Numerical and experimental investigation of prestressed steel-concrete composite beams

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Abstract. Prestressing in building structures has been used for a long time. However, the prestressing of structures with a combined cross section, such as steel-concrete structures, has appeared recently. The report is devoted to the structural types of prestressed steel – concrete structures, the description of technical solutions and comparative analysis with known sources. A comparative analysis of the methods of prestressing steel – concrete beams with widespread methods of prestressing reinforced concrete and steel structures is carried out. The article is devoted to prestressed composite beams, the identification of both the stress – strain state of beams of a composite section from prestressing and from operational loads is analyzed. Analytical expressions are given for assessing the strength of prestressed steel – concrete bending elements for different methods of prestressing, and the results of numerical and full-scale tests. Comparisons of the results of numerical and field experiments in the form of graphs are given. In conclusion, satisfactory convergence of various methods for assessing the strength of prestressed beams with experimental studies is noted.

Keywords: steel – concrete construction, prestress, self – stress, full – scale experiment, stresses, deflections.

1 Introduction

Prestressing in the area of building structures in many countries, including Russia, has been used for a long time. The idea of prestressing has been widely adopted in prestressed concrete and steel structures.

In reinforced concrete prestressed structures are mainly used with two types of prestressing: on steel ribs and on concrete. In steel structures, special ribs are welded at the ends of the beams, onto which tensile reinforcement (rope) is attached in parallel to the lower flange. In order to create a beam that is rational in terms of material consumption, the cross section of the upper flange of a steel beam is taken an order of larger magnitude, so the use of rolling profiles becomes irrational. In steel – concrete composite prestressed beams from a rolled profile, the compression force is absorbed by the steel flange together with concrete, therefore there is no need to increase the cross section of the upper flange as in steel prestressed beams. The structural solution of the beam is also simplified, unlike reinforced concrete beams, where in order to perceive the tensile forces at the ends it is necessary to arrange special anchor stops, in steel – concrete composite beams these efforts are perceived by supporting steel ribs.

Instructions for the construction of steel-reinforced concrete structures in European countries are described in [1, 2]. In [3, 4], the results of numerical studies of beams with prestressing of flexible reinforcement are described similarly to prestressing of reinforced concrete structures.

Article [5] is devoted to steel – concrete composite beams without prestressing, therefore, the expressions given for the strength assessing cannot be used in prestressed steel – concrete composite bending elements.

The prestressing of the steel part of the combined section is created through the use of shrinkage processes of the concrete part when changing the static structure deformation scheme [6-8].

The article [9] estimates the effectiveness of prestressing according to the shape of the diagrams of bending moments. Analytical expressions for determining stiffness are proposed. In article [10], the results of experimental studies of the effect of shrinkage on the stiffness steel – concrete composite
beams are given, the need to take into account shrinkage stresses at operational loads and the effect of shrinkage on the operation of anchors is noted. Articles [11, 12] are devoted to experimental studies of steel–concrete composite beams of prestressed external tendon. Based on the experimental results, a calculation method was proposed in [11] that takes into account bulk stresses. The article [12] is devoted to numerical studies of prestressed steel–reinforced concrete beam. Two-span beams are considered, prestressed reinforcement is placed inside a steel box-shaped beam.

The article [13] describes experimental studies of steel–concrete composite beams with different locations of strands inside the I-beam. Based on experimental studies, a method for calculating composite beams with external strands, but based on rectangular stress diagrams, is proposed. Article [14] is devoted to steel–concrete composite bridge with external prestressed strands of steel reinforcing beams, a calculation method is also proposed.

The paper [15] describes numerical modeling of steel–concrete composite beams, and a finite element model for short-term and long-term loads is developed. However, there are no comparisons of numerical studies with experimental data.

Article [16] describes experimental studies of steel–concrete composite concrete beams on the effect of a negative moment. Four strained beams with strands in the region of negative moments were tested.

