The impact of percentage content of basalt fiber-reinforced polymer and steel reinforcement on the strength indicators of experimental beams with hybrid reinforcement

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Abstract. The use of composite reinforcement in the structures subject to bending is limited due to their excessive deformation. One way to overcome this shortcoming is to use hybrid reinforcement where steel and composite reinforcement are used in combination. The effectiveness of this approach has been proven by previous studies. There are no studies on the establishment of the effective ratio between steel and composite elements. This paper presents the results of tests of prototype beams with hybrid reinforcement made of basalt fiber-reinforced polymer (BFRP) and steel. A total of 12 series of samples of beams, three beams in each series, were studied. The percentage of both types of reinforcement was variable; it varied from a ratio of 100% / 0% to 0% / 100% in increments of ≈ 20% (the numerator of the fraction corresponds to the percentage of steel reinforcement, and the denominator – to the percentage of BFRP reinforcement). According to the results of tests of beams by static loading, it was found that the use of hybrid reinforcement allowed to increase the bearing capacity of the samples by 33% – 74%, depending on the percentage of reinforcement in the cross section, compared with the beams of the control series. Based on the nature of breaks and load-bearing capacity, the most optimal ratio of steel and BFRP reinforcement was 60% – 40%. The optimal percentage of cross section reinforcement is 1.07%.

1. Introduction

The use of composite reinforcement in construction practice is increasing worldwide. One of the types of composite reinforcement is the one of basalt fiber-reinforced polymer. The advantages and disadvantages of the latter are widely known [1, 2, 3]. One of the main disadvantages of this type of reinforcement is the reduced modulus of elasticity [2], compared to steel reinforcement. In this case, structures reinforced with basalt fiber-reinforced polymer are more deformable, which does not allow, in certain cases, to ensure compliance of the moving structures to the requirements of the norms [1, 3]. The last remark is especially relevant for structures subject to bending.

At present, there are several areas for overcoming the excessive deformability of concrete structures reinforced with composite reinforcement, which are subject to bending. The latter include: prestressing the reinforcement, increasing the percentage of reinforcement in proportion to decreasing the modulus of elasticity of the reinforcement, hybrid reinforcement of the cross section [4, 5, 6]. The first two methods have their drawbacks. Due to the specifics of composite reinforcement, it is technologically difficult to generate prestress, and the cost of such a structure will be significantly higher than the structure without prestress. Increasing the percentage of reinforcement leads to increased spending of composite reinforcement and increased cost of the structure.

The use of hybrid reinforcement, when the working reinforcement of the cross section is composite and steel at the same time, is a promising method of increasing the stiffness parameters of concrete structures with composite reinforcement. This approach allows you to take full advantage of both
types of reinforcement – the stiffness and fire resistance of steel reinforcement and the high strength and corrosion resistance of composite reinforcement. Studies of experimental samples of beams with hybrid reinforcement indicate its efficiency [7, 8, 9, 10, 11] and the ability to ensure compliance of the mobility of structures with the requirements of the norms. At the same time, there are virtually no studies to determine the effective ratio of steel and composite reinforcement in beams with hybrid reinforcement. In view of the above, the current issue is to determine the impact of changes in the percentage of composite and steel reinforcement on the load-bearing capacity of beams with hybrid reinforcement.

2. Research methodology
This paper is a continuation of the study described in [10, 11, 12]. The latter considered the performance of beams under load reinforced with basalt fiber-reinforced polymer reinforcement (BFRP), steel reinforcement (control series) and with hybrid reinforcement (which had both steel and BFRP reinforcement at the same time). To be able to correctly compare the results, the percentage of reinforcement was assumed to be the same for the beams of all series. According to the test results, it was found that the strength of beams with hybrid reinforcement increased compared to the beams of the control series and was at the level of beams reinforced with BFRP reinforcement [10]. At the same time, deflections and crack opening width decreased, and at 60% of the destructive load level did not exceed the maximum values allowable by the norms, while in beams reinforced exclusively with basalt fiber-reinforced polymer reinforcement they exceeded the limit values by 30… 120% [11, 12].

