2020. 16(4). 290–297

СТРОИТЕЛЬНАЯ МЕХАНИКА ИНЖЕНЕРНЫХ КОНСТРУКЦИЙ И СООРУЖЕНИЙ

STRUCTURAL MECHANICS OF ENGINEERING CONSTRUCTIONS AND BUILDINGS

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ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ
EXPERIMENTAL RESEARCHES

DOI 10.22363/1815-5235-2020-16-4-290-297
UDC 624.012.45

RESEARCH PAPER

Results of experimental studies of high-strength fiber reinforced concrete beams with round cross-sections under combined bending and torsion

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Article history:
Received: April 07, 2020
Revised: June 24, 2020
Accepted: July 10, 2020

For citation
Travush V.I., Karpenko N.I., Kolchunov Vl.I., Kaprielov S.S., Demyanov A.I., Bulkin S.A., Moskovtseva V.S. Results of experimental studies of high-strength fiber reinforced concrete beams with round cross-sections under combined bending and torsion. *Structural Mechanics of Engineering Constructions and Buildings.* 2020;16(4):290–297. http://dx.doi.org/10.22363/1815-5235-2020-16-4-290-297

Abstract

The aim of the work – experimental investigation on crack propagation and deformation in high-strength fiber reinforced concrete beams with round cross-sections under combined bending and torsion for the development of practical methods of crack resistance, deformation and strength analysis of such structures, and also for the accumulation of new experimental data on resistance under combined loading. ***Method*** is experimental-theoretical. ***Results.*** Deflection plots and force-deformation relationships for high-strength fiber reinforced concrete beams with round cross-sections under combined bending and torsion are determined experimentally. Principal deformations in terms of elongation and compression of concrete for the experimental beam structures with high torsion to bending moment ratio are determined. It is established that for high-strength fiber reinforced concrete structures of circular cross-section, generally, development of one-two discrete cracks is observed, therefore the circular shape of the cross-section slightly reduces the concentration defined by the material structure of high-strength concrete. On the basis of the conducted investigation on high-strength fiber reinforced concrete structures with circular sections, new experimental data on the combined stress-strain state in the studied areas of resistance is obtained, such as: values of generalized cracking, and failure, load, its level relative to the ultimate load; distance between the cracks at different stages of crack propagation; crack widths at principal reinforcement axis level, at a double diameter distance from the principal rebar axes and also along the entire crack profile at various stages of loading; coordinates of nonplanar crack formations; patterns of crack formation, development and opening in reinforced concrete structures under combined bending and torsion.

Keywords: reinforced concrete structures, high-strength concrete, fiber reinforced concrete, combined bending and torsion, experimental results

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Introduction

In the last two-three decades the publications of researchers from different countries give increasingly greater attention to the investigation of reinforced concrete under special and emergency loadings, which cause combined stress state in the structures [1–8]. Architectural solutions and structural element cross-section shapes used in design practice are becoming more complex as well. It should be noted that until now a relatively limited number of studies on the stress-strain state of structures under combined loading have been conducted. In this field a number of Russian and various international studies on reinforced concrete structures from regular concrete can be mentioned, for example [9–15]. Even less studies are devoted to testing beams and other structures under combined bending and torsion. Existing experimental results, according to their methodologies [11; 13; 16–18], relate to particular individual stress-strain state cases, boundary condition kinds, reinforcement types, concrete grades and types. At the same time, resistance of reinforced concrete structures to combined loading (bending and torsion) until now remains globally underexplored due to a number of reasons, primarily due to the complexity of the experiment. As to high-strength reinforced concrete and fiber reinforced concrete structures, the studies of their combined stress state and crack propagation properties are practically absent. This is evidenced by the fact that in Russian, European, US and other countries' building codes there are no recommendations on designing structures under combined bending and torsion. There are general guidelines of particular individual stress state cases only for ultimate limit state and only for rectangular cross-sections of structures, which do not always correspond well enough to the real behavior of reinforced concrete in the stage of crack formation and development and also in the ultimate stage of their resistance.

