Designing of Standard Cross Sections of Composite Bending Reinforced Concrete Elements by the Method of Design Resistance of Reinforced Concrete

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Abstract. The principles of designing standard cross sections of composite bending reinforced concrete elements using modern deformation models have been considered in the proposed article. This paper is dedicated to composite beams with symmetrical cross sections, which are most frequently used in practical activity in construction sphere. In such elements there are neither torsion, nor tension in perpendicular plane of effect of forces, thanks to which they have the highest loading-carrying ability as compared to asymmetrical composite constructions. The authors have developed an alternative calculation method for the composite bending elements by using the method of analysis of design resistance of reinforced concrete. The given method makes it quite easy to make calculations of such elements, concurrently its precision corresponds to the accuracy of calculation of modern deformation models, taking into account non-linear deformation curves of materials. The procedure for calculating three types of problems, which are typically used in construction practice, has been proposed in this research work. This article presents the procedure of calculation of the following problems: determination of the required area of reinforcing steel according to the known size dimensions of composite beams and defined strength grade of materials; determination of the bearing capacity of standard cross sections with known reinforcement; checking procedure of the bearing capacity of composite bending elements. There have also been given calculation examples of standard cross sections of composite bending reinforced concrete elements made of different concrete grades.

Keywords: Deformation model, Method of design resistance of reinforced concrete, Composite beams with symmetrical cross sections.

Composite bending elements take their rightful place in modern design practice. Such elements are prevalently used in the reconstruction of existing beam elements. One of complicated problems that arise in the design of composite constructions is the issue of ensuring collaboration between composite constructions made of different concrete grades and, in some cases, even between different materials. Collaboration of composite elements is assured both by the adhesion between concrete of different grades, and by setting special anchors, screw bolts, drawing rods and confining elements. As these issues were properly investigated in the scientific study [1-13], we have not examined them in this paper.

1 Calculation elements is performed based on nonlinear calculation models through the use of factual deformation curves of concrete and reinforcing steel

Modern deformation models of calculation make it possible to perform the calculation of such elements, but at the same time this calculation is quite complex and can be realized only with the help of purposely designed programs on electronic computers.

Calculation of such elements is performed based on nonlinear calculation models through the use of factual deformation curves of concrete and reinforcing steel. Basic prerequisites for the calculation are the following:

1) composite cross-sections collaborate without displacing one respecting another;

2) The dependence of longitudinal deformations of concrete in the cross section of the composite elements is assumed to be linear;

3) The dependence of “tension – deformations” in the concrete of the compression area is taken as nonlinear – in the functional form, proposed in Eurocode-2 [14,18,20];

4) The dependence of “tension – deformations” in reinforcing steel is taken as a bi-linear Prandtl diagram;

5) We do not take into account the force in the tensile zone of the concrete in composite beams.

The calculation of cross sections of composite elements is performed on the basis of the following equations of equilibrium (Fig.1):

$$\sum_{i=1}^{n} N_{ix} = 0; N_{c1} + N_{c2} + N_s = 0; \tag{1}$$

$$\sum_{i=1}^{n} M_i = M_u; M_{c1} + M_{c2} + M_s = M_u. \tag{2}$$

In expressions (1), (2): N_{c1}, N_{c2} – forces in the section of compressed concrete of a composite beam, made of concrete grades C_1 and C_2 accordingly; N_s – stress in reinforcement; M_{c1}, M_{c2} – the moment of flection regarding the neutral axis of the corresponding parts of the compressed concrete; M_s – the moment of flection (bending moment) from the forces in the working reinforcement as to the neutral axis.

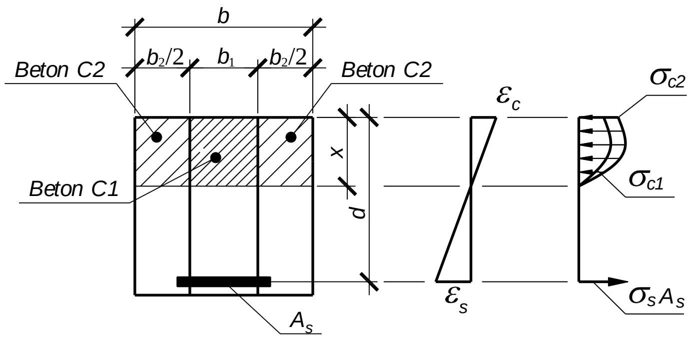

Fig. 1 The scheme of stresses and deformations in the cross section of a bending composite beam.

