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NONLINEAR MODELING AND ANALYSIS OF DAMAGED REINFORCED CONCRETE BEAMS USING ANSYS AND LIRA-SAPR SOFTWARE PACKAGES

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This article presents a comparative analysis of the nonlinear behavior of a reinforced concrete beam with damaged reinforcement in the tension zone under a gradually increasing load until failure. The experimental beam, measuring 2100 × 200 × 100 mm, consists of a 20 mm diameter rebar in the tension zone, two 6 mm diameter rebars in the compression zone, and 6 mm diameter stirrups spaced 75 mm apart for transverse reinforcement. Nonlinear calculations were performed using ANSYS and LIRA-SAPR, with identical initial conditions applied to both models for accurate comparison. The study focuses on key aspects such as result accuracy, ease of use, and time required for nonlinear calculations, including material and geometric nonlinearity. By highlighting the strengths and weaknesses of each software, the research offers insights for engineers and researchers working on complex structural modeling of reinforced concrete.

Key words: finite element method, nonlinear calculation, reinforced concrete beams, damage to reinforced concrete, residual bearing capacity, stress-strain state.

Intrdouction

Research and analysis of world construction market trends show that for several decades reinforced concrete structures occupy a leading place in construction due to various methods of their manufacture and construction. Taking into account the growing number of projects in which reinforced concrete structures play a key role, and the number of already existing buildings in operation, it can be concluded that a significant part of these structures is subject to various types of damage over time. Defects can appear at various stages of the life cycle of the structure, starting from the moment of manufacture of the elements and up to the stage of their long-term operation. One of the causes of damage can be the incorrect placement of reinforcement in concrete elements during their manufacture, which can lead to stress-deformed states. This can cause a decrease in the strength of the structure and its reliability in operation. Mechanical damage occurring during transportation or installation of reinforced concrete elements is also possible. There are often cases when reinforced concrete structures are not used for their intended purpose or are subjected to loads that exceed the calculated values, which can also lead to their damage. In addition, reinforced concrete elements are exposed to aggressive environments that can cause reinforcement corrosion, concrete cracking, and other damage that weakens the structure. The influence of natural factors, such as temperature fluctuations, moisture, wind loads, can also negatively affect the condition of reinforced concrete structures, which emphasizes the need for constant monitoring and timely repairs to ensure their durability and safe operation. Then the question arises as to how to take into account all the nuances and variants of structural damage in a convenient way without spending a large amount of equipment, people and time. For this, it is possible to use software complexes based on the method of finite elements in a non-linear formulation. Thanks to the possibility of modeling complex geometries and various physical processes, such programs allow accurate analysis of the behavior of structures under the influence of various loads, including taking into account the nonlinear material properties of concrete and reinforcement, as well as taking into account different forms of destruction. This ensures increased accuracy and reliability of calculations, which, in turn, contributes to the optimization of project decisions and increased safety of operation of reinforced concrete structures.

To date, conducting experimental studies of reinforced concrete structures, which, according to the author (Blikharskyy et al., 2021), are the most common load-bearing structures used in buildings, requires significant costs of materials, testing equipment, labor and time. The author of this article (Antony et al., 2023) provides clear arguments why using specialized software is a much more effective method. Using various programs for creating models from finite elements, the author of the article (Klym et al., 2023) was able to analyze in the Femap software complex and estimate the increase in stresses in concrete and reinforcement when the compressed zone of concrete is reduced by 50 mm. The author states (Tjitradi et al., 2023) that there are many other methods of modeling the behavior of reinforced concrete structures, in which analytical or numerical approaches are used for calculations, but according to the author of the source (Gurram et al., 2024), the ANSYS software package is an excellent alternative to replace some laboratory studies.

When creating analytical models, the author (Avci et al., 2019) notes that the finite element SOLID65 best conveys the work of a reinforced concrete structure, and for reinforcement - Link180, which perfectly shows real compression-tension diagrams. In the source (Tjitradi et al., 2022), the natural behavior of a reinforced concrete beam under the action of a load with an underestimated grade of concrete and reinforcement was investigated. In the source (Manasa et al., 2024), deep beams were modeled according to experimental samples, and all the necessary characteristics and deformations of the beams were determined using the ANSYS software complex. Using similar finite elements in the ANSYS software complex, the author (Shen et al., 2020) investigated the load at which cracks appear in a beam with a hole. Also, the author (Abouali et al., 2022) conducted an analysis of reinforcing reinforcement mounted on the surface of a reinforced concrete structure as a prestressed reinforcement that increases the tensile strength of the material (Tjitradi et al., 2022 and Sena-Cruz et al., 2022).