In [19–21] the authors begin the publications on the conducted experimental studies of high-strength reinforced concrete structures under combined loading. Here are the methodologies and some particular test results on structures with high-strength concrete of grade B100 or higher for rectangular, hollow circular and solid circular beam cross-sections. Following on these studies, the present article provides the experimental results of high-strength fiber reinforced concrete circular beams under combined loading. It is also worth mentioning that the cross-sectional shape accepted for the experiment is fairly often used in design practice (cores of high-rise buildings that act as cantilever beams, power transmission line supports, factory building columns, etc.).

Investigation results and their analysis

A series of six sample beams from high-strength fiber reinforced concrete has been tested (see Table). The following notation is used for the test structures: FB – fiber reinforced concrete beam, CR – circular cross-section, 720 – value of external force couple arm for creating torsional moment, (1) – number of test sample. Reinforcement details in the cross-sections of test sample structures are presented in Figure 1. Longitudinal reinforcement of the test samples is grade A240C and 6 mm diameter, positioned along the cross-section perimeter. Transverse reinforcement is grade A240C, 6 mm diameter with 100 mm spacing. Metallic plates 8 mm thick with reinforcement anchors from 10 mm A240C grade bars were placed on the ends of the test samples. A series of test samples were made from grade B130 high-strength fiber reinforced concrete. More detailed information on the structure of beam test samples, reinforcement details and testing methods are given in [20].

Obtained experimental results, their processing and analysis allow to state the following.

A characteristic feature of crack propagation in high-strength fiber reinforced concrete structures with circular cross-section is that they develop several discrete cracks, from which one stands out with increasing load and which then governs the failure. This crack becomes predominant over the others at the load steps close to failure and has the maximum opening size (Figure 1).

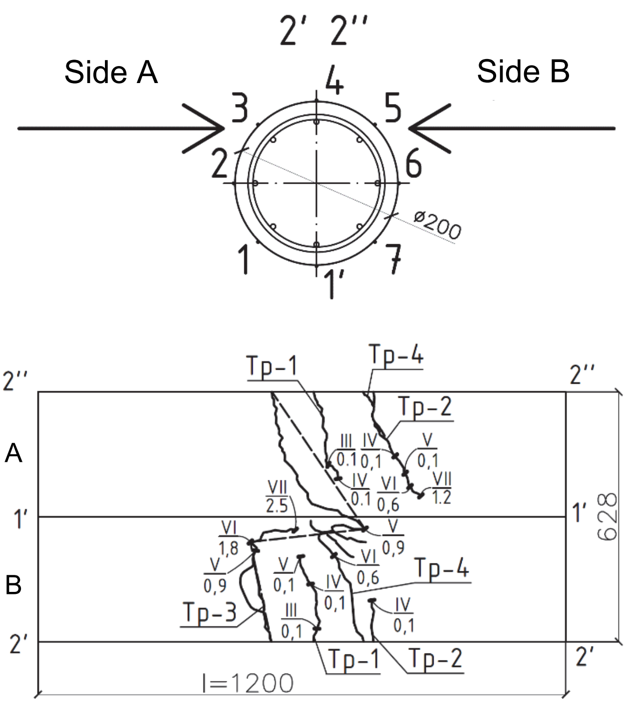

Figure 1. Crack pattern in test sample structure from high-strength fiber reinforced concrete FB-CR-720 (1)

Comparing the obtained crack pattern with the pattern in regular reinforced concrete structures in the acting region of bending and torsional moments [11; 18; 22] it can be stated that such structures form an entire network of cracks. In addition to that, with increasing load new cracks are being formed, and correspondingly the distances between them and the intensity of development of the already formed cracks change. Therefore, the deformation concentration in the reinforcement due to crack propagation is decreasing in the structures from regular concrete.

The obtained experimental results on the features and physical process of crack propagation in high-strength fiber reinforced concrete structures allow to conclude that the traditionally applied theoretical model of reinforced concrete deformation for service limit state, which is based on the hypothesis of averaging deformations after crack formation (coefficient ψ_s), needs correction in regards to the reinforced concrete in consideration.

