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MODELING OF STRESS-STRAIN STATE AND STRENGTH OF DAMAGED CONCRETE BEAMS REINFORCED WITH CARBON FIBER FABRIC IN PC "LIRA-SAPR"

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Abstract. The study examines the problem of preserving and improving the architectural heritage in Ukraine. Many buildings and structures have a long service life or are already deteriorating due to their age and other factors. This is particularly true for reinforced concrete structures, which often have various defects and damage. Unfortunately, there are no clear methods for assessing the residual load-bearing capacity of such structures. However, the research indicates that the residual potential of damaged elements may be significantly underestimated. Therefore, it is crucial to explore and apply effective innovative solutions for strengthening these constructions.

One such solution involves using composite materials (fiber-reinforced polymers, FRP) for external reinforcement of structures. Composite materials offer numerous advantages, including high strength, low weight, resistance to aggressive environments, and durability.

The article presents the results of a numerical experiment aimed at investigating the influence of damage and reinforcement with carbon fiber-reinforced polymer (CFRP) on the stress-strain state and residual load-bearing capacity of concrete beams with basalt-plastic reinforcement (BFRP). For the experiment, 15 rectangular beams with dimensions of 2000×200×100 mm were prepared and nonlinearly analyzed using the "LIRA-SAPR" software, which employs the finite element method. The data obtained for each beam were compared with the results of laboratory tests, revealing that CFRP reinforcement increases the residual load-bearing capacity of the beams without significantly affecting their working deformation. Additionally, a comparative analysis was conducted on the residual load-bearing capacity and stress-strain state of the beam components: CFRP fabric, concrete, and reinforcement. The authors assert that modeling the complex stress-strain state of experimental basalt-concrete beams using nonlinear finite element calculations through the "LIRA-SAPR" software accurately reproduces experimental results, provides insight into the most likely failure mode, and reliably predicts their load-bearing capacity.

Key words: non-metallic composite reinforcement, finite element method, modeling, bearing capacity, stress, fracture, basalt concrete beam.

Introduction. Ukraine is a country with a rich architectural heritage that requires preservation and improvement. Many buildings and structures have a long service life or are already out of order. Due to the age and other various factors (for example, emergency exposure, aggressive environment, violation of operating modes, etc.), the structures of buildings and structures are damaged. Reinforced concrete structures often have various defects and damages [1] that affect their load-bearing capacity. There are no clear methods for estimating the residual bearing capacity of such constructs [2], so decisions about their amplification are usually made on the basis of intuition. However, as shown in [3, 4], the bearing capacity of the elements can still be ensured – the residual potential of damaged structural elements is significantly underestimated. Therefore, it is important to research and apply effective innovative solutions to strengthen structures. One such solution is the use of composite materials (fiber reinforced polymers (FRP)) for external reinforcement of structures. Composite materials have many advantages, such as high strength and deformation coefficient, low weight, manufacturability, resistance to aggressive media, ability to repeat the shape of the reinforced structure and durability.

Modeling the behavior of structures in construction is a complex process aimed at determining the stress-strain state of the structure and finding the optimal design solution. Currently, software packages that utilize the finite element method (FEM) are widely used for structural analysis. The distinctive feature of the "LIRA-SAPR" software lies in its ability to define the calculation scheme, types, and number of finite elements, material properties, and other parameters to obtain results that closely match experimental data. This flexibility allows engineers to accurately simulate real-world scenarios and make informed design decisions.

The analysis of recent research and publications. Numerous scientific works are dedicated to the study of building structures. Specifically, a series of studies focuses on calculating damaged elements to determine their stress-strain state, taking into account their load-bearing capacity

In the work [5], the processes of modeling structural reinforcement using composite materials in the "LIRA-SAPR" software and verifying the load-bearing capacity of reinforced elements in the "ESPRIT" program were examined. The authors proposed an algorithm for calculating construction objects when changing the design situation, considering the modeling of structural reinforcement. The process of modeling structural reinforcement using metal clamps was investigated, and a numerical modeling example of frame reinforcement with the selection and verification of composite material was provided. The conclusion was drawn that the use of fiber-reinforced polymers for structural reinforcement significantly increases their load-bearing capacity, extends their service life, prevents or mitigates emergencies, rectifies construction or design errors, and ensures reliable operation and durability of structures. It is demonstrated that modeling structural reinforcement using fiber-reinforced polymer materials in the "LIRA-SAPR" software is sufficiently accurate for use in reinforcement design.

