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PUNCHING OF CONCRETE FLAT AND FOUNDATION SLABS

Abstract

This paper deals with punching of flat and foundation slabs. Te paper presents limiting values of maximum punching resistance of these slab structures with sudden and brittle mode of failure. In the paper are introduced graphs for design of flat and foundation slab thickness depending on load intensity, span length and reinforcement ratio.

Keywords

Punching, flat slab, foundation slab, brittle failure, progressive collapse.

1 INTRODUCTION

Taking into account results of the latest experimental programs [1], [2], [3] the sub-commission for concrete structures CEN/TC250/SC2 has imposed new limit for the maximum punching resistance of the members with shear reinforcement. Member states should implement this new limit to their National Annexes. This limit and its influence on the design of flat and foundation slab thickness are introduced in the contribution.

2 PUNCHING OF FLAT SLAB

Phenomenon of flat slab punching is shown in Fig.1. There are two modes of punching failure. The first one is strut diagonal failure (crushing of concrete) and the second one concrete shear-tension failure or failure of transverse reinforcement in area surrounded by the assumed control perimeter. Limits given by formula (1) and (3) deal with maximum punching resistance and this value cannot be exceeded even with stronger shear reinforcement. Crushing of a strut at perimeter u_0 is checked by compressive strength of concrete, see formula (1).

$$v = 0{,}6.\left[1-\frac{f_{\mathrm{ck}}}{250}\right] \qquad f_{\mathrm{ck}}\ [MPa]\ v_{\mathrm{Ed,max}} = \frac{\beta V_{\mathrm{Ed}}}{u_0 d} \le v_{\mathrm{Rd,max}} = 0{,}4 v f_{\mathrm{cd}} \tag{1}$$

$$v_{\mathrm{Rd,c}} = \frac{0{,}18}{\gamma_{\mathrm{C}}} k\left(100\rho_{\mathrm{l}} f_{\mathrm{ck}}\right)^{1/3} \ \ge\ 0{,}035 k^{3/2} f_{\mathrm{ck}}^{1/2} \tag{2}$$

$$v_{\mathrm{Rd,cs}} = 0{,}75.v_{\mathrm{Rd,c}} + \left(\frac{1{,}5.d}{s_{\mathrm{r}}}\right)\frac{A_{\mathrm{sw}}\cdot f_{\mathrm{ywd,ef}}}{u_1.d}\left(\sin\alpha\right) \le\ k_{\max}.v_{\mathrm{Rd,c}} \tag{3}$$

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The new limit is based on the punching resistance of a member without shear reinforcement $v_{Rd,c}$ see formula (2). The maximum punching resistance including effect of shear reinforcement at the basic control perimeter shall be less than value $k_{max}\,v_{Rd,c}$, see formula (3). If $v_{Rd,cs} > k_{max}\,v_{Rd,c}$ then v_{Ed} shall be less than $k_{max}\,v_{Rd,c}$.

