Reinforcement of concrete structures with external reinforcement system with composite materials

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Abstract. In the article propose two methods of strengthening of concrete beams with carbon fiber. The mechanism of destruction of samples and the maximum breaking stress depending on the method of reinforcement and the density of the carbon fiber are studied. The obtained results indicate the efficiency of the system of external reinforcement of concrete beams with composite materials.

1. Introduction

Reinforced concrete structures are often subjected to severe impulse loads under shock wave, blast wave, and direct impact conditions. Many incidents involving strikes and explosions cause significant structural damage, that leads to huge economic losses, and sometimes to the death of many people.

In the past, significant damage to the structure or structural elements meant that building structures would either be destroyed or completely abandoned, depending on the degree of destruction and how important they are as a social object. At the same time, the idea of reinforcement arose in order to maintain and repair existing structural elements that could be saved in time without completely destroying the structure, thereby saving time and not causing inconvenience to the user [1-4].

The advantage of strengthening concrete structures with an external reinforcement system is that it can be done at a reasonable price and in the shortest possible time, without causing unnecessary obstacles and delays in daily activities. Recently, a large amount of research has been devoted to the development of measures to mitigate damage to buildings and, consequently, to prevent serious injuries to people in the event of an impact and explosion. Over the years, modernization methods have been developed - from impact and explosive reinforcement with the addition of mass using concrete or steel to the use of lighter and more elastic materials, as well as methods for strengthening existing structures of industrial enterprises built in the mid-20th century [5-8]. Traditional methods of modernizing building structures are sometimes difficult to implement and time-consuming. Numerous studies in the field of new building materials show that methods that give plasticity to structures, rather than give strength from adding mass, can be more effective. Methods of reinforcement and modernization of reinforced concrete structures should be able to adapt to various existing conditions, easily transportable and cost-effective, while providing adequate impact and explosion resistance [9-12].

2. Description of samples and providing experiments
15 samples of concrete beams were selected for testing. These samples were made in 2013. When selecting concrete beams, the main emphasis was made on the same strength characteristics. The strength of all samples was determined by ultrasound using the UK-14P device.

Table 1. Results of the ultrasound method.

| Sample number | The length of sounding testing, mm. | The propagation time of the ultrasound in the sample, microsecond | The speed of ultrasound in concrete, m/s | R, MPa |
|---------------|------------------------------------|---------------------------------------------------------------|----------------------------------------|--------|
| 1             | 400                                | 104.1                                                         | 3842.4                                 | 34.2   |
| 2             | 400                                | 105.4                                                         | 3795.1                                 | 33.4   |
| 3             | 400                                | 109                                                           | 3669.7                                 | 31.4   |
| 4             | 400                                | 105.4                                                         | 3795.1                                 | 33.4   |
| 5             | 400                                | 106.4                                                         | 3759.4                                 | 32.9   |
| 6             | 400                                | 106.7                                                         | 3748.8                                 | 32.7   |
| 7             | 400                                | 109.4                                                         | 3656.3                                 | 31.2   |
| 8             | 400                                | 109.3                                                         | 3659.6                                 | 31.3   |
| 9             | 400                                | 106.6                                                         | 3752.3                                 | 32.7   |
| 10            | 400                                | 104.9                                                         | 3813.1                                 | 33.7   |
| 11            | 400                                | 108.9                                                         | 3673.1                                 | 31.5   |
| 12            | 400                                | 107.5                                                         | 3720.9                                 | 32.2   |
| 13            | 400                                | 102.7                                                         | 3894.8                                 | 35.0   |
| 14            | 400                                | 105.3                                                         | 3798.6                                 | 33.5   |
| 15            | 400                                | 106.7                                                         | 3748.8                                 | 32.7   |

The average compressive strength is 32.9 MPa.

To study the failure modes and efficiency of using carbon fiber as an external reinforcement system under static loading, five groups of beams with different reinforcement methods and different characteristics of the carbon fiber were prepared from 15 samples. The first group (control) is represented by two concrete beams. One sample without carbon fiber reinforcement. The second beam is coated with epoxy resin over its entire surface. The second group includes 4 beams with a carbon fiber density of 300 g/m2. Reinforcement is performed on one side in a tensile zone.

The third group consists of 3 beams with a carbon fiber density of 300 g/m2. Reinforcement is performed in a tensile zone with o-wrap at the ends of the samples.
Figure 2. Third group.

The fourth group is 3 beams with a carbon fiber density of 530 g/m2. The reinforcement is made on one side in a tensile zone.

Figure 3. Fourth group.

The fifth group is 3 beams with a carbon fiber density of 530 g/m2. Reinforcement is performed in a tensile zone with o-wrap at the ends of the samples.

