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Article

Nonlinear calculation of beam reinforcement using the finite element method

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Abstract. The article is devoted to the research of solution of the actual problem in construction, namely increase of ultimate loads of different kinds of constructions and possibility of effective application of innovative methods of reconstruction of beam constructions. In this work 2 kinds of different composite materials have been applied. The project considers the use of carbon fiber as an external reinforcement material for bridge girders. This study analyzes the performance of the reinforced structure under external loads. With the use of computer modeling of the finite element method, an analysis of the selection of reinforcement schemes, which allows to significantly increase the carrying capacity of reinforced concrete beam structures, is performed. Also, some proposals for the implementation of these experiments on real girder structures and constructions were considered. The data obtained as a result of the work allow the conclusion about the successful application of composite materials as reinforcement structures. Correctly chosen scheme of strengthening, confirmed by calculations allows you to significantly increase the carrying capacity of the beam reinforced concrete structures.
Keywords: beam reinforced concrete structures, composite materials, finite element, elastic modulus, the law of nonlinear deformation, mosaic of stresses, stress diagram.

1. Introduction

Currently, due to the growth of population in large cities, the construction of pedestrian and vehicular bridges is justified because of the increase in general traffic and increased traffic jams. But with the high cost of new construction, it is important to make reconstruction of old structures. In near future we will have to reconstruct actively the old highways to be able to pass traffic flows with high intensity, which will increase the load on the artificial structures of the road network. In addition, there is a constant tightening of standards and normative loads at which new bridges should be designed and existing bridges should be reconstructed. Changes in construction standards and increased loads lead to the need reinforcing bridge spans, increasing their bearing capacity. In addition, various defects and damages associated with both external adverse environment and physical deterioration of the structure constantly arise in the bridge structures during operation.

Composite materials based on carbon fibers have the following advantages:

1. The tensile strength is much higher than the reinforcing steel used;
2. Composite materials are easy to prestress;
3. The material can be used for reinforcement of reinforced concrete structures of any type, as due to its plasticity it repeats their design;
4. Composite materials can be used to reinforce structures with any radius of curvature;
5. It is allowed to install the composite material without stopping the exploitation of the construction;
6. The small thickness of the strips of composite material (from 1.5 to 2.0 mm) allows you to install them simultaneously in two directions to increase the carrying capacity of the structure.

This can explain the expansion of the use of composite materials for strengthening the building structures in the world. In this connection it is necessary to create working models of strengthened constructions for further operation and analysis of its elements work.

2. Methods

2.1 Research objectives

Evaluate the change in load-bearing capacity after carbon fiber reinforcement of a typical bending bridge beam. For this you need:

1. Modeling of reinforced concrete T-beam strengthened with composite material in PC Lira-SAPR.
2. Analysis of increase of ultimate allowable load acting on the beam after strengthening.
3. To carry out comparative analysis between different schemes of strengthening.

In the model for calculation in PC LIRA-SAPR the geometrical characteristics of the beam are preserved. The bends of the working reinforcement are also taken into account. The collars are set only on the supporting sections to calculate the strength of cross-sections inclined to the longitudinal axis of the element [1].

T-beam with non-stressed reinforcement, made according to the standard project of Soyuzdorproekt, inv.54022-M shown in the Figure 1 [2-3].

