Behavior of Beam with Fiber Reinforcement under Alternating Loads

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Abstract. The use of dispersed reinforcement improves the properties of concrete. Recently, some studies have been conducted to explore the effect of dispersed reinforcement on the behavior of structures under a static load of the same sign or alternating static load when reinforcing with relatively long fibers. The article presents a methodology for experimental study of the behavior of beam elements with dispersed and combined reinforcement under an alternating static load, based on mathematical planning using a specially made frame. The work considers the results of experimental studies of cubes and prisms on a static load and compression. It also presents the results of an experimental study of the behavior of beam structures with dispersed and combined reinforcement with relatively short fibers under low-cycle alternating static action. The behavior of fiber-reinforced concrete and reinforced concrete beam elements under similar influences are compared. The presented results of the experimental studies allow us to show a significant effect of dispersed reinforcement with relatively short fibers on the behavior of beam structures with alternating low-cycle static loads and the feasibility of combined reinforcement of structures operating under such loads. The use of dispersed reinforcement with relatively short fibers in combined reinforced beam structures operating under alternating loads will increase crack resistance, and with a certain percentage of reinforcement, the strength of such structures. Moreover, the use of relatively short fibers will significantly reduce the complexity of manufacturing such structures.

1. Introduction
A sufficiently large number of flexural structures can be subjected to low-cycle alternating action during operation. The most characteristic is the seismic impact. The search for efficient and economical earthquake-resistant structures is constantly underway [1]. Under such an impact, the behavior of the material of the structure is qualitatively different from the behavior of the material under the influence of the same sign. Therefore, the urgent task is to choose the most effective material for such an impact.

At present, dispersed reinforced concrete is being studied quite actively, with the aim of using it as a structural material. Research is being conducted both in Russia and abroad [2,3,4,5]. As the material of dispersed reinforcement, steel is most often used. Such concrete was called steel fiber concrete. It has
increased strength characteristics in comparison with ordinary concrete. An extensive analysis of the research is presented in [6].

In addition to studying the properties of disperse-reinforced concrete, research is being conducted to study the behavior of flexural beam structures made of steel fiber concrete and with combined reinforcement under various influences [7,8,9,10,11,12,13,14,15,16,17,18], including cyclic and alternating ones. Despite the significant amount of research, most of them are associated with loads of the same sign. Studies on alternating loads differ in the size of the beams, the type of fibers, their characteristics, reinforcement parameters, and experimental conditions.

This study is a supplement to [19] with the aim of experimentally clarifying the behavior of flexural steel fiber concrete and combined reinforced beam elements with relatively short fibers under alternating low-cycle loads.

2. Experimental samples

We made 5 series of beams, 3 beams in each series. The beams of series 1 are reinforced concrete with traditional reinforcement.

In series 2, the beams had combined reinforcement longitudinal rod reinforcement (4 rods of Ø 6 mm) and fiber (1%). In series 3, the beams had combined reinforcement, longitudinal rod reinforcement of the compressed and stretched zones (4 rods of Ø 6 mm) and fiber (2%).

In series 4 and 5, the beams had only fiber reinforcement of 2% and 1%, respectively, and symbolically are not shown. The data on the quantity of reinforcement in the beams are given in table 1.

| Series number | Sample code       | Longitudinal reinforcement (symmetrical), % | Fiber reinforcement, % | Total quantity of reinforcement, kg |
|---------------|-------------------|--------------------------------------------|--------------------------|------------------------------------|
| 1             | B-R-S-1; B-R-S-2; B-R-S-3 | 1.5                                        | -                        | 2.5                                |
| 2             | B-FR-S-1-1.0; B-FR-S-2-1.0; B-FR-S-3-1.0 | 1.5                                        | 1.0                      | 2.7                                |
| 3             | B-FR-S-1-2.0; B-FR-S-2-2.0; B-FR-S-3-2.0 | 1.5                                        | 2.0                      | 3.9                                |
| 4             | B-F-S-1-2.0; B-F-S-2-2.0; B-F-S-3-2.0 | -                                          | 2.0                      | 2.4                                |
| 5             | B-F-S-1-1.0; B-F-S-2-1.0; B-F-S-3-1.0 | -                                          | 1.0                      | 1.2                                |

We took the following designations in the table: B - beam; R - reinforced concrete; FR - fiber reinforced concrete; F - fiber concrete; S - statics; 1.2.3 - no. of samples; 1.0; 1.5; 2.0 - percent of volume fiber reinforcement.

In the experimental studies, we used relatively short metal fibers with a length of 36 mm and a diameter of 0.8 mm, made on a special machine from the wire. The fibers had a profiled surface to improve adhesion to the concrete matrix.

