Algorithm for Design of Steel Fiber Concrete Structures

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Abstract. It is shown that the widespread use of structures made from such building composites as steel fiber concrete (SFC) is constrained due to the lack in regulatory documents of the necessary information on the choice of initial data, possible options for fiber reinforcement and principles of their rational use, features of their calculation and design, as well as the data with SFC properties in accordance with the operational requirements for such structures. During a long period of time since the idea of concrete reinforcement with steel fiber (“iron hair”) emerged at the end of the XIX and the beginning of the XX century, numerous studies have been performed by Russian and foreign scientists, which became the basis for the further development and improvement of building structures with fiber reinforcement. The algorithm for the design of SFC-based structures has been presented, including the peculiarities of the composite nature of the material.

1. Introduction

Beddar M. [1] presented the analysis of the emergence and development of the concept of fiber reinforcement of construction materials. Though this work does not answer the question, when was this concept implemented for the first time, M. Beddar states: “Historically, there is no evidence for an exact time when the concept of fiber reinforcement of the construction materials was used first. However, a deep analysis of this concept shows that it is many years old and dates to antiquity... over time the idea became more complex”.

Since the beginning of the XX century, a number of patents have been issued related to the introduction of segments of wire or metal filings into concrete [2].

In 1910, Porter conducted a series of tests, the results of which led him to the conclusion that the presence of short fiber in concrete increases the tensile strength of the resulting material [3]. Later on, from about the middle to the second half of the XX century, the concept of fiber reinforcement of materials developed into the science of composite materials, which became the framework for the accurate formulation of the idea [4-6].

Composites are superior to traditional materials and alloys in their physical and mechanical properties. In the matrix, the reinforcing component is distributed evenly or by zones; it usually possesses high strength, hardness and elastic modulus — much higher than the corresponding parameters of the matrix itself.

Setting the properties of a structure by the directional reinforcement according to its stress-strain state or load conditions allows one to ensure the efficient functioning of both the material and the structure. From the perspective of principles of the composite structure formation [4,5], one can state that the elastic-strength properties of SFC as a composite material are affected by types of matrix and
fiber, volumetric content of the components, geometrical parameters of fiber, its volume distribution, the strength of interaction at the fiber-matrix interface.

Studies of SFC in the USSR began in the 1960s. The topic attracted the attention of scientists and experts from Soviet research institutes and universities, and the results of their research laid the foundation of knowledge about SFC.

The formation of the theoretical basis of the SFC involved works dedicated to the creation and analysis of the conventional structural materials, such as fiber-reinforced metal (FRM) or particulate-reinforced rubber (PRR) [4].

2. Design of SFC-based structures. Regulatory documents

In 1987, “Recommendations on Design and Construction of Steel Fiber Concrete Structures” [7] were issued based on the generalized results of studies performed by scientists from Soviet research institutes and higher educational institutions. This document contains the information on the choice of materials (concrete and fiber), rules for limit state design calculations, determination of the design resistance of SFC, design requirements, production technology issues, and examples of SFC-based structural elements calculation.

Later on, according to the Russian regulations, the design of SFC-based structures was required to adjust with the rulebook of the 2007 edition [8], then with the same rulebook of the 2010 edition [9], and currently, with the latest edition of the rulebook [10].

Over the past 50 years, since the start of the active study of SFC and SFC-based structures, Russian scientists obtained a large number of research results [7-20, etc.]. However, while the rulebook of the 2006 edition takes this experience into account to some extent, the latest regulatory document [10] discards it almost completely.

As a result, this document lacks data necessary for the design of SFC-based structures. Its examination raised a number of questions, which the document does not answer.

The analysis showed that instead of the design of structures based on the SFC composite, the document considers the design of steel mesh reinforced concrete with an “addition” of steel fiber. In world practice, this type of fiber reinforcement is known as a “scattered reinforcement”.

However, the SFC composite properties are determined by the interaction between the steel fiber as a structural component and the concrete matrix. This implies the mechanical interaction of the components through the surface links, i.e. cohesion. SFC properties are superior to average properties of its components or even their sum, thus exhibiting a synergetic effect [11].

SFC-based structures with characteristics specified in accordance to the operating conditions outperform known analogues in terms of technical and economic indicators.

3. Proposals on SFC-based structures design

Chamis, the lead NASA expert in composite mechanics, has noted in [6] that the appearance of composite materials and, in particular, fiber-reinforced composites gave the designer freedom of the efficient use of materials. It opened a possibility of the simultaneous design of the material and the structure. Being composite material, SFC is produced at the same time as the structure made of it. Thus, the design of the SFC composition is performed in accordance with strength and deformability requirements for steel fiber concrete (SFC) and steel fiber reinforced concrete (SFRC) structures, which in turn are determined from the operational requirements for the designed structure.

