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FINITE ELEMENT ANALYSIS OF DAMAGED BEAMS REINFORCED WITH FIBER CONCRETE

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Abstract. The results of the study of damaged reinforced concrete beams of rectangular cross-section reinforced with fiber concrete are considered. Previously, experimental studies of beams damaged in the stretched or compressed zone, reinforced with steel-reinforced concrete, were carried out. First, the theoretical value of the load-bearing capacity of a reinforced concrete beam without damage was determined using various existing methods, and then its load-bearing capacity was determined experimentally. Based on the results, graphs of the change in deflections under the increasing load, graphs of the dependence of the relative longitudinal deformation on the load for the left and right support parts of the beam, as well as for the zone of its net bending, were constructed for each sample. At the next stage of research, the bearing capacity of two groups of reinforced beams was determined. The first group consisted of three samples with compression zone damage; the second group had two samples with damage in the stretched zone. In addition to the bearing capacity, deflections and relative longitudinal deformations are determined for each sample.

Modeling and calculations were performed for five samples of reinforced beams with variation of the damage zone and its volume. In all calculations, the load was considered in the form of two concentrated forces applied symmetrically. Computer modeling and numerical analysis of damaged beams using the finite element method were performed in two computer programs — Robot Structural Analysis and LIRA-SAPR. The maximum deflections and stresses are determined.

A comparative analysis of the obtained results with the results of experimental studies was carried out. It was established that the deflections obtained as a result of calculations in the two programs are practically the same. And the tensions are somewhat different. The maximum difference in stresses is observed for the ZBP1 sample — 11.8%. For four other samples, it is approximately the same, and on average it is 5.8%. Comparing the results of calculating the maximum stresses in LIRA-SAPR with the results of experimental studies gives a maximum discrepancy of 5.85%. And the biggest discrepancy occurs in the deflections — here it fluctuates in the range of 19.0÷19.2%.

Keywords: damaged beam, reinforced concrete, experiment, finite element method, LIRA-SAPR, Robot.

СКІНЧЕНО-ЕЛЕМЕНТНИЙ АНАЛІЗ ПОШКОДЖЕНИХ БАЛОК, ПІДСИЛЕНИХ ФІБРОБЕТОНОМ

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Анотація. Розглядаються результати дослідження пошкоджених залізобетонних балок прямокутного поперечного перерізу, підсилених фібробетоном. Попередньо були проведені експериментальні дослідження балок, пошкоджених у розтягнутій або стиснутій зоні, посилених сталефібробетоном. Спочатку за різними існуючими методиками було визначено теоретичне значення несучої здатності залізобетонної балки без ушкоджень, а потім її несучу здатність визначили експериментально. За результатами для кожного зразка побудовано графіки зміни прогинів під дією навантаження, що зростає, графіки залежності відносної

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поздовжньої деформації від навантаження для лівої та правої опорних частин балки, а також для зони її чистого згину. На наступному етапі досліджень було визначено несучу здатність двох груп посилених балок. Перша група складалася з трьох зразків, що мали пошкодження стиснутої зони; у другій групі було два зразки з пошкодженнями у розтягнутій зоні. Окрім несучої здатності, для кожного зразка визначені прогини та відносні поздовжні деформації.

Моделювання та розрахунки виконувалися для п’яти зразків посилених балок з варіацією зони пошкодження та її об’ємом. В усіх розрахунках розглядалося навантаження у вигляді двох зосереджених сил, що прикладені симетрично. Виконане комп’ютерне моделювання і чисельний аналіз пошкоджених балок методом скінчених елементів у двох комп’ютерних програмах — Robot Structural Analysis і ЛІРА-САПР. Визначені максимальні прогини та напруження.

