Punching shear strength under static and dynamic loads

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Abstract. Modern domestic calculation methods and developed countries for determining the bearing capacity of monolithic reinforced concrete slabs for punching do not fully take into account all factors of design solutions and operating conditions. The available design provisions are made for the static operation of structures and there are no recommendations for taking into account the features of the dynamic impact on the overlap and the nature of the work of the node interfaces. The accepted empirical assumptions of the calculation, based on numerous experimental data, do not take into account the features of the stress-strain state of the coupling of the overlap with the column during destruction according to the punching scheme. This is due to the lack of computational models in which all the acting internal forces ensuring the resistance of the interface to penetration would be considered comprehensively. The complexity of the problem is due to the fact that the sections of the nodal interface are in an inhomogeneous stressed state. The stress-strain state of plates for punching under dynamic load is currently little studied. This article proposes a method for determining the bearing capacity of a symmetrical nodal coupling of a column with an overlap for punching under static and short-term dynamic loading. The proposed design model of the punching strength is based on the following prerequisites: the resistance to punching of a monolithic reinforced floor consists of the shear resistance along the surface of the reduced punching pyramid formed by the height of the compressed concrete zone; the strength of the concrete shear resistance increases due to volumetric compressive forces on the surface of the reduced punching pyramid; the angle of inclination of the faces of the punching pyramid depends on the loading speed. The obtained theoretical dependences are applicable under static and dynamic loading and are in satisfactory agreement with experimental data.

Keywords: coupling of a monolithic floor with a column; static and dynamic load; punching pyramid; tangential stresses; concrete shear strength; punching strength.

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1 Introduction

In modern technical literature, a lot of attention is paid to assessing the strength of monolithic slabs during punching [1-4]. This is due to the urgency of the problem associated primarily with the intensive development of monolithic multi-storey housing construction. The thickness of floors, which are the most material-intensive load-bearing elements of a building, is largely determined by the bursting strength criterion. The second factor that determines the importance of this problem is the imperfection of the current methodology for assessing the bearing capacity during punching.

The scheme of destruction from punching along the contour of the pyramid was proposed by A. Gvozdev on the basis of numerous experimental data and for a long time was not improved. At present, in the presence of a variety of design solutions for interfacing monolithic floors with vertical load-bearing elements of various configurations, the simplified approach of the destruction scheme along a pyramid or a punching prism does not provide reliable results on the bearing capacity. Theoretical methods for assessing the punching strength of foreign regulatory documents are based on empirical dependencies [5-9] obtained on the basis of numerous experimental studies. It should be noted that they give reliable results when certain design requirements are met, which reduces their versatility.

The need for a more detailed analysis of the stress-strain state during punching becomes obvious. You should start with an analysis of the combination of internal forces of the rigid connection of the plate with the column.

In the absence of longitudinal reinforcement in the tension zone, punching failure will occur along the surface of the pyramid. This case does not occur in the practice of designing juxtapositions of columns with an overlap.

Support bending moments act in two orthogonal directions along the junction line of a plate with a rectangular (square) column. The magnitude of these moments for the most common spans is large and in the elastic formulation exceeds the spans by a factor of two. Taking into account the redistribution of forces and the most likely formation of cracks in the tension zone, it can be argued that at the operational stage, the supporting sections of the plates have compressed and tension zones. This fact at the stage close to failure is confirmed by experimental studies [10-16] on symmetrical samples of fragments of the column-to-floor interface in the presence of working reinforcement in the tensile zone of the slab. With such a stress-strain state in the calculation scheme, when assessing the punching strength, one should exclude a part of the side surface of the "reduced" pyramid bounded by the neutral axis along all faces. Consequently, in the limiting stage in terms of bearing capacity, resistance is exerted by the surface of the pyramid located in the zone where compressive stresses act. And this, based on the current calculation method, will lead to a significant decrease in the bearing capacity for punching. However, this does not happen in practice, because, as experimental studies show [14, 15], shear strength under conditions of compression to a certain level from Rb increases. Obviously, the punching strength should be evaluated taking into account the volumetric stress state.

2 Methods

Based on the design scheme shown in Figure 1, which was proposed in [14, 15], the punching resistance is exerted by forces equal to the projection onto the vertical axis from shear stresses distributed over the surface of the reduced punching pyramid on four faces:

$$N = Q_{bx1} + Q_{bx2} + Q_{by1} + Q_{by2} \, , \quad (1)$$

where $Q_{bxi(yi)}$ – projection onto the vertical axis of the force perceived by concrete when punching along the corresponding faces X and Y.

