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Behavior of concrete beams reinforced with fiberglass composite rebar under load

M.V. Molodtsov*, E.P. Vshivkov, V.E. Molodtsova
South Ural State University, Chelyabinsk, Russia
* *E–mail: molodtcovmv@susu.ru*

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Abstract. Fiberglass composite reinforcement has been used in Russia for a long time, but there is still not enough research and necessary related data. Therefore this paper focuses on how exposure to loads affects concrete beams with fiberglass composite and metal reinforcement. The concrete beams samples (80×160×1400) were tested for bending as single-span hinged-supported elements. The load was applied within 20 seconds intervals in order to prevent relaxation of the concrete. All samples collapsed along the cross-section having maximum crack opening in the area of pure bending. The experiments show that the nature of beam collapsing and cracking does not depend on the type of reinforcement. However, the maximum crack opening width for beams with fiberglass composite reinforcement is 28.8 % greater than for beams with metal reinforcement. The value of the maximum deflection for fiberglass is 43.3 % greater. In addition, despite the initial experimental condition of equal loading onset time, the value of the crack formation for beams with fiberglass composite reinforcement is 15.5 % less. The average value of the breaking moment for beams with fiberglass composite reinforcement is 18.06 % less. Taken together, the data obtained in the course of the experiments suggest that the bearing capacity of the elements with fiberglass composite reinforcement, bent along the cross-section, decreases due to the low stiffness of the element itself. Therefore, this type of reinforcement is likely to be applicable for concrete structures on the elastic foundation.

1. Introduction

The construction of reinforced concrete buildings and structures plays a significant part of the overall construction works [1–3]. There is a need to increase - bearing capacity of reinforced concrete structures while reducing their size. In addition, the past decade has seen the rapid development of environmentally friendly construction processes. New safety requirements for construction have appeared and the cost of metal products has risen. All of the above has led to the introduction of new building materials. For example, V.A. Rybakov and K.G. Kozinetc suggested the lightweight steel concrete structures with foam and fiber-cement sheets [4], O.N. Stolayrov and A.S. Gorshkov proposed the use of high-strength textile materials as a component of concrete [5], and R.V. Lesovik and S.V. Klyuyev suggested using composite binders [6, 7].

The use of composite materials is one of the methods of strengthening concrete structures. Composite materials are made of polypropylene, carbon, basalt and glass fiber. The researches in this area have been carried out by D.V. Kyrlapov, A.S. Kyvaeva [8], F.N. Rabinovich [9]. A.I. Kirsanov and O.N. Stolyarov [10], T.S. Morozova and T.S. Kyznetsov [11].

Many researchers have also dealt with the problem of using new polymeric materials for reinforcing various types of concrete. For example, Z. Pehlivanli and his associates investigated the possibilities of using such materials in autoclaved aerated concrete [12], Wenjie Ge and Jiwen Zhang studied flexural behaviors of hybrid concrete beams reinforced with Basalt Fiber Reinforced Plastic (BFRP) bars [13], H. Ahmed experimented with geopolymer concrete (GPC) reinforced with glass fibre-reinforced polymer (GFRP) bars and carbon fibre-reinforced polymer (CFRP) bars [14] etc.

Fiberglass is one of the most promising composite materials [15, 16]. Fiberglass is a composite which contains continuous reinforcing compound made of glass fiber [17, 18]. A lot of Russian researchers, such as

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A.R. Gizdatullin, V.G. Khozin, A.N. Kuklin, A.M. Khusnutdinov, E.A. Nekliudova, A.S. Semenov, B.E. Melnikov, S.G. Semenov, N.V. Begunova have proved the positive properties of glass composite reinforcement. It possesses a considerable number of advantages in lightness, high tensile strength, low thermal conductivity, adaptability and resistance to aggressive environments over traditional metal [19–23]. But all of the above researchers mainly aimed at studying the properties of the reinforcement itself, and despite the fact that fiberglass composite reinforcement has been used in Russia for a long time, it has not received wide application due to the considerable lack of the proper research and the regulatory reference data for engineering design.

The overseas studies of fiberglass reinforcement application have been carried out since long ago. The article "Flexural behavior of concrete beams reinforced with GFRP bars" was published in 1998. This study presents the results of the comparison made between the predicted and the actual load-deflection relationships for 12 concrete beams reinforced either with steel or GFRP bars [24]. In the case of GFRP reinforced beams, the service load deflection predicted by the ACI model is in error by 70 %, while that predicted by the modified model is in error by less than 15 %. The structural behavior of tested GFRP beams is validated by developing FE models using the ANSYS software in further research. This simulation showed a very small error [25].

