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ON THE ASSESSMENT OF THE STRENGTH OF BENT REINFORCED CONCRETE ELEMENTS SUBJECTED TO CYCLIC LOADING

The results of a probabilistic and statistical analysis of the fatigue resistance of conventional and fibropropylene containing reinforced concrete bending elements using standard calculation methods based on limiting forces, nonlinear deformation models and experimental data of the internal resistance of composites after 50 loading cycles with an amplitude of n = 0.8 and zero asymmetry are presented. The increased strength and fa-tigue durability of elements with fiber-reinforced concrete, when reinforcing structures less than the boundary level, has been established. It is assumed that the introduction of polypropylene fine fibers contributes to the internal redistribution of forces in cyclic and subsequent monotonous loading.

Представлены результаты вероятностно-статистического анализа усталостного сопротивления обычных и фиброполипропиленсодержащих железобетонных изги-баемых элементов с использованием нормативных методов расчета по предельным усилиям, нелинейным деформационным моделям и экспериментальным данным внутреннего сопротивления композитов после 50 циклов нагружения с амплитудой η = 0,8 и нулевой асимметрией. Установлена повышенная прочность и усталостная долговечность элементов с фибробетоном при армировании конструкций менее граничного уровня. Предполагается, что введение полипропиленовых мелкодисперсных волокон способствует внутреннему перераспределению усилий в цикловом и последующем монотонном нагружении.

Keywords: *fatigue, polypropylene fiber-reinforced concrete, bendable elements*

Ключевые слова: *усталость, полипропиленфибробетоны, изгибаемые элементы*

Numerous data from technical monitoring of reinforced concrete structures of buildings and constructions indicate their gradual transformation under the influence of technological, temperature–climatic, geotechnical, and other impacts of moderate (below design) nonstationary intensity. Considering the physical laws of the initiated processes, consisting of the formation, development, and accumulation of microcracks, the expected consequences can be analyzed from the standpoint of low-cycle fatigue [1–3]. With this approach, the determining factor in the fatigue degradation of cement matrix structures is their ability to develop and form the main (critical) [4, 5] microcracks.

A technologically acceptable and technically effective method is finely dispersed fiber reinforcement, which creates "... an internal environment for stress transfer and prevents the fusion of microcracks and their unstable growth" [6–9]. The diverse fibers used allows for targeted correction of the internal resistance parameters of composites, considering the actual performance criteria. Previously [10, 11], we substantiated the technical feasibility of using polypropylene fibers with an aspect ratio lf/df = 40/0.8 = 50 as volumetric (randomly distributed) reinforcement. Their use promotes structural modification, with a high potential for plastic-shear deformation [11–13] and consequently, the internal redistribution of forces.

Probabilistic–statistical analysis of the fatigue resistance of bendable and eccentrically compressed reinforced concrete elements with combined (volumetric fiber–propylene and steel rod) reinforcement is the main content of this article.

Research method

The change in the internal resistance potential after the cyclic loading of varying intensity is predicted by validating the standard methodology (cl. 8.1.20-8.1.30 SP 63.13330 "Concrete and reinforced concrete structures") to compare the influence of fatigue consequences in conventional (CC series) and fiber-reinforced elements (FC series). Concurrently, an algorithm for calculating strength is developed in the Excel environment, using standard nonlinear deformation models, experimental diagrams σb-εb, and considering the heterogeneity of stress distribution along the section height.

Numerical modeling of strength is performed by conditionally dividing the section into segments of limited thickness, wherein the deformations (stresses) are assumed constant and correspond to the distribution for flat sections.

Using successive approximations at each stage, the relative height of the compressed zone ξi is established, at which the equilibrium of the external force N and internal resistance are observed.

$$N = \sum \sigma_{bi}\left(\varepsilon_i\right) \cdot A_{bi} + \sum \sigma_{sj}\left(\varepsilon_j\right) \cdot A_{sj} \qquad (1)$$

Here, the designations correspond to the standard ones, and the stresses in concrete and reinforcement are considered according to two-three-linear σb-εb diagrams verified by experimental data, depending on the deformation of the i, j-th layers and considering the sign and tensile concrete for fiber-reinforced elements.

