Improving calculating theory of multiple-cavity reinforced concrete floor panels

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Abstract. It is a known fact that core slabs are introduced as I-shaped beams (T-beams) to simplify calculations and are considered according to the beam theory. However, such a view may cause erroneous calculation results. This is particularly evident when calculating the second group of limit states. The aim of this survey is to examine the influence of the cross current representation of core slabs for samples of various length by defining the impact of these factors (the shape of the cross-section and length) on the bearing and nonrigid capacity as well as a cracking load. The paper makes the calculating theory of reinforced concrete framing clear, in particular, core slabs according to the limit states. The author dwells upon samples of slabs of various lengths with a natural cross-sectional shape in comparison with I-shaped samples of similar length. The author should emphasize that it is assumed both in analytical calculations and in software based on FE analysis in order to save time and computing resources. The author performs a computational investigation of core slabs in a nonlinear setting with forming a plastic centroid in the middle of a slab in the study. It is found out that the slab length affects the calculation results of the considered shapes. The shorter the length, the clearer cut the deviation in the load deflection plots.

1. Introduction

Core slabs with round, oval and dome-shaped through-holes are used in the slabs of civil buildings as well as in industrial buildings with small temporary loads to construct a smooth ceiling. The most economical in terms of content concrete are slabs with O-shaped voids. However, when producing such slabs, plants have technological difficulty caused by the fact that when removing the void formers of the channel borders of as-formed construction/making sometimes fall. Therefore, prelosas with O-shaped voids are taken as standard.

Their main advantage is their low weight compared to common slabs, which allows them to increase their length to cover relatively large spans as well as the imposed/running load on them. At the same time, some authors suggest new constructions of hollow core slabs with lighter and environmental materials.

One of this article describes four test series with spherical void former floors of the system "cobix" [1]. The study by A.A. Al-Azzawi and S.A. Abed [2], presents investigation of the behavior of moderately thick reinforced concrete slabs having hollow cores with different parameters.
The study of floor slabs based on the finite element method using reinforced concrete mechanics was carried out by Russian researchers A. S. Vasilyev [3-5], N. I. Karpenko [6,7], S. F. Klovanich [8,9]. M. F. Javed and et al [10] observe the efficiency of steel pipes filled with concrete. They consider their geometrical features in the studies. Many authors, such as Yuanli Wu [11], G. M. Chen [12], M. L. Bennegadi [13], review the methods of strengthening hollow slabs with composite materials. The stress and distorted condition of slabs with pre-stressed reinforcement was studied by P. Kankeri [14], Al-Negheimish [15], V. Albero [16].

It is known that to simplify the calculations of hollow core slabs, it is an I-beam form used. In the calculating theory of reinforced concrete structures, not only reinforcement inside the concrete (i.e. the presence of reinforcing material inside the reinforced one) is taken into account but also the redistribution of power between these materials when cracks appear and concrete breaks. Such rescheduling of power often has a serious impact on strain capacity and structure crack strength as well as on its bearing capacity. Nevertheless, the properties of cross sections can also affect the calculation results of reinforced concrete when redistributing power and forming a plastic centroid in a structure.

2. Materials and Methods

The paper covers hollow core floor slabs of various lengths according to the State All-Union standard 9561-91 «Reinforced concrete hollow core floor slabs for buildings» [17]. Standard slabs with a thickness of 220 mm with round voids with a diameter of 159 mm and a height of 220 mm were taken as a foundation. The width was constant and amounted to 1000 mm. This type of floor slabs was designed to support on two sides. 9 × 2 slab samples were considered depending on the length. These samples are shown in Table 1.

| No | Lengths, mm | Natural form | I-beams form |
|----|-------------|--------------|--------------|
| 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   |

Slab material: heavy concrete, heat-treated, class B25 (Rb1 = 14.5 MPa, Rbt1 = 1.05 MPa, Eb1 = 3 \cdot 104 MPa); working longitudinal reinforcement A- 400 (Rs = 365MPa, Es = 2\cdot10^5 MPa) - 6 bars with a diameter of 12 mm. A protective concrete layer is 30 mm. The geometric characteristics of the cross section samples and typical calculated scheme of a slab are shown in Figure 1.