In studies [17–21], the stress-strain state of the composite beam from shrinkage was considered, differential equations for determining the shear between layers from shrinkage were given in [17], and the sequence of concrete laying and its influence on the development of shrink stresses were studied in [18]. However, in the above studies, the prestressing of steel-reinforced concrete structures is performed by analogy with the prestressing of reinforced concrete structures, provided that the reinforcement and concrete are jointly deformed.

The purpose of this report is to analyze new technical solutions of prestressing, study the features of the steel-reinforced concrete beam with insulated prestressed flexible reinforcement and a comparative analysis of its work with the beam using traditional prestressing, as well as the stress–strain state of self-tensioning beams of composite section.

2 Methods
Numerical studies of steel–concrete composite beams of 4 different types were carried out, differing in the method of tension: the first series of tests was carried out on prestressed beams with reinforcement in contact with concrete, as in reinforced concrete structures, the second series of tests included beams with reinforcement according to the diagram of bending moments, in the third series, beams with prestressed reinforcement insulated in a polyethylene pipe were tested. In the fourth series of studies, steel–concrete composite beams were strained due to the use of an internal stress–strain state that occurs during shrinkage processes in the concrete part of a composite section.

Ansys software packages and Midas Civil were used to perform numerical studies. The geometric model of the beams was made in the PC Space Claim and Design Modeler.

Beams of the first series had the following parameters used in experimental studies: steel part from an I-beam 18.2 m long, transverse reinforcement Ø6 A240 with a pitch of 100 mm at the supports and 200 mm in the middle of the beam, an anchor welded to the walls of an I-beam Ø10, prestressed reinforcement Ø10, concrete of class B20.

The prestressing in the beams was created using – Bolt Pretention (Figure 1).

The stress diagram in concrete according to the results of numerical studies is given in (Figure 2).

The pre-stressed beams of the second series had rectangular sections: the steel part was from I-beam 20H1, 2m long.

The transverse reinforcement of Ø10 A240 was welded to the beam belts and was positioned at a step of 150 mm in the support zone and at a step of 200 mm in the middle of the span.

Beams of the third series with insulated reinforcement were made of I-beam 20 with a length of 1.86 m.
For prestressing the beam, 2Ø16 A500C reinforcement insulated in a 32 mm diameter polyethylene pipe was used. Confinement reinforcement is made of Ø10 A240 located with a step of 100 mm in the support zone and 175mm in the middle of the span.

![Figure 1](image1.png) **Figure 1.** Stresses in a steel – concrete beam in the stage of prestressing.

![Figure 2](image2.png) **Figure 2.** Stresses in beams from external loading.

Numerical studies of series 4 beams to determine the degree of self – stress taking into account the forces of shrinkage processes were performed in the PC Midas Civil. A general view of the stress-strain state of beams during self-stress is shown in (Figures 3-8).

![Figure 3](image3.png) **Figure 3.** 1 Stage bending moment diagram.

![Figure 4](image4.png) **Figure 4.** The inclusion of the plate in the bending (stage 2).

![Figure 5](image5.png) **Figure 5.** 2 Stage bending moment diagram.

![Figure 6](image6.png) **Figure 6.** Exclusion of support (stage 3).

![Figure 7](image7.png) **Figure 7.** 3 Stage bending moment diagram.

![Figure 8](image8.png) **Figure 8.** Moment diagram for a single-span.

Experimental studies were carried out taking into account all geometric and physical properties and parameters of materials used in numerical studies. The geometric parameters of the test beams were also dictated by the capabilities of the presses in the laboratory. As expected, steel-reinforced concrete beams were made with rectilinear and curvilinear arrangement of prestressed reinforcement (Figure 9-10).
Figure 9. Steel – concrete beam with rectilinear prestressed reinforcement.
Figure 10. Steel – concrete beam with reinforcement according to the envelope of the diagram of moments.

In order to study the strength, deformability and method of operation of the composite section, the test specimen had a number of features:
1. Prestressed steel – concrete beams were made as test specimen.
2. For the manufacture of samples, the most currently used steel grade (C245) and rebar and wire classes (A500C, B500) were used, the concrete class was laid according to the calculation - B20.
3. The prestressing was created using a torque wrench. The magnitude of the prestress was taken as calculated.
4. The geometric dimensions of the models of steel-reinforced concrete beams were taken according to the external dimensions of the test setup in the laboratory.
5. The relationship between the reinforced concrete and steel parts of the samples of steel - concrete beams was taken as calculated.