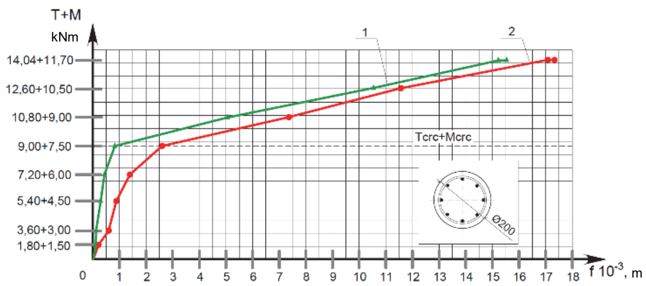

Figure 2. Deflections of test sample structure from high-strength fiber reinforced concrete FB-CR-720 (1):
1 – deflection according to indicator I2;
2 – deflection according to indicator I3

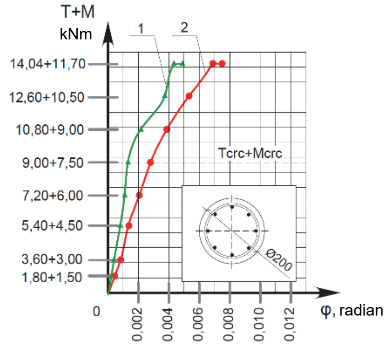

Figure 3. Angles of deflection of test sample structure from high-strength fiber reinforced concrete FB-CR-720 (1):
1 – angle of deflection according to indicators I1–I2;
2 – angle of deflection according to indicators I3–I4

From the analysis of experimental deflections and angles of deflection of tested structures (Figures 2 and 3) it can be noted that the relative cracking load level in fiber reinforced concrete beams (T+M)/(T_u+M_u) is significantly higher than in structures from regular concrete. For all FB-CR-720 beam test samples the mentioned ratio comprised 0,55–0,64. This implies that the presence of fiber in structures from high-strength reinforced concrete under the considered stress state substantially increases the second stage of the stress-strain state, and this feature should be accounted for in the design.

The obtained experimental graphs of concrete compressive strains in the test samples from strain gauge measurements are of interest as well (Figures 4 and 5). Strain gauge rosettes were processed after the gauge measurements according to the know formulas for determination of the principal tensile (compressive) deformations of concrete.

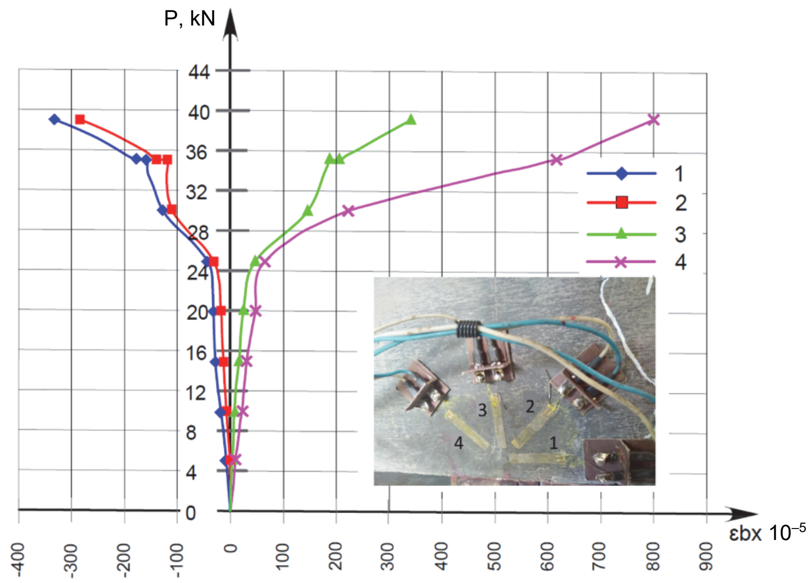

Figure 4. Loading force to concrete deformation relationship for test sample structure from high-strength fiber reinforced concrete FB-CR-720 (1), side A