The author of the source (Khong et al., 2020) modeled and analyzed fiber-reinforced beams, which are completely wrapped around a reinforced concrete structure, in the ANSYS software package. The work of high-strength concrete in the ANSYS calculation program was investigated by the author (Pandimani et al., 2022), using the model of finite elements in a nonlinear formulation. With the help of ANSYS software, the author (Mohammed et al., 2023) investigates different types of spiral transverse reinforcement and analyzes its effect on reinforced concrete beams, since many sources study different types of such spiral reinforcement (Narule et al., 2022), and the author (Habeeb et al., 2020) investigated that such reinforcement can be effectively used in reinforced concrete structures that work directly on torsion.

The author (Krantovska et al., 2023) described the method of numerical modeling of the stress-strain state of a reinforced concrete beam in the ANSYS software package and conducted a comparative analysis with experimental data. A detailed analysis of cracks in reinforced concrete structures was carried out by the author (Yang et al., 2023). Reinforced concrete beams using polymer carbon fiber were modeled using the most common finite elements in the structure of the ANSYS software complex by the author (Barour et al., 2021), and the results were compared in percentage terms. The effect of fire on reinforced concrete structures was analyzed by the author (Venkatesh et al., 2021) in PC ANSYS, where the behavior of reinforced concrete structures under the influence of fire was studied, taking into account different options for the protective layer of structures. The design and analysis of cantilever bridge beams operating under the action of torsion in a nonlinear setting were performed by the author (Jebur, 2021) and under the action of torsion of ordinary reinforced concrete beams by the author (Patane and Vesmawala, 2023)

The authors of the following sources, using the ANSYS software complex, were able to analyze cantilever beams (Siddiqui et al., 2021), reinforced concrete beams under load with numerical damage analysis (Karalar, 2021). The author (Bondok et al., 2021) studied different types of transverse reinforcement in reinforced concrete beams using the finite element model in the ANSYS software complex. After analysis, the welded frame showed much better performance. In this article, the author (Said et al., 2021) investigates the behavior of hybrid reinforcing bars inside a reinforced concrete beam, comparing the data with the results of an experimental study.

Another numerical experiment was conducted using the domestic software complex “LIRA CAD 2017” in work (Klymenko et al., 2019). The basis of this calculation is also a finite-element model, in which finite elements of the CE No.236 type were used – this is a universal 8-node parametric CE, the volume of which is 150 mm³ with the dimensions of the ribs 5×5×6 mm. The elements are connected to each other by rigid inserts, that is, nodes that have stiffness and small size, with six degrees of freedom. Reinforcement in the beam was also performed using similar finite elements, which had characteristics corresponding to the parameters of the given reinforcement. The process of obtaining data in this software complex takes considerable time. The achievement of one of the ultimate states by the reinforced concrete structure was accepted as a criterion for destruction: achievement of ultimate stresses by longitudinal or transverse reinforcement; achievement by concrete in the compressed zone of a significant number of SE limit stresses at the place of support of the sample or above the top of an inclined plane.

Materials and methods

To conduct a theoretical study and achieve all the set goals, 12 reinforced concrete beams were designed, which were divided into two series, one series of beams BM-1.1..BM-1.6, a series of beams designed in the ANSYS software complex, where beam BM-1.1 is not damaged, and BM-1.2...BM-1.6 are beams with damage in the stretched zone, similarly to the second series of beams, but calculated in the LIRA-SAPR software complex, where BM-2.1 is an undamaged beam, and BM-2.2...BM-2.6 is designed with damage in the stretched area. The overall dimensions of reinforced concrete beams are 2100×200×100 mm (Fig. 1). That is, these test samples are designed with a length of 2100 mm, a width of 100 mm and a cross-sectional height of 200 mm.

