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MODELING THE IMPACT OF DAMAGE TO THE CONCRETE COVER AND THE COMPRESSED REBAR OF A REINFORCED CONCRETE BEAM IN "LIRA-SAPR"

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Most modern buildings use reinforced concrete elements, which can sustain damage during operation, creating potential risks for their safe use. This article focuses on the analysis of reinforced concrete beams with cross-sectional damage using the LIRA-SAPR software suite. Special attention is given to the damage of the protective concrete layer and the top compressed reinforcement, which is crucial for assessing the residual load-bearing capacity and the stress-strain state of the structures. The modeling of reinforced concrete elements is performed using the finite element method. The obtained results have practical significance for further research and the improvement of methods for evaluating the residual load-bearing capacity of reinforced concrete structures, which will help reduce the risk of failure of such elements during operation.

Keywords: damage; reinforced concrete beam; modeling; LIRA-SAPR; stress; concrete cover.

Introduction

The impact of damage to the concrete cover and the upper compressed reinforcement on the load-bearing capacity of reinforced concrete beams is a pressing issue and of great importance for engineers who inspect such structures. It is crucial to effectively determine and use the residual load-bearing capacity of these structures. Damage to reinforced concrete structures can occur due to various factors at different stages of a building's life cycle. These factors include technological defects, the influence of various natural phenomena, mechanical damage, and the duration of operation. Classifications of such damage are presented in the works of (Blikharskyy, Kopiika, 2022; Kravchuk et al., 2024). Damage to reinforced concrete elements can lead to a reduction in the load-bearing capacity of beams, increasing the risk of emergency situations and accidents. Additionally, complex types of deformations of reinforced concrete elements may arise, which are not considered during design, complicating the prediction of their behavior in operation (Voskobiinyk et al., 2011). As a result, the need for additional research and adjustments to existing design standards becomes critically important to ensure the safety and durability of structures.

After analyzing recent studies and publications, we can confirm the importance of studying reinforced concrete elements with various types of damage. The investigation of these elements using software packages and numerical methods becomes especially relevant. A significant number of software packages have been developed for numerical calculations, including Robot, ANSYS, SCAD Office, ABAQUS, FEMAP, the "LIRA-SAPR" software package, and others.

The study of reinforced concrete elements using the ANSYS software package is presented in the works of (Ibrahim & Mahmood, 2009; Tjitradi et al., 2017; Hasan et al., 2020), where the authors investigate the failure behavior of reinforced concrete elements through simulations in the ANSYS software package.

The use of software packages to assess the impact of damage on reinforced concrete elements provides crucial information necessary to understand the behavior of these structures and predict their residual load-bearing capacity. A comparative analysis and the feasibility of using the LIRA-SAPR and ANSYS software packages are presented in the work of (Krasnitskyi et al., 2024). The results of studies using these software packages enable engineers to develop more effective methods for rehabilitation and ensure the safety and durability of reinforced concrete elements in real operational conditions.

In the work (Lobodanov et al., 2021), experimental studies showed the influence of load level and type of damage on the load-bearing capacity of reinforced concrete bending elements with damaged concrete in the compressed zone. Damage to the compressed concrete zone reduced the load-bearing capacity of the reinforced concrete element, with the reduction depending not only on the depth of penetration (30 mm) but also on the width of the damage. With a damage width of 20 mm, the reduction in load-bearing capacity relative to the control beam was 12.83 %, and with a damage width of 80 mm, it was 17.97 %. Furthermore, the study established the need to develop a separate methodology for investigating and calculating various types of damage and defects. Theoretical studies of damaged beams in the compressed concrete zone, conducted by Lobodanov et al. (2021), demonstrated the effectiveness of using the FEMAP software package for modeling and calculations. The FEMAP software provided variability in the studies and showed results close to the experimental ones.

Experimental studies conducted by (Blikharskyy Z. et al., 2018) showed that the load-bearing capacity of beams with damaged lower working reinforcement under load was found to be 10 % higher than that of beams with reinforcement of the same area but without damage. Additionally, the study established that beams without damage fail due to spalling of the compressed concrete zone, while damaged beams fail due to the rupture of the lower working reinforcement. These findings were also confirmed in the work of (Lobodanov et al., 2022), which investigated the damage to concrete in the compressed zone of beams. The studies showed a 3.8 % increase in the load-bearing capacity of reinforced concrete beams under load compared to damaged reinforced concrete beams without load.

The work by (Klymenko et al., 2019) presents the modeling of the behavior of damaged reinforced concrete beams using the LIRA-SAPR software package. The researchers created 15 different models of experimental beams with various damages to the compressed concrete zone, each of which had a separate calculation scheme developed. The calculation scheme for each sample consisted of small finite volumetric elements of type SE No. 236. The calculations were performed using a nonlinear step-by-step iterative method. The results of the calculations for each sample were compared with the data from laboratory tests. The beam modeling allowed for the analysis of all processes occurring in the beam during its gradually increasing static load. The results obtained from the modeling showed good convergence of the residual load-bearing capacity, with the difference between the modeled results and the laboratory tests ranging from 3.23 % to 21.46 %.

