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Strengthening of monolithic concrete slabs against pushing

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Abstract. Significant stress concentrations occur at the interface of floor slabs and columns in widely used monolithic reinforced concrete beamless frames. Therefore, the strength of the floor slabs must be checked for pushing under the loads from columns, bearing walls or stiffening diaphragms. The analysis of engineering solution of beamless monolithic reinforced concrete slabs of the administration nine-storey building with frame-walled load-bearing system is made. The strength thereof for pushing is found to be not provided under the given loads in a number of cases, due to this, experimental studies of strengthening the near-column areas of floor slabs have been carried out. When restoring the structures that suffered defects and damages in the course of their operation, composite materials having high tensile strength, low weight, constructibility and resistance to aggressive influence are widely used. The presented method for strengthening the near-column areas of floor slabs for ensuring their pushing strength with the use of chemical anchors has been developed, and a comparative analysis of the calculation results of the near-column areas of floor slabs with the adopted strengthening method with the results of experimental studies of slab fragments has been carried out. The operating conditions of the near-column areas of the floor slab have been simulated under the test method, and the results of the experimental samples testing are presented. All samples were found to have been destroyed by pushing through, with the destruction being of a plastic nature. The results of assessing the application of transverse reinforcement to the load-carrying capacity of the slab on pushing-through are presented. The results of experimental studies on assessing the pushing strength of extreme parts of monolithic floor slabs with columns reinforced with transverse glued-in reinforcement have shown good efficiency.

Keywords: monolithic floor slabs, composite materials, pushing strength, transverse glued-in reinforcement

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1. INTRODUCTION

Reinforced beamless frames are now widely used in the construction of such buildings and structures for various purposes as multi-storey shopping and multifunctional centers, underground parking lots and garages, with the use thereof being one of the main trends of recent years in the field of structural schemes of erected buildings [1, 2]. One of the main structural parts in the beamless frame of a building is the slab (floor slabs, roof slabs) [3, 4]. Major stress concentrations occur at the interface between floor slabs and columns in the slab-column structural scheme used [5, 6, 7]. This may result in the failure of the floor slabs due to column pushing-through [8, 9]. Therefore, when engineering buildings and structures, the strength of the floor slabs must be checked for pushing under the loads from columns, load-bearing walls or stiffening diaphragms [10, 11]. When restoring the structures that suffered defects and damages in the course of their operation, composite materials are widely used. Obvious advantages of composite materials are their high tensile strength, several times higher than that of steel, low weight, constructibility, and resistance to aggressive influence [12, 13]. The method of strengthening slabs against pushing through using chemical anchors is currently being applied in accordance with STO 36554501-29-2012 "Engineering of slab strengthening against pushing through with Hilti HZA-P chemical anchors. Calculation, engineering, installation". It was subsequently confirmed by field tests at the A.A. Gvozdev Concrete and Reinforced Concrete Research Institute. This procedure for strengthening floor slabs effectively increases resistance to pushing and deformations enabling uniform load distribution, reducing steel use and preventing structural failure, as well as reducing the timeframe of strengthening work relative to traditional methods if the requirements of STO 36545401-048-2016 "Anchoring to concrete. Design rules" and are met.

At the completion stage of construction of a nine-storey administration building with underground three-level floors made of monolithic reinforced concrete with a frame-walled load-bearing system it was found that the beamless structural solution of monolithic reinforced concrete slabs, adopted in the project, does not ensure the strength of their near-column areas for pushing under the given loads in a number of cases. In this regard, the general designer organization has raised doubts as to the sufficiency of the load-bearing capacity of separate near-column areas of flat slabs between floors, and it was decided to make experimental studies on strengthening the near-column areas of floor slabs [14, 15].

2. METHODS AND MATERIALS

Due to the above mentioned, the scheme of strengthening the near-column areas of floor slab was developed to ensure their pushing strength, and a comparative analysis of the calculation results of the near-column areas of floor slabs with the accepted scheme of strengthening with the results of experimental studies of slab fragments was carried out. The conditions of the near-column areas of floor slab were simulated by the test procedure. Five testing samples were tested: two samples without strengthening of the near-column areas with vertical bars (studs) and three samples with strengthening of the specified area with vertical 10 mm A500 bars, installed crosswise. Formwork dimensions and reinforcing schemes of the experimental samples are shown in Fig. 1, 2. The fragment samples were made in the field conditions at the plant from concrete with strength corresponding to the design one, with compressive strength of B25 grade.

