Strength Calculation Features and Tests Results on Bearing Capacity and Operational Serviceability of Hollow-Core Floor Slabs of Formwork-Free Shaping in Seismic Areas

Mirzaev Pulat, Umarov Kadir, Mirzaev Shavkat

Abstract. The technology of manufacturing reinforced concrete structures of long-line systems of formwork-free shaping is widely used lately in construction industry in many countries. Using this technology, industrial construction can be carried out in accordance with the requirements of modern regulatory documents that allow projects to be developed individually, and production can be reoriented in a very short time in accordance with emerging needs. This means that on the same production line it is possible to produce various structural elements of buildings and structures. Also, this technology allows the production of structures according to a wide range of products that meet operational requirements, and increases the possibility of their use in design of buildings and structures with various architectural, planning and structural decisions. Prestressed hollow-core slabs of formwork-free shaping reinforced with high-strength wire reinforcement are widely used due to the simplicity of construction and their relatively low cost, as well as their high bearing capacity, large spans and better quality. The problem of their introduction into construction industry of Uzbekistan is that the issues of designing, manufacturing and using them in construction have not been studied. Besides, the production technology of such slabs is mostly associated with the construction in non-seismic areas, and the country does not have an appropriate regulatory framework for the possibility of slab designing and production.

The aim of the study is to assess the strength and serviceability of hollow-core slabs of formwork-free shaping, designed on the basis of the proposed structural solution of the slab cross section and intended for construction in seismic areas. Therefor the issues of optimizing the main reinforcement consumption (prestressed high-strength wire reinforcement) at class B30 concrete strength without using the non-stressed reinforcement (reinforcing products) for the product range under consideration were addressed. Theoretical and constructive solutions of the slabs were developed in accordance with the standard requirements of Uzbekistan KMK 2.03.01-96 “Concrete and reinforced concrete structures”, KMK 2.01.03 “Construction in seismic areas” and considering the Euronorm EN 1168-2005 requirements “Precast concrete. Hollow-core slabs”.

The results of slab calculations according to the accepted methodology and the results of control tests to assess the bearing capacity, crack resistance and rigidity of slabs according to the product range ordered by the customer for the use in construction in seismic areas are given. Graphs are proposed by which it is possible to determine the values of permissible loads on slabs of various lengths with appropriate reinforcement. Based on the research results, design documentation and technical specifications for the production of hollow-core slabs of formwork-free shaping for the product range proposed by the customer were developed. The solution of design issues and the test results of the proposed floor slabs of formwork-free shaping make it possible to produce economic and technological slabs for construction in seismic areas, in which 90% of the country's population lives.

Keywords: hollow-core slab, formwork-free shaping, design, testing, strength, crack resistance, rigidity, range of products.

I. INTRODUCTION

Based on the well-known factor that concrete in the central part of sections of reinforced concrete bending elements is used incompletely, the principle of designing floor slabs of different section configurations consists in excluding the maximum volume of concrete from the stretched section zone, leaving vertical ribs to ensure the strength of the elements along the inclined sections [1]. A common option for reducing the weight of floor slabs is the design of a hollow-core slab. The above arguments are in agreement with another well-known thesis: "reducing material consumption without reducing the bearing capacity ensures an economic efficiency of the design."

The use of hollow-core floor slabs is a way to reduce the material consumption and the weight of structure without reducing its safety and reliability. It should be noted that there is another well-known thesis: "reducing the structure weight is an advantage in construction in seismic regions", as this reduces the magnitude of seismic impact. In this regard, in the “Basic Provisions” section in Uzbekistan regulatory norms and standards KMK 2.01.03-96 “Construction in seismic areas”, one of the requirements for reducing seismic loads on a building and structure is the use of materials and elements of a minimum weight.

