Modelling of a prestressed beam without concrete-to-steel bond

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Abstract. The article deals with the behavior of reinforced concrete beam using reinforcement without concrete bond based on the calculation models made in the calculation complexes. The maximum load corresponding to the ultimate limit state is determined. The modelling results are compared with the calculation results in accordance with the regulatory documents on the design of structures without concrete-to-steel bond. The proposals to determine the maximum load corresponding to destruction were made.

1. Introduction
In modern construction, the pre-stressing system for concrete without concrete-to-steel bond is increasingly used. Every year the number of sites using prestressing without such bond increases. The perfect examples of the implementation of this system in building construction are: IKEA shopping center in Moscow and Yekaterinburg, June shopping center in Cherepovets and others, in which spans from 8 to 16 m were performed using prestressing.

There are regulatory documents on the territory of the Russian Federation, allowing analytical methods to design prestressed structures using reinforcement without concrete-to-steel bond. They include Design Requirements 63.13330.2012 [1], the manual to Design Requirements 63.13330 on designing of monolithic reinforced concrete structures with prestressing reinforcement without concrete-to-steel bond [2], Design Requirements 35.13330.2011 [3]. These documents contain general cases of calculations of the most common structures. But in addition to analytical calculations, one of the designer’s tasks is to make a calculation model of the structure in modern software systems using FEM. Its calculation results should correspond to the real work of the structure and, with a certain percentage ratio, correspond to the calculation results in accordance with the regulatory documents mentioned above.

The aim of the article is to compare the results of strength calculations of FEM in the LIRA CAD and Ansys software systems with the results of analytical calculations in accordance with the documents for design of prestressed concrete structures using reinforcement without concrete to steel bond.

The object of the study was a 3-meter hinge-supported beam with a section b x h = 180 x 400 mm, shown in Fig. 1, with a rope (as prestressing reinforcement) K7-15,7-1650/1860 GOST 53772-2010 [4], A_{up}=150 mm², located rectilinearly, constructional reinforcement 206 A_{s}=A_{s}'=57 mm². The
calculated characteristics of the materials were obtained as a result of testing control samples because the tests will be conducted in the future. Their results will be compared with the calculations.

Concrete characteristics: \( R_b = 37.06 \) mPa, \( E_b = 40568.5 \) mPa.

Prestressed reinforcement characteristics: \( R_{sp} = 1716 \) mPa, \( E_s = 195000 \) mPa, \( \sigma_{sp(1)} = 1373 \) mPa (stress in wire-rope reinforcement after transfer of prestressing force, giving 1-x loss).

Constructional reinforcement characteristics: \( R_c = 593 \) mPa, \( E_s = 200000 \) mPa.

2. Analytical Strength Calculation

Analytical strength calculation is performed in accordance with the manual to Design Requirements 63.13330 for the design of prestressed monolithic reinforced concrete structures with prestressed reinforcement without concrete-to-steel bond [2]. The main feature of this type of construction is that the stress increments arising in a prestressed high-tensile rope is distributed evenly along its entire length, which leads to its incomplete use of strength properties. This effect is taken into account in calculating of the ultimate limit state. The stresses in high-tensile reinforcement at the time of destruction of the element are:

\[
\sigma_{s,u} = \gamma_{sp}\sigma_{sp} + \Delta\sigma_{s,u} \leq 0.8R_s, \quad \gamma_{sp} = 0.9
\]  

\( \sigma_{sp} \) – prestressing force, giving I and II losses,
\( \Delta\sigma_{s,u} \) – stress increment in prestressed reinforcement.

The normalized value of stresses in the rope at the time of destruction corresponds to the operation of the rope in the elastic stage, therefore, the destruction of the structure is possible as a result of rupture of constructional reinforcement or brittle failure of concrete in a compressed zone.

The maximum value of the bending moment in the normal section is:

\[
M_{ult} = \sigma_{s,u}A_{sp}\left(h_0 - \frac{x}{2}\right) + R_sA_s\left(h - a - \frac{x}{2}\right) + R_{sc}A'_s\left(\frac{x}{2} - a'\right)
\]  

The stress increment in prestressed reinforcement from external load in ultimate state:

\[
\Delta\sigma_{s,u} = 70\left(\frac{0.6}{\xi} - 1\right), \quad \xi = x/h_0
\]

The height of the compressed zone is calculated from the equation:
\[ x^2 - Ax - B = 0, \text{where } A = \frac{(\sigma_{sp} - 70)A_{sp} + R_s A_s - R_{sc} A'_s}{R_b b} \]

\[ B = \frac{42 h_0 A_{sp}}{R_b b} \]

When the height of the compressed zone is \( x < 2a' \), the compressed reinforcement is not taken into account because it is located in the proximity of the neutral axis.

The losses of prestressing are determined in accordance with article 6 of the manual to Design Requirements 63.13330 [2]. Since I losses were determined experimentally, by the extractant of prestressing reinforcement, they were taken into account in the initial data.

