NUMERICAL STUDY OF THE PUNCHING SHEAR MECHANISM FOR THIN AND THICK REINFORCED CONCRETE SLABS

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Abstract: The assessment of the punching shear capacity for reinforced concrete slabs, carried out according to the regulatory documents of a number of countries, leads to significantly various results. At the same time, the results of the calculated forecast may have great differences from the experimental data. A great influence on the accuracy of the results of the calculated forecast is exerted by the thickness of the examined slabs, as well as the value of longitudinal reinforcement. These parameters determine the features of the mechanisms of destruction of slabs in case of the punching shear mechanism, as indicated by individual interpretations of the results of experimental studies. In order to determine the features of the punching shear mechanism of reinforced concrete slabs of various thicknesses, numerical studies of the process of cracking and destruction of slabs of different thicknesses have been performed. Differences in the mechanism of formation and development of cracks in thin and thick slabs are revealed. The paper shows that the behavior of thin and thick slabs has qualitative distinctions at the initial stages of formation and development of the cracks leading to destruction. The authors have also shown the difference between stress-strain state of thick and thin slabs before destruction. In conclusion, it was established that the influence of longitudinal reinforcement on the strength during punching in thick slabs is much less than in thin ones.

Keywords: modeling, numerical methods, design model, stress-strain state, reinforced concrete structures, punching failure.

ЧИСЛЕННЫЕ ИССЛЕДОВАНИЯ ОСОБЕННОСТЕЙ МЕХАНИЗМОВ РАЗРУШЕНИЯ ТОНКИХ И ТОЛСТЫХ ПЛИТ В РЕЖИМЕ ПРОДАВЛИВАНИЯ

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Аннотация: Оценка несущей способности на продавливание железобетонных плит, выполненная по нормативным документам разных стран, приводит к существенно отличающимся результатам. При этом результаты расчётного прогноза могут иметь значительные отличия от опытных данных. Большое влияние на точность результатов расчётного прогноза оказывает толщина рассчитываемых плит, а также величина продольного армирования. Указанные параметры определяют особенности механизмов разрушения плит в режиме продавливания, на что указывают отдельные трактовки результатов экспериментальных исследований. В целях определения особенностей работы железобетонных плит различной толщины в режиме продавливания проведены численные исследования процесса трещинообразования и разрушения плит разной толщины. Выявлены различия в механизме образования и развития трещин в тонких и толстых плитах. Показано, что работа тонких и толстых плит имеет качественные отличия на начальных этапах процесса образования и развития трещин, приводящих к разрушению. Показаны различия в напряжённо-деформированном состоянии толстых и тонких плит перед разрушением. Установлено, что влияние продольной арматуры на прочность при продавливании в толстых плитах значительно меньше, чем в тонких.

Ключевые слова: моделирование, численные методы, расчетная модель, напряженно-деформированное состояние, железобетонные конструкции, продавливание.

1. INTRODUCTION

One of the most actual problems in the bearing capacity of reinforced concrete slabs according to the punching shear criterion is the issue of the behavior of slabs with longitudinal reinforcement. The prediction of the punching shear capacity based of reinforced concrete slabs with longitudinal reinforcement and without transverse reinforcement in the support zone is carried out using the basic formulas, which, as a rule, do not take consider the features of the failure of thin and thick slabs. The methods accepted in codes of number of countries have some differences, some one of which is very significant. Thus, the norms of the European Union EN 1992-1-1 Eurocode 2 [1] (hereinafter EC2) and in fib Model Code 2010 [2] (hereinafter MC2010) provide

accounting the longitudinal reinforcement of the stretched zone but according to various methods. The building code of the Russian Federation [3] (SP 63.13330.2018) does not take into account the work of longitudinal tensile reinforcement when calculating the punching shear capacity of the slab. Such significant deviations in the standardization of the punching shear design led to significant differences in the forecast of the bearing capacity. Experimental investigations on the behavior of slabs of various thicknesses have also established the differences between the actual level of capacity and the forecast one for various standards. Table 1 shows the analysis of various regulatory approaches based on experimental research data which were previously presented in the work [4].

