Розрахунок сталебетонних балок проводиться з жорстким з'єднанням бетону зі сталевою смугою. Це можливо здійснити, якщо встановити жорсткі упори, які перешкоджають зміщенню смуги відносно бетону. Зусилля, діюче на упор, кількість жорстких упорів та крок визначаються через кути повороту між двома суміжними упорами. Для визначення зусиль, діючих на жорсткі упори, та кроку необхідно спочатку визначити кут повороту між двома суміжними перерізами в межах балки. Кути повороту перерізів визначаються графо-аналітичним методом. Розрахунок по деформаціям залізобетонних та сталебетонних балок виконується за приведеними жорсткостями поперечних перерізів.

При виборі кроку жорстких упорів та їх кількості необхідно прагнути оптимізувати конструкцію сталебетонних балок. Оптимізація полягає в тому, щоб максимальні напруження в сталевій смузі дорівнювали її граничному значенню, а зусилля, діюче в упорах, та крок упорів були однаковими. Для того, щоб зусилля в кожному упорі були однаковими, необхідно нульову ділянку робити меншу за інші.

В ході досліджень був розроблений алгоритм підбору кількості, кроку жорстких упорів та зусиль в них. Підбір проведено по заданим характеристикам використаних матеріалів, діючого зовнішнього навантаження, довжині балки, звісним розмірам поперечних перерізів бетону та сталевої смуги. При цьому зусилля в усіх упорах однакові, крок упорів, окрім нульової ділянки, постійний, максимальне зусилля в сталевій смузі, виникаюче в середині прольоту, не перевищує граничного значення, отриманого за розрахунком. Наведений алгоритм дозволяє проводити розрахунок жорстких упорів при завданому значенні зусиль, що діють на них при існуючому навантаженні

Ключові слова: сталебетонна балка, жорсткий упор, крок упорів, зусилля в упорі, сталева смуга, приведена жорсткість, графо-аналітичний метод

CONSTRUCTION OF AN ALGORITHM FOR THE SELECTION OF RIGID STOPS IN STEEL CONCRETE BEAMS

A. Petrov
PhD, Associate Professor*
E-mail: petrovbmg@ukr.net
M. Pavliuchenkov
PhD, Senior Lecturer
Department of
Building Mechanics and Hydraulics
Ukrainian State University of Railway Transport
Feierbakh sq., 7, Kharkiv, Ukraine, 61050
E-mail: misha_83@ukr.net
A. Nanka
PhD, Associate Professor, Rector**
E-mail: nanka-1@i.ua
A. Paliy
Doctor of Agricultural Sciences,
Associate Professor*
E-mail: paliy.andriy@ukr.net
*Department of Technical Systems and Animal
Husbandry Technologies**
**Kharkiv Petro Vasylenko National Technical
University of Agriculture
Moskovskyi ave., 45, Kharkiv, Ukraine, 61050

1. Introduction

Structures with external reinforcement represent a direction that actively evolves. Steel-concrete structures in general, specifically steel-concrete beams, are increasingly popular as both the elements of new construction and for the renovation of existing buildings and facilities for various purposes.

Numerous studies [1, 2], carried out in this field, are aimed at improving the strength of concrete as concrete is the most widely used material in construction. The studies addressed two aspects: design and technology. Technological aspect implies changing the composition of the mixture. Design aspect deals with the rational combination of concrete and reinforcement or the application of a certain type of reinforcement itself. Such a combination is rational for steel-concrete structures because it makes it possible to improve the strength properties of concrete, which enhances the bearing capacity of an entire structure.

Application of steel-concrete structures makes it possible to effectively use a material of the structure, both during construction and during operation. In addition, the use of steel-concrete structures is a progressive solution for strengthening both the elements and structures in general for a wide variety of buildings and facilities in industrial and civil construction.

Despite all the advantages of steel-concrete structures, there are certain difficulties associated with both the fabrication and design solutions. For steel-concrete beams, specifically, it is a relevant task to combine concrete and a steel sheet. In most cases, this purpose is achieved by applying rigid stops or flexible anchors. However, a problem on calculating efforts in rigid stops has not been thoroughly investigated.

Regulatory documents, for example, DBN B2.6-160:2010 [3], consider a variety of types of steel-concrete beams and give recommendations to calculate them. Paragraph 9.2.1.4.1.a of this document notes that there is complete correlation

between structural steel, reinforcement, and concrete. Using rigid stops ensures a connection between concrete and a steel strip, which, in turn, would lead to the joint work of concrete and steel. It is also noted in paragraph 6.1.1 from Eurocode 4 [4] that the combination is complete if an increase in the number of connecting elements does not increase the estimated bearing capacity of an element in terms of bending moment.

Paragraph 9.5 from DBN 2.6-160:2010 [3] gives recommendations for designing and calculating the number of shear connections. Specifically, it is noted that shear connections should be installed to transfer the longitudinal shear efforts between concrete and a steel profile. The Ukrainian standard DSTU B 2.6-216:2016 [5] outlines basic provisions on the calculation of connecting elements for steel-concrete structures. Paragraph 4.3.1 gives a limit on the size of anchor stops. Such stops must be not less in height than 4 diameters of the stop itself, its diameter is not less than 16 mm and not larger than 25 mm. Paragraph 6.6.1.2 [4] gives the same recommendations. Consequently, the number of such stops should be minimized to save material and reduce labor costs associated with fastening the stops to a steel sheet. Paragraph 4.4.1 [5] states that connecting elements should be placed along the length of a beam to transmit a longitudinal shear and prevent the exfoliation of concrete from a steel sheet. In this regard, it is desirable to solve this task with a minimal number of stops. Paragraph 4.4.5 [5] notes that the required number of connecting elements can be distributed between a point of the maximum positive moment and an adjacent support, or a point of the maximum negative moment in line with the law of distribution of efforts of the longitudinal shear. Therefore, it is desirable, when taking into consideration the distribution of shear efforts, to place stops maximally efficiently.

