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ANALYSIS OF THE IMPACT OF CROSS-SECTION DAMAGE ON THE STRENGTH AND DEFORMABILITY OF BENT REINFORCED CONCRETE ELEMENTS

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The article analyzes defects and damage in reinforced concrete structures, particularly physical, biological, and chemical, with an emphasis on the impact of prolonged operation and aggressive environmental conditions. Research shows that mechanical damage, such as spalling and potholes, significantly reduces the load-bearing capacity of structures and causes complex deformations. Relevant directions in scientific research have been identified, particularly regarding the behavior of damaged reinforced concrete beams under load, which require further development and improvement of methods for assessing residual load-bearing capacity. The article emphasizes the need for additional experimental studies and the use of modern software for more accurate methods of predicting and calculating reinforced concrete structures.

Key words: bent reinforced concrete elements, damage, defects, residual bearing capacity, corrosion, stress-strain state.

Introduction

Reinforced concrete is widely used in construction today, both for mass residential and public buildings as well as for unique architectural structures due to its high strength, durability, and cost-effectiveness. By combining the compressive strength of concrete with the tensile strength of reinforcement, reinforced concrete enables the creation of reliable structures of various shapes and sizes that can withstand significant loads and extreme conditions. However, despite its effectiveness, reinforced concrete structures are subjected to negative environmental impacts and the conditions in which they are used. This reduces their reliability and service life. The stress-strain state of damaged reinforced concrete structures, especially under various factors, requires careful analysis. Damage to reinforced concrete structures can occur at different stages of a building's lifecycle due to a variety of reasons, ranging from technological defects to the effects of natural phenomena and mechanical damage. According to the article (Surianinov et al., 2023), damage resulting from prolonged use and wartime actions is particularly relevant today. Such damage typically manifests as cracks, reinforcement corrosion, concrete degradation, and surface spalling. Prolonged use and exposure to aggressive environments lead to gradual material degradation, weakening its load-bearing capacity. Wartime actions, in turn, can cause additional mechanical damage, significantly complicating the operation of structures and necessitating timely diagnosis and restoration to prevent emergency situations. These factors not only reduce the strength of such reinforced concrete structures but also subject them to complex stress-strain states, requiring comprehensive analysis and appropriate measures to maintain the integrity and continued use of buildings and structures.

Materials and methods

The main advantages of reinforced concrete structures include increased strength, fire resistance, durability, and rapid installation, which make them widely used in construction. However, reinforced concrete elements are exposed to various factors over extended periods of use, which can affect their service life. Underestimating the importance of regular maintenance of reinforced concrete structures, mechanical damage due to military actions, and aggressive environmental conditions can lead to significant damage to the structure of reinforced concrete elements, potentially impacting the operational suitability of the building.

The main purpose of this work is a literature review and analysis of damages and defects in reinforced concrete structures, as well as classification according to various parameters. A detailed classification of damages and defects is necessary to analyze the potential causes of reduced load-bearing capacity and serviceability of reinforced concrete structures. This issue is emphasized in numerous previous studies. For example, in the article (Blikharskyy & Kopiika, 2022), a recommendation is made to divide all causes of damage to reinforced concrete structures into groups: environmental, technological, and extraordinary influences (see Fig. 1).

