The Substantiation of Steel-Reinforced Concrete Composite Bridge Superstructure Design

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Abstract. The article presents the calculation of a composite reinforced concrete bridge superstructure 42 meters long and 15.9 meters clear width, taking into account the layout cross-section zero axis position correction. It is assumed to pair the concrete slab of the carriageway and the steel main beams along the neutral axis of the section, at the same time reinforced concrete will perceive only compressive forces, and the steel main beams will perceive only tensile forces. Steel beam and reinforced concrete slab are included in the work at the same time and together perceive internal forces from permanent and temporary loads. The bridge superstructure consists of composite steel reinforced concrete blocks, which are prefabricated and combined at the construction site. To ensure the simultaneous inclusion in the work of the whole cross-section, the installation of the bridge superstructure structure by means of a hinged method or on solid scaffolding is provided.

1. Introduction

Structures where main steel elements from double T-beam or box girder join to collective work with reinforced concrete slab is composite reinforced concrete bridge superstructure. Basically, it is began to use at the late forties of the last century in streets and roads bridges in Russian bridge building [1].

A strength of concrete in the construction of steel-concrete girders without force control is usually not fully used. At the same time concrete does not perceive or only partially perceives the internal forces from constant loads. It is fully included in the work only under the action of temporary loads [2]. The steel part of the girder cross-section bears an additional load in the form of a carriageway slab, which significantly affects the geometric characteristics of the entire cross-section [3]. The Russian and foreign practice of using composite still-concrete and composite girders is presented in the reports [4-17].

2. Materials and methods

In the author's certificates [18] and [19] it is proposed to carry out the junction of the reinforced concrete slab of the carriageway and the steel main beams at the level of the neutral axis of the cross-section. In this case reinforced concrete will perceive only compressive forces and steel main beams -
only tensile forces. A junction of reinforced concrete part with a steel one at the level of cross-section zero axis allows rational materials distribution in the section in accordance with their strength characteristics, thereby reducing the consumption of materials at construction.

The purpose of this study is to determine the material intensity ratio of the investigated steel-reinforced concrete girder and the typical one [6].

The object of the study is a steel concrete girder 42 meters in length with 15.9 meters transverse size. Its calculation was carried out by two methods: analytical [18, 19] and numerical - by the finite element method using the Midas Civil software for the effect of permanent and temporary loads. The junction of the reinforced concrete carriageway slab and the steel main beam is at the level of the neutral axis of the girder. The joint level as well as the neutral axis of a cross-section changes its position along a beam length depending on a cross-section geometric characteristics and an acting forces. Permissible compressive and tensile stresses in the carriageway reinforced concrete slab are 15.5 MPa and 1.1 MPa respectively for concrete class B30. Permissible tensile stresses in the main beam of 15XSND steel are 265 MPa.

A height of combined steel-reinforced concrete cross-section is determined as a calculation result and is assumed to be constant along the entire bridge superstructure. A height of a steel section is regulated by changing of a main beam wall height. A reinforced concrete section height is adjusted by a height of carriageway slab rib changing.

2.1 Analytical calculation

The cross-section zero axis change level through the bridge superstructure and bending moment \( M(x) \) dependent, forming a zero axis line. The zero axis position in each cross-section is adjusted by changing the cross-section geometric parameters. The bridge superstructure design case is presented in the figure 1.

We write the equation of equilibrium section \( \Sigma X = 0 \) from the condition of a longitudinal force absence in the beam cross-section

\[
- \int_{F_b} \sigma_b dF + \int_{F_s} \sigma_s dF = 0, \quad (1)
\]

where \( \sigma_b, \sigma_s \) - normal stresses in concrete and steel respectively; \( F \) - cross-section area; \( F_s \) – steel part area, \( F_b \) – reinforced concrete part area.

Taking into account the linear change in normal stresses along the height of the cross-section equation (1) is transformed into the following form:

\[
- \frac{E_b}{\rho} \int_{F_b} y dF + \frac{E_s}{\rho} \int_{F_s} y dF = 0, \quad (2)
\]

where \( E_b, E_s \) – resilient modulus of concrete and steel respectively; \( \rho \) – bending curvature radius.

From the equation (2) we have:

\[
S_b = n_b S_{st}, \quad (3)
\]

where \( S_b, S_{st} \) – the static moments of inertia the reinforced concrete and steel parts of the cross-section respectively; \( n_b \) - steel to concrete ratio factor:

\[
n_b = \frac{E_b}{E_s}. \quad (4)
\]

The strength condition for the lower flange of the beam we write in the form

\[
R_{us} = M(x) \frac{y_s}{I_{stb}}. \quad (5)
\]

where \( M(x) \) – bending moment, \( y_s \) – steel part depth, \( I_{stb} \) – whole cross-section moment of inertia, \( R_{us} \) – steel allowable stress.

After transformation (3) and (5), we get an equations system with two unknowns:

\[
\begin{bmatrix}
H \left( F_b k^2 + n_b F_l k_l^2 \right) + \frac{H^2 (S_b k^3 + n_b S_{st} k_l^3)}{3} + \left( k F_b h_p + k_1 F_l \delta_{gl} \right) \frac{1}{k_1 n_b} - \frac{M(x)}{R_{uc}} = 0 \\
F_b \left( y_b - \frac{h_p}{2} \right) + R_s \frac{y_b}{2} - n_b F_s \frac{y_s}{2} - n_b F_l \left( y_s - \frac{\delta_{gl}}{2} \right) = 0
\end{bmatrix} \quad (6)
\]
where \( k \) – the whole cross-section depth \( H \) to the steel part depth \( ys \) ratio; \( k_1 \) – the whole cross-section depth \( H \) to the reinforced concrete part depth \( y_b \) ratio.

