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Optimization of a flat slab with different type of punching reinforcement

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Pollack Periodica • An International Journal for Engineering and Information Sciences

16 (2021) 1, 52–57

DOI: 10.1556/606.2020.00256

Received: June 17, 2020 • Revised manuscript received: November 5, 2020 • Accepted: November 13, 2020
Published online: February 24, 2021

ORIGINAL RESEARCH PAPER

ABSTRACT

Several types of punching shear reinforcements are available for increase of the maximum resistance against punching shear failure of flat slabs. Conventional punching shear reinforcement in form of stirrups or double headed studs are in use for decades. They are well known due to their simplicity and good performance. A new type of punching reinforcement has been developed for the case, where the flat slab exposed to extreme load and resistance of conventional type of punching shear reinforcement is not sufficient. Another designs point out that new construction system can reduce the amount of CO_2. This paper presents some results of parametric study focused on design of the flat slab using different types of punching shear reinforcement and considering the concrete consumption.

KEYWORDS

punching failure, shear reinforcement, maximum resistance

1. INTRODUCTION

New materials and solutions have been developed in the building industry and even urban design [1]. The new design approach is based on the idea of optimizing space on floor area, saving the total height of a building and reducing an energy demand [2]. Reinforced concrete flat slabs are popular structural system for buildings, especially in structural frames of administrative and residential buildings. The system consists of slabs that are locally supported by columns or walls without down stand beams. In this detail, the load-bearing capacity of the slab is often limited by its resistance to punching shear failure. Punching is a shear failure, very dangerous, which happens suddenly without any previous warning (cracks, extensive deformation) and may lead to an in-chain failure of whole floor. The concrete cone is separated from the slab and top flexural reinforcement, as it is shown in Fig. 1. Several theoretical and experimental researches have been conducted to consider types of the punching reinforcement, particularly in [3–6], as well as study on influence of column size and slab slenderness [7, 8]. Punching capacity is often one of the key parameter for design of a reinforced concrete slab thickness in buildings [9, 10]. Location of columns supporting a flat slab, especially at the edge and corner positions may resist the sheer stresses caused by bending moments and transverse loads.

The aim of the study was to compare the different punching shear reinforcement types against punching failure and determination of minimum slab thickness. Newly used types of punching reinforcement and design principles are considered and recommendation formulated.

2. TYPES OF PUNCHING SHEAR REINFORCEMENT

The punching shear resistance of the reinforced concrete slab without the punching shear reinforcement is ensured by interlock the aggregate grains in an inclined crack, which is stabilized in the horizontal direction by horizontal reinforcement at upper surface of the slab.

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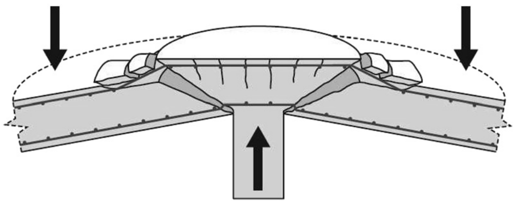


Fig. 1. Punching shear failure of a slab

Exceeding this resistance, brittle failure at support appears and structure fails without any warning. In the case of a higher load than the punching shear resistance, it is necessary to design punching shear reinforcement. Currently, stirrups and double-headed studs are the most common types of punching shear reinforcement used in Europe [11]. The maximum punching resistance of a flat slab with punching shear reinforcement is determined as:

$$V_{Rd,\max} = k_{\max} \cdot V_{Rd,c}, \tag{1}$$

where $k_{\max}$ is magnification factor depending on type of the punching reinforcement and $V_{Rd,\ c}$ is resistance of a flat slab without any punching shear reinforcement determined according to Eq. (2). The value $k_{\max}$ equals to 1.5 is specified for slabs reinforced by stirrups in accordance with EN 1992-1-1 [12]. The value 1.96 is recommended for slabs reinforced with studs in accordance to the ETA 13-0151 [13],

$$V_{Rd,c} = C_{Rd,c} \cdot k \cdot \left(100.\rho.f_{ck}\right)^{\frac{1}{3}} \cdot u_1 \cdot d. \tag{2}$$

The punching shear resistance of a flat slab without any shear reinforcement depends on the reinforcement ratio ρ; concrete compressive strength f_{ck}; parameter of influence of cross-section effective depth k (size effect); basic control perimeter u_1 and effective height of slab d. The distance of basic control perimeter from the face of the support is considered as $2d$.