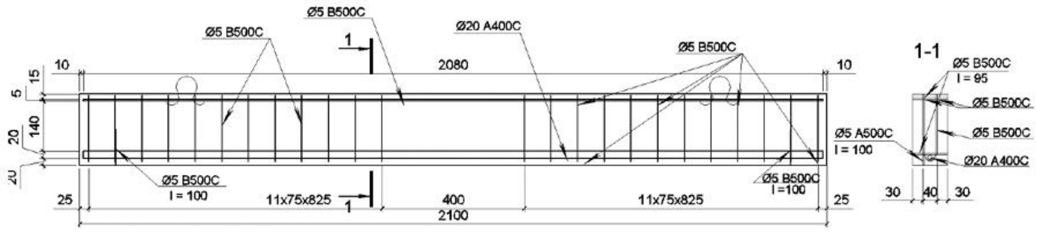

Fig. 1. Structural diagram of the beam

The reinforcing frame of the experimental samples is made of two types of reinforcing frame with minimal differences. In all reinforcing frames, the upper reinforcement in the compressed concrete zone of the reinforced concrete beam is structurally made of two rods Ø6 and steel class A240C, the distance between these rods is 40 mm. For a series of beams with damage, the reinforcement in the upper compressed zone of concrete is interrupted at the place of damage. The first type of reinforcing frame for a series of beams without damage (BM-1.1...BM-1.5) is designed with one rod of working reinforcement of steel grade A500C with gradation of diameters depending on the grade of reinforced concrete designs, working fittings vary from Ø20 to Ø12. Similarly, the working fittings for beams with damage are arranged without changes. As for the transverse reinforcement, it is presented the same for all frames and is made in the form of U-shaped transverse rods Ø6 and steel class A240C with a step of reinforcing rods of 75 mm, however, these transverse rods are not designed in the center of the cross-section of the reinforced concrete beam due to the lack of need for data arrangement rods and in the case of damaged beams to be able to make a slot in the beam.

Table 1

Properties of materials specified in the calculation model of the beam

Material	Material properties	Value
Concrete	Density Young`s Modulus Poisson`s Ratio Tensile Ultimate Stregth Compressive Ultimate Strength Shear Modulus	2500 kg/m³ 4000 MPa 0.2 2.5 MPa 1667 MPa
Reinforcement A500	Density Young`s Modulus Poisson`s Ratio Tangent Modulus Tensile Ultimate Stregth Compressive Ultimate Strength	7850 kg/m³ 200000 MPa 0.26 20 MPa 550 MPa 500 MPa
Loading & Supporting Plates	Density Young`s Modulus Poisson`s Ratio	7850 kg/m³ 200000 MPa 0.26

To create a finite element model of a reinforced concrete beam in the ANSYS software complex, we set the finite element for concrete SOLID65 – this is a solid eight-node 3-D element that can collapse during compression and crack during tension (Fig. 2, *a*). For reinforcement, we set the end element of the LINK 180 type (Fig. 2, *b*), and as the end element for modeling load plates and supports, we set SOLID185 (Fig. 2, *c*).

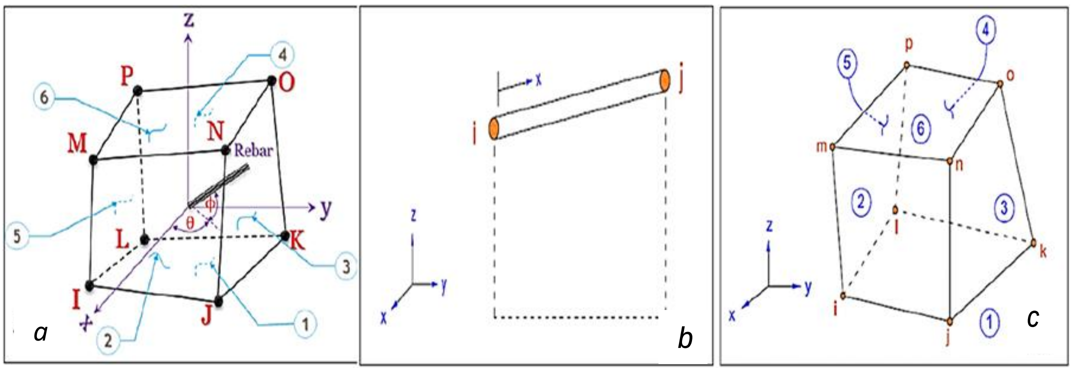

Fig. 2. FE model elements: a – SOLID 65; b – LINK 180; c – SOLID185

The structural model of a reinforced concrete beam is a single-span statically determined beam over two supports loaded by two concentrated forces (Fig. 3). The characteristics of these materials are given in Table 1. Modelling of the RC beams is idealized in the ANSYS. The RC beam has been modelled as volumes, such as the concrete, loading plates and supports. While the steel reinforcements and stirrups are modelled as line bodies. Concrete was simulated using a multilinear isotropic hardening model. For the high accuracy of the calculation, finite elements with a size of 25×25×25 mm were specified. Displacement boundary conditions are required to constrain the model to obtain a remarkable solution. To confirm that the model works similarly to the testing beam; boundary conditions must be applied to the supports. So, the support conditions in this study will be taken as a pin support with no movement in the X, Y and Z directions. In contrast, another support will be taken as a roller of which there will be only movement in the Z-direction with no movement in the other directions.

