Experimental Research of Strength Characteristics of Steel Fiber Reinforced Concrete Gutters and Modeling of Their Work Using the Finite Element Method

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Abstract. Steel fiber reinforced concrete and structures based on it have increased crack resistance, toughness and elasticity, abrasion resistance, service life and are less sensitive to vibration and shock effects than similar structures with typical reinforcement. These elements at short-term and repeated loads three series of experimental researches have been conducted. Testing of prototypes (gutters) is performed by applying a central vertical load to the metal traverse beam acting on the gutter as evenly distributed. The results of experimental research of strength characteristics the steel fiber concrete, reinforced concrete and steel fiber reinforced concrete in gutters under the action of single and repeated loads are given. The results of the simulation of gutters using the finite element method also presented. Increasing the percentage of reinforcement with steel fibers gives an increase in carrying capacity for SFRC gutters at repeated low-cycle loads. Cracks in RC and SFRRC samples were with direct nature, while in SFRC samples they were with net nature.

Keywords: Reinforced concrete · Steel fiber reinforced concrete · SFRC · Steel fiber rebar reinforced concrete · Steel fiber · Drainage · Gutter · Load-bearing capacity · Strength · Crack resistance · Modeling · Finite elements

1 First Section

Steel fiber reinforced concrete is an effective material for manufacturing many new and strengthening existing building structures [1–4].

Steel fiber reinforced concrete (SFRC) and structures based on it have increased crack resistance, toughness and elasticity, abrasion resistance, service life and are less sensitive to vibration and shock effects than similar structures with typical reinforcement [5–7].

Efficiency of SFRC application in building structures is achieved due to reduction of labor costs for reinforcement works, combination of technological operations for preparation, reinforcement, laying and tamping of SFRC mixture, reduction of costs for various types of current repair and, accordingly, prolongation of constructions life [8–10].

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The increased crack resistance and rigidity of steel fiber reinforced concrete in comparison with classical reinforced concrete allow to use it for the manufacture of gutters for highway drainage, which can also be used in melioration systems [11].

To investigate the features of strength and deformation characteristics of the stress-strain state of steel fiber reinforced concrete gutters and work of these elements at short-term and repeated loads three series of experimental researches have been conducted. For the planned research, it was made the samples of concrete, reinforced concrete, steel fiber rebar reinforced concrete and steel fiber reinforced concrete. Detailed design solutions, manufacturing techniques of experimental gutters are presented in the article [12]. In the first series the work of gutters made of concrete, reinforced concrete (RC), steel fiber rebar reinforced concrete (SFRRC) and steel fiber reinforced concrete (SFRC) under the action of short-term disposable loads was studied. In the second series the work of gutters made of reinforced concrete, combined reinforced concrete, and SFRC under the action of short-term repeated loads with the level of loading $\eta = 0.6$ of the destructive value was investigated. In the third series the work of SFRC gutters with a percentage of reinforcement $\mu = 1\%$; 2%; 3% at single and repeated loads with levels $\eta = 0{,}3$; $0{,}5$; $0{,}7$ was investigated.

Testing of prototypes (gutters) is performed by applying a central vertical load to the metal traverse beam acting on the gutter as evenly distributed. During the test, the lower part of the gutter is supported by a rigid base. For this purpose the hydraulic press PSU-125 is used (Fig. 1).

