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Optimization of Geometrical Parameters of Hollow-core Slabs by Formwork-free Shaping for Construction in Seismic Areas

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Abstract. The building norms and standards of Uzbekistan on the reinforced concrete structures do not regulate the design of hollow-core slabs of formwork-free shaping, reinforced with prestressed wire reinforcement. The manufacturing technology of such slabs allows creating a wide range of products that increase the possibility of their use in various structural systems in residential, civil and industrial buildings, but in non-seismic areas only. The aim of this work is to develop a constructive solution for the cross section of a prestressed hollow-core floor slab of bench formwork-free shaping, reinforced with high-strength wire reinforcement, in order to create a wide range of products intended for construction in seismic areas. To achieve the goal, the problem of determining the optimal combination of height and configuration parameters of the cross section of such a slab is solved, meeting the normalized operational requirements and limitations of earthquake-resistant building standards. The main variable parameters are the height and the void degree of the section, characterized by the size and shape of voids. In calculating the cross-section of a hollow-core slab when substantiating the theoretical basis for the calculation, the cross section is reduced to the equivalent I-section. As a result of research, a constructive solution was developed for the slab cross section of the maximum parameter values (the span, operational load) set by the customer. The parameters of the slab cross-section are: the height 190 mm, the hollowness 38%, the height of the upper thickened flange (compared with the height of the lower flange) of the given section is 0.27h, the height of the lower flange is 0.17h, the reduced (total) thickness of all ribs "b" is 0.32 of the width of the upper flange. The voids in the section along the height of the slab are arranged asymmetrically. A patent for a utility model has been received for the proposed constructive solution of the slab cross section.

Keywords: hollow-core slab, formwork-free shaping, optimization, height, cross-sectional configuration parameters, bearing capacity

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I. INTRODUCTION

In recent years, many enterprises in Uzbekistan (like in Italy, Spain, Russia) producing pre-fabricated reinforced concrete elements have been modernized using modern equipment of formwork-free technology of continuous shaping of structures on long-length (up to 120 m) stands. Reinforced concrete structures manufactured at enterprises operating on the technology of line-aggregate forming cannot satisfy the construction demand in terms of quality and price of products [1].

The prestressed floor slabs production by formwork-free shaping allows the creation of a wide range of products [2, 3], increasing the possibilities of their use in various structural systems of residential, public and industrial buildings. A big advantage of this technology is the ability to produce the slabs of required length from one molded pre-stressed strip (up to 110 m long) by cutting with a circular saw. To date, the design, production and use of hollow-core formwork-free slabs in construction have been poorly studied; this rises the problems of the use of new production lines for the articles manufacturing and their industrial use in construction [1, 4, 5], especially in seismic zones [6, 7]. The line-aggregate method for the production of hollow-core slabs is limited to the production of articles no longer than 7.2 m along with high metal consumption The production of one running meter of an article manufactured by the formwork-free shaping method, takes 2.5 times less metal compared to aggregate steel framework, horizontal grids in the flanges and indirect reinforcement at the slab ends and reinforcement of protruding ends [1, 8, 9]. Design features of formwork-free slabs do not meet the requirements of acting standards in Uzbekistan: KMK 2.03.01-96 "Concrete and reinforced concrete structures", and KMK 2.01.03-96 "Construction in seismic areas". In the Russian Federation (and other CIS countries, author's note) there is no normative document that regulates the design of hollow-core formwork-free slabs, except for Belarus, there acts the standard STB EN 1168-2012 "Precast concrete products. Hollow-core slabs", which includes recommendations on such slabs design. But it is problematic to use the methodology given in this standard for calculating hollow-core formwork-free slabs due to the difference between this methodology and the corresponding national norms of Uzbekistan (and Russian standards SP 63.13330. 2012 "Concrete and reinforced concrete structures"), since STB EN 1168-2012 is not adapted to these regulatory documents and in content repeats European standards EN 1168-2012 [6, 10]. The administration of the Uzbek-Russian joint venture JV “BINOKOR TEMIR-BETON SERVIS” invited the specialists of the Tashkent Institute of Architecture and Construction to develop a project “Creating a product range from prestressed hollow-core floor slabs of formwork-free shaping under uniform load 4.5; 6.0 and 8 kN/m^2, having a length of 4.7; 5.9; 6.2 and 7.2 m, and a width 1.2 m".

