Research of stressed-state stiffened hollow strengthened concrete slabs in cracked condition

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Abstract. In fact, while making engineering calculations, hollow slabs are presented as T-shaped and I-beams. In this case, the web face of a beam decreases according to the dimensions of cavity pockets inside a slab. The conventional theory of calculating building constructions with breaking stress involves the calculation of such hollow slabs focused on the beam theory. In this paper, the authors observe the stress condition of hollow slabs at failure. Numerical studies are carried out for slabs re-enforced in several ways. The authors perform calculations in nonlinear formulation with gradually increasing stress before the samples were distorted. The researchers compare the stress condition in the slabs with normal cross-sections to the stress condition in the similar I-beam slabs. The aim of the study is to outline the way the cross section shape representation influences the results of direct stress in section and the cracking moments from the bending moment in the center of the slab span. The scholars take into account various methods of reinforcing hollow-core slabs. The paper emphasizes that the moment of crack propagation for hollow slabs in a normal shape comes later than for I-beam slabs.

1. Introduction
At present, hollow slabs are widely used in building and construction. They are lightweight, so they can cover large spans with minimum-drop of weight-carrying capacity [1]. In addition, slabs are often used in bridge building [2]. There are a number of main reasons for strengthening hollow slabs. First of all, they are the following: stress increase of load-carrying elements (structural members) as a result of replacement; strengthening of constructions placed above (alteration of premises, upstairs of buildings); processing equipment upgrading in a building being reconstructed; process changes.

When calculations are made, hollow slabs are presented as T-shaped or I-beams and calculations themselves are performed according to the beam theory, based on models and general principles of structural theory. However, when the slab is represented as an I-beam, the test results can be invalidated greatly. This is the paper which indicates it. On the one hand, this method can cut the check-out hours. On the other hand, it affects the test outcome accuracy. The authors conducted a numerical investigation of the stress condition of hollow slabs in ANSYS computational software.

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], N. I. Karpenko [4,5], S. F. Klovanich [6,7]. M. F. Javed and et al [8] observe the efficiency of steel pipes filled with concrete. They consider their geometrical features in the studies. Many authors, such as Yuanli Wu [9], G. M. Chen [10], M. L. Bennegadi [11], 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 [12], Al-Negheimish [13], V. Albero [14].

The papers mentioned above were aimed at the study and development of the theory of building construction calculation, in particular, reinforced concrete ones. The purpose of this study is to find out to what extent simplification of the slab section shape influences the results of normal stress condition in concrete and the cracking moments caused by a bending moment in the middle of the hollow slab span. It should be noted that this paper presents the studies of the stress condition of hollow slabs with various types of reinforcement.

2. Materials and Methods
In this paper the scientists deal with several ways to strengthen hollow core slabs. There are 4 samples in total: a slab with no strengthening; a slab strengthened by an additional section strengthening (50 mm); a slab strengthened with additional rebar (3 rods of 10 mm in diameter each); a slab strengthened in a combined way (an additional section of 50 mm and 2 rods of 10 mm in diameter).

The geometry of cross section shape slab strengthened in a combined way, are shown in Figure 1.

Figure 1. Cross sections of hollow core slabs: a - strengthened in a combined way in a full-scale shape, b - strengthened by a combined I-beam shape slab.

Figure 2 shows a typical calculated scheme of a slab.

Figure 2. Typical calculated scheme of a slab.

Technological aspects of strengthening are presented in [15]. It should be mentioned that the sections filled with additional rebar are poured (filled with concrete) which is of a higher class than the one of the slab. The geometry of I-beam slab, the estimated cross section was determined according to [16].

In that regard, the authors used Finite elements of a more complicated shape for the full-scale section of slabs. All in all, 8 models were calculated. They are the following: an I-beam shape slab with no strengthening (sample 1.1); a full-scale non-strengthened shape slab (sample 1.2); strengthened I-beam shape slab by additional cross section method (sample 2.1); a full-scale strengthened shape slab by cross section method (sample 2.2); a strengthened I-beam shape slab by additional rebar method (sample 3.1); a full-scale shape slab strengthened by additional rebar method (sample 3.2); an I-beam shape slab strengthened in a combined way (sample 4.1); a full-scale shape slab strengthened in a combined way (sample 4.2).

