doi: 10.18720/MCE.79.4

Strength of composite steel and concrete beams of high-performance concrete

Прочность железобетонных балок с жесткой арматурой из высокопрочного бетона

V.I. Travush,
GORPROJECT, Moscow, Russia
D.V. Konin,
A.S. Krylov,
JSC Research Center of Construction, Moscow, Russia

Д-р техн. наук, профессор главный конструктор, заместитель генерального директора по научной работе В.И. Травуш,
ЗАО «ГОРПРОЕКТ», г. Москва, Россия
канд. техн. наук, заведующий сектором Д.В. Конин,
научный сотрудник А.С. Крылов,
АО «Научно-исследовательский центр «Строительство», г. Москва, Россия

Key words: reinforced concrete; composite steel and concrete structures; crack width; stresses; strain; standard-based calculation; crack resistance; numerical simulation; verification

Ключевые слова: сталежелезобетон; жесткая арматура; ширина раскрытия трещин; напряжения; относительные деформации; расчет по нормам; трещиностойкость; численное моделирование; верификация

Abstract. A brief review of the use of high-performance concrete in monolithic structures in Russia in recent years is made; the last experimental work for the study of high-performance concrete in composite steel and concrete structures is observed. Strength assessment of composite steel and concrete beams has been carried out by a pure-bending test. The models destruction pattern has been described. Vertical displacement and crack width measurement results have been conducted; comparison with the standardized values has been carried out. The models steel core and concrete stress-strain diagrams have been presented, their features have been pointed out. The existing methods of calculating composite steel and concrete structures have been estimated by the ultimate and service limit state. The results necessary to carry out numerical studies in the sphere of contact interaction have been obtained.

Аннотация. Выполнен краткий обзор применения высокопрочных бетонов в монолитном строительстве в РФ за последние годы; отмечены последние экспериментальные работы по изучению особенностей высокопрочных бетонов в составе комбинированных конструкций. Выполнена оценка прочности сталежелезобетонных балок из высокопрочных бетонов при испытании на чистый изгиб. Описан характер разрушения моделей. Приведены результаты измерений вертикальных перемещений и ширины раскрытия трещин; выполнено сравнение с нормируемыми величинами. Представлены графики напряжений и деформаций в стальном сердечнике и бетоне моделей, отмечены их особенности. Дана оценка существующих методик расчета изгибаемых сталежелезобетонных конструкций по первой и второй группе предельных состояний. Получены необходимые результаты для проведения численных исследований в области контактного взаимодействия.

1. Introduction

Against the background of the rapid development of the construction industry, increasing pace of construction, increasing buildings height, the need for new load-bearing structures materials and their production technologies has arisen. Most of the existing site-cast concrete buildings are made of compression breaking strength class concrete B25…B30. However, there is a tendency in these days to increase the strength class of concrete used especially for high-rise and long-span construction (for example, concrete of B40...B90 compression breaking strength class is used for the buildings of the City

Травуш В.И., Конин Д.В., Крылов А.С. Прочность железобетонных балок с жесткой арматурой из высокопрочного бетона // Инженерно-строительный журнал. 2018. № 3(79). С. 36–44.

of Moscow [1]). At the moment technologies of B80...B100 compression breaking strength class concrete mixture industrial scale production have been developed and successfully tested.

Currently a number of experimental works devoted to studying of composite steel and concrete structures made of high-performance concrete under eccentric compression has been carried out [2, 3]; specific features of the "steel-concrete" contact surface operation [4] have been studied. Use of high-performance concrete in bending structures, especially in a composite cross-section, has not been adequately studied. This shows the actuality of the issues under consideration and of the tests conducted. A series of experiments has been prepared and carried out in order to study the stress-strain state of composite steel and concrete beams. In preparation for the experiment, publications on the improvement of the theoretical foundations of reinforced concrete structures [5–9] and fiber-reinforced concrete [10, 11] were studied. Special attention was paid to research in the field of contact interaction of steel and concrete [12–15], including numerical investigations [16–18]. Issues of numerical modeling of reinforced concrete structures [19] and cracking [20–23] were considered. Examples of the use of high-performance concrete is considered [24, 25].

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.

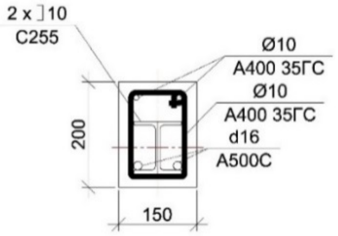
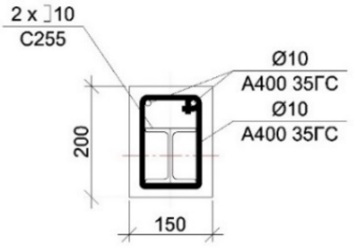
Objectives of the study:

- perform tests of 9 models of beams made of high-performance 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 stress-strain state of the models.