In the work [6], the stress-strain state of basalt-concrete beams was investigated, taking into account the combined action of concrete and basalt-plastic reinforcement. The actual load-bearing capacity of inclined sections of basalt-concrete beams was compared with the calculated values obtained using the "LIRA-SAPR" software. The study analyzed direct measurements of deflections, deformations of concrete and basalt-plastic reinforcement, as well as correlated displacements and stresses in experimental specimens before their failure.

The research provides valuable insights into the behavior of basalt-concrete beams and highlights the effectiveness of using basalt-plastic reinforcement for enhancing load-bearing capacity and ensuring structural durability.

In the work [7], the calculation of reinforced concrete beams of rectangular cross-section, reinforced with carbon composite tapes, in the software complex "LIRA-SAPR" is considered. Experimental and calculated deflection graphs for unreinforced and reinforced beams are presented.

The authors [8] in conducted nonlinear finite element modeling of reinforced concrete slabs strengthened with carbon composite strips under the action of impact loads (subjected to explosive loading) to assess the effectiveness of using carbon fiber-reinforced polymer (CFRP) as external reinforcement (EBR) to protect these slabs from explosions. The article aimed to develop comprehensive numerical models for predicting the behavior and response of these structures during the arrival and rebound phases of shock waves. In the concrete modeling, a plastic material model was employed, accounting for the influence of strain rate and capable of predicting crack formation. Elastic-plastic material models and elastic material models were used to simulate steel reinforcement and carbon composite strips, respectively. The interface between concrete and the carbon composite strip was modeled using a specialized contact algorithm that considers strain rate effects at the interface boundary, incorporating failure criteria. The simulation results were validated against experimental data. The concrete material model provided accurate predictions of the response of the reinforced concrete slab to explosions, both with and without EBR. Increasing the number of carbon composite strips reduced maximum deflections in the middle of the slab span and deformations in the steel reinforcement and carbon composite strips. The authors presented a qualitative picture of the stress-strain state of ordinary and EBR-reinforced reinforced concrete slabs under the influence of explosions and developed corresponding finite element models. However, specific recommendations for calculating and designing these slabs considering the impact of explosions were not provided.

The researched [9] presents the results of a numerical experiment to determine the stress-strain state and residual bearing capacity of reinforced concrete beams of rectangular section, which had damage in the compressed zone of concrete. 15 reinforced concrete beams were tested and calculated with different parameters of damage and relative cut run. The nonlinear calculation in "LIRA-CAD" SK was performed, which is based on the method of finite elements and relatively obtained data with the data of laboratory tests and good convergence of the residual bearing capacity and nature of the stress-strain state of concrete and transverse reinforcement was revealed.

In the work [10], models of a reinforced concrete bridge beam of T-section, ordinary and reinforced with carbon strips, were developed, and their comparative analysis was carried out with experimental data on deflections. The method of beam modeling using the software complex "LIRA-CAD," which uses the method of finite elements, is described. The problem of strengthening building structures, which requires an integrated approach and taking into account all technogenic and natural factors, is highlighted. The authors emphasized that the current state of Ukraine's bridges does not meet modern requirements, and the possibilities of their restructuring are limited. Therefore, it is proposed to look for methods that allow more accurate calculation of residual reserves of existing structures and effectively use various reinforcement methods, in particular, external composite reinforcement. It is proved that this method of reinforcement is optimal for many designs that work on bending and eccentric compression and are exposed to the external environment. It is shown that the simulation in the software complex "LIRA-CAD" of the work of structures reinforced with external composite reinforcement is accurate enough to use it in the design of reinforcement.

The analysis of recent research on the topic shows that today a large number of publications are devoted to experimental studies of reinforced concrete structures and analysis of experimental data. The calculation of reinforcement of building structures using the latest technologies, in particular composite high-strength tapes, is an extremely urgent issue. Modern engineering CAD can be a good tool for performing this calculation quickly and efficiently, provided that a sufficiently accurate design model is built.

Purpose of work. To provide the results of numerical modeling of the work of damaged basalt concrete beams reinforced with carbon fiber web, comparison with the results of laboratory studies of the strained state and residual bearing capacity.