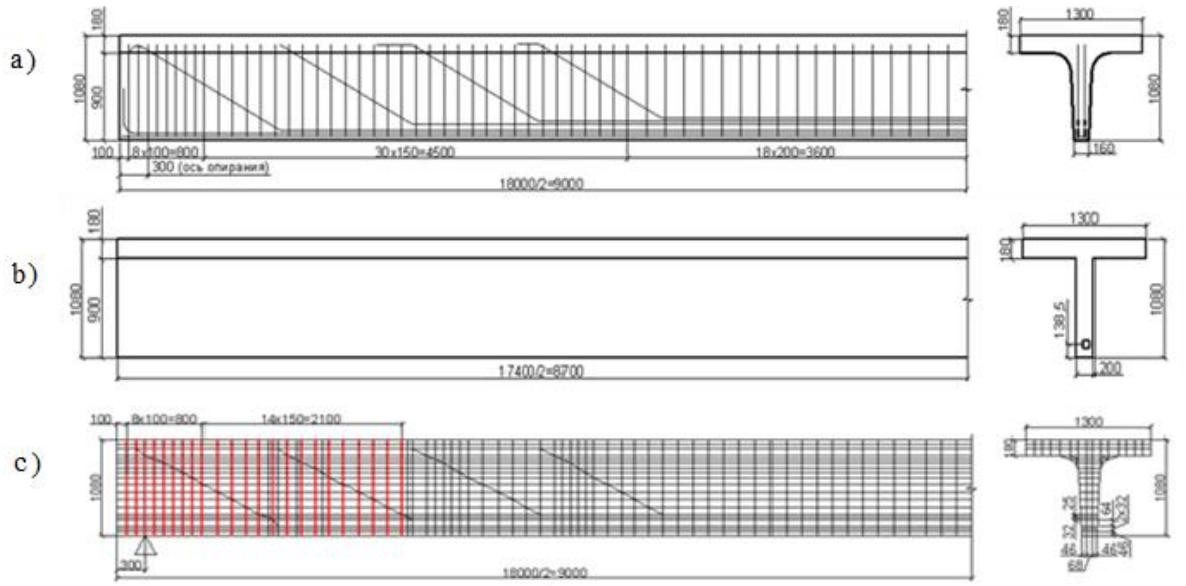


Figure 1 – T-beam with non-stressed reinforcement: a – diagram of a typical beam reinforcement; b – geometric parameters of the beam for manual calculation; c – girder partitioning grid for modeling in SP LIRA-SAPR

2.2 Characteristics of the materials that were used for the calculation

Initial data on the physical and mechanical properties of the materials are shown in the Tables 1 and 2. These data are taken as an average to be used for structural design in construction [4-5].

Table 1 – Accepted characteristics of concrete

Concrete grade by compressive strength	Density (for reinforced concrete structures), ρ, t/m^3 (MPa)	Modulus of elasticity, E_b, t/m^2	Poisson's ratio, v	Design resistance of concrete to compression, R_b, t/m^2 (MPa)	Standard resistance of concrete to compression, R_{bn}, t/m^2 (MPa)	Design resistance of concrete to tension, R_{bt}, t/m^2 (MPa)	Standard tensile strength of concrete, R_{btn}, t/m^2 (MPa)

B27.5	2.5	$3*10^6$	0.2	1458.6 (14.3)	2106.867 (20.656)	107.1 (1.05)	178.5 (1.75)

Table 2 – Accepted reinforcement characteristics

Name	Sectional diameter, d, cm	Sectional area, A, cm^2	Modulus of elasticity, E_s, t/m^2 (MPa)	Calculation resistance of the reinforcement to tension, R_s, t/m^2 (MPa)	Standard tensile strength of the reinforcement, R_{sn}, t/m^2 (MPa)
Working rebar:					
Ø28AIII (A400)	2.8	6.1544	$204*10^5$	35700	40209
Ø16AIII (A400)	1.6	2.0096	$(2,0*10^5)$	(350)	(394.211)
Clamps:					
Ø8AI (A240)	0.8	0.5024	$214.2*10^5$	21420	33821
2xØ8AI (A240)	1.13	1.0048	$(2.1*10^5)$	(210)	(232.105)

2.3 Manual calculation

Calculation of bendable reinforced concrete elements is made according to SP 35.13330.2011 Bridges and pipes. The scheme of forces and the stress diagram in the cross-section normal to the longitudinal axis of an eccentrically compressed concrete element is shown in the following Figure 2 [6].

