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Short-term and long-term testing of beams made of high-strength concrete with different types of reinforcement

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Abstract:

The object of research is the nature of deformation of flexural elements made of high-strength concrete, reinforced with classical bar and sheet reinforcement, under long-term loads. The relevance of the work is determined by the lack of data on the deformation characteristics of such structures in regulatory documents and scientific literature; this applies both to short-term loads and especially to long-term ones. Such experiments have not been conducted previously in our country, and they are also rare abroad. **Method.** Comprehensive experiments were carried out on beam specimens of the same cross-section, reinforced in three different ways – external sheet reinforcement (Type A), classical bar reinforcement designed for the same failure load (Type B), and bar reinforcement for twice the load (Type C). The experiment included short-term tests to failure and long-term tests with step-by-step loading; part of the beam specimens was loaded to 50% of the failure load before the long-term tests. During the testing, beam deflections and the nature of crack formation were investigated. **Results**. It was found that with the same load-bearing capacity and similar nature of deformation, significantly fewer cracks form in beams with external sheet reinforcement, but with a crack width an order of magnitude greater. Under long-term loading conditions, beams with external sheet reinforcement and initial cracks showed a smaller reduction in stiffness at the reloading stages compared to beams reinforced according to the classical scheme. The work confirmed the applicability of standard calculation methods for the first group of limit states to flexural elements with external sheet reinforcement. To increase crack resistance, the installation of additional structural bar reinforcement is recommended in them. The obtained data reveal the features of deformation of structures with external sheet reinforcement and determine the necessity for further research for other types of cross-sections and classes of concrete.

1 Introduction

Steel-reinforced concrete structures with external sheet reinforcement, in which the external solid steel sheet is designed to function as the primary working reinforcement without internal bar reinforcement, save for shrinkage control meshes, and which rely on welded stud bolts for composite action with concrete, have been an active research subject in Russia since the early 2020s. The very first ideas about using an external steel sheet as reinforcement appeared back in the 1970s [1]. Subsequently, floor structures using profiled sheet were developed [2], [3]; combined wall and shell structures, including both standard reinforcement and external sheet reinforcement, where the task of the external sheet, in addition to resisting loads, is also to provide additional protective properties for the structure (used in various tanks, nuclear industry facilities); and concrete-filled steel tubes. As for structures with external sheet reinforcement where internal working reinforcement is absent, as noted above, there are currently no regulatory documents in Russian Federation governing their application as they are under development. Since the 2000s, such studies have begun almost simultaneously in large numbers in different parts of the world: in South Korea [4], [5], North America [6], [7], [8], Europe [9], and there are examples of the application of such structures in the nuclear industry [10] and in the frames of high-rise buildings [11], [12]; the main advantage of such structures is the significant reduction in the time required for building frame erection, and a regulatory framework has already begun to be created, although so far these are mostly industry-specific regulatory documents. In Russian Federation, research on steel-reinforced concrete with external sheet reinforcement is also actively conducted; first of all, it is worth noting a whole range of experimental-theoretical works performed at the TsNIISK named after V.A. Kucherenko, Moscow, Russian Federation, which studied both small specimens [13, 14] and large-scale models [15] simulating individual structural units [16, 17]. Also noteworthy are works on the study of the contact problem of the interaction between anchor elements of the external sheet and concrete [18, 19], studies of the deformation characteristics of high-strength concrete as a material in particular, the determination of the dynamics of deformation over time [20], исследование effects of granite aggregate on strength and deformability [21] assessment of the applicability of creep models [22] investigation of creep of heavy [23] and light [24] высокопрочного бетона. It is worth highlighting the research conducted by the A.A. Gvozdev Institute of Scientific and Technical Research, Moscow, Russian Federation, on the operation of small samples with external sheet reinforcement under long-term load [25]. An important aspect of the application of such structures is ensuring their fire resistance and the possibility of controlling concreting quality [26, 27].

In conclusion, it can be noted that the strength characteristics of structures with external sheet reinforcement have already been researched to a certain extent, and calculation methods have been developed; in particular, for simple flexural elements, they are practically no different from the methods given in the main Russian codes of rules governing the design of reinforced concrete [28] and reinforced concrete structures [29]. As for the study of the deformation behavior of such structures, there are significantly fewer such studies, and for the combination of high-strength concretes with external sheet reinforcement, they are practically absent, moreover, there are very few such studies in world practice. Therefore, the objective of this study was defined as a detailed investigation of the deformation behavior of steel-concrete composite structures with external sheet reinforcement. To achieve this goal, comprehensive experimental studies were carried out with bending tests of beam specimens made of high-strength modified concrete with different types of reinforcement (classical and external sheet). The deformation of the beams under short-term load was studied in detail, with measurements of deflections at several points along the length, determination of fiber strains across the cross-section, and recording of the crack formation pattern at early stages; the behavior of beams under long-term load with step-by-step loading, simulating additional loading during building construction, was investigated; and the behavior under long-term load of beam specimens that already had initial damage in the form of cracks was studied.