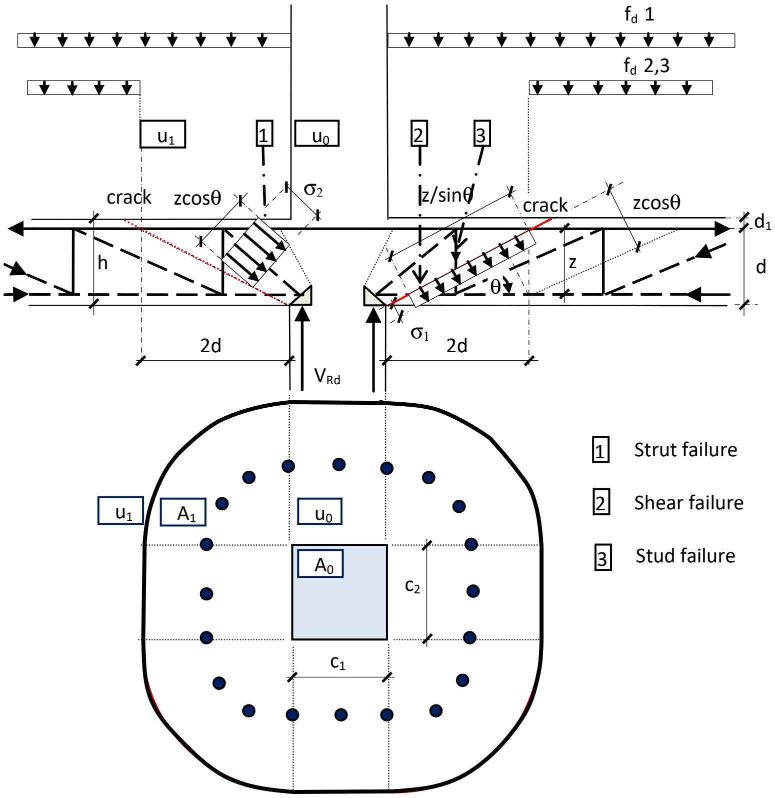


Fig. 1: Model for punching
1-crushing of the strut at perimeter u_0; 2-shear - tension failure at perimeter u_1;
3- shear - tension failure with shear reinforcement at perimeter u_1

Value k_{max} depends on a type of shear reinforcement, e.g. for double headed studs with diameter of head 3ϕ, the value of k_{max} is allowed to assume 1.9, where ϕ is diameter of the stud. For more see STN EN 1992-1-1/NA and [4]. An extensive experimental research indicated necessity to impose new limit because an application of higher quality concrete for experimental flat slabs led to the premature failure of the members without crushing of compressive diagonal even though theoretical model predicted this mode of failure.

3 FLAT SLAB THICKNESS DESIGN

Based on above mentioned limits of maximum punching resistance of flat slabs were elaborated graphs for design of slab thickness depending on a span length (distance between columns), intensity of design load and reinforcement ratio [7]. With results in fig.2 – fig.5 it is possible to design minimum thickness of a flat slab supported by columns with square cross-section having dimensions of 300 and 500 mm respectively and column spacing of 8 m, for concrete class of C25/30 and C35/45. Concrete cover was assumed 25 mm. Minimum thickness of a slab depends also on amount of main reinforcement located above columns. This is indicated in the graphs with lines made for different reinforcement ratios $\rho = 0{,}002$; 0,01 a 0,02.

