etc.).

Threats. The complexity of implementing the research results lies in the need for significant investment in staff training and the acquisition of modern instruments and equipment for structural diagnostics. In modern specialized construction testing laboratories, capital costs can be minimized.

8. Conclusions

1. A set of interrelated measures has been developed to determine the parameters of the technical condition of structures after various influences. This complex includes the following procedures:

– analysis of technical documentation;
– visual inspection of the state of structures;
– instrumental examination of the state of structures;
– analysis of the results of visual and instrumental examination;
– performance of verification calculations (if necessary);
– assessment of the technical condition;
– conclusions about the possibility of further operation and recommendations for bringing structures into serviceable condition;
– determination of residual life.

This complex allows to perform both reliable estimates of the current technical condition, and predict changes in the technical condition over time, which will prevent the occurrence of structural accidents and related losses. Such a circumstance will allow rational use of funds for current and overhaul repairs and regulate the technical condition in such a way as to achieve the most efficient use of fixed assets.

2. The proposed set of measures allows to analyze the structural design of the building, establish the parameters and criteria of the technical condition for calculating the stress-strain state and determine the technical condition of structures, buildings and structures in general. Based on the results of the visual examination, designs are established that have defects and damage, and an instrumental examination program is being developed. In this program, designs are noted for which it is necessary to establish controlled parameters (geometric dimensions, deflections, displacements, strength, etc.).

3. Within the framework of the developed complex, the geometric parameters, deflections, displacements, strength and stiffness of the elements of buildings and structures after various influences are determined. The strength of the structures of buildings and structures directly depends on the strength of the materials used (concrete, reinforcement), the location of the reinforcement in the section, as well as on loads and effects.

Differences in determining the strength characteristics of the material of structures are taken into account by introducing into the calculation of reliability factors that ensure normal operating conditions and guarantee the structure from the onset of the ultimate state. As can be seen from the results of laboratory tests of the mortar in the masonry of the building, the compressive strength of the mortar corresponds to grade M25 (in the room where there was a fire) and grade M50 (in other rooms).

4. Methods have been developed for calculating the stress-strain state, assessing the technical condition and the possibility of its regulation for the further operation of building structures after various influences. For most structures, the determining issue is the strength or calculation of the first group of limiting states. Based on the studies, the parameters and criteria of the stress-strain and technical condition of the real object are established. The stress-strain state of the building structures is calculated based on the mathematical model of the BASIS-FOUNDATION-BUILDING system. The spatial computational model, as a single structural system, is recommended to be composed of two substructures:

– substructure No. 1 – calculated finite-element model of the structural system of the building;
– substructure No. 2 – design model of the base.

Using a single structural system allows to perform calculations based on data obtained during operation.

The results of determining the internal forces in the elements and structures make it possible to compare them with the critical ones for the building structures, to conclude that further operation is possible, the need to develop measures to strengthen or replace structures.

References

1. Semynoh, M., Holodnov, O. (2009). Modelyuvannya napruzheno-deformovanoho stanu dlya obgruntuvannya mozhlyvosti prodovzhennya terminu ekspluatatsiyi budivel'nykh konstruktsiy, budivel' ta sporud. *Zbirnyk naukovykh prats' Ukrayins'koho naukovo-doslidnoho ta proektnoho instytutu stalevykh konstruktsiy im. V. M. Shymanovs'koho, 4,* 243–249.
2. Semynoh, M., Holodnov, O. (2011). Nadiynist' ekspluatatsiyi zalizobetonnykh konstruktsiy pislya sylovykh, deformatsiynykh i vysokotemperaturnykh vplyviv. *Budivel'ni konstruktsiyi, 74 (2),* 56–63.
3. Holodnov, O., Antoshyna, T., Otrosh, Yu. (2017). Pro neobkhidnist' rozrakhunku budivel' zi stalevym karkasom na temperaturni vplyvy. *Zbirnyk naukovykh prats' Ukrayins'koho instytutu stalevykh konstruktsiy im. V. M. Shymanovs'koho, 20,* 65–84.
4. Abdel-Fttah, A., Said, M., Salah, A. (2016). Nonlinear finite element analysis for reinforced concrete slabs under punching loads. *International Journal of Civil Engineering and Technology, 7 (3),* 392–397.
5. Balomenos, G. P., Genikomsou, A. S., Polak, M. A., Pandey, M. D. (2015). Efficient method for probabilistic finite element analysis with application to reinforced concrete slabs. *Engineering Structures, 103,* 85–101. doi: http://doi.org/10.1016/j.engstruct.2015.08.038

ISSN 2226-3780

6. Fraile-Garcia, E., Ferreiro-Cabello, J., Martinez-Camara, E., Jimenez Macias, E. (2016). Frail Optimization based on life cycle analysis for reinforced concrete structures with one-way slabs. *Engineering Structures, 109,* 126–138. doi: http://doi.org/10.1016/j.engstruct.2015.12.001
7. Kwan, A. K. H., Ma, F. J. (2016). Crack width analysis of reinforced concrete under direct tension by finite element method and crack queuing algorithm. *Engineering Structures, 126,* 618–627. doi: http://doi.org/10.1016/j.engstruct.2016.08.027
8. Lantsoght, E. O. L., van der Veen, C., Walraven, J., de Boer, A. (2015). Experimental investigation on shear capacity of reinforced concrete slabs with plain bars and slabs on elastomeric bearings. *Engineering Structures, 103,* 1–14. doi: http://doi.org/10.1016/j.engstruct.2015.08.028
9. Einpaul, J., Ospina, C. E., Fernández Ruiz, M., Muttoni, A. (2016). Punching shear capacity of continuous slabs. *ACI Structural Journal, 113 (4),* 861–872. doi: http://doi.org/10.14359/51688758
10. Smolka, J., Slupik, L., Fic, A., Nowak, A. J., Kosyrczyk, L. (2015). CFD analysis of the thermal behaviour of heating walls in a coke oven battery. *International Journal of Thermal Sciences, 104,* 186–193. doi: http://doi.org/10.1016/j.ijthermalsci.2016.01.010
11. Caldas, R. B., Fakury, R. H., Sousa Jr., João Batista M. (2014). Finite element implementation for the analysis of 3D steel and composite frames subjected to fire. *Latin American Journal of Solids and Structures, 11 (1),* 1–18. doi: http://doi.org/10.1590/s1679-78252014000100001
12. Vatulia, G., Orel, E., Kovalov, M. (2014). Evaluation of steel-concrete beams fire resistance with the selection of effective fire protection. *Proceedings of the 6th International Conference on Dynamics of Civil Engineering and Transport Structures and Wind Engineering, Zilina,* 327–331.
13. *DSTU-N B V.1.2-18:2016. Nastanova shchodo obstezhennya budivel' i sporud dlya vyznachennya ta otsinky yikh tekhnichnoho stanu.* (2017). Kyiv: DP «UkrNDNTs», 45.
14. *DBN V. 2.6-98:2009. Derzhavni budivel'ni normy Ukrayiny. Konstruktsiyi budynkiv i sporud. Betonni ta zalizobetonni konstruktsiyi. Osnovni polozhennya* (2011). Kyiv: Minrehionbud Ukrayiny, 71.

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