To the multi-hollow reinforced concrete floor panels’ calculation according to the two groups of the limit states

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Abstract. It is known that multi-hollow panels for simplification in the calculations are presented in the form of I-beams (T-shaped) beams and are considered according to the beam theory. The material for such structures is reinforced concrete - a composite material that combines the mutual work of concrete and steel reinforcement. The purpose of this work is to study how the cross-sectional representation shape of the multi-hollow panels made of the reinforced concrete structural material affects the samples of various lengths, by establishing the action of the above factors (the way the cross-section and length are represented) on the bearing and deformation ability, as well as the cracking load. We examined the various length panels’ samples, freely supported and working on bending, with a cross section in a natural form, in comparison with the similar length I-beam samples. The load was sequentially applied to the samples in increments of 1 kN, until the yield strength of the reinforcement in the stretched zone was reached. A numerical study of multi-hollow panels was carried out, taking into account the physical nonlinearity of reinforced concrete, with the formation of a plastic hinge in the middle of the span. The load-deflection graphs are obtained when modeling the corresponding lengths of the samples with a natural and I-section shape. It was found that the length of the panel affects the calculation results of the shapes under consideration, and the shorter the length, the more obvious the deviation in the load-deflection graphs. The correction factors to refine the calculations of reinforced concrete slabs for cracking, deformation and breaking loads are proposed.

Introduction
Hollow core slabs are prefabricated structures made of prestressed or non-tensile concrete, commonly used in the floors’ construction in multi-story residential buildings. Such stoves were especially popular in the countries of Northern Europe, as well as the former Soviet Union. The popularity of precast concrete is relevant, first of all, for the areas with low seismicity. Also, the use of prefabricated reinforced concrete panels is characterized by efficiency due to the quick assembly of buildings and the reduction in the dead structures’ weight. A precast reinforced concrete hollow core slab has tubular voids extending along the entire length of the slab, typically with a diameter of about two-thirds or three-quarters of the slab thickness. The main advantage of the hollow panels is their relatively light weight, which allows to increase the payload on the floor, or to use the longer floors for large spans.

Some authors propose new designs of the hollow core slabs with lighter and more environmentally friendly materials. Such properties, for example, are possessed by slabs of the Cobiax system, tested and proposed in [1]. In the work of A.A. Al-Azzawi and S. A. Abed [2] studied the behavior of the
reinforced concrete hollow core slabs, with various physical, mechanical and geometric characteristics. The shear strength of the hollow core slabs was investigated. The field experiments and the corresponding non-linear calculations by the finite element method (FEM) were carried out to prove that the shear strength of multi-hollow slabs is at least 50% of the shear strength of a similar continuous slab.

The study of floor slabs, by numerical methods, including FEM, using the theories of mechanics of reinforced concrete, was carried out by Russian researchers N. I. Karpenko [3,4], S. F. Klovanich [5,6]. Based on the models of reinforced concrete mechanics developed and described by the above-mentioned researchers, using modern software systems and numerical methods, the behavior of reinforced concrete slabs under load was investigated by A.S. Vasiliev [7,8,9], M.F. Javed et al. [10] in their work investigated the efficiency of steel pipes filled with concrete. Many authors, such as Yuanli Wu [11], G. M. Chen [12], and M. L. Bennegadi [13] investigated the methods for strengthening the multi-hollow slabs based on composites. The stressed and deformed state of the reinforced concrete slabs with prestressed reinforcement was carried out in the research of P. Kankeri [14], Al-Negheimish [15], V. Albero [16].

It is known that to simplify the calculations of the hollow core slabs, and to present them in the form of the bar beam finite elements, I-beam form is used. In the framework of the reinforced concrete structures calculation theory, not only the presence of reinforcement inside the concrete (i.e. the presence of reinforcing material inside the reinforced) is taken into account, but also the redistribution of the forces between these materials when the cracks appear and concrete breaks. At the same time, the geometric parameters of the cross section can also affect the calculation results of the reinforced concrete during the forces’ redistribution and the formation of a plastic hinge in the structure.

