Precast monolithic coating of an industrial building based on variable-height beam-slabs

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Abstract. We consider the coatings of single-story industrial buildings of frame type, which in a typical solution are made in the form of a flooring of ribbed plates on rafters, trusses or arches. There is a high complexity of manufacturing, transportation and installation of structures and a large height of the coating. We offer truss beams-slabs of box-shaped cross-section, the height of which varies stepwise along the length, being limited by a square parabola at the top. Beams are installed on the substructure structures in a row, and between them on a permanent formwork of wooden boards are arranged monolithic sections of the plate. The calculation of deformations is performed taking into account the inelastic deformation of concrete and rebar in accordance with the recommended norms of state diagrams: three-line for concrete and two-line for rebar. The results of the calculation of a beam-plate with a span of 30 m, which has 5 different stages, the height of which is selected so that the required cross-section of the reinforcement remains constant along the entire length of the structure.

1. Introduction

Reinforced concrete coatings for industrial buildings are usually used for spans up to 24 m [1-4]. In a typical solution, they are made in the form of a floor of ribbed slabs on rafters, trusses or arches, supported by columns or sub-rafters. The coating is obtained high; with spans of 24 m, it increases the height of the building by 3.75 m; the structures have a high complexity of manufacturing [5, 6], transportation and installation. There is a task to eliminate these shortcomings, and, in addition, it is desirable to have a coating of reinforced concrete for spans of 30 m.

There is a truss structure in the form of a low frame of a gable outline with a precast-monolithic upper belt [7], which includes a monolithic concrete insert that involves the end ribs and part of the shelf of ribbed plates in the construction.

There is also a spatial truss structure of a small height, consisting of two flat frames connected by lintels [8-11] at the points of support of the ribbed plates. The upper belt of the box-shaped section with a width of 2 m is located at the level of the plates, connected to them rigidly and performs both bearing and enclosing functions. The pitch of the building’s cross frames has been increased to 18 m.

Further development in this area, the struts of the truss frame are made of two cross walls, one of which is directed along the frame and gives it the greatest rigidity, the other is perpendicular and gives
support to the ribbed plates [12, 13]. Between the ends of the slabs is laid monolithic concrete, partially including the plates in the crossbar, which allows you to reduce the height of the coating [14].

A crossbar is proposed, which consists of two flat frames and a common upper belt of a box section 1.8 m wide, which simultaneously performs the bearing and enclosing functions. The crossbars [15-17] are supported on paired columns – two columns at a short distance from each other.

Next, we consider the cantilever-beam sub-truss system of a single-story industrial building, consisting of two types of beams: the first are supported by paired columns and have consoles on both sides, the second are based on the consoles of the first. The ends of adjacent beams of the second type are connected on the top by external reinforcement rods, which are stretched when loading the beams and create unloading moments. This reduces the consumption of concrete [18, 19] and allows the beams to be reinforced with A500 or A400 class rod reinforcement without pre-stress, which reduces the complexity of manufacturing and the cost of beams [20].

We propose to abandon the ribbed slabs and roof beams are forced to perform simultaneously the bearing and protecting functions.

We offer truss beams-slabs of box-shaped cross-section with a width of the upper shelf of 1.5 m, the height of which varies stepwise and is limited by a square parabola at the top (figure 1). On the substructure structures, beams-plates are installed in a row, with a distance between them of 1.5 m, which are then filled with a monolithic insert of the plate on a non-removable formwork made of wooden boards.

Figure 1. Rafter beam-slab box-shaped cross-section

Between the boards with a certain step, metal plates placed on the edge are clamped, which serve as edges and allow the entire width of the shelf to be taken into account in the calculation of the beam-plate. When laying concrete, they serve as guides [21, 22].

For example, we consider a beam-plate for a span of 30 m, the cross-section of which is shown in Figure 2.