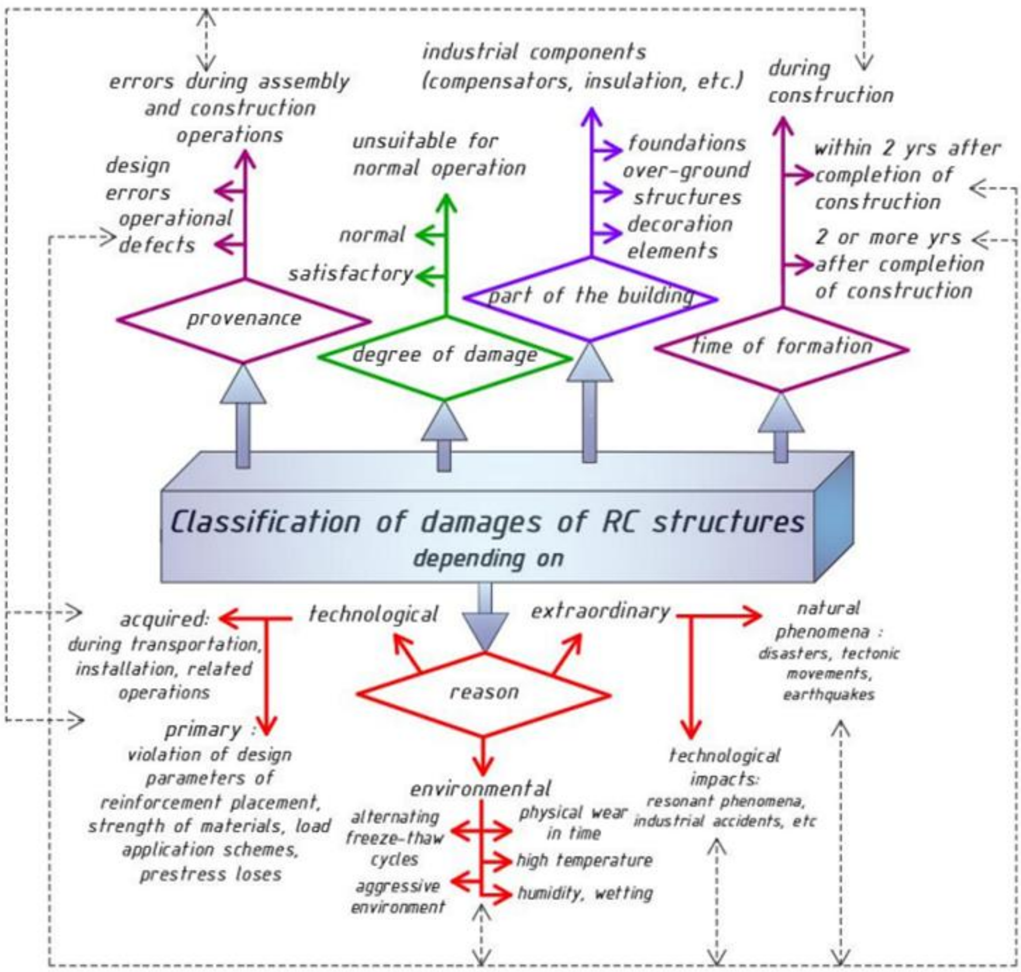

Fig. 1. Classification of damages in RC structures (Blikharskyy & Kopiika, 2022)

In their article, (Mykhalevskyi et al., 2023) establish a classification of damage causes and divide them into three main groups: physical, biological, and chemical. Physical damage can occur due to temperature changes, cyclic loading, and other mechanical influences. Biological damage is caused by the growth of plants and microorganisms within the structure of building components. Chemical damage is associated with corrosion, interactions with chemical substances, and so on.

The authors (Klymenko & Oreshkovich, 2013) emphasize that building codes in different countries, as well as research by scientists worldwide, define various classification systems for damage to reinforced concrete structures during operation. However, all these studies share common criteria for assessing the technical condition of structures and making decisions regarding their continued use. Since the evaluation of the technical condition of reinforced concrete structures is based on the identification and analysis of damage and defects, research in this area focuses on the classification and typification of identified defects and damage, simplifying the diagnosis and calculation of such structures.

The wear of reinforced concrete structures is a complex process that requires reliable and objective methods for detecting damage and defects. One method for determining residual load-bearing capacity is analyzing the degree of deformation of the reinforced concrete structure. An increase in deformations may indicate a deterioration of its condition. Additionally, changes in the failure mechanism and the accumulation of internal stresses within the material of the structures also suggest potential wear. It is important to consider the degree of strength reduction in an element by evaluating the structure's energy potential and changes in its dynamic characteristics (Hait et al., 2018). Analyzing changes in dynamic characteristics also aids in assessing the structure's condition and its ability to withstand applied loads. Therefore, a comprehensive approach to studying wear ensures an accurate evaluation of the technical condition of construction objects and determines the need for further maintenance and repair.