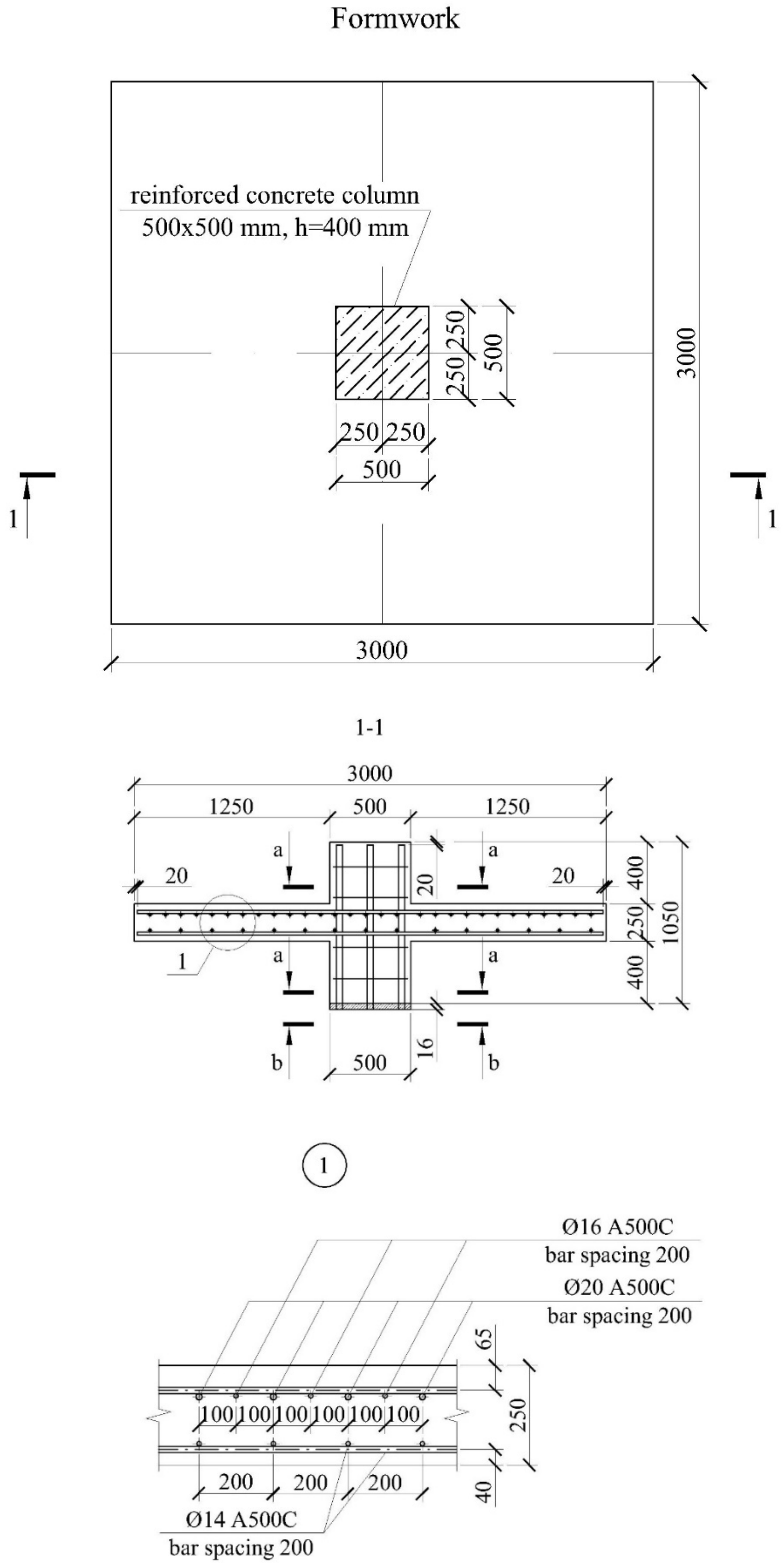
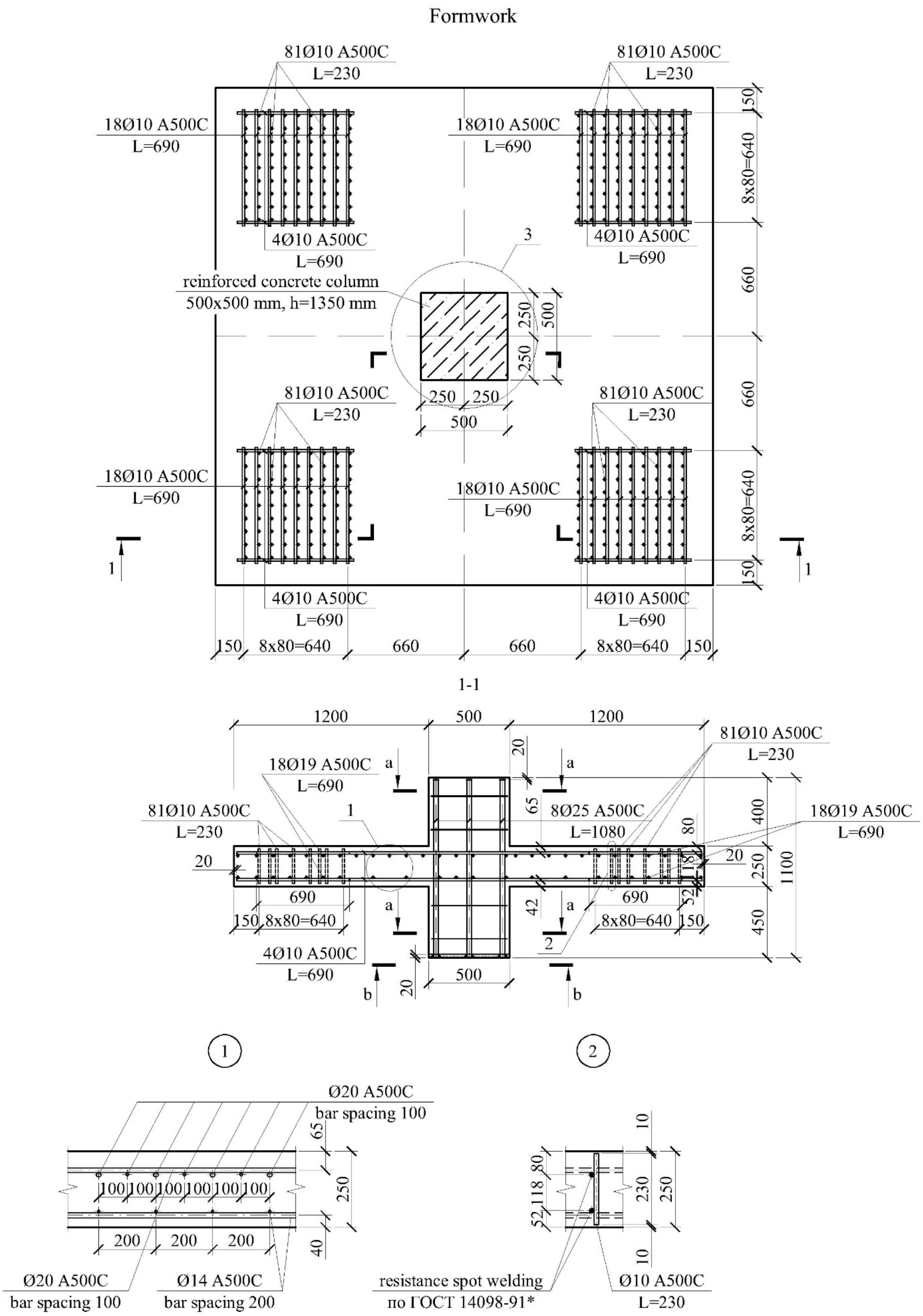