In the work by (Klymenko et al., 2021), numerical and laboratory experimental tests were conducted to determine the impact of concrete damage in the support zone of the compressed zone of reinforced concrete beams on their residual load-bearing capacity in inclined sections. Numerical tests of the samples were carried out using the LIRA-SAPR 2017 software package. The results of the laboratory and numerical experiments showed good agreement regarding the load-bearing capacity; however, the failure behavior of the samples did not coincide. Performing calculations in the LIRA-SAPR software package allowed for predicting the behavior of the elements and determining their load-bearing capacity with high accuracy. However, compared to real data, some discrepancies in the failure behavior were identified.

In the work by (Pavlikov et al., 2019), a numerical model of a beam operating under biaxial bending conditions was considered. The modeling allowed for accounting the features of the loss of load-bearing capacity and tracking changes in the position of the neutral axis during loading. It was established that computer modeling enables the planning of experimental studies, optimization of the number and sizes of samples for testing, and the identification of areas in the samples that require special attention during the experiment. In the research by (Kos et al., 2022), computer modeling in LIRA-SAPR effectively reproduced the results of the conducted experiments, allowing for reliable predictions of the strength of structures and their failure behavior.

The theoretical study of damaged beams in the compressed zone using the FEMAP software package, conducted in the work of (Mykhalevskyi et al., 2023), allowed for the examination of stresses in concrete and reinforcement under different damage scenarios and loading levels. The results of the study showed that every centimeter of damage to the compressed zone of the beam reduces the effective working height of the concrete and the load-bearing capacity of the beam. Additionally, the study enables the evaluation of the consequences of damage and defects occurring in existing structural elements under load, providing insight into their impact on the elements and their structural behavior. These findings were confirmed in the work of (Deineka et al., 2024), where similar studies were conducted using the LIRA-FEM software package. The use of software packages for modeling damaged beams provided more accurate results compared to analytical calculation methods.

In the study by (Barabash, 2018), the author focuses on calculations that consider the real properties of reinforced concrete. Reinforced concrete under operational loading, with plastic deformations and crack formation, reduces the stiffness of the element, which in turn leads to increased displacements. Therefore, the study of reinforced concrete requires realistic modeling and appropriate analysis. In the paper, the author suggests using the "engineering nonlinearity" method for calculations, which allows the engineer to more accurately assess the stiffness distribution of reinforced concrete elements. Modern computational systems allow for considering various types of nonlinearity during the calculation and analysis of building structures. This is particularly important for accurately modeling the real behavior of reinforced concrete structures under load. The work by (Gorodetsky & Romashkina, 2023) provides a detailed description of the main capabilities of the LIRA-SAPR calculation package, which accounts for both geometric and physical nonlinearity. This package enables engineers to model complex load and damage scenarios, considering factors such as plastic deformations, crack formation, and changes in element stiffness.

The study of beams considering physical nonlinearity is presented in the work by (Shakhmov & Amir, 2022), where it is confirmed that accounting for the physical nonlinearity of deformation in reinforced concrete beams is crucial for accurately modeling their stress-strain state. As a result, the LIRA-SAPR calculation package becomes a powerful tool for the design and analysis of reinforced concrete building structures, ensuring their reliability and safety during operation.

This article focuses on the analysis of stresses occurring in the structures and the evaluation of deformations of beams with damaged concrete protective cover and compressed reinforcement. The study of damaged beams is carried out using the LIRA-SAPR software package.

Materials and methods

For the theoretical study and modeling, a reinforced concrete beam was developed, which was reinforced according to the calculations based on current standards. The purpose of creating this beam is to conduct further experimental tests to gather practical data and compare them with the theoretical results obtained through modeling. This allows for verifying the accuracy of theoretical predictions, evaluating the effectiveness of the applied models and methods, as well as confirming or adjusting existing theoretical concepts regarding the behavior of concrete structures.

The test specimen is a reinforced concrete simply supported beam with a length (*l*) of 2100 mm, a cross-sectional height (*h*) of 200 mm, and a width (*b*) of 100 mm. The effective span (distance between supports) (*l*1) is 1900 mm.

The working reinforcement, located in the tensile zone of the beam, is made of rolled steel with a diameter of Ø16A500C. This steel has a Young's modulus (E) of 209200 MPa and a Poisson's ratio of 0.29. The upper reinforcement consists of two bars with a diameter of Ø10A500C, which will later be damaged by reducing their diameter. The beam is made of concrete of class C25/30, which has a Young's modulus (E) of 32500 MPa and a Poisson's ratio of 0.2. All material characteristics are taken according to the standards in DBN V.2.6-98:2009 and DSTU B V.2.6-156:2010. The transverse reinforcement is implemented in the form of stirrups with a diameter of Ø10A500C, spaced 100 mm apart. These stirrups are chosen to prevent the possibility of failure of the test specimens due to shear force (Fig. 1). The reinforced concrete beam is designed so that its failure occurs in the pure bending zone.