During the numerical experiment they loaded each slab gradually. It started with a zero load, with a load step $\Delta F = 1 \text{ kN}$, and ended with breaking from the bending point in the middle of the slab when...
the rebar reached the tensile yield strength. Normal strains in concrete and rebar, as well as deflections, were recorded at each stage.

The Finite element was used for the concrete called SOLID 65. This element implements Willam-Warnke’s model [17] used for fragile structurally heterogeneous materials. This scheme admits cracks to form along the site, which are normal to the current main strains when they exceed a given tensile yield strength. This model also was used for structural calculations in paper [18].

A hollow core slab with the following features is taken for the experiment. They are given below: nominal dimensions of the slab in the project: $0.8 \times 4 \, \text{m} \, (L = 4000 \, \text{mm}, b = 800 \, \text{mm})$; height, $h = 200 \, \text{mm}$; heavy concrete thermally treated, class B25 ($R_{c1} = 14.5 \, \text{MPa}, \, R_{c2} = 1.05 \, \text{MPa}, \, E_{c1} = 3 \times 10^4 \, \text{MPa}$); operational longitudinal connections A-400 ($R_s = 365 \, \text{MPa}, \, E_s = 2 \times 10^5 \, \text{MPa}$) 3 rods of 10 mm in diameter. The width of the concrete protective layer is 30 mm. Geometry is shown in Figure 3a.

3. Data on strengthening

The first way is strengthening by increasing cross section of concrete of 50 mm thick at the top of the slab. Characteristics of increasing cross section include the class concrete B30 ($R_{c2} = 17 \, \text{MPa}$, $R_{c2} = 1.15 \, \text{MPa}, \, E_{c2} = 33 \times 10^4 \, \text{MPa}$).

The second way is strengthening by additional rebar in the tensile part, operational longitudinal rebar, 2 rods of 10 mm in diameter, class A-400 ($R_s = 365 \, \text{MPa}, \, E_s = 2 \times 10^5 \, \text{MPa}$). Meanwhile, the rebar is placed in the hollow core sections of the slab, which are filled with concrete of a higher class than the one of the slab. On this occasion, it is concrete of class B30 ($R_{c2} = 17 \, \text{MPa}$, $R_{c2} = 1.15 \, \text{MPa}, \, E_{c2} = 33 \times 10^4 \, \text{MPa}$).

The third way is strengthening in a combined way: 50 mm of adding concrete of class B30 ($R_{c2} = 17 \, \text{MPa}$, $R_{c2} = 1.15 \, \text{MPa}, \, E_{c2} = 33 \times 10^4 \, \text{MPa}$). Characteristics of additional rebar in the tensile part, operational longitudinal rebar, 2 rods of 10 mm in diameter, class A-400 ($R_s = 365 \, \text{MPa}, \, E_s = 2 \times 10^5 \, \text{MPa}$). The concrete to fill is of class B30 ($R_{c2} = 17 \, \text{MPa}$, $R_{c2} = 1.15 \, \text{MPa}, \, E_{c2} = 33 \times 10^4 \, \text{MPa}$).

It should be noted that in all cases the adhesion on rebar and concrete of class B25 and B30 is supposed to be perfect. 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.

4. Results

Figure 3 shows the distribution of normal stress conditions along the height of the slab section, respectively, presented in a normal shape, and as an I-beam.

It corresponds to the graphs of distribution of normal stress conditions $\sigma_z$ over the height $h$ of the cross section in Figure 4a. Figure 4 compares the diagrams of normal stress conditions in the center section of the modeled samples 1.1 and 1.2 (samples without strengthening). As can be seen, at the same load, the concrete creep comes earlier for the I-beam sample, and this distinction just intensifies during further weighting.