Table 1

Specimen	B, m	h ₀ , m	r _g , m	ρ, %	f _c , MPa	f _y , MPa	V _{ex} , kN (100%)	V _{Rd,c} (EC2), kN/%	V _{Rd,c} (MC2010), kN/%	F _{b,ult} (SP 63.1330), kN / %
1	2	3	4	5	6	7	8	9	10	11
PG1 [5]	3	0.21	1.5	1.5	27.6	573	1023	950/7.1	841/17.8	947.5/7.4
PG2 [5]	3	0.21	1.5	0.25	40.5	552	440	594/-35.0	420/4.5	1263.36/-187.1
PG3 [5]	6	0.456	2.85	0.33	32.4	520	2153	2340/-8.7	1730/19.6	4806.6/-123.3
PG4 [5]	3	0.21	1.5	0.25	32.2	541	408	550/-34.8	344/15.7	1066/-161.3
PG5 [5]	3	0.21	1.5	0.33	29.3	555	550	583/-6.0	455/17.3	987/-79.5
PG7 [5]	1.5	0.1	0.75	0.75	34.7	550	241	189/21.6	197/18.3	257.6/-6.9
PG8 [5]	1.5	0.117	0.75	0.28	34.7	525	140	178/-27.1	137/2.1	323.7/-131.2
PG9 [5]	1.5	0.117	0.75	0.22	34.7	525	115	165/-43.5	109/5.2	323.7/-181.5
PG10 [5]	3	0.21	1.5	0.33	28.5	577	540	577/-6.9	454/15.9	987/-82.8
PG11 [5]	3	0.21	1.5	0.75	31.5	570	763	788/-3.3	682/10.6	1066/-39.7
PV1 [6]	3.0	210	1.38	1.5	34.0	709	974	1019/-4.6	792/18.7	1105.4/-13.5
PL4 [6]	3.0	267	1.38	1.58	30.5	531	1625	1538/5.4	1191/26.7	1685.5/-3.7
PL5 [6]	3.0	353	1.38	1.5	31.9	580	2491	2505/-0.6	2255/9.5	3023.2/-21.4
Π-4 [7]	1.98	360	0.79	1.06	29.6	385	1670	1804/-8.0	1830/-9.6	1822/-9.1
Π-5 [7]	2.34	460	0.97	0.83	27.9	385	2260	2189/3.1	2431/-7.6	2599/-15.0
Π-6 [7]	2.68	550	1.14	0.89	23.7	432	2450	2265/7.6	3368/-37.5	3152/-28.7
P300 [8]	1.975	300	0.89	0.76	39.4	468	1381	1392/-0.8	1220/11.7	1860/-34.7
P400 [8]	1.975	400	0.89	0.76	39.4	468	2224	2377/-6.9	2442/-9.8	3472/-56.1
P500 [8]	1.975	500	0.89	0.76	39.4	433	2681	3414/-27.3	3919/-46.2	4960/-85.0
Ch ₁₀₀ [9]	0.6	0.076	0.25	0.66	15	500	133.3	80/40.0	84/37.0	71.2/46.6
Ch ₁₂₀ [9]	0.6	0.096	0.25	0.52	15	500	161	110/31.7	121/24.8	101/37.3

Note: the designations in Table 1 are adopted in accordance with EN2 [1] and MC2010 [2]. % were determined by the following formula: $(V_{ex} - V_{Rd,c}) / V_{ex}$

Comparative analysis of the results of the normative forecast of the bearing capacity with the data of experimental studies shows:

- taking into account the longitudinal reinforcement in the normative forecast of the capacity of the slabs according to the punching shear criterion provides a better correlation with the results of experimental studies;

- the value of the increase in the bearing capacity does not have a linear correlation with the increase in the thickness of the slab.

Table 2 presents changes in the value of the slab capacity due to the change in the thickness for slabs of medium and large thickness.

Table 2

No	Investigation	Specimen	h_0 , mm	h_0 , %	Vex, kN	Vex, %	h_0 , %	Vex, %
1	2	3	4	5	6	7	8	9
1	S. Lips [6]	PV1	210	100	974	100	-	-
2		PL4	267	127.1	1625	166.8	100	100
3		PL5	353	168.1	2491	255.7	132.2	153.3
4	S. Guandalini [5]	PG-10	210	100	540	100	-	-
5		PG-3	456	217.1	2153	398.7	-	-
6	N.N. Korovin [7]	II-4	360	100	1670	100	-	-
7		II-5	460	127.8	2260	135.3	100	100
8		II-6	550	152.8	2450	146.7	119.5	108.4
9	Li K. K. L. [8]	P300	300	100	1381	100	-	-
10		P400	400	133.3	2224	161.0	100	100
11		P500	500	166.7	2681	194.1	125	120.5