Fig. 2: Thickness of a slab *h* - concrete C25/30

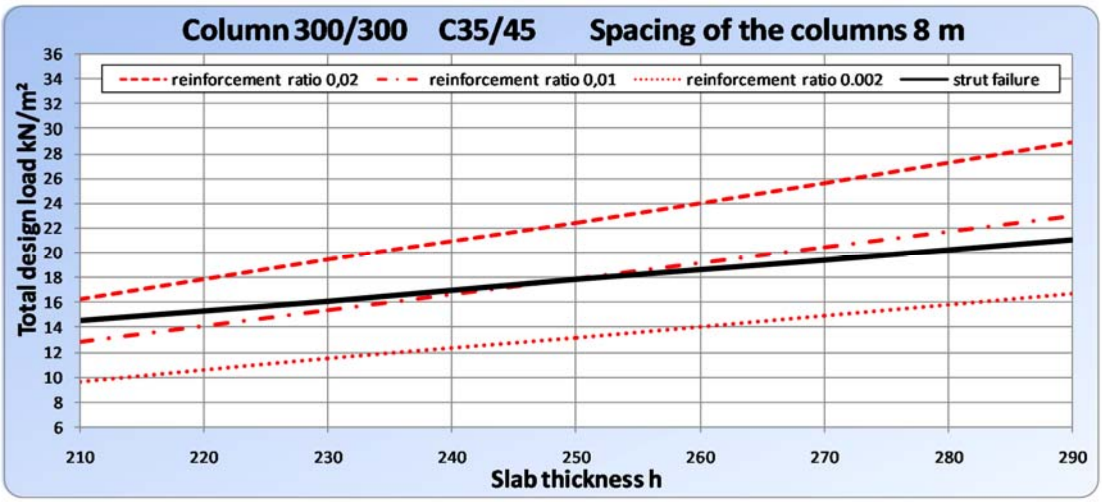


Fig. 3: Thickness of a slab *h* - concrete C35/45

Design value of full load of the slab with thickness h = 250 mm is limited by value of f_d = 16 kNm^{-2} for the column with dimension of 300 mm and reinforcement ratio ρ = 0,01 if limit k_{max} is imposed, see fig.2. When limit of strut diagonal crushing is assumed, the maximum load is only $f_d \cong$ 13 kNm^{-2}. In a case of flat slab with the same thickness and reinforcement ratio which is cast from concrete C35/45, see fig.3, the full design load would be limited by value of f_d = 18 kNm^{-2} if k_{max} limit is assumed. The criterion of strut diagonal crushing limits design load by the same value $f_d \cong$ 18 kNm^{-2}. All values of the load were obtained with factor β for internal columns 1,15 and k_{max} = 1,9.

In a case of column having dimension of 500 mm, design load of the slab with thickness h = 250 mm, concrete C25/30 and reinforcement ratio ρ = 0,01 is limited by value of f_d = 19 kNm^{-2} if limit k_{max} is imposed, see fig.4. If the limit of strut diagonal crushing is assumed, the maximum load is $f_d \cong$ 22 kNm^{-2}. In a case of flat slab with the same thickness and concrete C35/45, see fig. 5, the full design load would be limited by value of f_d = 22 kNm^{-2} if k_{max} limit is assumed. The criterion of strut diagonal crushing limits design load by value of $f_d \cong$ 30 kNm^{-2}. This value is even higher than maximum design load 27 kNm^{-2} obtained with reinforcement ratio of 0,02 and k_{max}.

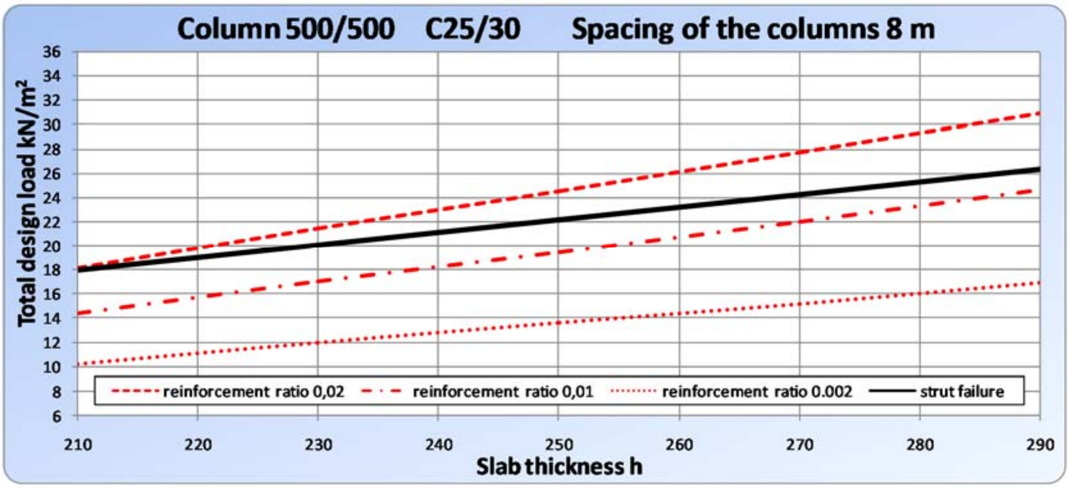
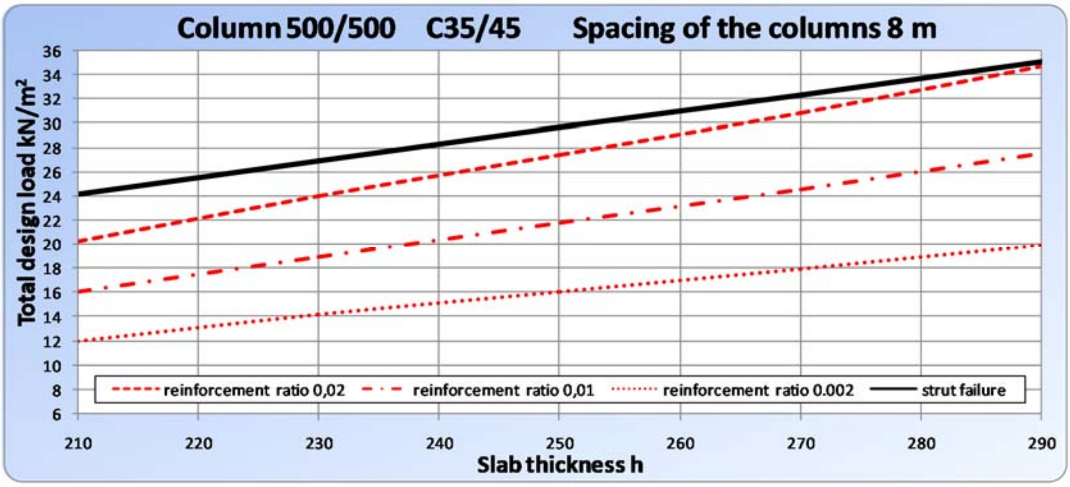