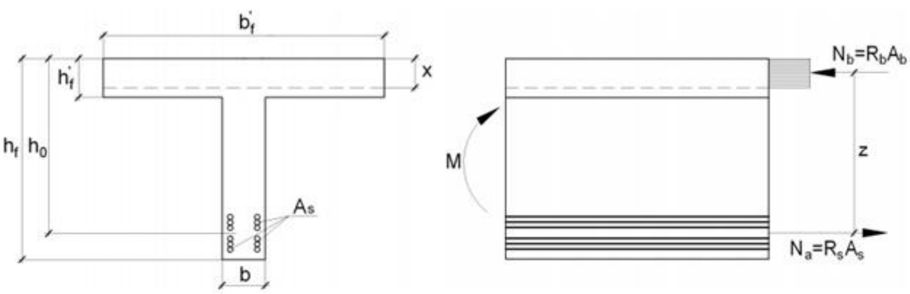


Figure 2 – Geometric section of a T-beam and stress diagram in the section

As a result of manual calculation, we obtain the following values:

The height of the compressed zone of concrete - 12.34 cm The maximum allowable value of bending moment - 205.86 t/m Conditional uniformly distributed load q, under the action of which in the beam the resulting moment occurs - 5.496 t/m (or 4.185 t/m^2 for uniformly distributed over the area of the beam plate load) [7].

2.4 Calculation in SP LIRA-SAPR

The basis of the method of calculation of reinforced concrete structures for bending is based on experimental data accumulated over many years of laboratory research. These data testify to the fact that as the bending moment M increases, the reinforced concrete element under consideration passes through three fundamentally different stages of the stress-strain state [8]. The first stage is characterized by the absence of cracks in the tensile part of the concrete. This corresponds to the level of effective tensile stresses below the ultimate strength R_{bt}. The second stage is characterized by the formation of cracks in the tensile zone of the concrete due to the exceeding of the acting stresses of the value R_{bt}. The formation of cracks leads to redistribution of stresses in the cross-section, the concrete in the tensile zone is gradually disconnected from the work. The moment of appearance of noticeable plastic deformations of the reinforcement is, in its turn, the beginning of the third stage of failure.

Therefore, it is necessary to take into account the physical non-linearity of deformation of reinforced concrete beams shown in the Figure 3 [9-10].