2.1. Double headed studs

Shear studs are mainly used as vertical reinforcement to increase the punching resistance of concrete flat slabs. This system is composed of steel double headed studs connected together by assembly profiles (Fig. 2). The assembly bar has no load bearing function. The installation is much simpler than traditional stirrups and the punching shear resistance is up to 40% higher than conventional reinforced slabs [13]. The double headed studs are produced in diameters from 10 to 25 mm. Elements are arranged radially around the column. The minimum flat slab thickness is 180 mm. The force transfer is interpreted by a strut-and-tie model, where the studs act as a vertical tensile component, as it can be seen in Fig. 3. Arrangement of the selected product of PSB® studs in a flat slab is shown in Fig. 4.

The maximum punching resistance for studs is determined as:

$$V_{Rd,\max,\mathrm{ETA}} = 1.96 \cdot V_{Rd,c}. \tag{3}$$

In Slovakia, a national annex to STN EN 1992-1-1 was issued in 2014, allowing the use of shear studs as a

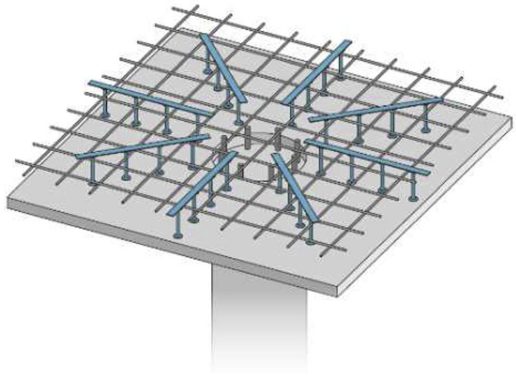


Fig. 2. Flat slab reinforced with studs

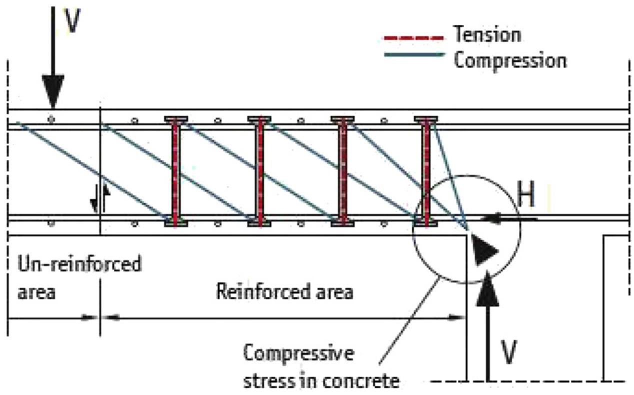


Fig. 3 Force distribution in a flat slab

reinforcement against punching shear failure by extrusion under conditions that are very similar to the recommendation defined in ETA 13/0151 [13].

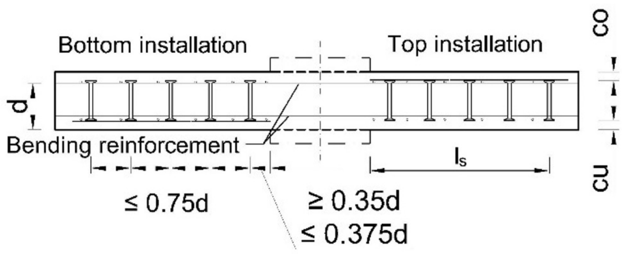
2.2. Novel type of punching system

A novel punching system PSB Plus® combines vertical double headed PSB® studs with horizontal studs (PSH - product name [14]), as it is illustrated in Fig. 5. This solution allows a higher resistance than the conventional punching shear reinforcement. Horizontal studs are placed above the column in the shape of a cross and parallel to the bottom bending reinforcement at a distance minimum $2d$ from the face of a column. Punching system can be used in flat slabs with minimum concrete strength class C 30/37. The maximum diameter of the PSH and PSB® studs depends on the effective depth d of the slab (min. 200 mm) according to Table 1. The structural performance of this system has been assessed by extensive research [10], which allowed developing the following design recommendations [15].