Fig. 1. Testing samples of near-column areas of floor slabs without strengthening with transverse reinforcement.



Notes:

1. Assembly 3 (scheme of strengthening the near-column area of the slab) is shown in Figure.
2. The scheme of assembly 2 was used to strengthen the slab areas in the places of load application during testing of samples.

Fig. 2. Scheme of strengthening testing samples in the areas of application of concentrated forces on the slab at testing.

The following technological sequence was adopted to realize the strengthening scheme:

1. Drill through or blind holes (up to 1.5...2.0 cm to the lower part of the floor slab) in diameter of 20...22 cm in the near-column area of the slab at the axes of the column contour on the upper plane side.
2. The inner surface of the hole is thoroughly cleaned.
3. 2...3 hours before injecting the holes with anchoring compound their inner surfaces should be thoroughly moistened (filled with water), therefore, if through holes are made on the side of the lower plane of the slab, they should be sealed with quick-setting repair compound.
4. Transverse (vertical) bars made of Ø10 reinforcing steel of A500C grade with anchors in the form of nuts at both ends of the bars are installed in the prepared holes.
5. The hole is filled with high-slump non-shrinkage cement-sand mixture.

To evaluate the efficiency of the rod anchors installed according to the above technological scheme, their embedment strength was tested. The tests were carried out on the experimental fragment No.1. The Ø10A500C reinforcement bar with a nut-shaped anchor at one end was installed in the prepared holes of fragment No. 1 (drilled outside the pushing area) according to three anchoring schemes:

- the entire length of the hole (Fig. 3, a);
- half the thickness of the slab from its upper plane (Fig. 3, b);
- half the thickness of the slab from its lower plane (Fig. 3, c).