Table 1 shows the calculation formulas of loss and their results.

| Number | Type of loses            | Relation                  | Amount, mPa |
|--------|--------------------------|---------------------------|-------------|
| 1      | Concrete contraction loss | \( \Delta\sigma_{sp5} = \varepsilon_{b,sh} E_s \) | 58.5        |
| 2      | Concrete creep loss      | \( \Delta\sigma_{sp6} = \varepsilon_{cp} E_s \) | 25.1        |
|        |                          | \( \varepsilon_{cp} = \frac{\phi_{b,cr} \cdot \sigma_{bp}}{E_{bp}} \) |             |
| 3      | Reinforcement relaxation loss | \( \Delta\sigma_{sp1} = r_{100a} \cdot \delta_{r} \cdot \sigma_{sp} \) | 51.5        |

| II Losses | \( \Delta\sigma_{sp(2)} \) | 135.1 |

The amount of the prestress, giving losses, is 1259.5 mPa. The initial relative strains of prestressing reinforcement, determined according to Hooke’s law, are 0.65%.

The height of the compressed zone and the ultimate moment of the section are determined according to formulas 2 and 4, and they are equal to 3,593 mm and 61.9 kN ∙ m, 59.6 kN ∙ m - taking into account and without taking into account the dead weight of the beam.

3. **The strength calculation for FEM in the LIRA CAD software complex**

A reinforced concrete beam with prestressed reinforcement without concrete-to-steel bond on hinged movable supports was designed in the LIRA. The material characteristics were non-linear according to the initial data.

Concrete is designed using the volumetric spatial physical non-linear 8-node finite elements. Constructional unit of the reinforcement was specified using the percentage of reinforcement. The prestressing was modeled using a finite element 208 — a physically nonlinear special two-node pretension element. The completely rigid body was set according to the area of anchor action for more accurate transmission of the compression force. The calculated model of the beam and the loads acting on it are presented in Fig. 2.
Anchorages are created at two points according to the test pattern, movements along the Y axis (along the length of the beam) are allowed on one side of the beam, and turns are allowed in all directions.

The prestressing force was set by pulling the FE 208 and numerically equal to 1259.5 mPa. The load was applied in the form of two concentrated forces applied 1 m from the supports, by a step-by-step method until the moment of failure, the dead weight is also set. The maximum loading was 75 kN, respectively, the maximum bending moment was 75 kN \cdot m, the resolution in the calculations in the LIRA occurs on concrete compressed zone. Figure 3 shows a normal stress distribution diagram in concrete before the failure stage.

Concrete was designed using the volumetric spatial physical non-linear 8-node finite elements - Solid 65. Constructional unit of the reinforcement and prestressed reinforcement were specified using the finite elements Link180. The prestressing force was modeled as a heat load and numerically equal to 1259.5 mPa. The conditions of fastening and loading correspond to the calculation model were performed in the Lyra calculation complex.

The moment of beam destruction was set after reaching the constructional reinforcement creep strength. The maximum moment from loading is 74.4 kN \cdot m. Fig. 4. shows the stress distribution diagram in the reinforcement at the time of failure.

4. The strength calculation of FEM in Ansys software complex

A reinforced concrete beam with prestressed reinforcement without concrete-to-steel bond on hinged movable supports was designed in the LIRA. The material characteristics were non-linear according to the initial data.

Concrete was designed using the volumetric spatial physical non-linear 8-node finite elements - Solid 65. Constructional unit of the reinforcement and prestressed reinforcement were specified using the finite elements Link180. The prestressing force was modeled as a heat load and numerically equal to 1259.5 mPa. The conditions of fastening and loading correspond to the calculation model were performed in the Lyra calculation complex.

The moment of beam destruction was set after reaching the constructional reinforcement creep strength. The maximum moment from loading is 74.4 kN \cdot m. Fig. 4. shows the stress distribution diagram in the reinforcement at the time of failure.
Figure 4. Stress Distribution Diagram in the Reinforcement at the Time of Failure

Stresses in high-tensile reinforcement at the moment of failure are equal to 1460 mPa., the relative strains are 0.76%. Figure 5 shows a diagram of the dependence of stresses on strains for wire-rope reinforcement K7-15,7-1650 / 1860, recieved by the tensile test of a sample, according to which the reinforcement is in an elastic state.

Figure 5. Diagram of the Dependence of Relative Stresses on Strains for Reinforcement K7-15,7-1650 / 1860

Figure 6 shows a stress distribution diagram in concrete at the time of failure.

Figure 6. Stress Distribution Diagram in Concrete at the time of Failure
5. Conclusions
The results of the calculations comparison of the beam bearing capacity, received by analytical calculations and calculations based on modeling in software systems (focused on the finite element method) are presented in Table 2.

| Number | Type of calculation | Amount, kN·m | %, ratio |
|--------|---------------------|--------------|----------|
| 1      | Analytical          | 59,6         | 100      |
| 2      | LIRA CAD            | 75           | 127,2    |
| 3      | Ansys               | 74,4         | 124,8    |

In accordance with the calculations, the prestressed reinforcement does not reach its creep strength when the beam is subjected to the maximum bending moment as well as the stress concentrations do not arise in the crack formation sites due to the even distribution of strains in the absence of friction, the rope cannot be damaged. As a result, the prestressing effect is maintained throughout the entire period of the construction. It is opposite in sign to the external load, and therefore the ultimate moment can be increased. Table 3 shows the results of analytical calculations, giving the increase in the limit moment due to the preservation of the prestressing force.

| Number | Type of calculation | Amount, kN·m | %, ratio |
|--------|---------------------|--------------|----------|
| 1      | Analytical          | 71,83        | 100      |
| 2      | LIRA CAD            | 75           | 104,4    |
| 3      | Ansys               | 74,4         | 103,6    |

This assumption must be verified by field tests.

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