2 Materials and Methods

As part of the experiment, three series of reinforced concrete beam specimens were developed (Series A – Model M13, Series B – Model M12, and Series C – Model M12'; all from the A.A. Gvozdev Research Institute of Concrete and Reinforced Concrete (NIIZhB), Moscow, Russian Federation). Six specimens were manufactured for each series: two were tested to failure, two were loaded to 50% of the ultimate load (these were prepared for further long-term studies), and two were immediately subjected to a sustained long-term load. The specimens were designed with the same cross-section and for the same ultimate load, with the exception that the reinforced concrete specimens in one series had twice the load-bearing capacity.The difference in flexural stiffness between the steel-reinforced concrete beam M13 and the reinforced concrete beam M12 is 15%, between M13 and M12' - 7.5%. The choice of exactly this set of experimental specimens is justified, on the one hand, by the maximally close values of stiffnesses, on the other hand, by the correspondence of the failure load, as well as the possibility of assessing how a multiple increase in the cross-section's strength will change the nature of deformation. The testing of these beams was conducted in the plane of least stiffness to simulate structural elements with high flexibility. The design characteristics of all beam types are given below.

A (M13). Steel-reinforced concrete beam specimens with external sheet reinforcement. Cross-section – 300x150(h)x2500. Concrete class B100. Initial modulus of elasticity E=55,000 MPa. Steel C345. Sheet thickness δ=3mm. Stud bolt (M8) length 40mm. Simply supported. Failure load 120 kN in thirds of the span, designed for the normal section.

B (M12). Reinforced concrete beam specimens with symmetrical bar reinforcement. Cross-section – 300x150(h)x2500. Concrete class B100. Initial modulus of elasticity E=55,000 MPa. Reinforcement 5Ø14 A400 on each side. Cover layer 15mm. Stirrups Ø8 A500 with a pitch of 100mm. Simply supported. Failure load 120 kN in thirds of the span, designed for the normal section.

C (M12'). Reinforced concrete beam specimens with symmetrical bar reinforcement. Cross-section – 300x150(h)x2500. Concrete class B100. Initial modulus of elasticity E=55,000 MPa. Reinforcement 8Ø14 A500 on each side. Cover layer 15mm. Stirrups Ø8 A500 with a pitch of 100mm. Simply supported. Failure load 240 kN in thirds of the span, designed for the normal section.

