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Strength of reinforced concrete beams of high-performance concrete and fiber reinforced concrete

Прочность железобетонных балок из высокопрочных бетонов и фибробетонов

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Key words: reinforced concrete; fiber reinforced concrete; crack width; stresses; strain; standard-based calculation; crack resistance; numerical simulation; verification

Ключевые слова: железобетон; фибробетон; ширина раскрытия трещин; напряжения; относительные деформации; расчет по нормам; трещиностойкость; численное моделирование; верификация

Abstract. The strength of reinforced concrete beams made of high-performance concrete and fiber reinforced concrete was evaluated in a pure-bending test. The efficiency of using straight steel fiber in bending structures was evaluated. The fracture pattern of models was described. The results of measuring the vertical displacement and crack width are provided and compared to the rated values. The diagrams of stresses and deformation in reinforcement and concrete of models are presented, and their specific features are noted. The current methods to evaluate reinforced concrete bending structures made of high-performance concrete were evaluated for Groups 1 and 2 limit states. Results were obtained for numerical studies of high-performance concrete. The results necessary to carry out numerical studies in the sphere of high-performance concrete have been obtained.

Аннотация. Выполнена оценка прочности железобетонных балок из высокопрочных бетонов и фибробетонов при испытании на чистый изгиб. Оценена эффективность применения прямой стальной фибры в изгибаемых конструкциях. Описан характер разрушения моделей. Приведены результаты измерений вертикальных перемещений и ширины раскрытия трещин; выполнено сравнение с нормируемыми величинами. Представлены графики напряжений и деформаций в арматуре и бетоне моделей, отмечены их особенности. Дана оценка существующих методик расчета изгибаемых железобетонных конструкций из высокопрочного бетона по первой и второй группе предельных состояний. Получены результаты для проведения численных исследований работы высокопрочных бетонов.

1. Introduction

High-performance concrete that complies with the latest requirements and promotes high-rise construction has been growing increasingly popular in the construction industry. Studies of construction materials with better strength and strain features have been the focus of attention. Studies to develop high-workability and self-compacting mixes for the production of high-performance self-compacting fiber concrete, B100 or higher compression strength [1], have been recently completed. The efficiency of such material in eccentric compression structures [2] has been evaluated, the specific features of such concrete performance at the steel-concrete contact surface [3] have been assessed. The workability of the material described in [1] and its higher strength and strain features contribute to its increasing use in cast-in-place construction including floor beams. Our study is dedicated to these issues. The efficiency of the developed concrete mix in bending structures is not studied enough. This shows the actuality of the issues under consideration and of the tests conducted. In preparation for the experiment, publications on

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the improvement of the theoretical foundations of reinforced concrete structures [4, 5, 12, 13, 17] and fiber-reinforced concrete [9] were studied. Special attention was paid to research in the field of contact interaction of steel and concrete [8, 10, 15, 16]. Issues of numerical modeling of reinforced concrete structures [6, 14] and cracking [7, 11] were considered.

The aim of the study is to obtain experimental data that will form a basis for numerical studies using of ANSYS models in strength calculation and in contact interaction tasks.

Objectives of the study:

• perform tests of 15 models of beams made of high-performance concrete and fiber reinforced concrete;

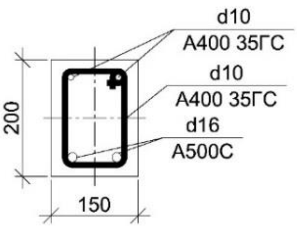
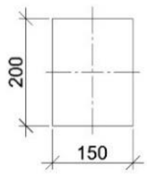
• to evaluate the existing methods of calculation of reinforced concrete structures at the ultimate limit state (ULS) and the service limit state (SLS) for high-performance concrete;

• to identify the characteristics of fracture, the nature of the formation and cracks propagation;

• to assess the effectiveness of the application in bending structures of 13 mm straight profile steel fiber.

Three models of high-performance concrete and twelve models of high-performance fiber concrete were tested during this research work. The models were constructed by rectangular cross-section, 200 x 150 mm, length 1.5 m. A detailed description of the models is contained in [18]. Table 1 contains the basic parameters of the models.