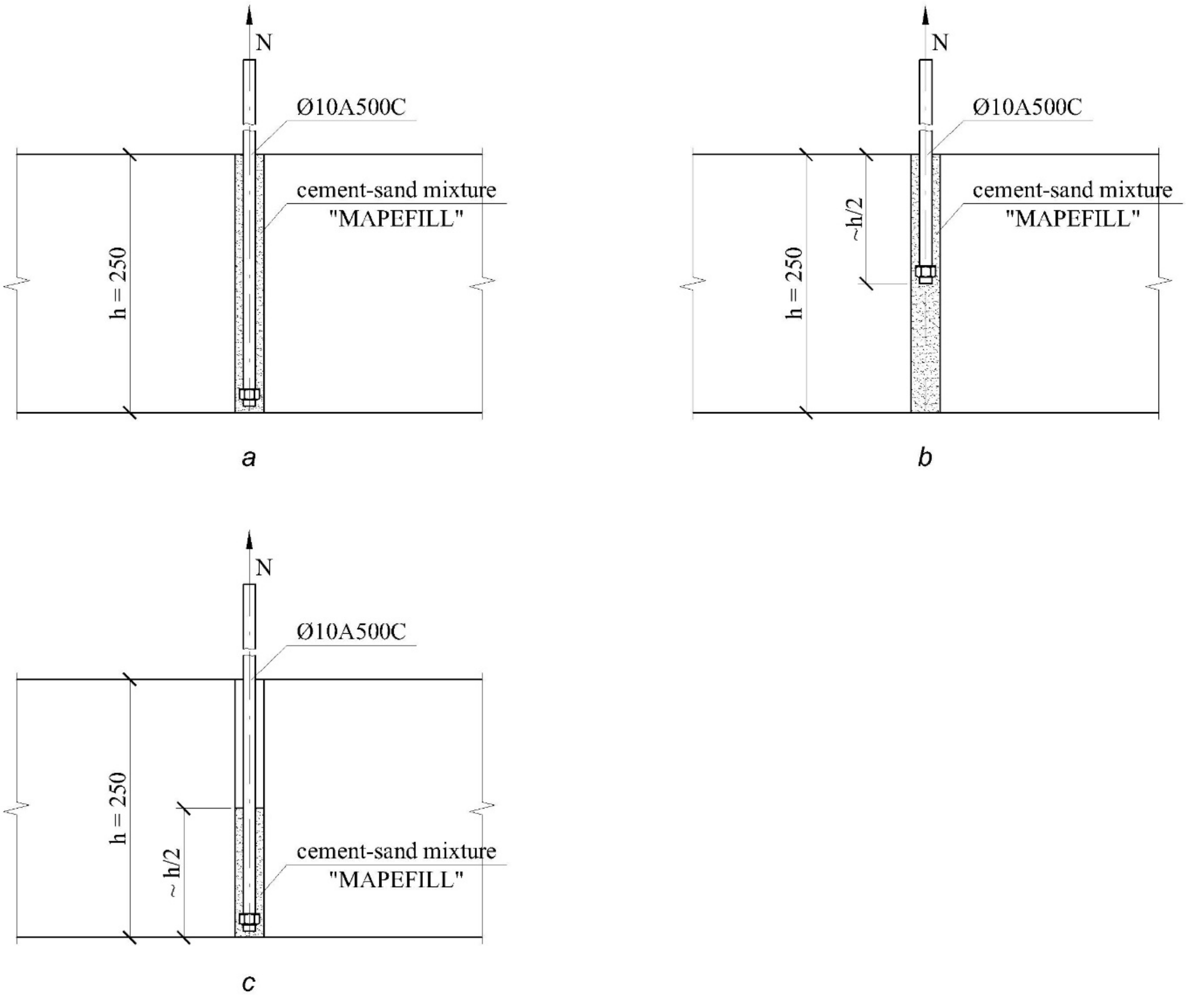


Fig. 3. Test scheme for anchoring of reinforcing bars in the concrete of the slab: a – when embedding the bars to the full thickness of the slab; b – when embedding to half the thickness of the slab from its upper plane; c – the same, from the lower plane of the slab.

3. RESULTS AND DISCUSSION

To apply the vertical force *N* during the anchorage strength test of reinforcing bars, a U-shaped frame was used as a stop for the hydraulic jack DG-12.5 mounted thereon. The force generated by the jack was transferred to the bar through a system of intermediate hinge elements. The tests were carried out on six bar samples, two for each of the anchoring schemes (Fig. 3). None of the six samples had a failure of the anchorage in the slab thickness, but there was a rupture along the cross-section of the bar outside the anchorage. The maximum force applied to the bar at its rupture was 50.7÷54.6kN.

Therewith the results of the studies have shown that the proposed scheme of embedding the transverse reinforcement with cement-sand mixture provides its reliable anchoring in the concrete of the slab under careful observance of the technology of work production.

When testing samples of the fragments of the near-column areas of the slab, deflection gauges and IBE-2 microscope were used. The concentrated pushing forces were generated by hydraulic jacks and applied to the floor slab by means of a system of steel beams at four points outside the intended drilling area. At the same time, the slab sections were strengthened with transverse reinforcement at the points of application of concentrated forces (fragment No. 2 Fig. 2). Tests of samples strengthened in the near-column area by transverse reinforcement were carried out in two stages. At the first stage, the load on the sample was brought to an average value of 590kN (excluding its own weight). After this loading, transverse reinforcement in the form of vertical "studs" was installed in the near-column area according to the scheme shown in Fig. 4. Then the fragment was extra loaded in stages until destruction with a holding time at each stage. The actual concrete strength of the test samples was determined under the results of shear tests according to GOST 18105-2018 "Concretes. Rules for control and assessment of strength" and tests of cores with a diameter of 80 mm drilled from the test samples after their testing. The average concrete strength of the samples was 30.4 ... 37.2 MPa (with B25 design concrete grade of the floor slabs). Tensile strength of concrete is calculated by the results of testing of 10×10×40 cm prisms. General view of testing one of the samples of the slab fragment is shown in Fig. 5.