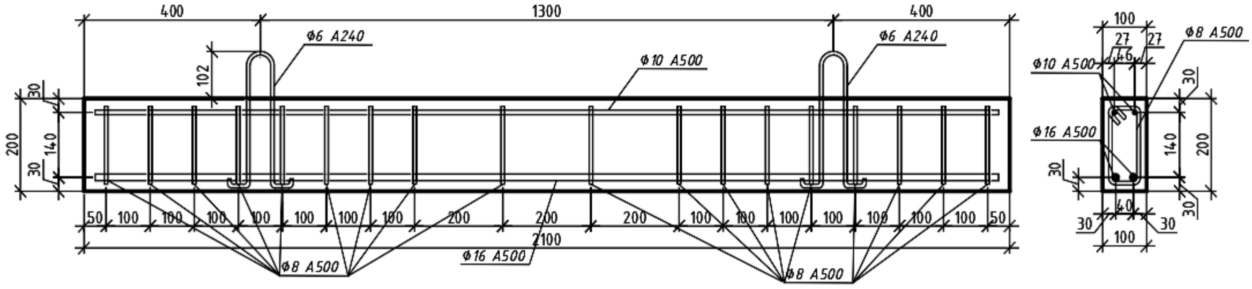

Fig. 1. General view of the beam reinforcement

The calculations of the beam were performed using the LIRA-SAPR software. To model the concrete beam, three-dimensional finite elements No. 236 were used, which allow for simulating the nonlinear behavior of the material. The choice of finite element type for modeling the concrete is shown in (Fig. 2).

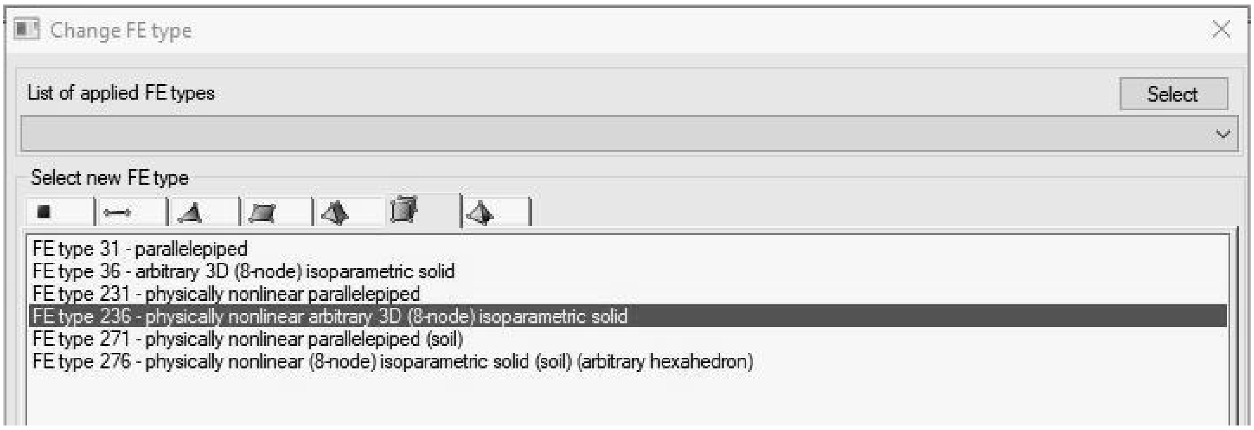

Fig. 2. Selection of the finite element type for modeling the concrete

During the modeling of the nonlinear behavior of concrete, the 25th exponential deformation law was used, which accurately accounts for the complex nature of deformation processes in concrete. The assignment of the stiffness characteristics of the concrete beam, considering nonlinearity, is shown in (Fig. 3).