The corresponding value of the moments of resistance of the internal forces is determined as follows

$$M = \sum \sigma_{bi}\left(\varepsilon_i\right) \cdot A_{bi} \cdot Z_{bxi} + \sum \sigma_{sj}\left(\varepsilon_j\right) \cdot A_{sj} \cdot Z_{sxj} \qquad (2)$$

When the criterion condition for destruction is met

$$\varepsilon b \le \varepsilon b,ult\ . \qquad (3)$$

The maximum permissible deformation $\varepsilon b,ult$ is assumed equal to the experimental values in the post-peak section of the compression diagrams up to stresses of $0.8\sigma u$.

A numerical experiment on the indicated deformation models and limiting normative (SP 63.13330 “Concrete and Reinforced Concrete Structures”) forces was performed using the example of a beam of rectangular cross-section (b × h = 100 × 200 mm) with one-sided reinforcement (class A400, μ = 1%–6%) made from common concrete (cement: sand: crushed stone: water = 1:1.42:3.31:0.55) and fiber-reinforced (the same with the addition of 1.5% polypropylene fibers with lf/df = 40/0.8). The fatigue resistance of the composites was assessed through the change in the Mult of various probability levels after 50 loading cycles with an amplitude η = 0.8 and zero asymmetry using the experimental data given in Table 1. Numerical values of the corresponding parameters of the nonlinear deformation models are graphically presented with a normalized probability of 99% (Fig. 1).

Discussion

The probabilistic change in the load-bearing capacity of beams of different reinforcement levels under static (SC) monotonic and identical postcyclic (PCC) conditions is presented in Fig. 2.

As expected, the kinetics of the bearing capacity of the beams of the series is the same with reinforcement μ under the limit (μR = 2.5 ÷ 3%), since it (per prerequisites (SP 63.13330 “Concrete and reinforced concrete structures”) is determined only by the strength potential of tensile reinforcement. This is also confirmed by the practical identity of changes in indicators of different levels of probability. Notably, in this reinforcement range, the bearing capacity of the beams of the FC series is higher than that of the conventional analogues of relatively lower strength concrete.

Table 1

Experimental Data for Calculations Based on the Ultimate Forces

Series	Designation	Measurement unit	Initial			After N = 50 η = 0.8		
			average	Min 95 %	Min 99 %	average	Min 95 %	Min 99 %
CC	R_b	MPa	43,57	41,03	39,76	37,43	33,54	31,59
	$\varepsilon_{b,ult}$	$\times 10^5$	313	277	258	238	182	153
	ξ_R		0,518	0,496	0,486	0,466	0,418	0,394
FC	R_{fb}	MPa	35,79	33,63	32,55	35,36	29,66	26,8
	$\varepsilon_{b,ult}$	$\times 10^5$	318	262	234	233	190	168
	ξ_R		0,521	0,489	0,473	0,462	0,425	0,406

