Structural solution of the horizontal joint of floor slabs in girderless frame

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Abstract. Despite the widespread use of monolithic construction, precast concrete remains in demand in the construction of residential and administrative buildings. Regardless of the advantages in technology and the quality of work, it is necessary and appropriate to modernize the existing design solutions, which allows you to simplify and speed up the technological operations during construction. Moreover, in the construction of complex nodes and joints, the qualification of workers is important, so simplifying the work without losing the quality of construction and ensuring strength, stability and durability is an important task. This problem can be solved by using modern embedded parts in the joints that do not require welding and other complex technological operations. In this paper, a constructive solution of the horizontal joint of the floor slabs located in the zone of action of minimal forces is proposed on the example of a girderless frame. The purpose of the study is to determine the stress-strain state of the proposed structural solution of the horizontal joint of floor slabs using loop-shaped embedded parts «PFEIFER» and to develop recommendations for determining the shear compliance. Based on the analysis of the results of numerical modeling, the features of the stress-strain state of the joint during shear operation are revealed. The results obtained can be used in the design of buildings with precast-monolithic ringless frames, in the modernization of existing standard solutions of precast-monolithic frames, as well as other load-bearing systems made of precast concrete.

Keywords. Multi-storey buildings, girderless frame, horizontal joint of floor slabs, loop-shaped embedded parts, welded joint, shear compliance.

1 Introduction

Today, the technology of monolithic reinforced concrete is widely used for the construction of buildings for various purposes, however, precast concrete does not give up its positions. Its main advantages are cost-effectiveness, quick construction, a high degree of control during production at the factory, the use of standard solutions, and others. Taking into account these advantages, as well as the relative simplicity of the technology and the quality of work, the construction of frame buildings for residential and administrative purposes from precast concrete elements remains relevant [1-3], but it is necessary and expedient to modernize existing design solutions [4, 5], which allows to simplify and speed up technological operations during construction [6-8]. The weak point of precast concrete is the

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connection of elements. The problem of choosing the optimal solution of the joint, ensuring its operation on vertical and horizontal loads is relevant. Attempts are being made to create durable, suitable for normal function, strong and technological joints [9], which will have a positive impact on the overall stability of precast concrete buildings [10]. In [11], for example, a new solution for the joints of a column and a plate in a girderless frame is proposed, which simplifies technological operations and optimizes the stress-strain state of the joint and the frame as a whole.

In Russia, one of the frames used is the ringless frames according to the UIKSS and CUB systems, the peculiarity of which is the rigid fixing of the floor slabs on the columns and the hinged connection between them due to the tamping of the keys [12, 13]. The dimensions of the floor slabs are designed so that the joints of the panels are located in the zones of zero bending moments. The structural solution of the horizontal joint of floor slabs in the construction of ringless frames is the joint of the design of Academician G.P. Perederia, which is also used in the design of bridge spans. However, this classic solution gives certain difficulties during installation. Many works of Russian and foreign authors are devoted to the modernization of this joint, finding the optimal solution for the placement of reinforcement, simplifying the installation technology, saving materials, determining the strength and deformation characteristics.

The main purpose of horizontal and vertical joints between panels or slabs is the perception of shear forces [14]. Experimental studies are limited to determining the optimal placement of reinforcement in the joints between wall panels, bridge plate joints [15-17], as well as issues of concrete work in the joint, issues of adhesion of panel concrete and butt concrete [18]. In addition, the issues of shear strength are also considered in relation to the construction of multi-layer wall panels [19-21], data on the flexibility of the reinforcement in the joints, the influence of its position on the nature of the destruction of the joints and the connected panels, the destructive loads are obtained. The obtained data can be partially applied to the joints of building elements, for example, when studying the influence of the number and location of embedded parts and fittings in the joints, studying the nature of joint failure during shear [22, 23].

It is known that buildings made of precast concrete have sufficient resistance to seismic loads, under the influence of which the main task of the joints is to work in shifts. Many works are devoted to determining the shear characteristics of various structural joints [24-26]. In [27], an analysis of joint damage after an earthquake was carried out in order to determine the weaknesses and strengths of each type of joint and further develop a design solution for joints with optimal strength and deformation characteristics.