Moreover, several researchers studied the flexural behavior and serviceability performance of GFRP-reinforced concrete beams under static and impact loading [26], fabricated with geopolymer concrete [27], or with regular and high-strength concretes [28, 29].

A lot of research has also been done on the behavior of GFRP-reinforced concrete elements such as columns [30], slabs [31], panels [32] and beams [26, 28, 29, 33–36].

One of the latest publications on this subject, written by Xiangjie Ruan and Chunhua Lu is quite significant. The researchers showed that the ultimate flexural capacity of GFRP concrete beams was nearly 91–97 % of that of steel-reinforced concrete beams [35]. The other results showed that the ultimate load of the beams reinforced with pultruded GFRP grating mesh ranged between 19 % and 38 % higher than the ultimate load of the beams reinforced with steel bars [36].

However, the above mentioned researches paid little to no attention to crack formation processes. This study aims to focus on the crack formation in concrete beams with fiberglass reinforcement in comparison with concrete beams with the traditional steel reinforcement. The experiments have been carried out keeping the same conditions.

2. Methods

In the experiments we used the following materials: Portland cement 500 made at Korkinsky cement plant (density – 3.15 g/cm^3, bulk density – 1.20 g/cm^3), 5-20 mm crushed stone from Novo-Smolinsky quarry (density – 2.55 g/cm^3, bulk density – 1.44 g/cm^3, compressive strength – 89 MPa, sand from Fedorovsky quarry (density – 2.60 g/cm^3, bulk density – 1.70 g/cm^3, sand contamination with dust and clay particles – 3 %, sand size modulus – 2.0) and tap water from Chelyabinsk water supply system.

The studies were conducted with concrete (class B25) of the following composition: cement – 298 kg; water – 190 kg; sand – 578 kg; crushed stone – 1257 kg. The composition of concrete based on the large number of previous studies [37–39]. The beams selected for the experiment had a cross section of 80×160 mm and a length of 1400 mm.

For the first series of samples we used metal reinforcement with a diameter of 12 mm, class AIII (A400), tensile strength – 350 MPa according to Russian State Standard GOST 5781-82 [40]. Technical conditions made into a single framework by spot welding. This reinforcement framework had a form of the grid with a spacing of 80 mm (Fig. 1) and increased reinforcement in the left and right thirds of the beam, which contributed to its destruction along its cross-section.

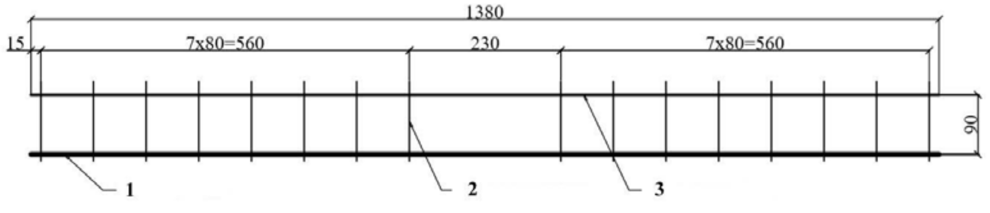

Figure 1. Reinforcement framework:
1 – bearing rod, 2 – wiring bar, 3 – structural bar.

For the second series of samples we used fiber glass composite reinforcement with a diameter of 10 mm, tensile strength of 1000 MPa according to Russian State Standard GOST 31938-2012 [41–43], assembled with plastic clamps in a framework similar to the above. The diameter of the reinforcement was determined in compliance with the physical-mechanical properties of the reinforcement itself and based on of the previous studies [44–46].

A series of cube samples with sides of 100×100×100 mm was made to verify the conformity of concrete to B25 class. All series of samples were stored under the same temperature and humidity conditions for 28 days during hardening. The difference in the masses between the lightest and the heaviest samples did not exceed 50 kg/m^3, which meets the requirements of [47]. According to the results of cubic samples tests, the average cubic strength corresponds to 31.30 MPa, the concrete class for the experimental composition was estimated as 24.37, with the coefficient of variation equal to 13.5 %.