Given the above, the need to undertake a research, proposed by authors, is to optimize the design of a steel-concrete beam by reducing the number of rigid stops. Such a reduction, although not providing for significant savings in a material, would reduce the amount of work on the manufacture of beams. In addition, the manufacturing process implies the connection of rigid stops with a steel strip. One of the connecting techniques is welding. A steel strip has small thickness that can lead to its deformation in the welding process. Decreasing the number of stops would bring down defects.

Paragraph 6.6.5.5 [4] gives recommendations related to the pitch of connecting elements. These recommendations, although imposing certain restrictions, still make it possible to vary the step and, therefore, the number of rigid stops. As mentioned above, reducing the number of stops would bring down labor costs. In addition, changing the pitch and number of stops would make it possible to control the magnitude of effort in a steel strip, thereby ensuring that the effort is equal to the limiting value. All this would enable a more rational use of a structure's material. Thus, the results of research could be of practical significance. Therefore, the optimization of steel-concrete beams is a relevant task.

2. Literature review and problem statement

Paper [1] considered steel-concrete beams made from composite concrete with added rubber. As shown in the work, such a solution makes it possible to improve the connection between steel and concrete, as well as the plastic properties of anchors. However, the proposed solution aims at improving the material used, rather than optimizing the design. Study [2] examined beams made from concrete with the addition of metal fibers. Fiber-concrete is gaining popularity for different structures. However, the optimization of steel-concrete beams, as is the case in a previous work, is achieved by using a more progressive material.

In work [6], beams are used as elements of complex structures for buildings in areas with high seismic activity. Emphasis of this research is on computer simulation of design diagrams for such structures. The proposed material, among other things, shows that the structures under consideration can be used under difficult operating conditions.

Article [7] reported a numerical study into steel-concrete beams. Such a study aimed at examining the impact of removing a bottom slab, the influence of change in the height of a steel beam and the thickness of a concrete slab. This approach, although it is associated with improvements in design, is not associated with an optimal arrangement of anchors. At the same time, anchor stops are used in the structure. Paper [8] presented analytical solutions based on general differential equations and finite element formulations for a beam analysis, specifically studying the interaction between concrete and steel by using flexible shear connections. The issue of the number of such connections and the techniques for their placement was not considered.

It should also be noted that the issues on calculating an increase in the strength of concrete under the multi-axes stressed state were left unresolved or not adequately solved. Studies by different scientists contain significant differences in the numerical values for the results obtained [9–15]. The reason for this is that the percentage of an increase in the bearing capacity of a steel-concrete structure, as a result of the transformation of the uniaxial stressed state into the multi-axes one, depends on many factors. These factors include both physical and mechanical properties of concrete, the ways to transfer an external load, the ratio of magnitudes of principal stresses, design features, etc.

There are variants to overcome the related difficulties in a variety of ways. Such techniques include experimental studies, both numerical and field, computer simulation or new design solutions.

Paper [9] reported such a research. It is shown that the anchor could act as a strengthening element in a steel-concrete beam. Techniques for the rational placement of anchors were not considered. In article [10], an experimental study aimed at studying the peculiarities of the stressed-strained state of pre-stressed steel-reinforced-concrete bending elements under the action of a short-term static load, taking into consideration the physical nonlinearity of concrete and steel.

Work [11] represented a computer model of the continuous beam. The authors explore a change in the bearing capacity of beams depending on the percentage of their reinforcement. The issues on steel and concrete connection were not addressed in this paper.

Study [12] addressed control over the position of the neutral axis of steel-concrete structures by resizing the cross-sections of constituent elements of beams. Such a study makes it possible to optimize the design of the beam itself; however, the issues related to a combination between steel and concrete were not considered.

The problem remains relevant for all steel-concrete structures in general. For steel-concrete beams specifically,

an important task refers to the connection between a steel sheet and concrete. Such a connection should ensure that steel and concrete work jointly under load. Paper [13] proposed joining a steel sheet with concrete by gluing. There are works, for instance [14], which explored a possibility of applying acrylic adhesives for joining a steel sheet with concrete. Although this technique has its own advantages, it cannot be considered universal. Work of these structures has not been thoroughly examined up to now. In addition, a glued connection has its own peculiarities, which must be taken into consideration during calculation and design of steel-concrete structures. Thus, paper [13] notes that the deflection curves charts that depend on stress show a sharp increase in deformativeness after the detachment of steel from concrete. Thus, we can say that the use of glue to connect steel and concrete, although it has a right to exist, cannot replace all other techniques yet.

At present, most such cases involve rigid stops or flexible anchors. Such a connection technique is considered in works by scholars from known scientific schools in Ukraine [15, 16] and others. However, these works emphasize other tasks related to steel-concrete beams. These include the search for new constructive solutions, the application of new types of anchors and connection techniques between steel and concrete, etc.