Forces in compressed concrete can be determined in two ways. The first method involves breaking down the cross section of a composite beam into a certain number of sections within which stresses are taken to be constant [15-17]. In that case, the shape of the accepted stress function in the concrete of the compression area is not significant. In order to obtain the required calculation accuracy, this method requires splitting the section into a considerable amount of sections. The second method is to integrate the obtained equations directly. When applying this method, the stress function in compressed concrete is of great importance, since in most cases when using complex formulae one will deduce transcendent equations, the solution of which usually leads to great complications. In such instance, it is advisable to use polynomial dependencies [19, 21-23] that can easily be integrated.

In order to obtain the value of the bearing capacity of a composite element, it is necessary to apply to the equations (1) and (2) one of the above-described methods of obtaining the force in the compressed concrete and also to apply the fracture criteria in the following form [24-26]:

$$\begin{cases} \dfrac{dM_d}{d\varepsilon} = 0\,,\ \varepsilon_c \le \varepsilon_{cu}; \\ \sigma_s \le f_{yd}; \\ \varepsilon_s \le \varepsilon_{su}. \end{cases} \tag{3}$$

This calculation, regardless of the means adopted, is performed by the method of iterations. At the same time, it remains quite difficult in practical application, especially in the absence of purposely designed computer programs.

2 Basis for calculation of standard cross sections of composite bending reinforced concrete elements by the method of design resistance of reinforced concrete

Let us consider composite bending reinforced concrete elements with symmetrical cross section. Such elements are most commonly used in the engineering practice of building composite constructions. In such elements there are neither torsion, nor tension in perpendicular plane of effect of forces, thanks to which they have the highest loading-carrying ability as compared to asymmetrical composite constructions.

We would like to offer an alternative method of calculating standard cross sections of composite bending elements. This method implies the usage of the properties of design resistance of reinforced concrete and greatly simplifies the whole process of calculation of composite elements.

All the foregoing prerequisites are the framework for the method of design resistance of reinforced concrete. However, after simple transformations and, taking into account the fracture criteria, the basic equations of equilibrium are transformed into the following strength condition (3).The real design decisions of the master plans of grain terminals or hopper enterprises, involve a simple arrangement of silos in the form of small groups with parallel, perpendicular placement or some angular deviation. Preferably, silo parks include silos of the same diameter and height, which greatly simplifies their study.

$$M = f_z W_c, \tag{4}$$

where f_z – the design resistance of reinforced concrete in bending, MPa, W_c – moment resistance of working cross section of concrete, m^3.

The design resistance of reinforced concrete in bending can be calculated by the formula:

$$f_z = k_z f_{cd}. \tag{5}$$

The parameter κ_z is functionally dependent on the mechanical percentage of reinforcement, which can be determined by the following expression:

$$\omega = \frac{\rho_f f_{yd}}{f_{cd}}, \tag{6}$$

where ρ_f – the reinforcement ratio of the cross-section with longitudinal reinforcement, f_{yd} – design resistance of the longitudinal reinforcement, f_{cd} – design resistance of compressive strength of concrete.

Functional dependency $k_z = f(\omega)$ is nonlinear in nature, so, to make its usage easier, it can be approximated by straight-line sections. In this case, the defining formulae for the parameter k_z or for the mechanical percentage of reinforcement will take the following form:

$$k_z = \alpha + \beta\omega; \tag{7}$$

$$\omega = (k_z - \alpha)/\beta. \tag{8}$$

This dependency and its approximation are presented in table 1.

Let us consider cross section of a composite beam with rectangular cross-section (Fig. 2). The cross-section consists of three rectangles – the average rectangular cross-section has compressive strength of concrete f_{c1} and width b_1, two boundary cross sections f_{c2} and the corresponding widths $b_2/2$. In such a situation, the total width of the cross-section will be $b = b_1 + b_2 / 2 + b_2 / 2$.

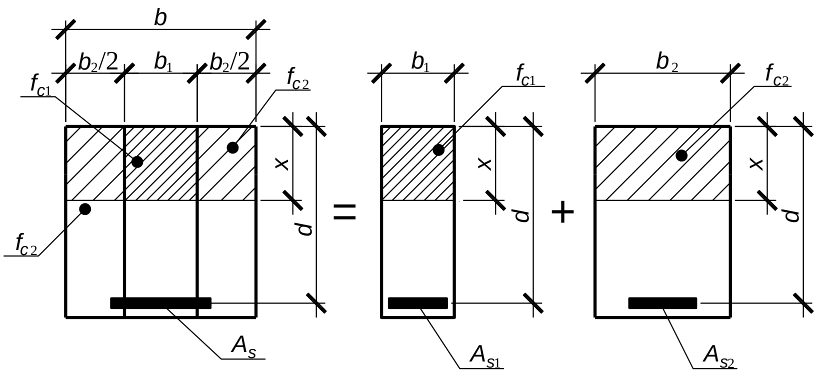

Fig.2. To the calculation of cross sections of a composite beam by the method of design resistance of reinforced concrete.