Здійснений порівняльний аналіз отриманих результатів з результатами експериментальних досліджень. Встановлено, що прогини, отримані в результаті розрахунків у двох програмах практично однакові. А напруження дещо відрізняються. Максимальна розбіжність у напруженнях спостерігається для зразка RCD1 — 11,8 %. Для чотирьох інших зразків вона приблизно однакова, і у середньому складає 5,8 %. Порівняння результатів обчислення максимальних напружень у LIRA-SAPR з результатами експериментальних досліджень дає максимальну розбіжність 5,85%. А найбільша розбіжність виникає у прогинах — тут вона коливається в інтервалі 19,0÷19,2 %.

Ключові слова: пошкоджена балка, сталефібробетон, експеримент, метод скінчених елементів, LIRA-SAPR, Robot.

1 INTRODUCTION

The field of application of reinforced concrete beams in construction is very large. They are used in various constructions and structures, such as high-rise residential and industrial buildings, airports, bridges, for laying railway and tram lines, etc.

Due to various reasons, these structures can be damaged. It can be both mechanical damage associated with the destruction of concrete and corrosion of fittings, and damage as a result of long-term operation. This problem is especially relevant in our time, since a large amount of damage occurs as a result of military operations. It is not always advisable to change the structure, in most cases it is more economical to strengthen the damaged part of the structure without its complete replacement. At the scale of the country, such an approach undoubtedly leads to a significant economic effect.

There are different ways of strengthening. The appearance of new materials led to new, more effective such methods. Reinforcement of building structures with composite materials reinforced with carbon, glass and other fibers has gained great popularity. Their indisputable advantages are increased strength, resistance to aggressive environmental influences, etc. But there are also some disadvantages, first of all, technological difficulties and the production of the necessary composites in our conditions. Reinforcement of the damaged area with steel-reinforced concrete is a very promising direction in strengthening damaged structures. Numerous studies prove that steel fiber concrete can improve concrete characteristics such as crack resistance, frost resistance, tensile strength, bending, torsion, etc. The use of fiber allows you to change the nature of the destruction process. Unlike ordinary concrete, in which this process occurs almost instantly, in fiber concrete there is no brittle failure, and the structure continues to resist the load, and the nature of the failure changes from brittle to viscous.

2 LITERATURE ANALYSES AND PROBLEM STATEMENT

Many works are devoted to the strengthening of reinforced concrete beams. All of them can be divided into experimental and theoretical, and the latter include analytical and numerical methods for calculating reinforcements. The theoretical methods of calculation of reinforcements are currently insufficiently developed. This is explained by the complexity of the mathematical model of amplification, regardless of the method used. This fully applies to beams reinforced with fiber concrete. In this regard, preference is given to numerical methods. First of all, the finite element method (FEM), because it is the only universal method, the possibility of which is practically not limited. This explains the use of FEM for numerical analysis in all modern engineering calculation programs. Implementation of the FEM algorithm is carried out using modern computer programs, such as ANSYS [1], ABAQUS [2], NASTRAN [3], etc., designed for numerical modeling and analysis of complex structures, including beams with inclusions.

The article [4] discusses 3D modeling in ANSYS of the destruction of an element of a structural reinforced concrete beam. The authors [5] show the use of the finite element method for modeling damaged reinforced concrete beams. The corresponding numerical analysis was carried out in ABAQUS using the concrete plasticity model. The article [6] considers the critical parameters affecting the efficiency of fiber-reinforced polymer systems with an external lateral connection based on the finite-element model developed by the authors. An interesting work is presented by the authors of the article [7], where a multifactorial numerical experiment was conducted using computer modeling in the ANSYS program.

Articles [8-10] are devoted to a similar problem. In [8], experimental data from four-point bending of six reinforced concrete beams and the results of finite-element modeling obtained using ANSYS are considered. [9] suggests using discrete fiber reinforcement for tunnel finishing. The task is also modeled in ANSYS. The same authors in [10] investigate the ability of fibers to control cracks by summarizing the results of more than ninety tensile tests of reinforced concrete prisms, conducted with different sizes, reinforcement ratios, number of fibers, and concrete strength. Recent finite element models for predicting crack spacing in fiber reinforced concrete composites are evaluated and critically discussed.