Figure 4. Fifth group.
For testing were used a primer and epoxy resin BASF

**Table 2. Characteristics of carbon fiber.**

| carbon fiber          | The tensile strength of fiber, MPa | Elastic modulus of the fiber, GPa | Density, г/м2 | Thickness, mm. |
|-----------------------|-------------------------------------|-----------------------------------|--------------|---------------|
| MasterBraceFib CF 230/4900.300g | 4900                               | 230                               | 300          | 0.166         |
| MasterBraceFib CF 230/4900.530g | 4900                               | 230                               | 530          | 0.293         |

**Table 3. Characteristics of the primer and epoxy resin.**

| epoxy resin    | Compressive strength, MPa | Flexural strength, MPa | The tensile strength, MPa | Adhesive strength to concrete, MPa |
|----------------|---------------------------|------------------------|----------------------------|-----------------------------------|
| MasterBrace P 3500 | 50                        | 40                     | 15                         | 7.5                               |
| MasterBrace 4500  | 60                        | 50                     | 17                         | 7.5                               |

All samples were chamfered using an angle grinder. Additionally, the surface of the samples was treated with a metal brush in order to create a rough surface. The need for this procedure is to improve the adhesion of the carbon fiber to the beam by using an appropriate epoxy resin. It is very important to clean and remove all dust particles after the above procedure for preparing the surface of concrete beams. This is done to prevent dust particles from getting between the epoxy layer and the beam surface.

The next step is applying the MasterBrace P 3500 primer. After preparing the primer mixture, a thin layer of about 0.2 mm thick was applied to each sample evenly on the sides of the beam where the carbon fiber was to be installed. The primer layer must be maintained for 7 days to set the required parameters.

![Figure 5. Primed surface.](image)

After applying the primer, the samples can be used for carbon fiber installation after 7 days. The lower fiber is glued in such a way that the fiber is oriented in the longitudinal direction of the beam. In
turn, the o-wrap should be mounted with the orientation of the fibers in the transverse direction of the beam.

![Figure 6. Gluing the fiber.](image)

The sample is installed on a metal frame with two supports in the test machine (press). The length of the free span of the beam is 300 mm. A frame with two round bars simulating a point load is installed on top of the beam. After the sample is completely ready for testing, the testing machine (press) is started. The lower part of the test press is raised, and the upper metal frame mounted on the sample and the upper part of the press come into contact. After contact, the press switches to the load increase mode of 0.05±0.01 MPa/s. The test is terminated after the sample is destroyed.

![Figure 7. The scheme of sample testing.](image)

The two-point load is transmitted through the load sensor and spherical bars to the beam. After destruction, the sample is removed from the test press for visual inspection. The second group (bottom reinforcement, the fiber density of 300 g/m²)

![Figure 8. The sample after the load.](image)
A beam under load with a shear crack at the support section. As expected, the first cracks appear in the middle of the beam span and extend to the support. The main crack with the opening appeared at the support of the beam, where a point load was applied.

It should be noted that the delamination of the carbon fiber did not occur.

At the initial moment of time, the sample is deformed in the elastic mode, until it reaches the ultimate strength (yield strength). After the ultimate strength is reached, the strain of the sample increases non-linearly, while the applied load increases slightly. The curve is represented by two linear sections (the graph view is bilinear).

The maximum breaking load for the sample was 30.5 kN.

![Image](image_url)

**Figure 9.** Maximum breaking load of sample No. 13.

The remaining samples from the second group have a similar type of destruction. However, the magnitude of the destructive load is different for all samples. This can be explained by the unevenness of the carbon fiber sticker. In cases where the carbon fiber of the sample under lower supports, the destructive load was higher. The results of testing samples of the second group are shown in table 4.

| Sample number | Carbon fiber density, g/m² | Load, kN | $R$, MPa | The time to failure, s |
|---------------|-----------------------------|---------|---------|----------------------|
| 13            | 300                         | 30.5    | 35.01   | 25                   |
| 14            | 300                         | 44.6    | 33.47   | 25                   |
| 2             | 300                         | 42.9    | 33.42   | 25                   |
| 11            | 300                         | 38.6    | 31.46   | 30                   |

The third group (lower reinforcement + o-wrap, fiber density 300 g/m²). The third group includes samples: 3, 5, 8.
Figure 10. Sample № 8 after loading.

Beam No. 8 under load with an shear crack at the support section. Just as in the case of sample 3, the first cracks appear in the middle of the beam span and extend to the support. The main crack with an opening of more than 3 mm appeared in the reinforcing o-wrap. With the growth of the opening of the main crack, there was no abrupt destruction of the sample. In the lower part of the beam, concrete was pushed through in the supporting spot.