Analysis of the change in the value of the capacity makes it possible to establish some features of the behavior of slabs of various thicknesses. With an increase in the thickness of the slab, an increase in the capacity according to the punching shear criterion is observed in the entire range of the investigated slab depths. However, the tendency for an increase in capacity for slabs of medium and large depths ($h_0 \geq 0.25$ m) changes significantly in relation to slabs of small thickness. In the range of medium and large slab depths, the increase in the capacity (%) decreases in relation to the increase (%) in thickness compared to thin slabs. See data in columns 8 and 9 of Table 2. In the most pronounced form, this phenomenon was observed in specimens of N.N. Korovin [7], Li

K. K. L. [8] et al. In scientific publications, this effect was called as "size effect".

The EC2 [1] and MC2010 [2] standards consider the size effect, but accounting methods differ significantly. SP 63.13330 does not take into account the size effect. Fig. 1 shows the influence of the size effect on slab capacity in accordance with experimental data and EC2 norms.

The current situation with the scientific substantiation of the size effect and the corresponding punching mechanisms of slabs of medium and large thickness requires additional scientific research. Therefore, the subject addressed in this article is worthy of investigation.

Figure 1. Influence of the size effect in the normative assessment of the punching shear capacity of the slab according to EC2

2. OBJECTIVE AND METHOD OF RESEARCH

Currently, there are two main concepts that explain the size effect when punching reinforced concrete slabs of medium and large thickness with longitudinal reinforcement in the stretched zone. The first concept is based on fracture mechanics [10], the second one on the critical shear crack theory (CSCT) [11].

According to the fracture mechanics [10, 12]: if the destruction of a reinforced concrete slab during compression is caused by the destruction of concrete, and not by the achievement of the yield strength of the reinforcement, then the dimensional effect appears. That is, if geometrically similar specimens are tested, differing only in thickness, then the nominal tensile stresses (σ_n) traditionally determined by formula (1) are higher in smaller specimens when it fracture. However, the traditional technique for determining stresses (1) does not explain the existing size effect.

$$\sigma_n = \frac{F}{u \cdot h_0} \quad (1)$$

Where F is an ultimate breaking load; u is a perimeter of the design cross-section contour; h_0 is an effective depth of the reduced cross section.

Consequently, if the fracture occurs due to the localization of cracks, which is typical for reinforced concrete structures, the capacity for the action of the transverse force decreases with increasing h_0 . According to P. Bažant [12], the main reason for the size effect is the nonlinear dependence between the energy released during the formation and development of a crack and the height of the reinforced concrete section. This energy effect corresponds to a situation where the main crack grows steadily until the maximum load is reached, and the size effect is due to the energy release rate growth with an increase in the structure size according to the fracture mechanism.

The fracture model of reinforced concrete slabs based on the critical shear crack theory (CSCT) was developed by A. Muttoni [11, 13]. The method for calculating slabs according to the punching criterion based on CSCT has been included in MS2010, where the punching shear strength of concrete slab without transverse reinforcement ($V_{Rd, c}$) takes into consideration the rotation angle of the slab support zone ψ and it is determined according to formula (2):

$$V_{Rd,c} = k_{\psi} \cdot \frac{\sqrt{f_c}}{\gamma_c} \cdot b_0 \cdot d \quad (2)$$

Where γ_c is the partial factor for concrete in compression; b_0 is a perimeter of the design cross-sectional contour with rounded corners at a distance of $0.5d$ from the loading area; d is effective depth of the reduced section; f_c is the compressive strength of concrete; k_{ψ} is coefficient taking into account the angle of rotation of the slab ψ , which is determined by the formula (3).

$$k_{\psi} = \frac{1}{1.5 + 0.9 \cdot k_{dg} \cdot \psi \cdot d} \quad (3)$$

Where k_{dg} is the coefficient taking into consideration the grain size of coarse aggregate; ψ is the angle of rotation of the slab. When calculating according to MC2010, the influence of the size effect on the punching shear strength of the slab is considered for the angle of rotation of the slab ψ according to the formula (4):

$$\psi = 1.5 \cdot \frac{r_s}{d} \cdot \frac{f_y}{E_s} \cdot \left(\frac{m_s}{m_R} \right)^{1.5} \quad (4)$$

Where r_s is the distance to the point where the radial bending moment equals to zero (for experimental specimens, the distance from the center of the specimen to the point of attachment); E_s is the modulus of elasticity of the reinforcement; f_y is the yield strength of the reinforcement; m_s is the bending moment in the slab average through the width b_s caused by the applied load. Here $b_s = 1.5 \cdot r_s$; m_R is an ultimate bending moment.