Revised Manuscript Received on May 07, 2020

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The studies in [2, 3, 4, 5, 6, 7] were devoted to the problems of safety (bearing capacity) and serviceability (stiffness, crack resistance) of the prestressed hollow-core slabs of formwork-free shaping. In these publications the basic provisions of design and structural features of slabs were considered; the tests results to assess the slab strength and rigidity, designed according to the requirements of European design standards were presented. The results of modeling the stress-strain state of slabs and their experimental testing were presented. These studies are not enough to make appropriate design of the slabs to be used in construction in seismic areas. In [8], it is noted that a project is being developed at the Innovation Center at the Tashkent Institute of Architecture and Civil Engineering to introduce the prestressed hollow-core slabs of formwork-free shaping into the construction in seismic areas. In that project, a solution to the problem of optimizing the geometrical parameters of the slab cross section was given, and in [9], constructive solutions were proposed for the antiseismic bracing of the slab with adjacent building structures to create hard disks in its floor slabs.

The aim of the study is to design and evaluate by control tests the prestressed hollow-core floor slabs of formwork-free shaping according to the product range proposed by the customer and assigned for construction in seismic areas, using the relevant regulatory documents adopted in Uzbekistan, and taking into account some requirements of the European Norms, according to which this type of slabs were designed for construction in non-seismic areas.

Research objectives are:

- strength assessment of inclined and supporting sections of prestressed hollow-core floor slabs of formwork-free shaping designed on the basis of the proposed structural solution of the slab cross section [2] (to be used in seismic areas), taking into account the requirements of European Design Standards, which differ from the design requirements of similar plates produced by aggregate-flow technology, traditionally and successfully used in Uzbekistan and other CIS countries for a long time;
- optimization of prestressed high-strength wire reinforcement consumption on slabs of various lengths and under different values of unified loads;
- creating a product range based on the proposed structural solution of the slab cross section having a length of 4.7; 5.9; 6.2; 7.2 m under unified loads of (450, 600, 800 kgf/m^2) with the development of detailed documentation and technical conditions for the slab production;
- evaluation by control tests of the bearing capacity, crack resistance and rigidity of slabs from the proposed product range for the possibility of slab production in an industrial volume and their use in construction in seismic areas.

The aim posed in the paper is to design the prestressed hollow-core slabs of formwork-free shaping reinforced only by high-strength wire fittings, according to the product range ordered by the customer and to evaluate their actual operational parameters (by conducting the tests of slabs manufactured as a pilot batch) in terms of bearing capacity and serviceability in normal operation.

The problem of optimizing the consumption of prestressed high-strength wire reinforcement for a given load and a given product range (at slab concrete strength no higher than B30) has been solved. Slabs were designed so as to prevent crack forming in the operation process. Control loads were determined to check the bearing capacity and the slab stiffness. The pilot slabs were tested to obtain data on their crack resistance, stiffness, bearing capacity and the failure pattern.

For the introduction of hollow-core floor slabs of formwork-free shaping reinforced with prestressed wire fittings into construction process in seismic regions, the product range proposed by the customer (from 4.7 to 7.2 m long, inclusive, under standardized loads of 450, 600 and 800 kgf/m^2) has been specified based on design section of a slab having a height of 190 mm and a width of 1.2 m.

II. METHODOLOGY

II.1. Calculation methodology and its interpretation

In European Norms (EN) 1992-1-1: 2004 + AC: 2008, IDT. Eurocode-2 “Design of reinforced concrete structures. Part 1-1. General Rules and Rules for Buildings” there is a provision establishing general rules for design, calculation and determination of parameters, for structures and structure elements suitable both for traditional construction methods and for innovative applications; however these norms do not contain the rules for the design of non-standard structure elements. Given this, the authors in [4, 10] stated that a designer, depending on "design circumstances", has the opportunity to establish the design scheme and to substantiate the bearing structure confirming its compliance with the Euro-norm requirements, ensuring the safety of the designed structures and structure elements. Some of the requirements of EH are as follows:

- for hollow-core formwork-free shaping floor slabs, high-strength wire of a periodic profile or rope reinforcement is used;
- the use of prestressed bar reinforcement is not allowed;
- as the slab is reinforced only by prestressed reinforcement, the slab width should not exceed 1.2 m (to prevent torsional moments);
- the slabs are designed so as to prevent crack forming in the operation process.