Fig. 4: Thickness of a flat slab *h* - concrete C25/30



Obr. 5: Thickness of a flat slab *h* - concrete C35/45

An influence of higher class concrete is evident from comparison of the results in fig.2 and fig.3, as well as in fig.4 and fig.5. E.g. for flat slab with thickness of 250 mm is design load limited by f_d = 13 kNm^{-2} for concrete class C25/30 and for concrete class C35/45 by f_d =18 kNm^{-2}. Punching resistance of flat slab can be increased in this way aprox. by 5 kNm^{-2} which represents cca 28%.

4 PUNCHING OF FOUNADTION SLAB

Punching of foundation slabs is schematically ilustrated in fig.6. Two modes of failure are drawn here: crushing of strut diagonal which is checked at perimeter u_0 and shear – tension failure of concrete at control perimeters with distance from face of column ranging from 0,5*d* and 2*d.* Presented limits concern of maximum punching resistance and thus this resistance cannot be higher even with higher amount of shear reinforcement.

The first limitation of maximum punching resistance in foundation slab or footing is coming from verification at control perimeter u_0, where may occur crushing of concrete in struts, see (4).

$$v_{\mathrm{Ed,max}} = \beta_0 \frac{V_{\mathrm{Ed}}}{u_0.d} \le v_{\mathrm{Rd,max}} = 0{,}4.0{,}6.\left(1 - \frac{f_{\mathrm{ck}}}{250}\right).f_{\mathrm{cd}} \tag{4}$$