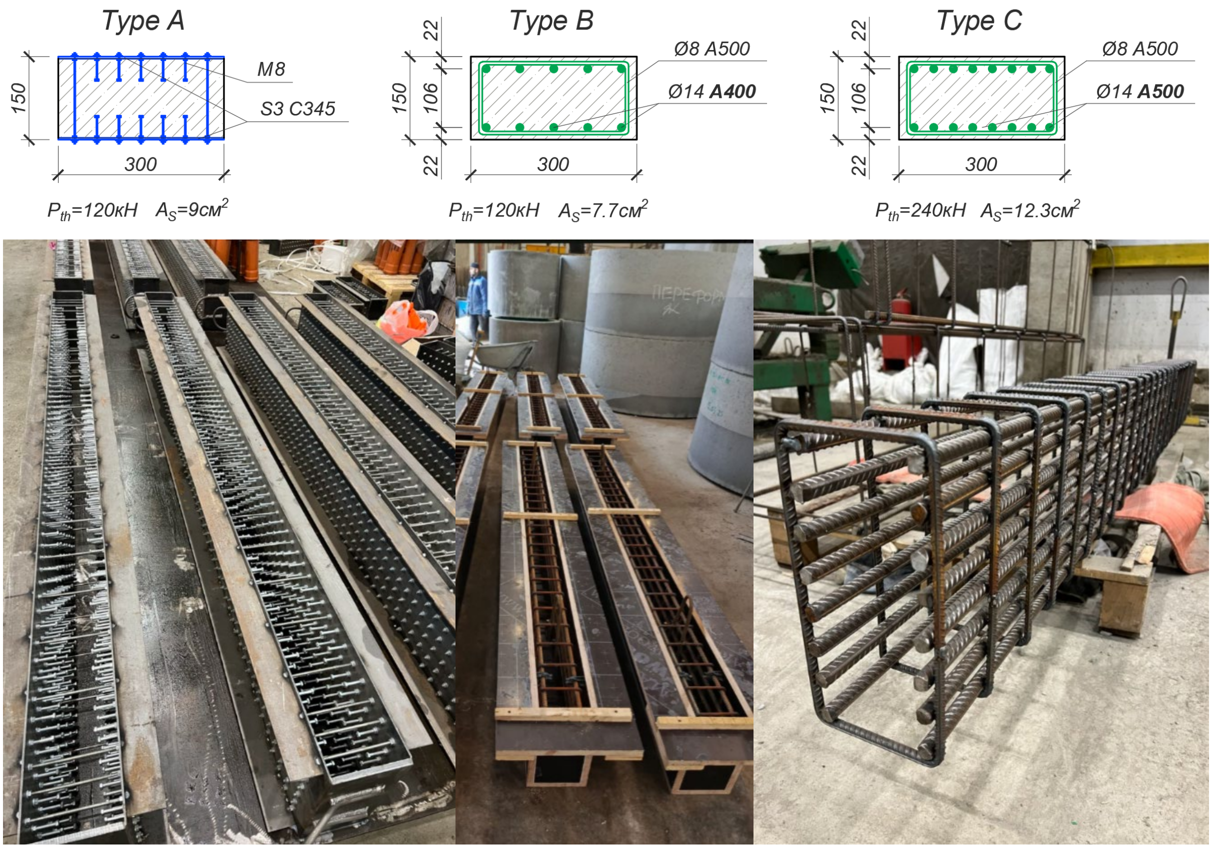

Fig. 1 - Reinforcement scheme of beams of types A, B and C
Image by the author of the article

The short-term load testing was conducted in load frames. During the testing, vertical deflections at mid-span, at the supports (to account for possible support settlement), and at one additional point (to determine the curvature of the beams) were recorded. Additionally, strain gauges were glued to the top and bottom surfaces of some beams.

The loading of the models was performed in accordance with GOST 8829-2018 "Prefabricated reinforced concrete and concrete building products. Load testing methods. Rules for assessing strength, stiffness, and crack resistance" (https://docs.cntd.ru/document/1200163873) [30] with load control using a dynamometer connected to a strain gauge station. The model tests were conducted with an increasing load until the models reached failure. The loading was carried out in stages, with steps not exceeding 0.1 of the design strength load. At each step, the model was held under load. The readings of the measuring instruments were recorded at each loading step. The next loading stage was performed only after the complete cessation of deformations in the test specimen. The load was applied smoothly and at a constant rate to avoid dynamic effects. The tests were conducted until the loss of the element's load-bearing capacity, characterized by an increase in deformations in the models with a simultaneous drop in the applied load value, or until the complete failure of the model. Figure 2 shows the beams during the short-term testing, as well as a general view of the connected measuring equipment.

To assess the nature of crack formation, the VIC-3D system was used. It is based on Digital Image Correlation (DIC) – a non-contact optical method for measuring object deformation. The essence of the method lies in tracking changes in the state (changes in the saturation level of the gray color) of a small area (subset) of a black-and-white texture during the loading process. Analyzing such an elementary cell allows for the calculation of spatial displacement and strain in a given area. To obtain a complete picture, the specimen's surface is programmatically divided into elementary cells, the analysis of which allows for the calculation of the strain distribution field over the entire surface. Figure 3 shows comparative results for reinforced concrete beams and beams with external sheet reinforcement.

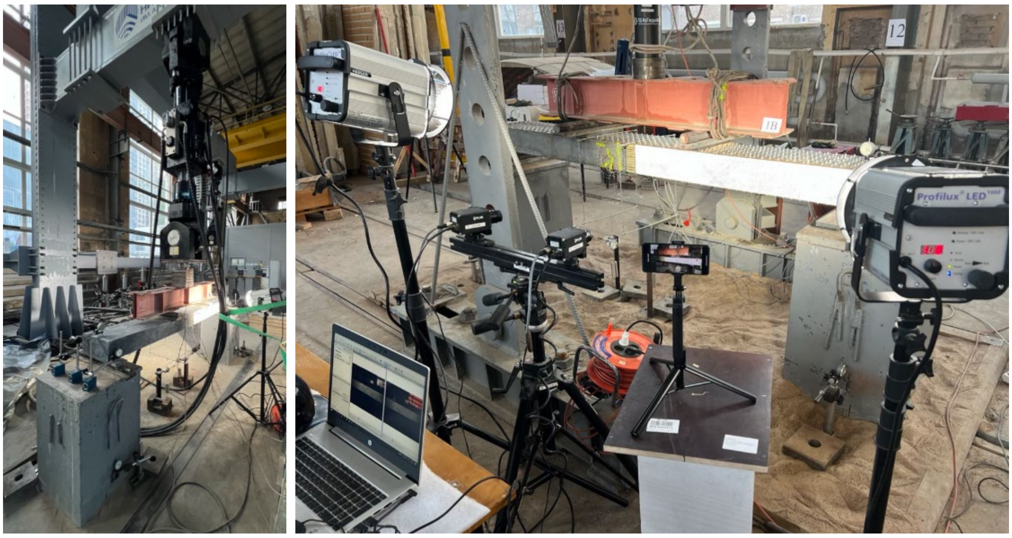

Fig. 2 - The testing process and operation of the VIC 3D system for monitoring the cracking process in the beam
Image by the author of the article

