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A NUMERICAL INVESTIGATION OF THE INFLUENCE OF THE EXTERNAL FIBRE COMPOSITE REINFORCEMENTS ON DAMAGED CONCRETE ELEMENTS UNDER COMPRESSION

ABSTRACT

The need for restoration and reinforcement of building structures damaged as a result of war and combat activities is noted in the paper. It has been determined that one of the methods for reinforcing concrete and reinforced concrete structures is the use of external reinforcement with fiber-reinforced composite materials, particularly carbon fibers. The paper considers the advantages and disadvantages of using this method. The main part of the article deals with methodology of numerical research, in which the finite element method and a nonlinear concrete deformation model implemented in the LIRA-SAPR software complex are used. The aim of the work is to determine the influence of external carbon fiber reinforcement on the behavior of a compressed concrete element and the optimization of parameters for the minimum necessary amount of materials, namely the length and thickness of the reinforcement.

The main test specimens included: a control specimen without damage; a specimen with damage and without reinforcement; three series of specimens with damage and external reinforcement of different thicknesses and lengths. SikaWrap®-231 C carbon fiber fabric was used for reinforcement with Sikadur®-300 adhesive mixture. Loads were applied at nodes on the upper surface of the test specimen.

In the numerical studies, volumetric finite elements and a nonlinear concrete deformation model 21 - exponential sequence for concrete were used to model concrete and reinforcement material. The calculation was performed taking into account the physical nonlinearity of concrete with the implementation of the step-by-step method during loading, with a total of 20 steps and a load increment value of 0.05 for each step.

Using the linear programming method, the optimal reinforcement parameters were determined to achieve the minimal use of external reinforcement materials. As a result of the calculations, the required area of external reinforcement A_{sf}=206.4 mm^2 was obtained from four layers, with a total thickness of t=0.516 mm, and the minimum size of the external reinforcement $B \geq 1.3A$.

KEYWORDS: reinforcement, carbon fiber, finite element method, stress-strain state, concrete.

ЧИСЛОВІ ДОСЛІДЖЕННЯ ВПЛИВУ ЗОВНІШНЬОГО ПІДСИЛЕННЯ КОМПОЗИТНИМИ МАТЕРІАЛАМИ СТИСНУТОГО БЕТОННОГО ЕЛЕМЕНТУ З ПОШКОДЖЕННЯМ

АНОТАЦІЯ

У роботі зауважується необхідність відновлення та підсилення будівельних конструкцій, пошкоджених внаслідок війни та бойових дій. Визначено, що одним із методів підсилення бетонних та залізобетонних конструкцій є застосування зовнішнього армування з волоконно-композитних матеріалів, зокрема вуглецевих волокон. У роботі розглянуто переваги та недоліки застосування цього методу. Основна частина статті присвячена методології числового дослідження, в якому використано метод скінченних елементів та модель нелінійної деформації бетону, що реалізовано в програмному комплексі LIRA-SAPR. Мета роботи – визначити вплив підсилення зовнішнім армуванням з вуглецевого волокна на роботу стиснутого бетонного елементу та оптимізацію параметрів за мінімально необхідною кількістю матеріалів, а саме довжину та товщину підсилення. Основні випробувальні зразки включали: контрольний зразок без пошкоджень; зразок з пошкодженням та без підсилення; три серії зразків з пошкодженнями та зовнішнім армуванням різної товщини та довжини. В якості армування використовувалася тканина з вуглецевого волокна SikaWrap®-231 C на клейовій суміші Sikadur®-300. Навантаження прикладалося у вузли по верхній грані дослідного зразка. У числових дослідженнях для моделювання бетону та матеріалу підсилення використано об'ємні скінченні елементи та нелінійну модель деформування бетону 21 – exponential sequence for concrete. Розрахунок виконувався з врахуванням фізичної нелінійності бетону з організацією крокового методу при навантаженні, всього 20 кроків зі значенням приросту навантаження 0,05 на кожен крок. За допомогою методу лінійного програмування було встановлено оптимальні параметри армування для досягнення мінімального використання матеріалів зовнішнього армування. В результаті розрахунків отримано необхідну площу зовнішнього армування A_{sf}=206.4 мм^2 з чотирьох шарів загальною товщиною t=0,516 мм, при цьому мінімальний розмір зовнішнього армування $B \geq 1.3A$.