Figure 2. Cross section of a beam-plate
Section height \( h \) changing stepwise in accordance with figure 1. It turns out three sections of different height, with the first and second consisting of two parts. Concrete of class B40 is used, rod reinforcement A500 without prestressing. Supporting the roof trusses is supposed to be articulated

2. Methods
Strength calculation is carried out according to the limiting state, based on the following premises [23]:
- in the compressed zone, the stresses in concrete at all points are the same and equal to the calculated resistance of concrete \( R_c \);
- the concrete resistance of the stretched zone is assumed to be zero;
- stresses in the reinforcement of the stretched zone are equal to the design resistance of the reinforcement \( R_s \);

The estimated snow load and dead weight of the coating elements is 0.013 MN/m. The required section of reinforcement in all sections is the same –10 Ø16 A500. Reinforcement coefficients for sections 1, 2, 3, respectively: 0.0306; 0.0254; 0.0189 and the height of the compressed zone, calculated on the strength of 0.0219; 0.0294; 0.028 m; thickness of upper shelf 0.03 m.

The calculation of the deflections is made taking into account the nonlinearity of the deformation of reinforced concrete, based on the following premises [24]:
- flat section hypothesis;
- the concrete of the compressed zone is deformed nonlinearly in accordance with the recommended three-line diagram;
- the reinforcement of the stretched zone of class A500 is deformed in accordance with the recommended two-line diagram;
- the work of the concrete of the stretched zone is indirectly taken into account using a coefficient \( \psi_s \), that increases the elastic modulus \( E_s \) to the value \( E_s / \psi_s \):

\[
\psi_s = 1 - 0.8 \frac{M_{crc}}{M},
\]

where \( M_{crc} \) – is the moment of crack formation;
\( M \) – moment from external load.

The moment of cracking is determined taking into account inelastic deformations of the concrete of the stretched zone based on the following premises:
- flat section hypothesis;
- in a compressed zone, concrete works elastically with an initial modulus of elasticity \( E_b \);
- in the stretched zone, the stresses in concrete increase elastically to the value of the calculated concrete tensile strength for the limiting states of the second group \( R_{s,ser} \), further deformation remain constant;
- the deformation of the most strained fiber of the stretched zone reaches the limit value for short-term load \( \varepsilon_{u,ser} = 0.00015 \);
- reinforcement is deformed elastically;
- the cross section (consider one edge with adjacent parts of the plate) of the beam at a moment equal \( M_{ser} \), is divided into elastic and plastic zones with deformation along \( \varepsilon_p = R_{ser,ser} / E_b \) the boundary (Figure 3).

The rate of change of deformations along the height of the plastic zone and the entire section can be found by the formula \( u = (\varepsilon_{u,ser} - \varepsilon_p) / y \), after which it is easy to find the strain and stress at any point in the section and the magnitude of the moment \( M_{ser} \).
The stiffness [25] of the beam-slab is determined by the deformation of the most strained concrete fiber of the compressed zone. It is required to determine the height of the compressed zone and the bending moment corresponding to this deformation - the sum of the moments relative to the neutral line of stresses in the concrete of the compressed zone and the forces in the reinforcement of the extended and compressed zones. The task is complicated by the fact that the compressed zone has a T-section. The following methodology is proposed:

- a plot of deformations is constructed within the height of the compressed zone \( x \);
- stress diagram is constructed in accordance with the strain diagram and the accepted diagram of concrete deformation;
- the resultant of stresses in the concrete of the compressed zone \( N_0 \) is calculated in parts \( N_{b, i} \), which are distinguished taking into account the T-shape of the cross section so that for each of them it was not difficult to determine the distance \( z_i \) to the neutral line of the cross section of the beam. Figure 4 gives an example for the case when \( \varepsilon_{b0} < \varepsilon_b < \varepsilon_{b2} \).

\[
\varepsilon_{b2} \quad \varepsilon_{b1} \quad \varepsilon_{b0} \quad \varepsilon_{b}\]

\[
0.6R_b \quad 0.4R_b \quad 0.4R_b (|q| + \bar{x} - h) \quad \text{neutral line} \quad d
\]

\[\sigma_b \]

\[\varepsilon_b \]

\[\varepsilon_{b0} \quad \varepsilon_{b1} \quad \varepsilon_{b2} \]

\[\varepsilon_{b0} - \varepsilon_{b1} \quad \varepsilon_{b1} - \varepsilon_{b2} \]

\[\varepsilon_{b0} - \varepsilon_{b0} \]

Figure 3. The cross section of the beam at a moment equal to \( M_{cr} \)

Figure 4. On the determination of the resultant and the moment of a relatively neutral stress line in concrete of a compressed zone during deformation of the most stressed fiber \( \varepsilon_b > \varepsilon_{b0} \).
3. Results and discussion