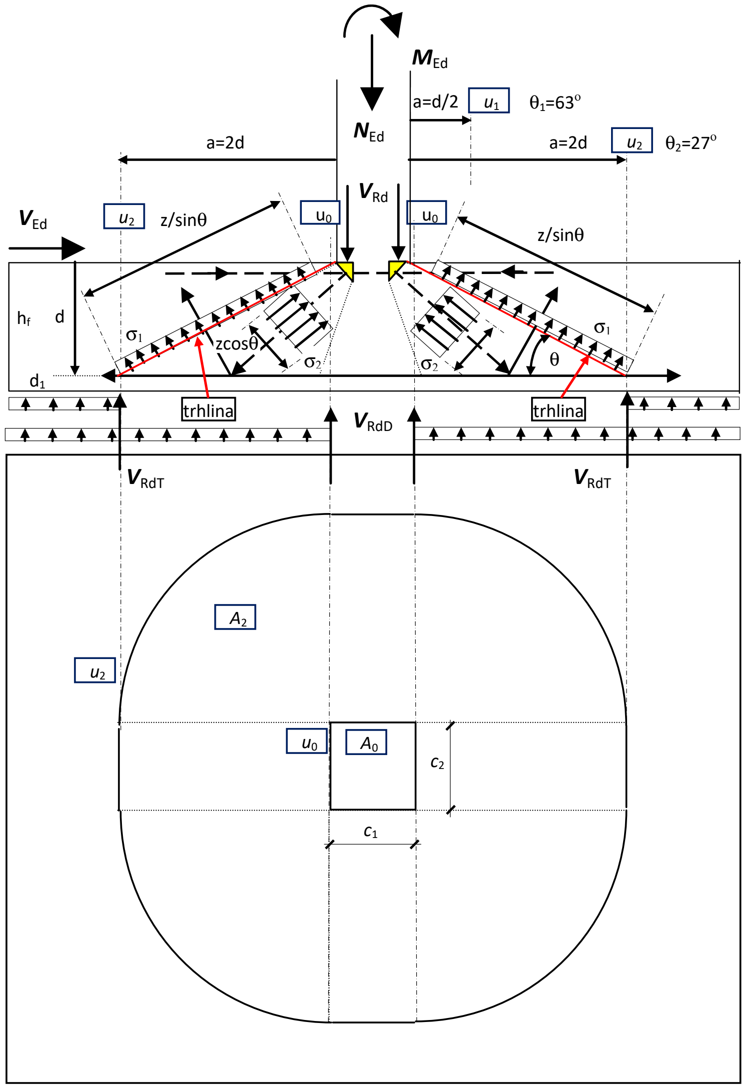


Fig. 6: Model for punching of foundation slabs or footings

The second limitation of maximum punching resistance in foundation slabs or footings is coming from verification at set of control perimeters u_i (i = 1,2 ...n). The punching resistance here cannot be higher than k_{max} times of punching resistance without shear reinforcement $v_{Rd,ca}$. The punching resistance of foundation slabs and footings with shear reinforcement can be calculated according formula (5) for control perimeters at distance $0{,}5d \le a \le 2d$. We recommend determine contribution of shear reinforcement to punching resistance by formula (6) in this area. Formulae (2) and (3) valid for control perimeters at distance $a > 2d$. Shear force $V_{Ed}(a)$ is possible to assessed using load (reaction of the ground pressure), which is laying behind assumed control perimeter $u(a)$.

$$v_{\mathrm{Ed}}(a) = \frac{\beta_{\mathrm{a}} V_{\mathrm{Ed}}(a)}{u(a)d} \le v_{\mathrm{Rd,cs}}(a) = \frac{2d}{a} 0{,}75 v_{\mathrm{Rd,c}} + v_{\mathrm{Rd,s}}(a) \le k_{\max}.\frac{2d}{a} v_{\mathrm{Rd,c}} \tag{5}$$

$$v_{\mathrm{Rd,s}}(a) = \left(\frac{0{,}75a}{s_\mathrm{r}} \right) \frac{A_\mathrm{sw} f_\mathrm{ywd,ef}}{u(a)d} \sin \alpha \qquad (6)$$

5 DESIGN OF FOUNDATION SLAB THICKNESS

For the column with square cross-section having dimension of 300 mm and spacing of column 8×8m, failure of strut will occur if average ground pressure is σ_{cg} = 60 kN/m^2, slab thickness 900 mm and concrete class C30/37, see fig. 7. For column with dimension 500 mm and the same spacing of columns, strut failure will occur if average ground pressure is σ_{cg} = 100 kN/m^2, see fig. 8. The maximum bearing capacity of foundation slab from punching point of view is possible to increase by 40% just only by changing of column dimension from 300 mm to 500 mm.

