Stress-strain Analysis of Reinforced Concrete Beam Strengthened with Carbon Fibre

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Abstract. The paper presents results in experimental studies of a reinforced concrete beam strengthened in the upper and lower zones as well as with carbon fibre-based composite material. The authors consider the current practice of using carbon fibre as part of strengthening concrete structures, the current regulatory documents of using carbon fibre in the Russian Federation, regulatory documents containing information on strength and stress-strain properties of carbon fibre. The paper provides information on loading scheme, beam support conditions, the geometry of a reinforced concrete beam, physical properties of concrete and reinforcement of a sample; technical specifications of elements strengthened with carbon fibre. The results are presented by a curve of structural deflection under load in the conditions where the beam is tested without cracks and with cracks before reinforcement, and also with reinforcement. The studies presented in the paper show that the use of carbon fibre as reinforcement of bending structures allows us to increase the bearing capacity, rigidity and crack resistance of bending reinforced concrete elements.

1. Introduction
Today, strengthening of building structures with composite materials is considered to be a ‘gentle’ method for restoring and enhancing performance. The method for the strengthening of reinforced concrete structures by external reinforcement can significantly increase their bearing capacity and crack resistance. It is worth noting that due to the high physical-mechanical characteristics of external strengthening using carbon fibre, the reinforcing elements practically do not increase the weight of structures, and the construction and installation works are not associated with big labour costs and deadlines. However, one of the main problems of using composite materials is the lack of technical guidance and software when designing methods for the strengthening of structures. Structural analysis with carbon fibre as a strengthening element is performed using the current Construction Rule SP 164.1325800.2014 [1]. However, the presented methodology raises a number of questions concerning the modelling and operating peculiarities at all life cycle phases especially concerning the second group of limit states.

2. Materials and Methods
The purpose of this work, with the reference to the carried out studies [2-4], is the efficiency of the carbon fibre strengthening on bending reinforced concrete beams with already existing cracks.
The sample testing includes two stages:

1\textsuperscript{st} stage – testing until cracks open up to 0.4 mm, which can be considered as the failure of the beam without reinforcement.

2\textsuperscript{nd} stage – the test of the strengthened beam till failure.

As a sample, we used the reinforced concrete beam manufactured in a laboratory. It has the following characteristics: beam section - 200×400 mm, concrete grade - B20, reinforcement grade - A500, beam length - 4 m, diameter of tensile reinforcement - 25 mm, diameter of compressive reinforcement - 12 mm. The beam section and its reinforcement are shown in Fig.1. The parameters of the tested beam are presented in table 1.

3. Results and discussions

| Table 1. Parameters of reinforced concrete beam |
|------------------------------------------------|
| Parameter | Design value, mm | Actual value, mm | Deviation, mm | Limit deviation GOST 9561-2016 [5], mm |
| Length | 4000 | 3992 | -8 | ±12 |
| Cross-section width | 200 | 199 | -1 | ±6 |
| Cross-section height | 400 | 398 | -2 | ±5 |
| Depth of concrete cover for bottom reinforcement | 40 | 37 | -3 | ±5 |
| Depth of concrete cover for top reinforcement | 40 | 43 | +3 | ±5 |

Design characteristics of the product: bearing distance of the beam \( L_p = 3700 \) mm; concrete grade: B20. Top reinforcement: 2 Ø 12 A500, which has the following strength and stress-strain properties: \( R_{sc} = 400 \) MPa; \( E_s = 2 \times 10^5 \) MPa. Bottom reinforcement: 2 Ø 25 A500, \( R_s = 435 \) MPa.

![Figure 1. Beam cross-section and reinforcement](image1)

![Figure 2. External beam reinforcement](image2)
The design diagram for testing a bending reinforced concrete beam was adopted as a statically definable hinged simple beam loaded with four concentrated forces applied at a distance, as shown in figure 2.

The structure was loaded in steps. The test points were selected based on the loading conditions - each step did not exceed 10% of the test load when testing strength and stress-strain properties.

Figure 3 shows photographs of the sample, prepared for testing and a pilot plant itself. After reaching the maximum force of 260 kN, the crack opening width is 0.4 mm which is the maximum permissible value. The maximum deflection was 18.81 mm. At that moment the structure is unloaded and the beam is reinforced by carbon fibre tapes FibArm Tape-230/300 with a width of 300 mm for the entire length of the beam in one layer. Technical characteristics of carbon fibre are presented in table 2.

### Table 2. Technical characteristics of carbon fibre

| Parameter                           | Unit of measure | Quantity   |
|-------------------------------------|-----------------|------------|
| Depth                               | mm              | 0.13       |
| Surface density                     | g/m²            | 230±10     |
| Type of warp thread                 |                 | Carbon thread 12K |
| Tension strength                    | GPa             | 4.3        |
| Modulus of elasticity in tension    | GPa             | 245        |
| Elongation at failure               | %               | 1.8        |

![Figure 3. Pilot plant for sample test](image)

a) beam unreinforced carbon fibre; b) carbon fibre reinforced beam
Figure 4. Dependency diagrams of deflection value on load efficiency: 1, 2 – values for carbon fibre reinforced beam; 3, 4 - values for beam without reinforcement

a) b)

Figure 5. Dependency diagrams of deflection on load before and after reinforcement of concrete beam: a) compressive concrete strains; b) tensile reinforcement strains.
Figure 6. Dependency diagrams of crack opening width on load before (blue line) and after (red line) reinforcement of the concrete beam

Figure 7. Reinforced concrete beam after testing
4. Conclusions
The beam failure with external reinforcement elements with FibArm Tape-230/300 carbon fiber ribbons occurred due to the separation of the concrete of the compressed zone and the achievement of the maximum stress value of the concrete of the compressed zone. At the same time, the tensile reinforcement of the lower zone and carbon fiber FibArm Tape-230/300 did not break.

After unloading beam and installing reinforcing elements with FibArm Tape-230/300 carbon fiber ribbons, the ultimate load at failure amounted to 387.6 kN which is significantly higher than the load before reinforcement (260kN). It indicates that external reinforcing elements are effectively commissioned.

The bearing capacity of samples and structures brought to failure and then reinforced is fully restored and may exceed the initial level.

Cracking in the reinforced structure is much slower, which makes it acceptable to reinforce with composite materials not only to increase the limiting effort but also to restore safe operating conditions.

References
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