Table 1. Characteristics of models

Group of models	Quantity of models in a group	Material of models	Concrete compressive strength class	Fiber reinforcement factor by volume μ_{fv}	μ, % reinforce-ment ratio	Cross-section
B1	3	concrete	B90	-	1.9	 Fig. 1. Cross-section of models, Groups B1, B2, and B7
B2	3	fiber reinforced concrete	B130	0.023		
B7	3	fiber reinforced concrete	B100	0.023		
B3	3	fiber reinforced concrete	B130	0.023	-	 Fig. 2. Cross-section of models, Groups B3 and B8
B8	3	fiber reinforced concrete	B100	0.023		

2. Methods

Restrictive strain sensors were installed, as follows, to describe the relative strain pattern in the experiment: 1 piece at each reinforcement beam in the beam span middles, and 1 to 3 pieces at upper and lower edges of the concrete surface in the pure bending zone (Fig. 3). The sensor layout is shown in Figure 4.

All models were tested for pure bending (Fig. 5). Model supports were hinged. The force distribution between two points was ensured by a steel I-shaped cross arm.

Figure 3. Surface cleaning, installation of strainsensors and epoxy resin protection

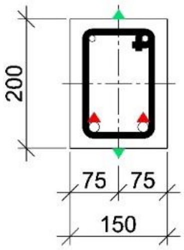


Figure 4. Layout of sensors

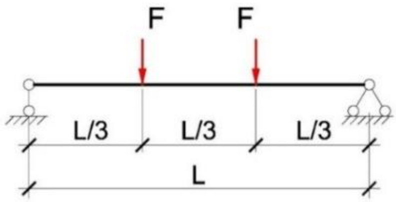


Figure 5. Model load application diagram

3. Results and Discussion

The concrete strength properties were monitored at 28 days and at the model test time; for this purpose 3 samples of 10 cm side cubes were prepared for each concrete batch. The results of cube testing according to [19] are presented in Table 2.

Table 2. Results of cube sample testing

Group of models	Cube concrete compression strength at 28 days, MPa	Cube concrete compression strength at test time, MPa
Б1	103.6	112.8
Б2	152.4	158.6
Б7	112.4	114.0
Б3	149.6	157.4
Б8	119.2	123.0

All models were tested according to provisions of standard [20]. The sequence of completed tests is described in [18].

The ultimate bending moments were calculated when preparing for testing according to [21–24]. The results of calculations and actual ultimate moments corresponding to the breaking load are shown in Table 3: Column 3 contains experimental ultimate moments, Column 4 contains theoretical values according to [21, 23], and Column 6 contains theoretical values according to [22].

A property of steel fibre concrete residual strength R_{fbt2}, R_{fbt3} has been added to the Document [22], which is being developed. No experimental data according to that property are available for the discussed material. The value of R_{fbt3} in our case was roughly obtained on the basis of the results of model tests, Groups B3 and B8, which have only dispersal reinforcement. Using the formula (6.3, 6.4) [22] we get:

$$M_{ult} = 0.5R_{fb} \cdot b \cdot x \cdot h \tag{1}$$

$$x = \frac{R_{fbt3} \cdot h}{R_{fbt3} + R_{fb}} \tag{2}$$

By plugging (2) in (1) and having the value of ultimate bending moment based on the M_{ult} experiment results, we find the R_{fbt3} value. It is noteworthy, that the R_{fbt3} value can differ from the value which is found using the method described in Appendix B [22]. The calculated R_{fbt3} values can be used in determining the beam strength, Groups B2 and B7.

Table 3. Ultimate bending moments

No.	Group of models	$M_{break, exper}$ (averaged for a group)	For models of high-performance concrete – according to [23] For models of high- performance fiber concrete – according to [21]		For models of high-performance fiber concrete – according to [22]	
			M theoretical, ultimate	Deviation from experiment (averaged for a group)	M theoretical, ultimate	Deviation from experiment (averaged for a group)
		kNm	kNm	%	kNm	%
1	2	3	4	5	6	7
1	B1	53.57	49.11	8.3	-	-
2	B2	63.27	62.72	0.5	56.99	9.6
3	B3	19.20	25.65	-34.1	-	-
4	B7	52.84	60.59	-14.8	50.56	4.2
5	B8	13.26	25.23	-90.4	-	-