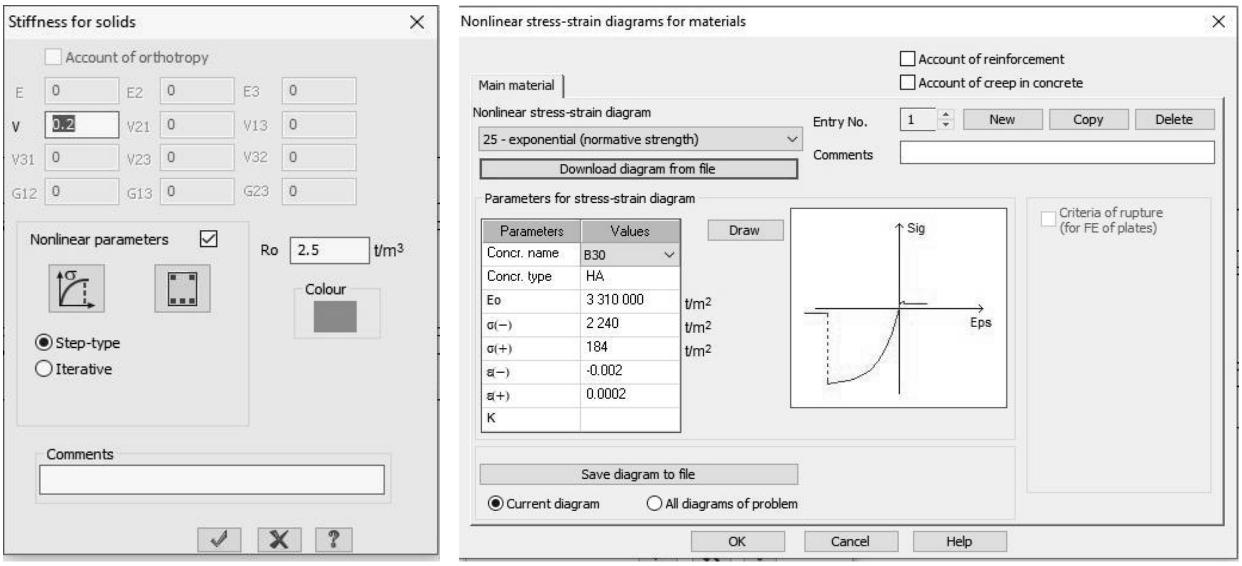

Fig. 3. Definition of the concrete beam stiffness characteristics considering nonlinearity

To model the behavior of the reinforcement cage, finite elements No. 210 were used, which are physically nonlinear universal spatial elements. These elements allow for the consideration of all the peculiarities of the reinforcement's behavior under load. To assign the material's physical nonlinearity, a 14-piecewise linear deformation function was used, ensuring an accurate representation of the reinforcement's actual performance within the structure (Fig. 4).

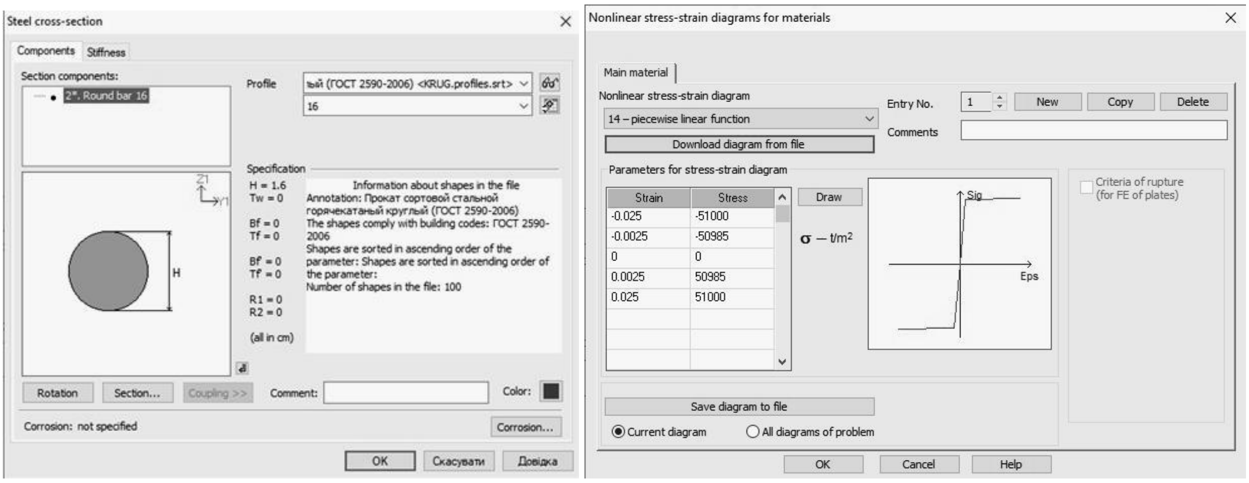

Fig. 4. Definition of the reinforcement stiffness characteristics considering nonlinearity

The beam cross-section is divided into finite elements (cubes) of 10 mm in size. This segmentation of the beam into cubic elements is related to the placement and step of the reinforcement, ensuring the accuracy of modeling its behavior under load. Supports are placed along the entire width of the beam at a distance of 100 mm from its edge. On one side, there is a fixed hinge support that prevents both horizontal and vertical displacements of the beam's end, while on the other side, a hinge support is provided, allowing only vertical displacements. This configuration ensures the required stability and creates the necessary conditions for accurate analysis.

The load *F* (kN) is applied to the beam at points located at a distance of 1/3 of the span length of the beam, as shown in (Fig. 5).

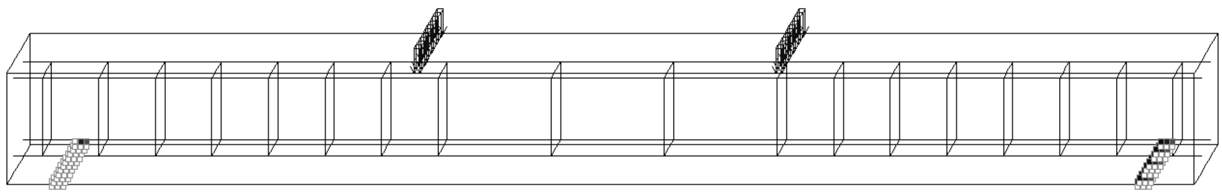

Fig. 5. The loading scheme of the beam

This loading arrangement ensures a pure bending zone, where a uniform bending moment can be observed in the middle of the beam span, allowing the behavior of damaged beams to be assessed. For further study and analysis of reinforced concrete beams with complete circular damage to the cross-section, four damage variants were selected (Fig. 6).