**Materials and Methods**

The paper considers the multi-hollow floor slabs of various length in accordance with GOST 9561-91. The standard panels were taken as a basis: height 220 mm, round voids with a diameter of 159 mm. The width was fixed and amounted to 1000 mm. This type of floor slabs is designed to support on two sides. 9 × 2 slab variations were considered depending on the length. These variations are given in Table 1.

| №  | Length, mm | Natural form | I-beam shape |
|----|------------|--------------|--------------|
| 1  | 2400       | sample 1.1   | sample 1.2   |
| 2  | 2700       | sample 2.1   | sample 2.2   |
| 3  | 3000       | sample 3.1   | sample 3.2   |
| 4  | 3300       | sample 4.1   | sample 4.2   |
| 5  | 3600       | sample 5.1   | sample 5.2   |
| 6  | 3900       | sample 6.1   | sample 6.2   |
| 7  | 4200       | sample 7.1   | sample 7.2   |
| 8  | 4500       | sample 8.1   | sample 8.2   |
| 9  | 4800       | sample 9.1   | sample 9.2   |

Table 1. The samples considered

Slab materials are: heavy concrete, heat-treated, class B25 (Eb = 3·10⁴ MPa, Rbt=1.05 MPa, Rb=14.5 MPa); working longitudinal reinforcement A- 400 (Rs = 365MPa, Es = 2·10⁵ MPa) - 6 rods with a diameter of 12 mm. Protective layer of concrete is 30 mm. The cross sections of the samples under consideration are shown in Figure 1.
Figure 1. The geometric characteristics of the reinforced concrete hollow core slabs: a - cross sections of a natural shape, b - cross sections of an I-beam, c - a typical design of the slab

Cross sections of the samples are presented in Figure 1a, b. A typical slab design is shown in Fig. 1c.

The most advanced software systems that implement FEM include ANSYS, Comsol Multiphysics, Nastran. The numerical experiments in this work are based on the ANSYS 19 R2 PC.

Discrete models (Figure 2) numbered from 70,000 to 150,000 cells and from 100,000 to 200,000 nodes depending on the cross-section type and the sample's length. The finite elements in the form of a hexahedron have the maximum size 20 mm. To reduce stress concentration at the edges, the round supports were simulated at the support points.

Figure 2. Finite element slab model

Each sample during a numerical experiment was sequentially loaded, starting from the zero load, with a load step $\Delta F= 1 \, \text{kN}$, to the fracture occurring from the action of a bending moment in the middle of the samples’ span, when the yield strength of the reinforcement in the stretched zone is reached. At each step of the load, a corresponding deflection was obtained. The behavior of concrete was modeled on the basis of the Willam-Warnke strength criterion [17], on the basis of the SOLID 65 finite element. Based on the model used, the cracks were formed along the site normal to the main stresses when they exceeded the specified tensile strength. Volumetric stress state was also taken into account.

Results and its discussion

To visualize the cracks in the ANSYS PC, a user function was used based on the Bazhant deformation criterion [18]. The picture of cracks and deflections of the slab is shown in Figure 3 (a, b).
Figure 3. The calculation results’ visualization: a - picture of cracks according to the Bazhant criterion, b - Picture of stresses in the reinforcement for a sample in the form of an I-beam

Figure 4. Graphs of the normal stresses distribution along the cross-sectional height of the samples 1.1 and 1.2: a - at the step 24 with a load of 10.31 kN/m², b - at the step 25 with a load of 10.74 kN/m², c - at the step 26 with a load of 11.17 kN/m², d - at the step 112 with a breaking load of 48.1 kN/m².