Paper [15] proposed a new type of steel-reinforced-concrete beams. The structure of such a beam represents a reinforced concrete shelf with a steel frame and a steel tee element. The study addressed the use of different types of connection between concrete and a steel tee element.

Article [16] reports an experimental study into five series of steel-concrete beams. The series differed by different ratios between the sheet and rod reinforcement. The task of this study, among other things, was to establish the optimal ratio between the use of steel sheet St-3 in a combination with the rod reinforcement of classes At-800 and A-1000.

Paper [17] reported results of studying the stressed-strained state of steel-concrete beams. Connection between a steel sheet and concrete was established via flexible anchors. It was shown that flexible anchors have certain pliability. In addition, the connection between the anchors themselves and a steel sheet can be made in various ways. Such a variety of design solutions creates by itself certain difficulties for the development of a unified estimation procedure. Various types of flexible anchors have different degree of malleability. Accounting for the pliability of a flexible anchor exerts a significant effect on the carrying capacity of the structure. The calculation procedure itself often does not account for the pliability of flexible anchors or takes it into consideration only partially. Thus, the issues related to the establishment of a unified estimation procedure for flexible anchors remain unresolved. It might be possible to refine this procedure by applying the method, proposed in this article, for calculating rigid stops to the calculation of flexible anchors, and that leaves an area for the further research. Statement of the problem of a given research implies the optimization of steel-concrete beams. A steel-concrete beam on two supports is considered. The technique to apply an external loading is adopted in the form of a concentrated force F=10 kN, applied in the middle of the beam's span.

We suggest that the optimization of such structures should be achieved by a rational arrangement of rigid stops. A step that could be considered rational is the one at which

efforts in rigid stops are the same, and effort in a steel strip is equal to the limit value.

3. The aim and objectives of the study

The aim of this work is to construct an algorithm for the selection of rigid stops in steel-concrete beams.

To accomplish the aim, the following tasks have been set:
– to calculate the step of stops with the same efforts through their rational placement and to obtain effort in a steel strip equal to a limit value, which would make it possible to optimize the design of a steel-concrete beam;
– to perform a numerical experiment to validate reliability of the study.

4. Materials and methods to construct a selection algorithm for rigid stops in steel-concrete beams

To solve the set tasks, we used both normative methods [3–5] and the methods proposed earlier [18, 19].

According to regulatory documents [3, 4], one accepts a hypothesis on the complete interaction between concrete and a steel sheet, which in the examined design is achieved by on stalling the rigid stops. We also accepted a hypothesis on the absolute rigidity of the applied stops. The type of the examined stops in the same normative documents is regulated as absolutely rigid.

Calculation of steel-concrete beams implies the rigid connection between concrete and a steel strip. That can be achieved by installing the rigid stops at beams, which prevent the displacement of the strip in respect to concrete. The effort that acts on the stop, the quantity and step, is determined from rotation angles between two adjacent stops. Therefore, we determine the elongation of fibers via rotation angles of cross-sections between the adjacent stops.

To determine the angles of rotation of cross-sections, in the work we use a graph-analytical method for determining displacements. We determine longitudinal efforts by calculating relative elongation at the same section where these longitudinal forces are applied.

The cross-section of a steel-concrete beam is composite. Such a cross-section includes concrete and steel. The calculation of such structures is carried out based on the reduced rigidity. The geometrical characteristics of the cross-section under consideration are the reduced magnitudes as well.

5. Results of constructing an algorithm for the selection of rigid stops

Radius of curvature of the curved beam's axis varies from infinity to its any specific value [19]. At bending, the neutral axis does not change its length l_0. At distance h_2 from the neutral axis the arc's length increases to l_2, at distance h_1 – reduces to l_1.

One can determine the extension of arc l_2 from Fig. 1. $\Delta l_2 = \alpha \cdot h_2$.

To determine the efforts acting on rigid stops, as well as their step, one must first find a rotation angle between two cross-sections within the beam. Thus, we consider a beam shown in Fig. 2. We shall derive a formula to determine

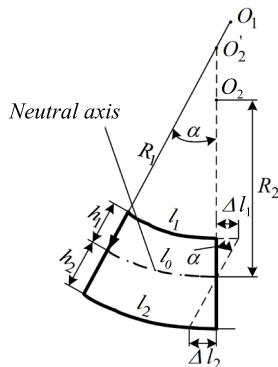the reciprocal rotation angle of the beam's section between points 1 and 2.

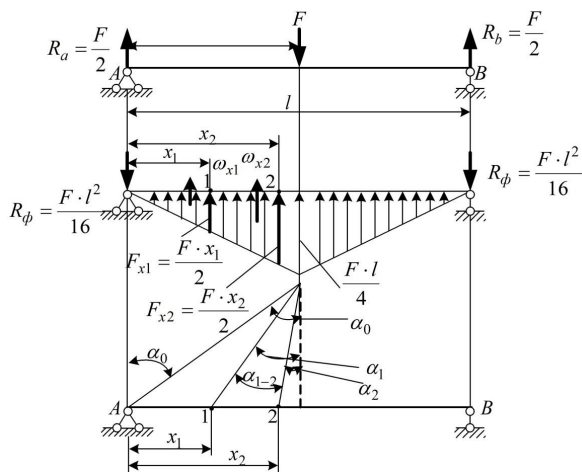Fig. 1. Determining the elongation of fibers through the cross-section's rotation angles

Fig. 2. Determining the reciprocal rotation angles of two cross-sections within the beam span

