Strength and deformability of concrete beams reinforced by non-metallic fiber and composite rebar

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Abstract. Production of durable and high-strength concrete structures with unique properties has always been crucial. Therefore special attention has been paid to non-metallic composite and fiber reinforcement. This article describes the experimental research of strength and deformability of concrete beams with dispersed and core fiber-based reinforcement. As composite reinforcement fiberglass reinforced plastic rods with diameters 6 mm and 10 mm are used. Carbon and basalt fibers are used as dispersed reinforcement. The developed experimental program includes designing and production of flexural structures with different parameters of dispersed fiber and composite rebar reinforcement. The preliminary testing of mechanical properties of these materials has shown their effectiveness. Structures underwent bending testing on a special bench by applying flexural static load up to complete destruction. During the tests vertical displacements were recorded, as well as value of actual load, slippage of rebars in concrete, crack formation. As a result of research were obtained structural failure and crack formation graphs, value of fracture load and maximum displacements of the beams at midspan. Analysis of experimental data showed the effectiveness of using dispersed reinforcement of concrete and the need for prestressing of fiberglass composite rebar.

1. Introduction

Current stage of scientific and technological development raised new requirements for building and construction materials: in addition to strength and deformation properties of the material, particular attention is now paid to the corrosion, electrical, magnetic and radio resistance. These requirements are applied in construction of buildings and structures of the energy, aerospace, medical and road-building industries. In this case, the main structural material is ordinary reinforced concrete which does not meet the above mentioned requirements [1].

One of the ways to solve this problem is to use non-metallic composite rebar as reinforcement of concrete structures. Fiberglass reinforced plastic (FGRP) bars have low specific weight, high strength, corrosion resistance, dielectric properties, magnetic inertness and radio transparency. However, these materials have some disadvantages which severely restrict fields of their application: a relatively high deformability, low fire resistance, the lack of sustainable technology of rebar prestressing. So, the aspects of designing, calculation and application of concrete structures reinforced with non-metallic composite materials are highly relevant [1 - 5].
2. Experimental procedure

Experimental studies have been held to determine flexural strength and deformability of concrete elements reinforced with FGRP bars, as well as reinforced with basalt and carbon fiber. The design of experiment is shown in Figure 1.

![Figure 1. The design of experiment.](image)

The initial data of experimental samples is given in Table 1, where \( \mu_r \) - percentage of rebar reinforcement in cross section of concrete element; \( \mu_f \) - the percentage of disperse reinforcement depending on the weight of the cement.

**Table 1. The initial data of experimental samples.**

| Sample identifier | Number of samples | Specification                  | \( \mu_r \), % | Weight of sample, kg |
|-------------------|-------------------|--------------------------------|----------------|----------------------|
| SR10              | 1                 | Steel bars of mark A400, 2Ø10 mm | 0,897          | 114,7                |
| FRP6              | 1                 | FGRP, 2Ø6 mm                    | 0,302          | 112,7                |
| FRP10             | 1                 | FGRP, 2Ø10 mm                   | 0,827          | 112,6                |
| FRP-BF            | 1                 | FGRP, 4Ø10 mm; Basalt fiber, \( \mu_f = 0,5\% \) | 1,654          | 112,3                |
| FRP-CF            | 1                 | FGRP, 4Ø10 mm; Carbon fiber, \( \mu_f = 0,2\% \) | 1,654          | 112,3                |

2.1. The design of experimental beams

For the purpose of studies flexural elements were designed and made, dimensions and design are given in Figure 2.

2.2. Properties of materials

For samples production fine grained concrete composition with a mobility class P2 and compressive strength with class B30 were used. Portland cement of M500 class was used as a hydraulic binder. Water-cement ratio equals to 0.65 [6].

As the longitudinal rebar reinforcement composite FGRP brand of “MONSTEROD” (HC “Composite”, Moscow, Russia) with an external diameter of 6 mm and 10 mm was used. Fiberglass rods have ribbed surface for bonding with concrete. There were also used reinforcing steel rods of class A400. As the transverse reinforcement reinforcing wire of Bp500 class was used [6].

Preliminary experimental testing of tensile strength and deformability of fiberglass rods showed that the reinforcement has a high tensile strength (up to 1200 MPa), the longitudinal deformation of the rods are in the range from 2 to 3\%, and modulus of elasticity is 35 - 45 GPa. However, these properties depend on the producer company. Specific weight of reinforcement is 1.95 g/cm\(^3\), that allows reduction of the total weight of the structures up to 1.9\% when replacing the steel reinforcement with composite rebar [7].
Basalt and carbon fiber were used as the disperse reinforcement. At first, before production of experimental flexural elements, the study was held to investigate strength and deformability of fiber-reinforced concrete based on basalt and carbon fibers. Further 48 fiber-concrete samples were fabricated and tested. The amount of fiber, chemical additives and production technologies were different.