3 PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of the work is the numerical analysis of damaged beams reinforced with fiber concrete and the subsequent comparison of the results with the data of experimental studies.

To achieve this goal, it was necessary to perform computer modeling and numerical analysis of damaged beams using the finite element method in two computer programs and to perform a comparative analysis of the obtained results with the results of experimental studies.

4 MATERIALS AND METHODS OF RESEARCH

For computer modeling of damaged beams and determination of their stress-strain state after strengthening, two software packages were used in the work — Robot Structural Analysis [11] and LIRA-SAPR [12].

5 RESEARCH RESULTS

Modeling and calculations were performed for five samples of reinforced beams with variation of the damage zone and its volume. In all calculations, the load was considered in the form of two concentrated forces, the value of $F = 40.3$ kN each, which corresponds to the average bearing capacity of undamaged beams. The forces are applied at a distance of 60 cm from the edge of the beam; the supports are located 5 cm from the edge. Thus, the net bending zone was 80 cm.

The elastic constants that were specified for the calculations were obtained after processing by the methods of mathematical statistics of primary indicators based on the results of tests of prisms and cubes: for fiber concrete: initial modulus of elasticity — $E = 3.6 \cdot 10^4$ MPa; Poisson's ratio — $\mu = 0.22$; for concrete: initial modulus of elasticity — $E = 2.6 \cdot 10^4$ MPa; Poisson's ratio is $\mu = 0.2$.

When modeling in Robot Structural Analysis, two types of finite elements were used — triangular elements with three nodes ($T3$), rectangular elements with four nodes ($Q4$). The size of the element was set to 2x2 cm, the grid was broken automatically. The results of calculations in Robot Structural Analysis are summarized in the Table 1.

In Fig. 1 shows the geometric model of the RCD3 beam sample, in which the compressed zone was damaged and then reinforced with fiber concrete. In Fig. 2, 3 show diagrams of deflections and stresses.

Table 1

Calculation results in Robot Structural Analysis Professional

Sample	Maximum deflection, mm	Maximum stress, *MPa*	
		XX	YY
RCD1	4,07	37,66	20,12
RCD2	4,08	35,26	18,28
RCD3	4,04	35,27	18,28
RCD4	4,05	35,30	17,98
RCD5	3,96	35,20	17,98