The slabs are intended for use in residential, public and industrial buildings (up to 7 floors) with load-bearing walls of complex construction made of masonry, reinforced with concrete inclusions, reinforced concrete frame and panel systems when constructing in areas of 7 and 8 points seismicity. Here, the issue of cost optimization for imported high-strength wire reinforcement for slabs should be solved, and the minimum concrete strength (no higher than class B30) should be determined; the possibility should appear to exclude the use of transverse reinforcement and the need to strengthen the supporting sections of slabs. In this regard, since February 2018, innovative studies have been carried out on the introduction in Uzbekistan of prestressed hollow-core floor slabs of bench formwork-free shaping on an industrial scale. To achieve the project goal, the initial task was set to determine the optimal cross-sectional parameters of a hollow-core floor slab, taking into account the above conditions and customer requirements.

II METHODOLOGY

It is known that one of the most important problems in the development of reinforced concrete structures is an increase in structure span along with minimizing the size of its cross section. In connection with this problem the following is stated in [15]: “Creation of new and development of existing methods for calculating concrete and reinforced concrete structures providing necessary reliability and durability is the basis for the development of modern structural decisions for buildings and structures that reduce the construction labor input and allow getting the maximum saving in material". Thus, the designers who want to implement an individual project cannot be satisfied with existing approaches to the calculation of reinforced concrete structures, based on a variety of design decisions that differ from the standard ones, for example, in the cross section configuration of a structure. In this regard, the parameters of the slab section were taken based on the following basic requirements:

- to provide the necessary stability, fracture strength and rigidity of a structure;
- structure production must be universal and technological.

The universality factor of hollow-core floor slabs of formwork-free shaping consists in the possibility of their use in buildings of various structural systems: frame, large-panel ones, with bearing masonry walls, etc. under different loads and span lengths. From the point of view of innovative implementation of the slabs under consideration, the technological ability is an ability to produce slabs using modern equipment (stand lines of formwork-free shaping) at an industrial volume with transformed geometrical parameters that do not impair their strength and rigidity parameters. The selection of optimal parameters of reinforced concrete structures is a multi-criteria task. In this regard, on the basis of experience, a relatively simple target function is set, which can be analyzed. As the target function the following aspects can be selected: consumption of materials, duration of construction, estimated cost, etc., taking into account the requirements of strength and serviceability of individual elements and the building as a whole. The minimum weight of a structure is often taken as a criterion for optimality of reinforced concrete structures, since it is the dead weight of a structure that has a significant impact on construction cost. Another criterion in assessing the effectiveness of reinforced concrete structures is a reduction of reinforcing steel consumption. From the experience of designing hollow core slabs for non-seismic areas, it is known that the hollowness of slabs varies from 40 to 55%. With an increase in slab hollowness, the load-bearing capacity of slabs at normal sections significantly decreases due to transition of the neutral line into the hollow partitions (ribs) of the slab; the strength along inclined sections in the supporting sections of the slabs decreases as well. In addition, the slab deformability increases, i.e., its rigidity decreases.

Thus, it is necessary to solve the following problem: to find the optimal combination of height and configuration parameters of the cross-section of a hollow-core slab of formwork-free shaping in compliance with standard operational requirements.

The main variable parameters are the height and degree of hollowness of the section, characterized by the size and shape of the voids.

The following requirements and restrictions of earthquake-resistant construction norms of Uzbekistan (KMK 2.01.03-96 “Construction in seismic areas) and Russia (SP 14.1330.2014. Building Code. Construction in seismic areas) were taken into account:

- when calculating the strength of bending elements reinforced with high-strength wire of Bp1400 class, an additional coefficient of operating conditions equal to 1.1 is introduced;
- the boundary relative height of concrete of the compressed section zone $\xi_R = x_R/h_0$ (x_R- is the boundary absolute height of the compressed section zone; h_0- is the working section height) of the element is taken with multiplication by a factor of 0.7 at 8 points design seismicity of construction site. It should be noted that the value of ξ_R according to the Russian Federation norms is taken differentially depending on the estimated seismicity of construction site: 0,5ξ_R - for a site with seismic impact intensity of 9 points; 0,7ξ_R - for a site with seismicity of 8 points; 0,85ξ_R - for a site with seismicity of 7 points. According to the standards of the Republic of Uzbekistan, ξ_R is taken by multiplying an integrated coefficient 0.85 for the sites with seismic impact intensity of 7, 8, 9 points. Thus, taking ξ_R with a coefficient of 0.7 set by the requirements of the Russian Federation norms, the calculated structure has the increased initial characteristics, "excluding damage of any nature or violation of operational integrity associated with the harm to human life or health, to property and environment".