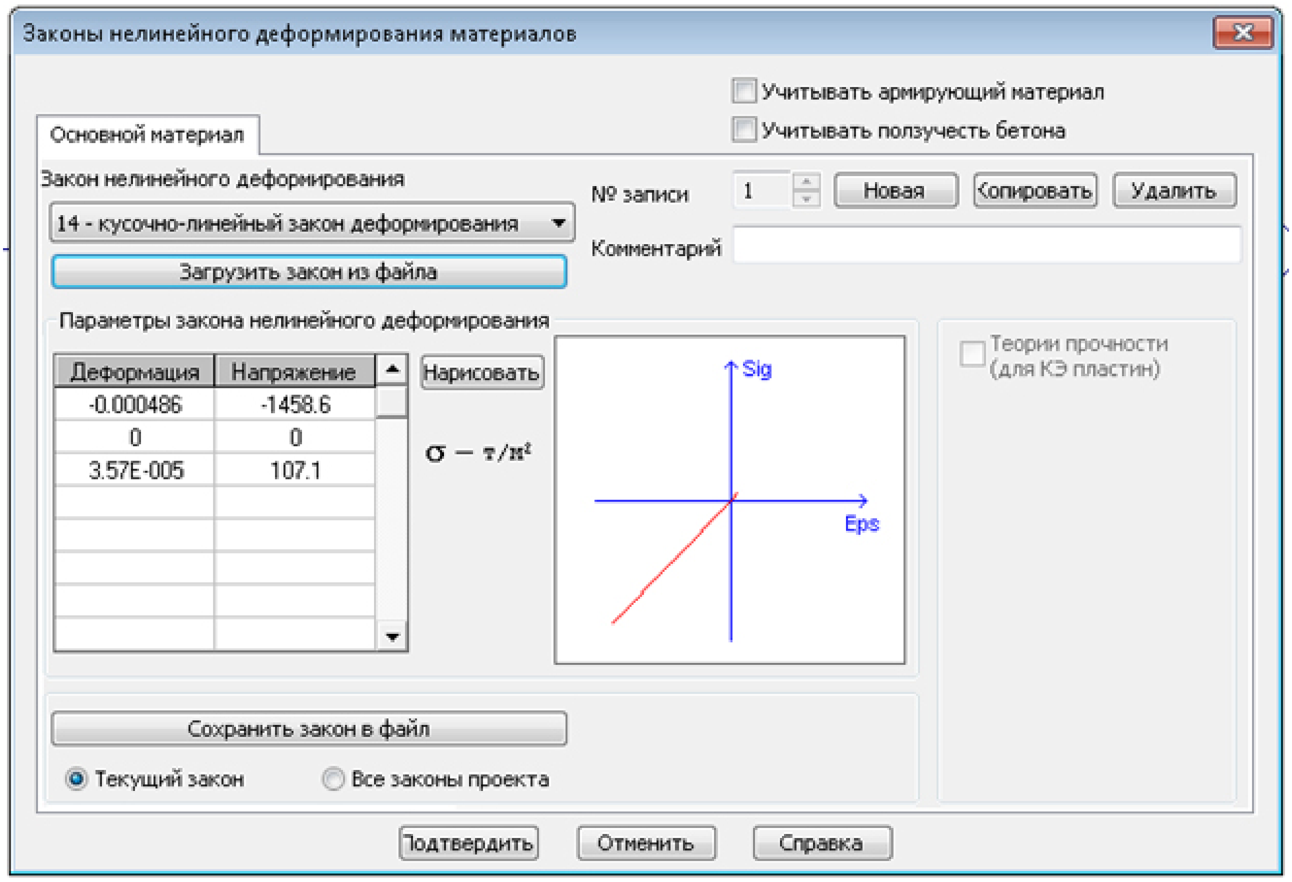


Figure 3 – Consideration of the law of nonlinear deformation of materials in SP LIRA-SAPR

During the calculation, you can immediately observe how the concrete collapses in the tensile zone in the Figure 4.