The calculation is performed according to the following formulas:

\[ N_{b,1} = R_b r x d ; \quad z_1 = x - \frac{r x}{2} \]  
\[ N_{b,2} = 0.6 R_b q x d ; \quad z_2 = px + \frac{q x}{2} \]  
\[ N_{b,3} = -0.6 R_b \left[ (q + r) x - h \right] (d - d_i) ; \quad z_3 = px + 0.5 \left[ (q + r) x - h \right] \]  
\[ N_{b,4} = \frac{1}{2} 0.4 R_b q x d ; \quad z_4 = px + \frac{2}{3} q x \]  
\[ N_{b,5} = - \frac{0.2 R_b}{q x} \left[ (q + r) x - h \right] (d - d_i) ; \quad z_5 = px + \frac{2}{3} \left[ (q + r) x - h \right] \]  
\[ N_{b,6} = \frac{1}{2} 0.6 R_b p x d ; \quad z_6 = \frac{2}{3} px \]  

The forces in the reinforcement are written as [26]:

- for stretched zone

\[ N_s = E_s A_s \varepsilon_s = \frac{E_s A_s}{\psi_s} \varepsilon_s \frac{h_0 - x}{x} \]  

- for compressed zone

\[ N'_s = E_s A'_s \varepsilon'_s = E_s A'_s \varepsilon_b \frac{x - d'_i}{x} \]  

An equilibrium equation \( N_s + N'_s - N_s = 0 \) is compiled, which turns out to be an equation of the form \( ax^2 + bx + c = 0 \) with the coefficients:

\[ a = R_b \left[ rd + 0.8 q d - 0.6 (q + r) - \frac{0.2}{q} (d - d_i)(q + r)^2 + 0.3 p d_i \right] \]  
\[ b = R_b \left[ (d - d_i) \left[ 0.6 h + \frac{0.4 (q + r) h}{q} \right] + E_s \varepsilon_b \left( A'_s - \frac{A_s}{\psi_s} \right) \right] \]  
\[ c = -0.2 R_b h^2 \frac{d - d_i}{q} + E_s \varepsilon_b \left( \frac{A_s}{\psi_s} h_0 - A'_s a' \right) \]
From the solution of the equation, the height of the compressed zone \( x \), is determined, after which the bending moment \( M \), the curvature of the curved axis of the beam \( k = \epsilon / x \) and the stiffness of the beam \( G = M / k \) are determined.

The calculation of the beam-plate begins with the fact that for each of its three sections, deformations of the extreme fiber of the compressed zone from \( \epsilon_b = 0.00001 \) to \( \epsilon_b = 0.00350 \) are sequentially set and the corresponding values of the bending moment, deformation \( \epsilon_b \), curvature of the curved axis and stiffness of the beam-plate are calculated and entered into the table.

Next, the elastic solution method is used in combination with the finite difference method. In each elastic solution, the beam-slab is divided along the length into small parts, along the borders of which dots \( j = 1, 2, 3, ... n \) are applied. Deflections of the beam at these points are taken as the main unknowns; they are determined from the solution of the system of equations of equilibrium of small parts selected in the vicinity of each point \( j \). According to the deflections, the curvature of the curved axis of the beam-slab is determined, and from them - the lines in the table, from where the stiffness is taken for the next elastic solution, and individually for each point \( j = 1, 2, 3, ... n \). The solution shows stable convergence.

The load to be calculated for the second group of limit States was 0.00919 MN/m. Figure 5 shows diagrams of bending moments, vertical displacements, beam-plate stiffness, height of the compressed zone and deformation of the most stressed fiber of the compressed zone.

![Figure 5](image-url)
4. Conclusions
We offer a prefabricated monolithic coating of a single-story industrial building, consisting of roof beams-slabs of box-shaped cross-section of variable height, bounded by a square parabola. Beams-plates are based on subfarm structures, stacked in a row and connected by a monolithic insert that complements the plate of the upper belt. They simultaneously perform a bearing and enclosing function. The height of the covering in the middle of the span is 1.85 m, the span overlap is 30 m, the required cross-section of the A500 class reinforcement is constant along the entire length without pretension. The design is easy to manufacture, provides a high speed of installation and a combination of installation and concrete work during the construction of the coating.

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