Beam B-0 is the control sample, which has no damage and serves as a reference for comparison with other samples. Sample B-1 contains a damage with a width of 80 mm located at the center of the pure bending zone. This damage simulates a localized concrete defect, allowing the impact of such defects on the beam's load-bearing capacity to be studied. Sample B-2 has a 200 mm wide damage, simulating concrete spalling. This damage simulates the effect of significant structural concrete degradation, enabling the study of beam behavior under more severe damage conditions. Sample B-3 is characterized by damage 80 mm wide, located at the center of the pure bending zone, with additional damage to the upper compressed reinforcement. Due to the damage, the diameter of the reinforcement is reduced from 10 mm to 8 mm, simulating corrosion damage to both the concrete and the reinforcement due to long-term exposure to an aggressive environment or other factors. Sample B-4 features damage 80 mm wide, displaced from the center of the pure bending zone. This damage allows the investigation of the impact of a localized defect, not positioned at the center of the pure bending zone, on the deformation and strength characteristics of the beam. All concrete damages are applied along the perimeter of the cross-section, simulating an even reduction in the cross-section from all sides.

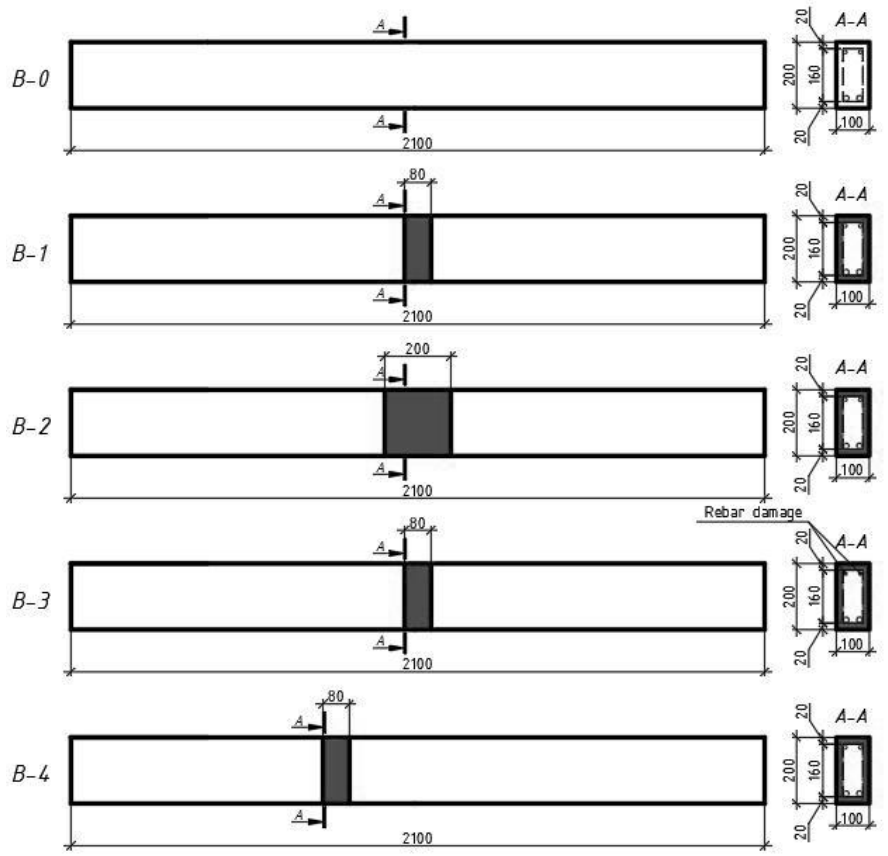

Fig. 6. Scheme of experimental reinforced concrete beams with different types of damage

Two types of studies were conducted in the LIRA-SAPR software. In the first study, the maximum force F_u that the beam without damage and the beams with various types of damage can withstand was determined. In the second study, a load of 0.5 F_u was applied to beams with different types of damage. The load of 0.5 F_u is close to the operational load typical for most reinforced concrete structures, which justifies its selection for this study. The applied load F =21.15 kN allows for the evaluation of the strength and deformation of the beam under conditions corresponding to real operational conditions.

Results and discussions

As a result of the simulation and static calculation in the LIRA-SAPR software, models and stress mosaics for reinforced concrete beams were obtained. The overall model of the control beam with the mosaic stress diagram in the concrete at F_u = 42.3 кН is shown in (Fig. 7).

The mosaic stress diagram in concrete, presented in (Fig. 8), demonstrates the distribution of stresses under the load of 0.5 F_u = 21.15 kN for the control beam. This diagram allows evaluating the behavior of the concrete under the 0.5 F_u load and provides a visual representation of the stress distribution in different zones of the beam.