By using a graph-analytical method, we determine the rotation angle at point 1 at distance $x=x_1$ when the beam is exposed to concentrated force F.

$$\alpha_1 = \frac{1}{EJ}\left(-R_\phi + \omega_{x1}\right) =$$
$$= -\frac{F \cdot l^2}{16EJ} + \frac{F \cdot x_1^2}{4EJ} = -\frac{F}{16EJ}\left(l^2 - 4x_1^2\right). \quad (1)$$

The angle of rotation at point 2, at distance $x=x_1$

$$\alpha_2 = \frac{1}{EJ}\left(-R_\phi + \omega_{x2}\right) =$$
$$= -\frac{F \cdot l^2}{16EJ} + \frac{F \cdot x_2^2}{4EJ} = -\frac{F}{16EJ}\left(l^2 - 4x_2^2\right). \quad (2)$$

Then the reciprocal rotation angle of cross-sections 1 and 2 is equal to

$$\alpha_{1-2} = \alpha_1 - \alpha_2 = -\frac{F}{16EJ}\left(l^2 - 4x_1^2\right) -$$
$$-\left[-\frac{F}{16EJ}\left(l^2 - 4x_2^2\right)\right] = \frac{F}{4EJ}\left(x_1^2 - x_2^2\right).$$

$$\alpha_{1-2} = -\frac{F}{4EJ}\left(x_2^2 - x_1^2\right). \quad (3)$$

This formula defines the reciprocal angle of rotation of two cross-sections between points 1 and 2.

This formula holds if $0 \leq x_1, x_2 \leq l/2$. The sign in equation (3) is determined from the cross-section rotation. If a cross-section is rotated clockwise, the sign of the rotation is negative, and vice versa.

Calculation of deformations at the reinforced concrete and steel-concrete beams, according to [3, 18], is performed based on the reduced rigidities of cross-sections. Reduced rigidity is determined from formula

$$B = \phi_{b1} E_b I_{red}, \quad (4)$$

where I_{red} is the reduced axial moment of inertia for the cross-section of a beam, φ_{b1} is the coefficient that accounts for the effect of a short-time creep of concrete – taken for heavy concrete to be 0.85, E_b is the concrete deformation module.

Thus, formula (3) takes the form

$$\alpha_{1-2} = -\frac{F}{4B}\left(x_2^2 - x_1^2\right). \quad (5)$$

Reduced axial moment of inertia for the cross-section of a steel-concrete beam is determined as follows (Fig. 3).

We determine the position of the center of gravity for the reduced cross-section. To this end, we first find the reduced static moment of the cross-section

$$S_{x1} = bh\left(\frac{h}{2} + \delta\right) + b\delta\frac{\delta}{2}n_1,$$

where

$$n_1 = \frac{E_s}{E_b}. \quad (6)$$

Find the reduced area

$$A = bh + b\delta n_1. \quad (7)$$

Position of the center of gravity

$$z_c = \frac{S_{x1}}{A} = \frac{bh\left(\frac{h}{2} + \delta\right) + bn_1\frac{\delta^2}{3}}{bh + b\delta n_1}. \quad (8)$$

The reduced axial moment of inertia for the cross-section

$$I_{red} = \frac{bh^3}{12} + bh\left(z_c - \frac{h}{2}\right)^2 + \frac{b\delta^3}{12}n_1 + n_1 b\delta\left(z_c - \frac{\delta}{2}\right)^2. \quad (9)$$

To determine the efforts between stops in a steel strip, we shall consider a half of the length of a beam of length l, which has n rigid stops installed at step c (Fig. 4).

Given that the neutral axis runs through the center of gravity of the reduced cross-section, elongation of the middle of the steel sheet in a steel-concrete beam section of length c is determined from formula $\Delta l_2 = \alpha \cdot h_2$. The distance from the neutral axis to the center of gravity of the steel sheet is equal to $b_1 = z_c - \delta/2 \cdot b_1$. A step between stops is $c = x_2 - x_1$.
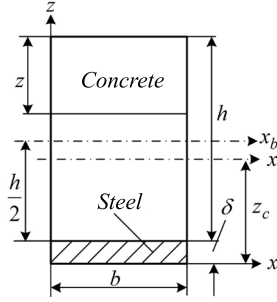
Fig. 3. Cross-section of a steel-concrete beam

Lengthening of the beam's fiber between two cross-sections 1 and 2:

$$\Delta l = \alpha_{1-2} \cdot b_1 = \frac{F \cdot \left(x_2^2 - x_1^2\right)}{4B} b_1. \tag{10}$$

Formula (10) then takes the form

$$\Delta l_c = \alpha_{1-2} \cdot b_1 = \frac{F \cdot \left(x_2 - x_1\right)\left(x_2 + x_1\right)}{4 \cdot B}\left(z_c - \frac{\delta}{2}\right). \tag{11}$$

To determine the longitudinal force acting at a section of length c, one must determine the relative elongation of this section

$$\varepsilon_c = \frac{\Delta l_c}{c} = \frac{F\left(x_2 - x_1\right)\left(x_2 + x_1\right)}{4 \cdot B\left(x_2 - x_1\right)}\left(z_c - \frac{\delta}{2}\right) = $$
$$= \frac{F\left(x_2 + x_1\right)}{4 \cdot B}\left(z_c - \frac{\delta}{2}\right). \tag{12}$$