Let us conditionally decompose a cross section of a composite beam in accordance with Fig. 2, in such a way, so that the strength of two cross sections from different concrete grades would correspond to the strength of the composite cross-section. Namely, upon the given geometrical parameters of two beams from different concrete grades, it is necessary to distribute the longitudinal reinforcement between them accordingly. In this case, according to the method of design resistance of reinforced concrete, the strength of the composite cross section will be equal to:

$$M_u = M_{u1} + M_{u2}; M_u = f_{c1}k_{z1}\frac{b_1 d^2}{6} + f_{c2}k_{z2}\frac{b_2 d^2}{6}. \tag{9}$$

As you can see from expression (9), it is possible to divide a composite beam into two beams only on condition of equality:

$$f_{c1}k_{z1} = f_{c2}k_{z2}. \tag{10}$$

Genuinely, if the condition of equality (10) is correct, then

Table 1.. Functional dependency kz = f (ω) and its approximation

Parameters for calculating bending elements				
n/n	k_z	Mechanical percentage of reinforcement t ω	Approximating parameters	
			α	β
1	0,000	0,00	0,000	5,678
2	0,568	0,10	0,048	5,196
3	0,828	0,15	0,096	4,874
4	1,071	0,20	0,161	4,553
5	1,299	0,25	0,241	4,231
6	1,511	0,30	0,338	3,910
7	1,706	0,35	0,450	3,588
8	1,885	0,40	0,744	2,852
9	2,028	0,45	1,649	0,841
10	2,070	0,50	1,722	0,696
11	2,140	0,60	1,808	0,554
12	2,195	0,70	1,928	0,382
13	2,310	1,00	2,143	0,166
14	2,476	2,00	0,000	5,678
15	2,542	3,00		

$$M_u = f_{c1} k_{z1} \frac{d^2}{6}(b_1 + b_2) = f_{c1} k_{z1} \frac{bd^2}{6}. \qquad (11)$$

In this case, the problem of calculating the strength of the composite beam reduces to finding the corresponding allocation of reinforcement between cross sections of regular beams.

Let us write the statement of the problem (10) with consideration to the expression (7):

$$f_{c1}(\alpha_1 + \beta_1\omega_1) = f_{c2}(\alpha_2 + \beta_2\omega_2). \qquad (12)$$

In expanded form, expression (12) will be the following:

$$f_{c1}\left(\alpha_1 + \beta_1 \frac{A_{s1} f_{yd}}{b_1 d}\right) = f_{c2}\left(\alpha_2 + \beta_2 \frac{A_{s2} f_{yd}}{b_2 d}\right). \qquad (13)$$

Given that:

$$A_{s2} = A_s - A_{s1}, \qquad (14)$$

after simple transformations of the expression (13) we will get:

$$A_{s1} = \frac{\dfrac{\beta_2 f_{yd} A_s}{b_2 d} + \alpha_2 f_{c2} - \alpha_1 f_{c1}}{\dfrac{\beta_1 f_{yd}}{b_1 d} + \dfrac{\beta_2 f_{yd}}{b_2 d}}. \qquad (15)$$

For ease of use of the expression (15) we will introduce the notation

$$f_1 = \frac{A_s f_{yd}}{b_1 d}, \; f_2 = \frac{A_s f_{yd}}{b_2 d}. \qquad (16)$$

Then the expression (15) will be written in the following form:

$$A_{s1} = A_s \frac{\beta_2 f_2 + \alpha_2 f_{c2} - \alpha_1 f_{c1}}{\beta_1 f_1 + \beta_2 f_2}. \qquad (17)$$

The abovementioned expressions allow you to solve three types of problems for calculating standard cross sections of composite beams:

1. Determination of the required area of the working reinforcement of composite beams;

2. Determination of strength of standard cross sections of composite beams;

3. Checking the strength of standard cross sections of composite beams.

The following offers the calculating procedure for the proposed problems.