Under the same failure load, the deformation of reinforced concrete beams and beams with external sheet reinforcement differs qualitatively. There are significantly fewer cracks in steel-reinforced concrete beams, but they have almost an order of magnitude greater width and, upon formation, immediately cross from 2/3 to 3/4 of the specimen's cross-sectional height. During the experiment, cracks were recorded both manually and automatically – by the VIC-3D system, with the first cracks detected at stress levels of 0.2 of the failure load. Reinforced concrete beams with different reinforcement deform according to the classical pattern with the gradual development of cracks and an increase in their number. The mandatory use of additional bar reinforcement in steel-reinforced concrete elements is recommended.

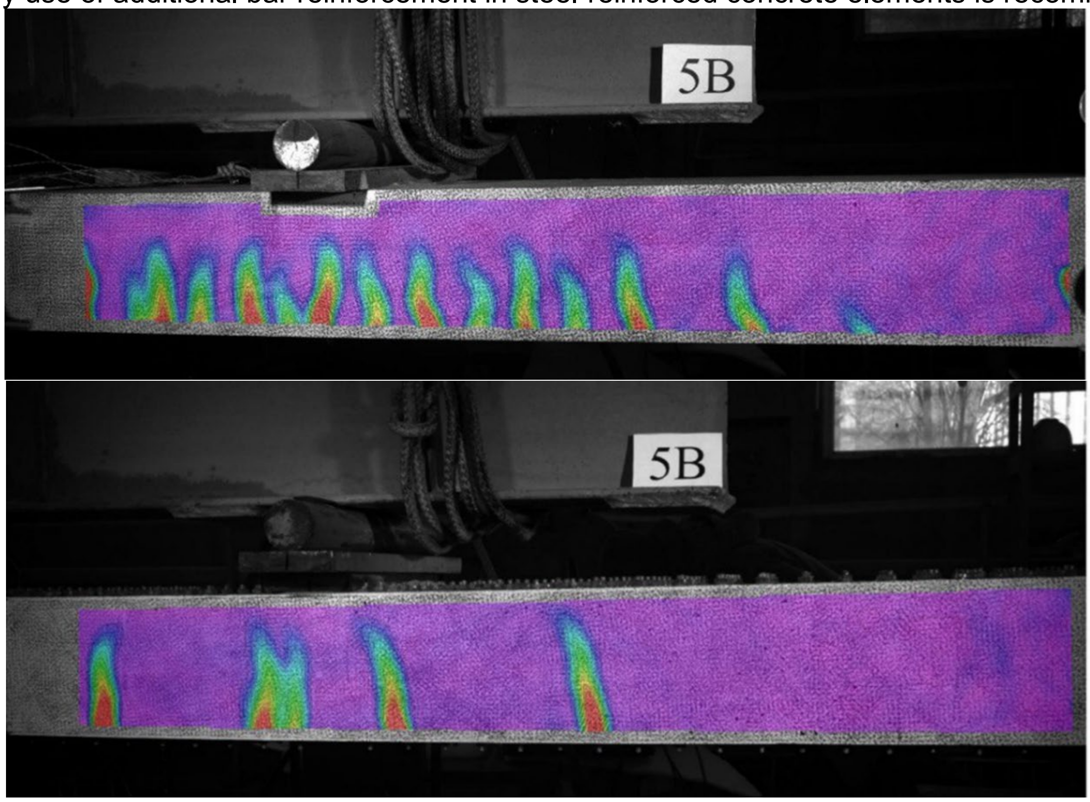

Fig. 3 - The nature of cracking in reinforced concrete beams (top) and beams with external sheet reinforcement (bottom)
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Based on the results of testing the control beam models under static short-term loading, the actual average values of the failure loads for subsequent long-term tests were obtained:

- for beams with external sheet reinforcement type A (M13) – Pexp = 118.0 kN;

- for reinforced concrete beams with symmetrical arrangement of reinforcing bars of strength class A400, series designation: B (M12) – Pexp = 116.0 kN;

- for reinforced concrete beams with symmetrical arrangement of reinforcing bars of strength class A500, series designation: C (M12') – Pexp = 234.0 kN.

Based on the obtained values of the failure loads, the values of the loads applied for the long-term testing of the beam models were determined. The long-term tests were conducted in a workshop with stable temperature and humidity conditions; window openings on the sunny side were closed to avoid uneven additional heating of the specimens by solar radiation.