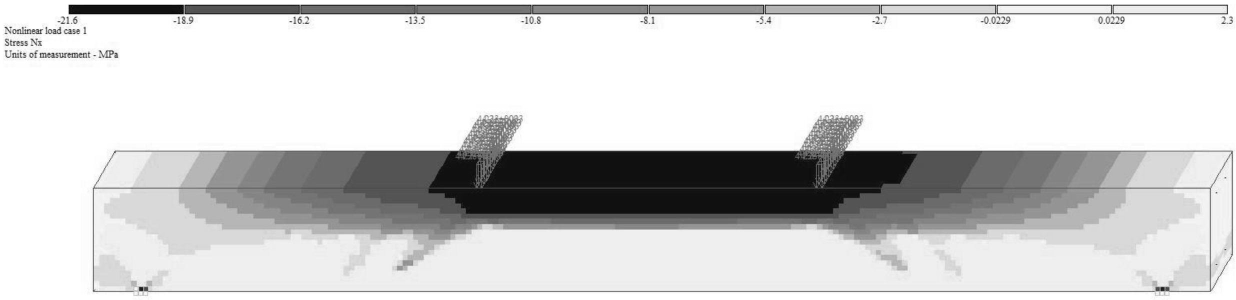

Fig. 7. Overall view of the calculation scheme in LIRA-SAPR and the mosaic stress diagram in the concrete at F_u = 42.3 кН

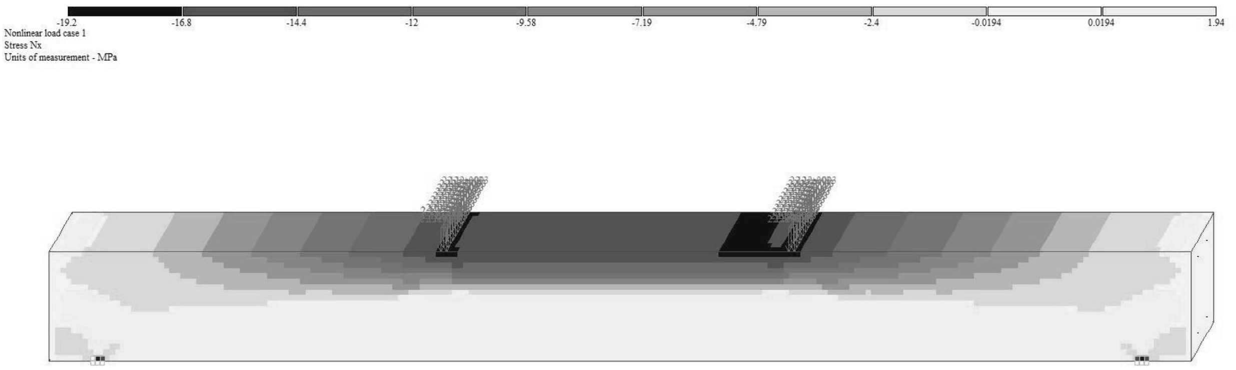

Fig. 8. Overall view of the calculation scheme in LIRA-SAPR and the mosaic stress diagram in the concrete at F = 21.15 кН

The forces in the reinforcement cage, presented in (Fig. 9), illustrate the variation of forces occurring in the compressed and tensioned zones of the reinforcement under the same load of F = 21.15 kN.

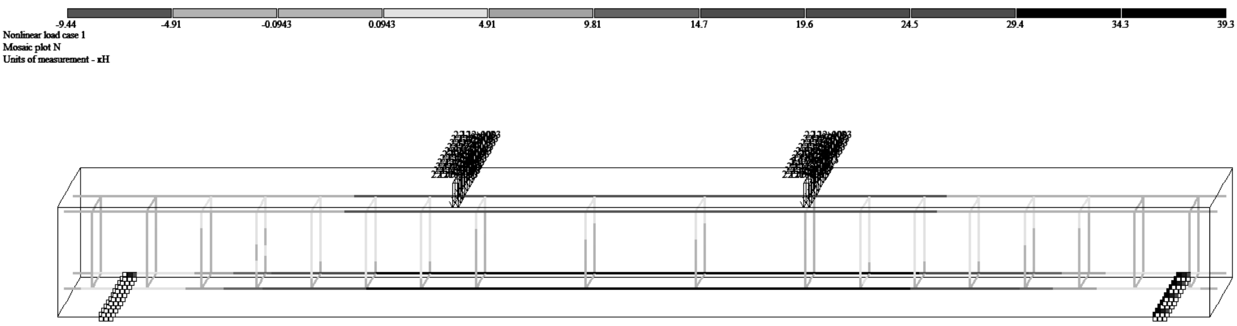

Fig. 9. Forces in the reinforcement cage

Theoretical results of concrete and reinforcement stresses for the test samples at 0.5 F_u of the control beam are presented in Table 1. Based on this data, a comparison of stresses occurring in beams with different types of damage can be made with the indicators of the control beam.

The stress results in concrete at the maximum force F_u that the test beams can withstand are presented in Table 2.

Table 3 presents the stress results in the compressed and tensile reinforcement at the maximum force that these beams can withstand. Based on this data, the stresses in the reinforcement of beams with various types of damage can be compared to the values of the control beam.

Table 4 presents the stress results in concrete and reinforcement under the maximum force Fu that these beams can withstand. Based on this data, the obtained values can be compared with the characteristic compressive strength values of concrete and the characteristic strength values of the reinforcement.