The geometric features of the beam sections are shown in Fig. 2, and the theoretical design features of the beams in Table 1. As it can be seen from Table 1, the reinforcement of the beams is chosen in a way that the supposed (design) time of the of crack formation is the same in both sample series.

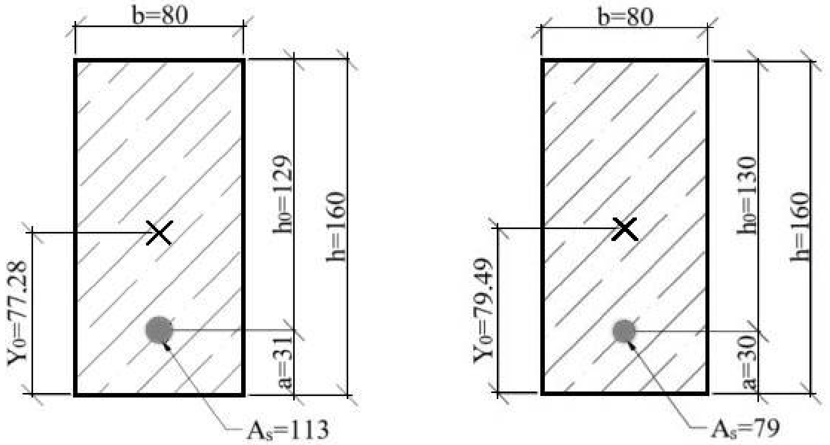

Figure 2. The geometric characteristics of the beam sections.

Table 1. The design features of the beams.

Feature	Value for a beam with metal reinforcement	Value for a beam with fiber glass composite reinforcement
Rb is calculated concrete compressive strength, MPa	14.5	14.5
Rbt is calculated concrete tensile strength, MPa	1.05	1.05
Eb is modulus of concrete elasticity, MPa	30 000	30 000
Rs is reinforcement tensile strength, MPa	350	1000
Es is modulus of reinforcement elasticity, MPa	200 000	50 000
γb is bulk weight of the beam, kg/m^3	2423.4	2412.6
A_{red} is area of the reduced section, mm^2	13553.33	12931.67
S_{red} is static moment of modified sectional area relative to the lower edge, mm^2	1047353.33	1027950.00
I_{red} is moment of inertia of the reduced section relative to the center of gravity of the section, mm^4	29014884.28	27632481.85
W_{red} is moment of resistance of the reduced section relative to the bottom edge, mm^3	375468.70	347618.12
W_{pl} is elasto-plastic moment of resistance relative to the lower edge, mm^3	657070.23	608331.71
$F_{crc.cal}$ is Load corresponding to the theoretical moment of crack formation, kN	3.09	2.89
$M_{crc.cal}$ is supposed moment of crack formation, kN·m	0.68	0.68

The samples were tested for bending as single-span hinged-supported beams. The load was applied with a delay of 20 seconds in order to prevent the relaxation of concrete. In the course of the test, the following indices were taken: the behavior of the supports, deflections of the beam and reinforcement in the area of pure bending, and the width of crack opening.

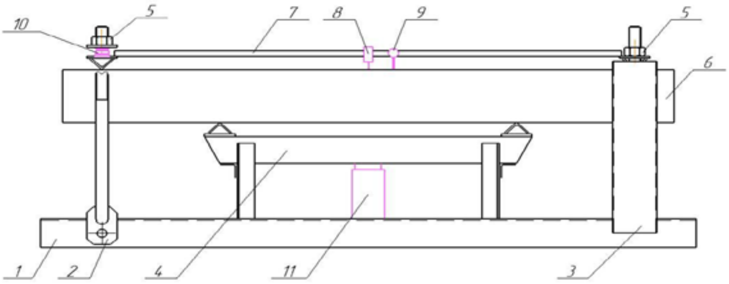

Figure 3. Installation setup for the experiment:
1 – stand base, 2 – mobile support, 3 – rigid support, 4 – traverse, 5 – adjusting nut, 6 – test sample, 7 – instrument rail, 8 – Huguenberger strain gauge, 9 – dial gauge, 10 – strain gauge LPA-4.7t-TOKBEC, 11 – jack.

