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STATISTICAL ANALYSIS OF DESIGN CODES CALCULATION METHODS FOR PUNCHING SHEER RESISTANCE IN COLUMN-TO-SLAB CONNECTIONS

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Abstract. This paper analyses the compliance of the design codes calculation methods for punching shear resistance in reinforced concrete slabs STR 2.05.05:2005, E DIN 1045-1, ENV 1992-1-1 EC 2, prEN 1992-1 [Final draft] EC 2, Model Code CEB-FIP 1990, BS 8110, ACI 318-99 to the experimental data. It has been analysed whether the difference in the results of the mean punching shear resistance received according to these methods and through experiments is statistically significant, when the level of significance value is 0,05. To analyse the significance of the difference of the means Student *t* test was used. An analysis was carried out to find out which methods show the least different resistance results from the experimental data. According to this analysis, a classification of methods was made. Student *t* test was applied to analyse in which methods the ratio between the punching shear resistance results obtained and the punching shear resistance results received through experiment is statistically insignificant. The level of significance value considered was 0,05.

It has been determined that almost in all cases the difference between the punching shear resistance results received experimentally and theoretically is statistically significant. It has also been found out that generally the punching shear resistance can be calculated by applying the prEN 1992-1 [Final draft] EC 2 method. The best method to describe the punching shear resistance in minimally reinforced slabs is ACI 318. The worst results are obtained by applying ENV 1992-1-1 EC 2 and E DIN 1045-1 methods.

Keywords: punching shear resistance of concrete slabs, design codes of concrete slabs, statistical analysis of punching shear.

1. Introduction

Most works [1–4] analyse the impact of the main parameters on the punching shear resistance in reinforced concrete column-to-slab connections under axial forces. These parameters are: punching shear resistance f_c^n, reinforcement ratios ρ, effective depth of the slab *d*, column geometry (transverse section *c* and form). Calculation methods for punching shear resistance of reinforced concrete constructions provided in design codes of different countries and international codes differ as well as the results obtained through these calculations.

Some works [1] provide a comparison of design codes punching shear resistance calculation methods. However, no statistical analysis of the compliance of the latest edition design codes calculation methods to the experimental data was found in the existing literature. Therefore, this work provides a statistical analysis of the Model Code CEB-FIP 1990 [5], E DIN 1045-1 [6], prEN 1992-1 [Final draft] EC 2 [7], ENV 1992-1-1 EC 2 [8], BS 8110 [9], ACI 318-99 [10] and STR 2.05.05 [11] calculation methods as well as experimental data. Further in this article the STR 2.05.05:2005 method is abbreviated to STR, E DIN 1045-1 to DIN, ENV 1992-1-1 EC 2 to EC2, prEN 1992-1 (Final draft) EC 2 to EC2Dr, Model Code CEB-FIP 1990 to MC, BS 8110 to BS and ACI 318-99 to ACI. Experimental data used were provided in [12]. It was analysed in which methods the difference between the mean punching shear resistance calculated theoretically and obtained experimentally is significant statistically. Also, it was examined which methods give the most precise calculation of the punching shear resistance.

2. Design codes

Punching shear of slabs under axial forces in column-to-slab connection occurs when a punching cone is formed. The area of the punching cone makes a 26,6° to 45° angle to the horizontal column face [2, 4]. Based on this failure mechanism, design codes of different countries and international design codes suggest to use a half empirical critical section method to calculate the punching shear resistance in a slab. This method is based on the assumption that the slab fails when there is a vertical section at a certain distance from the column face which extends to the whole perimeter of the column-to-slab connection. The perimeter of this section on the slab surface is called critical perimeter (*u*). The punching shear in slab occurs when punching shear strength in critical section exceed the punching shear resistance of the concrete.

The distance of the critical section from the column face as well as the geometry of the critical perimeter differ in design codes of different countries and international codes (Fig 1). Concrete punching shear strength dependence on approximation of cylindrical compressive strength also differs. These quantities are not precise in reinforced concrete theory. The values of these quantities provided in codes are empirical, based on experimental results [13].