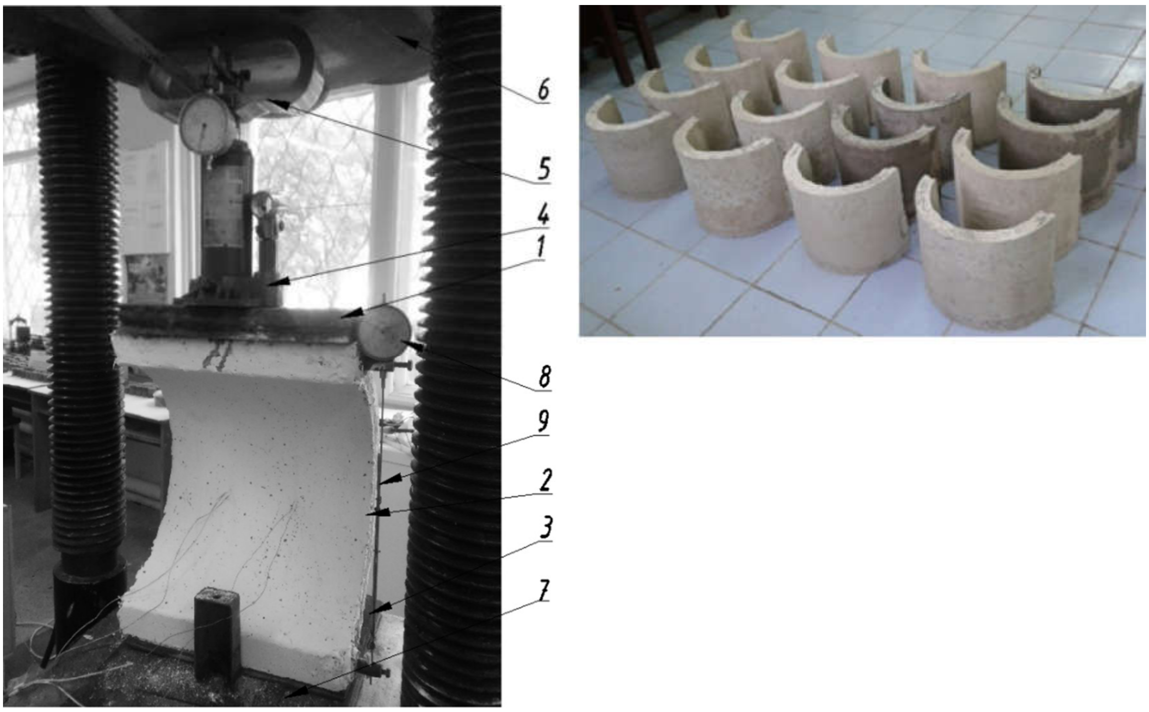

Fig. 1. General view of the drainage gutter research: 1 - metal traverse beam; 2 - experimental drainage gutter; 3 - fixed base; 4 - hydraulic jack; 5 - dynamometer; 6 - top plate of PSU-125; 7 - bottom plate of PSU-125; 8 - displacement detection sensor; 9 - displacement bar.

To improve the accuracy of measuring the acting force a dynamometer is used, which makes it possible to measure loads with an accuracy of 50 N. Load was supplied by the hydraulic jack in steps of 8–12% of the destructive force, determined by the theoretical calculation. The detailed technique of experimental gutters research is presented in works [13].

First series of research was done on gutters: 1C-1, 1C-2, 1C-3 without reinforcement; 1RC-1, 1RC-2, 1RC-3 with steel rebar frames reinforcement $\rho = 2\%$; 1SFRC-1, 1SFRC-2 and 1SFRC-3 made of SFRC with percentage of steel fiber reinforcement $\mu = 2\%$ and 1SFRRC-1, 1SFRRC-2 and 1SFRRC-3 with steel rebar frames reinforcement $\rho = 1\%$ and steel fiber reinforcement $\mu = 1\%$ (total reinforcement percentage 2%) according to the plan of the experiment [12]. Results on crack resistance obtained during the study of samples of the first series under short-term disposable loads are presented in Fig. 2.

Graphs of the average cross section displacements of the research elements of the first series are presented in Fig. 3.

