Evaluation of the load-bearing capacity of variously shaped steel-concrete slabs under short term loading

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Abstract. The article presents the evaluation results of load-bearing capacity exhaustion of steel-concrete slabs under concentrated and distributed short-term loading. The authors investigate the performance peculiarities of square, circular, and octagonal samples. The results of the experimental research were verified by comparison with the results of finite element modeling in the LIRA-SAPR software package. The obtained results proved the theoretical equations that allow to define the load-bearing capacity of steel-concrete slabs during their destruction over the cross-section and along the contact of sheet reinforcement with concrete. It is recommended to find the required intensity of sheet reinforcement anchoring from the condition of equality of ultimate loads. The authors provide further FEM analysis of square slabs to evaluate the impact of anchor spacing, the thickness of the steel sheet, and supporting conditions of slabs on their load-bearing capacity.

1. Introduction

Today, steel-concrete and composite structures, which are a combination of sheet steel or profiled steel, reinforcing bars, and concrete that work together, are commonly used worldwide [1-6], and their design is regulated by various standards [7-9]. The experience of the past three decades has proved the effectiveness of external reinforcement in bending structures. Extensive studies in this area are conducted to increase concrete strength. The existing research has two main directions: the constructive and the technological. The technological one deals with changing the concrete mixture composition. The constructive one deals with the rational bonding of concrete to reinforcement [10-13] or application of a certain type of reinforcement [14-16].

Solid-cast reinforced concrete slabs on profiled steel flooring, which simultaneously functions both as main reinforcement and as formwork, is becoming ever more commonly used [17-19]. This flooring design can significantly reduce labor costs, shorten construction time, and reduce the dead load of the floor on 30% vs. conventional reinforced concrete. With the reduced dead load of the floor, the consumption of materials for the casing and foundations of buildings can be also reduced, seismic resistance can be increased and costs of the construction of high-rise buildings can be cut significantly. Successful examples include the utilization of structures with external reinforcement in frames KUB2.5, IMET, ARCOS [20].
2. Description of experimental samples

The purpose of the study was the evaluation of stress-strain and ultimate states of steel-concrete slabs, the nature of their cracking and load-bearing capacity exhaustion. The work peculiarities of steel-concrete flooring slabs were determined during laboratory testing of the experimental samples that reflect the performance of a real structure [21]. The investigation examines square, circular and octagonal slabs, in which concrete and steel sheet external reinforcement were connected with the help of loop anchors, triangular keys, and U-shaped perforations.

Twenty samples were manufactured for the experimental studies, including:

- twelve samples (SqSCS 1-6 and SqSCSU 1-6) – square steel-concrete slabs, with dimensions in plan 1000×1000 mm and height \( h = 50 \) mm (figure 1a,d,e);
- four samples (OcSCS 1-4) – octagonal steel-concrete slabs, symmetrical in plan, with dimensions of the circumscribed circle \( R = 541 \) mm, inscribed circle \( r = 500 \) mm, side \( b = 414 \) mm and height \( h = 50 \) mm (figure 1b);
- four samples (CiSCS 1-4) – circular steel-concrete slabs, with diameter \( r = 1000 \) mm and height \( h = 50 \) mm (figure 1c).

Steel sheets with a thickness of \( t = 1 \) mm (SqSCS, SqSCSU, OcSCS) and 2 mm (CiSCS) were used as main external reinforcement.

In SqSCSU 1-6 samples (figure 1d, e), the steel sheet was made with flange and bonded with concrete using U-shaped perforations with a width of 20 mm and length from 80 to 260 mm, made in

![Figure 1. Slab samples: a) SqSCS, b) OcSCS, c) CiSCS, d) SqSCSU 1-2, e) SqSCSU 3-4.](image-url)
steel sheet. The perforations crossed the bending line of the flanges. The base of each perforation was placed on the steel sheet, while its bent edge was on the sheet flange. The following perforation layout variants were used: mutually perpendicular (at an angle of 90° relative to the sheet edge) in SqSCSU 1-2 samples (figure 1d), fanlike, at angles from 54° to 90° relative to the sheet edge, in SqSCSU 3-4 samples (figure 1e) and on corners – in SqSCSU 5-6 samples. For extra adhesion of the steel sheet with concrete in samples without U-shaped perforation, the loop anchors from the plain wire (class Vr-1) with diameter $d = 2$ mm, were bonded to the steel sheet. Anchors were located on diagonals of the steel sheet for each slab model.