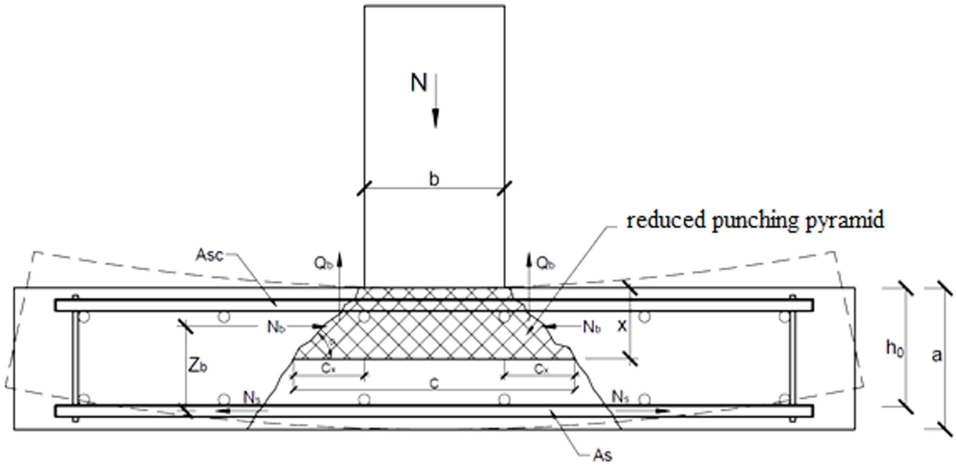

Fig. 1. Calculation scheme for determining the bearing capacity of the junction of a column with an overlap during punching.

The force perceived by concrete on the surface of the punching pyramid with a symmetrical nodal conjugation is equal to:

$$Q_{bi} = k_1\, \sigma_{sh} k_2 A_{redi} \sin\varphi \ , \tag{2}$$

where σ_{sh} – maximum shear stresses on the surface of the punching pyramid [17];

k_1 – coefficient of completeness of the shear stress distribution diagram (with stress distribution along the parabola $k_1 \cong 0{,}66$);

k_2 – coefficient taking into account the increase in shear strength in the presence of lateral compression [18];

A_{redi} and ϕ– the area of the lateral surface of the reduced punching pyramid and the angle of inclination of the pyramid face to the overlap plane.

Then the pushing force will be equal to:

$$N = 4Q_{bi} \tag{3}$$

The maximum shear stresses will be equal to the shear resistance, which can be determined from the well-known expression [17]:

$$R_{sh} = \sigma_{sh} = 0{,}75\sqrt{R_b R_{bt}}, \tag{4}$$

where R_b and R_{bt} - prism strength of concrete and tensile strength of concrete, respectively.

In this design scheme, the main unknowns are the compressive stresses in concrete, the stresses in tensile reinforcement, and the geometric parameters of the reduced punching pyramid.

The area of the face of the punching pyramid can be expressed in terms of the height of the compressed zone x_i:

$$A_{red,i} = \frac{b + c_i}{2} * h_{red,i} = \left(b + \frac{x_i cos\varphi}{sin\varphi}\right)\frac{x_i}{sin\varphi} \ , \tag{5}$$

where b – column width;

c_i - projection of the inclined face of the pyramid (see Figure 1);

$h_{red,i}$ – height of the punching pyramid on the i-th face.

$$h_{red,i} = \frac{x_i}{sin\varphi} \quad (6)$$

3 Results

Conducted experimental studies [13,14,15] showed that in the limiting stage (table 1):

Table 1. Calculation results according to the proposed method of calculation for punching