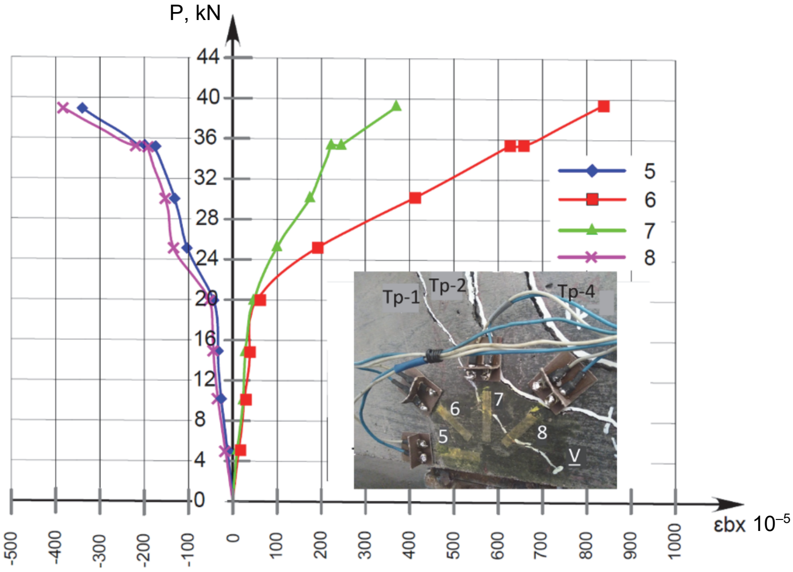

Figure 5. Loading force to concrete deformation relationship for test sample structure from high-strength fiber reinforced concrete FB-CR-720 (1), side B

So, with regard to FB-CR-720 (1) beam side A (Figure 4) the following is obtained:

– load step $P_i/P_{max} = 1,0,$

$$\varepsilon_1 = \frac{-231+340}{2} + \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}((-231)-(-183))^2+\\+((-183)-340)^2\end{matrix}} = 427.5, \quad (1)$$

$$\varepsilon_2 = \frac{-231+340}{2} - \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}((-231)-(-183))^2+\\+((-183)-340)^2\end{matrix}} = -318.5, \quad (2)$$

$$\mathrm{tg}2\varphi = \frac{2(-183)-((-231)+340)}{-231-340} = 0,83\left(20^\circ\right); \quad (3)$$

– load step $P_i/P_{max} = 0,8,$

$$\varepsilon_1 = \frac{-130+245}{2} + \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}((-130)-(-112))^2+\\+((-112)-245)^2\end{matrix}} = 261, \quad (4)$$

$$\varepsilon_2 = \frac{-130+245}{2} - \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}((-130)-(-112))^2+\\+((-112)-245)^2\end{matrix}} = -311, \quad (5)$$

$$\mathrm{tg}2\varphi = \frac{2(-112)-((-130)+245)}{-130-245} = 0,29\left(8^\circ\right); \quad (6)$$

– load step $P_i/P_{max} = 0,6,$

$$\varepsilon_1 = \frac{-116+98}{2} + \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}((-116)-(-96))^2+\\+((-96)-98)^2\end{matrix}} = 129.5, \quad (7)$$

$$\varepsilon_2 = \frac{-116+98}{2} - \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}((-116)-(-96))^2+\\+((-96)-98)^2\end{matrix}} = -147.5, \quad (8)$$

$$\mathrm{tg}2\varphi = \frac{2(-96)-((-116)+98)}{-116-98} = 0,81\left(20^\circ\right). \quad (9)$$

With regard to FB-CR-720 (1) beam side B (Figure 5) the following is obtained:

– load step $P_i/P_{max} = 1,0,$

$$\varepsilon_1 = \frac{-345+370}{2} + \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}((-345)-840)^2+\\+(840-370)^2\end{matrix}} = 917.5, \quad (10)$$

$$\varepsilon_2 = \frac{-345+370}{2} - \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}((-345)-840)^2+\\+(840-370)^2\end{matrix}} = -892.5, \quad (11)$$

$$\mathrm{tg}2\varphi = \frac{2\cdot 840-((-345)+370)}{-345-370} = -2,31\left(33^\circ\right); \quad (12)$$