3.1. Materials

After the preliminary choice of steel fiber type (in this step, it is practical to take into account the recommendations on the purpose of the designed object), the initial choice of concrete is made in accordance with fiber properties (i.e. its strength and deformability) [7,12,13].

After the selection of the design scheme, making the load summary, and performing the static calculation of the element, an analysis of stress fields obtained from the static calculation is carried
out, the results of which are used to refine the selection of fiber (or combined) reinforcement type [7,12-14].

When determining the fiber reinforcement parameters, one should observe the prevailing significance of the fiber length/diameter ratio $l/d_t$. In order to provide the sufficient tensile strength of the material, this ratio is recommended to be not less than 100, while the diameter of fiber $d_t$ should be comparable to the structural elements of the composite, i.e. to the grain size of filler in the case of SFC [7]. On the contrary, the compressive strength of SFC increases when $l/d_t < 50$, as in this case fibers may be equally oriented in space [12].

To gain a technical effect, it is expedient to use fiber with a diameter of 0.3...0.8 mm [7,12,13], hence one should select fine-grained concrete as SFC matrix. Studies show that SFC based on fine-grained concrete has a density of 2300 kg/m$^3$ [12].

Typically, in SFC the average thickness of the area of contact between the matrix and fiber is 300 μm [17,18], and SFC properties depend essentially on its condition, which is especially important in the case of composite with a brittle matrix. In SFC, the greater the volumetric content of the fiber in the matrix (provided it does not exceed its equilibrium value) and the smaller the diameter of the fiber, the greater the number of contact areas and the better the strength and deformability of the material.

The size and the shape of filler, its geometric characteristics and volumetric content affect not only the rheological properties of the SFC mix but also the properties of the structure after solidification of the mix [19].

Heavy concrete with coarse-grained filler must be selected considering fiber geometry [7,12]. Usually, the introduction of coarse-grained filler greatly reduces the efficiency of fiber reinforcement [19].

It is known that in order to provide the operational reliability of building structures, load and material safety factors are introduced into the calculations. Load safety factors are determined by operating conditions according to the rulebook. Material safety factors depend on the chosen type of material. If by all accounts, SFC is a composite material, the corresponding safety factors should be determined for the SFC composite, rather than for concrete and fiber separately, as the rulebook [10] suggests. For the ultimate limit state design calculations for SFC or SFRC structures, the reasonable values of material safety coefficient would be those determined for SFC in experimental and theoretical studies, taking into account steel fiber type, with a probability 0.95 [8].

### 3.2. Method of selecting the parameters of fiber reinforcement

If there is no information on the fiber reinforcement parameters of the SFC-based element being designed, the use of the software is recommended (Certificate of state registration of a computer program no. 2014615242 from 21.05.2014) that provides a set of graphs, with the aid of which the user can select the diameter of fiber ($d_t$), its length to diameter ratio ($l/d_t$) and the design resistance factor ($R_{cd}$), as well as the resistance factor of the concrete ($R_b$) and other parameters for given dimensions of the element cross-section ($b\times h$).

The preliminary selection of fiber reinforcement parameters is based on the fiber relative consumption coefficient for tension ($k_{th}$) and compression ($k_{bh}$), which is useful for estimating the fiber consumption per one percent increase in SFC strength related to the initial concrete.

Using the graph in figure 1, one could choose the $l/d_t$ ratio and the calculated tensile resistance of the fiber $R_{ct}$, then in accordance with these values, select the minimal relative fiber consumption $k_{th}$ [12] for the specified cross-section of the element. These data and the set of plots allow one to determine the missing parameters of the fiber reinforcement and the concrete.

After the preliminary selection of the fiber type based on static or dynamic calculations of the structural element, it is advisable to refine the optimal fiber consumption and tensile and compressive strength of the concrete using the software (Certificate of state registration of a computer program no. 2012619865 from 31.10.2012), cf. Table 1.


**Figure 1.** The relative consumption coefficient for tension versus the calculated resistance for different length/diameter ratios and element cross-section $b\times h = 40\times20$ mm.

Table 1 gives the optimal fiber consumption $\mu_{fv}$, the diameter of the fiber and its length/diameter ratio, the design tensile and compressive strength required for given tensile resistance of SFC in the structure obtained from tension caused by external loads $\sigma_t$.

**Table 1.** Input and output of the computer program for calculating the optimal fiber consumption.

| No. | Input Parameter                  | Value | Output Parameter                  | Value |
|-----|---------------------------------|-------|-----------------------------------|-------|
| 1   | Tensile stress $\sigma_t$, MPa  | 3.6   | Fiber diameter $d_f$, mm          | 0.8   |
| 2   | Cross-section dimensions $b\times h$, mm | 40×20 | Fiber length/diameter ratio $l/d_f$ | 100   |
| 3   | Fiber type                      | Wire, profiled | Initial concrete design resistance factor for tension $R_{bt}$, MPa | 0.74 |
| 4   | Anchors present                 | Yes   | Initial concrete design resistance factor for compression $R_b$, MPa | 8.5   |
| 5   | Fiber design resistance factor $R_{sf}$, MPa | 500   | Fiber volumetric content $\mu_{fv}$, % | 0.9   |

3.3. **Calculation and design of SFC-based structural elements**

Stresses and strains in dangerous sections can be determined by means of conventional engineering methods or using specialized software that implements the finite element method, such as LIRA-SPAR, SCAD, ANSYS, etc.