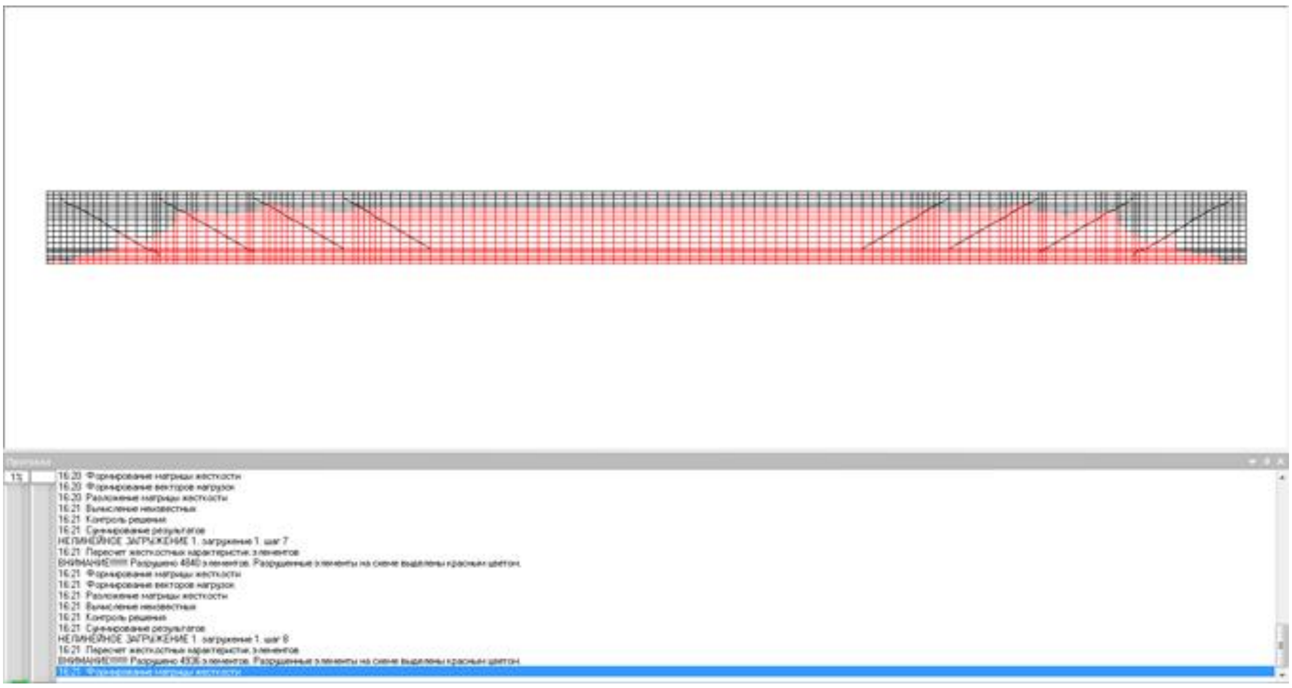


Figure 4 – Calculation process in the program

The mosaic of stresses in the middle of the beam span from the action of conditional uniformly distributed load corresponding to M_{ult} demonstrated in the Figure 5 [11]. The greatest stresses in the working reinforcement: 35625 t/m^2, which almost corresponds to the design tensile strength of the reinforcement Rs=35700 t/m^2.

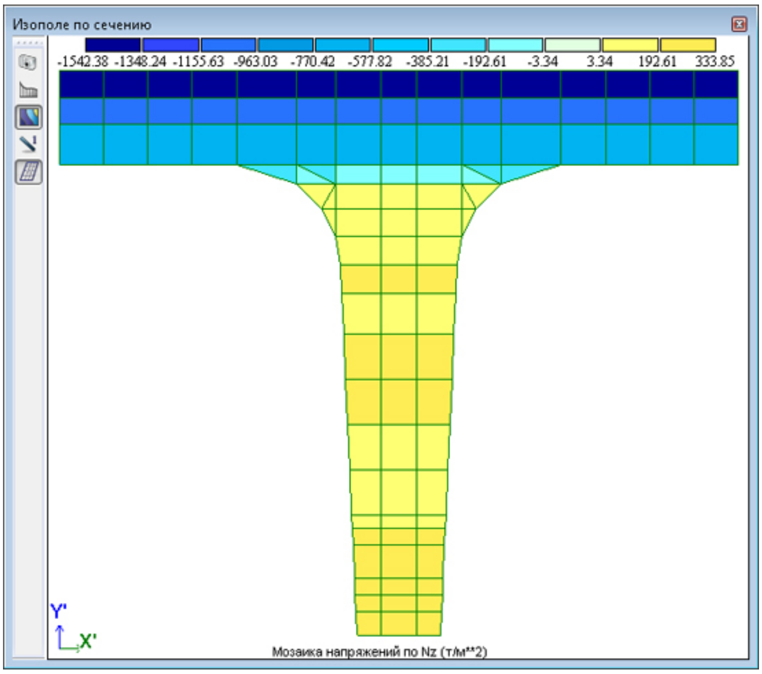
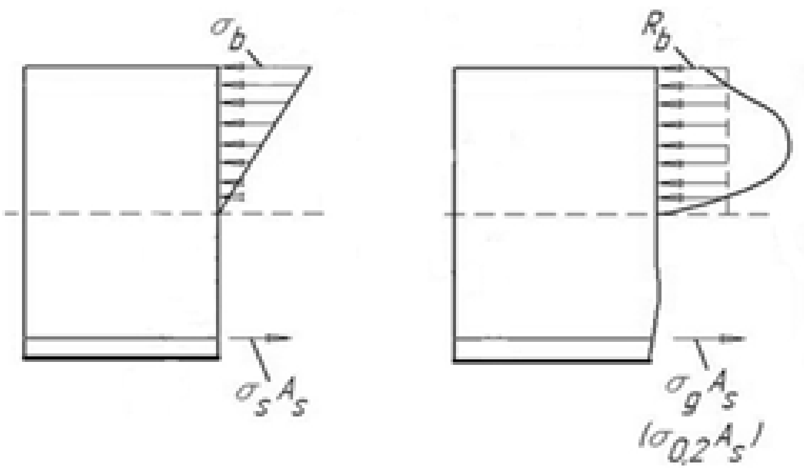