Research methodology. The stress-strain state and residual bearing capacity of the samples were determined by numerical modeling using the 2021 LIRA-CAD software, and their analysis was compared with the results obtained as a result of laboratory tests, deduction, generalization, conclusion formulation.

Research results. The stress-strain state of prototypes-beams of the – was simulated in a nonlinear exposition by the method of finite elements in the LIRA-CAD software complex of the 2021 version. This complex is based on the general theory of reinforced concrete with cracks developed by Professor M. Karpenko [11] and his students.

The study took into account the compatible work of materials such as concrete, basalt-plastic reinforcement and carbon-plastic fabric, which have different physical and mechanical characteristics. For concrete, the results of tests of cubes and prisms were used, and the characteristics of basalt-plastic reinforcement [12] and carbon-plastic fabric [13] were adopted in accordance with the relevant regulatory documents and quality certificates. According to the experimental plan, 15 different models of experimental beams were created in accordance with their characteristics.

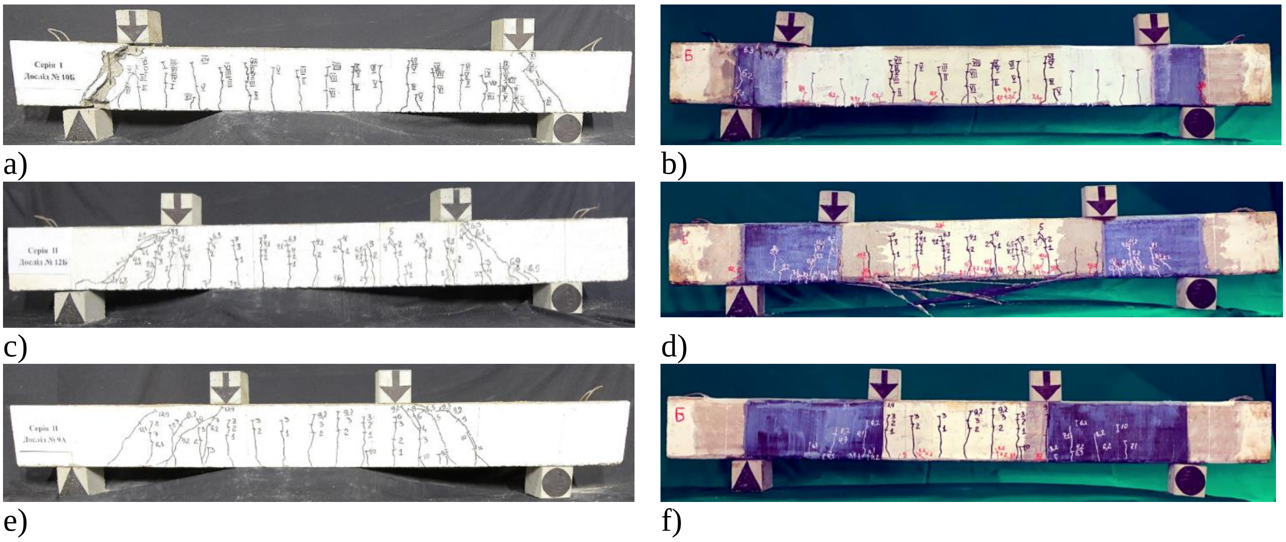
Basalt concrete beams size $2000 \times 200 \times 100$ mm. Longitudinal reinforcement beams – 2Ø14BFRP (AKB800). Transverse reinforcement beams – 2Ø 4, 6, 8 BFRP (AKB800). The beams are made of concrete of classes C16/20, C30/35 and C40/50.

As structural factors, factors were assigned that varied at three levels (Table 1): X_1 – the relative span of the cut (the distance from the support to the concentrated force), $a/h_0 = 1, 2, 3$ at $h_0 = d = 175$ mm; X_2 – concrete class C, MPa, C16/20, C30/35, C40/50; X_3 – transverse reinforcement coefficient ρ_{fw} (AKB-800) = 0.0029; 0.0065; 0.0115 for basalt concrete beams. Coefficients of upper and lower longitudinal reinforcement $\rho_{lf} = 0.0176$ for beams with design spans $L_0 = 9h_0 = 1575$ mm and width $b = 100$ mm.