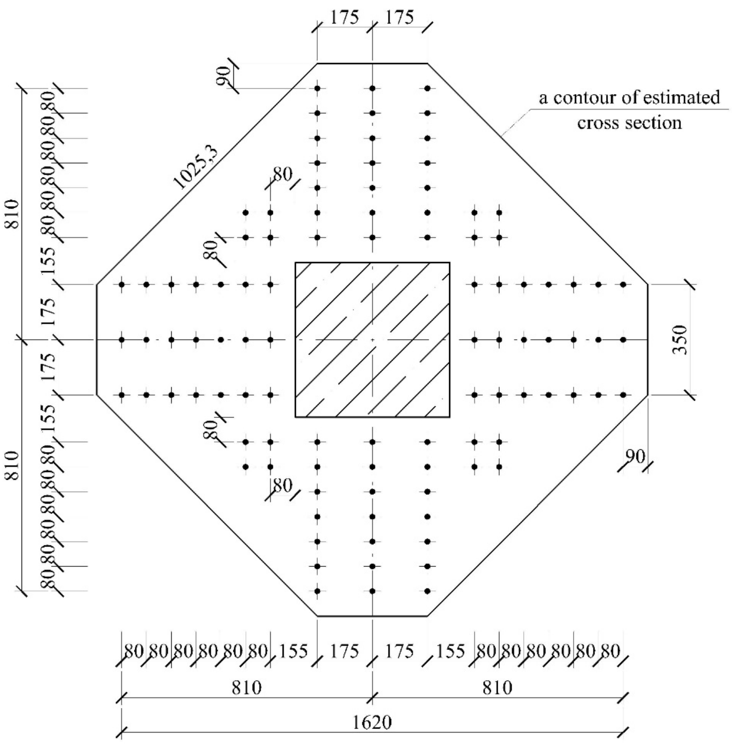


Fig. 4. Scheme of transverse reinforcement installation in the near-column area (plan view).

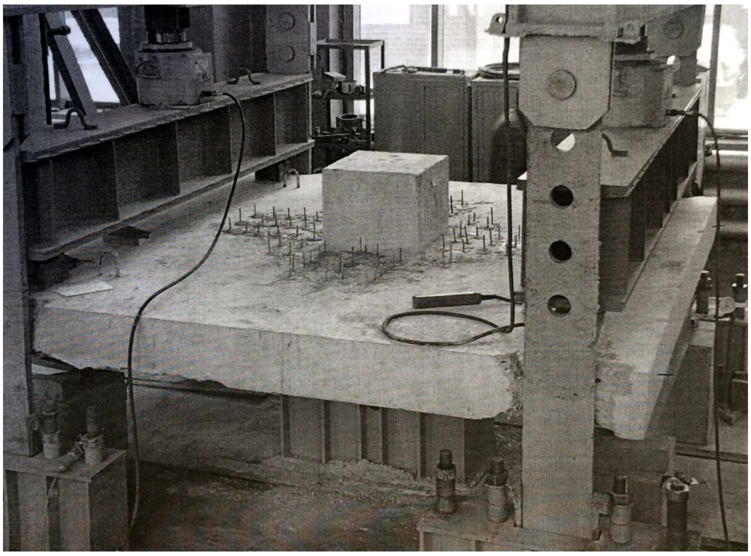


Fig. 5. General view of a fragment of the near-column areas of the floor slabs tested for pushing.

Similar studies were carried out in laboratory No. 2 “Reinforced Concrete Structures and Quality Control” of A.A. Gvozdev Concrete and Reinforced Concrete Research Institute where the efficiency of strengthening of floor slabs on pushing by placing inclined glued-in transverse reinforcement on the chemical composition of HILTI company was evaluated. The study included laboratory tests of samples of intermediate and extreme assemblies of slab-column interface.

Five experimental samples (2 reference samples without reinforcement and 3 with reinforcement) were tested. The experimental samples consisted of two column fragments with a cross section of 200×200 mm, height of 450 mm and a slab between them with a size of 1700×950 mm, thickness of 140 mm. (Fig. 6).