Figure 5 – Stresses in the concrete compression zone

As can be seen, the stresses in the compressed zone of the concrete exceeded the value of the design resistance of concrete to compression. This can be explained as follows. In our calculation, the linear law of deformation was taken, so the stress diagram of the compressed zone of concrete has a triangular form (Figure 6a). In the calculation of destructive forces (manual), the stress diagram has a rectangular outline (Figure 6b) [12-13]. Therefore, we shall take the value of 1542.38 t/m^2 as a destructive stress acting in the compressed zone. In the future, when calculating the reinforced models of the beam, we will rely on this value as the maximum permissible one.



a) b)

Figure 6 – Stress diagram of the compressed zone

2.5 Beam reinforcement with composite materials

Strengthening with MBRACE LAM CF210/2400.120x1.4.100m lamellas (at the bottom of the beam) - scheme 1. Strengthening with MBRACE LAM CF210/2400.120x1.4.100m slats (along the side edges of the beam ribs) - scheme 2. Strengthening with FibARM Tape - 230/300 - scheme 3 (Figure 7).

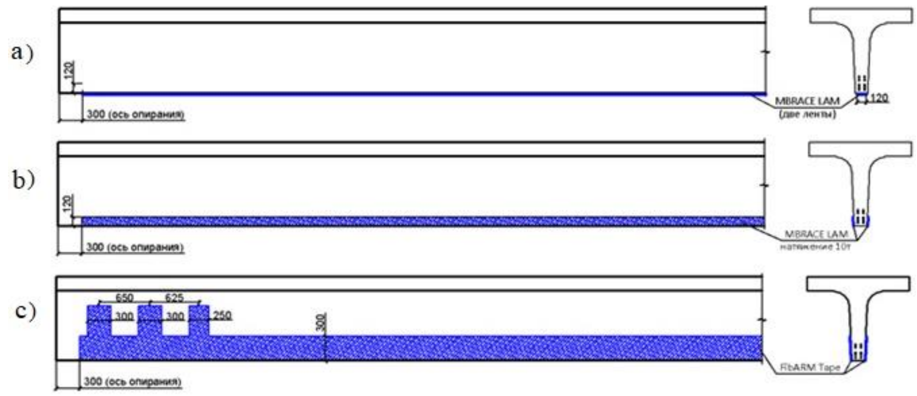


Figure 7 – Beam strengthening with composite materials: a – according to scheme 1; b – according to scheme 2; c – according to scheme 3

The following grades of composite materials were used for strengthening shown in the Table 3.

Table 3 – Characteristics of composite materials

Name	Modulus of elasticity, E_f, t/m^2 (MPa)	Tensile strength, R_f, t/m^2 (MPa)	Thickness, mm	Width, mm
MBRACE LAM CF210/2400.120x1.4.100m (LAMEL)	2,142e^7 (210 000)	244,8e^3 (2400)	1.4	120
FibARM Tape – 230/300 (unidirectional carbon tape)	2.346e^7 (230 000)	438.6e^3 (4300)	0.128	300

3. Results and Discussion

Mosaic of stresses in the middle of the beam span from the action of the load causing maximum allowable stresses in the compressed zone of concrete. Strengthening with MBRACE LAM CF210/2400.120x1.4.100m (at the bottom of the beam rib) (Figure 8).