Table 1 – CFRP of damaged beams with BFRP

Experiment No.	Plan of experiment					
	in coded variables			in natural values of factors		
	X_1	X_2	X_3	a/d	Concrete class C, MPa	ρ_{fw} BFRP-800
1	+	+	+	3	C40/50	0.0115
2	+	+	–	3	C40/50	0.0029
3	+	–	+	3	C16/20	0.0115
4	+	–	–	3	C16/20	0.0029
5	–	+	+	1	C40/50	0.0115
6	–	+	–	1	C40/50	0.0029
7	–	–	+	1	C16/20	0.0115
8	–	–	–	1	C16/20	0.0029
9	+	0	0	3	C30/35	0.0065
10	–	0	0	1	C30/35	0.0065
11	0	+	0	2	C40/50	0.0065
12	0	–	0	2	C16/20	0.0065
13	0	0	+	2	C30/35	0.0115
14	0	0	–	2	C30/35	0.0029
15	0	0	0	2	C30/35	0.0065

Damaged after testing concrete beams with BFRP were reinforced. (Fig. 1) from below in the stretched zone for their entire length. (1575 mm) and width ($b = 100$ mm) and on near-support areas in the form of closed shirts with a length of 150, 300 and 450 mm, respectively, with a carbon fiber cloth Sika®Wrap® – 230S glued with a two-component resin Sikadur – 300 according to the established technology [14, 15] with preliminary preparation of the surface of prototypes – beams and using fine-grained polymer cement repair mixtures for filling potholes, caverns and excessively open cracks.



a) b) c) d) e) f)

Fig. 1. The nature of crack formation and destruction of concrete beams with BFRP before (a, c, e) and after (b, d, f) their reinforcement with carbon fiber web in the lower stretched zone and in near-support areas with small, medium and large shear spans

A separate calculation scheme was created for each beam. In the LIRA-CAD software complex, finite elements No. 44 were used to simulate damaged basalt concrete beams – universal quadrangular FE shells and No. 236 – physically nonlinear universal eight-node spatial isoperimetric FEs with a volume of up to 1000 mm^3 (maximum size of edges of finite elements 10×10×10 mm) elements are connected by knots, which are absolutely rigid bodies of infinitely small sizes with six degrees of freedom.

The number of elements in the whole samples reached 84.724 units, knots – 87.360 units.

Reinforcement of elements in the design scheme was taken into account in the form of the same volume finite elements according to the specified characteristics of reinforcing materials and the percentage of reinforcement of the element. Fixing in the calculation scheme is set as follows. On the left support, links were superimposed on a number of nodes that limited movements along the axes Y, Z and turns relative to the axes Ux, Uz, on the right support – links that limit movements along the axes X, Y, Z and turns relative to the axes Ux, Uz.

To eliminate the effect of local crushing in the places of application of the load and supports, plates with a given rigidity and dimensions of 0.01 × 0.01 m were installed. The method of firing the experimental beam provided for blocking movements along the corresponding axes.

To set the properties of materials in the method of finite elements, such characteristics as modulus of elasticity, Poisson's coefficient, ultimate strength and others were used. It is important to take into account the anisotropy of the properties of the carbon fiber web, since it must differ in strength and rigidity in different directions.

The calculation was carried out by a nonlinear step-iterative method. As a criterion for destruction, the beam acquired at least one limit state: stresses in the longitudinal and/or transverse reinforcement reach limit values; achievement of limit stresses in a significant group of finite elements of compressed concrete at the place of sample burning or above the top of an inclined crack; achieving excessive values of displacements (deflections).

Analysis of the results of modeling the stress-strain state of experimental damaged concrete elements showed (stress isofields are shown in Figures 2, 3, 4) that the use of a nonlinear finite-element calculation for this purpose, based on the general mechanics of reinforced concrete using phenomenal strength criteria, allows us to reproduce the results of full-scale and numerical experiments with sufficient accuracy for practical calculations. To improve the accuracy of the calculation, it is desirable to use more advanced strength criteria. Therefore, the use of this nonlinear finite-element calculation makes it possible to simulate the stress-strain state of experimental elements at all stages of their work, including destruction. A consistent analysis of isofields of stresses, displacements and forces in materials of real design allows to reliably assess the influence of experimental structural factors and factors of external influence on their bearing capacity, to predict the nature of subsequent deformation and destruction.

