Results of experimental research of deformability and crack-resistance of two span continuous reinforced concrete beams with combined reinforcement

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Abstract. The article presents the analysis of deformability of the continuous reinforced concrete beams under single load. The authors conducted experimental studies of two-span reinforced concrete beams in which classical rebar frames and dispersed reinforcement of concrete with steel fibers were combined. To investigate and compare the effect of such reinforcement on the stress-strain state of the beams, test specimens were made with three different variants of the steel fiber volume distribution, but with the same relative percentage of reinforcement. During the study, the redistribution of effort in beams, maximum deflections in spans, the formation and development of cracks were recorded. The new experimental data were obtained in the course of the research, based on which it can be concluded that the use of additional disperse reinforcement with steel fibers in the stretched zones of continuous reinforced concrete beams allows to increase the flexural stiffness of the elements, their cracking strength, and durability.

1. Introduction

Static indeterminate reinforced concrete structures, mainly continuous, multi-span beams are widely used in modern construction. In particular, they are components of the structures of industrial and civil buildings, overpasses, bridge structures. The choice of continuous load-bearing elements is due to the peculiarities of their work, manufacturing technology, which is manifested in the most rational use of constituent materials, concrete and reinforcement.

When designing and manufacturing reinforced concrete structures, it is relevant to use dispersed reinforcement – steel fibers, as well as combined reinforcement (the combination of classical reinforcement with dispersed one). A significant advantage of this composite material – steel fibrous reinforced concrete (SFRC) is its high specific strength per unit mass. The components of the material, as a rule, have less low tensile and deformative properties than the final product of composite. Accordingly, concrete is much worse than steel for tensile, and their composition – steel fiber has a tensile strength 3–3.5 times higher than unreinforced concrete. Steel fiber-reinforced concrete is better resistant to the emergence and development of micro and macro cracks, more resistant to vibration and shock, and has the increased abrasion resistance, higher viscosity and elasticity, [1–4]. Combining rigid (and therefore high-strength reserves) fibers with matrix (concrete) allows to localize the dangers
associated with brittle matrix failure and thus actualize the basic properties of fiber – high potential tensile strength and increased modulus of rigidity. Efficiency of application of SFRC in building structures can be achieved by reducing labor costs for reinforcement work, combining technological operations for the preparation, reinforcement, laying and sealing of SFRC mixture, prolonging the life of structures and reducing the cost of various types of ongoing repair works [5,6].

It should be noted that the effect of the dispersed reinforcement on the stress-strain state, deflections, crack strength of statically indeterminate structures is poorly understood, [7,8] so the results of the experimental studies considered in the article are relevant at the present time.

2. Methodology of research
To determine the effect of the steel fiber reinforcement of concrete continuous beams on their deformation characteristics, three test specimens were tested. They were continuous two span reinforced concrete beams with a length of 300 cm with a cross-section size of 10 × 16 cm and with spans of 140 cm (Figure 1).

The composition of the cement-sand matrix was adopted as 1:2 [9]. Used M500 Portland cement, and previously filtered from clay, dust and silt impurities sand, with a modulus of size – 2.4. Simultaneously with the beams manufacturing, the cubes of size 15×15×15 cm and the 15×15×60 cm and 10×10×60 cm prisms were being concreted, which were used to determine the cubic and prism strength of concrete and its deformation characteristics. Mechanical characteristics of the cement-sand matrix are provided in table 1.

Table 1. Cement-sand matrix properties.

| Property                        | Value  |
|--------------------------------|--------|
| Compressive cubic strength $f_c$, MPa | 33.0   |
| Compressive prism strength $f_{ck,prism}$, MPa | 22.6   |
| Tensile strength $f_{ct}$, MPa    | 0.5    |

The main reinforcement was made in the form of two flat rebar frames, with the primary reinforcement in spans and over the support with Ø10 mm bars (selected with allowance for the redistribution of effort) and transverse reinforcement with Ø4 mm steel bars, which were arranged between the middle support and the point of application of loading in increments of 40 mm, and between the edge support and the place of application of force in 80 mm increments (Figure 1).
The additional, dispersed reinforcement of the test specimens was performed by using steel fibers, in a such way, that the specimens had different filling by the fibers volume of the beam, but with the same relative percentage of reinforcement, equal to \( \mu = 1\% \) [10]. Thus, the beam B-1 was reinforced with fiber throughout its volume, B-2 – in stretched zones, B-3 – to the height of the two minimum concrete cover zones (Figure 2). Crimped shape steel fibers, 50 mm in length and 1 mm in diameter were used. The compressive cubic strength of the SFRC was only 3% bigger than the cement-sand matrix but tensile was 340% bigger than the tensile strength of the cement-sand matrix. Characteristics of the steel fibrous-reinforced concrete are provided in table 2.