There is destruction of the o-wrap fiber and delamination of the lower layer.

At the initial moment of time, the sample is deformed in the elastic range, until it reaches the ultimate strength (yield strength). After the ultimate strength is reached, the deformation of the sample increases non-linearly, while the applied load increases slightly. When the breaking load is reached, the load curve decreases to the level of elastic deformations, after which the load begins to slowly increase to the value of the previously reached maximum value. The maximum breaking load for the sample was 50.3 kN. There is no abrupt destruction of the sample.

Figure 11. Maximum breaking load of sample No. 8.

The results of testing samples of the second group are shown in table 5.

| Sample number | Carbon fiber density, g/m² | Load, kN | R, MPa   | The time to failure, s |
|---------------|---------------------------|----------|----------|-----------------------|
| 5             | 300                       | 51.8     | 32.85037 | No failer             |
Evaluation of the test results of the fourth group (3 beams with a carbon fiber density of 530 g/m²). The third group includes samples: 4, 6, 12.

![Figure 12. Sample № 12.](image)

Beam No. 12 under load with the formation of an shear crack at the support section. The first cracks appear in the middle of the beam span and extend to the support. The main crack with the opening appeared at the support of the beam, where a point load was applied. There was no delamination of the carbon fiber. At the initial moment of time, the sample is deformed in the elastic range, until it reaches the ultimate strength (yield strength). After the ultimate strength is reached, the deformation of the sample increases non-linearly, while the applied load increases slightly. The curve is represented by two linear sections (the graph view is bilinear). The maximum breaking load for the sample was 38.8 kN.

![Figure 13. Maximum breaking load of sample No. 12.](image)

Other samples from the fourth group have a similar type of destruction. However, the magnitude of the destructive load of the samples is different. Just as in the second group, this can be explained by the unevenness of the carbon fiber sticker. In cases where the carbon fiber of the sample under lower supports, the destructive load was higher. Evaluation of the results of the fifth group - 3 beams with a carbon fiber density of 530 g/m². Reinforcement is performed in a stretched zone with o-wrap at the ends of the workpiece (samples 1, 9, 10). Special attention should be paid to the results of group 5 tests. All the samples were not completely destroyed.
Sample No. 10 under load with a shear crack behind the o-wrap fiber. As in all previous cases, the first cracks appear in the middle of the beam span and extend to the support. The main crack with an opening of more than 3 mm. appeared behind the o-wrap fiber. With the growth of the opening of the main crack, there was no abruptly destruction of the sample. In the lower part of the beam, concrete was pushed through in the supporting spots. The sample was severely deformed at the end of the tests.

There is no destruction or delamination of the fiber. At the initial moment of time, the sample is deformed in the elastic range, until it reaches the ultimate strength (yield strength). After the ultimate strength is reached, the deformation of the sample increases non-linearly, while the applied load remains unchanged. The curve is represented by two linear sections (the graph view is bilinear). The first section characterizes elastic properties, the second – horizontal plastic properties. The maximum breaking load for the sample was 43.8 kN. A distinctive feature of the fiber reinforcement system with a density of 530 g/m2 with o-wraps from the similar version with a fiber density of 300 g/m2 is a longer period of operation of the beam. No abruptly destruction of samples is observed.

The results of testing samples of the third group are shown in table 6.

| Sample number | Carbon fiber density, g/m2 | Load, kN | R, MPa     | The time to failure, s |
|---------------|---------------------------|----------|------------|-----------------------|
| 10            | 500                       | 43.8     | 33.71048   | No failer             |
| 9             | 500                       | 45.1     | 32.73752   | No failer             |
| 1             | 500                       | 48       | 34.17934   | No failer             |

At the end of the analysis of the results, the first group (control) should be affected. The first group includes samples 7 and 15. Sample 7 – not covered with primer or epoxy. Sample 15 – covered with a primer and epoxy resin (carbon fiber reinforcement was not performed). The type of the destruction of
the samples is similar. Destruction in the form of a single main crack begins in the center of the beam. The maximum breaking load of the samples differs. The sample without epoxy resin was destroyed at 11.6 kN, while the sample coated with epoxy resin was destroyed at 17.4 kN.

3. Conclusion
Tests have shown that the use of reinforcing tapes made of polymer composites can increase the load-bearing capacity of concrete beam samples by 2.5-4.5 or more times. When using reinforcing o-wraps, the type of the destruction of the concrete beam becomes safer. The destruction of a non-reinforced concrete beam occurs as a result of the rapid propagation of the main crack. When loading a beam reinforced with an external reinforcement system, a gradual accumulation of cracks occurs, which are restrained by the polymer composite and are able to close after the load is remove.

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