The destruction of experimental reinforced basalt concrete beams with large (a/d = 3) and medium (a/d = 2) shear spans corresponded to the stress-strain state of an almost balanced normal cross section, which was characterized by the achievement of closed deformations and rupture stresses in the outer carbon fiber layer of the CFRP reinforcement, and in the compressed zone of concrete – closed (at the bottom section of the diagram "$\sigma_c - \varepsilon_c$") deformations and stresses. This destruction of test beams with large and medium shear spans began with the rupture of the outer reinforcement of the CFRP and was accompanied by a sharp increase in stresses in the stretched basalt-plastic reinforcement of the BFRP, cracking and delamination of the protective layer of concrete and excessive uncontrolled increase in deflections.

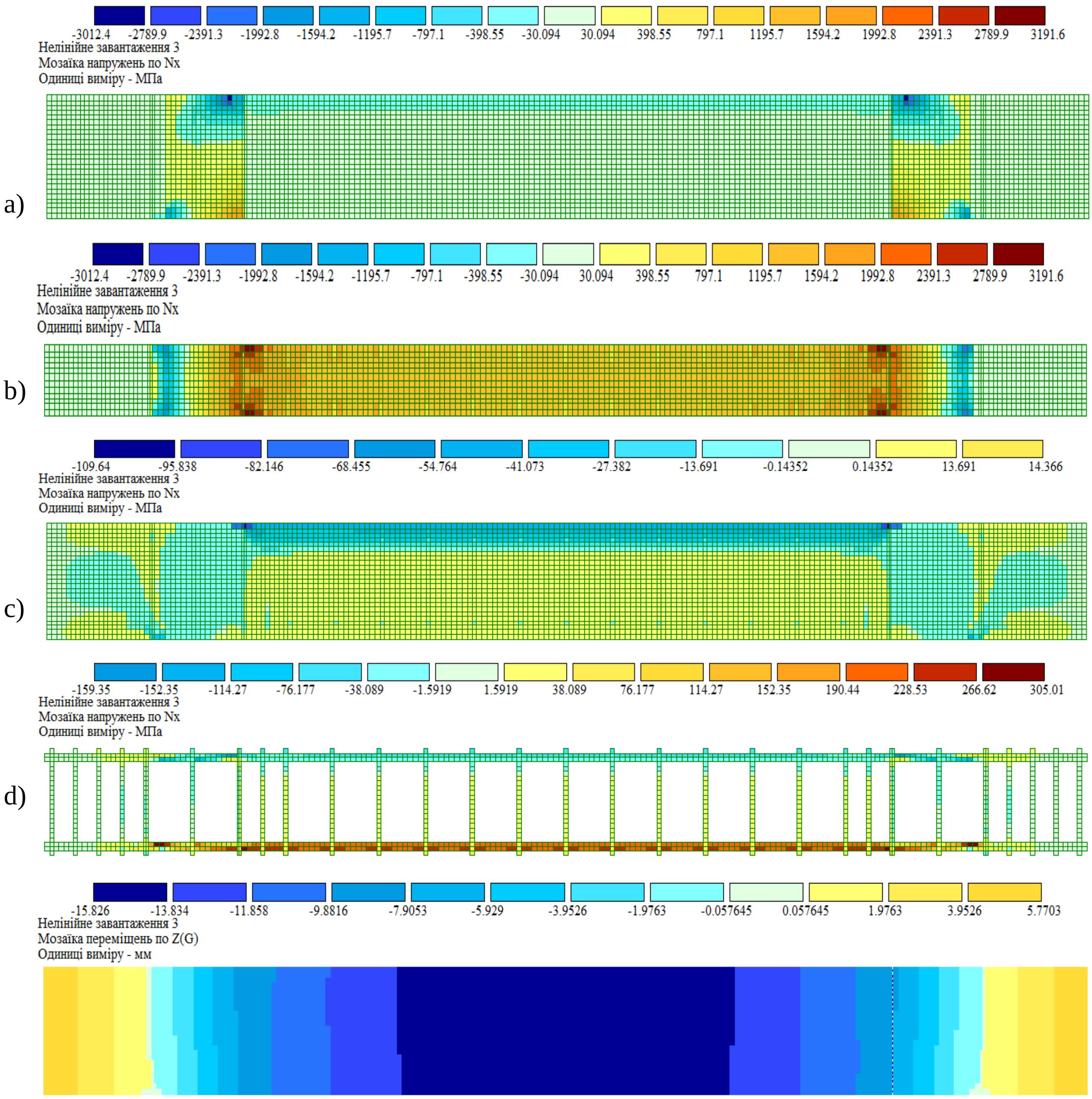
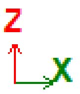