The longitudinal force at a section of length c acts as a result of elongation of the steel sheet, which is calculated from formula:

$$N_{1-2} = \sigma_s \cdot A_s = \varepsilon_s \cdot E_s \cdot A_s = \frac{F\left(x_2 + x_1\right)}{4 \cdot B}\left(z_c - \frac{\delta}{2}\right) \cdot E_s \cdot A_s.$$

$$N_{1-2} = \frac{F\left(x_2 + x_1\right)}{4 \cdot B}\left(z_c - \frac{\delta}{2}\right) \cdot E_s \cdot A_s = A_1\left(x_2 + x_1\right), \tag{13}$$

where

$$A_1 = \frac{F}{4B}\left(z_c - \frac{\delta}{2}\right) E_s \cdot A_s, \tag{14}$$

where A_s is the cross-sectional area of a steel sheet, σ_s is the stress in a steel sheet, E_s is the elastic modulus of steel, δ is the steel sheet thickness, x_1 is the distance from the stop to the first point, x_2 is the distance from the stop to the second point, z_c is the position of center of gravity of the reduced cross-section.

Using formula (13) we determine the longitudinal force acting between two rigid stops with a distance between them of $c=x_2-x_1$.

If one knows the way to determine a longitudinal force at each section between the stops, one can determine the number and step of stops, as well as efforts in them.

When one selects the step and the number of rigid stops, one should aim at the optimization of steel-concrete beams so that the maximum stress in a steel strip equals its limit value, and the efforts applied to stops and the step of stops are the same. In addition, in order for the efforts in all stops to be the same, it is necessary to make a zero section (Fig. 4) slightly less than the rest. Denote the length of this section through magnitude x.

At the number of stops at half the length of a beam n the number of sections of length c is also equal to n (Fig. 4). Now we can write an expression to determine the effort at section $n-l/2$ by using formula (13). Here, $x_2 = nc + x$, and $x_1 = (n-1)c + x$.

$$N_{n-\frac{l}{2}} = A_1\left(x_2 + x_1\right) = $$
$$= A_1\left[nc + x + (n-1)c + x\right] = \left[2nc - c + 2x\right]A_1. \tag{15}$$

The resulting magnitude of the effort at section $n-l/2$ must correspond to the force obtained in [17] to test the stresses in concrete and a steel sheet.

$$N_{n-\frac{l}{2}} = F_1 = \frac{M}{a_1} = \frac{Fl}{4a_1},$$

where

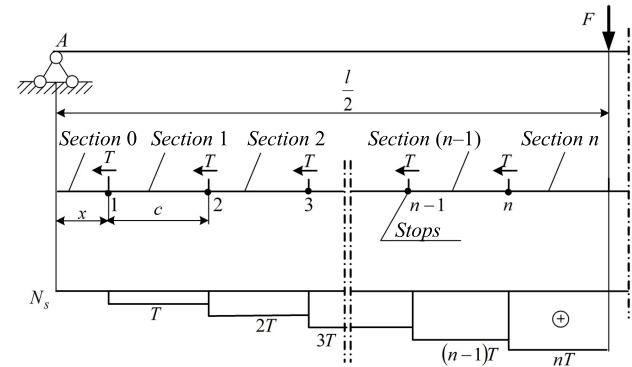$$a_1 = h_0 - \frac{z}{2}. \tag{16}$$

Fig. 4. Location of rigid stops and a diagram of longitudinal forces in a steel strip at the half of a steel-concrete beam

We determine from expression (15)

$$2x = \frac{N_{n-\frac{l}{2}} - 2ncA_1 + cA_1}{A_1}. \tag{17}$$

Represent the length of the beam by the length of sections and the number of stops

$$\frac{l}{2} = nc + x, \quad l = 2nc + 2x.$$

Hence

$$2x = l - 2nc. \tag{18}$$

By equating (17) and (18), we transform and obtain a formula that can be used to determine the length of a section if one knows magnitudes A_1, l, $N_{n-l/2}$.

$$c = \frac{A_1 l - N_{n-\frac{l}{2}}}{A_1}. \tag{19}$$

However, the length of sections depends on the effort to which the stops are exposed, as well as the number of stops. It is not reflected in formula (19). Therefore, we shall represent a step of the stops through the effort acting on the stop and the number of stops. To this end, we find an effort acting on the first stop.

$$T = (c + 2x) A_1. \tag{20}$$

Hence, we determine

$$x = \frac{T - cA_1}{2A_1}. \tag{21}$$

Expressions (18) is also used to determine the length of zero section x. At such a length of the zero section the efforts in all stops are the same

$$x = \frac{l - 2cn}{2}. \tag{22}$$

Equate expressions (22) and (21), following the simple transformations we derive a formula to determine the lengths of sections considering the number of stops and efforts that they are exposed to.

$$c = \frac{lA_1 - T}{A_1 (2n - 1)}. \tag{23}$$

The maximum value of the longitudinal force acting on a steel strip can be determined from formula

$$N_{n-\frac{1}{2}} = nT. \tag{24}$$

Formula (22) contains two unknown magnitudes n and c. Therefore, convert it. Substitute in formula (15) the value from formula (21)

$$N_{n-\frac{1}{2}} = [2nc - c + 2x] A_1 = 2ncA_1 - cA_1 +$$
$$+ 2A_1 \frac{T - cA_1}{2A_1} = 2ncA_1 - cA_1 + T - cA_1.$$

Hence, we find

$$c = \frac{N_{n-\frac{1}{2}} - T}{2A_1 (n - 1)}. \tag{25}$$

Equating formulae (23) and (25), after simple transformations, we obtain a formula to determine the step of stops

$$\frac{lA_1 - T}{A_1 (2n - 1)} = \frac{N_{n-\frac{1}{2}} - T}{2A_1 (n - 1)}, \quad n = \frac{2A_1 l - N_{n-\frac{1}{2}} - T}{2 \left(A_1 l - N_{n-\frac{1}{2}} \right)}. \tag{26}$$

The variant is possible when the effort acting on the stop is unknown. In this case, the step of stops is determined from formula (19). To determine the number of stops, we shall use formulae (20), (22) and (24).