The main code parameters of calculating punching shear in slabs are provided in Table 1. In this Table f_c – cylindrical compressive strength in concrete, $f_{cu} = 1,25 f_c$ – cubical compressive strength in concrete. As one can see from Table 1, all methods approximate punching shear resistance in concrete by function f_c^n, only exponent quantities are different. Differently from other methods, ACI 318 does not evaluate the impact of the longitudinal reinforcement and the scale factor on the punching shear strength. ACI 318 admits that the maximal punching shear strengths in a slab 0,5*d* from the column surface are of constant size and direct distribution. Other calculation codes evaluate the non-linear distribution of tangent stresses in column-to-slab connection by increasing the distance of the critical section from the column surface.

Further we concisely present different punching shear calculation methods when axial forces are located centrally.

The punching strength by MC, DIN, EC2Dr and STR methods may be calculated by the following expressions:

$$V = \xi k \left(100\rho f_c\right)^{1/3} ud, \tag{1}$$

where $\xi = 0,12$ by MC 90, $\xi = 0,14$ by DIN, $\xi = 0,18$ by EC2Dr and STR, $u = 2\left(c_1 + c_2\right) + 4\pi d$ by MC and EC2Dr, $u = 2(c_1 + c_2) + 3\pi d$ by DIN and STR, k – values are provided in Table 1. The punching strength according to EC2 method may be calculated by the following formulas:

$$V = \tau_R k \left(1,2 + 40\rho\right) ud, \tag{2}$$

where τ_R – concrete shear strength (MPa) [8], $u = 2(c_1 + c_2) + 3\pi d$. The k – value is given in Table 1. The punching strength by BS 8110 methods is as follows:

$$V = \xi \left(100\rho\right)^{1/3} k^{0,25} \left(f_c/25\right)^{1/3} ud, \tag{3}$$

where $\xi = 0,12$, $u = 2(c_1 + c_2) + 12d$. The resistance of punching shear force by ACI is as follows:

$$V = \left(2 + 4/\beta\right)\sqrt{f_c}\, ud \text{ (kips)}, \tag{4}$$

$$V = \left(\frac{\alpha_s d}{u} + 2\right)\sqrt{f_c}\, ud \text{ (kips)}, \tag{5}$$

$$V = ud\sqrt[4]{f_c} \text{ (kips)}, \tag{6}$$

where $u = 2(c_1 + c_2) + 4d$, β is the ratio the long side to the short side of the concentration load (or columns), α_s is 40 for interior column.

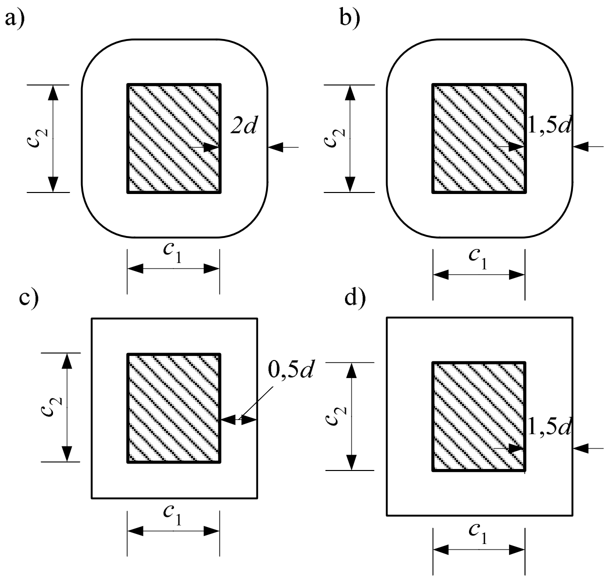

Fig 1. Critical perimeters of interior column: a – by MC, EC2Dr; b – by DIN, STR, EC2; c – by ACI; d – by BS

3. Statistical analysis of data

Due to the spread of the punching shear resistance data obtained through experiments, theoretically obtained values will always differ from the experimental results. However, this difference can be statistically insignificant. If the spread of the experimental data is only achieved because of an accidental error, as it is known, the bigger the number of experiments performed, the closer the mean of the accidental error to zero. Then the proximity of the theoretical method to the experimental data can be compared by applying the difference:

Table 1. Expressions of the main punching shear parameters in calculation codes

Parameters	MC	DIN	EC2Dr	EC2	BS	ACI 318	STR
Shear resistance	$\sqrt[3]{f_c}$				$\sqrt[3]{f_{cu}}$	$\sqrt{f_c}$	$\sqrt[3]{f_c}$
Reinforcement ratios	$\sqrt[3]{\rho}$			$1,2+40\rho$	$\sqrt[3]{\rho}$	–	$\sqrt[3]{\rho}$
Scale factor *k*	$1+\sqrt{200/d}$			$1,6-d$	$\sqrt[4]{400/d}$	–	$1+\sqrt{200/d}$
Critical section	2*d*	1,5*d*	2*d*	1,5*d*	1,5*d*	0,5*d*	1,5*d*

$$\frac{1}{n}\sum_{i=1}^{n}V_{calc,i}-\frac{1}{n}\sum_{i=1}^{n}V_{exp,i}=\overline{V_{calc}}-\overline{V_{exp}}=\Delta V\,, \quad (7)$$

where V_{exp} and V_{calc} are experimentally obtained and theoretically calculated values of punching shear resistance, $\overline{V_{exp}}$ and $\overline{V_{calc}}$ – the means of the experimentally obtained and theoretically calculated values of punching shear resistance. The smaller ΔV, the closer the theoretically obtained values to the experimental data. If $n \to \infty$, then $\Delta V \to 0$. In reality, the number of experimental data is always limited, that is why to verify the equality of the means hypothesis H_0 is put against a competing hypothesis H_1:

$$\begin{cases} H_0:\ \overline{V_{calc}}=\overline{V_{exp}}, \\ H_1:\ \overline{V_{calc}}\neq\overline{V_{exp}}, \end{cases} \quad (8)$$

where

$\overline{V_{calc}} \in \left\{\overline{V_{STR}},\overline{V_{DIN}},\overline{V_{EC2}},\overline{V_{EC2Dr}},\overline{V_{MC}},\overline{V_{BS}},\overline{V_{ACI}}\right\}$,

$\overline{V_{STR}}$, $\overline{V_{DIN}}$, $\overline{V_{EC2}}$, $\overline{V_{EC2Dr}}$, $\overline{V_{MC}}$, $\overline{V_{BS}}$, $\overline{V_{ACI}}$ – means of punching forces calculated according to STR, DIN, EC2, EC2Dr, MC, BS and ACI [5–11] methods.

It is important to analyse which methods allow more precise calculations of punching shear resistance. The test of accuracy is the V_{calc}/V_{exp} ratio mean $\overline{V_{calc}/V_{exp}}$. The closer this ratio to 1, the more precisely allows the theoretical method to calculate the punching shear. According to the closeness of the obtained $\overline{V_{calc}/V_{exp}}$ values to 1, theoretical calculation methods can be ranged into giving the best and the worst calculations of the punching shear resistance.

Sampling

Samples of 7 different slabs were chosen from [12] for statistical analysis. Parameters of slabs and characteristics of materials are given in Table 2. In this Table, c – measurements of transverse column section (m), ρ – relative area of tensile reinforcement (%), d – the useful height of reinforced concrete slabs (m), f_y – reinforcement yield point (MPa), f_c – compressive cylinder strength of concrete (MPa). Literature source [12] offers the estimate of the average compressive strength f_c in concrete of each slab; however, it does not provide the estimation of standard deviation and the number of tested samples. Without these data, it is not possible to evaluate the influence of distribution of compressive strength in concrete of each slab on the sheer strength V_{calc} that is calculated according to the theoretical model. Therefore, it is agreed that, for the purpose of further analysis, the compressive strength of concrete of the i^{th} slab is equal to the estimation of the average of the compressive strength of this slab provided in [12].

According to STR, DIN, EC2, EC2Dr, MC, BS and ACI methods, if we use parameters of each sample, it is possible to calculate the theoretical punching shear resistance of a slab V_{calc}. Concrete strength f_c in each slab is different. As for the formulas (1)–(6), the analyzed formulas evaluate the impact of f_c on the punching shear strength. That is why the theoretical punching shear strength values V_{calc} of a certain sample from a certain slab calculated with different f_c values are compared to the experimental punching shear strength V_{exp} of the same sample from the same slab. Since additionally to theoretical and experimental punching shear strength values we also analyze $\overline{V_{calc}/V_{exp}}$, in each sample additionally to V_{exp} and V_{calc} variables, we shall have V_{calc}/V_{exp} variables.

The data normality is verified by applying the Shapiro-Wilk W test. As shown in [14], this test is the best to verify the normality of the data.