### Table 2. Steel fibrous-reinforced concrete properties.

| Property                        | Value |
|---------------------------------|-------|
| Compressive cubic strength \( f_c \), MPa | 34.0  |
| Compressive prism strength \( f_{ck,prism} \), MPa | 23.2  |
| Tensile strength \( f_{ct} \), MPa | 1.7   |

![Figure 2. Steel fibrous reinforcement of beams](image)

1 — Zone of steel fibrous reinforcement, 2 — Main reinforcing bars.

The concrete mixture for the experimental samples was made in a concrete mixer, and the seals were made by using an immersion vibrator. The planned distribution of fiber by volume was carried out through layer-by-layer concreting of the samples. The interval between the embedding of the layer of cement-sand matrix and the layer with additional fiber reinforcement was not more than 20 minutes. Formwork was removed after 7 days, and after that beams stored in a humid environment for 28 days, and finally they were kept in the laboratory.

A special flexural testing frame was designed and manufactured for the prototype beam testing (Figure 3). The flat transverse bending of two-span beams in the testing device was created by means of a hydraulic jack and a steel beam, which transfers two identical (symmetrically arranged to the average support at a distance of 700 mm) actions (controlled by mechanical force gauge) from the hydraulic jack to the prototype beam.

The test samples were loaded in stages. After every effort, the data were recorded and the beams were visually inspected. The deflections were measured using mechanical gauge 6PAO, which were...
The deformations of the extreme fibers of the compressed and stretched zones of concrete were measured by the MIG-1 mechanical clock type strain gauges (based on 100 mm) and by 50 mm electrical strain gauges chains with chains through 30 mm. Reinforcement strain were determined by strain gauges based on 20 mm. Using the force gauge, which served as the edge support, the values of the support reaction force were recorded. The cracking process was investigated by using a microscope MPB-3. The load was accepted as fracture when the strain of reinforcement or concrete reached the limit values.

3. Results of experimental research
In the course of the research of specimens to destruction, the characteristic features of their work were observed. The fracture load for the prototype beam testing was: for B-1 $F_{\text{u}}=56$ kN, for B-2 $F_{\text{u}}=54$ kN, for B-3 $F_{\text{u}}=46$ kN. So all beams collapsed by the flexural failures due to the achievement of the maximum strains of the reinforcement in spans and above the middle support, as well as the maximum strain of concrete in compressed areas. Beams B-1 and B-2 had almost the same bearing capacity, the
fracture load of the beam B-2 was only 4% less than the beam B-1, which was reinforced with fibers throughout its volume. Beam B-3, which was reinforced with fibers only at the height of the two minimum concrete cover zone, collapsed during the loading, which was less than 18% of that of beams B-1, which indicates a significant effect of dispersive reinforcement throughout the volume on the bearing capacity of the reinforced concrete elements.

During the testing, the average experimental values of the reactions force of the edge supports $R$ were obtained and thus the statically indeterminate state of the beams was revealed. Given the elastic operation of the beams at a given load scheme, the theoretical values of edge support reactions force are equal to $R_{el}=0.3125F$, and with the redistribution of efforts they are equal to $R_{pl}=0.33F$.

As it can be seen from the graph (Figure 5), the change in reaction forces it the edge support in all three samples occurred with a significant deviation from the theoretical values, provided the beam working in the elastic stage and taking into account the redistribution of effort. The deviation of the $R/R_{el}$ ratio downward can be explained by the presence of cracks in the stretched concrete in spans and on the support. Beam B-1, which is reinforced with fiber throughout its volume, showed the greatest deviation from the theoretical values of the reference reactions, the maximum value of which was $R/R_{el}=0.6$, but before its destruction, it was almost equal to the theoretical and was $R/R_{pl}=0.96$. For beams B-2 reinforced with fibers only in stretched areas of concrete, the $R/R_{el}$ ratio ranged from 0.83 to 1.04 in fracture, and for beam B-3 this value was observed within 0.75–0.96.