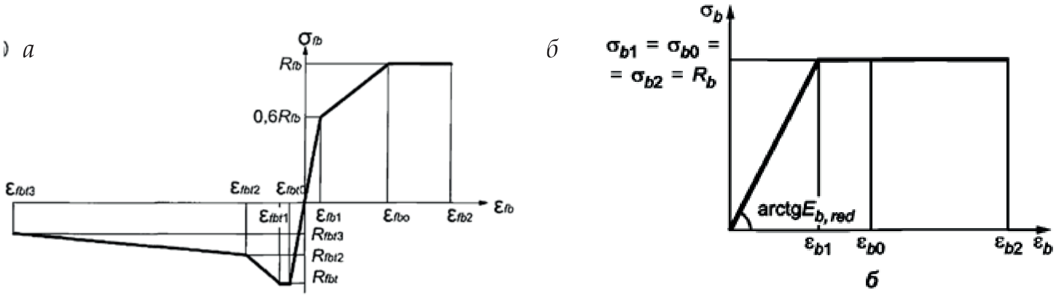

Fig. 1. Deformation models: a, fiber-reinforced concrete; b, concrete

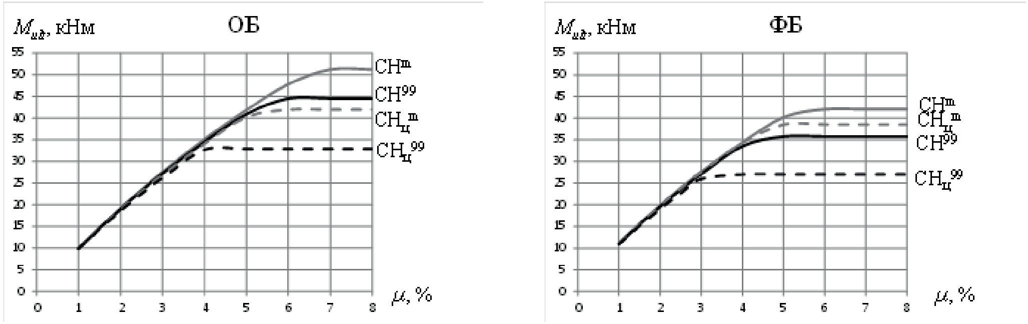

Fig. 1. Influence of reinforcement on the average (SC^m) and 99% probability (SC^{99}) strength

The influence of the factors of fatigue transformation of composites increases significantly in reinforced elements and affects the following:

- reduction in the level of stabilization of bearing capacity;
- differences in M_{ult} indicators, determined by the parameters of the average and standard (99%) levels of probability.

Concurrently, in the bending elements of classical reinforcement, a 20%–30% (depending on μ) decrease in postcyclic strength is probable.

To establish the cause-and-effect relationships of the increased dynamic stability of normally reinforced fiber composites, an additional assessment of the parameters of the compressed zone was performed using standard deformation models (Fig. 1, Table 2), which enabled identification of the stress distribution diagram of the compressed zone per the parameters of its layer-by-layer deformation. The acceptability of this approach for a comparative analysis of fatigue life is confirmed by the practical identity of the ratios of the heights

Table 2

Changes in the Parameters of the Compressed Zone under Cyclic Impacts

Series and state of the stage	Percentage of reinforcements	Based on the ultimate forces			Based on the deformation model		
		Comp. part hei.	Shear area	Ultimade moment	Comp. part hei.	Shear area	Ultimade moment
	μ	x	A_c	M_{ult}	x	A_c	M_{ult}
	%	sm	MPa·sm	кN·m	sm	MPa·sm	кN·m

End of Table 2

CC SC^{99}	1	1,5	59,5	9,97	6,26	66,34	9,44
	1,5	2,24	89,25	14,62	7,22	97,07	13,82
	2	2,99	119	19,04	8,03	128,82	18,15
	2,5	3,74	148,75	23,25	8,69	160,72	22,38
	3	4,49	178,5	27,23	9,21	189,4	26,41
CC PC$_{C}^{99}$	1	1,88	59,5	9,85	6,01	65,18	9,44
	1,5	2,83	89,25	14,36	6,95	94,64	13,79
	2	3,77	119	18,58	7,25	125,93	18,08
	2,5	4,71	148,75	22,53	8,42	154,21	22,04
	3	5,62	178,5	26,19	11,41	181,71	25,7
FC SC^{99}	1	2,25	73,17	11,11	7,42	78,58	11,09
	1,5	3,14	102,23	15,52	8,24	108,96	15,27
	2	4,03	131,29	19,65	8,94	139,65	19,36
	2,5	4,93	160,36	23,53	9,52	167,51	23,26
	3	5,82	189,42	27,14	10,1	196,69	26,92
FC PC$_{C}^{99}$	1	2,72	72,81	10,94	6,74	77,84	10,94
	1,5	3,8	101,73	15,17	7,62	107,86	15,17
	2	4,87	130,65	19,09	8,37	135,51	19,07
	2,5	5,95	159,57	22,68	9,1	159,93	22,13
	3	7,03	188,48	25,96	11,37	186,27	25,59

and areas of the compressed zone of the considered elements. Assumably, the established excess strength of bending fiber-containing elements can be explained through an increased ability to redistribute forces [13, 14] and consequently, a greater completeness of the stress diagram (Fig. 3). The difference in stresses in the corresponding sections of the elements increases in the layers adjacent to the neutral zone of the elements.