Specimens of all three types were tested according to two scenarios – one part of the specimens was installed for testing in their initial state; the second part was installed after preliminary loading with a bending load equal to half of the failure load. This was done to guarantee the appearance of cracks in the specimens; the load level of 50% of the failure load was chosen because it approximately corresponds to the design load for which the structure is designed. This testing scheme will allow for an assessment of how the flexural behavior under long-term load differs between specimens with and without cracks. The specimens were loaded in stages according to the following scheme: at the first stage, a load of 10% of the failure load is applied; at subsequent stages, after a holding period and the cessation of creep deformations, additional loading of 5% of the failure load is applied. The loading was carried out using concrete blocks with mass and dimensional characteristics selected for the planned loading stages. Figure 4 shows the process of the long-term testing.

Fig. 4 - Long-term testing of samples of beams by gravity load
Image by the author of the article

3 Results and Discussion

The deformation graphs of beam specimens of all types during short-term tests to determine the failure load are shown below in Figures 5-6. As can be seen from the graphs, considering the difference in stiffness (the steel-reinforced concrete beam is approximately 15% stiffer than the one reinforced with A400 reinforcement), they have a similar nature of deformation. Of particular interest is the graphical interpretation of the results; for example, in Figure 5, the stress level is plotted on the vertical scale, and in Figure 6, the actual load is plotted. It is evident that the deformation of type A and B specimens, reinforced with sheet and bar reinforcement and designed for the same load, is similar on both graphs, but the specimens reinforced for twice the load deform qualitatively differently, although the stiffnesses of all specimens are within 15%.