The issues of the durability of buildings as a whole [28] and the residual load-bearing capacity of joints and their reinforcement [29-31] are also of great importance. It is noted that to determine the effective method of reinforcement, data on the strength and flexibility of the joint are necessary not only at the design stage, but also taking into account various aspects of the operation of the object. Methods of reinforcement with carbon fiber, taking into account the direction of shear flows, fine-grained concrete, and their combination are proposed. Thus, each proposed structural solution of joints should be tested for changes in strength and compliance, and analytical expressions for determining these characteristics would reflect the actual stress-strain state.

Modernization of structural solutions of joints, proposed by scientists and engineers, is reduced to minimizing costs during construction, reducing the material consumption of the joint, increasing strength characteristics, reducing deformability. The possibility of using reinforcement with a shorter overlap length [32, 33], continuous reinforcement [34], reducing the joint width [35], using new anchor designs [6], as well as new forms of rods and dowels [24, 36] is widely discussed. Separately, we can distinguish solutions based on the use of welded loop-shaped embedded parts in the joints [37, 38], for which multi-factor experiments

The developed joint of reinforced concrete floor slabs is formed by reinforced key joints made of loop-shaped embedded parts. To determine the optimal structural solution of the joint, the following parameters were varied: the number of embedded parts located at the joint; the distances between the embedded parts; the concrete grade of the joint. Three variants of the arrangement of embedded parts along the length of the horizontal joint are considered: one embedded part in the middle of the length, two embedded parts at the edges of the joint, two embedded parts in the middle of the joint.

The model for the shear experiment is a joint of two precast reinforced concrete floor panels with a size of 2.98×2.98 m and a thickness of 160 mm. The joint width is 120 mm. The dowels have dimensions of 120×64×20 mm. The concrete of the floor panels is heavy of class B25, the joint is covered with fine-grained concrete, the class of which varies during the numerical experiment: B20, B25 and B30. The reinforcement rod of a round cross-section with a diameter of 12 mm is similar to the structural solution of the joint according to the CUB system, taken as a basis. The anchor made of flexible rebar is set by the rope TK 1×19(1+6+12) Ø8.1 mm.

Fig. 2. Structural solution of the joint. Options for placing embedded parts.

For verification, the data of a full-scale experiment on the study of the VAT of the vertical joint of wall panels with flexible hinges, conducted under the direction of B.S. Sokolov, were used [42]. As a result, it is obtained that the destructive load and the nature of the destruction obtained by numerical modeling are comparable with the data of the physical experiment.

The numerical study of the stress-strain state of the horizontal welded joint of the floor slabs was carried out in the LIRA-SAPR software package. The following model is adopted: the floor slabs and the joint are formed by three-dimensional finite elements with the dimensions of the faces no more than 12 cm, one of the slabs along the contour has rigid connections. For the three-dimensional FE models, the physical and mechanical characteristics of the concrete of the masonry and the concrete of the prefabricated element corresponding to the properties of the materials were used. The rope loops of the embedded parts, as well as the reinforcing rod, are set by the rod end elements. The compliance of the plate interface was modeled by two-node finite elements of the elastic bond (CE55). The load was gradually applied to the end of the left panel of the ceiling.

3 Results and discussion

On the basis of numerical modeling of horizontal key joints, their stress-strain state under the perception of shear forces is determined. The nature of the destruction of the samples on the action of the shear force on the horizontal joint is established. The load-bearing capacity of single-spar joints is almost three times lower than that of double-spar joints, and the load-bearing capacity of joints for shear loads practically does not change with an increase in the class of concrete masonry. The moment of crack formation and the nature of destruction of horizontal key joints of floor slabs with flexible transverse reinforcement under the perception of shear forces are established: cracks are formed in the stretched joint zone by the contact of the concrete of the plate and the concrete of the joint, the destruction occurs by the concrete of the masonry. The moment of crack formation increases with an increase in the class of concrete in the joint; the stiffness of the joint is directly proportional to the number of dowels formed by the embedded parts along the length of the joint. The numerical experiment showed that the compliance of a single-spline joint is almost two times higher than the compliance of a double-spline joint. At the same time, it was found that at a greater distance between the dowels (joint option II), the joint flexibility is less than at a close arrangement of the dowels relative to each other (joint option III).

Table 1. Stress-strain state of the joint depending on the class of concrete masonry.