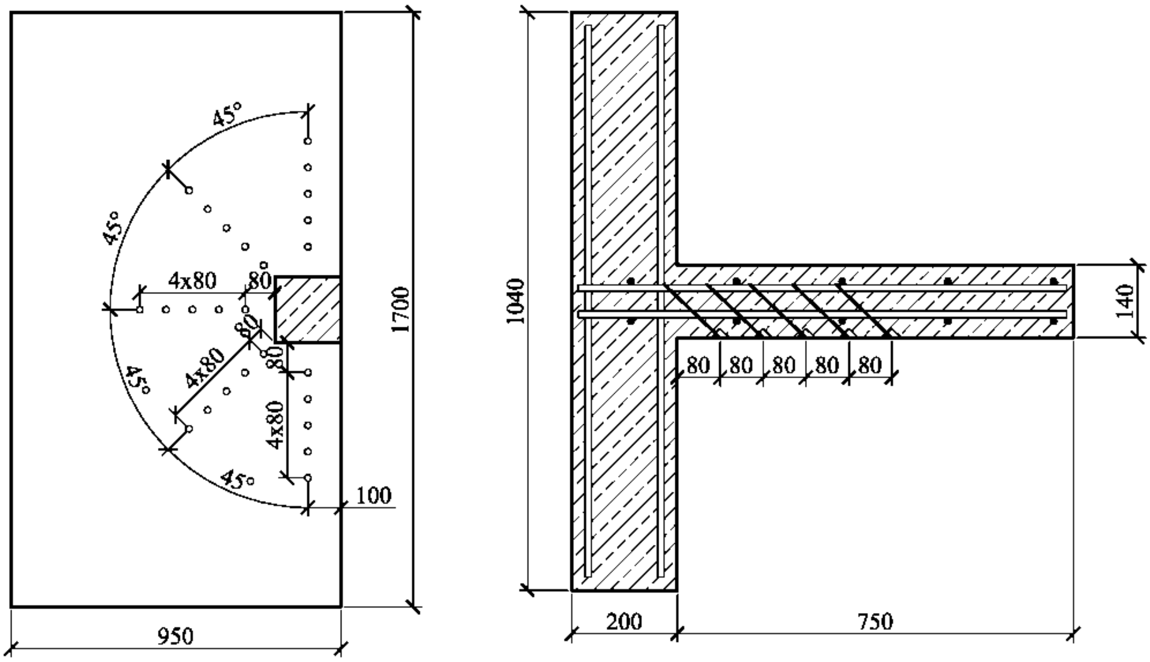


Fig. 6. Scheme for strengthening test samples.

One unreinforced and one reinforced reference samples were tested with an additional compressive force from the top column side that simulated the operation of the node of the intermediate floors in the building [18].

The strengthening included transverse reinforcement i.e. threaded bars M6 and M10 of 5.8 grade to be installed in pre-drilled holes at an angle of 45º on chemical anchors by HILTI. The location of transverse reinforcement was assumed to be radial. The scheme and geometric dimensions of the reinforcement are shown in Fig. 6.

Experimental samples were prepared from heavy concrete on granite crushed stone of 5-20 mm fraction. The compressive strength of concrete was measured by 100 mm control cubes and by shear test in the structure after testing the samples. Tensile strength of concrete was calculated from the data of 100 mm cube splitting tests according to GOST 18105-2018 “Concretes. Rules for control and assessment of strength”. In verification calculations, the tensile strength of concrete samples was calculated by formula:

$$R_{bt} = 0,232\sqrt[3]{R_{bn}^2},$$

where R_{bn} – characteristic concrete compressive cubic strength in MPa.

Data on the concrete strength of samples are given in Table 1.

Table 1. Physical and mechanical characteristics of concrete of test samples of studied slab fragments.

Sample grade	Operating height h0, mm	Concrete compressive strength $R_{b,m}$, MPa	Tensile strength of concrete R_{bt}, MPa
B0	100	37,1	2,22
BP0	100	39,9	2,33
SWR25	100	37,6	2,24
SWR75	100	37,6	2,24
SWR75P	100	39,9	2,33

The operating height of each sample was measured according to the actual values of the thickness of the protective layer.

Reinforcement of experimental samples:

- lower reinforcement – Ø12 A500 with a step of 200 mm;
- upper reinforcement – Ø12 A500 with a step of 75 mm.

Reinforcement of the columns of the test samples:

- longitudinal – 4Ø20 A500;
- transverse – Ø8 A240 with a step of 50 mm.

Physical and mechanical characteristics of the longitudinal reinforcement of the slab are given in Table 2.

Table 2. Physical and mechanical characteristics of the longitudinal reinforcement of slab test samples.

Diameter, mm	Yield strength $\sigma_т$, H/mm2	Breaking strength $\sigma_в$, H/mm2	Elastic limit $E_н$, H/mm2
12	596	682	2·105

Physical and mechanical characteristics of transverse reinforcement (threaded studs) were calculated by tensile tests. Characteristics of studs are given in Table 3.

Table 3. Physical and mechanical characteristics of the transverse reinforcement of slab test samples.

Diameter, mm	Yield strength $\sigma_{0.2}$, H/mm2	Breaking strength σ_B, H/mm2	Elastic limit E_H, H/mm2
M10	452	577	$1{,}8 \cdot 10^5$
M10	467	567	-"-
M10	437	569	-"-
M6	378	420	-"-
M6	392	430	-"-
M6	364		-"-

The concentrated moment was simulated by loading the samples by applying a vertical load to the lower column fragment and a horizontal load to the upper and lower column fragments. The horizontal forces were balanced by controlling the horizontal deformations of the column fragments.