КЛЮЧОВІ СЛОВА: підсилення, вуглецеве волокно, метод скінченних елементів, напружено-деформований стан, бетон.

INTRODUCTION

The website of the "Russia will pay" project, published data on the material damage caused by Russia's war against Ukraine: "The largest share in the total amount of direct damage belongs to residential buildings (37.1 % or $55.9 billion) and infrastructure (24.3 % or $36.6 billion)" [1, 2]. A huge number of damaged buildings are in a state of emergency or not suitable for normal operation. There is an urgent need to restore and strengthen the load-bearing structures in such buildings. One of the methods of strengthening concrete and reinforced concrete structures is the applications of carbon fiber composite materials as an external reinforcement. Among the normative documents in Ukraine, there are no standards for determining the physical and mechanical properties of carbon fiber products, and in the recommendations for the use of composite materials of the SIKA company for strengthening damaged concrete structures, little attention is paid to compressed elements. Therefore, we believe that numerical studies of the influence of the external fibre composite reinforcements on damaged concrete elements are needful and timely. Analyzing the works [3, 4, 5, 6, 7 etc.], the following advantages and disadvantages of using external composite reinforcement can be formulated: high strength, fatigue resistance, resistance to corrosion and aging, speed and ease of reinforcement work, the ability to perform reinforcement of any shape, and maintaining the aesthetic appearance of reinforced elements. However, despite these benefits, they have their drawbacks, such as high cost, anisotropy of properties, low strength in the transverse direction, and the complexity of manufacturing fibers and specialized equipment.

MAIN PART

The purpose of the work is to determine the influence of reinforcement with external carbon fiber composites on the operation of a compressed concrete element, and to optimize the parameters according to the minimum required amount of materials, namely the length and thickness of the reinforcement. The finite element method implemented in the LIRA-SAPR software complex was used to analyze the stress-strain state of concrete samples including damaged concrete samples with external fibre composite reinforcements.

In this investigation, volumetric finite elements and a nonlinear model of concrete deformation 21 - exponential sequence for concrete were used for concrete C 25/30. External reinforcement was also modeled by volumetric elements taking into account orthotropic properties. SikaWrap®-231 C carbon fiber fabric on Sikadur®-300 adhesive mixture was used as reinforcement.

Test samples:

- Control sample – a concrete prism measuring 100x100x500 mm, without damage;
- Sample 1 – a concrete prism measuring 100x100x500 mm, with damage along the length A=200 mm, depth 20 mm and opening width w =2 mm;
- Sample 2 – a concrete prism measuring 100x100x500 mm, with damage along the length A=200 mm, depth 20 mm and opening width w=2 mm, with one layer of external reinforcement SikaWrap®-231C t = 0.129 mm (fibers along the axis of the element). Three variable lengthes of the external reinforcement B = 1.25A, 1.5A and 2A were considered.
- Sample 3 – a concrete prism measuring

100x100x500 mm, with damage along the length A=200 mm, depth 20 mm and opening width w=2 mm, with two layers of external reinforcement SikaWrap®-231C t = 0.258 mm (fibers at an angle of 00 and 900 to the axis of the element). Three variable lengthes of the external reinforcement B = 1.25A, 1.5A and 2A were considered

- Sample 4 – a concrete prism measuring 100x100x500 mm, with damage along the length A=200 mm, depth 20 mm and opening width w=2 mm, with four layers of external reinforcement SikaWrap®-231C t = 0.516 mm (fiber orientation in the layup: 00/900/900/00). Three variable lengthes of the external reinforcement B = 1.25A, 1.5A and 2A were considered.

The load was applied at the nodes on the upper face of the test sample and, accordingly, the total load was up to 100 kN. The calculation was performed taking into account the physical nonlinearity of concrete with the organization of the step method of applying loads, a total of 20 steps with a load increment value of 0.05 at each step.

The volumetric finite elements (FE 231 - Physically nonlinear parallelepiped) were used to model the concrete sample. FE is meant for the strength analysis of solid 3D structures taking into account physical nonlinearity of the material [8]. Non-linear properties of concrete are taken into account thanks to the use of the law of deformation 21 - exponential sequence for concrete Fig. 2. In the nonlinear stress-strain diagram area specify the following parameters: grade of concrete; type of concrete; modulus of elasticity; ultimate stress in compression (negative value); ultimate stress in tension.