The deflections in all beams were developing practically in proportion to the increase of the external load to the level $F=40$ kN, after which their development became more intense. Thus, the deflections of the beam B-3 were much larger than those of the other beams, and amounted to 5.08 mm at the destruction of $F_{cr}=46$ kN before fracture. The deflections of beams B-1 and B-2 at this level of loading were $\Delta=3.75$ mm and $\Delta=3.8$ mm, which is 26.2% and 25.2% less than B-3. The maximum deflection was $\Delta=6.41$ mm at $F_{cr}=56$ kN for beam B-1, and $\Delta=4$ mm at $F_{cr}=54$ kN for beam B-2 (Figure 6).

The first cracks, normal to the longitudinal axis of the element in the beam B-1 (fiber-reinforced throughout its volume) appeared at a load of $F=16$ kN (approximately 30% of the destructive) and had a height of 4–6 cm. $a_{crc}=0.08$ mm in support, and $a_{crc}=0.05$ mm in spans. Subsequent loading of the beam showed the appearance of a large number of new cracks with partially expressed weave. The growth of the old cracks in height was almost not observed. The increase in the width of crack opening to approximately 75% of the destructive level occurred almost linearly, and at $F=40$ kN they were above the support $a_{crc}=0.03$ mm, and in the span $a_{crc}=0.14$ mm. With the increase of loading there was a significant increase in the width of the crack opening above the support, and immediately before fracture, and the maximum fixed width of the opening was $a_{crc}=0.85$ mm. At inclining $F=40$ kN, several sloping cracks appeared in the support zone, but their further development was negligible.
In beam B-2, which was reinforced with fibers only in the stretched areas, the cracking process was not very different from B-1, which is clearly seen in the graphs shown in Figure 7 and Figure 8. So the first cracks over the support appeared a little earlier, at $F=8$ kN, but its width was smaller and was $a_{cr}=0.05$ mm. At subsequent loading, the pattern of crack formation was similar to that in beam B-1, and at $F=32–44$ kN the width of the opening and the supporting and span cracks was even slightly smaller. At the last levels of loading, there was a significant increase in the width of the opening of several cracks above the support, and just before the destruction the maximum fixed width was $a_{cr}=1.4$ mm.

The nature of the cracks in the beam B-3 in the first stages of loading was similar to the previous samples. The width of the opening and the height of crack development were at the same level as in the beams B-1 and B-2. It is reported that the sharp activation of the cracking process started at a lower loading level than in the previous samples, already at $F=36$ kN. And just before fracture at $F=44$ kN, the maximum width of opening of normal cracks above the support was $a_{cr}=0.65$ mm, which is 62% more than in beams B-1 and B-2 at the same loading level. There were also more inclined cracks than in the previous samples, which can be explained by the lack of fiber reinforcement of the whole volume of the beam. The general appearance of the cracking process and the pattern of the cracks in the test beams B-1, B-2 and B-3 are presented in Figure 9.
4. Conclusions
Analyzing the results of the study, it can be stated that the beams B-1 and B-2, which are additionally reinforced with steel fiber throughout the whole volume of the element (B-1) and in the stretched areas (B-2), have approximately the same load-bearing capacity and crack strength at operational loading levels. Increase of the maximum crack opening width in B-2 beams (without steel fiber in compressed areas) can be observed only before the fracture.

The additional dispersion of reinforcement with the steel fibers throughout the stretched zone of concrete allows to increase the stiffness of the beam and reduce the deflections by 25% (in average) compared to the reinforcement of the zone of the two minimum concrete cover zone only.

In the course of the research, the new experimental data were obtained, on the basis of which it can be concluded that the use of additional disperse steel fiber reinforcement of stretched zones of continuous reinforced concrete beams allows to increase the stiffness of the elements, their crack strength and, accordingly, the life of the engineering structures made of them.

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