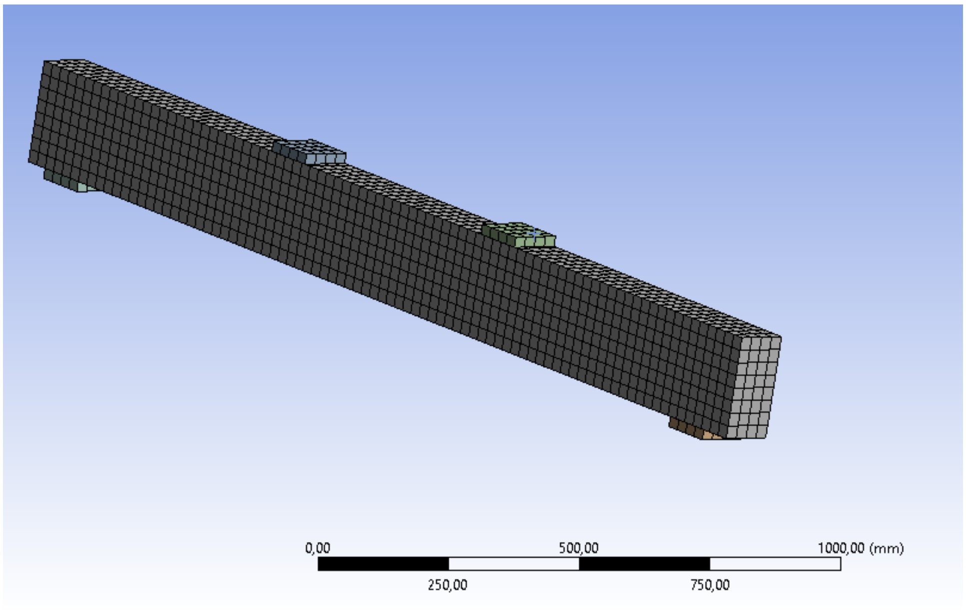

Fig. 3. Finite element model of the undamaged beam BM-1.1

To build a finite-element model in the LIRA CAD software complex for problem No. 236 with overall dimensions of 25×25×25 mm similarly to the model created in the ANSYS software complex. Therefore, it is necessary to perform several important stages. First, you should start the program and create a new project, which opens the working environment for performing simulations. The simulation of the finite element model will be performed with the help of the most commonly used finite elements No. 236 – universal spatial eight-node isoparametric volumetric KE for modeling the reinforced concrete beam itself, where these finite elements are given all the necessary characteristics and properties of non-linearity. To model the armature, we use No. 210 – universal spatial rod KE, which contains all the specified parameters for the necessary armature and nonlinear properties for performing nonlinear cal-culation. Fixation of the beam on two supports is specified with the help of a special tool "Elms", which allows you to limit the movement of nodes in specific directions. The load is applied identically to the value of the load specified in the ANSYS software complex for the most similar scenario of the development of events (Fig. 4).

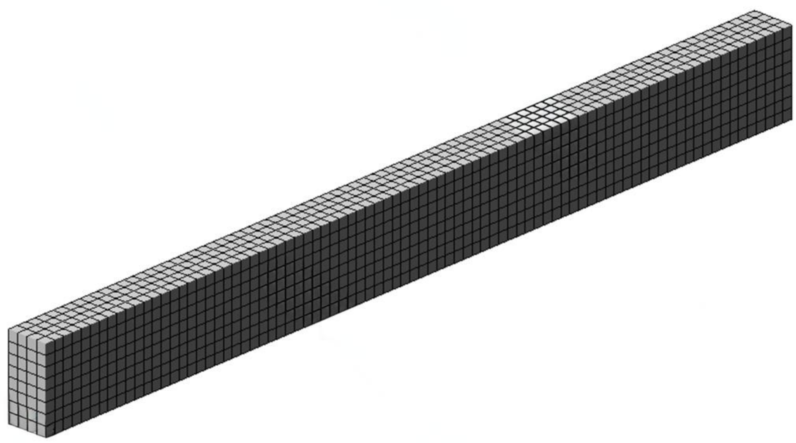

Fig. 4. Finite element model of the undamaged beam BM-2.1

The damage to reinforcement due to corrosion is modeled by reducing its diameter in the zone where the maximum pure bending moment occurs, which is located in the middle of the beam span. This is a critical area for the structural performance of the beam, as it experiences the greatest tensile forces. To accurately reflect the local effect of corrosion, the width of the damaged zone is set at 100 mm. This approach allows for a detailed analysis of how the reduction in the cross-sectional area of the reinforcement affects the overall strength of the beam.