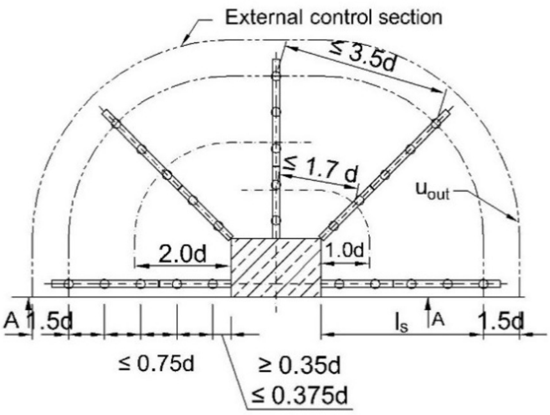
The maximum resistance of a slab reinforced with new system is determined as:

$$V_{Rd,\max,\mathrm{PLUS}} = V_{Rd,\max,\mathrm{ETA}} + \frac{\sum V_{Rd,\mathrm{dow}}}{2}. \tag{4}$$

The punching resistance $V_{Rd,\ \max,\ \mathrm{ETA}}$ is calculated from Eq. (3). The $V_{Rd,\ \mathrm{dow}}$ is the shear resistance of one horizontal



a) cross section



b) top view

Fig. 4. Arrangement of PSB® studs, a) cross section, b) top view

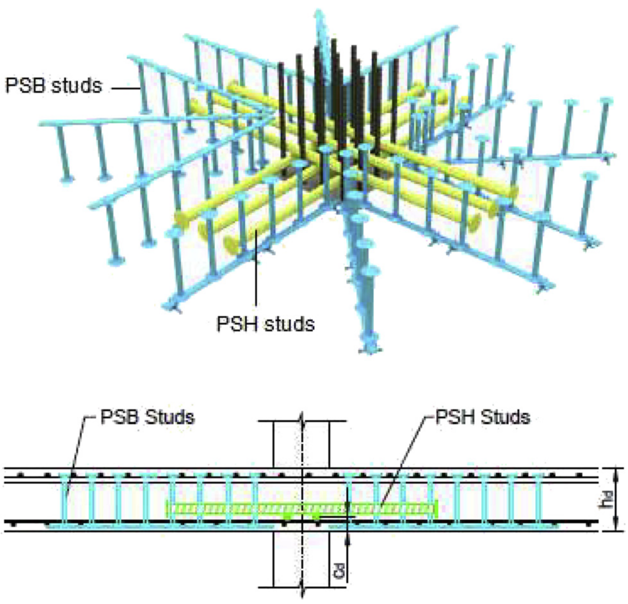


Fig. 5. Innovative punching system PSB Plus®

Table 1. Maximum diameter of PSB® and PSH studs

d [mm]	$Ø_{PSH.max}$ [mm]	$Ø_{PSB.max}$ [mm]
200–260	25	16
260–320	32	20
>320	40	25

Table 2. Single resistance of horizontal PSH stud for concrete class C 30/37

Diameter of horizontal PSH studs	Concrete cover of PSH studs	Design value of shear resistance for one PSH studs for one shear section
$Ø_{PSH}$ [mm]	c_d [mm]	$V_{Rd,\ dow}$ [kN]
25	46.5	24.6
32	50	40
40	54	56.8

PSH stud and n_{PSH} is number of shear section of PSH around column presented in Table 2.

$$\sum V_{Rd,\,dow} = n_{PSH} \cdot V_{Rd,\,dow}\,. \tag{5}$$

3. PARAMETRIC STUDY

The practical benefits that are now offered by the novel punching system have been demonstrated by a parametric study [16] where an administrative building illustrated in Fig. 6 has been designed considering the following alternatives for the design of punching shear reinforcement in flat slabs:

– Stirrups;
– Double headed studs (PSB®);
– Punching system (PSB Plus®).

The second aim of the study was to determine the minimum thickness of a flat slab with regards to punching shear failure for different punching shear reinforcement systems [17]. Besides the punching failure, the thickness of the slab was also limited by a maximum deformation of the slab at mid span limited to the span/250. In the following analysis the verifications of an edge and internal column are presented.