Concrete is modeled by volume finite elements FE 231 each size 10x10x10 mm Fig. 3a, from which the entire element is assembled layer by layer. In the zone of artificial damage, the elements from the top and from the bottom have dimensions of 9x10x10 mm and an additional element with the size of 2x10x10 mm is introduced in Fig. 3b, showing the zone of the element without damage, and Fig. 3c, showing the same zone but with damage.

Carbon fiber reinforcement is modeled by volumetric finite elements FE 231, with dimensions of 10x10x0.129 mm, shown in Fig. 4 with orthotropic properties.

As a result of the performed numerical studies, we obtained data on the stress-strain state of the test samples. The dependence graph between loads and displacementis shown in Fig. 5. For the convenience of data analysis, results from 6 out of 11 samples in the study are presented in the diagram. The failure of the samples are considered to have reached such a load that corresponds to the relative deformations ε_u = 0.002, 2 mm per 1 meter. From the deformation diagram, it can be seen that the sample 1 shows

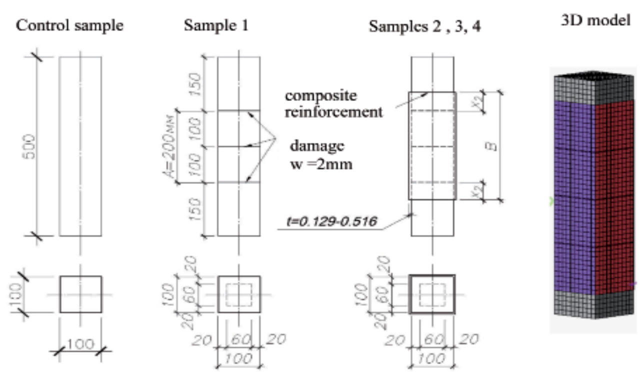

Figure 1 – Concrete column samples

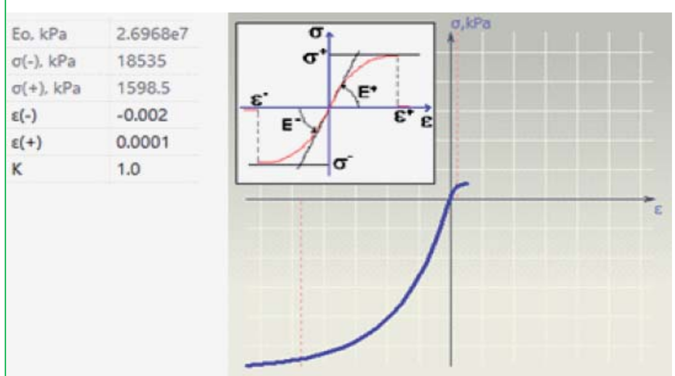

Figure 2 – Exponential sequence for concrete

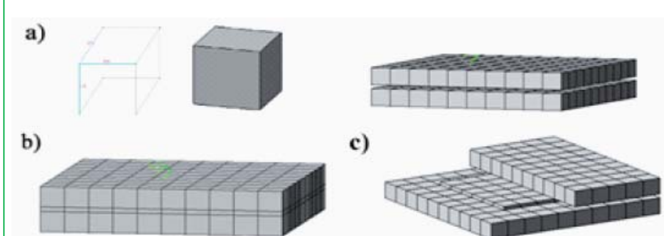

Figure 3 – Exponential sequence for concrete

Figure 4 – Reinforcement with carbon fiber

significantly lower indicators and has a nonlinear ability at the level of 45 % of the control sample. Sample 4 with B=2A showed deformation characteristics even better than the undamaged control sample.

In order to determine the optimal parameters of reinforcement of a concrete prism based on the minimum consumption of materials, namely the length and thickness of the reinforcement, the regression equation of two variables was obtained and the optimization problem was solved.

To obtain a result in relative units, the following are accepted as input parameters:

1. The ratio of the area of the reinforcement material to the cross-sectional area of the control sample:

$$x_1 = \frac{A_{sf}}{A_c}, \tag{1}$$

where, $A_{sf} = t \times 4b$ is the area of the reinforcement material, mm^2; A_c is the cross-sectional area of the prism, mm^2. x_1 – takes the following values (0.00516; 0.01032; 0.02064).