III. THE PROPOSED CALCULATION ALGORITHM

The slab section reduced to the equivalent I section is traditionally, but justifiably, taken (Fig. 1) as a design cross-section of hollow-core slabs calculated according to the first group of limiting states (in strength). Pre-stressed reinforcement is located in the rib of the reduced section at the level of the lower flange. Overhangs of the lower flange are not considered in calculation - all forces in the stretched zone are transferred to the reinforcement.

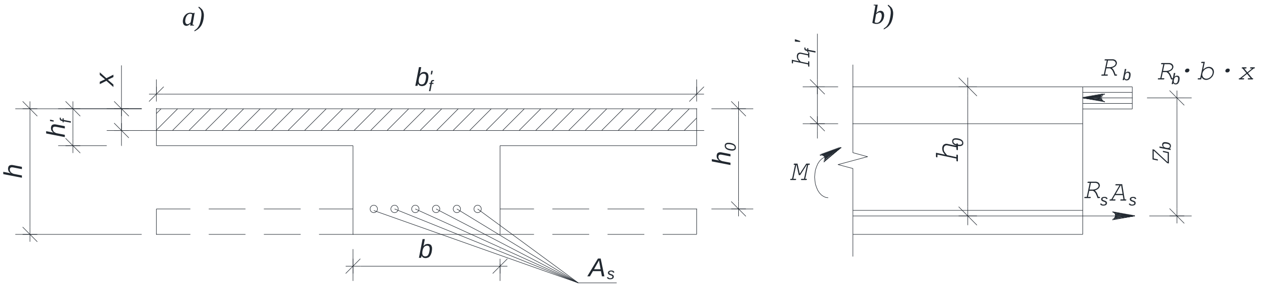
a) b)

Fig. 1. Design section (a), force and stress diagrams in section (b) of the slab at strength calculation

Hollow-core slabs of formwork-free shaping should be designed so that the boundary of compressed zone passes the upper flange, that is, the following condition should be met

$$R_s A_s \leq R_b \cdot b_f{}' h_f{}' \qquad (1)$$

As noted above, this is due to a sharp decrease in slab strength along inclined sections and an increase in its deformability when the boundary of compressed zone passes into the rib of the reduced slab section.

The bending moments perceived by the concrete of compressed zone M_{bu} and the tensile reinforcement M_{su} are determined as

$$M_{bu} = R_b \cdot b_f{}' \cdot x \cdot Z_b; \qquad (2)$$

$$M_{su} = R_s \cdot A_s \cdot Z_b, \qquad (3)$$

where R_b and R_s are the design resistance of concrete to compression and of reinforcement to tension;

A_s is the calculated cross-section area of the reinforcement located in the extended zone of the element section;

$b_f{}'$ is the width of the upper flange section;

b is the width of the rib of the reduced section;

h_0 is the effective depth of section;

x is the height of compressed zone of the section.

$Z_b = h_0 - 0{,}5x -$ is the lever of an internal pair of forces (the distance between the resultant forces in the compressed zone of concrete and tensile reinforcement).

From expressions (2, 3), it can be noted that at a decrease in cross-sectional height *“h”*, the value of Z_b decreases, which leads to a decrease in bearing capacity of the slab. It follows that the bearing capacity decreases in proportion to a decrease in height *“h”* provided that the height of the compressed zone of the section is x = *const*, that is, the resultant forces in concrete of the compressed zone $R_b \cdot b_f{}' \cdot x$ and reinforcement $R_s \cdot A_s$ remain unchanged.

If we take the void parameter V_v/V as constant (V_v is the void volume over 1 m length of the slab; *V* is the slab volume along its length of 1 m), then with an increase in height *h* section, the weight of the slab increases. Given this regularity, we can determine the maximum bending moment under external load *q*

$$M = \frac{[q + \gamma_b (V - V_\vartheta)] \cdot l_0{}^2}{8}, \qquad (4)$$

where $\gamma_b -$ is the volume weight of reinforced concrete;

l_0 is the calculated span of the slab.

The ratio Z_b/h is denoted by φ, then the lever of the internal pair of forces is $Z_b = \varphi \cdot h$.