A schematic diagram of a test bench with two concentrated loads is presented in Fig. 3. The jack 11 mounted on the base 1 creates pressure on the traverse 4, which slides along the guides in the vertical plane and creates pressure on the test beam at two points. Supports 2 and 3 due to the adjusting nuts do not let the beam move in the plane of the load application. Sensor 8 (Huguenberger strain gauge) relieves the deflection of the reinforcement in the area of pure bending. In order to install the Huguenberger strain gauge, the concrete in the samples was excavated until the reinforcement was exposed. Sensor 9 (dial gauge) reads the deflection of the beam. Sensor 10 (strain gauge LPA-4.7t-TOKBEC) reads the behavior of the support during the loading of the beam. The general view of the installation setup is shown in Fig. 4.

Figure 4. Installation setup for the experiment.

3. Results and Discussion

The diagrams of the forces arising in the beam in the course of the test were made based on the received data. It was determined that the onset of cracking occurred under the load $F_{crc,exp}$ = 3.06 kN, which corresponds to the moment $M_{crc,exp}$ = 0.67 kN·m, while the calculated value was $M_{crc,exp}$ = 0.68 kN·m. The discrepancy between the calculated and experimental values is 1.5 %.

The results of the laboratory tests for a series of beams with metal reinforcement were used to create the diagrams of bending deflections starting from the loading moment for all series of samples (Fig. 5).

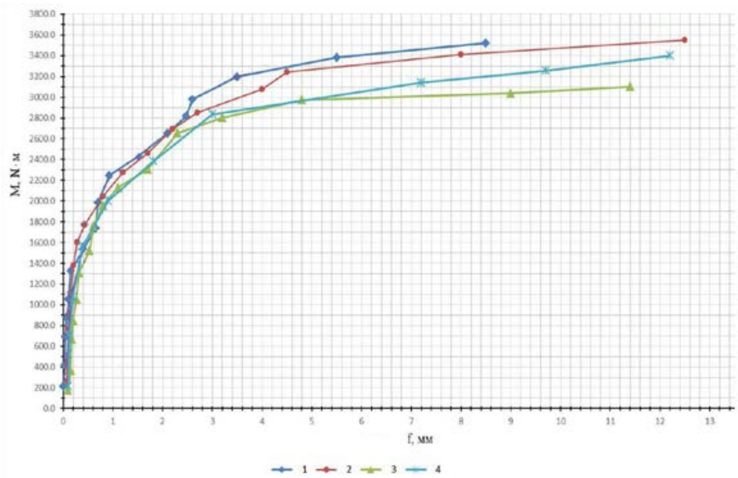

Figure 5. Deflection diagram of beams with metal reinforcement subject to the loading moment: 1, 2, 3, 4 – number of the sample series.

The destruction of the beams with metal reinforcement took place along the cross-section. The averaged out value of the breaking load is $F_{ult,exp}$ = 13.096 kN, which corresponds to the moment $M_{ult,exp}$ = 3.536 kN·m. The calculated value is $M_{ult,exp}$ = 3.67 kN·m. The discrepancy between the calculated and experimental values is 13.4 %. The first crack appeared in the area of pure bending. The deflection value in the area of pure bending increased with the increase in load. New cracks were formed in the area of pure bending; as well as inclined cracks appeared in the left and right thirds of the beam span (Fig. 6). Among all samples of the series, the maximum crack opening width in the area of pure bending is 3.2 mm. The maximum deflection value of the beam in the center is 12.5 mm among all samples of the series. The crack formation pattern is shown in Fig. 6, and the cracks themselves are shown in Fig. 7.

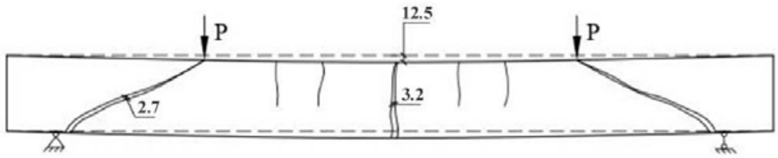

Figure 6. The crack formation pattern for the beam with metal reinforcement.

Figure 7. Cracking in the beam with metal reinforcement.

The results of the laboratory tests for a series of beams with fiber glass composite reinforcement were also used to create the diagrams of bending deflections starting from the loading moment for all series of samples (Fig. 8).