Required parameters are \( H \) – the whole cross-section depth, \( F_{gl} \) – the girder bottom flange area.

The system of equations (6) solution depends on the bending moment \( M(x) \). The bending moment from permanent and temporary loads are determined taking into account the transverse setting load coefficient into the bridge superstructure. The bridge superstructure transverse dimension is adopted similarly to the typical project [6]. Cross-section geometric parameters are presented in Figure 2.

Figure 1. The bridge superstructure design case.

If paste the elements cross-section minimum allowable geometric parameters according to [20] and the bridge superstructure middle maximum bending moment to (6), will have whole cross-section depth \( H \) and the girder bottom flange area \( F_{gl} \).

Girder top flange has a constructive purpose and does not take into account, because it is located in the level cross-section zero axis. The obtained parameters presented in the table 1.
Table 1. The bending moment dependent cross-section geometric parameters.

| Cross-section coordinate \( x, \) m | Bending moment \( M(x), \) kN-m | Bridge superstructure depth \( H, \) m | Steel part depth \( y_s, \) m | Reinforced concrete part depth \( y_b, \) m | Girder bottom flange thickness \( \delta, \) m | Girder bottom flange width \( b, \) m |
|---|---|---|---|---|---|---|
| 21 | 33.266 | 2.410 | 1.848 | 0.562 | 0.040 | 0.975 |
| 18 | 32.626 | 2.410 | 1.861 | 0.549 | 0.040 | 0.940 |
| 15 | 30.314 | 2.410 | 1.901 | 0.509 | 0.040 | 0.840 |
| 12 | 27.232 | 2.410 | 1.974 | 0.436 | 0.040 | 0.670 |
| 9 | 22.478 | 2.410 | 2.089 | 0.321 | 0.035 | 0.470 |
| 6 | 16.405 | 2.410 | 2.230 | 0.180 | 0.020 | 0.400 |
| 3 | 8.963 | 2.410 | 2.230 | 0.180 | 0.020 | 0.400 |
| 0 | 0.000 | 2.410 | 2.230 | 0.180 | 0.020 | 0.400 |

2.2 Finite Element Calculation

To verify the accepted assumptions we will carry out a finite element calculation in the Midas Civil software package using the obtained cross-section characteristics. The purpose of the finite element method calculation is to check the reliability of the analytical calculation, determine the stresses in cross-sections and compare them with the designed stresses.

Bridge superstructure design model has constant 2.41 meters depth. Steel part depth varies through the bridge superstructure and consist from plates 0.25 x 0.25 meters size finite elements. Reinforced concrete slab rib also has varies depth through the bridge superstructure. Reinforced concrete part consist from the 0.25 x 0.75 x 0.09 meters size solid elements. Clear width is 15.90 meters. Design model presented in the figure 3.

![Figure 3. The bridge superstructure model.](image)

a) Transverse cross-section.
b) Design model perspective (here is a half of design model)

Stress diagram presented in figure 4. In Figure 4 it can be seen that tensile stresses arise at the lower edge of the carriageway plate rib. It means that the line of zero axis passes above the expected level.

![Figure 4. Stress diagram in the middle section of the model.](image)
2.3 Construction conditions
Simultaneous activation of a steel and reinforced concrete parts of a beam cross-section is the main condition for an operation of this structure. It is provided by the use of special construction methods (Figure 5).

![Image of bridge construction](image_url)

**Figure 5.**
a) Installation scheme of bridge superstructure overhanging part
b) Installation scheme of the bridge superstructure suspension part.

It is assumed that the steel-reinforce concrete blocks of the superstructure are manufactured in the factory. The carriageway plate concreting is made in a print with the previous block. Then on the construction site is pre-assembly by bolting the main beams and adhesive bonding of the adjacent blocks of roadway plate. After a pre-assembly the superstructure is installed entirely in the span using crane equipment.

3. Analysis and calculations results
Let’s to compare the obtained parameters of the designed bridge superstructure with a typical project [20]. Comparative parameters are presented in table 2.

**Table 2. Comparison of the model obtained parameters and typical project.**

| Parameter                        | Model       | Typical project |
|----------------------------------|-------------|-----------------|
| Steel part depth, m              | 2.230…1.848 | 2.480           |
| Reinforced concrete part depth, m| 0.180…0.562 | 0.340           |
| Reinforced concrete slab mass, tons | 316.5   | 410.5           |
| Steel girders mass, tons         | 39.2        | 53.1            |
| Mass of the whole bridge superstructure with dead loads, tons | 823.4 | 894.8 |

Table 2 shows that mass of the steel girders in model less than in typical project. The typical project is designed for old loads that are less than the current loads taken into account.

4. Conclusion
According to the results of calculations mass of the steel girders of the designed model less than typical project on 26%. Reinforced concrete slab easier on 29.6%. This shows a significant reduction in the material intensity of the bridge superstructure than previously used structures in the domestic bridge building.

When calculating by the finite element method it has been established that in the reinforced concrete carriageway rib the tensile stresses arise. This requires us to introduce safety factors in an analytical calculation that takes into account the possibility of cracking in the reinforced concrete carriageway rib.
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