The concepts presented for considering the size effect make it possible to establish the actual mechanisms of destruction of slabs of various thicknesses under punching and to perform a comparative analysis of such mechanisms. In this paper, we investigate the features of the failure for thin and thick slabs, including the formation and development of cracks, as well as schemes for the slab destruction. The table 1 presents data

of such physical experiments. In numerical studies, we considered a model of a thin slab from [9] and thick slab model from [7].

Numerical studies were carried out using the ATENA software [14]. The applicability of this software for the analysis of reinforced concrete slabs under punching was substantiated in the work [4].

The main provisions of the ATENA PC methodology are as follows

Modeling of structures in ATENA software is generally performed taking into account the specific features of materials. Concrete is modeled by volumetric FE, reinforcement elements are modeled, as a rule, by bar elements. However, in some cases, it is quite acceptable to simulate reinforcement by specifying the percentage of reinforcement in the volume of concrete. The bond between concrete and reinforcing bars is modeled by introducing special connector that work according to the law specified by the user. In the studies presented in this work, the model of longitudinal reinforcement is made of discrete bars. The joint work of concrete and reinforcing bars was modeled under the assumption of ideal adhesion according to the verification work [15]. ATENA software includes dedicated models for finite element analysis of concrete and reinforced concrete structures. According to the official reference manual [14], the concrete model combines the equations of the theory of plasticity (in compression) and fracture mechanics (in tension). For concrete, the model uses the criterion of maximum principal stresses to assess the strength, an exponential law of softening. At the same time, the crack can be specified as rotating or stationary. The tensile behavior of concrete is modeled by nonlinear fracture mechanics combined with a smeared crack model. The main parameters of this approach are tensile strength of concrete, the nature and form of cracking, and the energy of destruction. The phenomenon of cracking is described by a model of smeared cracks in the form of a belt model [16]. Fig. 2 shows the crack formation law for the ATENA PC is shown in general.

Figure 2. The cracking model adopted in the ATENA software according to [14]

The cracking process can be divided into three stages as shown in fig. 3. The stage without cracks corresponds to the work of the material until it reaches the ultimate tensile strength. Crack formation occurs in the potential crack zone with a decrease in tensile stresses in this area. Then crack opening continues at zero tensile stresses at the crack tip.

Figure 3. Stages of formation and development of cracks in the ATENA PC according to [14]

For the plastic model concrete in compression, the Menetrey-Willam strength criterion is used. An algorithm has been developed that combines the fracturing model and the plasticity model. An important feature of the ATENA software is that the two above models are formulated independently of each other, but they are used together in the calculation. Another significant characteristic of the concrete model is the use of the so-called limiters of localization of deformations during destruction. This principle is used to designate discrete fracture planes independent of the finite element mesh. In the case of tension, these planes are represented by cracks. In the case of compression, it is shown by areas of crushing. In the computational model, these discrete fracture regions have dimensions that do

not depend on the dimensions of the element. For this reason, the planes of destruction are presented in the model as planes that do not depend on the dimensions of the FE mesh. For the case of tensile failure, this approach is known as the fracture belt model. ATENA software uses a similar approach for compression failure detection. Thus, limits of strain localization allow us eliminating two significant drawbacks of the traditional FE model of concrete: the effect of the size and orientation of the FE mesh on the result. Appliance of the smeared cracks' model makes it possible calculates and plots the propagation of discrete cracks quite accurately. Moreover, according to the developers of the software [17], this model does not inferior to models that implement discrete cracks in accuracy.

3. RESEARCH RESULTS

For the purpose of a comparative analysis, the research results are grouped for each of the considered parameters. The design model represents 1/4 of the support zone of the reinforced concrete slab (Fig. 4). The longitudinal reinforcement of the tensioned and compressed zone of the slab was modeled with bar finite elements. The load on the slab was transmitted through the column at the geometric center of the slab. The model of external restrains corresponds to the specimen support on a steel rectangular distribution frame along the contour. The slab, column, and support structure were modeled with 3D finite elements. The dimensions of the volumetric finite elements for the design model of the slab are determined in accordance with the requirements of the ATENA software [14].

Figure 4. 3D (left) and FE (right) model for numerical studies using ATENA software.