Current software systems perform calculations of building structures based on the finite element method, using modern strength theories based on general models and mechanics of deformable solid methods [8], [9]. The most advanced software systems that implement the finite element method include ANSYS, Comsol Multiphysics, Nastran. In this study, numerical experiments were performed in ANSYS Workbench 17.2 software package.

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method include ANSYS, Comsol Multiphysics, Nastran. In this study, numerical experiments were performed in ANSYS Workbench 17.2 software package.

Discrete models numbered from 70,000 to 150,000 cells and from 100,000 to 200,000 nodes depending on the type of cross-section and the sample length. The finite element mesh used FE as a hexahedron with a maximum size of 20 mm. In addition, for the natural section of slabs, finite elements of a more complicated shape were used.

![Figure 1. Geometric characteristics of reinforced concrete hollow slabs: a - cross sections of natural shape, b - cross sections of I-beam shape, c - typical calculated scheme of a slab.](image)

Within the numerical experiment, each slab was loaded sequentially. It began from zero load, with a load step \( \Delta F = 1 \text{kN} \) to damage from the moment of flexion in the middle of the slab when the reinforcement in the tensile side of limit of stretching strain reaches. At each stage, direct concrete stress and reinforcement were recorded as well as deflections/sags. The final element was used (SOLID 65) for concrete, which implements the Willam-Warnke calculation model [18] used for breakable, structurally inhomogeneous materials. This model allows the development of cracks in the area, which is normal to the active principal stresses when they exceed a specified tensile strength, and takes into account the volumetric stress. The destruction of the concrete material and the stiffness relieving of the finite elements happened according to strength condition mentioned above. A model with bilinear kinematic hardening was used for reinforcement.

To visualize cracks in the ANSYS PC, user functions were applied, for example, Bazant strain criterion [19], which allows considering cracking in slabs and visualize this process by means of ANSYS. Concrete functions in a compressed area, but steel takes a load until it achieves the tensile yield strength in connection with a standard Elasticity and Plasticity theory applied [20, 21]. The destruction factor of the construction was caused by increasing strain in the rebar over its estimated resistance [22]. A destructive load was recorded at the load stage, where the rebar achieved the tensile yield strength.

3. Results

To display cracks, a custom function was added as the Bazant deformation criterion [19], which allows one to take into account slab cracking and visualize this process using ANSYS.

The picture of cracks and deflections of a slab is shown in Figure 2 (a, b).

The main results are presented in the load deflection graphs in Figure 2 (a, b, c, d).

As is clear from Figure 3, at the same load in I-beam (in its lower part), nonlinearity and disturbance have already begun to appear, while the slab sample in its natural form behaves as a linear material. Therefore, the cracking load is higher for the slab in its natural form. A similar phenomenon was observed for all samples with given latitude but shorter than 3900 mm. Ranging from 3900 mm, cracks in the samples appeared at the same load. The main results are shown in Tables 2 and 3.
Figure 2. Visualization of the calculation results: a - picture of cracks according to the Bazhant criterion, b - isopole of vertical movements of the slab.

Figure 3. Comparison of the results of load-deflection calculations for samples in I-beam and full-scale shapes slabs: a - samples 2400 mm long, b – samples 2700 mm long, c - samples 4500 mm long, d – samples 4800 mm long.

Table 3 presents the deviations of calculating results for the load of crack appearance, maximum deflections and bearing capacity. Slabs with a natural cross-sectional shape are taken as standard.

As can be seen from Table 3, the deviation of the cracking moment for various samples averaged about 4.37%, deviation of maximum deflections was approximately 10.84%; and deviation in the breaking load was about 4.3%. The author used the method of statistical research - correlation analysis to identify a degree of general dependence of the load-deflection graphs of different length slabs.

4. Conclusion
Thus, the obtained data let the authors summarize the following findings:
With increase in the length of samples, the correlation coefficient increases and tends to unity/one, which affirms an increase in the connection between the load-deflection graphs.