– load step $P_i \big/ P_{\max} = 0{,}8$,

$$\varepsilon_1 = \frac{-234+273}{2} + \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}\left(\left(-234\right)-612\right)^2 + \\ +\left(612-273\right)^2\end{matrix}} = 666.5, \quad (13)$$

$$\varepsilon_2 = \frac{-234+273}{2} - \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}\left(\left(-234\right)-612\right)^2 + \\ +\left(612-273\right)^2\end{matrix}} = -627.5, \quad (14)$$

$$\mathrm{tg}2\varphi = \frac{2\cdot 612 - \left(\left(-234\right)+273\right)}{-234-273} = -2{,}34\left(33^\circ\right); \qquad (15)$$

– load step $P_i \big/ P_{\max} = 0{,}6$,

$$\varepsilon_1 = \frac{-203+220}{2} + \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}\left(\left(-203\right)-329\right)^2 + \\ +\left(329-220\right)^2\end{matrix}} = 394, \quad (16)$$

$$\varepsilon_2 = \frac{-203+220}{2} - \frac{\sqrt{2}}{2}\sqrt{\begin{matrix}\left(\left(-203\right)-329\right)^2 + \\ +\left(329-220\right)^2\end{matrix}} = -377, \quad (17)$$

$$\mathrm{tg}2\varphi = \frac{2\cdot 329 - \left(\left(-203\right)+220\right)}{-203-220} = -1{,}52\left(28^\circ\right). \qquad (18)$$

Experimental investigation of the considered beam structures from high-strength reinforced concrete produces a number of important parameters for the evaluation of resistance of reinforced concrete structures to combined loading – bending with torsion, given in Table. They include the following: coordinates of nonplanar crack formation, generalized cracking load $R_{\sup,crc}$; failure load $R_{\sup,u}$; width of nonplanar crack which governed failure on the level of longitudinal and transverse reinforcement axes, at a double diameter distance from reinforcement axes and along the entire crack profile; changes in the distance between cracks l_{crc} with increasing load.

Table

Experimental parameters of resistance of fiber reinforced concrete structures under combined bending and torsion

Structure notation	$R_{\sup,crc}$, kN	$R_{\sup,\max}$, kN	$P_{\max}$, kN	Load step, P_i / $P_{\max}$	Nonplanar crack, which governed failure			Actual height of the compression zone, x_{fact}, mm	Coordinates of nonplanar crack formation	
					$a_{crc,1}$, mm	$a_{crc,2}$, mm	$l_{crc,\max}$, mm		$x_{\exp}$, mm	$y_{\exp}$, mm
FB-CR-720 (1) Side A	12.5	17.5	35.0	0.57	–	–	368	–	–35.3	–22.5
				0.85	0.2	0.3		50		
				1	1.8	4.8		0		
FB-CR-720 (1) Side B				0.57	–	–		–	–154.7	43.9
				0.85	0.1	0.2		70		
				1	1.2	1.6		20		
FB-CR-720 (2) Side A	15.0	19.5	39.0	0.64	–	–	377	–	–44.8	–18.0
				0.77	0.1	0.2		40		
				1	0.5	1.8		0		
FB-CR-720 (2) Side B				0.64	–	–		–	–168.1	35.6
				0.77	–	–		95		
				1	0.1	1		15		
FB-CR-720 (3) Side A	17.5	260	52.0	0.67	–	–	224	-	122.5	–93.4
				0.76	0.1	0.17		102		
				1	3.5	4		10		
FB-CR-720 (3) Side B				0.67	–	–		–	–116.8	–36.4
				0.62	0.1	0.11		30		
				0.82	0.1	0.16		0		

The actual height of compression zone x_{fact} and the height of compressed concrete above the inclined crack x_B in the effective section 1–1 (going through the end of the nonplanar crack), deflections and angles of deflection, values of nonplanar cracks projections onto the horizontal were also determined.

As a result, the obtained experimental data allow to verify the accuracy of the analytical model of resistance of fiber reinforced concrete structures to combined bending and torsion, and will be useful for the accumulation of new experimental information on the stress-strain state of reinforced concrete structures under combined loading.