Substitute in formula (20) the value from formula (22).

$$T = (c + 2x) A_1 = cA_1 + 2 \frac{l - 2nc}{2} A_1 = cA_1 + lA_1 - 2cnA_1.$$

Substitute in this formula expression (24)

$$\frac{N_{n-\frac{1}{2}}}{n} = A_1 \frac{lA_1 - N_{n-\frac{1}{2}}}{A_1} + A_1 l - 2nA_1 \frac{lA_1 - N_{n-\frac{1}{2}}}{A_1}.$$

Upon transformations, we obtain a quadratic equation relative to n

$$2n^2 \left(lA_1 - N_{n-\frac{1}{2}} \right) - n \left(2lA_1 - N_{n-\frac{1}{2}} \right) + N_{n-\frac{1}{2}} = 0.$$

By solving the quadratic equation, we obtain

$$n = \frac{2lA_1 - N_{n-\frac{1}{2}}}{4 \left(lA - N_{n-\frac{1}{2}} \right)} \left[1 + \sqrt{1 - \frac{8 \left(lA_1 - N_{n-\frac{1}{2}} \right) N_{n-\frac{1}{2}}}{\left(2lA_1 - N_{n-\frac{1}{2}} \right)^2}} \right]. \tag{27}$$

Having a set of formulae, one can select a step, the number of rigid stops, and determine efforts in them.

The result of the research conducted is the algorithm for the selection of rigid stops provided one knows the characteristics of materials, the size of cross-sections of a beam, beam length l and external load F acting on the beam. The sequence of actions in line with the proposed algorithm is given below.

Using equation (9), we determine the reduced axial moment of inertia for the cross-section of a beam.

$$I_{red} = \frac{bh^3}{12} + bh \left(z_c - \frac{h}{2} \right)^2 + \frac{b\delta^3}{12} n_1 + n_1 b \delta \left(z_c - \frac{\delta}{2} \right)^2.$$

Applying formula (4), we determine the reduced rigidity for the cross-section of a beam.

$$B = \phi_{b1} E_b I_{red}.$$

Employing formula (14), we determined coefficient

$$A_1 = \frac{F}{4B} \left(z_c - \frac{\delta}{2} \right) E_s \cdot A_s.$$

Using formula (16), we find

$$N_{n-\frac{1}{2}} = \frac{Fl}{4a_1} = \frac{Fl}{4 \left(h_o - \frac{z}{2} \right)}.$$

Applying formula (19), we determine the step of stops

$$c = \frac{A_1 l - N_{n-\frac{1}{2}}}{A_1}.$$

Employing formula (27), we find the number of stops

$$n = \frac{2cA_1 + N_{n-\frac{1}{2}}}{4cA_1} \left[1 + \sqrt{1 - \frac{8cA_1 N_{n-\frac{1}{2}}}{\left(2cA_1 + N_{n-\frac{1}{2}} \right)^2}} \right].$$

Determine the effort acting on the stop from formula (24)

$$T = \frac{N_{n-\frac{1}{2}}}{n}.$$

Determine the zero-section length from formula (22)

$$x = \frac{l - 2cn}{2}.$$

Check the maximum stress in a steel strip

$$N_{max} = [2nc - c + 2x] A_1 \approx N_{n - 1/2}$$

or

$$N_{max} = nT \approx N_{n - 1/2}.$$

Check the full length of the beam

$$l = 2nc + 2x.$$

If one knows the efforts acting on stops, one can select their sizes.

---

6. Numerical examination of steel-concrete beams

Based on the algorithm for the selection of rigid stops in steel-concrete beams, we carried out numerical calculations. We considered a beam on two supports, with a span of 2 m. We applied to the beam a load of 10 kN. The load was applied at the middle on the span. The cross-section of the beam is shown in Fig. 5.
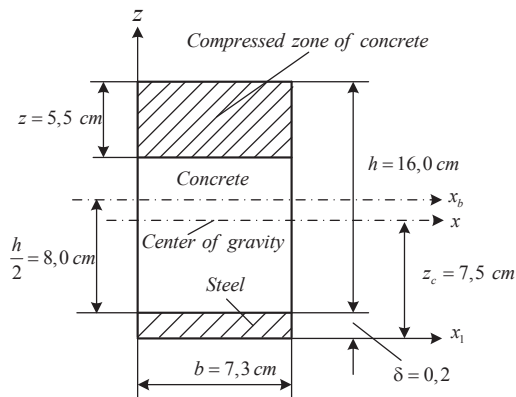

Fig. 5. Cross-section of a steel-concrete beam

Based on the estimation from the proposed algorithm, the number of rigid stops is four. A step between stops is 22.2 cm. The zero span is 11.11 cm. The magnitude of efforts in rigid stops is the same and equals 9.363 kN. The maximum longitudinal effort in a steel sheet is 37.453 kN, which is the limit value calculated using the same algorithm.