In order to clarify the impact of changes in the content of basalt fiber-reinforced polymer reinforcement in relation to steel on the performance of beams with hybrid reinforcement, 6 series of beam samples were designed, manufactured and studied.

Reinforcement of cross sections of beam samples of all series (new and previous studies [10, 11, 12]) is shown in Table 1. To be able to compare them with each other and with the results of previous studies, the chosen class of concrete is the same as in [10, 11, 12], and the percentage of reinforcement is as close as possible to a similar figure in the mentioned studies. The percentage of beam reinforcement of new and previous studies was:

- BM, BMD, BB, BBD – 0.95%;
- BMB, BMBD – 0.84%;
- B 6/10, B 10/6 – 0.89%;
- B 8/10, B 10/8 – 1.07%;
- B 6/12, B 12/6 – 1.18%.

The length of all samples was the same – 2000 mm, cross sectional dimensions b x h = 120 x 220 mm. Reinforcement of the beams was performed with a spatial reinforcing frame. Transverse reinforcement is made of reinforcing bars Ø6 A240 with a step of 70 mm in the support zones. The accepted structural reinforcement in the compressed zone is 2Ø6 A240C.

Concreting of experimental beams was carried out in the inventory metal formwork at the reinforced concrete production plant, PJSC “Kryvorizhindustrbud” (Figure 1).
## Table 1. Scheme of reinforcement of cross sections of beams.

| Series no. | Marking of beams | Cross section of beams | Series no. | Marking of beams | Cross section of beams |
|------------|------------------|------------------------|------------|------------------|------------------------|
| 1          | BM-1, BM-2, BM-3 | ![Diagram](image1)     | 4          | BMD-1, BMD-2, BMD-3 | ![Diagram](image2)     |
| 2          | BB-1, BB-2, BB-3 | ![Diagram](image3)     | 5          | BBD-1, BBD-2, BBD-3 | ![Diagram](image4)     |
| 3          | BMB-1, BMB-2, BMB-3 | ![Diagram](image5)     | 6          | BMBD-1, BMBD-2, BMBD-3 | ![Diagram](image6)     |
| 7          | B 6/10-1, B 6/10-2, B 6/10-3 | ![Diagram](image7)     | 8          | B 10/6-1, B 10/6-2, B 10/6-3 | ![Diagram](image8)     |
| 9          | B 8/10-1, B 8/10-2, B 8/10-3 | ![Diagram](image9)     | 10         | B 10/8-1, B 10/8-2, B 10/8-3 | ![Diagram](image10)     |
1 – cross sections of beams used in previous studies [10, 11, 12].
2 – accepted notation: the numerator of the fraction in the notation corresponds to the diameter of the steel reinforcement, and the denominator corresponds to the diameter of the BFRP reinforcement.

To determine the physical and mechanical characteristics of concrete samples, the cube samples with a side of 100 mm and prisms with dimensions of 100x100x400 mm were made.

The tests of beams were carried out according to the scheme of a beam on two hinged supports loaded in the thirds of span. The load was created using a hydraulic press P-125 in steps of 0.1 from the estimated destructive load. Maksymov’s deflectometer was used to measure the deflections; the deformation of the marginal fibers of the faces of the beam was measured using dial test indicators with a scale interval of 0.01 mm; the crack opening width was recorded using a MBP-2 microscope. A general view of the stand used for the testing of beam samples and placement of measuring instruments is shown in Figure 2.
3. Results and discussion
The testing of beams by short-term loads up until breaking began on the 151st day and ended on the 161st day after the production of samples.

The testing of beams was preceded by the study of strength, deformability of concrete and reinforcement. For the convenience of comparison in Table 2 and Table 3, the specified indicators of both concrete and reinforcement of "new" beams and beams of previous researches are given [10].