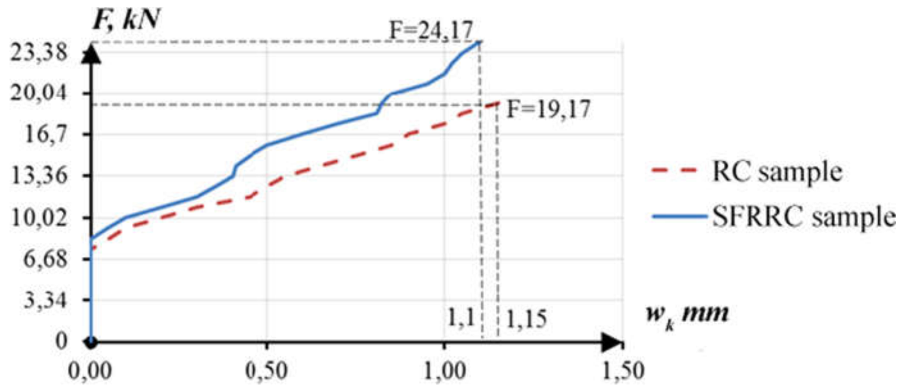

Fig. 2. Dependence of crack opening width on load.

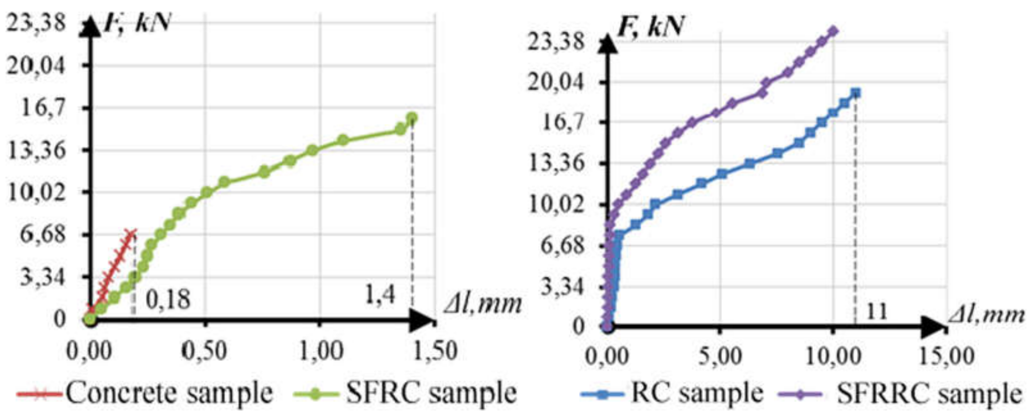

Fig. 3. Average cross section movements of research elements.

Second series of research was conducted on gutters: 2RCr-1, 2RCr-2 and 2RCr-3 with steel rebar frames reinforcement ρ = 2%; 2SFRRCr-1, 2SFRRCr-2 and 2SFRRCr-3 with steel rebar frames reinforcement ρ = 1% and steel fiber reinforcement μ = 1%, and the total 2% according to the plan of the experiment [12].

Results on crack resistance obtained during the study of samples of the second series at short-term repeated loads are presented in Fig. 4.

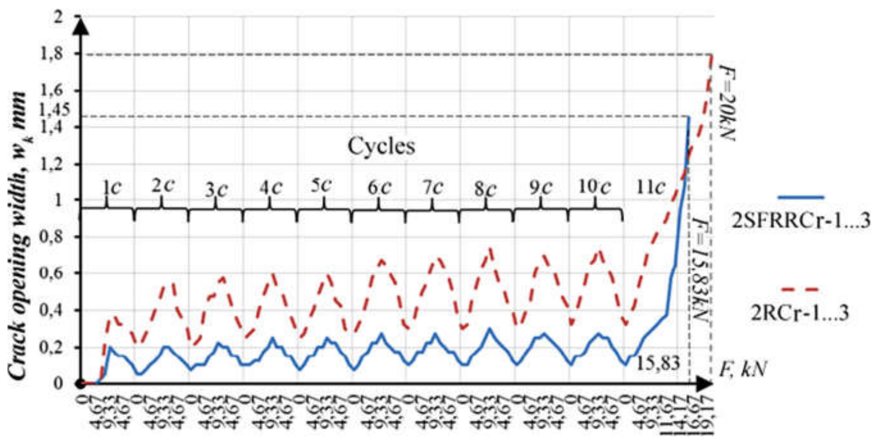

Fig. 4. Dependence of crack opening on the load of second series gutters

Third series research was conducted on gutters: 3SFRCr$_{+1;+1}$–1…3 at η = 0.7 and μ = 3%; 3SFRCr$_{+1;-1}$–1…3 at η = 0.3 and μ = 3%; 3SFRCr$_{-1;+1}$–1…3 at η = 0.7 and μ = 1%; 3SFRCr$_{-1;-1}$–1…3 at η = 0.3 and μ = 1%, and the control sample 3SFRCr$_{0;0}$–1 at η = 0.5 and μ = 2% according to the experiment plan [12].