Fig. 2. Isofields of normal stresses in MPa in the carbon fiber web (a), concrete (b), basalt plastic longitudinal reinforcement (c) and vertical displacements (d) in mm of the damaged concrete beam reinforced with external fibro-reinforced carbon fiber (CFRP) with a small cut span

Coordinate axes 

– for stress isofields in a carbon fiber web;

Coordinate axes 

– for stress isofields in concrete, reinforcement and vertical displacements.

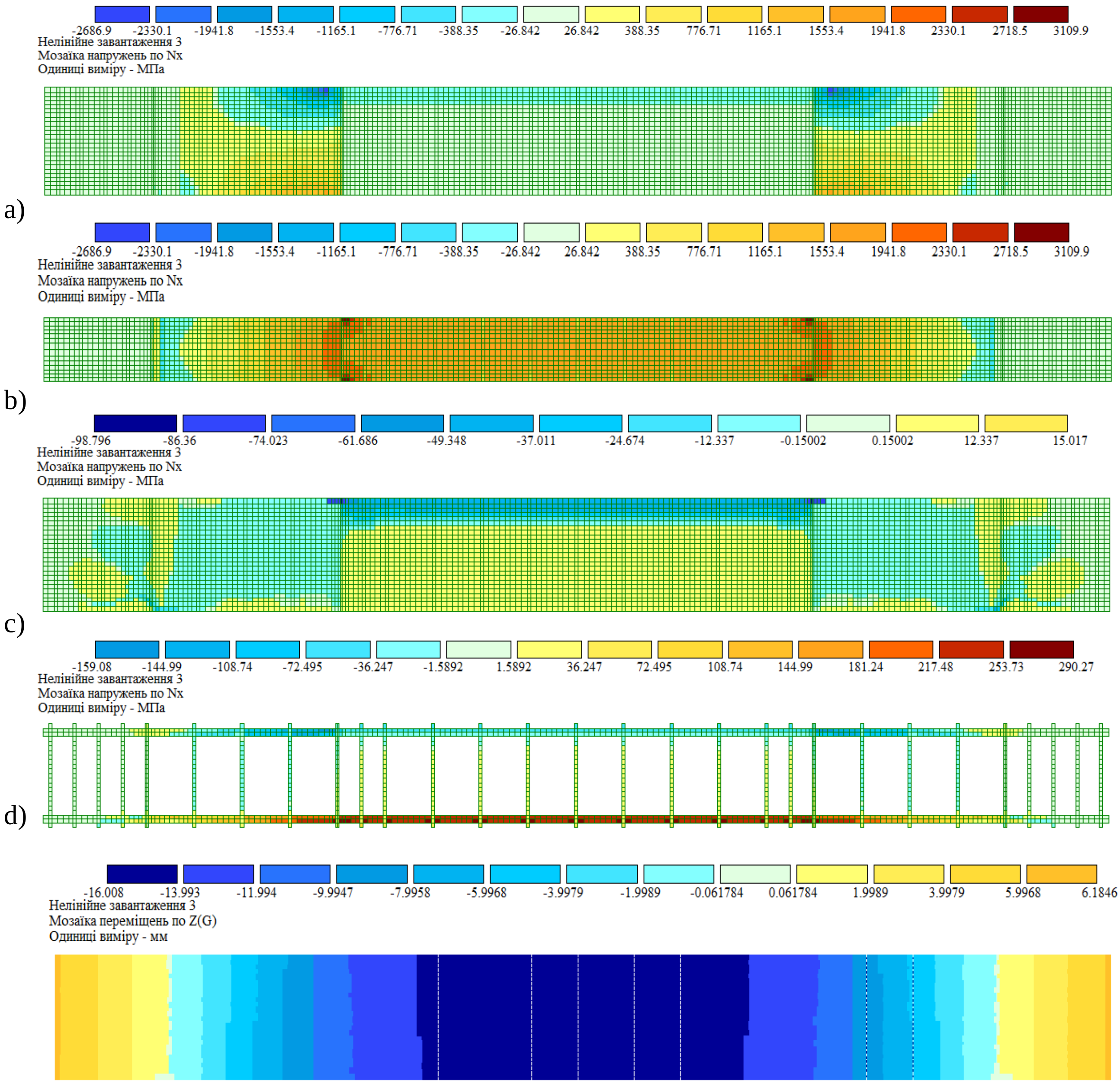
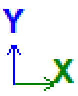
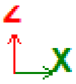