For a comparative study, we calculated two beams with similar dimensions and loading. The difference was the number of rigid stops, three and five, respectively. The magnitudes of efforts in rigid stops changed. The maximum longitudinal effort also does not correspond to the limit value. Schematic and diagrams of longitudinal forces in a steel sheet are shown in Fig. 6.

The above calculations show that the number and the step of rigid stops affect the magnitude of a maximum effort in a steel sheet. It is advisable that limit efforts should occur in a steel sheet and concrete at the same time. That would lead to the simultaneous destruction of steel and concrete

in a beam. Such a design, in terms of the rational use of a material, would be optimal.
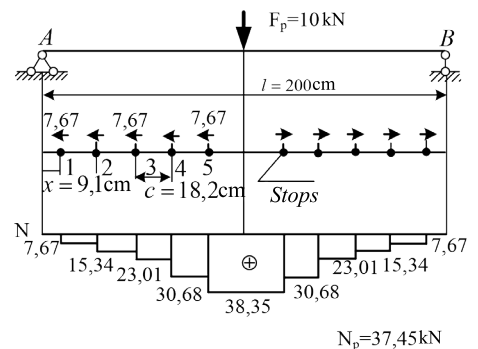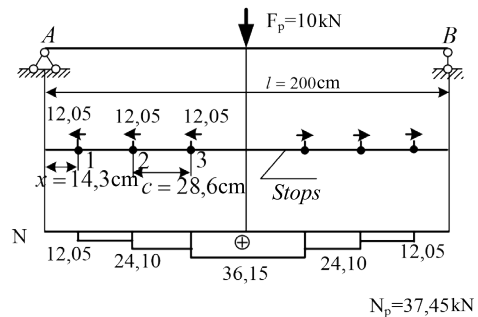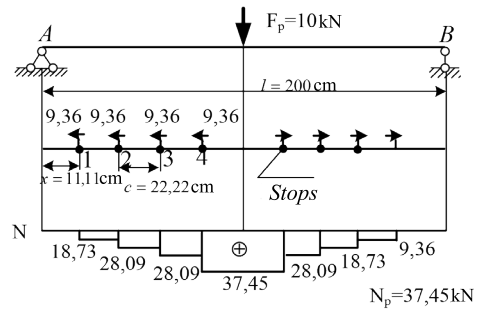

Fig. 6. Schematic of a steel-concrete beam and diagrams of longitudinal efforts in a steel sheet

We performed a numerical experiment to calculate steel-concrete beams. Similar beams were simulated and estimated by using the software package Lira. A beam model is shown in Fig. 7, the scheme of anchors arrangement is shown in Fig. 8.

Fig. 7. Model of a steel-concrete beam

Fig. 8. Scheme of anchors arrangement

The estimation study that we conducted has confirmed the calculation results derived when using the proposed algorithm.

7. Discussion of results of constructing the algorithm for the selection of rigid stops in steel-concrete beams

The result of the study performed is the constructed algorithm that makes it possible to calculate the number, the step, and the cross-section of rigid stops so that the efforts in them are the same. The effort in a steel sheet and the effort in concrete are also similar and correspond to the limit values. That would lead to that the destruction of concrete and a steel sheet occurs simultaneously. Therefore, the material of the structure, concrete and steel, are utilized more rationally, which is an optimal design in terms of saving a material.

There are no calculation results in normative documents, both in Ukraine [3] and in Europe [4], which does not make it possible to compare the reported results of our research to data from regulatory documents. Papers that address the steel-concrete beams typically pay little attention to the issue on the rational placement of anchors. For example, study [20] describes experimental studies into steel-concrete beams with different types of anchors. A step between the reinforcement rods is taken to be 50 mm, the step of loop anchors – 100 mm; the choice of such a step is not explained. Instead, the algorithm presented in our paper makes it possible to calculate the rational step between anchors. A comparative analysis is impossible. The rational step between clamps implies similar efforts in all anchors. Paper [20] reports no efforts in stops.

The results from a given study show that a change in the step of anchors would lead to the redistribution of efforts in a steel sheet. It is also shown that such a shift would change the maximum effort in a steel sheet. Thus, a change in the step between anchors could probably optimize the structure proposed in [20].

At present, the proposed algorithm could only be used for beams loaded with a concentrated force in the middle of the span. However, by changing the formulae for determining the loads, one can apply it for other types of loading. The proposed algorithm has been constructed taking into consideration a possibility to extend it to other structures and their operating conditions. The resulting procedure could be employed for other types of loading, including a beam loaded with a distributed load and with a change in the position of force lengthwise.

The proposed procedure also fails to calculate steel-concrete beams if connection between concrete and a steel sheet is achieved by using flexible anchors. The estimation of such beams requires certain refinements. In the future, it is planned to extend this procedure to the calculation of steel-concrete beams with flexible anchors.

A widespread application of steel-concrete structures in agricultural facilities and buildings would be contributed to by studying, identification of regularities of rational operation of constituting materials in these structures, as well as the results of development of the algorithm for selecting rigid stops. Given this, the application of a method for the calculation of rigid stops when esimating flexible anchors could uncover untapped reserves in their bearing capacity, thereby improving their reliability and durability.

8. Conclusions

1. We have constructed an algorithm for the selection of the number, the step between stops, and efforts in them, based on the assigned characteristics of materials, external load F=10 kN, the length of a beam, known sizes of the cross-sections of concrete and a steel sheet. In this case, efforts in all stops are similar, the step of stops, except for the zero span, is constant, the maximum effort in a steel sheet that occurs in the middle of the span is equal to a limit value, which is 37.45 kN.