3.1. Numerical model

Structural analysis was performed in computing program (Scia Engineer). Optimisation through the parametric study takes the advantage of a real reinforcement considering calculation of cracks and long-term deflections. The building was designed as a monolithic reinforced skeleton structure system made of concrete class C 30/37 with the span of slabs

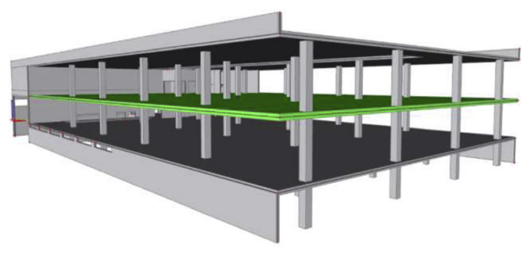


Fig. 6. Finite element model of the building

Table 3. Input parameters for analysis

Type reinforcement		Deck thickness h_d [mm]	Effective depth d [mm]	Reinforcement ratio ρ	Force in column [kN]	
					$V_{Ed,ic}$	$V_{Ed,ec}$
M1	Stirrups	350	300	0.838	1,725	1,112
M2	PSB® studs	300	240	1.409	1,673	1,180
M3	PSB Plus® system	270	210	1.870	1,588	1,187

in both directions of 9.6 m. The dimensions and shape of the columns were considered on each floor with the same width of 500 mm.

Punching shear reinforcement was considered in the form of stirrups, double headed studs and novel punching system in three numerical models [16].

The first numerical model M1 represents a flat slab of 350 mm depth, reinforced with bending reinforcement B500B with diameter of 20 mm and the spacing 125 mm (ø20/125 mm). The shear force was carried by closed stirrups, designed of steel grade B500B with 12 mm in diameter and spacing 130 mm.

The second numerical model M2 was created for a flat slab of 300 mm depth, reinforced with bending reinforcement B500B with diameter of 22 mm, spacing 110 mm (ø22/110 mm). Double headed studs (PSB®) were proposed as shear reinforcement.

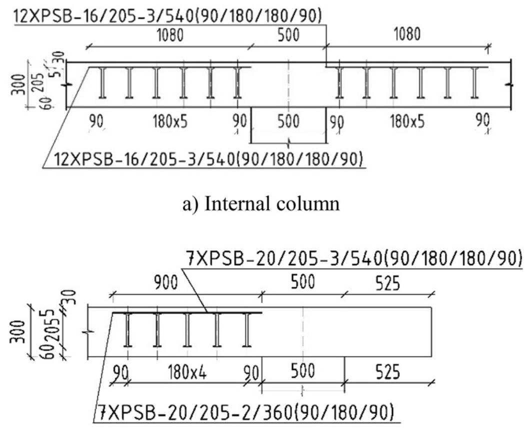
The third numerical model M3 was verified for a thin flat slab of 270 mm. The punching resistance was ensured by the new punching system PSB Plus. The flat slab was reinforced with bending reinforcement B500B of 25 mm in diameter, at a distance of 125 mm (ø25/125 mm).

In addition, in Table 3 the input parameters are shown for each model as a function of the effective depth d and the flexural reinforcement ratio ρ. The $V_{Ed,ic}$ is a reaction from support in internal column and $V_{Ed,ec}$ is a reaction in edge column.

3.2. Design configuration of punching reinforcement

The final layout of the selected flat slab reinforced with double headed studs (PSB®) is shown in Fig. 7. The twelve elements are placed around the internal column with stud diameter of 16 mm and a depth of 205 mm. The three studs are installed within one element with a length of 540 mm, a stud spacing of 180 mm (Fig. 7a). The seven elements are placed around the edge column with the stud diameter of 20 mm and a depth of 205 mm. The three studs are installed within one element with length of 540 mm (Fig. 7b). The bottom concrete cover totals 60 mm and top concrete cover stays 30 mm.