Sample RCD3

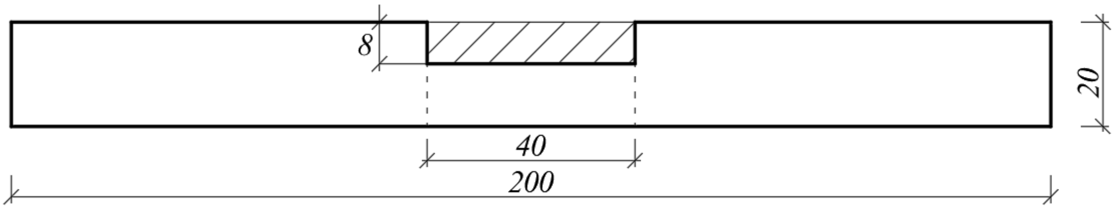

Fig. 1. Geometric model of RCD3 sample

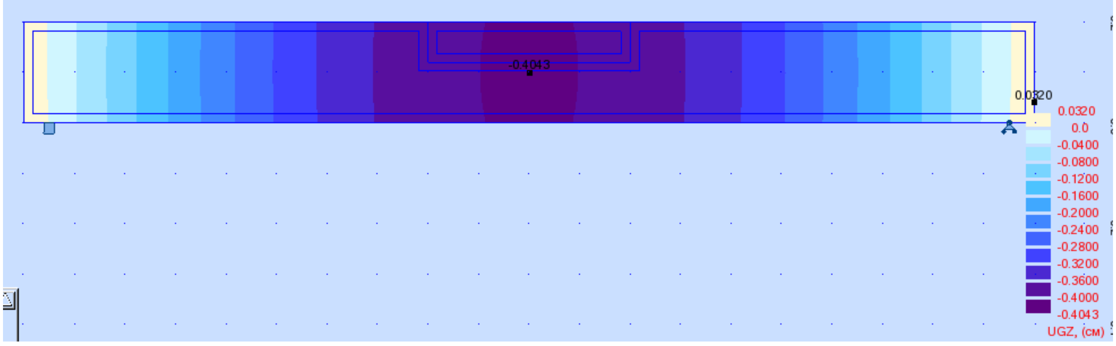

Fig. 2. Deflections of sample RCD3

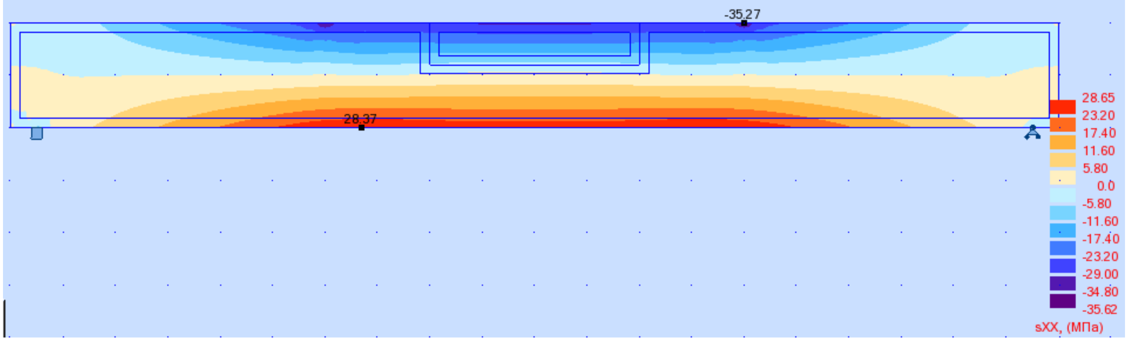

Fig. 3. Stress XX in sample RCD3

In Fig. 4 shows the geometric model of the RCD5 beam sample, in which the stretched zone was damaged and then reinforced with fiber concrete. In Fig. 5, 6 show graphs of stresses and deflections.