The main statistical variable estimates: the minimal and the maximal values, the mean, standard deviation as well as the values of estimation test of hypotheses on the normality of data are given in Table 2. In this Table W – the obtained Shapiro-Wilk test values, and P – Shapiro-Wilk test P values. The W was calculated according to the method described in [15] and P values were taken from [15]. As shown in Table 2, the P values of the W with all variables except for f_c and V_{calc} of sample 1 and for V_{MC} of sample 4 is higher than the usually applied significance level $\alpha = 0{,}05$. That is why the theoretically and experimentally obtained punching shear values V_{exp} and V_{calc}, except in sample 1, do not contradict the hypothesis that the data are distributed in a normal distribution.

Verification of the hypothesis about the equality of the means obtained experimentally and theoretically

When data are in normal distribution (8), we can apply the Student t test for independent samples when general set variances are unequal [16] to verify the hypothesis. First of all, the t statistics is calculated applying the formula [16]:

$$t=\frac{\overline{V_{\exp}}-\overline{V_{calc}}}{\sqrt{S_{\exp}^2/n+S_{calc}^2/n}}\,, \quad (9)$$

where

$S_{calc} \in \left\{S_{STR},S_{DIN},S_{EC2},S_{EC2Dr},S_{MC},S_{BS},S_{ACI}\right\}$ – $V_{STR}-V_{BS}$ standard sample deviations (Table 2).

Hypothesis H_0 is rejected if $|t| > t_{\alpha/2}(k)$. Here $t_{\alpha/2}(k)$ is the critical value of $\alpha/2$ level in Student distribution with k degree of freedom. It is supposed that $\alpha = 0{,}05$. Results of verifying (8) hypothesis is given in Table 3.

Calculation degree of freedom k, which is the smallest whole number satisfying the condition:

$$k \le \left(S_{\exp}^2/n+S_{calc}^2/n\right)^2 \Big/ \left(S_{\exp}^4/n^3+S_{calc}^4/n^3\right). \quad (10)$$

As shown in Table 3, the difference of experimentally and theoretically obtained means of punching shear forces, except for sample 3 $\overline{V_{EC2Dr}}=\overline{V_{exp}}$ is statistically significant. Therefore, generally we can make a conclusion that we cannot get an accurate calculation of punching shear force by applying the mentioned methods.

Table 2. The main statistical sample estimates and the values of verification test for hypotheses about the normality of data