Maximum stresses in the working reinforcement: 35652 t/m^2 < R_s=35700 t/m^2.

Maximum stresses in lamella: 40072 t/m^2 < 244800 t/m^2.

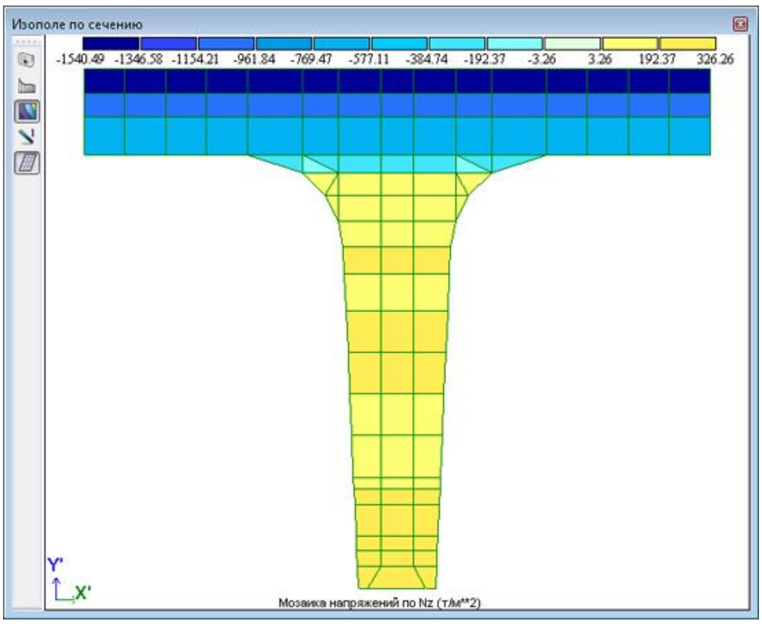


Figure 8 – Mosaic of stresses in the middle of the beam strengthened according to scheme 1

Mosaic of stresses in the middle of the beam span from the action of the load causing maximum allowable stresses in the compressed zone of concrete. Strengthening with MBRACE LAM CF210/2400.120x1.4.100m (along the side edges of the beam ribs) (Figure 9).

Maximum stresses in the working reinforcement: 35415 t/m^2 < R_s=35700 t/m^2.

Maximum stresses in lamella: 98565 t/m^2 < 244800 t/m^2.

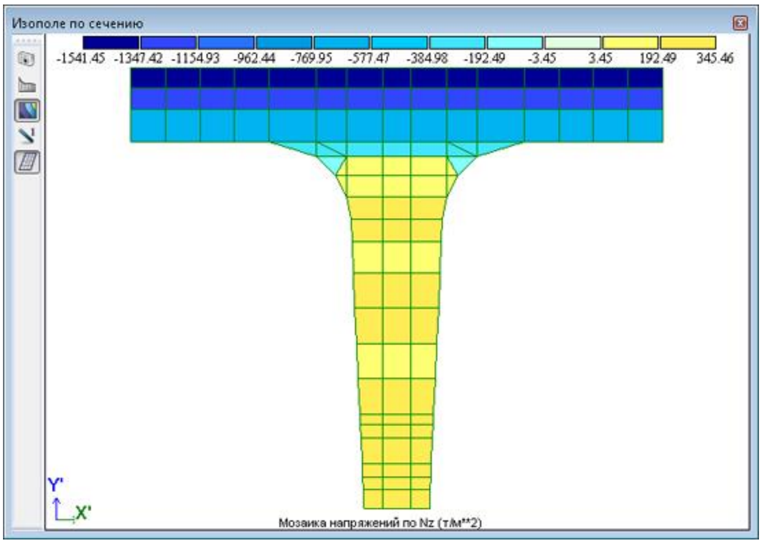


Figure 9 – Mosaic of stresses in the middle of the beam strengthened according to scheme 2

Mosaic of stresses in the middle of the beam span from the action of the load causing maximum allowable stresses in the compressed zone of concrete. Strengthening with FibARM Tape - 230/300 (Figure 10).