Sample RCD5

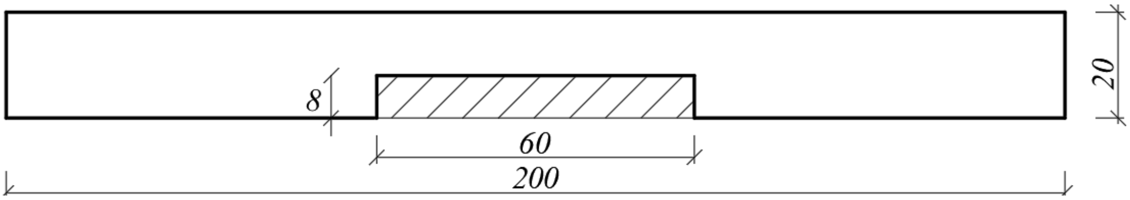

Fig. 4. Geometric model of RCD5 sample

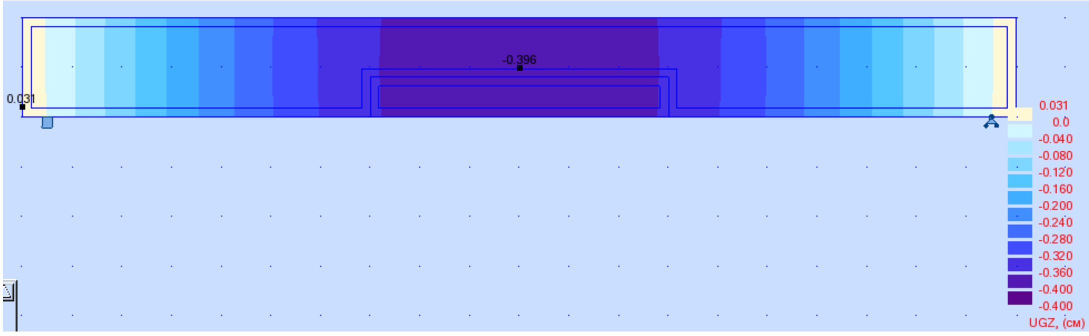

Fig. 5. Deflections of sample RCD5

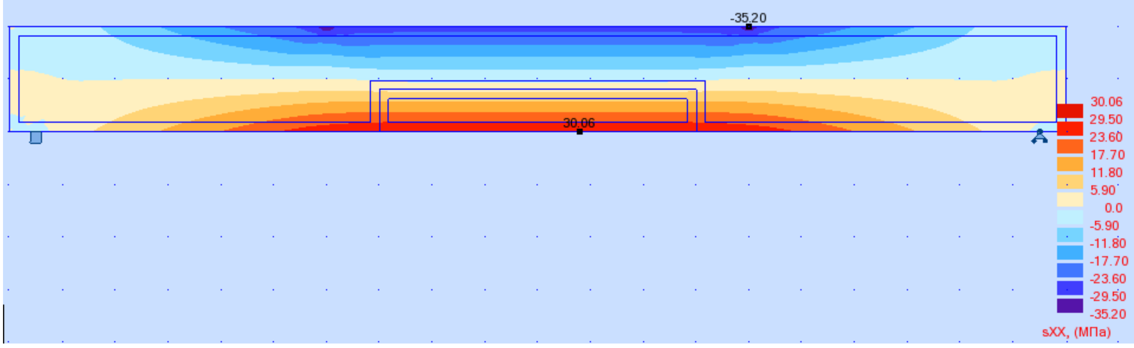

Fig. 6. Stress XX in sample RCD5

Other results of simulation and calculation of damaged beams in the Robot Structural Analysis Professional program look similar.

When calculating the reinforced concrete beam and the fiber concrete element located in it, LIRA-SAPR used finite element types No. 44, No. 42 — plates. A linear type of calculation was used.

The results of the calculations are summarized in the Table 2.

Table 2

Results of calculations in LIRA-SAPR

Sample	Maximum deflection, mm	Maximum stress, *MPa*	
		XX	YY
RCD1	4,09	33,22	32,87
RCD2	4,06	33,22	23,64
RCD3	4,03	33,22	23,65
RCD4	4,03	33,23	23,81
RCD5	3,94	33,12	24,40

In Fig. 7, 8 show curves of deflections and stresses of sample RCD3.

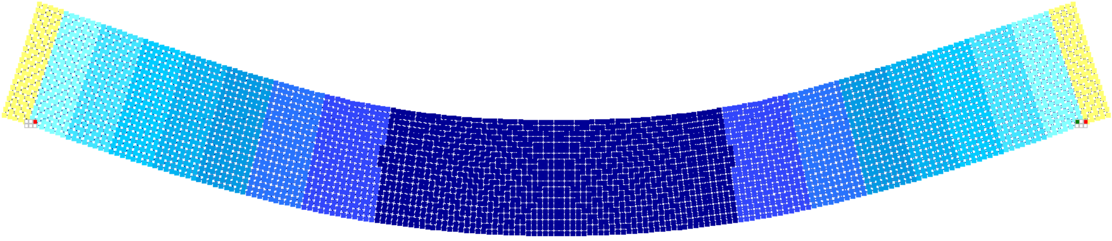

Fig. 7. Deflections of sample RCD3

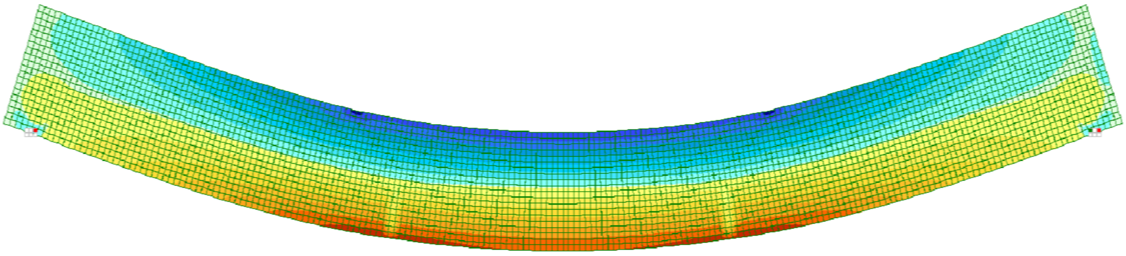

Fig. 8. Stress XX in sample RCD3

In Fig. 9, 10 show curves of deflections and stresses of sample RCD5.

