Complete diagrams of strain under axial tension of steel-fiber reinforced concrete with different fiber types and content

Rostislav Krasnovsky\textsuperscript{1}, Dmitriy Kapustin\textsuperscript{1,2}, Dmitry Korotkikh\textsuperscript{1,3} and Luka Efshov\textsuperscript{1}
\textsuperscript{1}JSC "Institute "Orgenergostroy", Moscow, Russia
\textsuperscript{2}Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia
\textsuperscript{3}Voronezh State Technical University, Russia

E-mail: kde90@bk.ru

Abstract. The work provides the results of experimental investigation of strain properties of steel-fiber reinforced concrete with high-strength cement-sand matrix and various content of fiber (up to 6\% by volume). The work demonstrates influence of the type and content of steel fiber over changes of characteristics of complete diagrams of strain under axial tension. It shows that introduction of fiber gives elastic properties to the matrix that (properties) in a greater degree depend upon the type of fiber than upon percent of fiber reinforcement.

The available in the literature information about strength and strain properties of steel-fiber reinforced concrete (SFRC) was obtained mainly based on the results of compression and bending tests. The amount of the results of axial tension tests is small, that, probably, is related to significant complexity of performance of such tests, ensuring homogeneous stress condition in a specimen in process of specimen loading. Taking into account the results of analysis of the literature data we have performed axial tension testing of SFRC, taking complete strain diagram.

Influence of fiber type and content over SFRC characteristics was assessed. SFRC with the same high-strength cement-sand matrix (Table 1) and five fiber types (Table 2, Fig.1) was subject to investigation. Fiber content (by volume) in matrix varied from 0.5\% to 6\%. The exception was only SFRC with FSWW 0.3x30 fiber since when content of fiber in matrix is over 1.5\%, when SFRC mix is being mixed, the fibers were clinging between each other forming so called “hedgehogs”.

\textbf{Table 1.} Composition of SFRC cement-sand matrix.

| Cement | Sand | Water | Microsilica | Hyper-plasticizer Sika 5-800 |
|--------|------|-------|-------------|-----------------------------|
| 800    | 1250 | 260   | 45          | 8                           |
Table 2. Examined types of fiber.

| Fiber type     | Fiber characteristics                                           | Fiber size, mm | Fiber steel standard tensile strength, MPa |
|----------------|----------------------------------------------------------------|----------------|-------------------------------------------|
| FSWW 0.8×30    | Cut of wire, crimped                                          | 30             | 860                                       |
| FSWW 0.3×15    |                                                                | 15             | 2450                                      |
| FSWA 0.3×30    | Cut of wire with long plain anchors by string ends             | 30             | 2650                                      |
| «Dramix» type  |                                                                |                |                                           |
| Harex 1.2×32   | Machined of slabs with short hooky anchors by string ends      | 32             | 600                                       |
| FSS 0.8×40     | Of varied shape cut of steel sheet                             | 40             | 580                                       |

Figure 1. Types of steel fiber: a) FSWW 0.8×30, b) FSWW 0.3×15, c) FSWA 0.3×30, d) Harex 1.2×32, e) FSS 0.8×40.

Investigations were performed using specimens in form of plates with bar-shaped moldings (Figure 2).

Figure 2. Specimen for axial tension testing.
With the purpose to take the complete strain diagram, the tests were performed using electro-mechanical machine Instron 3382 providing continuous, with constant speed, motion of the grip. Since the grips of the testing machine were designed for fixing the bar-shaped specimens in them, so to fix the plate-specimens we have added the intermediate grips with Hook joints to ensure application of the load along specimen axis (Figure 3).

![Figure 3. Axial tension test: a) general view b) fixing the specimen in intermediate grips with Hook joints.](image)

The design of testing machine Instron 3382 allows measuring strains by displacement of cross-member while the strain values determined by cross-member displacement (especially at the initial loading stage) included displacements referred both to free-motion of cross-member mechanism, and to punching and slipping of specimen in the grips of testing machine. That is why a combined system of strain measurement was applied [1], with which the strains, before cracks formation, were measured using resistive strain gage, while after cracks formation – by displacement of testing machine cross-member. The gages with gage length of 30 and 100mm were stuck on the lateral edges of the specimens. The strains were registered using automatic registration station National Instruments using software complex LABVIEW. The loads and strains in process of testing were continuously registered in automatic mode.