The results of this experiment will be used as the basis for numerical studies of composite steel and concrete beams in a nonlinear setting contact interaction simulation. The obtained experimental data are the necessary stage of work for further verification of calculation methods.

Within the research 9 models of composite steel and concrete beams with rectangular cross-section 200 x 150 mm and a length 1.5 m have been tested. A detailed description of the models is stated in paper [26]. The models characteristics (cross-section type, construction materials) are stated in Table 1.

Table 1. The Models Characteristics

Group of models	Number of models in the group	Concrete compression breaking strength class	μ, % reinforcement ratio	Cross-section
1 (B4)	3	B90	9.13	 **Figure 1. Cross-section for models group 1,2**
2 (B5)	3	B75	9.13	
3 (B6)	3	B90	7.79	 **Figure 2. Cross-section for models group 3**

2. Methods

Preparation of the beams models for the experiment has been carried out in the following sequence: steel cores have been manufactured and frame reinforcement has been tied (Figure 3); resistive-strain sensors have been installed on the pretreated steel surface and protected by epoxy resin (Figure 4); concrete has been poured and resistive-strain sensors have been attached to the concrete surface. The sensors location schemes are shown in Figure 5.

All models have been tested in pure-bending test (Figure 6). Models supports were hinge. Uniform distribution of forces between two points was ensured by steel I-shaped cross arm mounted on the rollers, transferring the load to the beam through steel plates (Figure 7).

Figure 3. Frame reinforcement tying

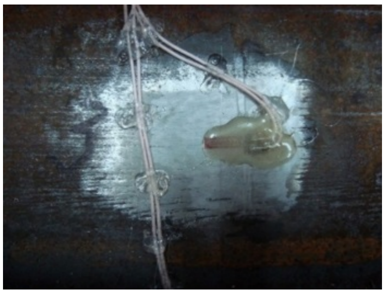


Figure 4. Cleaning of resistive-strain sensors installation places; fixing wires and measuring points protection with epoxy resin

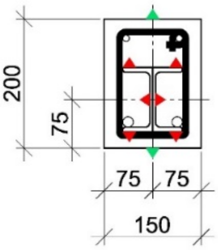


Figure 5a. Diagram of resistive-strain sensors installation on group 1, 2 model

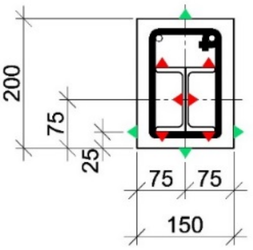


Figure 5b. Diagram of resistive-strain sensors installation on group 3 model

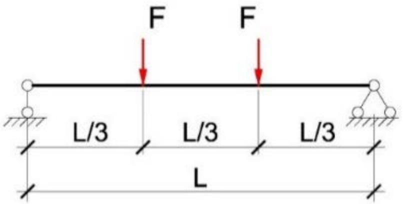


Figure 6. Diagram of load application to the models

Figure 7. Diagram of load transfer to the models

3. Results and Discussion

In order to determine strength properties of concrete 3 test cubes with 10 cm side were prepared for each group of models. The cubes according with Russian State Standard GOST 10180-90 “Concretes. Methods for determining the strength of control samples” test results are stated in Table 2.

Table 2. Test results of the test cubes

Group of models	Concrete cube crushing strength at the age of 28 days, MPa	Concrete cube crushing strength during beams model testing, MPa
1 (B4)	105.3	115.7
2 (B5)	86.7	96.4
3 (B6)	103.8	117.5

All models have been tested in accordance with the provisions of Russian State Standard GOST 8829-94 “Product construction of concrete and reinforced concrete prefabrication. Test methods the loading. Rules for the evaluation of strength, stiffness and crack resistance”. The sequence of the operations performed is described in paper [26].

Before the tests, theoretical calculations was carried out: the ultimate bending moment values were calculated that can be perceived by the models according to Construction Rules SP 266.1325800.2016

“Composite steel and concrete structures. Design rules” in accordance with the formulas (6.52), (6.53). The actual concrete strength were used in the calculations. Theoretical calculation results and experimental ultimate moments are stated in Table 3.

Table 3. Ultimate bending moment

Group of models	**$M_{theor}^{ultimate}$, kNm**	**$M_{experimental}^{ultimate}$ (average for models group), kNm**	**Average deviation for models group, %**
1 (B4)	91.89	90.94	-1.0
2 (B5)	86.62	88.66	2.3
3 (B6)	71.02	77.03	7.8

Table 3 shows that theoretical calculations have a fairly good convergence with the test results (the maximum deviation is 7.8 %), which indicates the possibility to apply for the high-performance concrete the approach stated in Russian Construction Rules SP 266.1325800.2016 “Composite steel and concrete structures. Design rules”.

In the course of the experiment, the crack width and crack propagation mode were registered. The crack width (experimental and theoretical) and the loads under which it has been tested are shown in Table 4.