The procedure for determining the required area of the working reinforcement of composite beams:

1) Initially, we define the necessary parameters:

$$k_{z1} = \frac{6M_u}{bd^2 f_{c1}}, \; k_{z2} = \frac{6M_u}{bd^2 f_{c2}}.$$

2) Then we will determine mechanical reinforcement ratios:

$$\omega_1 = (\mathrm{k}_{z1} - \alpha_1)/\beta_1, \;\; \omega_2 = (\mathrm{k}_{z2} - \alpha_2)/\beta_2 .$$

3) Now it is necessary to determine the required area of reinforcement of each element:

$$A_{s1} = \frac{f_{c1}}{f_{yd}} \omega_1 b_1 d, \; A_{s2} = \frac{f_{c2}}{f_{yd}} \omega_2 b_2 d.$$

4) The full area of the longitudinal reinforcement of a composite element is equal to:

$$A_s = A_{s1} + A_{s2}.$$

The procedure for determining the strength of standard cross sections of composite beams with the known longitudinal reinforcement is the following:

1) We determine the area of the longitudinal reinforcement A_{s1}. by the expression (17). The fault-identifying variables (auxiliary parameters) α and β are taken preliminarily and can be refined as necessary.

2) We find out the mechanical percentage of reinforcement by the following expressions:

$$\omega_1 = \frac{f_{yd} A_{s1}}{f_{c1} b_1 d}, \; \omega_2 = \frac{f_{yd}\left(A_s - A_{s1}\right)}{f_{c2} b_2 d}.$$

3) We define the fault-identifying variables (accessory parameters) α_1, α_2, β_1, β_2 according to table 1 and check the correctness of their assumption in example 1.

4) We define an accessory parameter $\mathrm{k}_{z1} = \alpha_1 + \beta_1 \omega_1$.

5) We define the bearing capacity of a composite bending element by the following expression:

$$M_u = f_{c1} k_{z1} \frac{bd^2}{6}.$$

The proposed technique is based on the universal dependence of strength characteristics on stress-related characteristics, that is why it can also be applied to different concrete grades and, even, to rock materials, for which in some cases it is necessary to limit the value of mechanical percentage of reinforcement ω.

3 Calculation examples of standard cross sections of composite bending reinforced concrete elements

Example (sum) 1. It is necessary to determine the cross-sectional area of the longitudinal working reinforcement of the composite beam. A beam with cross section b × h = 400 × 400 mm (d = 35 cm) made of concrete grade C12 / 15 b_1 = 150 mm (f_{c1} = 8,5 MPa) and concrete C20 / 25 b_2 = 250 mm (f_{c2} = 14,5 MPa) should perceive the beam moment (moment of flection) M_u = 100 kN × m (see Fig. 3).

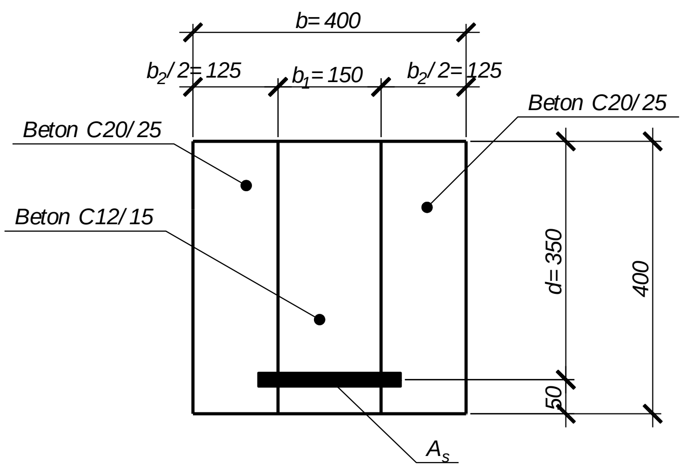

Fig.3. To examples (sums) 1 and 2.

The solution to the problem.

1) We define the necessary parameters

$$k_{z1} = \frac{6M_u}{bd^2 f_{c1}} = \frac{6 \times 100 \times 10^6}{400 \times 350^2 \times 8{,}5} = 1{,}441.$$

$$k_{z2} = \frac{6M_u}{bd^2 f_{c2}} = \frac{6 \times 100 \times 10^6}{400 \times 360^2 \times 14{,}5} = 0{,}844.$$

2) We set up mechanical percentages of reinforcement:

$$\omega_1 = (\mathrm{k}_{z1} - \alpha_1)/\beta_1 = (1{,}441 - 0{,}241)/4{,}231 = 0{,}284;$$

$$\omega_2 = (\mathrm{k}_{z2} - \alpha_2)/\beta_2 = (0{,}844 - 0{,}096)/4{,}874 = 0{,}153.$$