2. We have performed a numerical experimental study into steel-concrete beams using the software package Lira. The results coincide with those derived when using the algorithm that we proposed. Divergence does not exceed 15 %.

References

1. Experimental and numerical study on static behavior of elastic concrete-steel composite beams / Xing Y., Han Q., Xu J., Guo Q., Wang Y. // Journal of Constructional Steel Research. 2016. Vol. 123. P. 79–92. doi: https://doi.org/10.1016/j.jcsr.2016.04.023

2. Sudhir P. P., Keshav K. S. Tests of steel fibre reinforced concrete beams under predominant torsion // Journal of Building Engineering. 2016. Vol. 6. P. 157–162. doi: https://doi.org/10.1016/j.jobe.2016.02.004

3. DBN V.2.6-160:2010. Stalezalizobetonni konstruktsiyi. Kyiv: Minrehionbud Ukrainy, 2011. 93 p.

4. TKP EN 1994-1-1-2009 (02250). Evrokod 4: Proektirovanie stalezhelezobetonnyh konstrukciy. Ch. 1-1. Obshchie pravila i pravila dlya zdaniy. Minsk: Minstroyarhitektury, 2010. 95 p.

5. DSTU B V.2.6-216:2016. Rozrakhunok i konstruiuvannia ziednuvalnykh elementiv stale zalizobetonnykh konstruktsiy. Kyiv, 2016. 40 p.

6. Hsiao P.-C., Lehman D. E., Roeder C. W. Improved analytical model for special concentrically braced frames // Journal of Constructional Steel Research. 2012. Vol. 73. P. 80–94. doi: https://doi.org/10.1016/j.jcsr.2012.01.010

7. Mahmoud A. M. Finite element modeling of steel concrete beam considering double composite action // Ain Shams Engineering Journal. 2016. Vol. 7, Issue 1. P. 73–88. doi: https://doi.org/10.1016/j.asej.2015.03.012

8. Analytical solutions for the in-plane behavior of composite steel/concrete beams with partial shear interaction / Luan N. K., Bakhshi H., Ronagh H. R., Barkhordari M. A. // Asian Journal of Civil Engineering. 2011. Vol. 12, Issue 6. P. 751–771.

9. Medvedev V. N., Semeniuk S. D. Durability and deformability of braced bending elements with external sheet reinforcement // Magazine of Civil Engineering. 2016. Issue 3. P. 3–15. doi: https://doi.org/10.5862/mce.63.1

10. Zamaliev F. S. Numerical and full-scale experiments of prestressed hybrid reinforced concrete-steel beams // Vestnik MGSU. 2018. Vol. 13, Issue 3. P. 309–321. doi: https://doi.org/10.22227/1997-0935.2018.3.309-321

11. Rahmanov A. D., Solov'ev N. P., Pozdeev V. M. Computer modeling for investigating the stress-strainstate of beams with hybrid reinforcement // Vestnik MGSU. 2014. Issue 1. P. 187–195.

12. Utkin V. A. Regulirovanie polozheniya neytral'noy osi pri proektirovanii secheniy stalezhelezobetonnyh balok // Vestnik SibADI. 2010. Issue 4 (18). P. 55–60.

13. Storozhenko L. I., Lapenko O. I., Horb O. H. Konstruktsiyi zalizobetonnykh perekryttiv po profilnomu nastylu iz zabezpechenniam sumisnoi roboty betonu i stali za dopomohoiu skleiuvannia // Visnyk NU «Lvivska politekhnika». 2010. Issue 662. P. 360–365.

14. Mel'man V. A., Torkatyuk V. I., Zolotova N. M. Ispol'zovanie akrilovyh kleev dlya soedineniya betonnyh i zhelezobetonnyh konstrukciy // Kommunal'noe hozyaystvo gorodov. 2003. Issue 51. P. 61–68.

15. Storozhenko L. I., Krupchenko O. A. Stalezalizobetonni balky iz zalizobetonnym verkhnim poiasom // Visnyk NU «Lvivska politekhnika». 2010. Issue 662. P. 354–360.

16. Osoblyvosti roboty stalebetonnykh balok armovanykh sterzhnevoiu vysokomitsnoiu armaturoiu riznykh klasiv / Bobalo T. V., Blikharskyi Z. Ya., Ilnytskyi B. M., Kramarchuk A. P. // Visnyk NU «Lvivska politekhnika». 2011. Issue 697. P. 35–48.

17. Raschet i konstruirovanie chastey zhilyh i obshchestvennyh zdaniy / Vahnenko P. F., Hilobok V. G., Andreyko N. T., Yarovoy M. L. Kyiv, 1987. 423 p.

18. Petrov A. N., Kobzeva E. N., Krasyuk A. G. Vybor optimal'nyh po stoimosti parametrov stalebetonnyh balok // Materialy III mizhnarodnoi naukovo-praktychnoi konferentsiyi. Kharkiv-Krasnyi Lyman, 2015. P. 330–336.

19. Darkov A. V., Shpiro G. S. Soprotivlenie materialov. Moscow: Vysshaya shkola, 1975. 654 p.

20. Kruhmalev A. V. The strainstress state of steel reinforced concrete beams // Vestnik DNUZHT: Nauka i progress transporta. 2010. P. 143–145.