Based on the above arguments (I. Introduction), theoretical studies on strength, stiffness and crack resistance can be carried out according to the norm requirements adopted in Uzbekistan - KMK 2.03.01-96 “Concrete and reinforced concrete structures” under controlled, unified, uniformly distributed loads, the values of which are determined with or without the relevant safety factors; the assessment of the bearing capacity, stiffness and crack resistance of the slab normal sections can be carried out according to the Interstate standard GOST 8829-94 “Prefabricated reinforced concrete and concrete products. Load test methods. Rules to assess strength, stiffness and crack resistance". In this case, the criteria for assessing the bearing capacity are the maximum allowable deflections under control load of stiffness and crack resistance, crack width and breaking load with a safety factor "C" depending on the failure pattern.

Since hollow-core slabs of formwork-free shaping do not contain transverse reinforcement according to the requirements of the aforementioned Eurocode-2, the bearing capacity of hollow-core slabs of formwork-free shaping is determined by the resistance of the inclined sections to shear under the impact of a concentrated force applied at a distance of 2.5 *h (h* – is the height of the slab section) from the support axis and is no less than 600 mm (Fig. 1).

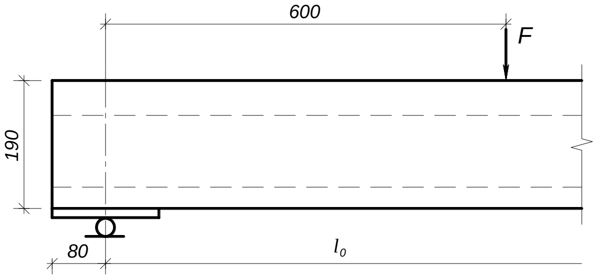

Fig. 1. Design scheme of a slab when assessing the resistance of inclined sections to shear under the impact of a concentrated force (Eurocode-2 requirement)

The checking of bearing capacity in the inclined sections of slabs according to Eurocode-2 is performed by the following formula characterizing the crack resistance of inclined sections on the near-support sections of the slab:

$$Q \le Q_b = \frac{I_{red}\cdot b}{S'_{red}}\sqrt{R_{bt}^2 + \sigma_{bp,0}\cdot R_{bt}}\,, \qquad (1)$$

where Q is the design transverse force under the impact of a temporary load;

Q_b is the design bearing capacity in the inclined section;

I_{red} is the moment of inertia of the section;

S'_{red} is the static moment of the cross-sectional area located above the axis, passing through the center of gravity of the cross-section relative to this axis;

b is the total thickness of vertical partitions between the voids;

R_{bt} is the design tensile strength of concrete;

$\sigma_{bp,0}$ is the stress in concrete from reinforcement prestressing at the level of the section center of gravity.

As noted above (I. Introduction), the slabs of formwork-free shaping in the operation process must function without cracking. The norms of Uzbekistan - KMK 2.03.01-96 “Concrete and reinforced concrete structures” and Russian building standards SP 63.1330.2018 “Concrete and reinforced concrete structures. Basic Provisions” allow in design of floor slabs reinforced with prestressed high-strength reinforcement the crack forming of limited width during operation: 0.2 mm — is the width of the long-term opening of cracks; 0.3 mm – is the width of the short-term opening of cracks. However, design experience has shown that the slabs structure with allowable crack forming often requires a greater consumption of reinforcing steel than the amount that ensures the accepted norms that prevent cracking. This is apparently due to the fact that when the cracks appear in the slab, the slab stiffness sharply decreases, which leads to deflections, the values of which exceed the limit values allowed by the Uzbekistan norms KMK 2.01.07-96 “Loads and impacts” and similar Russian standards. Therefore, the bending moment “*M*” from the allowable design load due to crack resistance is equated to the moment of crack forming M_{crc} of the prestressed slab, using the formula for determining the moment of crack forming in the bending element of the above mentioned norms KMK 2.03.01-96, in accordance with the design scheme shown in Fig. 2.

$$M \le M_{crc} = W_{pl}\cdot R_{bt,ser} + P\cdot\left(e_{op}+r\right), \qquad (2)$$

where W_{pl} is the elastic-plastic moment of resistance of the reduced section of the slab for the extreme stretched fiber of concrete;

$R_{bt,ser}$ is the design tensile strength of concrete when calculated according to group II of limiting states (according to serviceability in normal operation);

P is the force in prestressed slab reinforcement considering stress loss;

$\left(e_{op}+r\right)$ is the distance from the point of application of preliminary compression force “*P*” to the core point farthest from the ptensile zone of the reduced section of the slab, the cracking of which is checked;

e_{op} - the same, to the center of gravity of the reduced section of the slab;

r is the distance from the center of gravity of the reduced section to the core point.