1 - Column; 2 - Supporting structure; 3 - Floor slab; 4 - Reinforcement bars; 5 - Point for monitoring of displacement along the vertical axis; 6 - Place of load application; 7 - Restraints of the specimen along the axis of symmetry

Based on the results of the finite element analysis, it was established that the destructive loads obtained in numerical experiments have an acceptable correlation with the results of physical experiments. Deviations of $P_{\max}$ from V_{ex} are: for

the design model of the P-6 sample according to [7] 10.45%, for the design model of the Ch120 sample according to [9] 2.28%. The results of numerical studies are presented in Fig. 5, 7 - 9.

Figure 5. Diagrams of deformation vs. values of ultimate loads (kN) for numerical models; a - model of the Ch_{120} sample [9]; b - model of specimen P-6 [7]

Analysis of the deformation diagrams demonstrates significantly different punching mechanisms of slabs of various thicknesses. In a thin slab, a pronounced unloading section is formed (after the 14th step of the calculation). In a thick slab, the unloading phenomenon is not observed. It should be noted that the phenomena of unloading in thin slabs were also established in previous

studies [4]. To study the case, refer to fig. 6. Thus, the formation of the unloading section during loading and deformation of thin slabs can be defined as one of the most important features of the operation of such slabs under punching. Fig. 7 shows the state of the models at the moment of initial fracturing.

Figure 6. Diagram deformation vs. magnitude of ultimate loads (kN) of thin slabs (thickness of 200 mm) obtained numerically for specimens from the work [4]

Figure 7. Crack formation diagram in models a.1 and b.1; isofield of principal stresses (max) a.2 and b.2 at the cracking moment; a - 14th stage of calculating the specimen Ch120 [9]; b - 29th stage of calculating specimen P-6 [7]

Analysis of the stress-strain state at the time of initial cracking demonstrates significantly different operating schemes for slabs of various thicknesses. In a thin slab, a crack is formed in the tensile zone of concrete [9], which corresponds to the pattern of cracking of a bent element. A similar picture of cracking in the tensile zone according to the bending element scheme was established for all specimens of thin slabs in studies [4] (Fig. 6), in which the parameters of longitudinal reinforcement were varied (from 0.48% to 1.93%). In accordance with the provisions of the mechanics of

reinforced concrete flexure structures, cracking in the tensioned zone forms the unloading mechanism, which is confirmed by the diagram in Fig. 7a. In a thick slab, initial cracks are formed in the middle part of the section (thickness) of the slab [7]. Such a cracking scheme does not form a mechanism for unloading the sample as a whole, and diagram of the deformation does not have an inflection point. An important feature characterizing the process of formation and development of cracks is the diagram of the directions of the main tensile stresses in the studied slab samples (Fig. 8).

Figure 8. Diagram of the directions of the principle tensile stresses at the moment of cracking (a) and at the moment of failure (b); a.1 - 14th stage of calculating the specimen Ch120 [9], a.2 - 36th stage of calculating the specimen Ch120 [9]; b.1 - 29th stage of calculating specimen P-6 [7], b.2 - 39 stage of calculating specimen P-6 [7].

Analysis of the diagram of the directions of the principle tensile stresses provides the summary of the reasons for the formation and development of cracks up to the destruction of the specimen under an increasing load. In accordance with the laws of mechanics, Figures 8.a.1 and 8.b.1 show that cracks in concrete are formed in the zones of maximum tensile stresses, and

the crack axis is perpendicular to the directions of the main tensile stresses. At the stage of calculation, corresponding to the failure (Fig. 8.a.2 and 8.b.2), the directions of the principle tensile stresses in the fracture zone are distributed chaotically.

The analysis of the isofields of the principal stresses (max) at the moment of initial cracking

also demonstrates fundamentally different schemes for the operation of thin and thick slabs. In a thin slab, the tensile stresses in the lower concrete zone are significantly less than those in a thick slab [9]. Such a scheme is formed as a result of stress relaxation in a thin slab during the formation of a crack in the stretched zone with the subsequent inclusion of the stretched reinforcement into operation. In a thick slab, the concrete of the lower zone is in

tension with parameters close to the limiting ones [7], but it does not exceed them. The diagram of the distribution of the principal stresses in the thin and thick slabs corresponds to the diagram of the deformation of the specimen under investigation. It seems important to analyze such characteristic of stress-strain state as the value of the loss of concrete strength according to the tensile criterion at the beginning of cracking (Fig. 9).