Table 2. Indicators of strength and deformability of concrete by its types.

| Item no. | Type of concrete | Cube strength, R, MPa | Prism strength, Rb, MPa | Initial modulus of elasticity, Еb·10^-3, MPa | Tensile strength, Rbt, MPa | Boundary deformation during compression, ЕbR·10^-5 |
|----------|------------------|-----------------------|------------------------|---------------------------------------------|---------------------------|---------------------------------------------|
| 28       | Based on the waste material of the ore mining and processing plant | 35.17 | 51.82 | 26.8 | 30.86 | 31.17 | 36.02 | 2.11 | 3.11 | 162 |
| 151      | Quartz sand concrete | 32.09 | 46.13 | 23.86 | 27.49 | 29.72 | 34.7 | 1.93 | 2.77 | 204 |

* – used in the manufacture of samples of beams series BB, BM, BMB.

Table 3. Physical and mechanical characteristics of the reinforcement.

| Reinforcement class | Yield limit, N/mm² | Ultimate tensile strength, N/mm² | Modulus of elasticity, N/mm² | Tensile elongation at break, % |
|---------------------|--------------------|----------------------------------|-----------------------------|-------------------------------|
| A400C (8) steel     | 508                | 622                              | 198·10¹                  | 23.4                           |
| A400C (10) steel    | 519                | 629                              | 200·10¹                  | 21.6                           |
| A400C (12) steel    | 527                | 602                              | 201·10¹                  | 20.6                           |
| A240 (6) steel      | 298                | 373                              | 210·10¹                  | 17.8                           |
| B500 (6) steel (conditional) | 620         | 663                              | 192·10¹                  | 2.12                           |
| BFRP (6)            | -                  | 961                              | 57.3·10¹                 | 2.7                            |
| BFRP (8)            | -                  | 992                              | 59.5·10¹                 | 2.85                           |
| BFRP (10)           | -                  | 953                              | 46.1·10¹                 | 2.9                            |
| BFRP (12)           | -                  | 925                              | 53·10¹                   | 2.9                            |

The nature of breaking of samples with hybrid reinforcement depended on the ratio of the content of steel and BFRP reinforcement. This content for beams of all series amounted to:
- BM, BMD – 100% / 0% [10];
- BB, BBD – 0% / 100% [10];
- BMB, BMBD – 50% / 50% [10];
- B 6/10 – 27% / 73%;
- B 10/6 – 73% / 27%;
- B 8/10 – 39% / 61%;
- B 10/8 – 61% / 39%;
- B 12/6 – 80% / 20%;
- B 6/12 – 20% / 80%.

In the dependences shown above, the numerator of the fraction corresponds to the percentage of steel reinforcement, and the denominator of the percentage – to the percentage of BFRP reinforcement.
The under load performance of beams with hybrid reinforcement can be divided into two stages – before the occurrence of yield in metal reinforcement and after it. The first normal cracks appeared at the load level of 0.2… 0.3 of the destructive one. Up to the level of loads 0.4… 0.5 of the destructive load the beams performed similarly to those reinforced with steel reinforcement – occurred in proportion to the increasing load the development of main cracks and the new cracks located in the middle third of the span occurred. The latter is due to the predominant influence of steel reinforcement. A further increase in load led to the occurrence of the reinforcement yield. At this stage, the main resistance to the load is provided by the basalt fiber-reinforced polymer reinforcement. At the same time the width of opening of existing cracks increases sharply, new ones are formed, deflections grow. This character of performance is typical for beams reinforced with composite reinforcement.

In general, the B 6/10, B 10/6, B 8/10, B 10/8, B 6/12, B 12/6 series beams showed a similar character of performance and destruction. The difference was that, depending on the percentage of steel reinforcement, the moment of crack formation in the beams with the predominant content of steel reinforcement occurred at load levels close to the similar indicator of the control series beams (BM series, see [10]). The width of the crack openings and their number by length was also similar to the beams of the BM series in the B 12/6, B 10/6, B 10/8 series beams, and close to the BB series beams in the B 6/12, B 6/10, B 8/10 series beams (see [12]).