It should be noted that modeling damaged reinforced concrete structures, assessing their damage under the influence of various factors, and changes in the stress-strain state have gained significant relevance in recent scientific research. Determining the impact of damage on reinforced concrete structures, especially in the context of numerous buildings that remain damaged due to military actions, has become a pressing task (Krasnitskyi et al., 2024). The use of existing methods only partially addresses this issue, as the impact of damage on structures is complex and depends on many factors. Each evaluation or calculation method applies only to certain conditions. Current standards lack calculation methods for determining the residual load-bearing capacity of damaged reinforced concrete bending elements that have been subjected to operational loads. The use of general recommendations is not an effective solution to this problem. Ongoing studies of damaged reinforced concrete structures using software packages aim to understand damage mechanisms and their effect on the load-bearing capacity of beams. The research includes an analysis of numerical calculations of two different types of damage using the “ANSYS” and “LIRA-SAPR” software packages, where the discrepancy between theoretical calculations and experimental results does not exceed 10 % (Krasnitskyi et al., 2024). The results obtained may serve as a foundation for developing standards and recommendations for inspecting and calculating such structures. Thus, assessing the technical condition of reinforced concrete structures is crucial, as it serves as the main diagnostic tool during their operation. This process requires accurately determining load-bearing capacity and selecting optimal reconstruction methods, which are essential for ensuring the safety and longevity of buildings and structures.

In the article (Klymenko & Polianskyi, 2019), the researchers presented experimental results aimed at determining the stress-strain state of damaged inclined sections of reinforced concrete beams. The observed concrete deformations allowed tracing changes in the stress-strain state. As the damage angle of the beams increased, the deformations also increased. Additionally, it was noted that in the damaged beam samples, the position of the neutral axis shifted. The neutral axis rotated toward the damage and became nearly parallel to the damage front. These observations were confirmed through the modeling of damaged beams using software such as “LIRA-SAPR” and FEMAP (Pavlikov et al., 2019; Klymenko et al., 2019; Mykhalevskyi et al., 2023; Deineka et al., 2024). The results of the studies indicate that the larger the damage area, the lower the residual load-bearing capacity of the element. Moreover, the concrete deformation in the beam under load supports the laboratory experimental data on the tilt of the neutral axis towards the damage. It was also established that each centimeter of damage reduces the effective working height of the beam and its load-bearing capacity. The stress-strain state data obtained from these experiments revealed the actual behavior of damaged reinforced concrete beams with lateral damage.

The study (Voskobiinyk et al., 2011) analyzes the impact of existing damage in reinforced concrete bending elements and experimentally determines their behavior under load during the assessment of their technical condition. In their work, the authors highlight the most common types of damage, namely: delamination of the concrete protective layer, reinforcement corrosion, and mechanical damage (cuts, potholes, spalling), which together lead to changes in the geometric characteristics of the cross-section of reinforced concrete structures. This, in turn, results in a reduction of the load-bearing capacity of the reinforced concrete elements, increasing the risk of accidents. The study's findings on beams with significant defects and damage confirmed actual behavior under inclined bending, as evidenced by the strain distribution diagrams based on strain gauge measurements (Voskobiinyk et al., 2011; see Fig. 2).

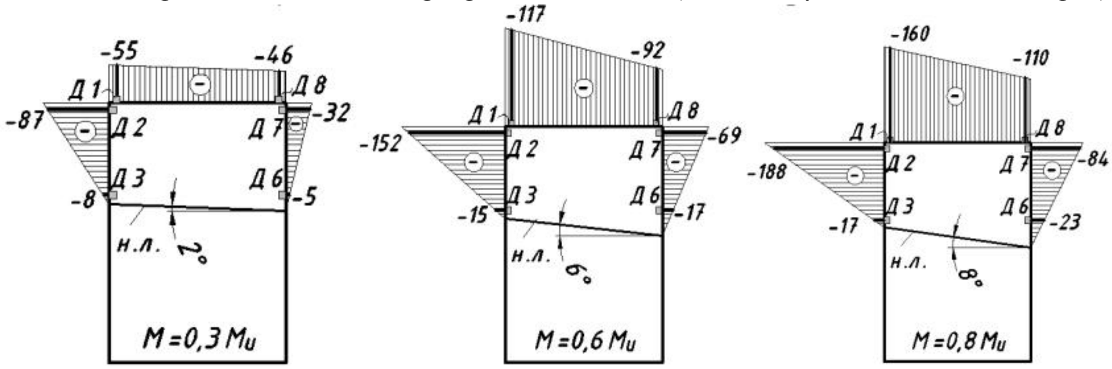

Fig. 2. Strains contours ($\varepsilon \times 10^{-5}$) in the compressed zone of concrete and the inclination angle of the neutral axis at different levels of loading (Voskobiinyk et al., 2011)

Operational defects and damage to reinforced concrete structures, as well as changes in the magnitude and nature of the load during reinforcement, according to (Pavlikov et al., 2019), can lead to complex types of deformations such as inclined bending and compression.