2. The ratio of the length of the anchoring zone to the side of the prism is defined as:

$$x_2 = \left(\frac{B-A}{2}\right) \div b, \tag{2}$$

where, A is the length of the damage zone 200 mm; B is the length of the reinforcement zone (mm); b is the edge size of the square of the prism 100 mm. x_2 - takes the following values (0.25, 0.5, 1).

The parameter Y is needed to determine the ratio of the load value of the test specimen to the corresponding load level of the control specimen at the limit values of deformations in concrete $\varepsilon_u = 0.002$, e.g., 2 mm per 1 meter length. Dependence can be sought by Eq. 3.

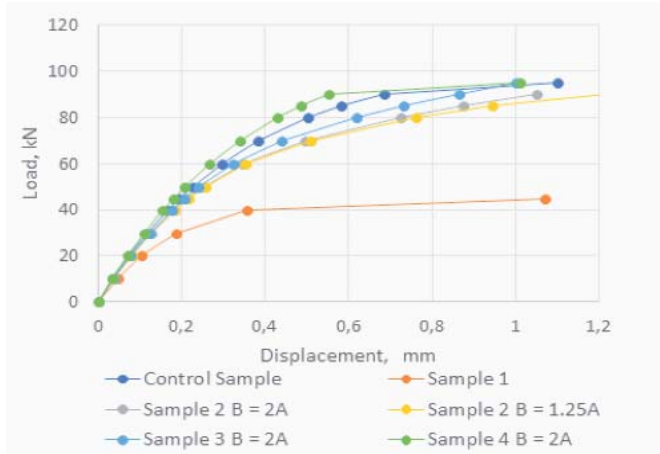

Figure 5 – Deformation diagram of test samples

$$A_1x_1 + A_2x_2 + A_3 = Y \tag{3}$$

Methodology for the analysis of the received numerical research data to obtain the regression equation in the form of (3). The results of mixing at each load step for all test samples are shown in Table 1.

Then, to obtain the dependence in the form (3), we will construct and present the matrix of the experiment in the following form Table 2. Where the parameter *X1* takes into account the influence of the change in the thickness of the reinforcement (1), and the parameter *X2* takes into account the change in the length of the anchoring of the reinforcement (2).

Coefficients *A1, A2, A3* in Eq. 3 obtained by linear regression according to experimental data, calculations were performed in Excel. Substituting the Eqs. 1 and 2 into Eq. 3 results in Eq. 4.

$$0{,}951 + 2{,}136\frac{A_{sf}}{A_c} + 0{,}0164\frac{B-A}{2b} = Y \tag{4}$$

Table 1 – Displacement in test samples under load, mm

Load, kN	Control Sample	Sample 1	Sample 2 B = 1.25A	Sample 2 B = 1.5A	Sample 2 B = 2A	Sample 3 B = 1.25A	Sample 3 B = 1.5A	Sample 3 B = 2A	Sample 4 B = 1.25A	Sample 4 B = 1.5A	Sample 4 B = 2A
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.035	0.048	0.038	0.038	0.038	0.037	0.037	0.039	0.0348	0.034	0.034
20	0.073	0.105	0.081	0.080	0.080	0.079	0.078	0.078	0.073	0.072	0.070
30	0.117	0.186	0.125	0.128	0.127	0.123	0.125	0.123	0.116	0.114	0.110
40	0.167	0.356	0.185	0.184	0.182	0.180	0.179	0.176	0.164	0.161	0.155
45	0.195	1.070	0.218	0.217	0.214	0.211	0.210	0.206	0.191	0.187	0.180
50	0.225		0.256	0.255	0.252	0.247	0.245	0.241	0.22	0.216	0.206
60	0.295		0.352	0.350	0.345	0.334	0.331	0.324	0.288	0.281	0.266
70	0.384		0.509	0.504	0.496	0.456	0.450	0.439	0.375	0.363	0.340
80	0.503		0.760	0.741	0.725	0.658	0.640	0.619	0.492	0.467	0.430
85	0.582		0.943	0.899	0.873	0.801	0.763	0.733	0.577	0.535	0.486
90	0.686		1.220	1.100	1.050	1.020	0.914	0.865	0.709	0.620	0.553
95	3.380							3.580	3.480	3.290	3.200