In the OcSCS 1-4 samples, the steel sheet was bonded to the concrete core with anchors made of corrugated reinforcing wire (class Vr-1) with a diameter $d = 4$ mm.

At the same time, to obtain data on the physical and mechanical properties of concrete and steel [21], concrete cubes with dimensions of $100 \times 100 \times 100$ mm were made, as well as prisms with dimensions of $150 \times 150 \times 600$ mm. The steel strips with dimensions of $250 \times 25 \times 1$ mm (2 mm) were cut from the external reinforcement of experimental models. Concrete and steel samples were tested following the requirements of the national standards [22, 23].

### 3. Tests progress and experimental results analysis

The SqSCS, OcSCS samples were tested for the concentrated load applied in the center of the slab through the rigid stamp with dimensions of $200 \times 200 \times 20$ mm.

SqSCSU slabs were tested under the action of distributed load applied in the center of the slab through a rigid stamp with external dimensions of $400 \times 400$ mm and internal dimensions of $200 \times 200$ mm, which provided load transfer in a closed strip with an area of $0.12$ m$^2$.

CiSCS slabs were tested under the action of a concentrated load applied in the center of the slab, which was transmitted through a rigid stamp with a radius of 10 mm. The test specimens were placed on a rigid support circuit of the test bench. To prevent the break-off of the slab from the support contour, brackets were installed in the corners of the experimental samples of the SqSCS and SqSCSU series, which allowed for free angular displacement.

The slabs were loaded in steps of approximately 0.1 of the destructive load value ($F_{ud}$). The readings of the measuring equipment without load were taken as zero reading. After each step, the load was maintained for 10 minutes to take the measuring equipment readings.

The vertical displacements of slabs during the loading were recorded along the slab symmetry axis by clock-type indicators with a division value of 0.01 mm. The indicators were located at a distance of 150, 300, 500 mm (i.e. in the center of the slab) from the slab edge (figure 2c).

Relative strains in all samples were measured using strain gauges BF350-2EB, which were glued both to the concrete and steel sheet. Strain gauge station VNP-8 was used to record sensor readings. The layout of the sensors and their quantity depends on the characteristics of each sample. On the concrete compressed zone the sensors were located equally in all samples: in pairs, perpendicular to each other in the transverse and longitudinal directions, in the middle and diagonally of the slab (figure 2a,b,d).

![Figure 2. Sensors, indicators and deflection meters layout.](image_url)
Slab deflections were measured in the middle (below the load point) by a clock-type indicator with the division value of 0.01 mm. Figures 3-6 show the “load-deflection” curves for samples of all series in the middle of the slab.

**Figure 3.** “Load-deflection” curves for samples SqSCS.

**Figure 4.** “Load-deflection” curves for samples SqSCSU.

**Figure 5.** “Load-deflection” curves for samples CiSCS.

**Figure 6.** “Load-deflection” curves for samples OcSCS.

It can be noted that the “load-deflection” diagrams for all samples of steel-concrete slabs were nonlinear, due to the crack formation in the concrete stretched zone and the development of plastic deformations in the cross-sectional components.

The results of the deformation measurements in the steel sheet and concrete of SqSCS samples showed that plastic deformations in the sheet appear at a load of 40 kN, while at a load of 50-60 kN the destruction of the upper concrete fiber occurs in the middle of the slab.

Meanwhile, analysis of the nature of slabs deformation and the development of plastic deformations in the steel sheet during destruction, suggests that the load-bearing capacity exhaustion in the test samples occurred due to the strength loss of normal sections [5, 11, 19].