In software packages such as ANSYS or LIRA-SAPR, this reduction in diameter is implemented by modifying the geometric parameters of the finite elements that correspond to the reinforcement bars. For instance, if the initial diameter of the reinforcement is Ø20 mm, it is reduced to Ø16 mm in the damaged zone. This change in the geometry of the reinforcement allows the model to account for the weakening effect of corrosion or mechanical damage, which can significantly impact the load-bearing capacity and overall behavior of the reinforced concrete structure under various loads.

The described methods of creating calculation models in both software packages allow for the most accurate description of the working conditions of the reinforced concrete structure and the loads that will affect the given structures. Using these methods, it is possible to conduct the most precise analysis of the behavior of reinforced concrete structures under load in a nonlinear setting.

Results and discussion

Analysis of the test results of reinforced concrete beams allows a deeper understanding of how damage affects their behavior under load. The drawings were Fig. 5 and Fig. 6 presents the results for undamaged beams, providing a benchmark for further analysis. These beams showed the same deformation values, which indicates the correctness of the nonlinear calculation and good accuracy in the calculations of specialized software complexes. Visualization of beam structures without damage, given in the drawings, allows you to make sure that they are all in good condition, without visible defects or anomalies. This makes it possible to use the obtained strain values as a basis for comparison with the results obtained for damaged beams. Also in Fig. 7 and Fig. 8 shows the results of the nonlinear calculation of beams with damage, which additionally shows the correctness and identity of the performed calculations.

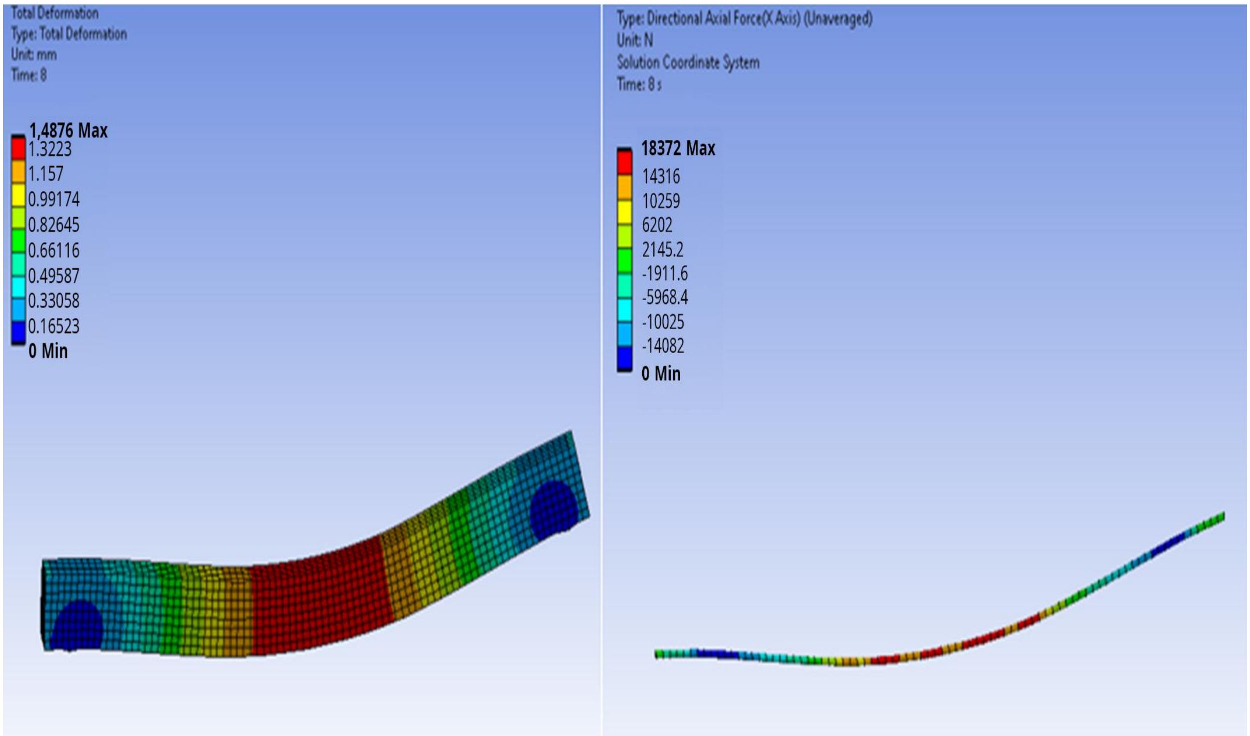

Fig. 5. The value of deformations of concrete and reinforcement for the experimental sample BM-1.1