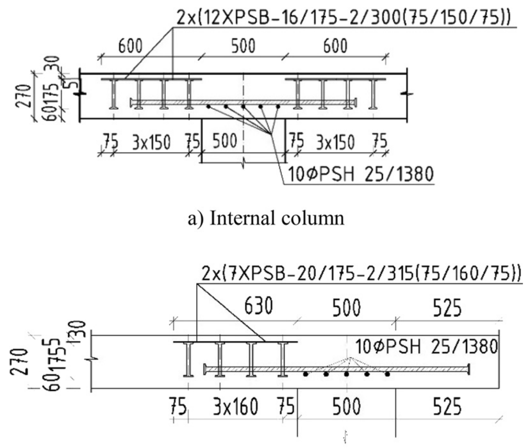
An example of the selected flat slab reinforced with newly punching shear system (PSB Plus) is illustrated in Fig. 8. The structural performance above internal column has been verified for combination of 12 vertical elements with shear studs (PSB®) and 10 horizontal shear studs (PSH). The vertical studs are designed with diameter of 16 mm and a depth of 175 mm. The two studs are installed within one element with a length of 300 mm, a stud spacing of 150 mm (Fig. 8a). A horizontal single stud is determined by length of 1,380 mm and diameter of 25 mm. The bottom concrete cover totals 60 mm and top concrete cover stays 30 mm. The layout of the edge column is following, the seven vertical elements with shear studs of 20 mm and a depth of 175 mm, ten horizontal single studs 1,380 mm long with diameter of 25 mm (Fig. 8b).



a) Internal column

b) Edge column

Fig. 7. Layout of double headed studs in flat slab: a) internal column; b) edge column



a) Internal column

b) Edge column

Fig. 8. Layout of punching system (PSB Plus®) in flat slab

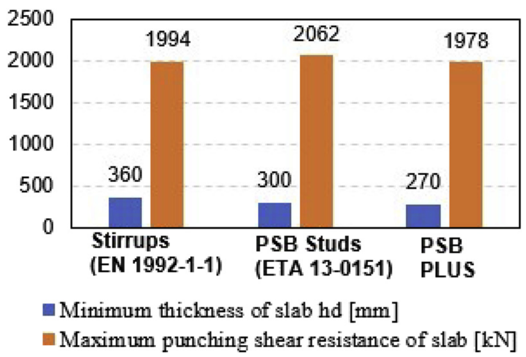


Fig. 9. Comparison of minimum slab thicknesses and maximum punching shear resistances for various systems

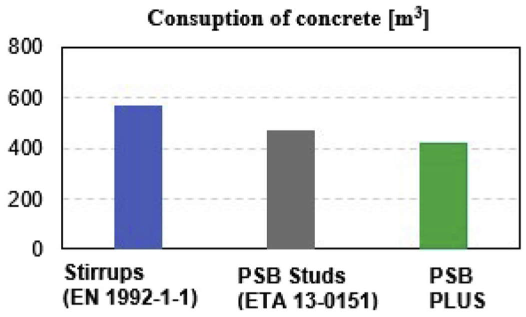


Fig. 10. Comparison on concrete consumption for one floor slab

3.3. Remarks

The comparison between different punching reinforcements has been made. Finally, the punching shear reinforcement increases the punching shear strength and the ductility. With the new punching system the maximum punching resistance of a slab can be increased up to $2.2V_{Rd,c}$, for the situation presented in this parametric study. This superior performance of the punching shear reinforcement allows optimizing the thickness of the slab even in comparison to slabs reinforced by double-headed studs. Details are shown in Fig. 9. In addition, to satisfy the serviceability limit state (SLS), the deflection behaviour of a flat slab was controlled with respect of cracks and creep of concrete. The slab was not exceeding the deflection limit for the span/250 (38.4 mm). The calculation of a slab deflection M3 was 31.4 mm, 24.7 mm for M2 and 17.5 mm for M1.

In the case of an environmental impact, the concrete consumption results in a significant decrease. With regard to the consumption of concrete per one floor slab, it is about 25% less than the original design solution with stirrups, as it can be seen in Fig. 10. The concrete consumption between slabs reinforced with double headed studs (PSB®) and punching system (PSB Plus®) is approximately 10%.

4. CONCLUSION

A flat slab without vertical shear reinforcement has only a very limited resistance against punching failure. Benefits provided by an innovative punching system have been illustrated by a parametric study. The study shows that using the novel punching system leads to optimization of the reinforced concrete flat slab if the punching shear failure limits design of slab thickness. The system is especially suitable for slabs exposed to extreme loads, where the resistance of conventional shear reinforcement is not sufficient. In case of an environmental impact, the concrete consumption results in a significant decrease. A revision of Eurocode is currently being prepared and the methodology for the shear studs and new reinforcement system will be presumably incorporated into this standard at the European level, by the latest in 2022.

ACKNOWLEDGEMENTS

This research work was supported partly by The Slovak Scientific Grant Agency under contract No. 1/0343/18.

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