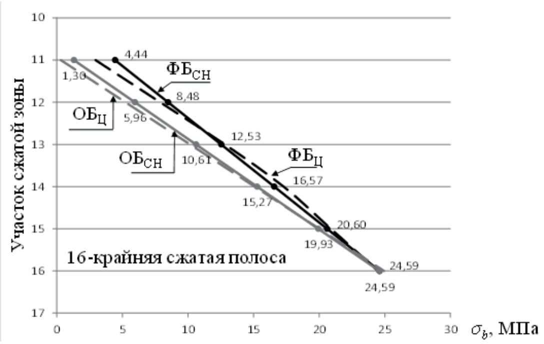

Fig. 3. Layer-by-layer change in the stresses of the compressed zone

Conclusions. Fiber reinforcement of concrete with polypropylene fibers:

- increases the load-bearing capacity of bending reinforced concrete elements when their structural reinforcement is under the limiting one;
- increases the fatigue resistance of the elements due to the development of internal friction.

REFERENSES

1. Kuzovchikova E.A., Yashin A.V. Investigation of influence of low-cycle compression impact on deformability, strength and structural changes of concrete. *Izvestiia vuzov. Stroitelstvo i arkhitektura* [Universities News. Construction and architecture], 1976, no. 10, pp. 30–35 (in Russian)

2. Isojeh B., El-Zeghayar M., Vecchio F.J. Concrete damage under fatigue loading in uniaxial compression. ACI Materials Journal. 2017. No. 114 (2). P. 225–235. DOI:10.14359/51689477

3. Gao L., Hsu, T.C.C. Fatigue of concrete under uniaxial compression cyclic loading. ACI Materials Journal. 1998. No. 95(5). P. 575–581.

4. Rabinovich F.N. *Kompozity` na osnove dispers-*

no-armirovanny`x betonov. Voprosy` teorii i proektirovaniya, texnologiya, konstrukcii [Composites based on dispersedly-reinforced concrete. Questions on theory and design, technology, constructions]. Moscow, ASV, 2004. 563 p.

5. Huang B., Li Q., Xu S., Zhou B. Effect of loading frequency on the fatigue behavior of ultra-high toughness cementitious composites in compression 14th International Conference on Fracture (ICF 14) June18-23, 2017, Rhodes, Greece.

6. Liu F., Zhou J. Fatigue strain and damage analysis of concrete in reinforced concrete beams under constant amplitude fatigue loading. Shock and Vibration. 2016. DOI:10.1155/2016/3950140

7. Cachim P.B., Figueiras J.A., Pereira P.A.A. Fatigue behavior of fiber-reinforced concrete in compression. Cement and Concrete Composites. 2002. No. 24(9). P. 211–217.

8. Paskova T., Meyer C. Low-cycle fatigue of plain and fiber reinforced concrete. ACI Materials Journal. 1997. No. 94(4). P. 273–285.

9. Ramakrishnan V., Gollapudi S., Zellers R. Performance Characteristics and Fatigue of Polypropylene Fiber Reinforced Concrete. SP-105, American Concrete Institute, Detroit, 1987. P. 159–177.

10. Korneeva I.G., Pinus B.I. Deformation fatigue fibroproliferative concrete under dynamic effects. Contemporary Problems of Architecture and Construction Proceedings of the 12th International Conference on Contemporary Problems of Architecture and Construction, November Saint Petersburg, 25–26, 2020, Pub. Location London Imprint CRC Press eBook ISBN 9781003176428. P. 198–202. DOI: 10.1201/9781003176428

11. Korneeva I.G., Pinus B.I. Energy aspects of low-cycle fatigue of fibropolypropylene concrete. IOP Conf. Series: Materials Science and Engineering International Conference on Construction, Architecture and Technosphere Safety Sochi, 6-12 September 2020 г. № 962 IOP Publishing, United Kingdom ISSN:1757-899X DOI: 10.1088/1757-899X/962/2/022020

12. Sorokin E.S. *K teorii vnutrennego treniya pri kolebaniyax uprugix system* [On the theory of internal friction during oscillations of elastic systems]. Moscow, Gosstrojizdat, 1960. 131 p.

13. Li C. Y., Song Y. P. Study of residual strain of concrete under fatigue loading. Journal of Dalian University of Technology. 2001. vol. 41, No. 3. P. 355–358.

14. Lee M. K., Barr B. I. G. An overview of the fatigue behaviour of plain and fibre reinforced concrete. Cement & Concrete Composites. 2003. No. 26(2004). P. 299–305.

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