Table 1

Stress results in concrete and reinforcement under the load of 0.5 Fu for the control beam

Type of damage	Maximum concrete stress, MPa		Maximum stress in compressed reinforcement, MPa		Maximum stress in the tensile reinforcement, MPa	
	$f_{ck.m}$	$\frac{f_{ck.m}^{B-x}}{f_{ck.m}^{B-0}}100\,\%$	$f_{yk.m}$	$\frac{f_{yk.m}^{B-x}}{f_{yk.m}^{B-0}}100\,\%$	$f_{yk.m}$	$\frac{f_{yk.m}^{B-x}}{f_{yk.m}^{B-0}}100\,\%$
B-0	–19.2	100	–120.1	100	195.5	100
B-1	–21.4	112	–298.9	249	235.9	120
B-2	–21.3	111	–299.4	249	237.2	121
B-3	–21.4	112	–439.2	366	238.6	122
B-4	–21.5	113	–305.7	255	231.8	119

Table 2

Stress results in concrete under the load F_u

Type of damage	Maximum concrete stress, MPa		Load-bearing capacity of the beam, kN	
	$f_{ck.m}$	$\frac{f_{ck.m}^{B-x}}{f_{ck.m}^{B-0}}100\,\%$	F_u	$\frac{F_u^{B-x}}{F_u^{B-0}}100\,\%$
B–0	–21.6	100	42.3	100
B–1	–21.7	113	32.5	77
B–2	–25.1	131	32.5	77
B–3	–24.4	127	27	64
B–4	–28.3	147	32	76

Table 3

Stress results in reinforcement under the load F_u

Type of damage	Maximum stress in compressed reinforcement, MPa		Maximum stress in the tensile reinforcement, MPa		Load-bearing capacity of the beam, kN	
	$f_{yk.m}$	$\frac{f_{yk.m}^{B-x}}{f_{yk.m}^{B-0}}100\,\%$	$f_{yk.m}$	$\frac{f_{yk.m}^{B-x}}{f_{yk.m}^{B-0}}100\,\%$	F_u	$\frac{F_u^{B-x}}{F_u^{B-0}}100\,\%$
B-0	–392	100	442	100	42,3	100
B-1	–542	138	370	84	32,5	77
B-2	–498	127	380	86	32,5	77
B-3	–512	130	323	73	27	64
B-4	–500	128	366	83	32	76

The analysis of the maximum compressive stresses in concrete showed that for the control beam B-0, under a load of 0.5 F_u, the maximum stress is 19.2 MPa. For the damaged specimens, this value increases to 21.5 MPa for specimen B-4, indicating a slight decrease in the concrete's resistance to compression under various types of damage at this load level.

The analysis of stresses in the reinforcement showed that damage to the concrete cover and reinforcement significantly affects the maximum stresses in the reinforcement at this load level, reducing the beam's strength. The stress in the compressed reinforcement for the control beam B-0 is 120.1 MPa.

For beams with damage, the stresses increase significantly: for specimen B-4, it reaches –305.7 MPa (2.5 times higher than the control specimen), and for specimen B-3, the maximum stress reaches –439.2 MPa (3.6 times higher). This significant increase in stress for specimen B-3 is due to the reduction in the reinforcement area from 0.79 cm² to 0.5 cm² as a result of simulating reinforcement corrosion. The maximum stress in the tensile reinforcement for the control beam B-0 is 195.5 MPa. For damaged specimens (B-1, B-2, B-3, B-4), this value increases by 18–22 % depending on the type of damage, with an increase of up to 22 % for specimen B-3.

Regarding the load-bearing capacity, for the control beam B-0, it is 42.3 kN. Damage to the beams leads to a reduction in their ability to withstand loads. For beams B-1 and B-2, the load-bearing capacity is 32.5 kN (77 % of the control beam's capacity). Beam B-3 showed the most significant reduction in load-bearing capacity – it decreased by 36 % and now stands at 27 kN. In beam B-4, the reduction is 24 %, which is a better result compared to beam B-3. This reduction in load-bearing capacity in all beams is due to the decrease in cross-sectional area caused by the circular damage to the concrete cover, which decreased from 200 cm² to 96 cm². The cross-sectional area of all damaged specimens decreased by a factor of 2.1. Additionally, in specimen B-3, the reinforcement area was reduced from 0.79 cm² to 0.5 cm² as a result of simulating corrosion.

Table 4

Comparison of stresses in concrete and reinforcement with characteristic values under the load F_u

Type of damage	Characteristic compressive strength of concrete, MPa	Maximum concrete stress, MPa		Characteristic strength of reinforcement, MPa	Maximum stress in the compressed reinforcement, MPa		Maximum stress in the tensile reinforcement, MPa	
	f_{ck}	$f_{ck.m}$	$\frac{f_{ck.m}^{B-x}}{f_{ck}}100\,\%$	f_{yk}	$f_{yk.m}$	$\frac{f_{yk.m}^{B-x}}{f_{yk}}100\,\%$	$f_{yk.m}$	$\frac{f_{yk}}{f_{yk.m}^{B-x}}100\,\%$
B-0	22	–21.6	98	500	–392	79	442	88
B-1		–21.7	99		–542	108	370	74
B-2		–25.1	114		–498	100	380	76
B-3		–24.4	111		–512	102	323	65
B-4		–28.3	129		–500	100	366	73

The analysis of the stress results presented in Table 4 for concrete, under the maximum load F_u that the test beams can withstand, shows that both the control and damaged beams reach the characteristic compressive strength of concrete. The analysis of the maximum stresses in the compressed reinforcement, presented in Table 4, under the maximum load F_u indicates that in the damaged beams, the maximum stresses in the compressed reinforcement increase to the characteristic strength values of the reinforcement, suggesting a potential rupture. Meanwhile, in the control beam, these values are 27–38 % lower. The stresses in the tensile reinforcement, under damage, decrease from 442 MPa for the control beam to 323 MPa for specimen B-3, not reaching the characteristic strength values of the reinforcement.