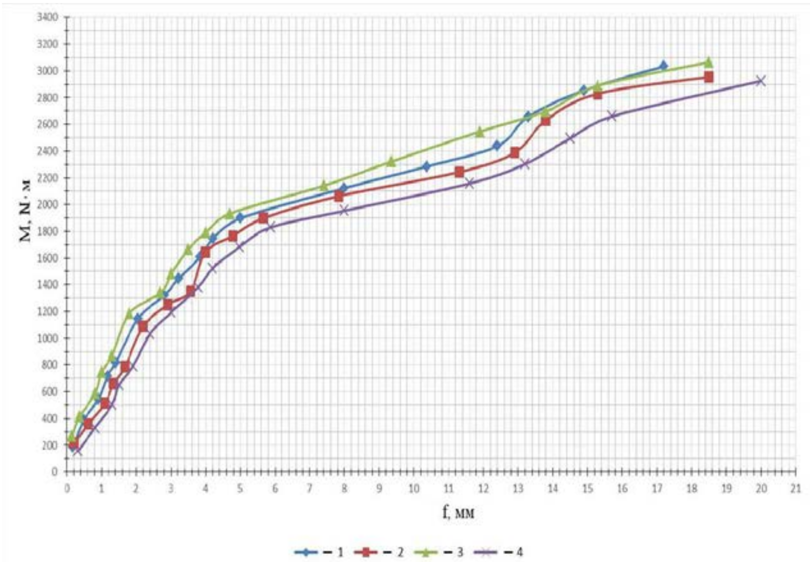

Figure 8. Deflection diagram of beams with fiber glass composite reinforcement subject to the loading moment: 1, 2, 3, 4 – number of the sample series.

The diagrams of the arising in the beam forces in the course of the test were made based on the received data. It was determined that the onset of cracking in the beams with fiber glass composite reinforcement occurred under the load $F_{crc,exp}$ = 2.57 kN, which corresponds to the moment $M_{crc,exp}$ = 0.58 kN·m, while the calculated value was $M_{crc,exp}$ = 0.68 kN·m. The discrepancy between the calculated and experimental values is 17.2 %.

In general, the destruction of beams with fiber glass composite reinforcement was of the same nature as the destruction of the beams with metal reinforcement. The averaged out value of breaking load is $F_{ult,exp}$ = 11.092 kN, which corresponds to the moment $M_{ult,exp}$ = 2.995 kN·m.

The ultimate flexural capacity of GFRP concrete beams is 85 % of steel-reinforced concrete beams. Other researchers show the capacity nearly 91 % [35].

Among all samples of the series, the maximum crack opening width in the area of pure bending is 4.5 mm. The maximum deflection value of the beam in the center is 20 mm among all samples of the series. The crack formation pattern is shown in Fig. 9, and the cracks themselves are shown in Fig. 10.

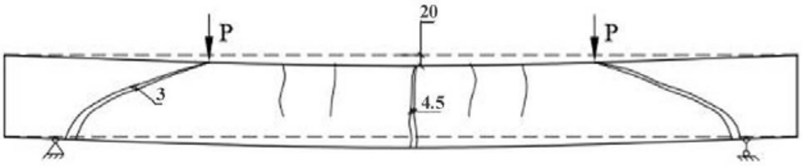

Figure 9. The crack formation pattern for the beam with fiber glass composite reinforcement.

Figure 10. Cracking in the beam with fiber glass composite reinforcement.

The summarized data of the test results for all series of samples are presented in Fig. 11. The graph clearly indicates that the moment value for the onset of crack formation is smaller by 15.5 % for a beam with fiber glass reinforcement compared to a beam with metal reinforcement. For the beams with metal reinforcement, the onset of the crack formation the moment $M_{crc,exp}$ corresponds to 0.67 kN·m, while for the beams reinforced with glass-composite reinforcement the moment $M_{crc,exp}$ equals to 0.58 kN·m.

Overall, the destruction of all the beams was of the same nature and did not depend on the type of reinforcement. However, for the beams with fiber glass composite reinforcement the averaged value of the breaking load $F_{ult,exp}$ was 11.092 kN, which corresponded to the moment $M_{ult,exp}$ = 2.995 kN·m. The averaged value of breaking load for beams with metal reinforcement $F_{ult,exp}$ was 13.096 kN, which corresponded to the moment $M_{ult,exp}$ = 3.536 kN·m. So, the value of the breaking load for the beams with fiber glass composite reinforcement was by 18.06 % less compared to the beams with metal reinforcement.

Another anticipated finding was that the value of the maximum deflection for the beams with fiber glass composite reinforcement amounted to 18.55 mm. While the maximum deflection of the beams with metal reinforcement was as much as 10.5 mm. Thus, the maximum deflection for the beams with fiber glass composite reinforcement was 43.3 % more than the maximum deflections of the beams with metal reinforcement. Other researchers show the same deflection for the GFRP beams [23, 35].