It is apparent from Table 3 that the best convergence of theoretical calculations and experimental data was achieved for models implemented using reinforcement bars (both according to the current [21, 23] and developing standards [22]). The maximum deviation was noted in calculation according to [21] for beams with only dispersed reinforcement. The probable reason could be the use of a relatively short fiber of 13 mm, straight section, whereas the corrugated or hooked-end fiber is recommended for use in bending structures. The prestressing of fiber concrete implemented for models B7 and B8 produced no positive effect on the load-bearing capacity of those models. Therefore, the discussed fiber type (13 mm straight profile steel fiber) does not contribute significantly to the bearing capacity of bending elements. It is noteworthy that the use of ratios [22] in calculations provides for some reserve of structure bearing capacity (up to 9.6 %), whereas the ratios [21] produce results exceeding the experimental data, which is not permissible for real structures.

The pattern of crack width and distribution for each load step was registered in the experiment. The control loads to check the crack width values were found by [20]. The conditionally calculated loads were found at models by dividing the ultimate breaking loads by the safety factor (according to the terms of Russian State Standard GOST 8829-94). The nominal loads for calculating the second limit state were accepted to be conditionally equal to 0.8 of the calculated values.

As per Russian Set of Construction Rules SP 63.13330.2012 [23], the calculations for cracking that are normal to direct axis in bending structures should be made subject to:

$$\mathrm{M} > \mathrm{M}_{crc} \tag{3}$$

where M is the bending moment from an external load relative to the axis normal to the plane of moment action and passing through the center of gravity of the reduced cross section of a structure;

M_{crc} is the bending moment perceived by the normal section of a structure in cracking.

At this stage, the outdated (inoperative) nominal documents, the valid documents and those being developed as applicable to structures made of high-performance concrete were compared in calculation for the service limit state (SLS) (according to the crack width value). For models with reinforcement bars B1 the calculations were made according to Russian Set of Construction Rules SP 63.13330.2012 [23] using the formula (8.128):

$$a_{crc,i} = \varphi_1 \varphi_2 \varphi_3 \psi_s \frac{\sigma_s}{E_s} l_s, \tag{4}$$

where $\sigma_s$is stress in tension reinforcement with normal section with cracking;

l_s – base distance between adjacent normal cracks;

ψ_s – a coefficient to account for a non-uniform distribution of strains of tension reinforcement between cracks;

φ_1 – a coefficient to account for load time;

φ_2 – a coefficient to account for a longitudinal reinforcement profile;

φ_3 – a coefficient to account for a loading condition;

E_s – reinforcement elasticity module.

Also as per Russian Construction Norms and Rules SNiP 2.03.01-84* [24] using the formula (144):

$$a_{\text{т}} = \delta\varphi_l\eta\frac{\sigma_s}{E_s}20(3{,}5 - 100\mu)\sqrt[3]{d} \tag{5}$$

where δ is a coefficient to account for a loading condition;

φ_l – is a coefficient to account for load time;

η – is a coefficient to account for a longitudinal reinforcement profile;

σ_s – stresses in bars of the end reinforcement row;

μ – is a coefficient to account for reinforcement section;

d – reinforcement diameter, mm;

E_s – reinforcement elasticity module.

For models with fiber concrete (B2, B7) the crack width value was found as per Russian Set of Construction Rules SP 52-104-2006* [21] using the formula (7.17*) and according [22] using the formula (6.115).

The crack width value and loads at which it could be controlled are shown in Table 4: Column 4 – crack width found by [22, 23], Column 5 – crack width found by [21, 24], Column 6 – experimental values.