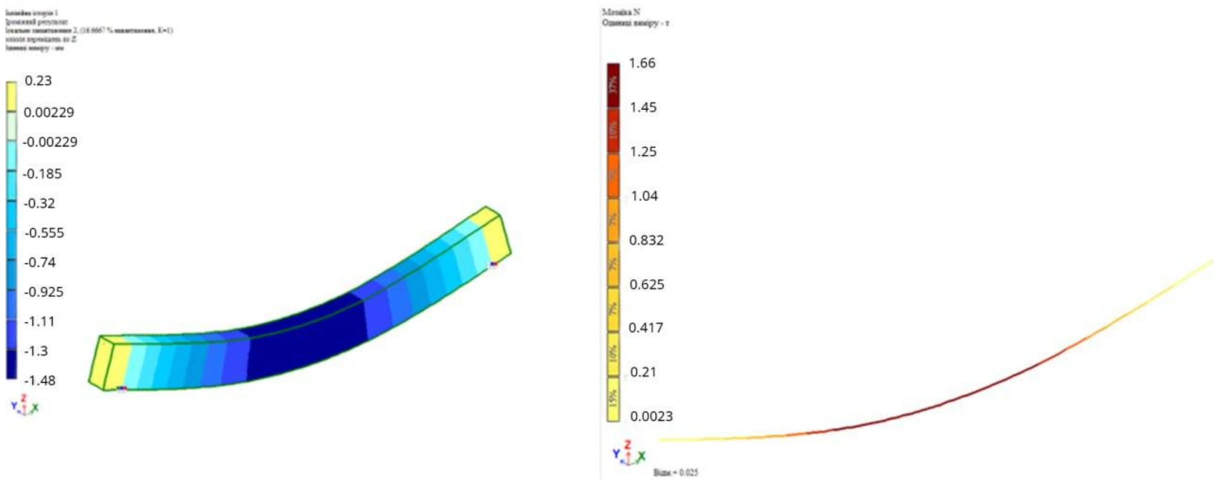

Fig. 6. The value of deformations of concrete and reinforcement for the experimental sample BM-2.1

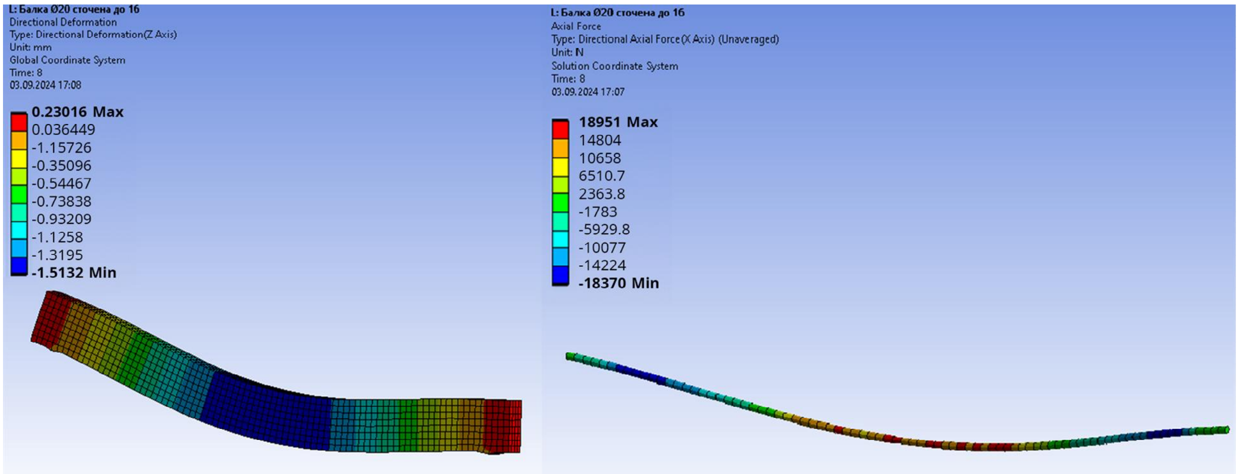

Fig. 7. The value of deformations of concrete and reinforcement for the experimental sample BM-1.3