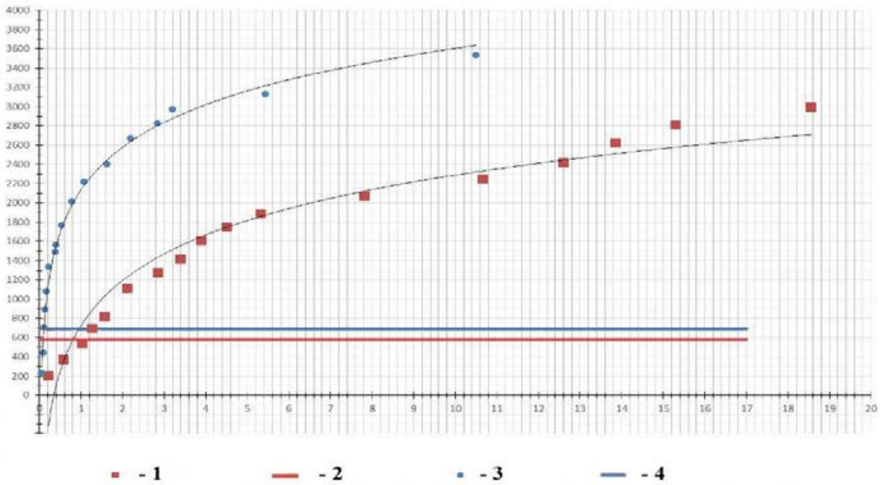

Figure 11. A generalized diagram of the beam deflection with reference to the loading onset: 1 – beams with fiber glass composite reinforcement, 2 – moment of crack formation in beams with fiber glass composite reinforcement, 3 – beams with metal reinforcement, 4 – moment of crack formation in beams with metal reinforcement.

The further analysis of the data showed that the cracks in the beams with fiber glass composite reinforcement began to open at the lower values of the loading moments and the larger deflections of the beams by an average of 40 ... 60 %, especially in the initial loading period, if compared to the same characteristics of the beams with metal reinforcement. The maximum crack opening for beams with fiber glass composite reinforcement was also 28.8 % larger. The results clearly demonstrate lower rigidity of concrete structures with fiber glass composite reinforcement and, as a consequence, a reduction in the entire bearing capacity of such elements. It is possible to increase the bearing capacity of fiber glass composite elements by either increasing the percentage of reinforcement or the elasticity modulus of fiber glass composite reinforcement. Both methods will lead to large additional costs, and therefore, the use of fiber glass composite in the reinforcement of simple flexible elements is not economically feasible. This type of reinforcement is likely to be applicable for concrete structures on the elastic foundation. However, it is clearly understood that further research should be done on this matter further before.

4. Conclusion

1. The destruction of the beams has taken place along their cross-section; the nature of the destruction and cracking in general has been of the same nature with no dependence on the reinforcement type.

2. The averaged value of the breaking moment $M_{ult,exp}$ is 2.995 kN·m for beams with fiber glass composite reinforcement, and 3.536 kN·m for beams with metal reinforcement, which makes a considerable discrepancy of 18.06 %.

3. Despite the initial experimental condition of equal loading onset moment, the moment $M_{crc,exp.}$ is 0.67 kN·m for beams with metal reinforcement, and 0.58 kN·m for beams with metal reinforcement. Thus, the value of the crack formation for beams with fiber glass composite reinforcement is 15.5 % less compared to the same value for beams with metal reinforcement.

4. The cracks in the beams with fiber glass composite reinforcement began to open at the lower values of the loading moments and the larger deflections of the beams by an average of 40 ... 60 %, especially in the initial loading period, if compared to the same characteristics of the beams with metal reinforcement.

5. The value of the maximum deflection for beams with fiber glass composite reinforcement (18.55 mm) is 43.3 % more than the maximum deflection for beams with metal reinforcement (10.5 mm). The maximum crack opening for beams with fiber glass composite reinforcement is also 28.8 % greater than the maximum crack width for beams with metal reinforcement.

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Contacts:

Maxim Molodtsov, molodtcovmv@susu.ru

Evgeniy Vshivkov, laito174@gmail.com

Valeriya Molodtsova, molodtcovave@susu.ru

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