Table 4. Crack width

<table>
<tr><th rowspan="4">Group of models</th><th rowspan="4">Concrete of models</th><th rowspan="4">Control load, kN</th><th colspan="5">Crack width, m ×10 -3</th></tr>
<tr><th colspan="2">Theoretical</th><th rowspan="3">Experi mental</th><th colspan="2">Deviation from experimen-tal data, %</th></tr>
<tr><th>For models of high-performance concrete - according to [23]</th><th>For models of high-performance concrete - according to [24]</th><th>For models of high-performance concrete - according to [23]</th><th>For models of high-performance concrete - according to [24]</th></tr>
<tr><th>For models of high-performance fiber concrete - according to [22]</th><th>For models of high-performance fiber concrete - according to [21]</th><th>For models of high-performance fiber concrete - according to [22]</th><th>For models of high-performance fiber concrete - according to [21]</th></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td></tr>
<tr><td>B1</td><td>concrete, B90</td><td>141.8</td><td>0.307</td><td>0.269</td><td>0.370</td><td>16.9</td><td>27.3</td></tr>
<tr><td>B2</td><td>fiber-concrete, B130</td><td>167.5</td><td>0.247</td><td>0.143</td><td>0.187</td><td>-32.2</td><td>23.4</td></tr>
<tr><td>B7</td><td>fiber-concrete, B100</td><td>139.9</td><td>0.259</td><td>0.120</td><td>0.198</td><td>-30.8</td><td>39.5</td></tr>
</table>

The values of crack width (both theoretical and actual), which are shown in Table 4, do not exceed the permissible crack width subject to reinforcement safety $a_{crc,ult} = 0.4$ мм, as envisaged by Para 8.2.6 [23] in short-term fracture opening. However, significant deviations of theoretical values from the actual crack width were revealed. The difference in values reaches 40%. The error in calculation according to actual Russian Set of Construction Rules SP 63.13330.2012 [23] is essentially lower vs that envisaged by the previous Russian Set of Construction Rules SP 2.03.01-84* [24]. For models with fiber concrete the calculations according to the document [22], which is being currently developed, provide for some reserve: up to 32 % for models B2 and up to 31 % for models B7 implemented with self-stress. The results of calculation according to [21] are lower vs the experimental data by 23 % and 40 % for Groups of models B2 and B7, respectively.

The fracture process of models in all groups was characterized by the emergence of many vertical and inclined cracks. The time of cracking was registered at the values of 20 %, 27 %, and 26 % of the breaking load for groups of models B1, B2 and B7, respectively. Therefore, the models with fiber concrete have a somewhat higher crack resistance vs the models of high-performance concrete without fiber.

The high-performance models in Group B1 collapsed due to concrete chips in the compressed area (Fig. 6a); the high-performance fiber concrete models in Group B2 collapsed due to tension reinforcement breakage (Fig. 6b); the high-performance fiber concrete models with self-stress in Group B7 broke due to concrete collapsing in the compressed area but without reinforcement rupture or concrete chips (Fig. 6c). In all cases of collapse the tension values in tension reinforcement reached the yield stress.

Figure 6a. Typical collapse in models of Group B1

Figure 6c. Typical collapse in models of Group B7

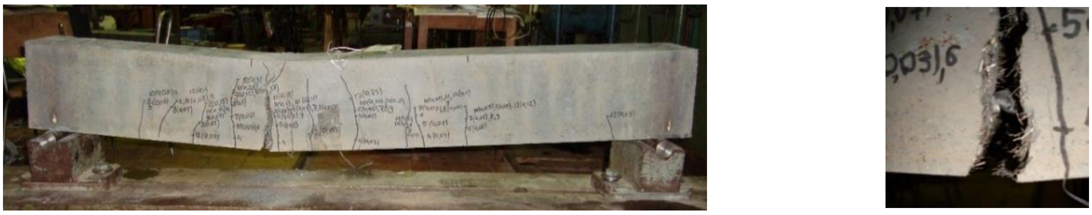


Figure 6b. Typical collapse in models of Group B2

On the basis of test results diagrams of vertical displacement for on-load models were constructed (Fig. 7), additionally, diagrams to illustrate the fracture opening width were constructed for each load step (Fig. 8).