Sample number	Slab parameters	Sample size	Sample variables	Minimal value (MN) (for f_c – (MPa))	Maximal value (MN) (for f_c – (MPa))	Mean (MN) (for f_c – (MPa))	Standard deviation (MN) (for f_c – (MPa))	W	P
1	2	3	4	5	6	7	8	9	10
1	c=0,015; ρ=2,53 ; d=0,046; f_y=361–467	20	f_c	$2{,}090\cdot10^{1}$	$2{,}910\cdot10^{1}$	$2{,}580\cdot10^{1}$	2,247	0,781	0,000
			V_{exp}	$5{,}600\cdot10^{-2}$	$8{,}940\cdot10^{-2}$	$7{,}328\cdot10^{-2}$	$9{,}844\cdot10^{-3}$	0,966	0,661
			V_{STR}	$5{,}230\cdot10^{-2}$	$5{,}840\cdot10^{-2}$	$5{,}605\cdot10^{-2}$	$1{,}660\cdot10^{-3}$	0,893	0,031
			V_{DIN}	$4{,}070\cdot10^{-2}$	$4{,}540\cdot10^{-2}$	$4{,}361\cdot10^{-2}$	$1{,}292\cdot10^{-3}$	0,889	0,026
			V_{EC2}	$3{,}960\cdot10^{-2}$	$4{,}420\cdot10^{-2}$	$4{,}243\cdot10^{-2}$	$1{,}253\cdot10^{-3}$	0,893	0,031
			V_{EC2Dr}	$6{,}130\cdot10^{-2}$	$6{,}840\cdot10^{-2}$	$6{,}570\cdot10^{-2}$	$1{,}948\cdot10^{-3}$	0,892	0,029
			V_{MC}	$4{,}100\cdot10^{-2}$	$4{,}600\cdot10^{-2}$	$4{,}380\cdot10^{-2}$	$1{,}361\cdot10^{-3}$	0,916	0,086
			V_{BS}	$5{,}500\cdot10^{-2}$	$6{,}200\cdot10^{-2}$	$5{,}930\cdot10^{-2}$	$1{,}895\cdot10^{-3}$	0,877	0,016
			V_{ACI}	$4{,}100\cdot10^{-2}$	$4{,}900\cdot10^{-2}$	$4{,}580\cdot10^{-2}$	$2{,}093\cdot10^{-3}$	0,874	0,014
			V_{STR}/V_{exp}	$6{,}359\cdot10^{-1}$	$9{,}656\cdot10^{-1}$	$7{,}772\cdot10^{-1}$	$9{,}726\cdot10^{-2}$	0,963	0,601
			V_{DIN}/V_{exp}	$4{,}946\cdot10^{-1}$	$7{,}510\cdot10^{-1}$	$6{,}045\cdot10^{-1}$	$7{,}565\cdot10^{-2}$	0,963	0,600
			V_{EC2}/V_{exp}	$4{,}813\cdot10^{-1}$	$7{,}308\cdot10^{-1}$	$5{,}882\cdot10^{-1}$	$7{,}362\cdot10^{-2}$	0,963	0,600
			V_{EC2Dr}/V_{exp}	$7{,}451\cdot10^{-1}$	1,131	$9{,}106\cdot10^{-1}$	$1{,}140\cdot10^{-1}$	0,963	0,601
			V_{MC}/V_{exp}	$4{,}970\cdot10^{-1}$	$7{,}540\cdot10^{-1}$	$6{,}071\cdot10^{-1}$	$7{,}594\cdot10^{-2}$	0,962	0,594
			V_{BS}/V_{exp}	$6{,}710\cdot10^{-1}$	1,019	$8{,}205\cdot10^{-1}$	$1{,}027\cdot10^{-1}$	0,962	0,603
			V_{ACI}/V_{exp}	$5{,}180\cdot10^{-1}$	$8{,}030\cdot10^{-1}$	$6{,}358\cdot10^{-1}$	$7{,}689\cdot10^{-2}$	0,972	0,803
2	c=0,287; ρ=1,06; d=0,114; f_y=399-483	8	f_c	$2{,}050\cdot10^{1}$	$2{,}540\cdot10^{1}$	$2{,}344\cdot10^{1}$	$1{,}666\cdot10^{1}$	0,956	0,776
			V_{exp}	$3{,}114\cdot10^{-1}$	$3{,}923\cdot10^{-1}$	$3{,}622\cdot10^{-1}$	$2{,}793\cdot10^{-2}$	0,923	0,456
			V_{STR}	$2{,}394\cdot10^{-1}$	$2{,}571\cdot10^{-1}$	$2{,}502\cdot10^{-1}$	$6{,}012\cdot10^{-3}$	0,950	0,710
			V_{DIN}	$1{,}862\cdot10^{-1}$	$2{,}000\cdot10^{-1}$	$1{,}946\cdot10^{-1}$	$4{,}680\cdot10^{-3}$	0,951	0,725
			V_{EC2}	$1{,}700\cdot10^{-1}$	$1{,}826\cdot10^{-1}$	$1{,}777\cdot10^{-1}$	$4{,}267\cdot10^{-3}$	0,952	0,734