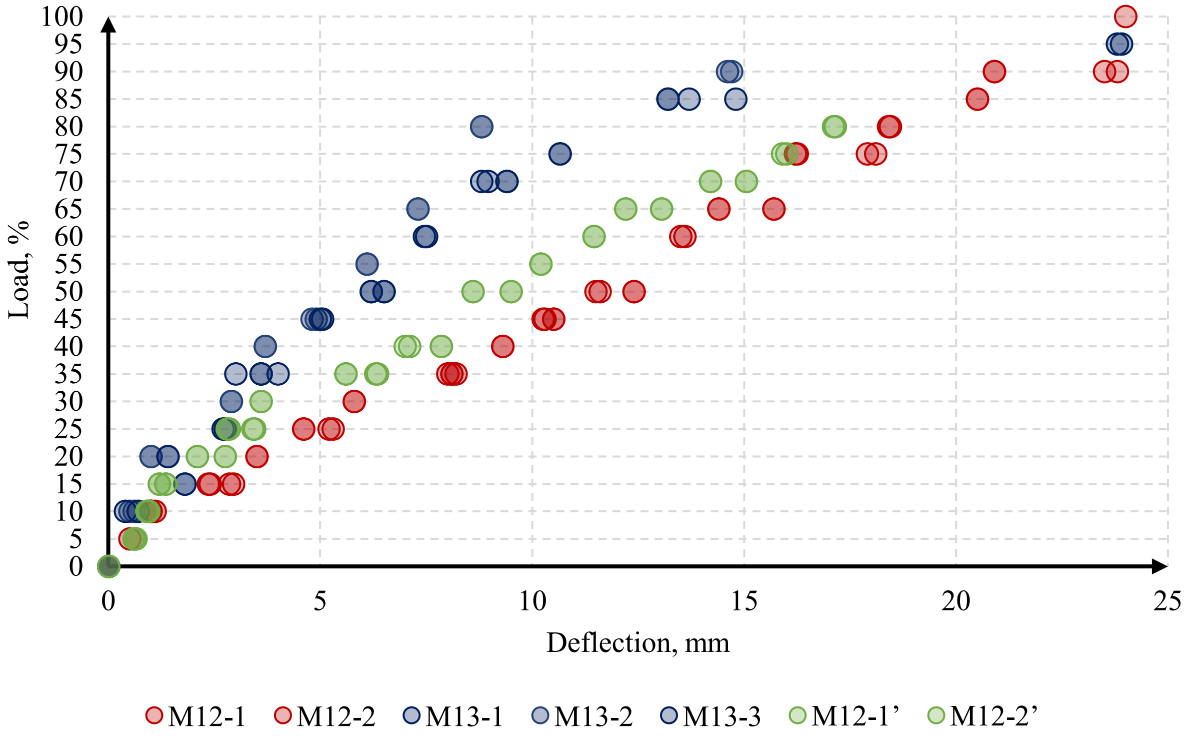

Fig. 5 - Graph of deformation of beams M12, M13 and M12' depending on % load
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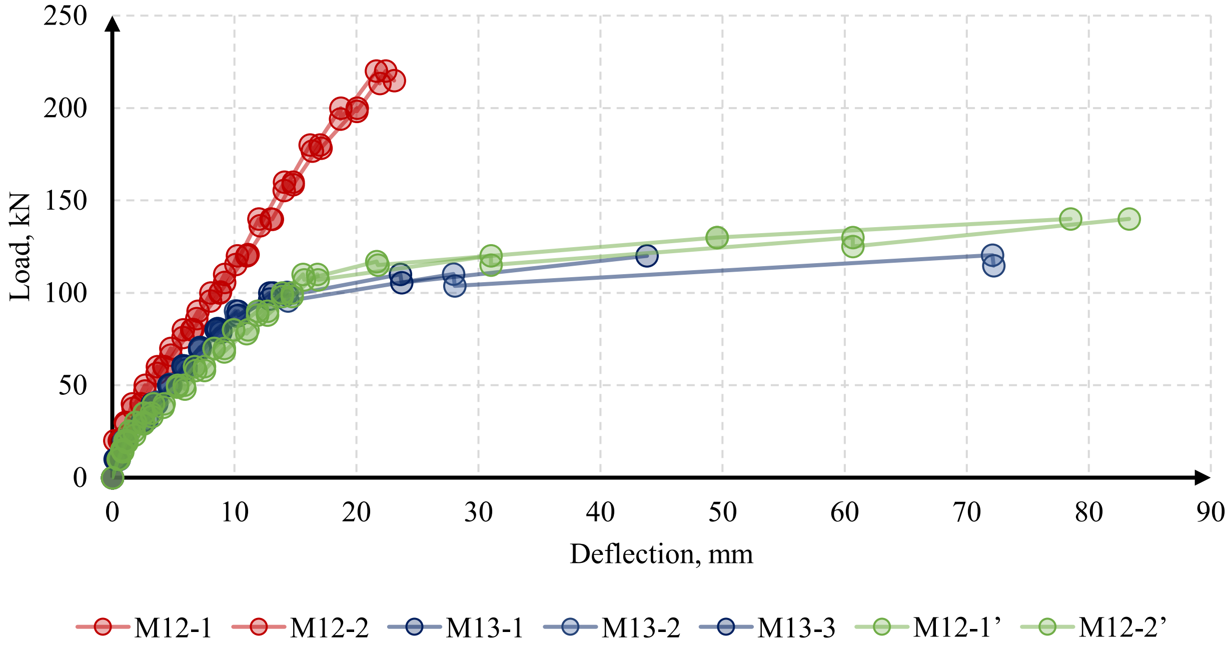

Fig. 6 - The graph of deformation of beams M12, M13 and M12' depending on the load
Image by the author of the article

Based on the graphs, it is evident that the calculation methodology based on Set of rules 63.13330.2018 «Concrete and reinforced concrete structures. General provisions» (https://docs.cntd.ru/document/554403082) [31] and Set of rules 266.1325800.2016 « Composite steel and concrete structures. Design rules» (https://docs.cntd.ru/document/456044285) [32] is applicable for calculations of normal sections for the first group of limit states of steel-reinforced concrete beams made of high-strength concrete with external sheet reinforcement; when developing the testing program, the beams were calculated according to these regulatory documents. Comparative results of the calculation of these beams with the experimental results for the first and second group of limit states are presented in work [33], which is also of interest due to the large number of experimental studies of steel-reinforced concrete beams with external sheet reinforcement, the results of which were compared with regulatory calculations.

Figure 7 presents comparative graphs of the long-term deformation of beams of types A, B, and C under sequential additional loading, both with and without cracks. Figures 8-10 show comparative graphs of long-term deformation for each applied reinforcement type.