The values of the cross section movement of the 3SFRCr research elements at 1 and 10 cycles were averaged and presented in Fig. 5 and Fig. 6.

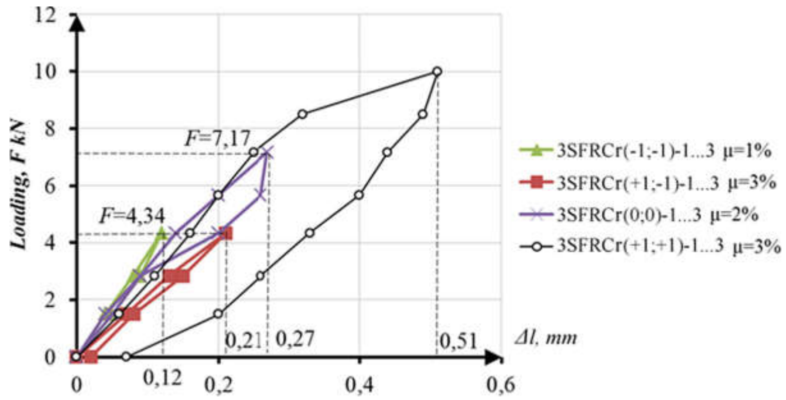

Fig. 5. Average cross-sectional displacements of the 3SFRCr on 1 cycle

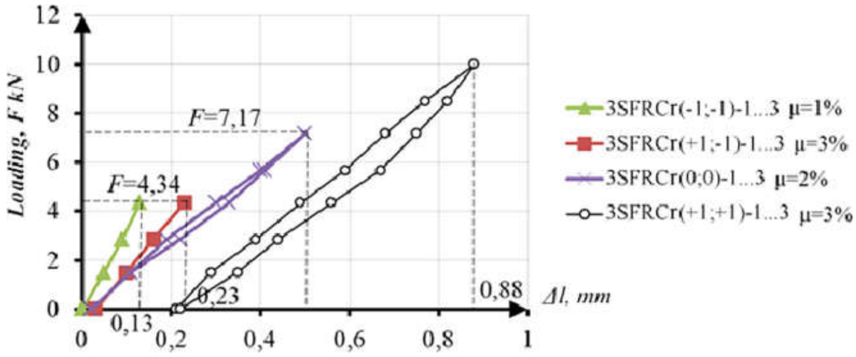

Fig. 6. Average cross-sectional displacements of the 3SFRCr on 10 cycle

According to the purpose of the work, the modeling of SFRC gutter by the finite element method (FEM) was carried out, numerical values of stresses, bending moments and displacements arising in SFRC gutters under the action of known loads on them were determined. During the research of SFRC gutters work it was applied physically nonlinear final volume elements № 236 (universal spatial 8-angle isoparametric finite elements (FE).

For this purpose, the gutter was simulated in the form of a semi-tube with dimensions in accordance with experimental models (Fig. 7), and its triangulation to the finite elements was performed under the following conditions:

- the tray wall is divided into four layers by its thickness (at t_w = 40 mm thickness of one layer t_l = 10 mm). Within one layer we accept that there is one finite element with thickness t = 10 mm respectively;
- the length of a half-circle along the axial radius of the gutter element is l_c = 54 cm. We divide it into FE with the length of the sides by l_{fe} = 10 mm. We have 54 finite elements along the axial radius.
- gutter length l = 300 mm. According to the gutter length, we divide it into FE with the condition that the length of each FE l = 10 mm (i.e. the FE has a cubic geometric shape). In the length of the gutter element there are 30 finite elements.