Analysis of experimental test results of CiSCS samples suggests that plastic deformations in the steel sheet appeared at a load of about 60 kN, while at a load of 80-90 kN the destruction of the upper concrete fiber occurs in the middle of the slab.

A specific feature of slabs SqRCSU with triangular keys was that the bearing capacity exhaustion was accompanied by the break-off of the edges of the perforations from the flanges of the steel sheet at the welding sites. When all samples were tested, this phenomenon was present only in the slabs where the perforations were welded perpendicular to the edge of the sample (SqSCSU 1-2).
As for steel-concrete slabs (OcSCS 1-4), the results of the deformation measurements of external reinforcement and concrete show that plastic deformations in the sheet appear at a load of 12 kN, while at a load of 25 kN the destruction of the upper concrete fiber occurs in the middle of the slab.

The dismantling of the slab steel sheet was carried out to examine the character of crack formation in the stretched zone of concrete.

4. Results verification and implementation

LIRA-SAPR software package [25], which implements the finite element method (FEM), was used during the numerical modeling of steel-concrete slabs. The following finite elements were used to create the calculation mathematical model: FE 241 (shell physically non-linear FE for slabs’ concrete during the numerical modeling of steel-concrete slabs. The following finite elements were used to account the actual physical and mechanical characteristics of concrete at different stress levels.

The theoretical results ($F_{FDM}$) were obtained utilizing the equations which allow to define the load-bearing capacity of steel-concrete slabs during their destruction over the cross-section and along the contact of sheet reinforcement with concrete [3, 24]. The finite difference method (FDM) was used during the theoretical investigations.

The results of the experimental ($F_{exp}$) and theoretical ($F_{FDM}$) data comparison with numerical ($F_{FEM}$) calculations are presented in Table 1. The additional values mentioned in table 1 describe the mechanical characteristics of the implemented materials, as follows [9]: $f_c$ – nominal value of the yield strength of structural steel and $f_{c,prism}$ – value of the prismatic compressive strength of concrete.

| Samples | $f_c$, MPa | $f_{c,prism}$, MPa | $F_{exp}$, kN | $F_{FDM}$, kN | $F_{FEM}$, kN | $F_{exp}/F_{FDM}$ | $F_{exp}/F_{FEM}$ |
|---------|------------|---------------------|--------------|---------------|---------------|----------------|----------------|
| SqRCS-1 | 220        | 25.68               | 128          | 115           | 118           | 1.11           | 1.08           |
| SqRCS-2 | 220        | 25.68               | 119          | 115           | 118           | 1.03           | 1.01           |
| SqRCS-3 | 220        | 25.68               | 121          | 115           | 118           | 1.05           | 1.03           |
| SqRCS-4 | 220        | 25.68               | 123          | 115           | 118           | 1.07           | 1.04           |
| SqRCS-5 | 220        | 25.68               | 100          | 115           | 118           | 0.87           | 0.85           |
| SqRCS-6 | 220        | 25.68               | 123          | 115           | 118           | 1.07           | 1.04           |
| SqRCSU-1| 220        | 31.54               | 130          | 118           | 122           | 1.10           | 1.07           |
| SqRCSU-2| 220        | 31.54               | 120          | 118           | 122           | 1.02           | 0.98           |
| SqRCSU-3| 220        | 31.54               | 135          | 123           | 125           | 1.10           | 1.08           |
| SqRCSU-4| 220        | 31.54               | 130          | 123           | 125           | 1.06           | 1.04           |
| OcRCS-1 | 190        | 25.68               | 40           | 32.3          | 33            | 1.24           | 1.21           |
| OcRCS-2 | 190        | 25.68               | 34           | 32.3          | 33            | 1.05           | 1.03           |
| OcRCS-3 | 190        | 25.68               | 30           | 29.7          | 29            | 1.01           | 1.03           |
| OcRCS-4 | 190        | 25.68               | 22           | 20.7          | 21            | 1.06           | 1.05           |
| CiRCS-1 | 221        | 16.8                | 143          | 139           | 138           | 1.03           | 1.04           |
| CiRCS-2 | 221        | 16.8                | 149          | 139           | 138           | 1.07           | 1.08           |
| CiRCS-3 | 221        | 24.3                | 122          | 115           | 114.6         | 1.06           | 1.06           |
| CiRCS-4 | 221        | 24.3                | 118          | 115           | 114.6         | 1.03           | 1.03           |

The maximum load-bearing capacity was obtained for a slab with a fanlike perforation layout (SqSCS 3-4). A comparison of the experimental values of the destructive loads ($F_{exp}$) with the loads for the SqSCS slabs 1-6 (see table 1) shows that the proposed method of combining (using perforations) helps to increase the slab load-bearing capacity to 10%.