Concrete mixture for test specimen was made in the factory.

The manufacture of test specimen steel – concrete beams was carried out in the following sequence. According to the drawings, both longitudinal and transverse reinforcement were installed. In series, the prestressing was set to the reinforcement by the value of the controlled force \( N_k = 2324 \text{ kgf} \) as calculated for one reinforcement. The achievement of the required prestressing was controlled by the relative elongation of the reinforcement by \( \Delta l \) with a force \( N_k \) (\( \Delta l = 1 \text{ mm} \)). Then, concrete was laid with constant vibration by an internal vibrator and concrete was steamed in the factory. Prestressed beams after gaining concrete strength were tested in laboratory conditions of KSUAEN.

The beams were tested being freely supported by two concentrated forces in the middle part of the span, applied at a distance of 400 mm from the vertical axis of the beam. The span of the beams was 1700, 1900 mm. The load was transferred with the IPS –200 hydraulic press system to a flexible steel-reinforced concrete beam using a steel beam at two points: in one through a movable steel roller with a diameter of 20 mm, and in the other through a fixed steel roller of the same diameter. To prevent twisting of the beam during the test, a steel roller with a diameter of 50 mm was installed between the metal traverse and the lever of the test setup.

During the test, longitudinal deformations of concrete and steel beams were measured, as well as deflections and crack widths. Deformations (concrete) and (steel) were recorded by resistance strain gauges with bases of 50 mm and 20 mm, respectively, through AID – 4 electronic equipment with a switch magazine. Deflections in the zone of pure bending at each stage of loading and draft of the supports were measured using dial gauges with a division value of 0.01 mm.

The prototypes of the beams were tested with a one – time short – term static load before physical destruction in order to establish the nature of the destruction and the laws of development of deflections, deformations of concrete and steel during their joint deformation as part of a single structure.

All tested samples of steel-reinforced concrete beams were destroyed at normal sections due to the development of plastic deformations in the compressed zone of concrete. Beams of the first series were destroyed gradually. Beams with insulated reinforcement were destroyed intensively after breaking reinforcement.

To analyze the stress-strain state of prestressed steel – concrete composite structures, expressions for assessing the strength of steel and reinforced concrete beams can be used. The efforts of prestressing \( N_H \) arising before the concrete profile of the steel profile are determined by the known expressions [3].

\[
N_H = \frac{R \varphi_H A_{pr} W_H}{W_H + h_H A_{pr}} 
\]  

(1)

where \( R \) - design resistance of steel, \( \varphi_H \) - buckling coefficient, \( A_{pr} \) - cross-section area, \( W_H \) - section moment, \( h_H \) - design height of prestressed strand.

If the reinforcement is tensioned after the concrete has gained strength, the ultimate tensile force should not cause concrete cracks in the upper area of the beam:

\[
N_H = R_{bt} A_{bt} = R_{bt} bx
\]  

(2)

where \( R_{bt} \) - ultimate tensile stress of concrete, \( b \) - profile width, \( x \) – height of compressive zone of the concrete.

It is necessary to write down the moment expressions for the cross section of the beam after concreting under the action of the operating load (Figure11).

Height of compressive zone of the concrete is determined by the expression:

\[
\int \sigma_h \varphi_h \text{d}x + \sigma_{H}^\prime 0.5(h - x)A_{pr} - \sigma_{H}^\prime 0.5xA_{pr} = 2\int \sigma_{pr} t_{as} d(0.5h - x) + N_H
\]  

(3)

In cases of applying a rectangular stress diagram:
where the internal stresses in the upper and lower zones of the profile:

\[
\sigma_{pr}^u = -\frac{N_H Z}{A_{pr} + A_{bh} n} \frac{M - (N_H + Z)h}{W_n + nJ_b / y_1}
\]

(5)

\[
\sigma_{pr}^l = -\frac{N_H Z}{A_{pr} + A_{bh} n} + \frac{M - (N_H + Z)h}{W_n + nJ_b / y_1}
\]