Thus, damage to the concrete cover and compressed reinforcement significantly affects the load-bearing capacity of the beams, with the most substantial decrease observed in the beam with damage to the concrete cover and compressed reinforcement in the pure bending zone. At the same time, the width of the damage has almost no effect on the load-bearing capacity, as the results for damage widths of 80 mm and 200 mm remain nearly identical.

Conclusions

The use of finite element methods for modeling existing reinforced concrete elements allows for more accurate and reliable results compared to traditional analytical methods. This approach makes it possible to account for the complex behavior of materials and structures under load, which cannot be achieved using standard calculation methods. Theoretical research of damaged reinforced concrete beams in the LIRA-SAPR software environment enables a detailed study of the distribution of stresses and deformations in the concrete and reinforcement under various types of damage. This research reveals important patterns regarding the impact of damage on the strength and deformability of structures, as well as allows for a precise assessment of the stresses that occur in the beam depending on the damage parameters. Modeling reinforced concrete beams demonstrates the effectiveness of this method for evaluating the influence of defects on the load-bearing capacity and behavior of elements under load in real operating conditions. The analysis of the results showed that damage to the concrete cover around the perimeter of the beam's cross-section leads to a reduction in the load-bearing capacity of the beams by 23–24 %. In the case of additional damage to the compressed reinforcement, the load-bearing capacity decreases by 36 %. At the same time, changing the width of the damage from 80 mm to 200 mm has almost no effect on the load-bearing capacity of the beams. The analysis of stresses in the reinforcement of damaged beams shows that, under damage, the maximum stresses in the compressed reinforcement increase to the characteristic strength values of the reinforcement, indicating a possible rupture. For the control beam, these values are 27–38 % lower.

Despite the obtained results, this research requires further improvement and enhancement, particularly through the comparison of theoretical results with experimental data. This will help increase the accuracy of the results and make the methodology more reliable for use in real construction and reconstruction projects.

Prospects for further research

The application of the finite element method continuously expands the prospects for engineers and researchers, creating a foundation for the improvement of calculation methods for loaded reinforced concrete elements using advanced finite element modeling technologies. This method also serves as a primary tool for preparing and optimizing field studies, making the development of its application capabilities (and the method itself) a relevant task.

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МОДЕЛЮВАННЯ ТА АНАЛІЗ ВПЛИВУ ПОШКОДЖЕННЯ ЗАХИСНОГО ШАРУ БЕТОНУ ТА ВЕРХНЬОЇ СТИСНЕНОЇ АРМАТУРИ ЗАЛІЗОБЕТОННОЇ БАЛКИ В ПК"ЛІРА-САПР"

Більшість сучасних будівель і споруд використовують залізобетонні елементи, які можуть зазнавати різноманітних пошкоджень під час експлуатації. Виникнення різноманітних пошкоджень призводить до небезпеки експлуатації будівель та споруд. У цьому дослідженні особливу увагу приділено аналізу залізобетонних балок із суцільними пошкодженнями поперечного перерізу балок за допомогою програмного комплексу LIRA-SAPR. Такі пошкодження охоплюють пошкодження захисного шару бетону та верхньої стисненої арматури, що мають велике практичне значення у майбутньому розрахунку оцінки залишкової несучої здатності та напружено-деформованого стану залізобетонних конструкцій. Моделювання залізобетонних елементів виконано методом скінченних елементів у програмному комплексі LIRA-SAPR. Результати дослідження містять аналіз напружень в залізобетонних балках без пошкоджень та з різними типами пошкоджень захисного шару бетону та верхнього стиснутого армування, а також порівняння максимальних напружень дослідних зразків із характеристичними значеннями міцності бетону та арматури. Аналіз результатів дослідження показав, що пошкодження захисного шару бетону по периметру перерізу балки призводить до істотного зниження несучої здатності балок. Це дослідження дає можливість виявити важливі закономірності, що стосуються впливу пошкоджень на міцність та деформаційну здатність конструкцій, а також точно оцінити напруження, які виникають в балці, залежно від параметрів пошкодження. Отримані результати мають велике практичне значення і можуть бути використані для подальших практичних досліджень із метою покращення методів оцінювання залишкової несучої здатності залізобетонних конструкцій, що допоможе знизити ризики руйнування таких елементів під час експлуатації.

Ключові слова: пошкодження; залізобетонна балка; моделювання; LIRA-SAPR; напруження; захисний шар.