Figure 9. Isofields of concrete strength loss according to the tensile criterion in models a - stage 14 of the model calculation [9]; b - 29 stage of calculation model [7]

The analysis of the isofields of the loss of concrete strength by the tensile criterion demonstrates various schemes of slab operation. In the center of a thin slab specimen, localization of finite elements in a narrow zone with an almost complete loss of tensile strength is observed [9], which corresponds to the formation of a normal crack according to the flexure element scheme. In a thick slab, areas of concrete with a loss of tensile strength are localized in the zones of formation of cracks in the thickness of the slab [7]. This allows us to conclude that in a thick slab, the cause of the formation of inclined cracks at the initial stage is tensile stresses, the maximum values of which in accordance with the basic principles of mechanics are localized in the central zones of the thickness of solid structures under the accepted loading schemes. Fig. 10 shows destruction of the models.

The analysis of the stress-strain state at the destruction of the specimens demonstrates significantly different schemes of slab operation. In a thin slab, destruction occurs according to the normal crack propagation pattern [9], which is typical for bending elements. In this case, in addition to a normal crack, a system of inclined cracks with corresponding stress relaxation zones is formed (Fig. 10 a.2). The scheme of destruction of a thin slab is most clearly shown in Fig. 10 a.3 as isofields of the loss of tensile strength of concrete.

In a thick slab, destruction occurs due to the formation of a system of inclined cracks, forming a punching prism, with single normal cracks in the lower zone. Such normal cracks have a slight development along the depth of the slab. The general scheme of the destruction of a thick slab corresponds to the formation of a punching shear prism, which is clearly seen in the diagram of

isofields for the loss of tensile strength of concrete (Fig. 10 b.3).

Analysis of stresses in the reinforcement of the tensile zone of concrete, thin [9] and thick [7] slabs demonstrate significantly different levels of stresses and, consequently, the growth of the crack opening width in tensioned concrete. In a thin slab, the tensile stresses in the reinforcement are 1.6 - 3.7 times higher than the similar parameter of the reinforcement of a thick slab at

various stages. Even without taking into account the more complex factors of the influence of the thickness of the slab on the magnitude of stresses in the reinforcement of the tensile zone of concrete, it can be seen that there are large deviation in the factors of the influence of longitudinal reinforcement on the formation of cracks and the processes of destruction of thin and thick slabs.

Figure 10. Crack formation diagram a.1 and b.1; isofields of principal stresses (max) a.2 and b.2; isofields of loss of tensile strength of concrete a.3 and b.3 b at the moment of destruction;

a - 36th stage of the model calculation [9]; b - 39th stage of calculation model [7]

Figure 11. Stresses in reinforcement in tension at the moment of cracking (a) and at the moment of failure (b); a.1 - 14th stage of calculating the specimen Ch120 [9], a.2 - 36th stage of calculating the specimen Ch120 [9]; b.1 - 29th stage of calculating specimen P-6 [7], b.2 - 39th stage of calculating specimen P-6 [7]

4. CONCLUSION

As a result of numerical studies, it was found that the failure of thin and thick slabs under punching have significant differences.

Thin slabs are destroyed, as a rule, by the mechanism of the formation of an initial normal crack under load. And this leads to the formation of an unloading phenomenon in the deformation pattern of the "column - slab" structural joint. The formation of a normal crack together with the inclusion of longitudinal reinforcement in the work leads to relaxation of stresses in concrete. By the time of failure, concrete in the zone of a normal crack and concrete in the zone of a system of inclined cracks is destroyed according to the tensile strength criterion. Thus, in thin slabs, longitudinal reinforcement plays an important role in the

general fracture mechanism according to the punching shear criterion.

Thick slabs are destroyed by a mechanism with the formation of inclined cracks forming a punching prism. At the initial stage, inclined cracks are formed in the middle zone of the slab thickness, where the extrema of the principal tensile stresses exceeding the ultimate tensile strength of concrete are localized. With an increase in the load, the number of inclined cracks increases with the formation of a system of such cracks, the length of which grows from the central zone of the slab to the upper and lower planes. By the moment of destruction, concrete in the zone of the system of inclined cracks is destroyed according to the tensile strength criterion. Thus, in thick slabs, the fracture mechanism corresponds to the formation of a system of inclined

cracks, which are formed due to an increase in the principal tensile stresses with an excess of the tensile strength of concrete. The contribution of the longitudinal reinforcement of the stretched zone to the punching failure resistance of thick slabs is not as significant as for thin slabs.

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