We selected the geometric parameters of the fibers based on the sizes of the experimental samples and they are consistent with the recommendations of Committee 544 [20]. In particular, the ratio of the length to the diameter of the fibers in the range from 20 to 100 is recommended, as well as the production of fibers by cutting the wire having a diameter of 0.25 - 1.00 mm. The use of fibers of such sizes made it easy enough to introduce them into the concrete mix. Moreover, they are evenly distributed in the finished structure.
We designed the prototype beams with a span of 1500 mm, with a total length of 1650 mm. For the manufacture of the samples, we used a fine-grained concrete mixture with the composition C:S=1:2.5. We used Portland cement M400 as a binder. The ratio W/C was 0.45. We removed the forms after 72 hours on the condition of shape preservation. Then the samples were kept under normal conditions of hardening. We tested the samples at the age of 30 days.

3. Test procedure
We tested all the beams under a load applied in thirds of the span with the formation of a clean bend zone. Such a loading scheme gives a smaller dispersion of results than with a concentrated load applied at the center of the span.

To conduct experimental studies on static loading and the subsequent unloading of reinforced concrete beams according to the designated test scheme, we designed and manufactured a rigid power frame. To exclude the influence of the bending moment from the beam’s own mass, as well as the mass of the equipment, we loaded the test beam in a horizontal plane. The test scheme of the beam with the measuring instruments is shown in Fig. 1.

To exclude the influence of systematic errors caused by external conditions, we used the randomization method to implement the experiment planning matrix. We carried out the test by step loading using a hydraulic jack. We chose the loading step based on the predicted strength of the samples, we took it equal to 0.375 kN.

We loaded the beam in a horizontal plane until plastic deformations of a certain value appeared (corresponding to approximately two elastic deflections), after which we unloaded the beam and loaded on the other side until plastic deformations of the same magnitude appeared. We subjected the beams to two alternating loading cycles.

![Figure 1. Beam test setup:](image)

1 – the sensor measuring the deflection of the beam in the span, 2 – the sensor measuring the displacement of the beam on the support, 3 - the place of attachment of the frame to the load bearing floor, 4 – the specially made rigid frame, 5 – the beam support, 6 – the beam fixing mechanism, 7 – the hydraulic pump, 8 – the jack, 9 – the traverse for transferring the load to the beam, 10 – the bracket for securing the cord.

At each step, the exposure of the load lasted 5...7 minutes. This time is necessary for taking readings and visual inspection of the beams. We loaded the beams with a hydraulic jack DG25 with a piston diameter of 100 mm. We measured the pressure in the hydraulic jack by gauges with a tubular spring. To measure the deflections of the beam in the span, we used the deflection meters of the Aistov PAO6...
system with a division value of 0.01 mm. We took the instrument readings after applying the load and at the end of the exposure at each step. We recorded cracks and their nature after the examination. To observe the formation and opening of the cracks, we wetted the surface of the beams with acetone. We measured the deformations of the tensile reinforcement using strain gauges glued to the reinforcement before concreting samples.

4. Results and discussions
To determine the strength characteristics of concrete and fiber concrete, we made cube samples with dimensions 150x150x150 mm and prism samples with dimensions 100x100x400 mm. According to the test results, the average breaking load of cubes was: for concrete - 707 kN, for fiber concrete (1%) - 735 kN, for fiber concrete (1.5%) - 740 kN, for fiber concrete (2%) - 745 kN.

The average breaking load of the prisms was: for concrete - 262 kN, for fiber concrete (1%) - 279 kN, for fiber concrete (1.5%) - 284 kN, for fiber (2%) - 289 kN. All the prisms with dispersed reinforcement broke viscously, in contrast to the brittle fracture of the concrete prisms.

The test results of the beams are presented in table 2. We took the following designations in the table: $M_{T1}$, $M_{T2}$, $M_{T3}$, $M_{T4}$ - average yielding moments in the corresponding loading half-cycles, $M_{T1p}$, $M_{T2p}$ - average moments corresponding to the appearance of cracks in the first and second half-cycles of loading.

Testing of purely fiber concrete beams showed that fiber reinforcement cannot completely replace longitudinal reinforcement. It should be noted that during alternating loading, fiber concrete beams bear the limit moment, not much greater than the moment of crack formation, and sometimes, immediately after the formation of visible cracks in the beam, deformations begin to grow rapidly. The moment corresponding to the rapid increase in the deflection of fiber concrete beams can be arbitrarily called the “yielding moment”.

| Series number | Beam code   | $M_{T1}$, kN | $M_{T1p}$, kN-m | $M_{T2}$, kN | $M_{T2p}$, kN-m | $M_{T3}$, kN | $M_{T4}$, kN-m |
|---------------|-------------|--------------|-----------------|--------------|-----------------|--------------|----------------|
| 1             | B-R (S1, S2, S3) | 2.33         | 1.1             | 1.79         | 0.82            | 1.65        | 1.45           |
| 2             | B-FR-1.0 (S1, S2, S3) | 2.75         | 1.64           | 2.2          | 1.64            | 1.92        | 1.8            |
| 3             | B-FR-1.5 (S1, S2, S3) | 2.2          | 1.4            | 1.92         | 1.1             | 1.65        | 1.4            |
| 4             | B-FR-2.0 (S1, S2, S3) | 4.12         | 2.2            | 3.3          | 1.92            | 2.75        | 2.5            |
| 5             | B-F-2.0 (S1, S2, S3) | 1.1          | 1.1            | 0.82         | 0.82            | 0.55        | 0.55           |
| 6             | B-F-1.0 (S1, S2, S3) | 0.82         | 0.82           | 0.55         | 0.55            | 0.34        | 0.34           |

More through cracks formed in the beams of series 1. This was due to the retention of residual tensile deformations and open cracks after the first half-cycle of the beam deformation. Therefore, with a change in the sign of deformation, cracks formed faster in a new tensile zone and developed through. As a criterion for crack formation, we took the load of the appearance of a surface visible crack. Such cracks were detected upon evaporation of acetone from the surface of the samples.