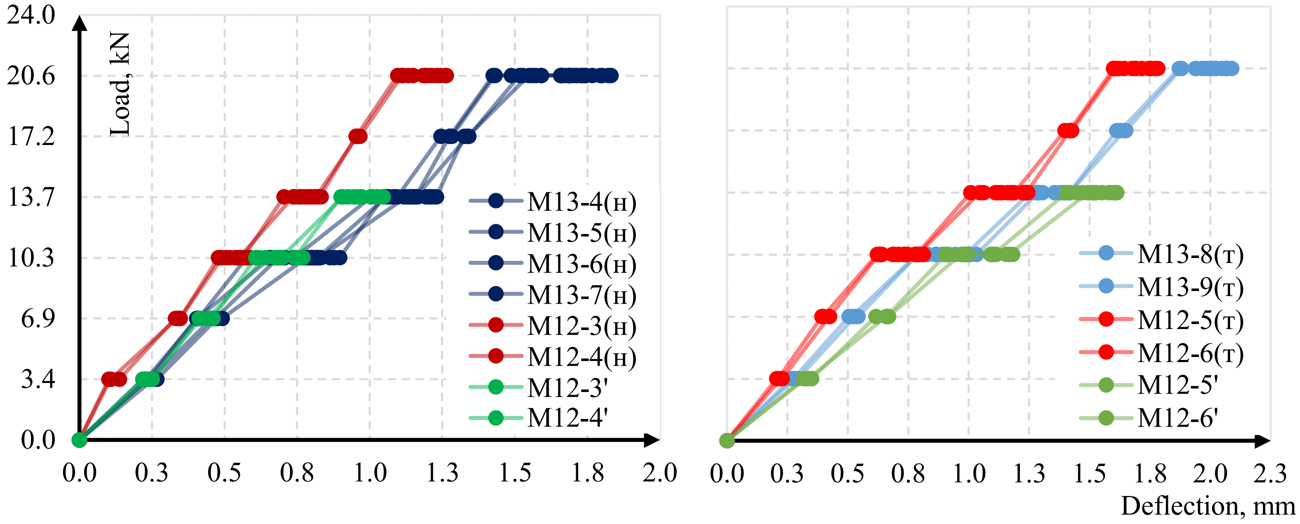

Fig. 7 - Graphs of long–term deformation of beams of types A B and C during sequential loading, on the left - without cracks (н), on the right – with cracks (t)
Image by the author of the article

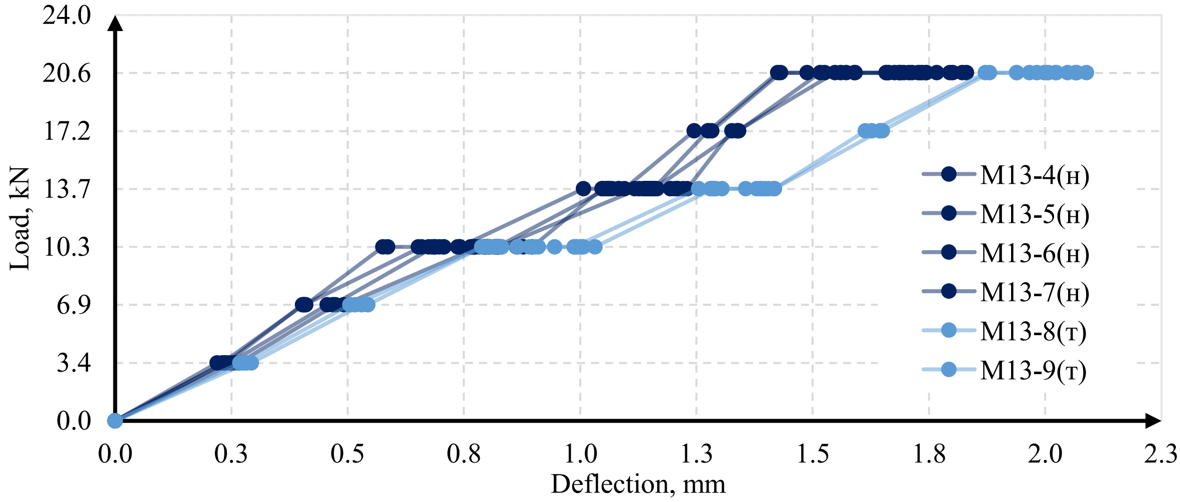

Fig. 8 - Graphs of long-term deformation of beams with external sheet reinforcement of type A with cracks (t) and without (н)
Image by the author of the article