The results of calculations are given in Table 1. The results of calculations of full-scale cross section slabs are taken as standard, and deviations of I-beams shape slabs calculations are considered to be relative to the former. The authors took the reference a full-scale (normal) slab.
Figure 3. Comparison of stress conditions in sample sections 1.1 and 1.2 in slabs of normal/simple and I-beams: a - normal stress conditions $\sigma_z$ in sample sections 1.2, b - normal stress conditions $\sigma_z$ in sections 1.1, c - normal stress conditions $\sigma_y$ in samples 4.2, d - normal stress conditions $\sigma_{xx}$ in sample sections 4.1.

Figure 4. Diagrams of distribution of normal stress conditions along the height of the cross section samples 1.1 and 1.2: a - with a load of 2.8125 kN / m², b - with a load of 3.125 kN / m², c - with a load of 3.377 kN / m², d - with a load of 3.750 kN / m².
As can be seen from the figure, the cracks occur earlier for slabs represented as an I-beam, both for reinforced and non-reinforced ones. In figure 3 a, b there are normal stress conditions $\sigma_z$ in sample sections of 1.1 and 1.2 with a load of 2.8125 kN/m². It can be seen in figure 3 that cracks in sample 1.1 predate (the green area at the bottom shows the expulsion of finite elements from the model at the bottom of the cross section).

| Slabs tested | Cracking load, kN/m² | Deflections at the cracking load of the corresponding full-scale (normal) slab, mm | Maximum stress at crack appearance of the corresponding full-scale (normal) slab, MPa | Stresses in the reinforcement with the appearance of the first cracks of the corresponding full-scale (normal) slab, MPa |
|--------------|----------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| A full-scale | Sample 1.2           | 3,125                                                                            | 0,64489                                                                         | -1,0564                                                                         | 4,74                                                                 |
| (normal)     | Sample 2.2           | 4,375                                                                            | 0,43033                                                                         | -0,41607                                                                        | 5,25                                                                 |
| slab         | Sample 3.2           | 3,75                                                                             | 0,65711                                                                         | -1,1039                                                                        | 4,99                                                                 |
|              | Sample 4.2           | 5,625                                                                            | 0,47855                                                                         | -0,563                                                                         | 5,45                                                                 |
| I-beam shape | Sample 1.1           | 2,8125                                                                           | 0,7176                                                                          | -1,1145                                                                        | 5,228                                                                |
| slab         | Sample 2.1           | 4,0625                                                                           | 0,47568                                                                         | -0,43259                                                                        | 5,75                                                                 |
|              | Sample 3.1           | 3,4375                                                                           | 0,70681                                                                         | -1,1316                                                                        | 5,29                                                                 |
|              | Sample 4.1           | 5,3125                                                                           | 0,50419                                                                         | -0,57204                                                                        | 5,75                                                                 |

The maximum deviation of the cracking load is about 10% observed for hollow core slabs without strengthening. The minimum deviation for slabs strengthened in a combined way is about 5.5%. A similar trend is maintained for stresses in the reinforcement with the appearance of the first cracks (slab with no strengthening - 10.3%, slab strengthened in a combined way – 5.5%) and deflections at the cracking load (slab with no strengthening - 11.3% slab strengthened in a combined way – 5.3%).

5. Conclusion

Thus, the obtained data let the authors summarize the following findings:

Cracks in a normal cross-section specimen appear later. On average, a cracking load for various methods of reinforcement is 7.7% less for slabs in a normal shape. It should also be noted that when filling cavities with concrete (samples 2 and 4), the deviation from the calculation results is reduced when comparing I-beam sections and those in a normal shape.

The deflexion while cracking is larger for I-shaped slabs. It means this section is less hard than the section in the normal shape of a slab. An average bending deflection caused by a cracking load for all types of reinforcement was about 8.68%.

The reinforcement stress while cracking also differed for the normal cross-section slabs and the corresponding I-beam slabs. The average deviation was about 7.8%.

It seems clear that, the cross section shape affects the calculation data for the second group of ultimate-load conditions. Therefore, it is necessary to work out factors that would take into account inaccuracy when presenting beam slabs for calculating elements of building constructions.

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