Figure 4 shows the normal stresses that are distributed over the entire height of the slab in its middle section. The samples in a natural form and an I-beam of a similar length are compared at the corresponding loading steps. It can be seen that at the step 24, the stresses in the sample 1.1 (a slab in a natural form) are linearly distributed over the cross section, while nonlinearity begins to appear in the Sample 1.2 (a T-shape), as can be seen from the graph curvature in the stretched zone. In this case, at the steps 24, 25, 26, instability appears in the lower part of the diagrams, and a part of the graph at the boundary shows insignificant values of compressive stresses. This can be explained by the redistribution of forces between reinforcement and concrete, as the traditional theory claims that the
normal stresses in the stretched zone should be equal to zero, which can be observed at step 112 in
general during the samples’ destruction. On all the graphs, a consistent shift of the neutral axis to the
upper part of the samples is clearly visible. It is obvious that this shift occurs faster for the sample 1.2
than for the sample 1.1. The empty section in the lower part of the sample 1.1 section in each of the
graphs is explained by the presence of a reinforcing bar in the lower part of the section, the stresses in
which were not studied in this paper and are different from the stresses in concrete when the cracks
appear and are further exposed.

![Graphs showing normal stresses distribution](image)

**Figure 5.** The normal stresses distribution graphs along the cross-sectional height of the samples 9.1
and 9.2: a - in the step 12 with a load of 2.58 kN / m², b - in the step 13 with a load of 2.79 kN / m², c -
in the step 14 with a load of 3.00 kN / m², d - at the step 57 with a breaking load of 12.24 kN / m²

Similar trends can be seen in Figure 5. However, it can be noted that in the steps 12, 13 and 14,
when the concrete of the stretched zone is destroyed, however, the stress graphs of the samples 9.1 and
9.2 correlate much better.

**Table 2.** The multi-hollow panel calculation results

| Slab Samples | Cracking load [kN / m²] | Breaking load [kN / m²] | Stresses in the reinforcement at the cracking load for the slab in its natural form, [MPa] |
|---------------|-------------------------|-------------------------|------------------------------------------------------------------------------------------|
| Natural slab  | sample 1.1 11.16838488  | 49.39862543             | 14.978                                                                                   |
|               | sample 2.1 9.163802978  | 38.18251241             | 9.3773                                                                                   |
The Figure 3 of the Table 1 shows the calculation results’ deviations for the cracking load, ultimate deflections and breaking loads. The slabs with a natural cross-sectional shape are taken as the standard ones.

The deviation of the cracking moment for various samples averaged about 2.8%, and the deviation in the breaking load was about 4.3%. Moreover, as can be seen from the normal stresses in the reinforcement during the cracking load for the slab in its natural form, this value in all cases was greater for the slabs in the form of an I-beam. This is due to the fact that the cracks with this form of the slab representation occur at a lower load, therefore, the forces redistribution between reinforcement and concrete occurs earlier. Therefore, in all cases, for all lengths, it is possible to observe an increased value of stresses in the reinforcement for a slab in the form of an I-beam at the same cracking load, however, with an increase in the length of the samples, this difference decreases noticeably.

The results of the analytical calculations for the joint venture also have significant deviations from the numerical. For the crack formation load, the calculation deviation according to the joint venture from the numerical with the natural cross-sectional shape of the slab showed an average value of -3.5%, with a maximum value of about -15%.

The bearing capacity of the hollow core slabs in their natural form is less than the bearing capacity calculated analytically in the joint venture by an average of 29%.

**Summary**

Based on the data obtained, the following conclusions can be drawn.

With an increase in the length of the samples under consideration, the deviations in the load of the cracks’ occurrence gradually decrease, and for the samples 3900 mm or more, it is reduced to zero. However, for the slabs from 2400 mm to 3600 mm, the slabs calculations’ results in the form of an I-
beam should be multiplied by the 1.03 factor. If the calculation is performed analytically, according to the regulatory documents, this coefficient will be approximately 0.97.

The bearing capacity as a result of the analytical calculation has a very large safety factor, which leads to an overspending of the material when designing the reinforced concrete structures and performing the calculations according to the first group of the limit states. Further research should be carried out and the coefficients that would clarify the calculations of the bearing capacity of hollow core slabs should be performed. For the slabs with a width of 1 meter, the results of the bearing capacity obtained in analytical calculations for the joint venture can be reduced by an average of 30%.

In all cases, for all the lengths, an increased value of stresses in the reinforcement for a slab in the form of an I-beam at the same cracking load can be observed, however, this difference decreases noticeably with an increase in the samples’ length.

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