Sample mark	R_b, **MPa**	A_b, **sm²**	A_s, **sm²**	$\frac{\sigma_b}{R_b}$	$\frac{\sigma_s}{R_s}$	ξ	$K_{2\ exp}$	K_{2theor}	N_{exp}, **kN**	N_{theor}, **kN**
Static loading										
S_{h100}^{b15}	15	177,4	1,51	0,61	0,97	0,45	2,64	2,66	104,9	105,8
S_{h120}^{b15}	15	229,7	1,51			0,46	2,46	2,46	129,5	140,0
S_{h100}^{b20}	18,5	177,4	1,51			0,48	2,63	2,63	124,7	125,9
S_{h120}^{b20}	18,5	209,5	1,51			0,47	2,65	2,65	160,9	161,2
Dynamic loading										
D_{h100}^{b15}-1	15	137,5	1,51	0,63	0,75	0,43	3,02	2,66	105,9	93,2
D_{h100}^{b15}-2	15	137,5	1,51			0,4	2,92	2,92	102,4	93,2
D_{h100}^{b20}-1	18,5	134,4	1,51			0,41	2,47	2,47	102,2	110,1
D_{h100}^{b20}-2	18,5	134,4	1,51			0,4	2,58	2,58	106,8	110,1
D_{h120}^{b15}-1	15	172,7	1,51			0,38	2,54	2,54	115,2	120,7
D_{h120}^{b15}-2	15	168,8	1,51			-	2,48	2,48	111,8	119,7
D_{h120}^{b15}-3	15	172,7	1,51			0,44	2,64	2,64	119,7	120,7
D_{h120}^{b20}-2	18,5	168,8	1,51			0,36	2,27	2,27	121,6	142,4
D_{h120}^{b20}-3	18,5	165,1	1,51			0,38	2,31	2,31	122,7	141,3

Note: A_b is the area of one face of the punching pyramid, A_s is the area of tension reinforcement within one face of the punching pyramid; ξ – relative height of the compressed zone of concrete.

- the relative height of the compressed zone under static loading in the limiting stage corresponds to ξ=0,46, and under dynamic loading on average ξ=0,36;
- the stress level in the concrete of the compressed zone was 0,62R_b under static and dynamic loading;
- stresses in tensile reinforcement under static loading reached the design resistance R_S, under dynamic loading the stress level was 0,75R_S;
- coefficients k_2 of concrete shear strength increase according to experimental data and recommendations [18] turned out to be close;
- discrepancies between the values of the bearing capacity according to the proposed dependence (1), (2) and the experimental data do not exceed 14%.

The proposed method for assessing the bearing capacity of the junction of a monolithic floor with a column during destruction according to the punching scheme was used for samples of well-known authors [1, 2, 3, 4]. The results of comparing the theory with experimental data are presented in Table 2.

Table 2. Calculation results for experimental samples of well-known authors using the proposed method

Author	R_b, MPa	A_b, sm^2	A_s, sm^2	N_{exp}, kN	$K_{2\,exp}$	K_{2theor}	N_{theor}, kN	$\frac{N_{theor}}{N_{exp}}$, %
D. Pekin	22	2460	11,3	1180	1,84	1,95	1253,1	6,2
S. Klovanich	21,6	1167,3	9,04	776	2,19	2,34	830,75	7,1
A. Bolgov	33	380,3	3,14	254	1,71	1,86	276	8,7

As can be seen from Table 2, the convergence of the experimental and theoretical data is satisfactory.

4 Conclusion

1. The results of experimental and numerical studies [13,14,15] based on the finite element method showed that in case of central punching in the presence of upper and lower reinforcement in the slab in the limiting stage in terms of bearing capacity, the resistance to punching is exerted by the reduced surface of the pyramid, which has a height equal to the height compressed zone of concrete. In this case, the shear resistance is increased by lateral compression.
2. The decrease in the bearing capacity of the overlap for punching at a loading time from zero to failure of 3,22 mks compared with the static application of the load averaged 15%;
3. In the limiting stage during destruction according to the scheme of punching, the stresses in the tensile reinforcement and compressed concrete within the limits outlined by the face of the pyramid do not reach the limit. With the selected percentage of reinforcement, the tensile stresses in the reinforcement reached: under dynamic loading – 0,7R_S; under static loading – 0,9R_S, the maximum compressive stresses in concrete under static and dynamic loadings were 0,65R_b.
4. The increase in shear resistance due to the presence of lateral compression at the corresponding levels was $R_{sh} = (1{,}28 - 1{,}72)\sqrt{R_b R_{bt}}$.

5. The formulated recommendations for improving the methodology for calculating the strength of slabs under central punching under static and dynamic loads are based on the actual fracture scheme and take into account the work of longitudinal reinforcement of floor slabs, the compressed part of concrete under conditions of equilibrium of internal and external forces, taking into account the increase in the strength properties of concrete in a complex stress state.

6. Using the results of theoretical and experimental studies, the causes of a decrease in the bearing capacity under dynamic loading due to a decrease in the cut surface of the compressed part of the punching pyramid due to an increase in the angle of inclination of its faces by 10 - 20% are revealed.

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