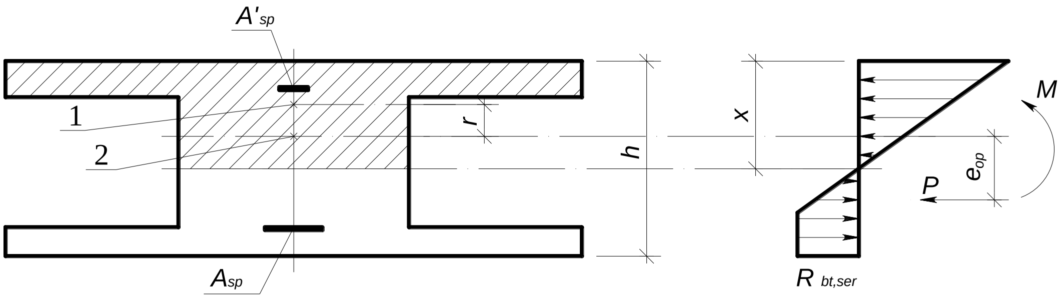

Fig. 2. Stress diagram in the reduced cross section of slab cracks when calculating the crack forming during the operation process: 1 is the core point; 2 is the center of gravity of the reduced section; x is the height of the compressed zone of the cross section during the crack forming in tensile zone; A_{sp} is the total calculated cross-sectional area of prestressed rods in the stretched section zone; A'_{sp} - the same in the compressed section zone.

When designing hollow-core slabs of formwork-free shaping based on the proposed structural section of the slab, the requirements and limitations of the earthquake-resistant building norms of Uzbekistan, listed in [2], were taken into account. The following limitations were stated in these norms: the design forces on the slab section strength should be 25% higher than the forces perceived by the section of the crack forming. A similar limitation is established in seismic construction norms of the CIS countries, including Russian ones (SP 14.13330.2014. Building Code. Construction in seismic areas).

Such a limitation is provided to prevent the destruction of brittle prestressed concrete structures, and to significantly improve the resistance of these structures to seismic impacts. In a prestressed structure, until the crack formation, mainly elastic strains appear, and the structure itself is characterized by significant rigidity. After the crack formation, the concrete in the tensile zone is gradually excluded from work, tensile forces are transferred to the reinforcement, the structural rigidity is reduced, as a result of which there is an increase in strains and cracks. The pre-stress effect disappears, and the structure in terms of resistance to external forces approaches the conventional reinforced structure [11]. In ordinary normally reinforced (not over-reinforced) concrete structures, working on bending, the cracks formation and plastic strain development is accompanied by a decrease in seismic load [12, 13].

II.2. Testing methods

The load bearing capacity of slabs from the pilot batch was evaluated by control tests with verification of strength, stiffness and crack resistance. The slabs were made and tested at the JV “BINOKOR TEMIR-BETON SERVIS”. The tests were conducted in accordance with the requirements of the Interstate standards GOST 8829-94 “Prefabricated reinforced concrete and concrete products. Load tests methods. Rules to assess strength, stiffness and crack resistance". The criteria for assessing the bearing capacity were the maximum allowable deflections of the slabs under a control load in terms of stiffness and crack resistance, as well as the value of the breaking load with a safety factor "C" depending on the failure pattern.

The slabs were tested under a uniformly distributed load from concrete blocks (using electronic crane scales OCS-SP-1) with steps of 0.1 of the control load strength. The supports vertical displacements and the slab deflection in the middle of the span were measured by deflection meters with dial gauges with a division value of 0.01 mm (these values were monitored by conventional laser range finders mounted on the floor of the test site under the slab). After each loading step, the concrete of the slab tensile zone was checked for cracks by a microscope to measure the crack opening width in MPB-2 concrete with a division value of 0.05 mm.

