Reinforced concrete beams strengthened with steel fiber concrete

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Abstract. The aim of the study at exploring joint behavior under load of steel fiber concrete strengthening jackets (SFRC) and reinforced concrete beams at all loading stages. It is necessary for further development of calculation methodology for this strengthening method for members subjected to bending. Experimental results were obtained for assessment of strength, stiffness, crack resistance and failure behavior with a crack propagation pattern for the examined 4 samples (two with strengthening jackets and two reference non-strengthened samples). It has been found that the use of an SFRC jacket 45 mm in thickness with 2.5% fiber content (at the rate of 196 kg per cubic meter) increases the failure load by 20%, the stiffness – 3.4–11 times in the course of loading, and crack resistance – about 2.6 times. The results obtained were compared with the computer simulation in ANSYS PC: the discrepancy between the cracking load, failure load and deflection values for full scale samples and the computer model were found to be within 6.3 %.

Keywords: building, construction, strengthening, repairing, fiber concrete jacket, durability.

1 Introduction

Unfortunately, the necessity of reinforced concrete structure strengthening is caused by a wide range of design or assembly defects. So, according to experts on technical diagnostics of buildings of the group of companies “City Center of Expertise” [1], construction and installation work accounts for 32 %, poor quality building materials 9%, design errors 6% (from May 2017 to May 2018). Those defects may be found at the construction stage, more specifically, before applying the design loads to the structures. If this is the case, the structure may not have any damages and may be made of new concrete (at the age of 28-360 days).

In such situations, the use of the most economical and efficient methods and materials for strengthening is a crucial task. Very promising for this is the use of steel fiber-reinforced concrete (SFRC). It possesses outstanding properties: relatively high compressive strength, high tensile strength, strain-hardening behaviour under tensile stress (given a certain volume of fibres) and very low permeability since an optimised dense matrix is used [2, 3, 4]. Steel fiber-reinforced concrete jackets were successfully used to reinforce the vertical and horizontal bearing elements of the school building in Zagurolo in Italy.

Attention is now being given on using high strength concretes in strengthening conventional concrete members. The results demonstrated improvement in both flexural and shear capacity of the composite systems [5-8]. The flexural behaviour of RC beams damaged up to 80 and 90% of the failure capacity of the beams and repaired with overlay of ultrahigh-performance fibre-reinforced concrete (UHPFRC) was investigated [9, 10]. The results indicated that adding UHPFRC overlay on the tension face of damaged RC beam increases both load capacity and ductility. A series of experimental studies conducted on composite beams in which RC beams were strengthened with thick element of steel reinforced UHPFRC (R-UHPFRC) as additional tensile reinforcement. Results show significant improvement in the failure load of the beams by 2.0 to 2.8 times higher than the control beams [11, 12]. El-Enein et al. [13] investigated the flexural behaviour of an RC slab column joint strengthened with carbon fibre-reinforced polymer (CFRP) at the tension side. The results indicated that there is an increment in the flexural capacity and stiffness of the RC slab column joint. Monti and
Liotta [14] conducted experimental and analytical works on the shear behaviour of strengthened RC beams with CFRP. The results demonstrated the promising shear enhancement of strengthened RC beams as compared to the control beam. Most research works highlight the two significant features of UHPFRC (durability and strength), which show promising recent outcomes, as reported by many researchers [15–20]. Studies on the mechanical properties of the fiber-reinforced concrete have shown that the compressive strength could be up to 160.2-163 MPa [21, 22]. The results have also demonstrated that the improved fiber orientation will result in increasing the flexural strength of UHPFRC [23]. The use of steel fiber concrete reduces the cracking width versus similar high-performance concrete structures by 1.5 – 2 times [24].

The efficiency of its use is proved by research of performance of reinforced concrete bending members strengthened with SFRC jackets based on computer simulation in ANSYS PC [25]. It is essential to note that, nowadays, there is no standard engineering calculation of reinforced concrete structure strengthening involving steel fiber concrete jackets in the literature, as its analysis has shown, and there are insufficient experimental works in this field for its development.

In view of the above, the objective of this study was to experimentally explore the joint behavior under load of strengthening steel fiber concrete jackets and reinforced concrete beams at all loading stages for further development of the calculation methodology for this way of bending member strengthening.

In this context, firstly, the concrete for fabrication of the beams and their strengthening jackets is assumed to be of approximately the same age, therefore, the difference in rheological properties of older and relatively newer concrete is not taken into consideration. Secondly, the absence of the design loads at the preoperational stage allows disregarding initial damages such as force tension cracks. The admissibility of both assumptions is explained in the first paragraph of the introduction.