Conclusion

Experimental investigation of beams from high-strength fiber reinforced concrete with circular cross-section produced new data on the stress-strain state parameters of such structures under combined bending and torsion. They include the values of generalized cracking load and failure load, concrete deformation in the region of the reference section, structure deflections and angles of deflection, nonplanar crack patterns and the distance between cracks at different loading stages, crack widths on the level of principal reinforcement axis and at a double diameter distance from this axis, and also along the entire crack profile at different loading stages, coordinates of nonplanar crack formation at the considered stress state.

It is established that for beams from high-strength fiber reinforced concrete with circular cross-section during cracking several discrete cracks propagate, from which one stands out with increasing load and which then governs the failure. At the stages close to failure this crack becomes predominant over the other and has the maximum width. It was also established that the relative cracking load in fiber reinforced concrete structures is high and it comprised 0.55–0.64 from the failure load for the tested structures.

The obtained and previously undetermined experimental parameters on the stress-strain state of fiber reinforced concrete structures are relevant for the analysis and verification of the developing analytical model, evaluation of resistance of such structures under combined bending and torsional moments.

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DOI 10.22363/1815-5235-2020-16-1-290-297

НАУЧНАЯ СТАТЬЯ

Результаты экспериментальных исследований сложнонапряженных балок круглого поперечного сечения из высокопрочного фиброжелезобетона

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История статьи:
Поступила в редакцию: 7 апреля 2020 г.
Доработана: 24 июня 2020 г.
Принята к публикации: 10 июля 2020 г.

Аннотация

Цель исследования – экспериментальное изучение особенностей трещинообразования и деформирования сложно напряженных балок круглого поперечного сечения из высокопрочного фиброжелезобетона для развития практических методов расчета трещиностойкости, жесткости и прочности таких конструкций при кручении с изгибом, а также для накопления новых опытных данных о сложном силовом сопротивлении. ***Метод исследования*** – экспериментально-теоретический. ***Результаты.*** Экспериментально определены опытные значения и построены графики прогибов и углов поворота, зависимостей деформаций бетона от нагрузки для сложнонапряженных балок круглого поперечного сечения из высокопрочного фиброжелезобетона. Определены главные деформации удлинения и укорочения бетона для опытных конструкций балок с высоким уровнем соотношения крутящего и изгибающего моментов. Установлено, что для железобетонных конструкций из высокопрочного фиброжелезобетона круглого сечения, как правило, наблюдается развитие дискретных одной-двух трещин, следовательно, круглая форма поперечного сечения несколько снижает концентрацию, обусловленную структурой высокопрочного бетона. На основании проведенных испытаний железобетонных конструкций из высокопрочного фиброжелезобетона круглого сечения получены новые экспериментальные данные о сложном напря-

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Для цитирования
Travush V.I., Karpenko N.I., Kolchunov Vl.I., Kaprielov S.S., Demyanov A.I., Bulkin S.A., Moskovtseva V.S. Results of experimental studies of high-strength fiber reinforced concrete beams with round cross-sections under combined bending and torsion // Строительная механика инженерных конструкций и сооружений. 2020. Т. 16. № 4. С. 290–297. http://dx.doi.org/10.22363/1815-5235-2020-16-4-290-297

женно-деформированном состоянии в исследуемых областях сопротивления, такие как: значения обобщенной нагрузки трещинообразования и разрушения, ее уровень относительно предельной нагрузки; расстояние между трещинами на разных уровнях трещинообразования; ширина раскрытия трещин на уровне оси рабочей арматуры и на удалении двух диаметров от осей арматуры, а также вдоль всего профиля трещины на различных ступенях нагружения; координаты точек образования пространственных трещин; схемы образования, развития и раскрытия трещин железобетонных конструкций при рассматриваемом сложном напряженном состоянии – кручении с изгибом.

Ключевые слова: железобетонные конструкции, высокопрочный бетон, фиброжелезобетон, кручение с изгибом, результаты эксперимента

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