In the study (Lobodanov et al., 2021), the focus was on an experimental investigation aimed at determining the strength and deformability of reinforced concrete bending elements damaged under loading in the compressed zone. Previous research (Lobodanov et al., 2018) confirmed the relevance of studying damaged elements with damage in the compressed zone under load. The author emphasized the neglect of damage factors in current standards and the potential for determining residual bearing capacity. A series of experiments were conducted on reinforced concrete beams, including undamaged beams, beams with damage but without loading, and beams with damage under loading. Experimental investigations revealed that the level of loading and type of damage affect the bearing capacity of reinforced concrete bending elements with damaged concrete in the compressed zone. Damage in the compressed zone of the concrete led to a reduction in the element's bearing capacity, which depended not only on the depth of the damage (30 mm) but also on its width. With a damage width of 20 mm, the bearing capacity decreased by 12.83 % compared to the control sample, while with a width of 80 mm, it decreased by 17.97 %.

The study (Blikharskyy et al., 2018) determined the impact of damage to the tensile working reinforcement in reinforced concrete beams that had sustained damage under a certain level of loading. Reinforced concrete beams damaged under a load level of 0.5 of their bearing capacity showed 18 % higher load-bearing capacity compared to samples damaged without loading. This indicates that the load level significantly affects the load-bearing capacity of the damaged samples. It was established that the load-bearing capacity of beams with damaged working reinforcement was higher than that of beams with equivalent reinforcement area in the control samples. The control samples without damage failed in a brittle manner, with spalling of the compressed concrete zone, whereas the damaged samples experienced rupture of the tensile reinforcement.

The corrosion of steel reinforcement embedded in concrete is a global issue affecting numerous reinforced concrete structures. Although research on the impact of corrosion on reinforced concrete structures became relevant as early as the 1960s, the question of how corrosion behaves under load remains a topic of much debate today. Corrosion processes have a significant impact on reinforced concrete structures, leading to deterioration of their load-bearing capacity, increased deflections, and reduced operational characteristics (Shmyh, 2017; Bonić et al., 2015). These processes actively alter the cross-sectional shape of the reinforced concrete element and affect its physical-mechanical properties. The principle of reinforcement corrosion formation in reinforced concrete structures and the process of corrosion crack formation are shown in (Fig. 3). Most corrosion processes result from interaction with aggressive environments, such as chlorides, salts, water, and other chemically active substances, which can penetrate the concrete and damage the reinforcement, leading to weakening of the structure and non-compliance with operational requirements.

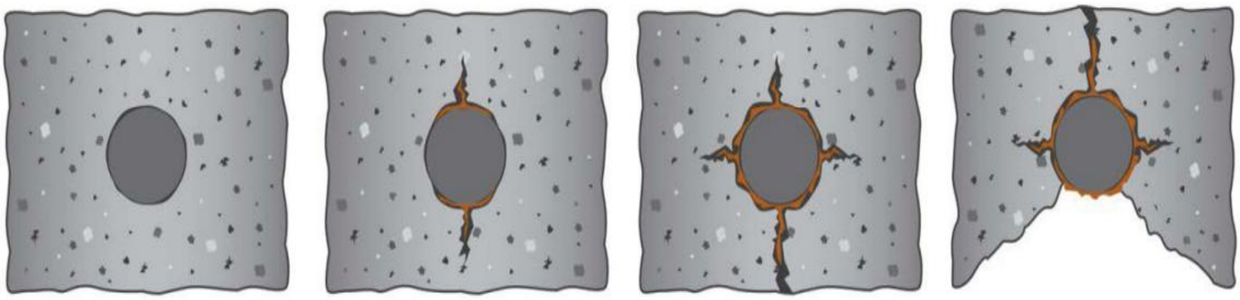

Fig. 3. Development of corrosion of a reinforcement bar in concrete (Bonić et al., 2015)