2 Materials and methods

At the first stage of the research, the authors carried out a computer simulation of the stress-strain state of SFRC jacket strengthened beams whose results are published in [25]. The simulation results were validated by comparison with experimental findings [7] which allowed revealing the failure behavior and the actual performance of the strengthened structures, extending the research area and, finally, reasonably developing herein a procedure for a physics experiment aimed at studying joint behavior under load of SFRC jackets and reinforced concrete beams.

Thus, 2 series of samples were fabricated for the full-scale experiment:

Series 1 – non-strengthened reinforced concrete beams – reference samples – two twins B-2 and B-4 (Figure 1, a);
Series 2 – beams strengthened with SFRC jackets – twins B-1p, B-3p (Figure 1, b).

The experiment program is represented in Table 1.

The beams were fabricated of class B25 concrete at Kazan Reinforced Concrete Products Plant, ZBI-3, in molds for window lintels dimensioned 1810x220x120. Proportioning of materials per 1 m3: M350 cement – 475 kg, sand – 600 kg, chippings and gravel – 1150 kg, water – 125 kg, plastifying agent – 5 kg, multi-purpose admixture – 7 kg.
Figure 1. Reinforcement layout and geometrical dimensions of beams, a) non-strengthened reinforced concrete beams, b) beams strengthened with SFRC jackets, (503)* - actual size with imperfections.

Beam reinforcement in the pure bending area was performed only at the lower edge with 2Ø10 mm A400 bars (reinforcement ratio: $\mu=0.59\%$), in the beam bearing areas – in the shear span – bars were additionally installed at the upper edge – 2Ø6 A240 (reinforcement ratio: $\mu=0.216\%$) in order to allow for installation of shear stirrups – Ø6 A240 at intervals of 100 mm. The assumed reinforcement met the following design requirements:

- reinforcement with transverse links was overdesigned in order to prevent shear and diagonal tension failure;
- tension longitudinal reinforcement was selected in such a way that flexural failure takes place with reinforcement achieving the yield point ($\xi<\xi_R$).

Table 1. Full-Scale Testing Program.

| Series No. | 1 | 2 |
|------------|---|---|
| beam designation | B-2, B-4 | B-1p, B-3p |
| Q-ty | 1+1 | 1+1 |
| Reinforced concrete beam parameters | | |
| Section, mm | 120x220 | 120x220 |
| Length, mm | 1810 | 1810 |
| Reinforcement | 2 Ø10 A400 | 2 Ø10 A400 |
| Concrete class | B25 ($R_b=31.9$ MPa; $E_b=29787$ MPa) | B25 ($R_b=31.9$ MPa; $E_b=29787$ MPa) |
| Strengthening jacket parameters | | |
| Concrete matrix class | - | B25 ($R_b=35.8$ MPa; $E_b=29787$ MPa) |
| Reinforcement | - | - |
| Thickness, mm | - | Fiber size 0.7x0.8x35mm |
The beams were tested in the laboratory of the Department of Reinforced Concrete and Masonry Structures of Kazan State University of Architecture and Engineering (the city of Kazan). The loading was applied using GRM-1 testing machine (500kN) (Figure 2) according to the diagram shown in Figure 3.

Figure 2. GRM-1 testing machine and B-1p strengthened beam ready for the experiment.

Figure 3. Design diagram of beam testing.

In order to measure strain in representative points of beams, resistance strain gauges were attached as shown in Figure 4. Some of the strain gauges were attached to the principal reinforcement, some – to the beam concrete and others – to the jacket concrete. All resistance strain gauges were connected to ZET 017-T8 strain-gauge station using a bridge joint.

Figure 4. Strain gauge layout in beams.

Before jacket installation, the surface of the beams to be strengthened was made rough using an electric hammer drill. As the results of the further experiments showed, this created a secure adherence of the jacket to the beam (Figure 5). The SFRC jacket was concreted in the laboratory by means of
pouring the concrete mix into an open-top mold of the appropriate size. The steel fiber concrete mixture was vibrated by rodding.

![Figure 5](image1.jpg) **Figure 5.** Rough surface of the beam to be strengthened.

In order to record the deflections and support movements, dial gauges with scale intervals of 0.001 mm and a caliper gauge with scale intervals of 0.02 mm were used. The gauge layout is shown in Figure 2. Load was applied with increments of 3-4 kN, which corresponds to 5-7% of the failure load.

### 3 Results

According to the test results, it was established that all samples failed at the normal section due to formation of flexural cracks and achievement of the yield point by reinforcement. The sample failure pattern is shown in Figure 6.

![Figure 6](image2.jpg) **Figure 6.** Samples after failure a), b) series 1, c), d) series 2.

The first cracks in the reference samples appeared at the load of $P_{\text{crc}} = 10$ kN; the failure load was $P_{\text{ult}} = 48$ kN. The beam deflection plot is shown in Figure 7.