The studies resulted in the developed production technology of fiber-reinforced concrete mixture that ensures good dispersion of fibers in concrete matrix. Testing of fiber-concrete samples showed that introduction of estimated amount of basalt fibers into concrete mixture enables to increase compressive strength of concrete up to 51.2% and tensile strength up to 28.8%. The introduction of the carbon fibers into concrete allows increasing compressive strength up to 43% and tensile strength up to 18% [8, 9].

2.3. Testing of samples under static load

Figure 3 shows the scheme of installation of devices, the applied load was measured by dynamometer (D), vertical deformations were defined by inductive displacement sensors (S1 - S5). Slippage of rebar into concrete was recorded by dial indicators installed on rebar (I1 - I4).

Experimental investigations of strength and deformability of flexural elements were performed on special bench (Figure. 4). Tests were conducted by static stepwise load according to the scheme of single-span beam jointed with the hinge support, and up to complete destruction of the samples.

Figure 2. The design of the experimental beams:
(a) samples SR10, FRP6, FRP10; (b) samples FRP-BF, FRP-CF.

Figure 3. The scheme of installation of measuring devices.
3. Results
The results of the tests enabled to obtain common crack formation patterns and failure of beams reinforced with steel (Figure 5, b), fiberglass rods Ø6 mm (Figure 5, c) and fiberglass rods Ø10 mm (Figure 5, g). Analysis of cracking and failure schemes showed that disruption of elements went by the cross section, normal to the longitudinal axis with formation of main crack within the area of pure bending. During the tests, the slip in the concrete of steel and fiberglass rods has not been identified.
Figure 5. Beams testing by static load: the test circuit (a); characteristic schemes of cracking and failure constructions SR10 (b), FRP6 (c), FRP10 (d), FRP-BF (e), FRP-CF (f).

The main experimental results are given in Table 2, where: $F_i$ - acting force; $F_{ult}$ - calculated critical force; $F_{max}$ - actual critical force; $M_{max}$ - the ultimate bending moment; $a_{cr,i}$ - the width of the cracks under the current force; $f_i$ - deflection of element in the current force; $f_{max}$ - maximum deflection of the element in the middle of the span [7].

| Sample identifier | $F_i = F_{ult} = 41.3$ kN | $a_{cr,i}$, mm | $f_i$, mm | $F_{max}$, kN | $M_{max}$, kN*m | $f_{max}$, mm |
|-------------------|--------------------------|---------------|----------|---------------|----------------|-------------|
| SR10              | 0,1                      | 7,7           | 61,2     | 15,3          | 12,8           |
| FRP6              | 1,8                      | 37,1          | 64,4     | 16,1          | 64,5           |
| FRP10             | 1,15                     | 31,1          | 67,2     | 16,8          | 52,1           |
| FRP-BF            | 0,25                     | 15,4          | 85,2     | 21,3          | 40,4           |
| FRP-CF            | 0,45                     | 14,4          | 91,2     | 22,8          | 39,2           |

4. Conclusions

It was found out that the replacement of steel rods with FGRP leads to increase in the bearing capacity of concrete beams under static load up to 5 - 10%. At the same time, the deformability of the element increases by 4 - 5 times as compared with a steel reinforced concrete element, but when the load ceases, the elements reinforced with fiberglass rods get the initial geometry of elements. High
deformability of flexural elements reinforced with composite rods may increase bearing capacity and durability of flexural elements subjected to dynamic loads, further research is needed in this area.

Under load $F_1 = F_{ult}$ in beams reinforced with fiberglass rods the deflections and crack width unacceptable by construction codes took place. This indicates the necessity of the prestressing FGRP rebar if it is used in flexural structures.

Application of fiber-reinforced concrete based on basalt and carbon fibers can increase the strength of the compressed zone in a flexible element, thereby increasing the bearing capacity of the construction and increasing stiffness, as well as there is an increase in crack resistance.

Thus, the use of FGRP rebar in flexural structures, including in conjunction with dispersed fiber reinforcement makes it possible to increase bearing capacity of the element and deformability. Probably, glassfiber rebar prestressing will reduce the unacceptable deformation and cracking in flexural elements, but this issue requires further research.

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