The fiber-reinforced concrete beams had greater crack resistance than reinforced concrete ones. The load, during which visible cracks appeared in the beam of the 2nd, 3rd series in the first half-cycle of loading, was respectively 49%, 100% higher than in the reinforced concrete beams.

Observations of the process of crack formation in the second loading half-cycle showed that cracks in the reinforced concrete beams, as a rule, form in the same sections as in the first half-cycle. In fiber-reinforced concrete beams, in many cases, cracks formed in new places, which prevented the formation of through cracks. In addition, in the fiber-reinforced concrete beams in the center of the cross section of the beam, there remained a part of the section in which the fibers worked elastically. This part of the section did not allow a through crack with a large opening to form even when a crack was formed in the second loading half-cycle in the same section as in the first half-cycle.
At the second loading half-cycle, the increase in crack formation load was 100% and 130% compared with the reinforced concrete beams. In fiber-reinforced concrete beams, cracks in the first half-cycle of deformation were distributed more evenly along the length and had a smaller opening, which increased their crack resistance in the second half-cycle of deformation.

In the fiber concrete beams, the moment of cracking almost coincided with the moment of yield and clearly depended on the percentage of fiber reinforcement.

Based on the test results, we built generalized moment-curvature relationships, shown in Fig. 2, 3. To compare the strength, we took the results of tests of the beams of series 1 (Fig. 2a). The beams of series 1, 2 had almost the same amount of metal reinforcement. Replacing the crosscut reinforcement with fibers in the beams of series 1 in the same amount did not reduce the strength of the beams. The beams of series 2 had an increased strength by 18% in the first half-cycle and by 23% in the second half-cycle.

Figure 2. The moment-curvature graph:

- a – the beams of series 1,
- b – the beams of series 2.

An increase in the quantity of metal reinforcement in beams of series 3 (Fig. 3) relative to series 1 led to a significant increase in the structural strength - by 76.8% in the first half-cycle and by 84.4% in the second, which in turn can reduce the thickness of the structures if necessary.

Figure 3. The moment-curvature graph for series 3 beams.
After the first loading cycle, through cracks formed in the reinforced concrete beams and the concrete stopped bearing the load both in the tensile and in the compressed zones. In the fiber-reinforced concrete beams of series 2, a smaller amount of through cracks appeared after the second loading cycle.

No through cracks were formed in the beams of series 3 (they formed in different sections). Therefore, the series 3 beams had an increased strength with respect to the series 1 beams in the third and fourth loading half-cycles, respectively, by 66.7% and 72.4%.

We can see from the same graphs that with each loading half-cycle in the beams of the 1st series, the decrease in stiffness occurs more intensively than in the beams of series 2 and 3.

5. Conclusions

We specified experimentally the behavior of flexible steel-fiber concrete and combined reinforced flexible beam elements with relatively short fibers under an alternating low-cycle load.

Steel fibers cannot be considered as a direct replacement for longitudinal reinforcement in reinforced concrete structures. In the structures where the direction of the main tensile stresses is known, it is advisable to use combined reinforcement, leaving full or partial longitudinal reinforcement.

The presence of fibers in concrete structures increases the crack resistance of the structure. That is, the number of cracks formed after testing in the beams with combined reinforcement was greater, and the opening width was less. This is especially evident when changing the sign of loading. This increase is most likely due to the fact that the fibers distributed throughout the concrete volume prevent cracks on the surface of the beams.

Purely fiber-reinforced concrete beams showed the lowest strength values. Therefore, for flexible beam elements with only fiber reinforcement, relatively short fibers are less effective than long fibers and their effectiveness strongly depends on the uniformity of distribution [21-24] in the structure.

Replacing of the transverse reinforcement by fibers does not reduce their strength, and a slight increase in the consumption of fiber reinforcement leads to a significant increase in strength.

In the reinforced concrete beams after the first loading cycle, a through crack is formed and the concrete stops bearing the load. After the formation of cracks in the fiber-reinforced concrete beams, the fiber concrete continues to bear part of the tensile forces, therefore, these beams in the second loading cycle withstand a greater load than the reinforced concrete ones.

In general, the tests showed the promising advantages in using fiber reinforcement with relatively short fibers in fiber reinforced concrete structures subjected to alternating loading, taking into account the reduction in the complexity of manufacturing.

6. References

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