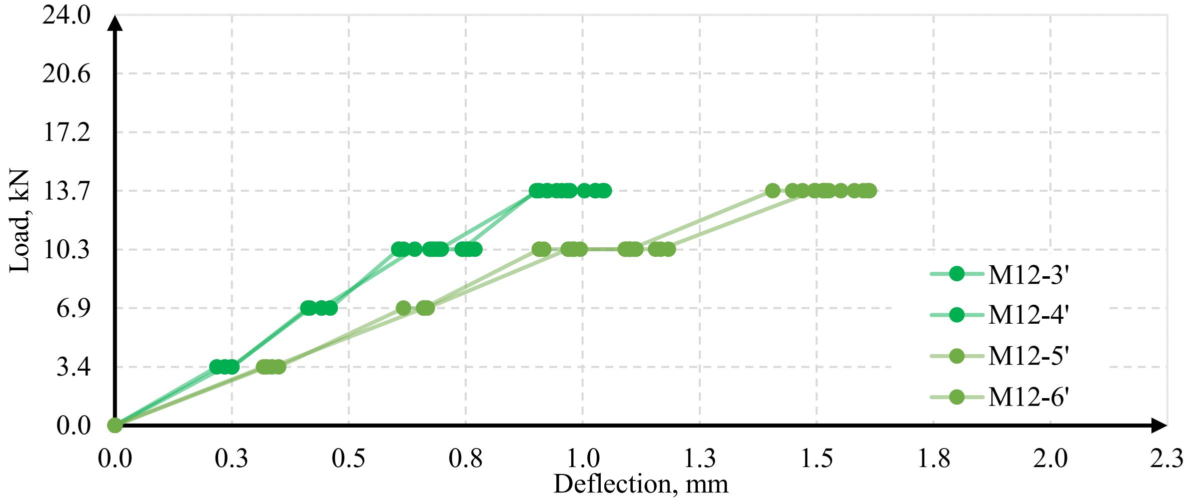

Fig. 9 - Graphs of long-term deformation of beams with type B rod reinforcement with cracks (t) and without (н)
Image by the author of the article

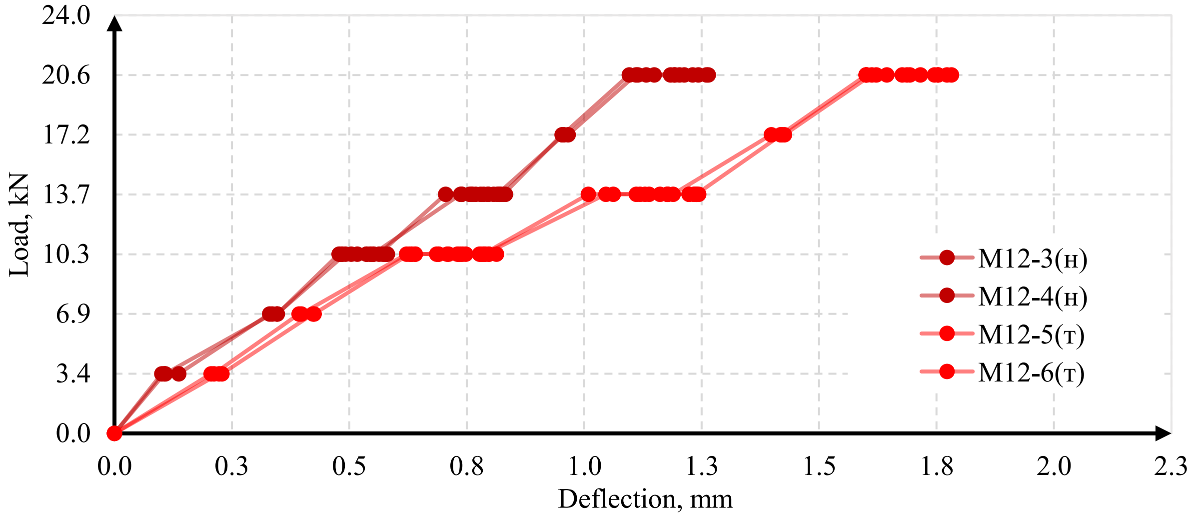

Fig. 10 - Graphs of long-term deformation of beams with type C core reinforcement with cracks (t) and without (н)
Image by the author of the article

4 Conclusions

Based on the results of the conducted long-term and short-term comprehensive tests of beam specimens reinforced with bar and sheet reinforcement made of high-strength modified concrete, a number of the following conclusions can be drawn.

1. The calculation methodology based on SP 63.13330 and SP 266.1325800 is applicable for calculations of normal sections for the first group of limit states of steel-reinforced concrete beams made of high-strength concrete with external sheet reinforcement.
2. Under short-term loading within the operational modes of the structure (up to 0.5 of the failure load), the deformation of steel-reinforced concrete beams corresponds to the deformation of reinforced beam specimens designed for the same load.
3. According to the results of long-term tests of reinforced beam specimens, no reduction in bending stiffness was recorded under short-term exposure, as can be seen from Figures 7-10) – the slope of the load/deflection relationship (qualitatively corresponding to the stress/strain relationship) during additional loading after the holding period is not less than the slope during initial loading.

4. During long-term tests of specimens with cracks, at each subsequent loading stage, there is both an increase in creep deformations in the specimens with cracks and a general decrease in stiffness during short-term additional loading compared to undamaged specimens.
5. Under long-term loading, specimens with external sheet reinforcement show a smaller reduction in stiffness at each subsequent stage of additional loading when initial cracks are present and when compared to the deformation of undamaged specimens, relative to beam specimens with classical bar reinforcement designed for the same load and having similar stiffness.
6. The obtained results help to understand the mechanics of deformation under long-term load for specimens made of high-strength concretes, reinforced with both classical bar reinforcement and external sheet reinforcement. Analysis of literary sources shows that long-term tests of reinforced beam specimens in bending are rare both in our country and abroad. It is recommended to continue testing with the investigation of this type of stress-strain state for other concrete classes, reinforcement types, and considered cross-sections.

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6 Conflict of Interests

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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