The first cracks on the concrete surface for strengthened B-3p beam appeared at the load of 24.68 kN, on the surface of the SFRC jacket – at the load of 28.68 kN. For B-1p: on the concrete surface – at 13.52 kN, on the jacket surface – at 24.52 kN. The failure load was 58.4 kN for B-3p and 54.5 kN for B-1p. The beam deflections plot is shown in Figure 7.
The crack propagation pattern for series 1 and 2 beams is shown in Table 2.

**Table 2. Crack Propagation Pattern.**

| Load | Series 1 beams |
|------|----------------|
| Stage I up to \( P_{rc,b} = 0.2\cdot P_{ult} \) | ![Image](image1.png) |
| Stage II up to \( P_{ult} \) | ![Image](image2.png) |
| Stage III \( P_{ult} = 48 \text{ kN} \) | ![Image](image3.png) |

| Load | Series 2 beams |
|------|----------------|
| Stage I up to \( P_{rc,b}^* = 0.278\cdot P_{ult} \) | ![Image](image4.png) |
| Stage II up to \( P_{rc,fb}^* = 0.62\cdot P_{ult} \) | ![Image](image5.png) |
| Stage III up to \( P_{ult} \) | ![Image](image6.png) |
| Stage IV \( P_{ult} = 58.4 \text{ kN} \) | ![Image](image7.png) |

Note: \( P_{rc,b}^* \) is the load at appearance of in concrete (the main part of the beam) caused by crack formation; \( P_{rc,fb}^* \) is the load at appearance of cracks in the SFRC jacket.

In the course of loading, a deterioration of the joint behavior under load of the SFRC jacket and the reinforced concrete beam was not observed until the load was close to the failure load – 0.93\( P_{ult} \). At the same time, 4 specific stages were defined in the strengthened structure performance which is in conformity with the computer simulation results [25]:

**Stage I** – elastic behavior: linear dependence between external and internal forces, ending in Ia stage where the stress diagram in the tension area of concrete curves;

**II** – inelastic behavior: appearance and development of pseudoplastic strains in concrete (the main part of the beam) due to formation of microcracks, further accumulation of damages in the material – breakdown of the linear dependence;

**III** – appearance and development of visible cracks in the SFRC jacket;

**IV** – failure – loss of carrying capacity of the beam when the reinforcement reaches the yield point.
Discussion
The bearing capacity of the beams with SFRC jacket increases by 1.2 times (Figure 7a), whereas the strengthening of beams with ultrahigh-strength fibrous concrete increases the strength up to 1.5-1.7 times (7b [26]). The high performance fiber reinforced cementitious composites (HPFRCC) use allows increasing the bearing capacity of the beam (2.15 times), even if the post peak behavior becomes softening [7]. Differences are due to the characteristics of the strengthening materials.

Figure 7a. Deflections – load plot.

Figure 7b. Deflections – load plot [26].

Figure 8 shows the crack width opening along which failure has occurred, for all beams. Stresses in reinforcement in the middle of the span are shown in Figure 9. The stress diagrams in concrete, SFRC in normal section are shown in Figure 10-12.
Figure 8. Crack width opening – load plot.

Figure 9. Reinforcement strain – load plot.

Figure 10. Concrete strains – load plot for series 2 beams, 1 – the stage of jacket getting into action after formation of cracks in the strengthened beam concrete.
Conclusions

1. It was found that the use of SFRC jacket increases the failure load by 20%, stiffness – by 3.4–11 times (depending on the load level), the cracking load – from 10 kN to 24–28 kN, load at admissible crack opening $a_{cr,ult}=0.3$ mm (based on the condition of permeability limitation at short-term crack opening) – from 24.36 kN to 42.52 kN. It decreases the number of cracks more than twofold while the crack width opening (at the load of $0.85P_{ult}$) is reduced from 0.9 mm to 0.4 mm.

2. The results obtained were compared with those of a computer simulation in ANSYS PC: the discrepancy between the cracking load, failure load and deflection values for full scale samples and the computer model were found to be within 6.3 % which proves the adequacy of the numerical results and the possibility to use the suggested computer models in further research related to the subject of this article.

3. 4 specific stages of strengthened beam performance were defined which is in conformity with the results of the computer simulation carried out earlier [25].

4. It was found that separation of the jacket from reinforced concrete beams took place at the load close to the failure load ($0.93P_{ult}$). Therefore, roughing of the concrete surface of strengthened beams ensures their proper adhesion with the jacket.
5. When cracks appear in the SFRC jacket, the diagram of strains in the normal section curves, which is indicative of breakdown of the Euler–Bernoulli beam theory. Therefore, corrections have to be introduced, when it is used in calculation methods.

6. The obtained experimental data about the joint behavior under load of strengthening SFRC jackets and reinforced concrete beams will be used when developing a program of further experiments aimed at studying the impact of the most significant (geometric, physical and static) factors on the strength, stiffness and crack resistance as well as for development of a calculation method and recommendations for strengthening of reinforced concrete beams.

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