According to the Manual for design of reinforced concrete structures with rigid reinforcement [27], calculations of crack formation normal to the longitudinal axis of the bending elements are made on the following condition:

$$\mathrm{M} \le \mathrm{M}_{\text{т}} \qquad (1)$$

where $\mathrm{M}_{\text{т}}$ is the moment perceived by the cross-section normal to the element's longitudinal axis during cracks formation.

The theoretical crack width normal to the longitudinal axis of the bending element is determined according to empirical formula (43) [27]:

$$a_{crc} = \mathrm{c}_l \frac{\sigma_{\mathrm{a}}}{E_{\mathrm{a}}} 25(3.5 - 100\mu)\sqrt[3]{d_{red}} \qquad (2)$$

where c_l is the coefficient depending from the duration of load application, $\mathrm{c}_l = 1.5$;

σ_{a} is the stress in the bars of the edge tensioned reinforcement;

E_{a} is the reinforcement steel elasticity modulus;

μ is the cross-section reinforcement ratio equals to the ration between the area of the entire tensioned reinforcement to concrete area, but not more than 0.02;

d_{red} is the equivalent diameter of steel core and beam reinforcement located in the tensioned cross-section area.

Table 4. Crack width

Group of models	**Test load, kN**	**Crack Width, m×10^{-3}**		**Deviation, %**
		Theoretical in accordance with [27]	Experimental *	
1 (B4)	248.29	0.229	0.283	19.2
2 (B5)	242.06	0.224	0.230	2.6
3 (B6)	211.45	0.231	0.344	32.8

The values given in Table 4 (both theoretical and experimental) do not exceed the maximum allowable crack width from the condition of the reinforcement safety $a_{crc,ult} = 0.4\,mm$ as specified in Russian Construction Rules SP 63.13330.2012 “Concrete and reinforced concrete structures” with short-term crack opening. However, significant deviations between the theoretical values obtained according to [27] and the actual crack width have been found out. The difference in values is up to 33 %, which indicates the necessity to make changes in the methodology used to calculate the crack resistance set forth in the Manual [27].

Destruction of all model groups was similar and was characterized by the appearance of a large number of vertical and inclined cracks as well as horizontal cracks along the upper and lower sides of the beam, which led to partial spall of the protective layer concrete and exposure of the reinforcement cage and steel cores fragments in the extreme thirds of the beam – between the bearing point and the load application point at the last stages (Figure 8). Crack formation due to the high-performance concrete fragility began at the early stages of loading. Thin cracks (visible without optical instruments) were noted at the first loading stage for almost all models (the first loading stage corresponded to less than 10 % of the ultimate breaking load).

Figure 8. Representative beam destruction

Based on the test results, graphs of the models vertical displacements under load (Figure 9) and diagrams illustrating the crack width at each loading stage (Figure 10) have been made.