Fig. 3. Isofields of normal stresses in MPa in the carbon fiber web (a), concrete (b), basalt plastic longitudinal reinforcement (c) and vertical displacements (d) in mm of the damaged concrete beam reinforced with external fibro-reinforced carbon fiber (CFRP) with average span of cut

Coordinate axes 

– for stress isofields in a carbon fiber web;

Coordinate axes 

– for stress isofields in concrete, reinforcement and vertical displacements.

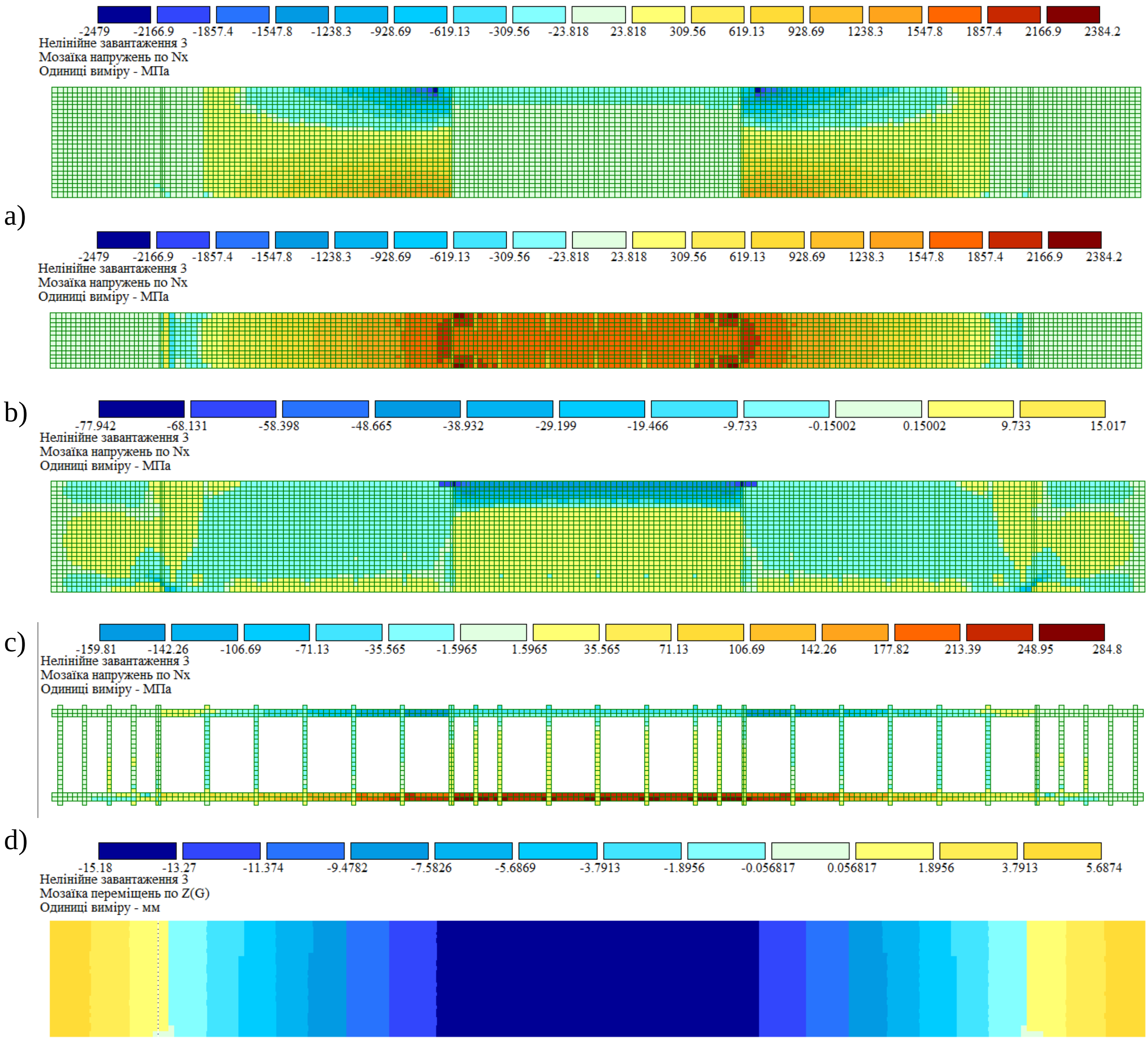
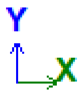
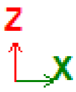