Joint option	Class of concrete for masonry	Crack load kN	Breaking load kN	Shear compliance, *10 ⁻⁶ m/kN	
				Before cracking	After the formation of cracks
1	B20	17.88	29.8	2.16	9.63
	B25	20.86		2.14	8.83
	B30			2.13	8.49
2	B20	29.80	80.50	1.01	4.39
	B25	35.76		0.97	3.92
	B30	41.72	92.38	0.95	3.61
3	B20	47.68	74.5	1.02	5.32
	B25	41.72		1.00	3.82
	B30	59.60		0.98	3.69

The breaking loads were determined for all variants of plate coupling: for a single – spar joint, it is 29.8 kN, for the two considered variants of a joint with two keys – 80.5 kN (option II) and 74.5 kN (option III). When comparing the load-bearing capacity of two-spar joints and

the joint according to the CUB system, the comparability of the results obtained is noted. The discrepancy is 4.1% and 12.55%, respectively. The maximum displacements of the finite elements in the joint are obtained and the values of joint compliance at the stages before and after the crack are calculated. It is noted that the work of the joint under study is similar to the existing joint solution for the UIKSS and CUB systems. The values of the strength and stiffness of the joint models obtained during the numerical study are comparable to the results of previous studies of similar structures [42]. Based on this, we can conclude that the model of the studied coupling of floor slabs is correct and applicable.

According to the results of the numerical study, it is recommended to use the joint option No. II for the design – a two-step joint of reinforced concrete floor slabs with a size of 2980×2980 mm, formed by embedded parts of the Tire VS PFEIFER (VS 50/200) and fine-grained concrete of class B25. The embedded parts are located at a distance of 520 mm from each other with an offset from the ends of the plates at a distance of 40 mm (to provide an armo-protective layer), the dowels have dimensions of 120×64×20 mm.

The destructive shear load for joint No. II was 80.5 kN, the nature of the failure is the formation and development of cracks along the contact of the prefabricated panel and the monolithic concrete of the joint. The moment of crack formation is 35.8 kN, which is 44.5% of the breaking load. The value of the shear compliance of the joint at the elastic stage was $0.97 \cdot 10^{-6}$ m/kN, at the stage after the formation of cracks $-3.92 \cdot 10^{-6}$ m/kN.

The strength and ductility of joints at the stage before and after the formation of cracks were calculated according to existing methods [44, 45], as well as their comparison with the data of a numerical experiment. According to the results of theoretical calculations and numerical research, it is obtained that the values of compliance during the operation of the joint in the elastic stage before the formation of cracks are close.

In reinforced joints, when cracks appear due to shear forces, the forces are redistributed between the dowels and the rope loops of the joint are «turned on». According to the results of theoretical calculations and numerical experiments, it is obtained that the values of the joint compliance differ by a coefficient approximately equal to the ratio of the initial modulus of elasticity of the concrete of the floor slab and the initial modulus of elasticity of the concrete of the joint masonry. For this stage, in this paper, we propose to use the expression for vertical keyway connections of wall panels, taking into account the coefficient:

$$\gamma = \frac{E_{b,p}}{E_{b,j}}, \quad (1)$$

$E_{b,p}$ – modulus of elasticity of concrete floor slabs;

$E_{b,j}$ – modulus of elasticity of concrete for joint masonry.

Based on this, it is proposed to improve the existing expression for determining the shear compliance of a loop-shaped weld-free joint by applying the coefficient γ in the general compliance formula set out in [44].

The calculated expression for the shear compliance at the stage after the crack is presented in the following form:

$$\lambda_{\tau} = \gamma \cdot (\lambda_{tb} + \lambda_{ts}), \quad (2)$$

where λ_{tb} – flexibility of the concrete key;

λ_{ts} – flexibility of the reinforcement connection.

For the constructions considered in this paper, the coefficient γ has the following values:

- when concrete is used for masking the joint, cl. B20: $\gamma = 1.36$;
- when concrete is used for masking the joint, cl. B25: $\gamma = 1.25$;
- when concrete is used for masking the joint, cl. B30: $\gamma = 1.15$.

The value of shear compliance at the stage after the crack is shown in Table 2.

Numerical studies have shown that the load-bearing capacity of the joint increases insignificantly with an increase in the class of concrete masonry, so for further design, it is recommended to use the joint option No. II with fine-grained concrete cl. B25 in the joint.

Comparison of the calculation results, shown in Table 2 reflects the possibility of applying the proposed calculation expression in assessing the shear compliance of horizontal welded joints of floor slabs with flexible transverse reinforcement. The calculation of strength and load-bearing capacity is proposed to be performed according to the method proposed in the manual for the design of residential buildings [44].