In the study (Blikharskyy et al., 2019), the impact of simultaneous exposure to an aggressive environment and loading on the strength of steel reinforcement bars was investigated. It was found that increasing the aging time of samples in a corrosive environment leads to significant changes in their plastic properties. These findings were confirmed in the works (Santos et al., 2021; Royani et al., 2020). The study (Blikharskyy et al., 2019) revealed that plastic properties exhibit greater sensitivity to corrosion on the surface of reinforcement than strength properties. Tests of control samples under uniaxial tension showed that corrosive damage over 15–30 days had virtually no impact on the tensile strength of reinforcement bars, keeping them within the experimental error. However, plasticity characteristics, such as elongation and reduction, decreased by 1.04–1.22 times, indicating a reduction in the plasticity of the reinforcement due to corrosion. The research uncovered new aspects of reinforcement steel properties, including the deterioration of its plastic characteristics during use in structures, which may have negative consequences.

In the study (Xia et al., 2011), the shear characteristics of reinforced concrete beams with varying levels of corrosion in longitudinal reinforcement and stirrups were investigated. The study established correlations between the width of corrosion-induced cracks in the concrete cover and the level of reinforcement corrosion. It was found that as the corrosion level increases, both the stiffness and shear strength of the beam decrease. However, the reduction in stiffness is minimal if the loading is relatively small. Only when the load exceeds 20–30 % of the ultimate load does the loss of stiffness caused by reinforcement corrosion become significant. The shear strength of the beam decreases with an increase in the level of corrosion of the reinforcement bars or with an increase in the width of the cracks. Research (Al-Saidy et al., 2010) showed that corrosion affects the strength of reinforced concrete beams. Corroded beams had lower stiffness and strength compared to non-corroded ones. However, the loss of strength in these samples was not linearly proportional to the percentage loss of mass of the corroded reinforcement.

In their study, it was found (Zhu & François, 2013) that corrosion leads to an increase in the ratio of ultimate strength to yield strength and a decrease in ultimate deformations under maximum loading in reinforcement. They also noted that the intensity of corrosion is significant for the plastic properties of reinforcement. Asymmetric corrosion distribution on the surface is a key factor that can seriously impact the ultimate deformation under maximum stresses in the bars. A model developed (Lu et al., 2018) predicts the residual shear strength of reinforced concrete beams, taking into account the effect of corrosion. Comparative studies showed that this model provides an effective calculation of beam strength over a wide range of corrosion damage, which aids in predicting their strength with acceptable accuracy and assessing the service life of reinforced concrete structures.

Results and discussions

The analysis of defects and damage in reinforced concrete structures is a complex and multifaceted process, as it encompasses various aspects related to prolonged operation and environmental impact. A review of scientific research and analysis of the types of defects in reinforced concrete structures based on recent studies reveals several key directions and problematic aspects.

Physical Defects. Studies focused on concrete damage in reinforced concrete beams show that mechanical defects, such as cuts, dents, and spalling of the concrete, significantly impact the load-bearing capacity of structures. Experiments confirm that the level of loading and the type of damage have a substantial effect on the strength of the structures. Such damage typically alters the geometric characteristics of the structures, leading to complex deformation patterns, changes in the stress-strain state, and a reduction in their load-bearing capacity.

Chemical Defects. Studies emphasize the significance of reinforcement corrosion as a global issue. Corrosion processes, caused by aggressive environments, significantly reduce the load-bearing capacity and performance characteristics of reinforced concrete structures. It has been found that corrosion, especially under loading, deteriorates the plastic properties of reinforcement and increases the deflections of specimens.

Overall, the analysis shows that there is a significant field of research requiring further investigation and improvement to enhance the understanding and assessment of the behavior of reinforced concrete structures under various conditions. The issue of studying damaged reinforced concrete beams under loading has been inadequately addressed in foreign research. Only a few domestic studies focus on reinforced concrete structures that have sustained damage under loading. Moreover, these studies have not considered damage to the compressed reinforcement caused by loading, nor have they explored the behavior of beams with complete damage around the perimeter of the concrete cover.

Such research remains relevant and requires further development to devise effective methodologies for determining the residual load-bearing capacity of damaged structures. Currently, these structures are assessed using the equivalent section method, which significantly underestimates the load-bearing capacity and does not account for the actual stress-strain state of the structures. Therefore, it would be beneficial to conduct additional research using software tools and validate their results experimentally to develop effective prediction and calculation methods aimed at more accurately determining the load-bearing capacity and serviceability of reinforced concrete structures.