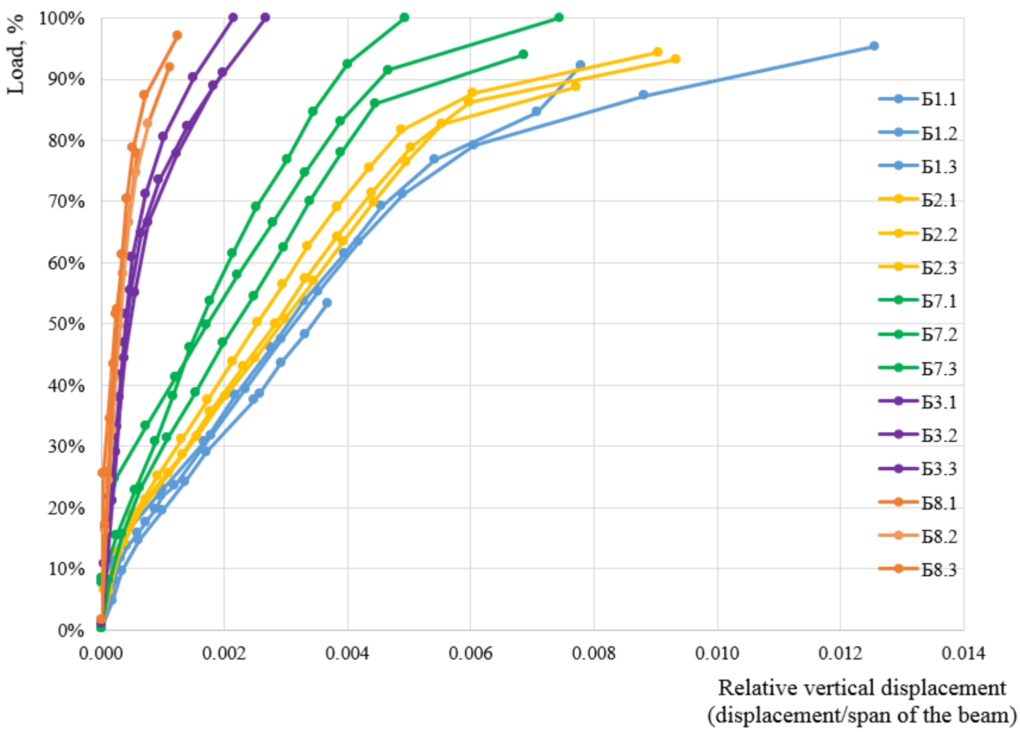


Figure 7. Vertical displacement of models B1, B2, and B7 by load steps

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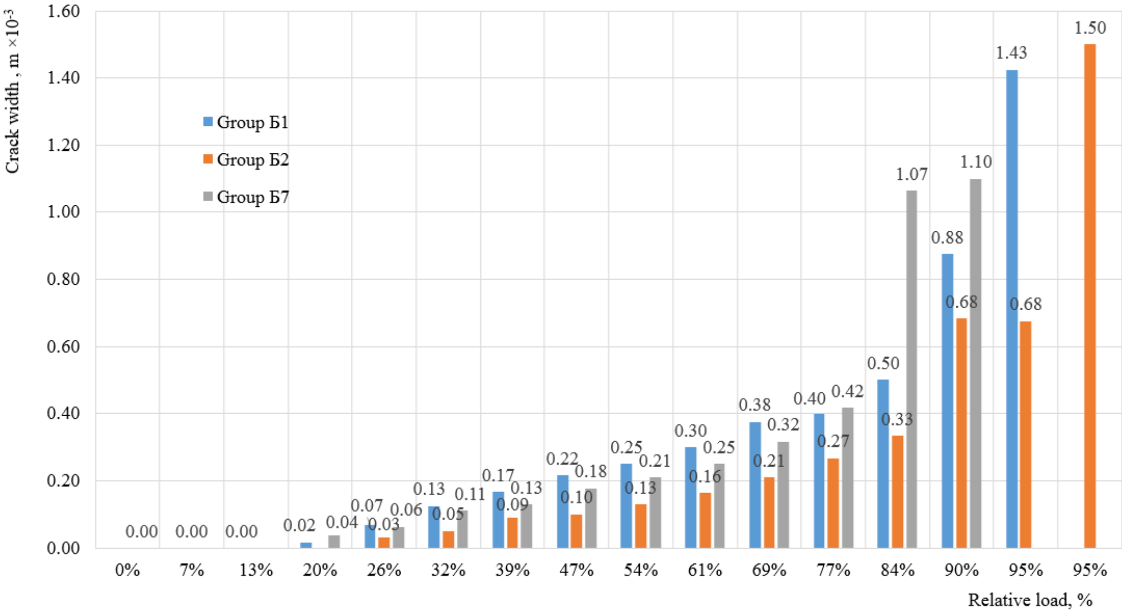

Figure 8. Fracture opening width in models B1, B2, and B7 by load steps

The maximum model displacement values at collapse time are shown in Table 5. The maximum vertical displacement values were registered for models of Group B1, i.e., 14.28 mm, which is 1/98 of the beam span value. Low vertical displacement values are typical of models with dispersed reinforcement only.