Table 2. Comparison of the values of shear compliance in the horizontal joint of floor slabs at the stage after the formation of cracks.

Joint option	Class of concrete for masonry	Shear compliance, m/kN			
		by the method [44]	by the method [45]	based on the results of a numerical experiment	by the formula (2)
№ 1	B20	$6.59 \cdot 10^{-6}$	$6.03 \cdot 10^{-6}$	$9.63 \cdot 10^{-6}$	$8.98 \cdot 10^{-6}$
	B25	$6.27 \cdot 10^{-6}$	$5.86 \cdot 10^{-6}$	$8.83 \cdot 10^{-6}$	$7.83 \cdot 10^{-6}$
	B30	$6.03 \cdot 10^{-6}$	$5.71 \cdot 10^{-6}$	$8.49 \cdot 10^{-6}$	$6.96 \cdot 10^{-6}$
№ 2	B20	$3.3 \cdot 10^{-6}$	$3.02 \cdot 10^{-6}$	$4.39 \cdot 10^{-6}$	$4.5 \cdot 10^{-6}$
	B25	$3.13 \cdot 10^{-6}$	$2.93 \cdot 10^{-6}$	$3.92 \cdot 10^{-6}$	$3.91 \cdot 10^{-6}$
	B30	$3.0 \cdot 10^{-6}$	$2.85 \cdot 10^{-6}$	$3.61 \cdot 10^{-6}$	$3.46 \cdot 10^{-6}$
№ 3	B20	$3.3 \cdot 10^{-6}$	$3.02 \cdot 10^{-6}$	$5.32 \cdot 10^{-6}$	$4.5 \cdot 10^{-6}$
	B25	$3.13 \cdot 10^{-6}$	$2.93 \cdot 10^{-6}$	$3.82 \cdot 10^{-6}$	$3.91 \cdot 10^{-6}$
	B30	$3.0 \cdot 10^{-6}$	$2.85 \cdot 10^{-6}$	$3.69 \cdot 10^{-6}$	$3.46 \cdot 10^{-6}$

The maximum discrepancy between the values of the shear compliance of the joint according to the formula proposed in this paper and the numerical experiment was 22.04%. This discrepancy is acceptable, since it does not lead to a significant change in the forces in the elements. According to experimental data, for vertical joints of prefabricated elements of a similar design [46, 47], it was noted that a 25% reduction in joint flexibility leads to an increase in forces by 10.7%. When comparing the values of the compliance of the numerical model of the joint according to the CUB-system and the joints No. II and No. III considered in the work, the differences in the values were 8% – for the stage of elastic work, 9% – in the stage after the formation of cracks. These values indicate the possibility of comparing the existing joint design with the proposed ones. The reliability of the model under study is confirmed by comparing the data obtained with the results of previous experiments, as well as by the comparability of the results of the numerical study with theoretical calculations.

Numerical simulations were used to obtain data on the stress-strain state of various variants of horizontal joints using flexible loops. According to the results of the comparison of the stress-strain state of the joint models for the CUB and UIKSS-systems and the proposed models of the two-step joint, a similar nature of work is noted, which is confirmed by the data of field experiments and allows us to consider the proposed solutions adequate. The closest approach to the existing solution is joint No. III with fine-grained concrete of class B25 in the joint. However, the parameters (moment of cracking, breaking load, stiffness) of the joint option No. II with the same class of concrete in the joint are higher. Since the load-bearing capacity of the joint increases slightly with an increase in the class of concrete of masonry, it is recommended to use the joint option No. II with fine-grained concrete of class B25 in the joint.

4 Conclusion

Based on the results of this work, it can be concluded that it is possible and expedient to use embedded parts made of flexible PFEIFER loops in the horizontal joints of floor slabs in the design of residential and administrative buildings with the ringless frame systems UIKSS, CUB. Further development of the topic of this work is possible in the field of studying the

influence of the work of PFEIFER embedded parts in the joints of floor slabs on the overall VAT of the building frame, on the possibility of using these embedded parts in construction in areas with seismic activity. Using the results of Russian and foreign researchers on the compliance of reinforcement in vertical non-welded loop-shaped joints, it is possible to transform the analytical expression (2) and obtain data on the operation of joints, taking into account the residual load-bearing capacity. Thus, the data obtained in the presented work opens up a wide range of research in the direction of modernization of existing design solutions.

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