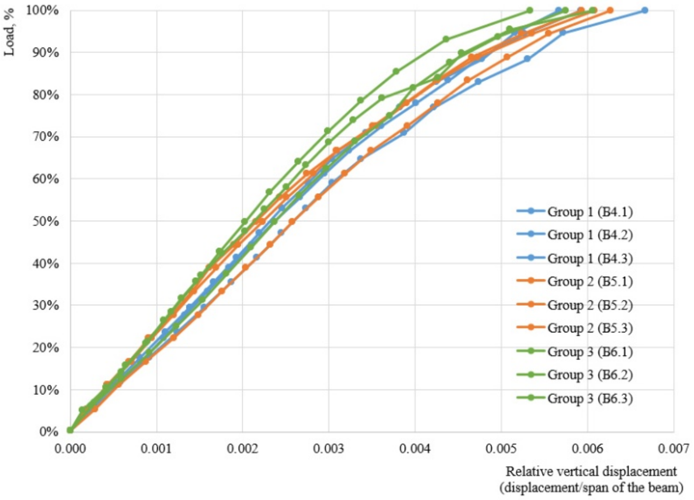


Figure 9. Vertical models displacements by loading steps

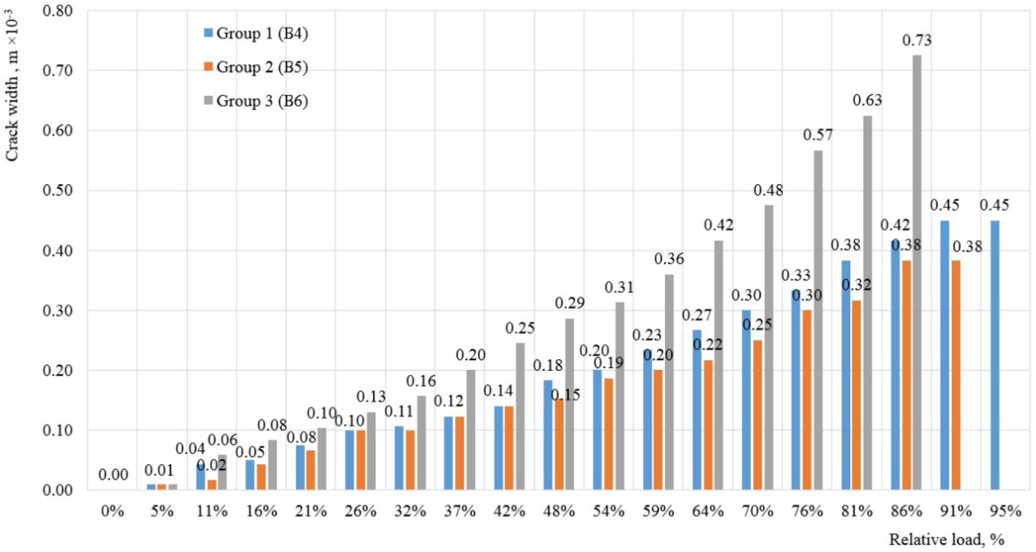


Figure 10. Crack width in the models by loading steps

In general, vertical displacements of all models before destruction do not exceed 9 mm, which is 1/155 of the beam span value (according to the test diagram). Herewith, the maximum crack width for groups 1, 2, 3 was 0.47 mm, 0.40 mm and 0.68 mm respectively. The greatest crack width was registered for the beams with a smaller reinforcement percentage (group 3 (B6)).

As a result of the resistive-strain sensors readings processing stress and strain diagrams for the concrete and steel parts of the models were made. The graphs are of similar nature for different groups of models. Figures 11–14 show the dependencies for models group 1.

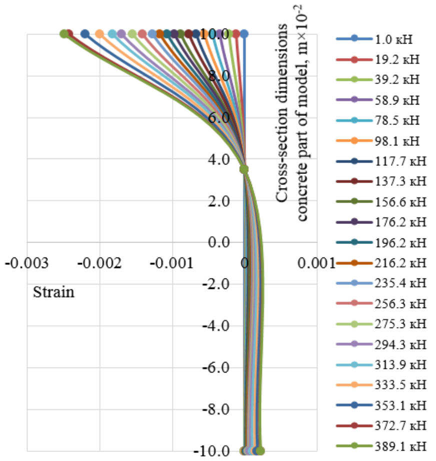


Figure 11. Strains in the concrete part of model by loading steps

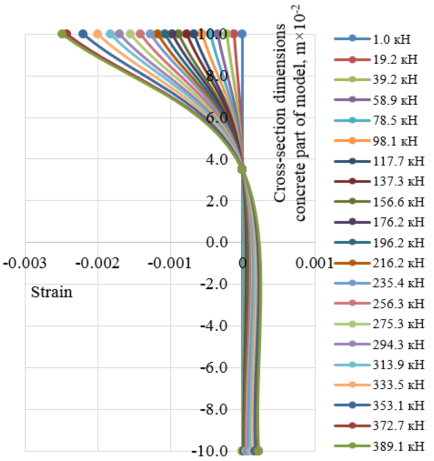


Figure 12. Strains in the rigid reinforcement of model by loading steps

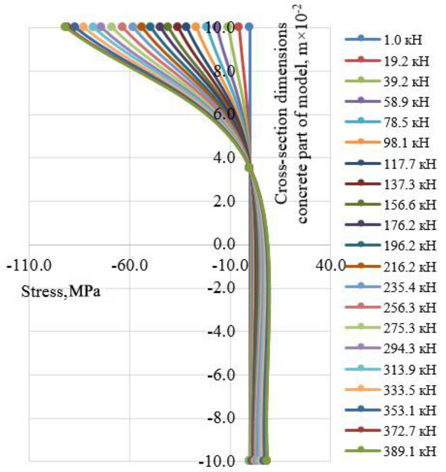


Figure 13. Stress in the concrete part of model by loading steps

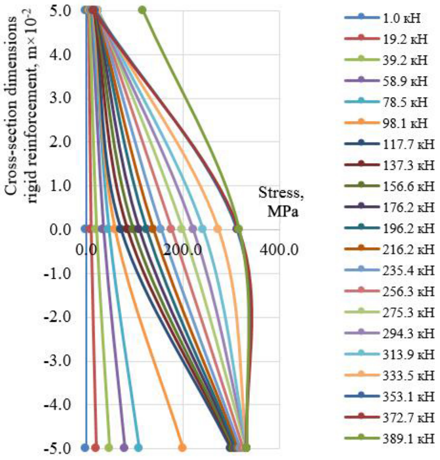


Figure 14. Stress in the rigid reinforcement of model by loading steps

The cross-section neutral axis near the top flanges of the U-profiles can be traced clearly in the graphs. The plane section hypothesis is observed up to the total load on the model of 235 kN (Figure 14), 203 kN and 213 kN, which constitutes 60 %, 53 % and 64 % of the ultimate breaking load for groups 1, 2 and 3 respectively. Apparently, further loading caused the influence of the progressive cracks.