The first cracks in the samples appeared around the edges of the columns at loading stages of 0.3-0.35 of the breaking force and they almost did not depend on the strengthening. Radial cracks were formed at loads of 0.35-0.45. They appeared and were growing in the direction towards the outer sides of the slab.

All samples were destroyed by pushing through. The destruction had a plastic character i.e. the ultimate load was accompanied by deformation increase. At the final stage of loading, a pushing body was formed as a half conical frustum, with the existing cracks in the samples not coinciding with the future destruction surface.

Strengthened samples were destroyed in the area of transverse reinforcement. After failure, the samples took the load up to 0.5-0.7 of the ultimate value. Inspection of the samples in the area of critical crack after the test showed that the transverse reinforcement of the first two rows had a fracture.

The strength of the samples was calculated in accordance with the main provisions of SP 63.13330.2018 "Concrete and reinforced concrete structures. Basic Provisions", with the force in the reinforcement was measured considering the possible failure of the anchoring of the bars over the adhesive composition, as well as concrete spalling in accordance with [16]. The comparison of theoretical and experimental values of the breaking forces in the experimental samples is given in Table 5.

The failure in the transverse reinforcement area in strengthened samples is the design one, i.e. it must occur in the transverse reinforcement area. Only the transverse rebars that crosses the pushing pyramid is included in the calculation of the pushing in the area of transverse reinforcement.

The least of the three failure mechanisms is accepted to assess the transverse reinforcement action to the load-bearing capacity of the slab for pushing:

a) failure of the upper end anchorage (bond failure);
b) failure of the lower end anchorage (stud end spalling);
c) yield stress of the transverse bar is reached.

$$F_{sw,ult} = \min(F_{si,b}, F_{si,p}, F_{si,y}),$$

where $F_{si,b}$ – ultimate force in transverse reinforcement at the bond failure in the upper part of the reinforcement; $F_{si,p}$ – ultimate force in transverse reinforcement when the lower end of the bar is spalled; $F_{si,y}$ – ultimate force that may be produced by transverse reinforcement when the yield strength is reached.

$F_{si,b}$ depends on the adhesive composition, diameter and length of anchorage, with the latter extending from the contour of the pushing pyramid to the end of the inclined bar. The shear strength of the adhesive composition was taken according to GOST R 57066-2016 “Test method for lap shear adhesion for bonded joints”.

$F_{si,b}$ is calculated by formula:

$$F_{si,b} = A_{swi}\frac{4\tau_{bd}l_{bsi}}{d_{bi}},$$

where l_{bsi} – distance from the calculated cross-section to the end of the bar (the actual average value was taken); d_{bi} – diameter of the cross-section of the inclined bar.

The ultimate force in the transverse reinforcement at the spalling of the bottom end of the bar ($F_{si,p}$) is calculated by formula

$$F_{si,p} = \varphi_2\varphi_3 A_b R_{bt},$$

where φ_2 – coefficient taken for heavy concrete as 0.5; φ_3 – coefficient taken as 1.0; A_b – projection area on the plane normal to the anchors of the spalling surface coming from the anchor reinforcement (edges of anchor washers) at an angle of 45º to the anchor axes (value of A_b was calculated by average actual bar lengths).

The ultimate action of transverse reinforcement when yield stress therein was reached was calculated by formula ($F_{si,y}$) and found by formula:

$$F_{si,y} = A_{si}R_{sw}\sin\alpha.$$

Initial data for calculating the experimental samples for pushing are presented in Table 4. The results of calculating the action of transverse reinforcement to the load-bearing capacity of the reinforced test samples for pushing are given in Table 5. Only two rows of transverse reinforcement that fell into the inclined cross-section were considered in the pushing calculation.

Table 4. Initial data for calculating the samples simulating the end columns.

Sample grade	Concrete grade	R_{bt}, MPa	h_0, cm	u_b, cm	u_{sw}, cm	W_{bx}, cm^3	W_{by}, cm^3	W_{swx}, cm^3	W_{swy}, cm^3	A_{sw}, cm^2	R_{sw}, kg/cm^2
B0	B28.7	2.17	10.0	80	80	901	322	901	322	0.00	4520
BP0	B32.4	2.36	10.0	80	80	901	322	901	322	0.00	4520
SWR25	B31.6	2.32	10.0	80	80	901	322	901	322	1.96	3780
SWR75	B31.1	2.29	10.0	80	80	901	322	901	322	6.08	4520
SWR75P	B32.6	2.37	10.0	80	80	901	322	901	322	6.08	4520

Table 5. Calculation results of samples simulating the end columns.