Table 2 – Matrix for constructing the regression equation

	№	Y	x_1	x_2
Sample 2 B = 1.25A	1	0.94973	0.00516	0.25000
Sample 2 B = 1.5A	2	0.96610	0.00516	0.50000
Sample 2 B = 2A	3	0.97797	0.00516	1.00000
Sample 3 B = 1.25A	4	0.98853	0.01032	0.25000
Sample 3 B = 1.5A	5	0.99529	0.01032	0.50000
Sample 3 B = 2A	6	0.99631	0.01032	1.00000
Sample 4 B = 1.25A	7	0.99936	0.02064	0.25000
Sample 4 B = 1.5A	8	1.00142	0.02064	0.50000
Sample 4 B = 2A	9	1.00289	0.02064	1.00000

Table 3 – Comparison of the results of the experiment with the theoretical data of equation 4

	Y	X1	X2	*Predicted Y*	error
1	0.94973	0.00516	0.25000	0.9662	1.7%
2	0.96610	0.00516	0.50000	0.9703	0.4%
3	0.97797	0.00516	1.00000	0.9785	0.1%
4	0.98853	0.01032	0.25000	0.9772	1.1%
5	0.99529	0.01032	0.50000	0.9813	1.4%
6	0.99631	0.01032	1.00000	0.9895	0.7%
7	0.99936	0.02064	0.25000	0.9992	0.0%
8	1.00142	0.02064	0.50000	1.0034	0.2%
9	1.00289	0.02064	1.00000	1.0116	0.9%

To analyze the adequacy of the obtained dependence, we obtained the data of the regression analysis and compared the theoretical data obtained by equation 3 and the results of numerical studies Tab. 3.

The adequacy of the obtained dependence was checked by Fisher's test and R-squared distribution, which was 0.74. Equation (4) describes the obtained data well enough and can be used in solved optimization problems.

Formulation of the optimization problem. It is necessary to find such minimum values of the area of the external reinforcement and the anchorage zone that the right-hand side of equation (4) is equal to unity.

Objective function

$$F = A_{sf} \times B \rightarrow \min. \quad (5)$$

Restrictions imposed

$$\begin{cases} 0,951 + 2,136\dfrac{A_{sf}}{A_c} + 0,0164\dfrac{B-A}{2b} \geq 1; \\ A = 200 \\ b = 100 \\ 1,25A < B \leq 2,0A; \\ A_{sf} = 51,6;103,2;206,4. \end{cases} \quad (6)$$

Solving the optimization problem by the graphic method of linear programming [9], a solution is obtained as: the area of the external reinforcement A_{sf}=206.4 mm^2 with four layers, the total thickness t = 0.516 mm, while the size of the external reinforcement is: B ≥1.3A.

Conclusions and future work. Using the finite element method and a nonlinear model of concrete deformation, numerical studies of the influence of external composite material reinforcements on a compressed damaged concrete element were performed. Using the graphical method of linear programming, minimizing the objective function (Eq. 5) with the fulfillment of the constraints (Eq. 6), the optimal parameters of the reinforcement of the concrete prism were determined with the minimum consumption of materials. As a result of calculations, we obtained the required area of external reinforcement A_{sf}=206.4 mm^2 with four layers, total thickness t=0.516mm, while the minimum size of external reinforcement is B≥1.3A.

In further research, it is planned to conduct physical experiments to validate the numerical investigation through comparing test work with modelling results. And a basic benchmark for repairing damaged concrete elements using carbon fiber composites as external reinforcements will be conducted in terms of experimental and numerical work. In the future work, fundamental study of fatigue performance of damaged concrete samples with carbon fibre-adhesive composite repairs is required for some infrastructures under fatigue loading, e.g., bridges. Designing repairs in the structural level needs the advanced extended cohesive damaged element method to predict the damage/fracture performance of concrete structures with carbon fibre-adhesive composite repairs to provide optimised solutions. Therefore, development of the extended cohesive damaged element method with fatigue loading function to account for cyclic effects in accumulating damages is needed in the future.

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