3) Then we determine the required area of reinforcement of each element:

$$A_{s1} = \frac{f_{c1}}{f_{yd}} \omega_1 b_1 d = \frac{8{,}5}{415} 0{,}284 \times 150 \times 350 = 305{,}4\ mm^2.$$

$$A_{s2} = \frac{f_{c2}}{f_{yd}} \omega_2 b_2 d = \frac{14{,}5}{415} 0{,}153 \times 250 \times 350 = 467{,}8\ mm^2.$$

4) The full area of the longitudinal reinforcement of a composite element is equal to:

$$A_s = A_{s1} + A_{s2} = 305{,}4 + 467{,}8 = 773{,}2\ mm^2.$$

For reinforcement we take on 4∅16 A500 (f_{yd}=415 MPa), A_{sl}=804 mm^2.

Example (sum) 2. We must determine the bearing capacity of the cross-section of the composite beam. A beam with a cross section b × h = 400 × 400 mm (d = 35 cm) made of concrete grade C12 / 15 b_1 = 150 mm (f_{c1} = 8.5 MPa) and concrete grade C20 / 25 b_2 = 250 mm (f_{c2} = 14.5 MPa), the longitudinal working reinforcement is 4∅16 A500 (f_{yd} = 415 MPa), A_s = 804 mm2 (see Fig. 3).

The solution to the problem.

1) We define the area of the longitudinal reinforcement A_{s1}, for this purpose we take on the following accessory parameters:

$$f_1 = \frac{A_s f_{yd}}{b_1 d} = \frac{804 \times 415}{150 \times 350} = 6{,}36\ MPa.$$

$$f_2 = \frac{A_s f_{yd}}{b_2 d} = \frac{804 \times 415}{250 \times 350} = 3{,}81\ MPa.$$

1) The approximative parameters are taken on in advance and specified subsequently. In this particular case, we will immediately accept the refined coefficients (from the example 1).

$\alpha_1 = 0{,}241,\ \beta_1 = 4{,}231;\ \alpha_2 = 0{,}096,\ \beta_2 = 4{,}874.$

$$A_{s1} = A_s \frac{\beta_2 f_2 + \alpha_2 f_{c2} - \alpha_1 f_{c1}}{\beta_1 f_1 + \beta_2 f_2} =$$

$$= 804 \times \frac{4{,}874 \times 3{,}81 + 0{,}096 \times 14{,}5 - 0{,}241 \times 8{,}5}{4{,}231 \times 6{,}36 + 4{,}874 \times 3{,}81} =$$

$$= 804 \times 804 \times 0{,}394 = 316{,}68\ mm^2.$$

2) We set up the value of mechanical percentage of reinforcement by the following expressions:

$$\omega_1 = \frac{f_{yd} A_{s1}}{f_{c1} b_1 d} = \frac{415 \times 316{,}68}{8{,}5 \times 150 \times 350} = 0{,}295;$$

$$\omega_2 = \frac{f_{yd}\left(A_s - A_{s1}\right)}{f_{c2} b_2 d} = \frac{415 \times (804 - 316{,}68)}{14{,}5 \times 250 \times 350} = 0{,}159.$$

3) Then we determine accessory parameters α_1, α_2, β_1, β_2 according to the table 1 and check the correctness of their assumption.

4) After that we determine the accessory parameter in the following way:

$$\mathrm{k}_{z1} = \alpha_1 + \beta_1 \omega_1 = 0{,}241 + 4{,}231 \times 0{,}295 = 1{,}49.$$

5) The next stage in the process is to determine the bearing capacity of a composite bending element by the following expression:

$$M_u = f_{c1} k_{z1} \frac{bd^2}{6} = 8{,}5 \times 1{,}49 \times \frac{400 \times 350^2}{6} \times 10^{-6} = 103{,}4\ \kappa H \times m.$$

4 Conclusions

The authors of the article have offered the calculation method for standard cross sections of composite bending reinforced concrete elements by using the method of analysis of design resistance of reinforced concrete. This approach makes it possible to solve three types of problems: determination of the required area of reinforcing steel according to the known size dimensions of composite beams and defined strength grade of materials; determination of the bearing capacity of standard cross sections with known reinforcement; checking procedure of the bearing capacity of composite bending elements. In the future, it is planned to make an experimental comparison of the proposed approach (method) on composite beams made of different concrete grades.

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