The slabs were tested under a uniformly distributed load of piece weights in the form of concrete blocks in steps of 0.1 of the expected breaking load. During the test, the vertical displacements of the supports and the slab deflection in the middle of the span were measured using deflection meters with a division value of 0.01 mm, (these values were controlled by conventional laser range finders installed on the floor of the test site under the slab). After each loading step, the slab was examined for cracks by a microscope with a division value of 0.05 mm.

Reaching the load value corresponding to the control load on bearing capacity with a coefficient C = 1.2, the measurements were stopped and removed; further slab loading was conducted under control for the applied load only.

At the time of slab testing, the average concrete compressive strength of standard cubic samples, determined by the certified laboratory of the “BINOKOR TEMIR-BETON SERVIS” joint venture, was: 39.6 MPa; 41.8 MPa; 38.8 MPa, respectively, which corresponds to the design class of concrete B30.

III. RESULTS

III.1. Results of calculations and their consideration

The results of calculating the bearing capacity of the inclined sections for slabs with spans of the considered product range under the impact of the greatest calculated unified load of 800 kgf/m^2 (7.85 kN/m^2) are given in Table 1. The calculated bearing capacity of slabs of considered product range in terms of lateral force is much higher than the values of transverse forces from external load, i.e., the strength of these slabs is ensured.

Table 1. The calculation results of the bearing capacity of the inclined sections of slabs

Slab spans, l_0, m	Transverse force Q from external load, kN	Design bearing capacity on transverse force Q_b, kN
7.04	56.8	112.6
6.04	49.6	99.5
5.74	47.1	95.1
4.54	30.3	80.6

The results of calculating the cross-sectional area of the reinforcement in the slab lower sectional area of the product range under consideration and the bending moments in terms of crack resistance and strength are given in Table. 2. The cross-sectional area of the reinforcement in the lower zone (the number of rods) is taken in accordance with the requirements and limitations considered in II.1 “Calculation methodology and its interpretation”. Similar reinforcement (4Ø5Bp1400) is taken in the upper zone of the slabs to increase the strength of the normal (support) sections at the slab ends. Slab reinforcement schemes are shown in Fig. 3.

Table 2. The calculated cross-sectional area of the reinforcement in terms of the slab strength and crack resistance by brands of product range proposed by the customer

Design span l_0, m	Design unified load q, kgf/m^2	Calculated cross-sectional area of the reinforcement of the lower zone A_{sp}, cm^2	Limit bending moment perceived by the cross-section M_u, kNm	Bending moment perceived by the cross-section during cracking M_{crc}, kNm	$\frac{M_u - M_{crc}}{M_u} \cdot 100\%$
7.04	800	5.684	93.88	65.44	30.3
6.04		4.116	73.74	46.95	36.3
5.74		3.528	68.77	42.73	37.8
4.54		1.960	40.45	27.22	32.0
7.04	600	4.116	77.46	47.87	29.6
6.04		2.940	58.67	35.10	40.1
5.74		2.744	55.19	34.11	38.2
4.54		1.570	32.65	23.25	28.8
7.04	450	3.528	68.77	43.53	36.7
6.04		2.352	48.13	31.45	34.6
5.74		2.156	44.29	29.35	33.7
4.54		1.372	28.70	21.34	25.5