Sample grade	M, т·м	F, тс	qbt, kgf/cm2	qsw, kgf/cm2	qN, kgf/cm2	qM, kgf/cm2	Fact/ Ftheor	Expected theoretical strengthening	Actual strengthening
B0	2.04	14.9	21.7		18.60	18.60	1.71		
BP0	2.82	24.1	23.6		30.10	30.10	2.55	1.00	1.62
SWR25	2.16	18.3	23.2	4.07	22.85	22.85	1.68	1.15	1.23
SWR75*	2.21	17.6	22.9	11.09	21.98	21.98	1.29	1.38	1.18
SWR75P	2.77	31.9	23.7	11.09	39.85	39.85	2.29	1.38	1.32

Note: * Sample destruction was due to equipment failure

The efficiency of strengthening is better analyzed by expressing the strength condition of GOST 18105-2018 "Concretes. Rules for control and assessment of strength" through the tangential stresses along the design contour and dividing all terms of the equation by $u{\cdot}h_0$.

By expressing the condition of strength for pushing as:

$$\frac{F}{R_{bt}uh_0 + 0{,}8R_{sw}A_{sw}\sin\alpha} + \frac{M}{R_{bt}Wh_0 + \frac{0{,}8R_{sw}A_{sw}W\sin\alpha}{u}} \leq 1,$$

by making the following transformations:

$$\frac{F}{uh_0\left(R_{bt} + \frac{0{,}8R_{sw}A_{sw}W\sin\alpha}{uh_0}\right)} + \frac{M}{Wh_0\left(R_{bt} + \frac{0{,}8R_{sw}A_{sw}W\sin\alpha}{uh_0}\right)} \leq 1.,$$

and making substitutions:

$$q_b = R_{bt}; \quad q_{sw} = \frac{0{,}8R_{sw}A_{sw}\sin\alpha}{uh_0}; \quad q_N = \frac{F}{uh_0}; \quad q_M = \frac{M}{Wh_0}.$$

the strength condition finally takes the following form:

$$\frac{q_N + q_M}{q_b + q_{sw}} \leq 1..$$

The results of calculation of pushing through the experimental samples are presented in the table 5.

The actual working height of the sample slabs was 100 mm, with the transverse reinforcement spacing being $4h_0/5$. Thereby, the transverse reinforcement spacing significantly exceeded the one permitted by SP 63.13330.2018 "Concrete and Reinforced Concrete Structures. Basic Provisions" ($h_0/2$) as well as the requirements of EU 2 ($3/4h_0$).

The strength of the reinforced samples depends on several factors (amount of transverse reinforcement, upper column compression, variation in concrete strength) according to STO 36554501-029-2012 "Design of reinforcement slabs for pushing with Hilti HZA-P chemical anchors. Calculation, design, installation". To analyze the reinforcement action and to exclude the impact of concrete strength variation in the samples, the theoretical values of the breaking forces were corrected by multiplying by the correction factor

$$k = R_{bt,reinf.}/R_{unreinf.}.$$

For sample B0, the ratio of ultimate breaking load to theoretical load was 1.71.

Table 5 shows that the compression from the upper column side increased the ultimate breaking load of the test sample (BP0), compared to the reference sample (B0), by 62 %. For sample SWR25, the theoretical increase in pushing strength due to the installation of transverse reinforcement compared to the reference (B0) is 15 % while the actual reinforcement is 23 %.

When SWR25 sample was loaded at the steps close to failure, the tie bar holding the slab was broken. Therefore, the sample had to be unloaded and the test had to be repeated. As a result, the strength of the sample was slightly reduced. The ratio of ultimate breaking load to theoretical load was 1.29. The theoretical increase in strength of the sample (SWR25) due to installation of transverse reinforcement, compared to the reference sample (B0) is 38 % while the actual increase is 18 %.

The transverse reinforced SWR75P sample was tested in compression in the upper column. The ratio of ultimate breaking load to theoretical load is 1.57. The total actual strength increase of this sample due to installation of transverse reinforcement and compression of the slab from the upper column side compared to the sample (B0) is 97 %. The theoretical increase in the pushing strength of

SWR75P sample due to installation of transverse reinforcement compared to the reference (BP0) is 38 % while the actual increase is 32 %. So, the increase in ultimate breaking load due to compression of the slab from the upper column side amounted to 65 %.

Table 5 shows that the proposed procedure for calculating the strength of the extreme samples has a significant margin, with the calculation error being more than 2 times.

4. CONCLUSIONS

Therefore, the results of experimental studies to assess the pushing strength of extreme joints of monolithic floor slabs with columns reinforced with transverse glued-in reinforcement using Hilti technology have shown good efficiency.

Compression from the upper column side increases the load-bearing capacity of the slabs for pushing. For the unreinforced sample the strength increase amounted to 62 %, for the reinforced one - 65 %. However, the proposed procedure for calculating the pushing strength of reinforced samples gives a significant margin and should be improved. The coefficient of the ratio of experimental data to theoretical values of the pushing strength amounted to 1.68-2.55.

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