Detailed studies of the characteristics of the high-performance concrete used are given in [28], where the ultimate unit strains (the maximum strains at the moment before the test sample destruction during bending tests) of the compressed concrete are fixed at 0.00254 value. The experimental values of the unit compression strains before destruction of individual models obtained within the framework of the present study made up 0.002975, which is 17 % higher than the values given in [27], but almost completely coincides with the values in Russian Construction Rules SP 63.13330.2012 “Concrete and reinforced concrete structures”. This result is probably achieved due to the fact that concrete works as part of a composite construction. The excess ultimate tensile strains (obtained experimentally) have been noted as compared with Russian Construction Rules SP 63.13330.2012. This can be explained by the formation and opening of a large number of cracks in the tensioned part of the cross-section, some of which fell within the resistive-strain sensor gauge length, which increased its readings. Comparison of the obtained unit strain values at the time of the models destruction and the values indicated in [28] and Construction Rules SP 63.13330.2012 is given in Table 5.

Table 5. Ultimate strains of concrete models

Group of models	Experiment		Construction Rules SP 63.13330.2012		According to [28]		Eurocode 2	Average deviation from SP 63.13330.2012, %	Average deviation from [28], %
	Compression	Tension	Compression	Tension	Compression	Tension		Compression	Compression
1 (B4)	0.00249	0.00022	0.00297	0.00015	0.00254	0.00048	0.0026	19.5	5.9
	0.00234	0.00381							
	0.00234	0.00381							
2 (B5)	0.00274	0.00025	0.00322	0.00015	0.00254	0.00048	0.0026	14.7	-8.2
	0.00285	0.00381							
	0.00266	0.00028							
3 (B6)	0.00290	0.00381	0.00297	0.00015	0.00254	0.00048	0.0026	4.3	-11.9
	0.00298	0.00381							
	0.00265	0.00036							

4. Conclusions

1. A set of works of composite steel and concrete structures models bending test has been carried out. Nine models made of high-performance concrete of B75 ... B90 compression breaking strength class have been tested.

2. Behavior of composite steel and concrete structures with the use of high-performance concrete in the calculations for the ultimate limit state (ULS) is well described by the calculation methods presented in Russian Construction Rules SP 266.1325800.2016 “Composite steel and concrete structures. Design rules” – deviation between the theoretical and experimental values does not exceed 8%.

3. The results of the calculations performed for the service limit state (SLS) according with “Manual for design of steel and concrete structures” have significant deviations from the experimental data. The formulas given in Manual for determining crack width give the erroneously low result in relation to the experimental data. The difference in values is up to 33%, which indicates the necessity to make changes in the methodology used to calculate the crack resistance set forth in Manual.

4. The process of destruction of all tested models was similar and characterized by abundant crack formation (vertical and inclined cracks along the lateral sides of the models and horizontal ones along the lower and upper sides). Cracks were formed at the early stages of loading, which confirms high-performance concrete fragility. Thin cracks have been noted at the first loading stage (less than 10% of the ultimate breaking load) for almost all models.

5. In general, the measured strains of the compressed concrete part of the cross-section before destruction do not exceed the limit values given in design rules Construction Rules SP 63.13330.2012 “Concrete and reinforced concrete structures”, but are somewhat overestimated as compared with the experimental data given in scientific work Romkin D.S. “The Influence of age high-strength concrete on the physical, mechanical and rheological properties” and the data given in the Eurocode 2. Such a discrepancy (up to 17 %) was probably due to the casing effect achieved by composite cross-section formation from rigid reinforcement, clamps and longitudinal reinforcement bars.

6. The measured strains of the tensioned concrete part of the cross-section before destruction significantly exceed the corresponding values regulated by Russian Construction Rules SP 63.13330.2012 “Concrete and reinforced concrete structures”. This can be explained by the formation and opening of a large number of cracks in the tensioned part of the cross-section, some of which fell within the resistive-strain sensor gauge length, which increased its readings.

7. It can be concluded from the strain graphs that the plane section hypothesis is observed to a value that constitutes on the average 60 % of the ultimate load.

8. The analysis of the model's displacements under load and cracks opening by loading stages demonstrated absence of abrupt changes and drops (even at the moment before destruction), which is

illustrative of smooth development of plastic strains and cracks. The composite steel and concrete cross-section destruction is not sudden, which is of great importance for design of real structures of buildings and constructions including unique ones, where brittle destruction prevention is required and stricter requirements are applied to the structures reliability.