Due to the adequacy of the obtained calculation results during the finite element modeling, the load-bearing capacity exhaustion of square steel-concrete slabs (SqSCS) was further investigated under different support conditions, anchors spacing, and thickness of steel sheet.
On the basis of the analysis of the experimental diagrams [11, 19] and results of FEM investigation, when spacing of loop anchors increases from 50 mm to 100 mm, under the same conditions of hinged support along the contour, the load-bearing capacity reduces to 17% in the SqSCS slabs, and to 15% in the CiSCS slabs.

If steel sheet thickness changes from 2 mm to 4 mm the load-bearing capacity of steel-concrete slabs increases from 17 to 38% when the hinged support along the edge is changed to rigid restraint.

The authors additionally examine five types of slab supporting commonly used in frames KUB2,5, IMET, ARCOS [20], namely: hinged slab; restrained slab; slabs with hinged and restrained edges; slabs with two restrained edges, one hinged edge and one unrestrained edge; and slabs with one restrained edge, one hinged edge and two unrestrained edges (figures 7-11).

The theoretical values of slab deflection (FD method) were obtained utilizing the methodology described in [3]. The comparison of the calculation (FEM) results with the theoretical (FDM) ones of square slab deflection for different supporting conditions are shown in figures 7-11. As a result, the proposed approaches for finite-element modeling of the frames with external reinforcement structures can be utilized during their design and reconstruction.

**Figure 7.** Deflection curves for hinged slab.

**Figure 8.** Deflection curves for the restrained slab.
Figure 9. Deflection curves for a slab with hinged and restrained edges.

Figure 10. Deflection curves for a slab with two restrained edges, one hinged edge, and one unrestrained edge.

Figure 11. Deflection curves for a slab with one restrained edge, one hinged edge, and two unrestrained edges.

5. Conclusion
On the basis of the conducted research, conclusions were made about the load-bearing capacity exhaustion of steel-concrete slabs, the pliability of shear connections, and the impact of the support and loading conditions, as well as the thickness of a steel sheet on the load-bearing capacity of structures with external reinforcement:
• if the anchor spacing increases from 50 mm to 100 mm, under the same conditions of hinged support along the contour, the load-bearing capacity reduces to 17% in the SqSCS slabs, and to 15% in the CiSCS slabs;
• the method of concrete and steel sheet external reinforcement connection (using perforations) helps to increase the SqSCSU slab load-bearing capacity to 10% in comparison with loop anchors used in SqSCS slabs;
• change of the steel sheet thickness from 2 to 4 mm allows for increasing the load-bearing capacity of steel-concrete slabs from 17 to 38% if hinged support along the edge is changed to rigid restraint;
• the comparison of calculated \(F_{\text{FEM}}\), theoretical \(F_{\text{FDM}}\) and experimental \(F_{\text{exp}}\) results demonstrate the adequacy of the finite-element modeling of steel-concrete slabs. The stresses, deformations, and crack distribution fields, which were obtained during the FE modeling, correspond to the physics of the process that occurs during the mechanical testing of bending structures.