With increase in the length of the samples focused, the deviations in the load and cracked condition decrease gradually, and it is reduced to zero for samples of 3900 mm or more. However, the calculating results of I-beam slabs should be multiplied by a factor of 1.05 for those from 2400 mm to 3600 mm.

The pattern of deflection deviation is similar to the situation with a load of cracked condition. However, deviations in deflections between the samples make rather big difference. In this regard, it should be multiplied by a factor of 0.85 for slabs from 2400 to 3000 mm, it should be multiplied by a factor of 0.9 for slabs from 3300 to 3600 mm, and samples over 3600 mm should be multiplied by a factor of 0.95 to clarify the results when presenting hollow I-beam slabs.

Speaking of bearing capacity, the calculating results of I-shaped slabs should be also multiplied by a factor of 0.95.
Table 2. Multi-hollow panel calculation results.

| Slabs tested          | Crack appearance load step, No | Cracking load, kN/m² | Maximum deflection, mm | Breaking load, kN/m² |
|-----------------------|--------------------------------|----------------------|------------------------|----------------------|
| A full-scale (normal) slab |
| sample 1.1            | 26                             | 11,16838488          | 6,875                  | 49,39862543          |
| sample 2.1            | 24                             | 9,163802978          | 8,360                  | 38,18251241          |
| sample 3.1            | 22                             | 7,560137457          | 10,084                 | 30,58419244          |
| sample 4.1            | 20                             | 6,248047485          | 12,282                 | 25,61699469          |
| sample 5.1            | 19                             | 5,441008018          | 14,485                 | 21,47766323          |
| sample 6.1            | 18                             | 4,758128469          | 17,115                 | 18,50383294          |
| sample 7.1            | 17                             | 4,172803142          | 19,734                 | 15,95483554          |
| sample 8.1            | 15                             | 3,006872852          | 22,272                 | 13,74570447          |
| sample 9.1            | 14                             | 3,006872852          | 25,652                 | 12,24226804          |
| I-beam shape slab     |
| sample 1.2            | 24                             | 10,395189            | 7,851                  | 48,1096564           |
| sample 2.2            | 23                             | 8,781977854          | 10,123                 | 39,70981291          |
| sample 3.2            | 21                             | 7,216494845          | 12,115                 | 32,3024055           |
| sample 4.2            | 19                             | 5,935645111          | 13,959                 | 26,55420181          |
| sample 5.2            | 18                             | 5,154639175          | 16,216                 | 22,6231386           |
| sample 6.2            | 18                             | 4,758128469          | 17,977                 | 19,29685435          |
| sample 7.2            | 17                             | 4,172803142          | 20,342                 | 16,44575356          |
| sample 8.2            | 15                             | 3,006872852          | 22,234                 | 13,74570447          |
| sample 9.2            | 14                             | 3,006872852          | 25,556                 | 12,24226804          |

Table 3. Deviation of calculation results.

| Slabs tested          | Cracking load, % | Maximum deflection, % | Breaking load, % | The overall correlation coefficient for the respective graphs |
|-----------------------|------------------|-----------------------|------------------|-------------------------------------------------------------|
| samples 1.1 & 1.2     | 6,923076923      | -14,1730851           | 2,608695652      | 0,997121503                                                 |
| samples 2.1 & 2.2     | 4,166667         | -21,0512              | -4               | 0,998304465                                                 |
| samples 3.1 & 3.2     | 4,545455         | -20,1408              | -5,61798         | 0,998249                                                   |
| samples 4.1 & 4.2     | 5                | -13,6541              | -3,65854         | 0,999003                                                   |
| samples 5.1 & 5.2     | 5,263158         | -11,9503              | -5,33333         | 0,999826                                                   |
| samples 6.1 & 6.2     | 0                | -5,03652              | -4,28571         | 0,999856                                                   |
| samples 7.1 & 7.2     | 0                | -3,08098              | -3,07692         | 0,999868                                                   |
| samples 8.1 & 8.2     | 0                | -5,172413793          | -5               | 0,99991                                                    |
| samples 9.1 & 9.2     | 0                | -3,30189              | -3,50877         | 0,999952                                                   |

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