If we substitute the expression $Z_b = \varphi \cdot h$ in formula (3) and solve it with equation (4), we obtain a dependence for the section height, which takes into account the hollowness:

$$h = \frac{q + \gamma_b (V - V_\vartheta)}{8 R_s \cdot A_s \cdot \varphi / l_0{}^2} \qquad (5)$$

IV. RESULTS

In calculations, the hollowness $V_v/V = 0{,}5$ of a typical hollow-core slab of a height 220 mm and width 1.2 m, produced by line-aggregate technology, was adopted as the base option.

Substituting the varied values of the slab section height *h* (220, 210, 200, 190 and 180 mm) into formula (5) at constant values of hollowness V_v/V (0.5; 0.45; 0.4; 0, 35), we obtain the values of external load, which the slab is able to bear (table).

The greatest load (including the dead weight), born by a slab at different section heights and given hollowness

№	**Height of the slab, mm**	**The load born by a slab, kN/m^2**			
		at hollowness, V_v/V			
		0,5	**0,45**	**0,4**	**0,35**
1	220	16,43	16,71	16,98	17,24
2	210	15,40	15,66	15,92	16,17
3	200	14,39	14,63	14,88	15,13
4	190	13,37	13,60	13,83	14,07
5	180	12,36	12,58	12,80	13,02

V. SUBSTANTIATION OF SIGNIFICANCE OF RESULTS

According to the calculation results, a section of a slab with a height of 190 mm and a hollowness of 38% was adopted, i.e., the slab strength with such a section at a calculated span of 7.04 m and the effect of a calculated unified load of 8.0 kN/m^2 on the slab is ensured.

The geometry and constructive solution of the slab cross section is shown in figure 2

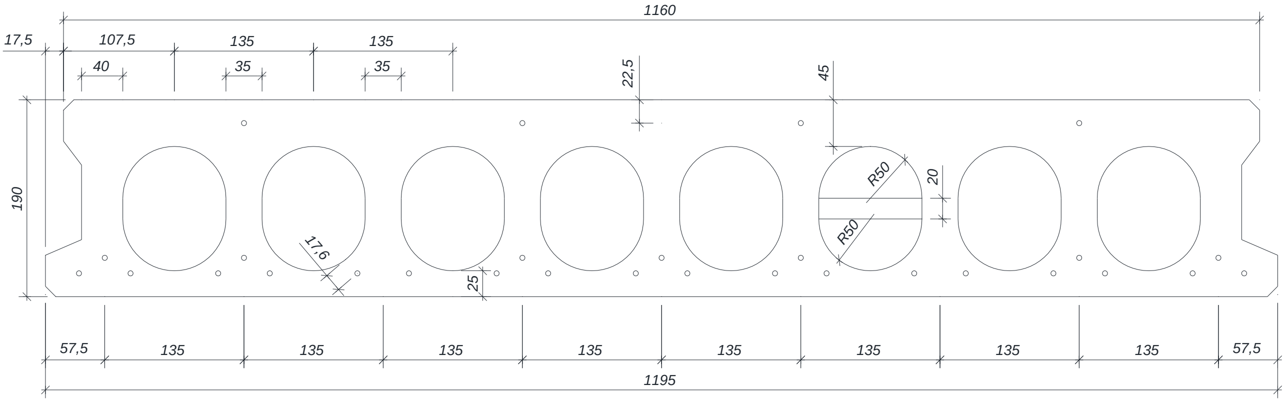

Fig. 2. The structural section of the slab

An account for above requirements of the standards of the Republic of Uzbekistan and the Russian Federation in calculations led to an increase in the upper flange height relative to the height of the lower flange of the slab section, i.e., the voids in the slab were located asymmetrically.

The height of the upper widened flange (compared with the height of the lower flange) of the reduced section of the slab (Fig. 2) is 0.27*h*, the height of the lower flange is 0.17*h*. The asymmetric arrangement of voids in the slab cross section allows increasing the moment of inertia and the moment of resistance of the entire section and helps to increase fracture strength and rigidity of the slab.

The reduced (total) thickness of all ribs "*b*" is $0{,}32\,b_f{}'$. The reduced height of the concrete section area, reduced to a solid rectangular section of the slab, is 118 mm.

VI. CONCLUSIONS

1. The configuration of the slab cross section shown in Fig. 2 is accepted for the entire product range under consideration, as noted in section I.

2. A patent for a utility model has been obtained [12] for the proposed constructive solution of the cross-section of hollow-core floor slab of the bench formwork-free shaping, designed for construction in seismic areas.

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