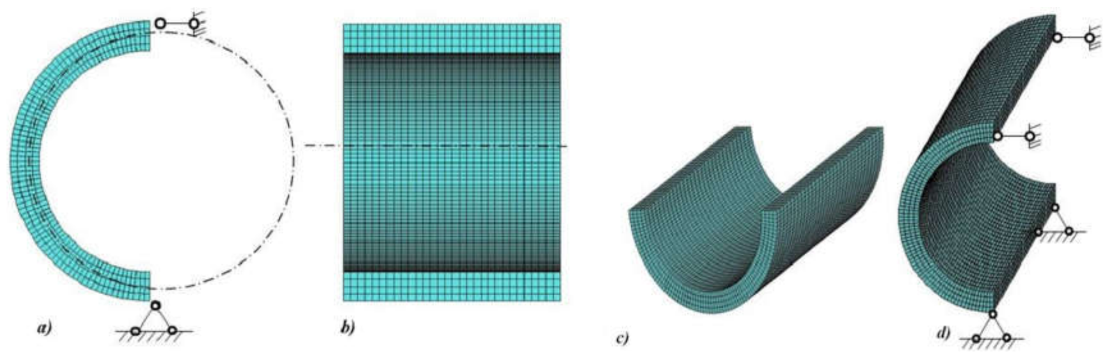

Fig. 7. Simulation of gutters: *a* - YOZ projection (front view); *b* - XOY projection (side view); *c, d* - isometric projections (position during operation and during testing)

After modeling the gutter element in the shape of a half-pipe and dividing it into finite elements, the mechanical characteristics corresponding to the real properties of the materials from which it is made using the phenomenon of physical non-linearity are set.

SFRC as a material from which a gutter in the shape of a half-pipe is made was set using a graph, describes the dependence of stress-strain (σ - ε). Evenly distributed load is set using a simple step-by-step calculation method with uniform steps (10 steps with 300 iterations in each of these steps are taken). Before starting the calculation process for the SFRC half-pipe gutter we set the 14 law of non-linear deformation ("piecewise linear law of deformation").

By using the "LIRA-SAPR" software we simulated and calculated a SFRC half-pipe gutter with parameters corresponding to the natural samples. The values of moments in the middle of the cross-section obtained as a result of this calculation are presented in Table 1. The values of certain bending moments and stresses in trays are also presented in Table 1.

Table 1. Values of bending moments and stresses in the SFRC gutter (1SFRC-1…3).

№	Efforts, *F*		Theoretically calculated in lateral cross section		LIRA-SAPR, *σ, MPa*	Error, %
	kN	*kN/m*	Moment, $(M, kN \cdot m)$	Tension (*σ, MPa*)		
1	0,83	2,77	0,16	1,97	2,00	1,52
2	1,67	5,57	0,32	3,97	4,00	0,75
3	2,50	8,33	0,48	5,94	7,00	17,84
4	3,33	11,10	0,63	7,91	9,00	13,78
5	4,17	13,90	0,79	9,90	11,00	11,11
6	5,00	16,67	0,95	11,88	13,00	9,42
7	5,83	19,43	1,11	13,85	16,00	15,52
8	6,67	22,23	1,27	15,84	18,00	13,63
9	7,50	25,00	1,43	17,81	20,00	12,29
10	8,33	27,77	1,58	19,78	22,00	11,22
11	9,17	30,57	1,74	21,78	24,00	10,19
12	10,00	33,33	1,90	23,75	26,00	9,47
13	10,83	36,10	2,06	25,72	29,00	12,75
14	11,67	38,90	2,22	27,72	30,00	8,22
15	12,50	41,67	2,38	29,69	33,00	11,14
16	13,33	44,43	2,53	31,66	35,00	10,54
17	14,17	47,23	2,69	33,65	37,00	9,95
18	15,00	50,00	2,85	35,63	40,00	12,26
19	15,83	52,77	3,01	37,60	41,00	9,04

2 Conclusions

At repeated loads which level does not exceed 70% of destructive ones, SFRC gutter works elastic.