References

1. Kapriyelov S.S., Travush V.I., Sheynfeld A.V., Karpenko N.I., Kardumyan G.S., Kiseleva Yu.A., Prigozhenko O.V. Modifitsirovannyye betony novogo pokoleniya v sooruzheniyakh MMDTs «Moskva-Siti». [Modified concretes of new generation in the construction of MIBC "Moscow-city"]. *Building materials.* 2006. No. 10. Pp. 8–12. (rus)
2. Travush V.I., Konin D.V., Rozhkova L.S., Krylov A.S., Kapriyelov S.S., Chilin I.A., Martirosyan A.S., Fimkin A.I. Eksperimentalnyye issledovaniya stalezhelezobetonnykh konstruktsiy, rabotayushchikh na vnetsentrennoye szhatiye [Experimental study of composite structures, working for eccentric compression]. *Academia. Architecture and Construction.* 2016. No. 3. Pp. 127–135. (rus)
3. Travush V.I., Konin D.V., Rozhkova L.S., Krylov A.S. Otechestvennyy i zarubezhnyy opyt issledovaniy raboty stalezhelezobetonnykh konstruktsiy na vnetsentrennoye szhatiye [Domestic and foreign experience in research of composite structures for eccentric compression]. *Building and Reconstruction.* 2016. No. 5(67). Pp. 31–44. (rus)
4. Travush V.I., Kapriyelov S.S., Konin D.V., Krylov A.S., Kashevarova G.G., Chilin I.A. Opredeleniye nesushchey sposobnosti na sdvig kontaktnoy poverkhnosti «stal-beton» v stalezhelezobetonnykh konstruktsiyakh dlya betonov razlichnoy prochnosti na szhatiye i fibrobetona [Determination of the bearing capacity in shear on the contact surface "steel-concrete" of steel-concrete structures for concretes of different compressive strength and fiber reinforced concrete]. *Building and Reconstruction.* 2016. No. 4(66). Pp. 45–55. (rus)
5. Krylov S.B., Arleninov P.D. Inzhenernyy podkhod k resheniyu zadachi ob izgibe uprugo-polzuchego sterzhnya [The engineering approach to solving the problem of bending of elastic-creeping rod]. *Structural Mechanics and Analysis of Constructions.* 2013. No. 2(247). Pp. 6–9. (rus)
6. Krylov S.B., Arleninov P.D. Uravneniye izgiba sterzhnya pri kusochno-lineynom zakone deformirovaniya polzuchego materiala [The equation of bending of a rod with a piecewise-linear law of deformation of the creeping material]. *Structural Mechanics and Analysis of Constructions.* 2013. No. 3(248). Pp. 9–11. (rus)
7. Lubliner J., Oliver J., Oller S., Onate E. A. Plastic-damage model for concrete. *International Journal of Solids and Structures.* 1989. Vol. 25. No. 3. Pp. 229–326.
8. Mazars J. A description of micro- and macro-scale damage of concrete structures. *Engineering Fracture Mechanics.* 1986. Vol. 25. No. 5/6. Pp. 729–737.
9. Willam K.J., Warnke E.D. Constitutive model for the triaxial behavior of concrete. *Proceedings, International Association for Bridge and Structural Engineering.* Zurich, 1975. Report 19. Section III. 30 p.
10. Gribniak V., Kaklauskas G., Hung Kwan A.K., Bacinskas D., Ulbinas D. Deriving stress-strain relationships for steel fibre concrete in tension from tests of beams with ordinary reinforcement. *Engineering Structures.* 2012. Vol. 42. Pp. 387–395.
11. Yuguang Y., Walraven J.C., den Uijl J.A. Combined effect of fibers and steel rebars in high performance concrete. *Heron.* 2009. Vol. 54. No. 2/3. Pp. 205–221.
12. Torre-Casanova A., Jason L., Davenne L., Pinelli X. Confinement effects on the steel-concrete bond strength and pull-out failure. *Engineering Fracture Mechanics.* 2013. Vol. 97. Pp. 92–104.
13. Shima H., Chou L.-L., Okamura H. Micro and Macro models for bond in reinforced concrete. *Journal of the Faculty of Engineering: University of Tokyo*. 1987. Vol. XXXIX. No. 2. Pp. 133–194.