Due to the fact that in the B 6/12, B 6/10 series beams the high-strength B500 cold-drawn reinforcement was used, the absence of a yield plateau in this reinforcement provided stable indicators of the beams’ performance. The latter varied linearly, depending on the applied load. At loads ≈ 0.9 of the destructive load there occurred a break of the steel reinforcement, after which the resistance was continued by the basalt fiber-reinforced polymer reinforcement. Further increase in load led to the emergence of ultimate compressive stresses in the concrete of the compressed zone, followed by its crushing. No break of the basalt fiber-reinforced polymer reinforcement was recorded. In some areas, the fibers of the surface layer of this reinforcement were damaged (Figure 3).

Figure 3. Sample beam series B 12-6-3 after the test. (a) Destroyed beam specimen; (b) destruction of the protective layer of the beam concrete; (c) breakage of part of the fibers of one of the rods used in the basalt fiber reinforced polymer reinforcement.

In B 12/6 series sample beams at a load level of 0.8 of the destructive load and in B 10/6 series samples at a load level of 0.6 of the destructive load, yield deformations occurred within the metal reinforcement. After that, the deformations of the samples increased as a result of which the deformations in the concrete of the compressed zone and stretched basalt fiber-reinforced polymer reinforcement reached the limit values. The destruction of the samples occurred due to the crushing of the concrete of the compressed zone with the simultaneous break of the BFRP reinforcement.

The destruction of the B 8/10, B 10/8 beam samples, as well as in the beams of other series, was caused by the fragmentation of the concrete of the compressed zone. The latter was preceded by the occurrence of the yield effect in steel reinforcement. The destruction of B 8/10 series beams was accompanied by the destruction (delamination) of the surface layer of the BFRP reinforcement fibers.
at loads equal to 0.9 – 0.95 of the destructive load, which led to a rapid increase in deformation and final crushing of the concrete in the compressed zone.

The only series of sample beams with hybrid reinforcement, the test of which was not accompanied by break of steel reinforcement or the occurrence of defects (partial break of fibers, fiber stratification) in BFRP reinforcement were B 10/8 series beams. The latter suggests that the ratio of metal reinforcement to the BFRP reinforcement in the proportion of 61% / 39% (≈ 60% / 40%) allows to perform reinforcement of the cross section that provides the sufficient level of structural reliability – the combined performance of both types of reinforcement at any load level, as well as the predictability of the nature of destruction of the beams due to crushing of the concrete in the compressed zone. The indicators of strength of experimental beams and beams used in previous studies [10], by series, are shown in Table 4.

Table 4. Indicators of strength of test sample beams.

| Item no. | Series of beams | Breaking force, $F_{ui}$, kN | Relative value of strength, $F_{ui}/F_u$ | Percentage of cross section reinforcement, $\mu$, % | The ratio of the content of metal and BFRP reinforcement in cross section, % / % |
|----------|-----------------|-----------------------------|-----------------------------------------|-----------------------------------|---------------------------------|
| 1        | BM$^3$          | 70.22$^1$                   | 1                                       | 0.95                              | 100 / 0                        |
| 2        | BMDD$^3$       | 75.87$^1$                   | 1.08                                    | 0.95                              | 100 / 0                        |
| 3        | BB$^3$          | 100.88                      | 1.43                                    | 0.95                              | 0 / 100                        |
| 4        | BBBD$^3$       | 101.17                      | 1.44                                    | 0.95                              | 0 / 100                        |
| 5        | BMB$^4$        | 96.1 (45.13$^{11}$)        | 1.37                                    | 0.84                              | 50 / 50                        |
| 6        | BMBD$^3$       | 99.24 (49.7$^{11}$)        | 1.41                                    | 0.84                              | 50 / 50                        |
| 7        | B 6/10$^5$     | 96.25                       | 1.37                                    | 0.89                              | 27 / 73                        |
| 8        | B 10/6$^5$     | 93.08 (63.77$^{14}$)       | 1.33                                    | 0.89                              | 73 / 27                        |
| 9        | B 8/10$^5$     | 119.67 (59.17$^{14}$)      | 1.7                                     | 1.07                              | 39 / 61                        |
| 10       | B 10/8         | 112.92 (69.53$^{19}$)      | 1.61                                    | 1.07                              | 61 / 39                        |
| 11       | B 6/12$^5$     | 106.25                      | 1.51                                    | 1.18                              | 20 / 80                        |
| 12       | B 12/6         | 122.05 (101.5$^{11}$)      | 1.74                                    | 1.18                              | 80 / 20                        |

Notes:
1. $F_u$ – breaking force of the BM series beams.
2. $1$ – a force that corresponds to the beginning of the yield of the metal reinforcement.
3. $2$ – high-strength B500 reinforcement B500 used.
4. $3$ – the results of previous studies are given [10].