Increasing the percentage of reinforcement with steel fibers with $\mu = 1\%$ to $\mu = 2\%$ gives an increase in carrying capacity (average) for SFRC gutters at repeated low-cycle loads up to 40%, and with $\mu = 1\%$ to $\mu = 3\%$ gives an increase in carrying capacity up to 58%.

Cracks in the test samples occurred in the area with maximum bending moment. Cracks in RC and SFRRC samples were with direct nature, while in SFRC samples they were with net nature.

The error of bending stress values obtained by using of "LIRA-SAPR" software and theoretical calculation is mainly within the range of 8…13% with arithmetic mean value of error $\bar{X} = 10.56$ and average square deviation $\sigma = 3.96$. Variation coefficient value $\upsilon = 37\%$.

References

1. Hameed, A.A., Mohannad, H.A.: Influence of steel fiber on the shear strength of a concrete beam. Civ. Eng. J. **4**(7), 1501–1509 (2018)
2. Babych, E.M., Andriichuk, O.V.: Strength of elements with annular cross sections made of steel-fiber-reinforced concrete under one-time loads. Mater. Sci. **52**, 509–513 (2017)
3. Babych, Y.M., Andriichuk, O.V., Kysliuk, D.Ya., Savitskiy, V.V., Ninichuk, M.V.: Results of experimental research of deformability and crack-resistance of two span continuous reinforced concrete beams with combined reinforcement. IOP Conf. Ser. Mater. Sci. Eng. – MSE **708**(1), 012043 (2019). 1–8
4. Dvorkin, L., Dvorkin, O., Ribakov, Y.: A method for optimal design of steel fiber reinforced concrete composition. Mater. Des. **32**(6), 3254–3262 (2011)
5. Kinash, R., Bilozir, V.: Deformational calculation method of bearing capability of fiber-concrete steel bending elements. Czasopismo Techniczne **8-A**(7), 49–58 (2014)
6. Shmyh, R., Bilozir, V., Vvsochenko, A., Bilozir. V.: Carrying capacity of bending concrete elements reinforced by fibro and stripes taken from used PET bottles. In: International Scientific and Practical Conference World science, ROST, vol. 1, no. 2, pp. 88–93 (2018)
7. Soetens, T., Matthys, S.: Different methods to model the post-cracking behaviour of hooked-end steel fibre reinforced concrete. Constr. Build. Mater. **73**, 458–471 (2014)
8. Oliveira, M., Ramos, E., Oliveira, D., Neto, B.: Analysis of influence of concrete element format and properties steel fibers on flexural toughness. Matéria (Rio J.) **23**(3), 1–14 (2018)
9. Sameh, Y.: Effect of steel fibers and gfrp sheet on the behavior of lightweight concrete specimens using waste lightweight sand bricks. Int. J. Eng. Res. Tech. **7**(03), 69–75 (2018)
10. Islam, M.M., Dhar, A., Patowary, F., Asif, J.H., Rahman, S., Das, S.S., Das, S., Chowdhury, M.A., Siddique, A.: Experimental investigation and finite element analysis on P-M interaction diagram of RC square columns made of steel fiber reinforced concrete (SFRC). In: Joint Conference on Advances in Bridge Engineering-III, IABSE-JSCE, pp. 192–200. Dhaka, Bangladesh (2015)
11. Vegera, P., Vashkevych, R., Blikharskyy, Z.: Fracture toughness of RC beams with different shear span. In: MATEC Web of Conferences, vol. 174, p. 02021 (2018)

12. Andriichuk, O., Babich, V., Yasyuk, I., Uzhehov, S.: The influence of repeated loading on work of the steel fiber concrete drainage trays and pipes on the roads. In: MATEC Web of Conferences, vol. 116, no. 02001, pp. 1–9 (2017)
13. Andriichuk, O., Yasyuk, I.: Metodyka eksperymentalnoho doslidzhennya dyspersno-armovanykh prydorozhnikh lotkiv vodovidvedennya. Visnyk Odeskoi natsionalnoi akademii budivnytstva ta arkhitektury: zbirnyk naukovykh prats **58**, 11–18 (2015)