Maximum stresses in the working reinforcement: 35455 t/m^2 < R_s=35700 t/m^2.

Maximum stresses in lamella: 42456 t/m^2 < 438600 t/m^2.

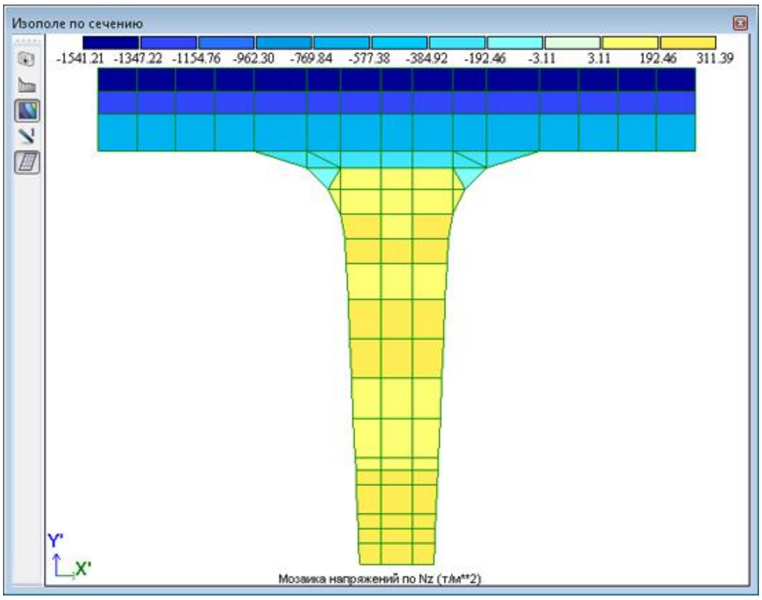


Figure 10 – Mosaic of stresses in the middle of the beam strengthened according to scheme 3

Table 4 below shows the comparative analysis of the results of strengthening.

Table 4 – Comparative analysis of the results of strengthening

Calculation	Load value (t/m^2)	Increment of the maximum allowable load [%]

Regular beam	4.185	0
Strengthening according to scheme 1	4.28	2.3
Strengthening according to scheme 2	4.43	5.9
Strengthening according to scheme 3	4.37	4.4

According to this table, it can be argued that when using composite material to strengthen the beam structure, the maximum permissible load increased in the 1st scheme by 2.3%, in the 2nd scheme by 5.9% and, respectively, in the 3rd scheme by 4.4%. Thus, the maximum increase of 5.9% is observed in the 2nd scheme.

In the article of V.L. Chernyavskiy, P.P. Osmak "Strengthening of Reinforced Concrete and Brick Structures Using Composite Materials" the positive results of application of composite material in the strengthening of beam reinforced concrete, slab reinforced concrete and brick structures are reported. In particular, the data given in the above article are not confirmed by specific calculations and laboratory studies. In general, taking into account the correctness of the approach (direction) of the solution of this particular situation, in my work was extended general scientific approach to the problem in question using various calculations and 3D modeling.

4. Conclusions

The following research objectives were achieved in this paper:

1. The design of reinforced concrete T-beam reinforced with composite material in PC LIRA-SAPR has been simulated.
2. A comparative analysis between different reinforcement schemes has been carried out.
3. The change in the maximum allowable load acting on the beam after the reinforcement has been traced.

The data obtained as a result of the work allow drawing a conclusion about the successful application of composite materials as reinforcement structures. Correctly chosen scheme of reinforcement, confirmed by calculations allows significantly increase the bearing capacity of girder reinforced concrete structures. These conclusions can be recommended for application of the considered composite materials, taking into account increase of limiting loads on structures in various sectors of construction.

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