(6)

Then the height of compressive zone of the concrete is determined by the expression:

\[
x = \frac{2R_{pr} t_w h + 0.5\sigma_{pr}^u hA_{pr} + N_H}{2R_{pr} t_w + R_b b - 0.5(\sigma_{pr}^u A_{pr} + \sigma_{pr}^l A_{pr})}
\]

(7)

where \( n = E_{pr}/E_b \) – modular ratio, \( t_w \) – web thickness, \( A_{pr} \), \( A_{pr}' \) – sectional area of stretched and compressed profile sectional zones, \( y_1 \) – distance to concrete compressed zone.

Strength of the section is performed by the expression:

\[
M \leq 0.5 \left[ \sigma_{pr} b x^2 + R_{pr} \left( W_{pl} + (0.5h - x)^2 t_w \right) \right] + 0.5 \left[ \sigma_{pr}^u (bt_f + t_w x) dx - hf + 0.5 \left[ \sigma_{pr}^u \left[ bt_f + t_w (h - x) \right] d(h - x) + N_H (h - x - a) \right] \right]
\]

(8)

where \( W_{pl} \) - plastic moment of resistance, \( t_f \) - top flange thickness, \( \sigma_{pr}^u \), \( \sigma_{pr}^l \) – stresses in the upper and lower zones of the profile.

**Figure 11.** Diagram of stresses and forces in a steel – concrete section: a) transverse section; b) stress diagram from \( N_H \); c) stress diagram from \( q \); d) resulting stresses.

**3 Results and Discussion**

Figures 12-15 show diagram of the distribution of stresses along the height of the section of the beams at various stages of prestressing and loading, and comparisons with data from numerical experiments.
Figure 14. Stress in the middle of steel beams after prestressing forces

Figure 15. Stresses in the normal section of the beam in the concrete part (insulated reinforcement)

Figures 16 – 17 show diagrams of beam deflections and comparisons with the calculated data obtained using ANSYS PC.

Figure 16. Deflection in the middle of the beams (beam with prestressed reinforcement).

Figure 17. Comparison of deflections (beam with insulated reinforcement)

Figure 18 shows the type of fracture and the general view of the tested beam with traditional prestressed reinforcement.

Figure 18. General view general view of the development of cracked beams.

4 Conclusions
1. The stress – strain state of prestressed steel – reinforced concrete beams prestressed using reinforcement, as well as through the use of internal forces of shrink processes, is investigated.

2. Numerical studies were carried out using the Ansys and Midas programs to identify the general stress – strain state of prestressed structures taking into account the elastic and nonlinear properties of materials under gradual prestressing and the action of external loads.

3. Experimental studies have shown that concrete perceives tensile stresses at 0.4P. In the compressed zone, the concrete is deformed together with the steel beam until the development of forces of 0.85 P.
4. As shown by experimental and numerical studies, the bearing capacity of the prestressed curvilinear reinforcement of the beam is higher than 5-8 %, and the magnitude of the deflection is 4 – 9 % less when compared with a beam with rectilinear reinforcement.

5. The bearing capacity of prestressed beams with insulated reinforcement is greater than with reinforcing deformable together with concrete. The maximum stress value in concrete turned out to be 2 times less.

4. The convergence of numerical and experimental studies:
- for deflections in the stage of prestressing the beam is up to 8 %.
- for stresses in the stage of prestressing the beam is up to 5 %.
- for deflections in the loading stage is up to 15 %.
- for stresses in the loading stage is up to 10 %.

5. The convergence the results of numerical experiments from full – scale:
- for stresses is up to 15 %.
- for deflection is up to 15 %.
- by strength is of 10-15 %.

6. This article describes the possibility of prestressing steel – concrete structures by taking into account the shrinkage deformation of the concrete part.

7. The use of self-stressing in a steel – concrete beam when installing two temporary supports in the middle of a span leads to a decrease in:
- the values of the pre-operational bending moment by 3.25 times;
- stresses in the stretched profile belt by 1.47 times.

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