Table 5. Maximum model displacements

Group of models	Displacement, m $\times 10^{-3}$	Displacement in relation to beam span
B1	14.28	L/98
B2	12.48	L/112
B7	9.11	L/154
B3	3.19	L/438
B8	1.66	L/846

On the basis of interpretation of tension sensor readings diagrams for tension and deformation occurring in bar reinforcement and concrete of models were constructed; dependences are shown in Figures 9, 10.

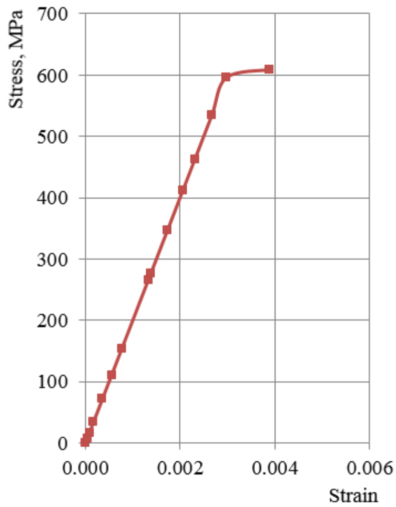

Figure 9. Dependence of tension on relative deformation for rod reinforcement, Group B1 models

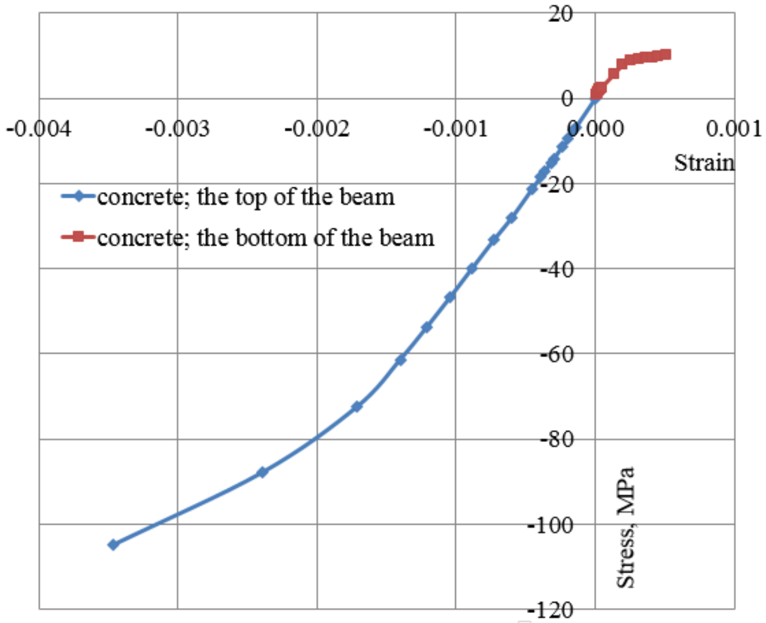

Figure 10. Dependence of tension on relative deformation for concrete, Group B1 models

Figure 9 shows distinctly the yield strength ranging from 600 to 620 MPa, which fully coincides with the results of testing the reinforcement bar samples for tension – 616 MPa. The experimentally obtained values of strains (Fig. 10) for bar reinforcement models B1, B2 and B7 somewhat exceed the values rated in [23] and presented in [25, 26]. This is explained by the uniform stressed state of concrete which is due to lateral and transverse reinforcement. The experimentally obtained limit tensile strength values (Fig. 10) exceed also the values specified in [23]. This is due to many cracks in the concrete tension area, some of which are covered by the tension sensor measuring surface.