References
[1] Nie J and Zhao J 2009 Flexural Behavior of Steel-Concrete Composite Beams Key Engineering Materials 400 pp 37–42
[2] Ong K C G, Mays G C and Cusens A R 1982 Flexural tests of steel-concrete open sandwiches Magazine of Concrete Research 34(120) pp 130–138
[3] Chikhladze E D, Vatulia G L and Kitov Y P 2006 Basis for calculation and design of composite and steel-concrete constructions (Transport of Ukraine) p 104
[4] Vatulia G, Rezunenko M, Petrenko D and Rezunenko S 2018 Evaluation of the load-bearing capacity of rectangular steel-concrete columns Civil and Environmental Eng. 14 pp 76–83
[5] Smolyanyuk N V 2004 Stress-strained and ultimate state of steel-concrete plates (Ph.D. thesis) (Ukrainian State University of Railway Transport) p 184
[6] Krainskyi P, Bliharskyy Y, Khmil R and Bliharskyy Z 2018 Experimental study of the strengthening effect of reinforced concrete columns jacketed under service load level MATEC Web Conf. 183 02008
[7] DBN V.2.6-160 2010 Composite structures: General rules (Kyiv: Min. bud-va, arkhit. ta zhyltovo-kom. hosp) 2011
[8] ANSI/AISC 360-16 2016 Load and resistance factor design specification for structural steel buildings (Chicago, Illinois) 2016
[9] CEN 2004 EN 1992-1-1: Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings (Brussels: BSI) 2004
[10] Aboobucker M A M, Wang T Y and Richard Liew J Y 2009 An experimental investigation on shear bond strength between steel and fresh cast concrete using epoxy IES J. Part A: Civil Struct. Eng. 2(2) pp 107–115
[11] Shevchenko A A Stress-strained state of circular steel-concrete plates Collected scientific works of Ukrainian State University of Railway Transport 130 pp 113–120
[12] Kwon G, Engelhardt M D and Klingner R E 2010 Behavior of post-installed shear connectors under static and fatigue loading J. Constr. Steel Res. 66(4) pp 532–541
[13] Smitha M S and Kumar S R S 2013 Steel-concrete composite flange plate connections finite element modeling and parametric studies J. Constr. Steel Res. 82 pp 164–176
[14] Bobalo T, Bliharskyy Y, Kopiika N and Volynets M 2020 Serviceability of RC Beams Reinforced with High Strength Rebar’s and Steel Plate Lecture Notes in Civil Eng. 47 pp 25–33
[15] Saravanan M, Marimuthu V, Prabha P, Arul Jayachandran S and Datta D 2012 Experimental investigations on composite slabs to evaluate longitudinal shear strength Steel Compos. Struct. 13(5) pp 489–500
[16] Lobodanov M, Vegera P and Bliharskyy Z 2020 Planning Experiment for Researching Reinforced Concrete Beams with Damages Lecture Notes in Civil Engineering 47 pp 243–250
[17] Ong K C G and Mansur M A Punching Shear of Steel-concrete Open Sandwich Slabs *Magazine of Concrete Research* 37(133) pp 216–226
[18] Nie J, Fan J and Cai C 2008 Experimental study of partially shear-connected composite beams with profiled sheeting *Eng. Struct.* 30(1) pp 1–12
[19] Chikhladze E D and Vatulya G L 1999 Experimental Researches of Steel-Concrete Plates *Proc. of the IASS 40th Anniversary Congress* 1 pp 13–18
[20] Shmukler V S, Klimov Y A and Burak N P 2008 Lightweight Frame Systems (Kharkiv) p 336
[21] Vatulia G L, Orel Y F and Kovalchuk A M 2011 Steel-concrete slabs experimental studies, *Collected scientific works of Ukrainian State University of Railway Transport* 125 pp 314–318
[22] DSTU B V.2.7-217:2009 Construction Materials. Concrete. The methods of the prismatic strength, modulus of elasticity and Poisson's ratio evaluation (Kyiv: Min. region bud) 2011
[23] GOST 12004-81 The reinforcement steel. The tensile test methods (Moskow) 1995
[24] Chikhladze E D and Vatulya G L 2011 Stress-strained state of steel-concrete structures under force and temperature effect *Proc. of the 5th International Conference on Dynamics of Civil Engineering and Transport Structures and Wind Engineering* pp 181–184
[25] Gorodetsky A and Evzerov I 2007 *Computer models of structures* (Kyiv: Fact)