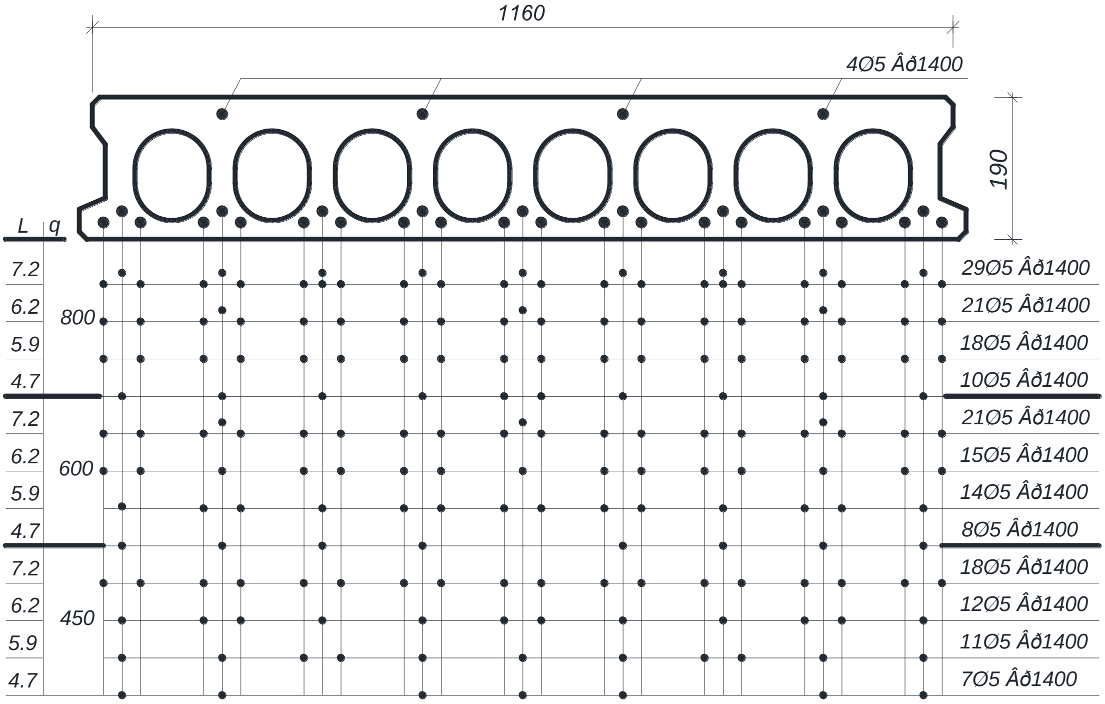

Fig. 3. Structural cross-section of the slab and reinforcement schemes by brands of product range. L is slab length, m; q is design unified load, kgf/m^2

III. 2. Test results and their analysis

The following conclusions were made based on the results of control tests of the slabs (Table 3).

1. When the loads acting on slabs are commensurate with the control loads in terms of stiffness and crack resistance (under 30 minutes of load effect on slabs), the deflections in the mid-span of slabs ranging from 0.1 to 1.2 mm are recorded; they are much less than the maximum values allowed by the norms of Uzbekistan KMK 2.01.07-96 “Loads and impacts”. No cracks were detected in the slabs under these loads.
2. The destruction of all tested slabs occurred due to concrete crushing in the compressed zone. In this regard, the bearing capacity of all tested slabs was considered on the basis of control loads with a safety factor of C = 1.6 in accordance with the requirements of the Interstate standards GOST 8829-94 (II. 2. Fundamentals of the test procedure).
3. Two tested slabs with a calculated span of 7.04 mm, designed for a unified load of 800 kgf/m^2 (7.85 kN/m^2), collapsed at a significantly lower load (compared to the control load in terms of strength (13.82 kN/m^2)) with a safety factor of C = 1.6. The coefficients of actual safety factors "C" for these slabs are less than those required by the aforementioned Interstate standards GOST 8829-94 which is 1.6, i.e. these slabs failed the tests on load bearing.

There is a version that in the sections on the supporting sections of tested slabs in the ribs (hollow vertical bridges), the concrete exhausted its shear strength (the cracks appeared in the concrete ribs) before the concrete in the compressed zone of the slabs was destroyed. But this assumption needs to be elaborated in future experimental studies.

4. The destruction of the rest of the tested slabs occurred at loads significantly higher than the control loads in terms of strength with actual safety factors C from 1.71 to 2.03, i.e., these slabs have passed the tests on bearing capacity.
5. Considering the advantage of formwork-free shaping technology, which makes possible to produce the slabs of any length necessary for the consumer, and the absence of the need to calculate the slab in terms of its bearing capacity, crack resistance and deformability, since the maximum loads have already been taken into account in production, there is a favorable opportunity to use the floor slabs with original grid of reference axes. For the practical possibility to use this technological feature of slab production, the graphs have been plotted to determine the values of permissible loads on slabs of various lengths (with a gradation of 100 mm) under appropriate reinforcement (Fig. 4).