Литература

1. Каприелов С.С., Травуш В.И., Шейнфельд А.В., Карпенко Н.И., Кардумян Г.С., Киселева Ю.А., Пригоженко О.В. Модифицированные бетоны нового поколения в сооружениях ММДЦ «Москва-Сити» // Строительные материалы. 2006. № 10. С. 8–12.
2. Травуш В.И., Конин Д.В., Рожкова Л.С., Крылов А.С., Каприелов С.С., Чилин И.А., Мартиросян А.С., Фимкин А.И. Экспериментальные исследования сталежелезобетонных конструкций, работающих на внецентренное сжатие // Academia. Архитектура и строительство. 2016. № 3. С. 127–135.
3. Травуш В.И., Конин Д.В., Рожкова Л.С., Крылов А.С. Отечественный и зарубежный опыт исследований работы сталежелезобетонных конструкций на внецентренное сжатие // Строительство и реконструкция. 2016. № 5(67). С. 31–44.
4. Травуш В.И., Каприелов С.С., Конин Д.В., Крылов А.С., Кашеварова Г.Г., Чилин И.А. Определение несущей способности на сдвиг контактной поверхности «сталь-бетон» в сталежелезобетонных конструкциях для бетонов различной прочности на сжатие и фибробетона // Строительство и реконструкция. 2016. № 4(66). С. 45–55.
5. Крылов С.Б., Арленинов П.Д. Инженерный подход к решению задачи об изгибе упруго-ползучего стержня // Строительная механика и расчет сооружений. 2013. № 2(247). С. 6–9.
6. Крылов С.Б., Арленинов П.Д. Уравнение изгиба стержня при кусочно-линейном законе деформирования ползучего материала // Строительная механика и расчет сооружений. 2013. № 3(248). С. 9–11.
7. Lubliner J., Oliver J., Oller S., Onate E.A. Plastic-damage model for concrete // International Journal of Solids and Structures. 1989. Vol. 25. No. 3. Pp. 229–326.
8. Mazars J. A description of micro- and macro-scale damage of concrete structures // Engineering Fracture Mechanics. 1986. Vol. 25. No. 5/6. Pp. 729–737.
9. Willam K.J., Warnke E.D. Constitutive model for the triaxial behavior of concrete // Proceedings, International Association for Bridge and Structural Engineering. Zurich, 1975. Report 19. Section III. 30 p.
10. Gribniak V., Kaklauskas G., Hung Kwan A.K., Bacinskas D., Ulbinas D. Deriving stress-strain relationships for steel fibre concrete in tension from tests of beams with ordinary reinforcement // Engineering Structures. 2012. Vol. 42. Pp. 387–395.
11. Yuguang Y., Walraven J.C., den Uijl J.A. Combined effect of fibers and steel rebars in high performance concrete // Heron. 2009. Vol. 54. No. 2/3. Pp. 205–221.
12. Torre-Casanova A., Jason L., Davenne L., Pinelli X. Confinement effects on the steel-concrete bond strength and pull-out failure // Engineering Fracture Mechanics. 2013. Vol. 97. Pp. 92–104.
13. Shima H., Chou L.-L., Okamura H. Micro and Macro models for bond in reinforced concrete // Journal of the Faculty of Engineering: University of Tokyo. 1987. Vol. XXXIX. No. 2. Pp. 133–194.
14. Smith F., Brown R. The Shearing Strength of Concrete // Bull. Univ. of Washington. 2001. No. 106. Pp. 205
15. Balazs G.L. Connecting reinforcement to concrete by Bond // Beton- und Stahlbetonbau. 2007. No. 102. Pp. 46–50.
16. Brisotto D.E., Bittencourt V. Simulating bond failure in reinforced concrete by a plasticity model // Computers and Structures. 2012. Vol. 106–107. Pp. 81–90.
17. Kashevarova G.G., Martirosyan A.S. Computational and experimental research of the contact debonding process

14. Smith F., Brown R. The Shearing Strength of Concrete. *Bull. Univ. of Washington.* 2001. No. 106. Pp. 205
15. Balazs G.L. Connecting reinforcement to concrete by Bond. *Beton- und Stahlbetonbau.* 2007. No. 102. Pp. 46–50.
16. Brisotto D.E., Bittencourt. V. Simulating bond failure in reinforced concrete by a plasticity model. *Computers and Structures.* 2012. Vol. 106–107. Pp. 81–90.
17. Kashevarova G.G., Martirosyan A.S. Computational and experimental research of the contact debonding process when rigid reinforcement is pressed into concrete. *PNRPU Mechanics Bulletin.* 2016. No. 3. Pp. 62–75.
18. Sajedi S., Grassemzaden F., Shekarchi M., Faraji F., Solemani M. Numerical investigation on the effect of concrete-FRP bond on the flexural behavior of RC beams. *Concrete Repair, Rehabilitation and Retrofitting III: 3rd International Conference on Concrete Repair, Rehabilitation and Retrofitting ICCRRR-3.* Cape Town, South Africa, 2012. Pp. 417–418.
19. Schnobrich W.C., Suidan M. Finite element analysis of reinforced concrete. *ASCE Journal of the Structural Division.* 1973. October. ST10. Pp. 2109–2122.
20. Broms B.B. Stress distribution in reinforced concrete members with tension cracks. *JACI.* 1965. Vol. 62. No. 9.
21. Goto Y. Cracks formed in concrete around deformed tension bars. *Journal of the American Concrete Institute.* 1971. Vol. 68. No. 4. Pp. 244–251.
22. Coronado C.A., Lopez M.M. Numerical modeling of concrete-FRP debonding using a crack band approach. *Journal of Composites for Constraction.* 2010. Vol. 14. No. 1. Pp. 11–20.
23. Kwon S-H., Ferron R.P., Akkaya Y., Shah S.P. Cracking of fiber-reinforced self-compacting concrete due to restrained shrinkage. *International Journal of Concrete Structures and Materials.* 2007. Vol. I. Pp. 3–9.
24. Almansour H., Lounis Z. Innovative precast bridge superstructure using ultra high performance concrete girders. *Proceedings of the PCI National Bridge Conference*. Phoenix, Arizona, 2007. Pp. 1–21.
25. Graybel B. *Ultra-high performance concrete. Federal Highway Administration*. Publication number FHWA-HRT-11-038. [Electronic resourse]. System requirements: AdobeAcrobatReader. URL: http://www.fhwa.dot.gov/publications/ research/infrastructure/slTuctures/l 103 8/index.cfm (date of application: 14.11.2013).
26. Travush V.I., Konin D.V., Krylov A.S., Kapriyelov S.S., Chilin I.A. Eksperimentalnyye issledovaniya stalezhelezobetonnykh konstruktsiy, rabotayushchikh na izgib [Experimental study of composite structures for bending elements]. *Building and Reconstruction.* 2017. No. 4(72). Pp. 63-71.
27. *Rukovodstvo po proyektirovaniyu zhelezobetonnykh konstruktsiy s zhestkoy armaturoy* [Manual for design of steel and concrete structures]. Moscow: Stroiizdat, 1978. 55 p. (rus)
28. Romkin D.S. *The Influence of age high-strength concrete on the physical, mechanical and rheological properties*. Cand. Diss. (Engineering). Moscow. 2007. 139 p. (rus)