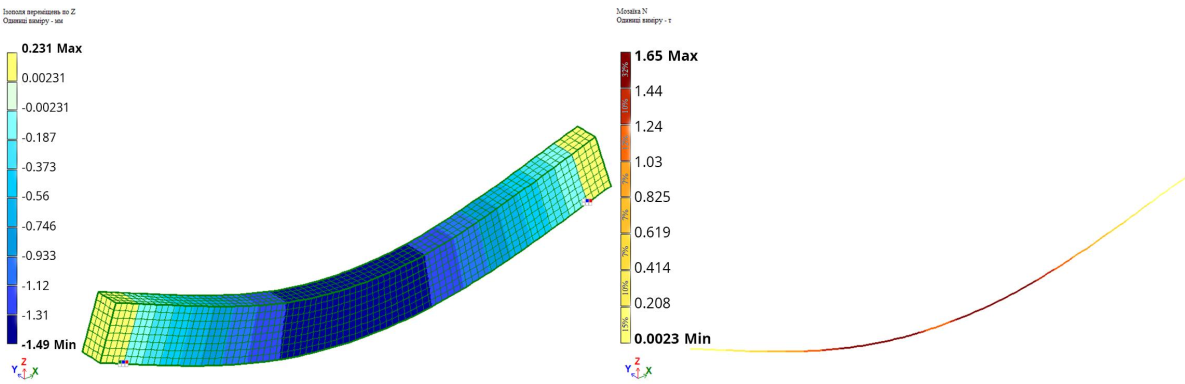

Fig. 8. The value of deformations of concrete and reinforcement for the experimental sample BM-2.3

When analyzing the calculation data for five different types of reinforced concrete beams, it became clear that damage has a significant impact on their bearing capacity. This influence can be observed both in the concrete itself and in the reinforcement, as confirmed by the data presented in Table 2. The bearing capacity of reinforced concrete structures depends on several key factors, including the condition of the materials and the degree of damage they have sustained during operation or under various loads. Even at first glance, minor damage can cause significant changes in the characteristics of both the concrete and the reinforcement, which in turn leads to changes in the overall behavior of the structure under load.

In particular, damage to the concrete can lead to a reduction in its compressive strength, which is especially critical in areas with maximum loads. The reinforcement, which takes on tensile forces, may lose its load-bearing capacity due to corrosion, fatigue, or mechanical damage, leading to a decrease in the stiffness of the structure and an increase in deformations. This can be critical in cases where the structure is subjected to repeated or long-term loads, as the gradual accumulation of damage leads to a progressive reduction in the strength and stiffness of the entire system.

Moreover, it is important to note that damage to both concrete and reinforcement can mutually reinforce each other. For example, damaged concrete may reduce the level of protection for the reinforcement against corrosion, further deteriorating its properties. At the same time, weakened reinforcement can contribute to the formation of cracks in the concrete, leading to further damage. Such a comprehensive approach to damage analysis allows not only to identify the causes of the structure's performance degradation but also to evaluate possible scenarios for its behavior under design loads.

Table 2

Configuration of numerical models

The initial diameter of rebar	Diametr of rebar after damage	Marking of beams calculated in the ANSYS software complex	The value of the force arising in the armature, t	The value of the ultimate deflection occurring in the beams, mm	Marking of beams calculated in the LIRA-SAPR software complex	The value of the force arising in the armature, t	The value of the ultimate deflection occurring in the beams, mm	Percent discrepancy of longitudinal forces, %	Percent discrepancy of limit deflections, %
Ø 20	–	BM-1.1	1.937	1.487	BM-2.1	1.66	1.48	15	0
	Ø 18	BM-1.2	1.90	1.503	BM-2.2	1.65	1.49	14	1
	Ø 16	BM-1.3	1.895	1.513	BM-2.3	1.65	1.49	13	2
	Ø 14	BM-1.4	1.795	1.515	BM-2.4	1.65	1.50	9	1
	Ø 12	BM-1.5	1.737	1.529	BM-2.5	1.64	1.51	6	1

We can clearly see that with the same load, the change in deformations in the reinforcement under the action of damage, as a result of which the diameter of the working reinforcement is reduced by almost half – from 20 mm to 12 mm, has a significant effect on the behavior of the reinforced concrete structure. The largest increase in deformations in compressed concrete by 9 % is observed when the diameter of the reinforcement in the zone of maximum moment is reduced from Ø 20 to Ø 12 mm. However, it is worth noting that deformations also increase significantly in fittings with a diameter from Ø 18 to Ø 16 mm, where this indicator is 13 %. Accordingly, such a change in diameter to Ø 16 mm causes a significant change in the spatial redistribution of stresses in the zone of maximum moment.

Despite the fact that the maximum deformations occur in the damaged armature, the cross-sectional area of which is almost halved, it is important to emphasize also the effect of these changes on the overall stability of the structure. In addition to the change in the maximum values of deformations in concrete and reinforcement, which is associated with a fragmentary decrease in the diameter of the tensioned reinforcement, there is also a change in the spatial redistribution of stresses in the samples. This is especially visible in Fig. 7 and Fig. 8, where the places of maximum stresses in concrete are compared.

It should also be taken into account that with a decrease in the diameter of the working reinforcement, the load-bearing capacity of the reinforced concrete beam decreases, which also causes an increase in concrete deformations. This approach to the calculation allows predicting a relatively real picture of the behavior of a reinforced concrete structure under the influence of one or another factor without using a large number of means. This, in turn, opens up an opportunity for further development of the research topic, involving more and more information in the experiment and even using ready-made experimental data for comparison.