Table 3. Slab Test Results

№	Design span, m	Design load, q, kN/m^2	Control load in terms of stiffness and crack resistance, kN/m^2	Control load in terms of strength at $C = 1.6$, kN/m^2	Breaking load at testing q_u, kN/m^2	Actual safety factor $C = q/q_u$
1	7.04	8.64	6.57	13.82	11.06	1.28
2	7.04	8.64	6.57	13.82	11.75	1.36
3	5.74	8.64	6.57	13.82	17.11	1.98
4	7.04	6.48	4.91	10.37	11.08	1.71
5	6.04	6.48	4.91	10.37	12.05	1.86
6	4.54	8.64	6.57	13.82	12.29	1.87
7	4.54	4.42	3.68	7.07	8.97	2.03

Note. The loads are given without the slab own weight.

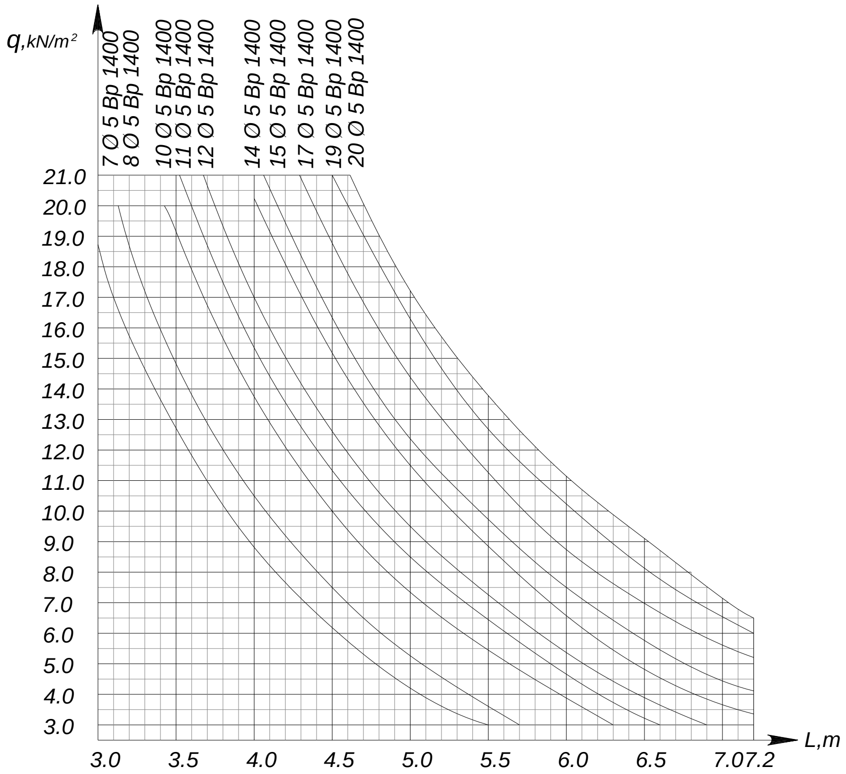

Fig. 4. Graphs of dependence of permissible uniformly distributed design load "q" without own weight of a slab "g" on the slab length "L" at corresponding reinforcement of the lower section area of the slabs and concrete of class B30

IV. CONCLUSIONS

1. The methodology for calculating the strength of the normal and inclined sections of prestressed flexible elements in Building norms and standards of Uzbekistan for the design of reinforced concrete structures is not adapted to the production technology of hollow-core slabs of formwork-free shaping and structural decision of such slabs.
2. As a result of studies, design documentation was prepared and technical conditions for the slab production were developed. According to this document, the slabs with a length of 7.2 m (design span 7.04 m) under unified load of 800 kgf / m^2 (7.85 kN/m^2) were not included in the product range.
3. Based on the proposed constructive decision of the slab cross-section, intended for the use in construction in seismic areas, it is planned to develop the standard series of hollow-core slabs for the use in design of residential, public and industrial buildings; this would ensure the production of such slabs in industrial volume on the country's enterprises manufacturing prefabricated reinforced concrete structures.

4. It should be noted that the production of structures in the near future using the technology of long-line system of formwork-free shaping along with modern methods of building [14], and the use of a new generation of structural systems of buildings [15, 16, 17, 18, 19] can provide a significant economic effect compared with the construction based on monolithic reinforced concrete and small-piece wall elements, traditionally used in the country.

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