Using a software package for calculations, one can obtain fields of stresses and strains in the element’s sections, then on the basis of these data refine the parameters of the fiber reinforcement and mesh reinforcement (if necessary), as well as the concrete strength. The fiber reinforcement can be
done evenly by the entire section or by zones [7,12,20]. Regular reinforcement with bar or wire mesh is used when the increase in the fiber volumetric contents leads to a decrease in the efficiency of the design, while the combined reinforcement satisfies the operational requirements for the element but does not increase its cost and does not complicate the production technology. When the design decision is made, calculations of dangerous sections of the element should be performed for both ultimate and serviceability limit states.

Load-bearing capacity and stiffness of the element under static or dynamic load, its resistance to frost, corrosion, and heat are determined by the particular operational conditions. Typically, the material capacity of fiber-reinforced structures is up to 50% lower than that of conventional structures of a similar purpose.

![Figure 2](image-url)

**Figure 2.** Results of static calculation of the space frame of a cinema hall roof (1/2 of the entire area) using the SCAD software package: (a) the strain field in elements of the bottom layer of the space frame caused by the most unfavorable load combination Ny, MPa; (b) the layout of prefabricated pyramidal elements in the bottom layer of the space frame.

As an example, a fragment of the strain field in the space frame of a cinema hall roof is presented in figure 2a, which is obtained from static calculation. The scheme of zones for fiber reinforcement was developed, and the layout of pyramidal elements of the bottom layer of the structure was designed (figure 2b). Based on strain values, the unification of pyramidal elements was performed. Groups of unified elements are presented in Table 2. For each element, a scheme of fiber reinforcement and regular reinforcement (if necessary) should be designed. Figure 3 gives an example of the strain field in a common pyramidal element P3 of the bottom layer of the space frame, obtained from the static calculation in the SCAD software package. The design description of the pyramidal element P3 is as follows.

Pyramidal element P3 is reinforced by zones with monodisperse fiber: zone 1 - sides affected by both tension $\sigma_t = 1.1$ MPa and compression $\sigma_c = -2.7$ MPa are reinforced with fiber with following parameters: $d_f = 0.6$ mm, $l_f = 70$ mm; $\mu_{fv} = 0.5\%$; $R_{sf} = 500$ MPa; zone 2 - edge connecting tension sides $\sigma_t = 4.78$ MPa. The accepted parameters of fiber reinforcement give design tensile resistance of SFC $R_{fbt} = 1.74$ MPa and compressive resistance $R_{fb} = 17.99$ MPa, which together with bar reinforcement dia. 10 A400 in each edge of tension side ensure the load bearing capacity of P3 element.
Table 2. Unification groups and parameters of prefabricated unified SFRC-based pyramidal elements of the 30×72 m space frame.

| Type of element | Number of element | Concrete consumption per element, m$^3$ | Steel consumption per element, kg | Element weight, kg | Total weight, ton |
|-----------------|------------------|------------------------------------------|----------------------------------|-------------------|------------------|
| P1              | 128              | 0.119                                    | 3.5                              | 297               | 38               |
| P2              | 150              | 0.119                                    | 3.1                              | 297               | 44.5             |
| P3              | 334              | 0.119                                    | 2.9                              | 297               | 99.2             |
| Total           | 612              |                                          |                                  |                   | 181.7            |

![NX. Combination (L1)*1+(L2)*1+(L3)*1+(L4)*1) (GPa/m²)](image)

Figure 3. Strain field in a common SFRC-based pyramidal element of the space frame P3.

4. Conclusion
The results of various studies accumulated in the years since the appearance of the idea of composite materials creation, in particular, reinforcing the concrete with “steel hair”, i.e. fiber, could provide today the possibility to fully use the advantages of SFC and SFRC-based structures proven both in Russia and worldwide.

We believe that the rulebook Steel Fiber Concrete Structures definitely should contain the necessary and sufficient information on the design and production of SFC-based structures, which is based on the experience of our predecessors - Russian scientists, using justified data from foreign experts [21-25].

In order to benefit from the practical use of SFC-based structures in the Russian construction industry, the development of a system of normative documents is required, including rulebooks Steel Fiber, Steel Fiber Concrete Mix, Steel Fiber Concrete, and Steel Fiber Concrete-based Products and Structures.

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