Column 300/300 C30/37 Column distance 8 m × 8 m

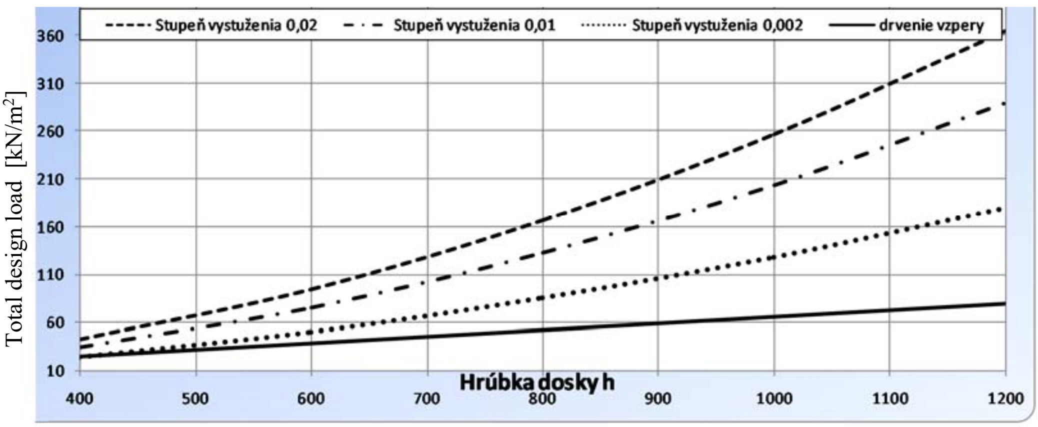


Fig. 7: Design of foundation slab thickness *h* – column 300/300 mm

Column 500/500 C30/37 Column distance 8 m × 8 m

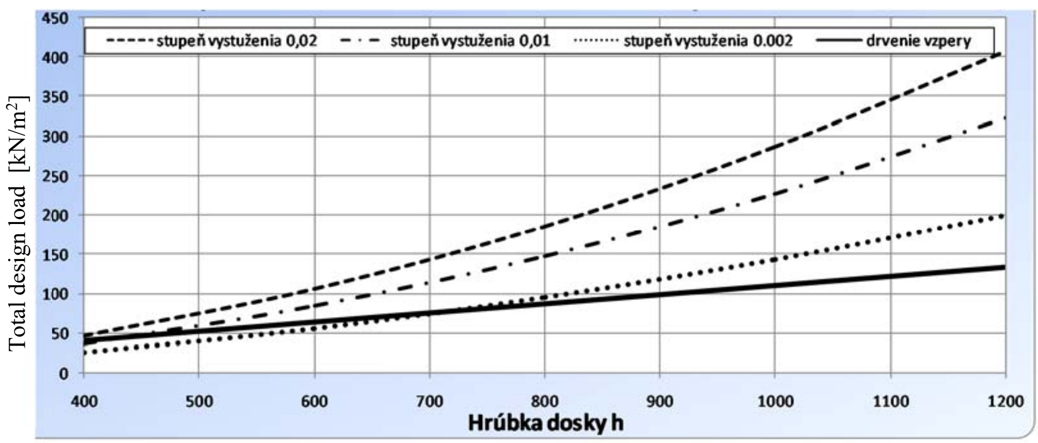


Fig. 8: Design of foundation slab thickness *h* – column 500/500 mm

Assumption of uniformly distributed ground pressure and concrete cover of 50 mm was taken into account in the analysis in fig.7 and fig.8. Calculation of the maximum σ_{cg} was also carried out for a set of control perimeters at distance ranging from 0,5d to 2d. Assessment was performed with three different reinforcement ratios: minimum value of 0,2%, maximum value of 2% and 1%.

$$\frac{v_{\mathrm{Ed}}(a_{\mathrm{crit}})}{v_{\mathrm{Rd}}(a_{\mathrm{crit}})} = \max \rightarrow a_{\mathrm{crit}} \qquad (7)$$

Control perimeters a_{crit} , where assumption indicated in (7) is met, is introduced in Tab.1 for different thicknesses of foundation slab cast from C30/37, with column having cross-section dimension of 500 mm and column spacing of 8 m.

Tab. 1: Position of critical control perimeters established based on (7)

h	a_{cr}	h	a_{cr}	h	a_{cr}	h	a_{cr}	h	a_{cr}
[mm]		[mm]		[mm]		[mm]		[mm]	
400	3,5d	600	2,5d	800	1,75d	1000	1,3d	1200	1,0d

6 CONCLUSION

The paper presents issue concerning of punching in flat and foundation slabs and in footings. Limits of maximum punching capacity are introduced here. Graphs for design of minimum slab thickness were elaborated based on these limits with k_{max} value of 1,9 where shear reinforcement consists of double headed studs. It is clear from presented graphs that the limit based on k_{max} factor will govern minimum effective depth and thus thicknesses of flat slabs with higher strength class of concrete, lower amount of main reinforcement and for flat slabs supported by columns with larger dimensions. The limit of strut failure is usually decisive for flat slabs cast from lower quality of concrete with higher amount of main reinforcement above/below column and smaller cross-section dimensions of the column.

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