The data provided in Table 4 show that the replacement of metal reinforcement with BFRP reinforcement and the use of hybrid reinforcement increased the bearing capacity of the beam samples by 33% – 74% (see column 4, Table 4). The nature of destruction of the experimental beams indicates that the samples reinforced using the BFRP reinforcement collapsed due to the crushing of the concrete in the compressed zone. The latter is due to the high tensile strength of the BFRP reinforcement, as a result of which the beams had an overwhelming strength margin in the stretched area, and were “over-reinforced”. That is, the strength of the beams was largely determined by the strength of the concrete in the compressed zone. According to the “traditional” method of beam design, “reinforcement” of the cross section should be avoided in order to save reinforcement materials. At the same time, due to the crumbling nature of breakup of the BFRP reinforcement, a more acceptable option is the destruction by crushing of the concrete in a compressed zone, because it does not occur suddenly, and BFRP reinforcement continues to perform resiliently without allowing the beam to collapse.

Analysis of the data given in columns 3, 5 of Table 4 indicates that, in addition to the strength of the concrete in the compressed zone, the strength of the beam samples was influenced by the percentage of reinforcement. The reinforcement of the stretched zone, when taking the tensile force,
unloads the cross section, increasing the height of the compressed zone, thereby reducing the stress within it. Thus, the smallest increase in strength (33% – 41%) was shown by the BMB, BMBD, B 6/10, B 10/6 series beams with 0.84%, 0.89% percentage of reinforcement. Increase in the percentage of reinforcement has led to increase in strength. The optimal percentage of reinforcement should be considered 1.07%, which corresponded to the B 8/10, B 10/8 series beams. For those beams, the increase in strength was 61% – 70%, which is close to the maximum values.

Further increase in the percentage of reinforcement to 1.18% (B 6/12, B 12/6 series beams) virtually did not increase and, in case of the B 6/12 series, even decreased the value of the breaking force. The latter indicates that for this class of concrete in terms of the compressive strength, the optimal percentage of the BFRP reinforcement, or the combination of BFRP and steel reinforcement, is 1.07%. The latter statement is valid only in terms of strength and requires additional experimental studies in the case of the use of concrete of another class.

4. Conclusions
1. Replacement of steel reinforcement with BFRP reinforcement allows to increase the bearing capacity of beam samples by ≈ 44%.
2. The use of hybrid reinforcement allows to increase the bearing capacity of the beam samples by 33– 74% depending on the percentage of reinforcement of the cross section.
3. The samples of beams reinforced with BFRP reinforcement and beams with hybrid reinforcement are destroyed due to the crushing of the concrete in the compressed zone.
4. The determining factors of strength indicators of the beams reinforced with BFRP reinforcement and beams with hybrid reinforcement are the strength of concrete of the compressed zone and the percentage of reinforcement of the cross section.
5. The optimal percentage of reinforcement of beams with hybrid reinforcement is 1.07%, which allowed to achieve the maximum strength increase – 61–70% compared to the beams with steel reinforcement. The latter statement should be verified by conducting additional experimental tests on sample beams with different classes of concrete for compression.
6. For beams with hybrid reinforcement, from the point of view of reliability, the optimal percentage of the ratio of metal and BFRP reinforcement should be considered 60% / 40%. At this ratio, the joint work of both types of reinforcement took place at all levels of load without its physical destruction. In samples with a different percentage of metal and BFRP reinforcement, the destruction of one or another type of reinforcement at load levels close to destructive.

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