Fig. 4. Isofields of normal stresses in MPa in the carbon fiber web (a), concrete (b), basalt plastic longitudinal reinforcement (c) and vertical displacements (d) in mm of the damaged concrete beam reinforced with external fibro-reinforced carbon fiber (CFRP) with a large span cut.

Coordinate axes -  – for stress isofields in a carbon fiber web;

Coordinate axes  – for stress isofields in concrete, reinforcement and vertical displacements.

The destruction of beams with small (a/d = 1) shear spans was accompanied by the subsequent opening of previously formed inclined cracks and the rupture of closed carbon-plastic jackets on the side faces of their near-support sections and a sharp increase in deflections caused primarily by deformations of mutual shear of individual parts of prototypes.

Conclusions. Simulation of the complex stress-strain state of experimental basalt-concrete beams by nonlinear finite-element calculations using the LIRA-CAD software complex makes it possible to reproduce the results of experiments, the most probable scheme of work and destruction and reliably predict their bearing capacity. It is worth noting that the whole process from the construction of the calculation scheme to the analysis of the data takes a rather long period of time. Therefore, the development of a simple engineering technique for calculating such elements is an important and urgent task.

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МОДЕЛЮВАННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ПОШКОДЖЕНИХ БЕТОННИХ БАЛОК, ПІДСИЛЕНИХ ВУГЛЕПЛАСТИКОВИМ ПОЛОТНОМ В ПК «ЛІРА-САПР»

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Анотація. У дослідженні розглядається проблема збереження та покращення архітектурної спадщини в Україні. Багато будівель і споруд мають тривалий термін експлуатації або вже виходять з ладу через вік та інші фактори. Особливо це стосується конструкцій залізобетону, які часто мають різні дефекти та пошкодження. На жаль, немає чітких методів для оцінювання залишкової несучої здатності таких конструкцій. Проте дослідження показує, що залишковий потенціал пошкоджених елементів може бути значно недооцінений. Тому важливо досліджувати та застосовувати ефективні інноваційні рішення для зміцнення конструкцій.

Одним з таких рішень є використання композитних матеріалів (армованих волокнами полімерів, FRP) для зовнішнього армування конструкцій. Композитні матеріали мають багато переваг, таких як висока міцність, мала вага, стійкість до агресивних середовищ та довговічність.

У статті представлено результати чисельного експерименту, який мав на меті дослідити вплив пошкодження та підсилення вуглепластиковим полотном на напружено-деформований стан і залишкову несучу здатність бетонних балок з базальтопластиковою арматурою (BFRP). Для експерименту було підготовлено 15 балок прямокутного перерізу розмірами 2000×200×100 мм, які були розраховані нелінійно за допомогою програми “ЛІРА-САПР”, що використовує метод скінчених елементів. Дані, отримані для кожної балки, були порівняні з результатами лабораторних випробувань, які показали, що підсилення вуглепластиковим полотном збільшує залишкову несучу здатність балок, але не впливає на їх робочу деформацію. Також було проведено порівняльний аналіз залишкової несучої здатності та напружено-деформованого стану складових балок: вуглепластикового полотна, бетону та арматури. Автори стверджують, що моделювання складного напружено-деформованого стану дослідних базальтобетонних балок нелінійними звичайно-елементними розрахунками за допомогою програмного комплексу “ЛІРА-САПР” дозволяє точно відтворити результати експериментів, найімовірнішу схему роботи та руйнування, а також достовірно спрогнозувати їхню несучу здатність .

Ключові слова: неметалева композитна арматура, метод скінчених елементів, моделювання, несуча здатність, напруження, руйнування, базальтобетонна балка.

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