Conclusions

A comparison of the theoretical results of calculations obtained with the help of two software complexes confirms the effectiveness and feasibility of using these methods in the process of determining the necessary cross-section characteristics of a reinforced concrete beam with damage to the working reinforcement in the stretched zone. Both software complexes used for calculations are based on a deformation model that corresponds to the current building regulations and standards that regulate the assessment of the strength and stability of reinforced concrete structures. The proposed methodology includes a two-stage approach to modeling: at the first stage, the calculation of the beam is performed before the appearance of damage in the stretched zone of concrete, and at the second stage, the design is calculated after the formation of damage with a subsequent increase in load.

The analysis of the calculation results shows that reinforced concrete beams with working reinforcement, the diameter of which varies from ø20A500C to ø12A500C, without the presence of damage, show deviations between the theoretical results obtained in two software complexes, ranging from 1 % to 15 %. This testifies to the high accuracy and adequacy of the calculation models used in both software complexes. In the case when the beam is damaged, the deviation between the calculation results increases slightly and ranges from 1 % to 15 %. This confirms that even in the presence of local damage in the tensile zone of concrete, the accuracy of calculation models remains high and suitable for practical use.

It is important to note that the impact of damage in the stretched zone of concrete on the overall load-bearing capacity of reinforced concrete beams is relatively insignificant. Damage of such dimensions does not lead to a critical decrease in the load-bearing capacity of the structure, which allows us to conclude that it is sufficiently stable and strong even in the presence of damage. This also indicates the expediency of using theoretical models to assess the condition of damaged beams, which can be useful when planning the further operation of these structures or carrying out their repair.

Studies have shown that both software packages, which were used for calculations, demonstrate satisfactory accuracy, reliability and efficiency. This means that they can be successfully used to solve various engineering problems related to the analysis of reinforced concrete structures. Thanks to this, engineers get flexibility in choosing tools for calculations, which allows them to choose the most suitable software complex depending on specific tasks and preferences. This approach contributes to increasing the efficiency of engineering calculations and provides a more accurate and reliable assessment of the state of structures, which is especially important for their safe and long-term operation.

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НЕЛІНІЙНЕ МОДЕЛЮВАННЯ ТА АНАЛІЗ ПОШКОДЖЕНИХ ЗАЛІЗОБЕТОННИХ БАЛОК ЗА ДОПОМОГОЮ ПРОГРАМНИХ КОМПЛЕКСІВ ANSYS ТА ЛІРА-САПР

Наведено детальний порівняльний аналіз нелінійної поведінки залізобетонної балки з пошкодженою арматурою в розтягнутій зоні під впливом поступового зростання навантаження до моменту, коли балка досягає критичного стану й починає руйнуватися. Експериментальна балка має розміри 2100 × 200 × 100 мм і містить один стержень арматури діаметром 20 мм у розтягнутій зоні бетону, два стержні діаметром 6 мм у стиснутій зоні, а також поперечну арматуру діаметром 6 мм, розташовану з інтервалом 75 мм для забезпечення додаткової міцності конструкції. Це дає змогу створити конструкцію, здатну витримувати значні навантаження. Нелінійні розрахунки були проведені в програмних комплексах ANSYS та LIRA-SAPR. Для обох моделей задано однакові початкові умови, що забезпечує коректне порівняння їхньої поведінки у різних режимах навантаження. Особливу увагу під час дослідження було зосереджено на трьох ключових аспектах: точності результатів, зручності користування програмним забезпеченням, а також часі, необхідному для виконання розрахунків. Додатково розглянуто різні типи нелінійних задач, включно з матеріальною нелінійністю, яка відображає складну поведінку бетону та арматури, і геометричною нелінійністю, що враховує зміну форми конструкції під навантаженням. У результаті дослідження були виявлені основні переваги й недоліки кожного з програмних комплексів. Це дає змогу інженерам і науковцям обґрунтовано вибрати оптимальний інструмент для розв'язання конкретних інженерних задач. Дослідження є надзвичайно корисним для інженерів, проєктувальників та науковців, які займаються моделюванням і аналізом складних залізобетонних конструкцій під дією значних навантажень. Отримані результати надають важливі інсайти щодо вибору відповідного програмного забезпечення для моделювання залізобетонних елементів у різних сценаріях навантаження й експлуатації.

Ключові слова: метод скінченних елементів, нелінійний розрахунок, залізобетонні балки, пошкодження залізобетону, залишкова несуча здатність, напружено-деформований стан.