The comparison of the obtained values of unit strains at the time of model collapses and of the values specified in [21–23, 25–26] is shown in Table 6.

Table 6. Limit unit strains of concrete models

Group of models	Experiment (averaged for a group)		Standardised according to [21, 22, 23]		Eurocode	Experimentally obtained according to [25, 26]		APOD from [21, 22, 23]	APOD from [25, 26]
	Compression	Tension	Compression	Tension		Compression	Tension	Compression	Compression
B1	0.00343	0.00216	0.00297	0.00015	0.0026	0.00254	0.00048	-15.5	-34.9
B2	0.00288	0.00331	0.00262	0.00015- for concrete matrix (0.01-0.02 * – for concrete)	0.0026	0.00327	0.00300	-10.0	11.8
B7	0.00286	0.00232	0.00280		0.0026	0.00327	0.00300	-2.3	12.3
B3	0.00087	0.00256	0.00262		0.0026	0.00327	0.00300	66.9	73.5
B8	0.00057	0.00286	0.00280		0.0026	0.00327	0.00300	79.8	82.7
	* - the value needs to be refined in testing the residual strength of fiber concrete to axial tension								

4. Conclusions

1. A series of works has been completed to study the workability of steel fiber concrete using a 13 mm straight profile steel fiber in bending structures. Nine models with reinforcement bars and 6 high-performance and fiber concrete models with dispersed reinforcement (including self-tension), B90...B130 compression breaking strength, were tested.

2. The ultimate limit state (ULS) of high-performance and fiber concrete structures with reinforcement bars is satisfactorily described by the calculation procedures presented in Construction

Rules – the difference between theoretical and experimental values does not exceed 10 %.

3. The calculation procedures for reinforced structures for the service limit state (SLS) (which is a basis for several normative documents) have been compared. The theoretical results differ from the experimental data up to 40 %.

The results of calculations of crack width according to the methods envisaged by Russian Set of Construction Rules SP XXX (draft) “Steel fibre concrete structures. The rules of design” and SP 63.13330.2012 “Concrete and reinforced concrete structures” are more consistent with the experimental data versus the calculation results according to Construction Rules SP 52-104-2006* “Steel fibre concrete structures” and SNiP 2.03.01-84* “Concrete and reinforced concrete structures”.

4. The fracture process of models in all groups was characterized by emergence of many vertical and inclined cracks. The moment of cracking was registered at the values of 20 %, 27 %, and 26 % of the breaking load for Groups of models B1, B2 and B7, respectively. Models of high-performance fiber concrete had a somewhat higher crack resistance versus the models of high-performance concrete.

The fracture pattern of reinforcement models: the high-performance models collapsed due to concrete chips in the compressed area; the high-performance fiber concrete models collapsed due to tension reinforcement breakage; the high-performance fiber concrete models with self-stress broke due to concrete collapsing in the compressed area but without reinforcement rupture or concrete chips.

The modes with dispersed reinforcement only collapsed abruptly and almost without any cracking.

5. The experimentally obtained values of strains for reinforcement models somewhat exceed the values rated in Construction Rules. This is explained by the uniform stressed state of concrete which is due to lateral and transverse reinforcement. The experimentally obtained limit tensile strength values exceed also the values specified in Construction Rules. This is due to many cracks in the concrete tension area, some of which are covered by the tension sensor measuring surface.

6. The analysis of on-load models and of fracture opening width by load steps showed no abrupt variations or difference for bar-reinforced beams. The cracks emerged and quickly opened just ahead of collapse in models with dispersed reinforcement only.

7. Summarizing the results of testing the dispersed reinforcement models (13 mm straight profile steel fiber), it can be concluded that the use of such fiber in not very effective in terms of the bearing capacity of bending elements. Other types of fiber (corrugated or hooked-end) should be used for the purpose. However, the main advantages of the used material would be wasted in such case, i.e., high workability (flow class, within the range of 70–75 cm) and a higher cohesion or non-segregation [1], which allow for classifying the material as belonging to the self-compacting category.

Having said that, the use of steel fiber concrete discussed in the study reduces the cracking width versus similar high-performance concrete structures by 1.5 – 2 times, which is necessary in some construction industry activities.

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