when rigid reinforcement is pressed into concrete // PNRPU Mechanics Bulletin. 2016. No. 3. Pp. 62–75.

18. Sajedi S., Grassemzaden F., Shekarchi M., Faraji F., Solemani M. Numerical investigation on the effect of concrete-FRP bond on the flexural behavior of RC beams // Concrete Repair, Rehabilitation and Retrofitting III: 3rd International Conference on Concrete Repair, Rehabilitation and Retrofitting ICCRRR-3. Cape Town, South Africa, 2012. Pp. 417–418.
19. Schnobrich W.C., Suidan M. Finite element analysis of reinforced concrete // ASCE Journal of the Structural Division. 1973. ST10. Pp. 2109–2122.
20. Broms B.B. Stress distribution in reinforced concrete members with tension cracks // JACI. 1965. Vol. 62. No. 9.
21. Goto Y. Cracks formed in concrete around deformed tension bars // Journal of the American Concrete Institute. 1971. Vol. 68. No. 4. Pp. 244–251.
22. Coronado C.A., Lopez M.M. Numerical modeling of concrete-FRP debonding using a crack band approach // Journal of Composites for Constraction. 2010. Vol. 14. No. 1. Pp. 11–20.
23. Kwon S-H., Ferron R.P., Akkaya Y., Shah S.P. Cracking of fiber-reinforced self-compacting concrete due to restrained shrinkage // International Journal of Concrete Structures and Materials. 2007. Vol. I. Pp. 3–9.
24. Almansour H., Lounis Z. Innovative precast bridge superstructure using ultra high performance concrete girders // Proceedings of the PCI National Bridge Conference. Phoenix, Arizona, 2007. Pp. 1–21.
25. Graybel B. Ultra-high performance concrete. Federal Highway Administration. Publication number FHWA-HRT-11-038. [Electronic resourse]. System requirements: AdobeAcrobatReader. URL: http://www.fhwa.dot.gov/publications/ research/infrastructure/slTuctures/l 103 8/index.cfm (дата обращения 14.11.2013).
26. Травуш В.И., Конин Д.В., Крылов А.С., Каприелов С.С., Чилин И.А. Экспериментальные исследования сталежелезобетонных конструкций, работающих на изгиб // Строительство и реконструкция. 2017. № 4(72). С. 63–71.
27. Руководство по проектированию железобетонных конструкций с жесткой арматурой. М.: Стройиздат, 1978. 55 с.
28. Ромкин Д.С. Влияние возраста высокопрочного бетона на его физико-механические и реологические свойства : дис.… канд. техн. наук : 05.23.01. Москва, 2007. 140 с.

Vladimir Travush,
+7(495)775-75-65; travush@mail.ru

Denis Konin,
+7(926)853-99-73; konden@inbox.ru

Alexey Krylov,
+7(919)723-05-71; kryl07@mail.ru

Владимир Ильич Травуш,
+7(495)775-75-65; эл. почта: travush@mail.ru

Денис Владимирович Конин,
+7(926)853-99-73; эл. почта: konden@inbox.ru

Алексей Сергеевич Крылов,
+7(919)723-05-71; эл. почта: kryl07@mail.ru

Травуш В.И., Конин Д.В., Крылов А.С. Прочность железобетонных балок с жесткой арматурой из высокопрочного бетона // Инженерно-строительный журнал. 2018. № 3(79). С. 36–44.