Fig. 9. Deflections of sample RCD5

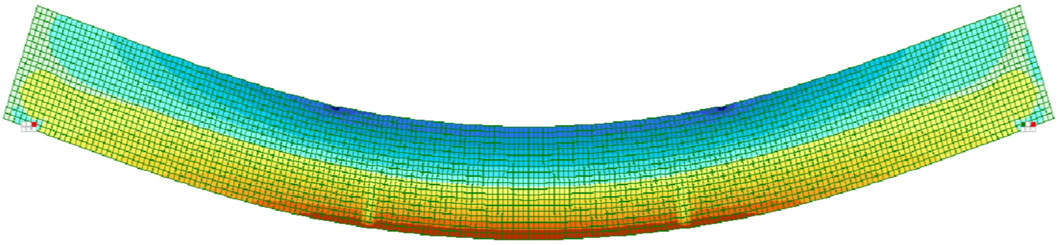

Fig. 10. Stress XX in sample RCD5

Other results of simulation and calculation of damaged beams in the LIRA-SAPR program look similar.

6 DISCUSSION OF RESEARCH FINDINGS

Previously, experimental studies of beams damaged in the stretched or compressed zone, reinforced with steel-reinforced concrete, were carried out. First, the theoretical value of the load-bearing capacity of a reinforced concrete beam without damage was determined using various existing methods, and then its load-bearing capacity was determined experimentally. Based on the results, graphs of the change in deflections under the increasing load, graphs of the dependence of the relative longitudinal deformation on the load for the left and right support parts of the beam, as well as for the zone of its net bending, were constructed for each sample.

At the next stage of research, the bearing capacity of two groups of reinforced beams was determined. The first group consisted of three samples (RCD1, RCD2, RCD3) that had damage to the compressed zone; the second group had two samples with damage in the stretched zone (RCD4, RCD5). In addition to the bearing capacity, deflections and relative longitudinal deformations are determined for each sample.

In the Table 3 shows the maximum deflections and stresses obtained from the results of experimental studies and finite element analysis in two programs.

Table 3

Comparison of experimental results and computer analysis

Sample	Maximum deflection, mm			Maximum stress, *MPa*		
	LIRA-SAPR	Robot	Experiment	LIRA-SAPR	Robot	Experiment
RCD1	4,09	4,07	4,97	33,22	37,66	33,71
RCD2	4,06	4,08	4,98	33,22	35,26	32,18
RCD3	4,03	4,04	4,84	33,22	35,27	31,62
RCD4	4,03	4,05	4,95	33,23	35,30	31,28
RCD5	3,94	3,96	4,76	33,12	35,20	31,76

7 CONCLUSIONS

Thus, computer modeling and finite element calculations of five samples of reinforced beams were carried out in two programs — LIRA-SAPR and Robot Structural Analysis. Obtained values of stresses and deflections. It was established that the deflections obtained as a result of calculations in the two programs are practically the same. And the tensions are somewhat different. The maximum difference in stresses is observed for sample RCD1 — 11.8%. For four other samples, it is approximately the same, and on average it is 5.8%. Comparing the results of calculating the maximum stresses in LIRA-SAPR with the results of experimental studies gives a maximum discrepancy of 5.85% (Sample RCD4). And the biggest discrepancy occurs in the deflections — here it fluctuates in the range of 19.0÷19.2%.

8 ETHICAL DECLARATIONS

The authors have no relevant financial or non-financial interests to report.

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