The results of testing demonstrated that SFRC tensile strength value is higher than matrix strength. Moreover the degree of increasing (that, mainly, is within 2 – 40%) is related, mainly, to fiber type. Since no regular changing of SFRC strength value resulting from fiber content and from fiber steel strength was revealed, so it might be supposed that the decisive factor is the strength of adhesion of fiber with matrix that (strength), in turn, is defined by fiber structure characteristics.

The complete diagrams of longitudinal strain ($\sigma_t - \varepsilon_t$) of matrix and SFRC with different types of fiber are shown in Figure 4. It is shown that that the diagrams of strain of SFRC have descending branch, while such branches are missing in matrix ones. It means that introduction of fiber into matrix gives plastic properties to SFRC that is the due to formation of micro-cracks [2].
Figure 4. Complete diagrams of longitudinal strains under tension of matrix and SFRC with different content of fiber.
The descending branch of the strain diagram (Figure 5) can be described by the following characteristics:

- strain $\varepsilon_{t,\sigma_{\text{max}}}$ corresponds to max. stress (max. tensile stress);
- strain $\varepsilon_{t,\text{max}}$ corresponding to the end of the descending branch of diagram;
- strain $\Delta \varepsilon_{t,\text{max}}$ at the section of the descending branch ($\varepsilon_{t,\text{max}} - \varepsilon_{t,\sigma_{\text{max}}}$);
- stress $\sigma_{t,\varepsilon_{\text{max}}}$ corresponding to the end of the descending branch of diagram (residual strength).

![Figure 5. Characteristics of the point of the complete strain diagram.](image)

The strain corresponding to SFRC ultimate tensile strength (Figure 6) exceeds respective matrix strains (fiber content is equal to zero), but by not more than 75% even when fiber content is 6%.

![Figure 6. Dependence of strain $\varepsilon_{t,\sigma_{\text{max}}}$, corresponding to ultimate axial tensile strength upon reinforcement percent of SFRC with different types of fiber.](image)

The length of the descending branch of strain diagram (Figure 7) defines SFRC plastic properties. As it is shown in Figure 7, the strains corresponding to length of the descending branch of the diagram depend upon the type of fiber that defines the nature of adhesion of fiber with matrix. Depending upon the type of fiber, the adhesion is realized either by the whole length of fiber, as it takes place for waved fiber, or due to the anchors on the end of fiber. In the latter case the type of anchor is matter...
The large strains take place with anchors of the type like with fiber FSWA 0.3x30. In course of specimen straining, the anchors are straightening and slipping in the concrete channel. Moreover, micro-cracks in concrete (Figure 8) creating effect of plasticity occur.

![Figure 7](image)

**Figure 7.** Dependence of length of descending branch of the diagram ($\Delta \varepsilon_{\text{tmax}}$) of SFRC with different fiber type and contents.

![Figure 8](image)

**Figure 8.** Photo of concrete failure as a result of pulling out the wire fiber with anchor.

With fiber Harex 1.2x32, having anchors in form of rigid hook, a concentrator of stresses is formed that leads to formation of cracks that, next, join analogous cracks from hooks of other fibers that leads to unstable failure of specimen.

Max. strains $\varepsilon_{\text{tmax}}$ (Figure 9), measured immediately before specimen failure, for waved fiber ensuring adhesion with matrix along the whole length of fiber, little depend on fiber type. Just when adhesion is ensured by anchors, the max. strains, depending on fiber type, may differ twice.
Figure 9. Dependence of max. strain $\varepsilon_{\text{t,max}}$ of SFRC with different fiber types upon fiber content.

The SFRC residual strength value is insignificant and did not exceed, generally, 2MPa (see Figure 4). It little depends upon fiber type and content.

The results of performed investigations allow making following conclusions.

Introduction of steel fiber into cement-sand matrix gives plastic properties to it and as a result the complete diagrams of SFRC have descending branches as distinct from those (diagrams) of matrix.

Strains of descending branch of the diagram characterizing plastic properties of SFRC depend upon fiber type. Moreover, it is significant if adhesion between fiber and matrix is ensured due to fiber shape (profile) or due to structure singularities of anchors at the ends of fiber.

The SFRC residual strength value is insignificant (does not exceed 2MPa) and little depends upon fiber type and content.

The obtained data is essential to undertake the calculations of SFRC structures using deformation models [5], [6].

References
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