Conclusions

The analysis of defects and damage in reinforced concrete structures demonstrates the complexity and multifaceted nature of this process, which is influenced by various factors associated with prolonged operation and environmental impacts. The conducted literature review and analysis of damage to reinforced concrete structures have identified key aspects of their classification. The main causes of damage can be grouped according to physical, biological, and chemical factors. Additionally, modern research also highlights environmental, technological, and extraordinary influences that significantly affect the reduction of load-bearing capacity and serviceability of reinforced concrete structures.

Based on the review and analysis of domestic and foreign literature sources, it has been established that physical defects, such as cuts, spalling, and delamination of concrete, significantly impact the load-bearing capacity of reinforced concrete structures by altering their geometric characteristics and causing complex types of deformations. Moreover, chemical defects, particularly rebar corrosion, are also a significant issue that negatively affects the strength and operational characteristics of structures, especially under load.

The simultaneous impact of physical damages to the cross-section, which are hazardous for the compressed part of the cross-section, along with possible corrosion damage that is most dangerous for steel reinforcement, can lead to a sharp decrease in the load-bearing capacity of the damaged structure. This synergistic effect is currently under-researched. Additionally, the overall analysis revealed significant gaps in studies concerning the behavior of reinforced concrete beams damaged under load. The lack of sufficient studies in this area, particularly regarding damage to compressed reinforcement under load and full-scale damage to the concrete cover, indicates the need for further research.

Given the limitations of existing methodologies, such as the equivalent cross-section method, which underestimates load-bearing capacity and does not account for the actual stress-strain state of structures, as well as the lack of methodologies in current standards for calculating the residual load-bearing capacity of reinforced concrete bending elements damaged during service, the need for experimental research and further development in this area becomes evident. The use of modern software tools and experimental methods will enable the development of more accurate and effective prediction and calculation methods, contributing to a more reliable assessment of the load-bearing capacity and serviceability of reinforced concrete structures under real operating conditions.

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АНАЛІЗ ВПЛИВУ ПОШКОДЖЕНЬ ПОПЕРЕЧНОГО ПЕРЕРІЗУ ЗГИНАНИХ ЗАЛІЗОБЕТОННИХ ЕЛЕМЕНТІВ НА МІЦНІСТЬ ТА ДЕФОРМАТИВНІСТЬ

Залізобетонні елементи є невід’ємною частиною більшості будівель та споруд, виконують функцію несучих конструкцій. Проте вони зазнають різних видів пошкоджень і дефектів, що можуть істотно знизити їхню міцність і поставити під загрозу безпеку експлуатації. У статті розглянуто основні публікації, що стосуються типів пошкоджень залізобетонних елементів, факторів, що на них впливають, та методів оцінки несучої здатності пошкоджених конструкцій. Проаналізовано дефекти залізобетонних конструкцій, зокрема фізичні, біологічні та хімічні пошкодження, з особливою увагою до впливу тривалої експлуатації та агресивних умов навколишнього середовища. Дослідження показують, що механічні пошкодження, такі як відколи, вибоїни та відшарування бетону, істотно знижують несучу здатність конструкцій, змінюючи їхні геометричні характеристики та спричиняючи складні деформації. Корозія арматури також істотно впливає на міцність конструкцій, особливо під навантаженням. Результати досліджень вказують на суттєві прогалини у вивченні поведінки залізобетонних балок із пошкодженнями, отриманими під навантаженням, що підкреслює актуальність подальших досліджень у цій галузі. Вивчення впливу пошкоджень на залізобетонні елементи важливе для ефективного визначення залишкової несучої здатності, особливо під дією навантажень.У статті акцентовано на необхідності додаткових теоретичних та експериментальних досліджень, спрямованих на розроблення ефективних методик оцінювання залишкової несучої здатності пошкоджених конструкцій. Особлива увага повинна приділятися дослідженню поведінки конструкцій із суцільними пошкодженнями поперечного перерізу бетону та стиснутого армування, отриманими за різних рівнів навантаження, а також використанню сучасних програмних комплексів для точнішого прогнозування напруження, деформації та експлуатаційної придатності таких конструкцій.

Ключові слова: згинані залізобетонні елементи; пошкодження; дефекти; залишкова несуча здатність; корозія; напружено-деформований стан.