			V_{EC2Dr}	$2{,}804\cdot10^{-1}$	$3{,}012\cdot10^{-1}$	$2{,}931\cdot10^{-1}$	$7{,}047\cdot10^{-3}$	0,952	0,730
			V_{MC}	$1{,}870\cdot10^{-1}$	$2{,}010\cdot10^{-1}$	$1{,}954\cdot10^{-1}$	$4{,}627\cdot10^{-3}$	0,959	0,802
			V_{BS}	$2{,}390\cdot10^{-1}$	$2{,}560\cdot10^{-1}$	$2{,}495\cdot10^{-1}$	$5{,}806\cdot10^{-3}$	0,944	0,655
			V_{ACI}	$2{,}520\cdot10^{-1}$	$2{,}810\cdot10^{-1}$	$2{,}696\cdot10^{-1}$	$9{,}812\cdot10^{-3}$	0,953	0,737
			V_{STR}/V_{exp}	$6{,}419\cdot10^{-1}$	$7{,}688\cdot10^{-1}$	$6{,}937\cdot10^{-1}$	$4{,}581\cdot10^{-2}$	0,869	0,147
			V_{DIN}/V_{exp}	$4{,}993\cdot10^{-1}$	$5{,}980\cdot10^{-1}$	$5{,}396\cdot10^{-1}$	$3{,}564\cdot10^{-2}$	0,869	0,146
			V_{EC2}/V_{exp}	$4{,}558\cdot10^{-1}$	$5{,}459\cdot10^{-1}$	$4{,}926\cdot10^{-1}$	$3{,}253\cdot10^{-2}$	0,869	0,147
			V_{EC2Dr}/V_{exp}	$7{,}519\cdot10^{-1}$	$9{,}005\cdot10^{-1}$	$8{,}126\cdot10^{-1}$	$5{,}364\cdot10^{-2}$	0,869	0,147
			V_{MC}/V_{exp}	$5{,}010\cdot10^{-1}$	$6{,}000\cdot10^{-1}$	$5{,}418\cdot10^{-1}$	$3{,}572\cdot10^{-2}$	0,870	0,151
			V_{BS}/V_{exp}	$6{,}400\cdot10^{-1}$	$7{,}670\cdot10^{-1}$	$6{,}919\cdot10^{-1}$	$4{,}571\cdot10^{-2}$	0,871	0,153
			V_{ACI}/V_{exp}	$6{,}910\cdot10^{-1}$	$8{,}170\cdot10^{-1}$	$7{,}471\cdot10^{-1}$	$4{,}542\cdot10^{-2}$	0,902	0,303
3	c=0,287; ρ=1,15; d=0,114; f_y=328	13	f_c	$2{,}340\cdot10^{1}$	$2{,}840\cdot10^{1}$	$2{,}565\cdot10^{1}$	1,626	0,924	0,281
			V_{exp}	$2{,}455\cdot10^{-1}$	$3{,}714\cdot10^{-1}$	$3{,}092\cdot10^{-1}$	$3{,}670\cdot10^{-2}$	0,930	0,341
			V_{STR}	$2{,}571\cdot10^{-1}$	$2{,}742\cdot10^{-1}$	$2{,}650\cdot10^{-1}$	$5{,}569\cdot10^{-3}$	0,927	0,312
			V_{DIN}	$2{,}000\cdot10^{-1}$	$2{,}133\cdot10^{-1}$	$2{,}061\cdot10^{-1}$	$4{,}328\cdot10^{-3}$	0,929	0,327
			V_{EC2}	$1{,}816\cdot10^{-1}$	$1{,}937\cdot10^{-1}$	$1{,}872\cdot10^{-1}$	$3{,}927\cdot10^{-3}$	0,929	0,328
			V_{EC2Dr}	$3{,}011\cdot10^{-1}$	$3{,}212\cdot10^{-1}$	$3{,}104\cdot10^{-1}$	$6{,}520\cdot10^{-3}$	0,929	0,336
			V_{MC}	$2{,}010\cdot10^{-1}$	$2{,}140\cdot10^{-1}$	$2{,}068\cdot10^{-1}$	$4{,}318\cdot10^{-3}$	0,916	0,224
			V_{BS}	$2{,}560\cdot10^{-1}$	$2{,}730\cdot10^{-1}$	$2{,}643\cdot10^{-1}$	$5{,}663\cdot10^{-3}$	0,923	0,278
			V_{ACI}	$2{,}700\cdot10^{-1}$	$2{,}970\cdot10^{-1}$	$2{,}824\cdot10^{-1}$	$8{,}732\cdot10^{-3}$	0,930	0,339
			V_{STR}/V_{exp}	$7{,}179\cdot10^{-1}$	1,117	$8{,}701\cdot10^{-1}$	$1{,}212\cdot10^{-1}$	0,883	0,078
			V_{DIN}/V_{exp}	$5{,}583\cdot10^{-1}$	$8{,}688\cdot10^{-1}$	$6{,}767\cdot10^{-1}$	$9{,}430\cdot10^{-2}$	0,883	0,078
			V_{EC2}/V_{exp}	$5{,}071\cdot10^{-1}$	$7{,}890\cdot10^{-1}$	$6{,}146\cdot10^{-1}$	$8{,}562\cdot10^{-2}$	0,883	0,078
			V_{EC2Dr}/V_{exp}	$8{,}409\cdot10^{-1}$	1,308	$1{,}019\cdot10$	$1{,}420\cdot10^{-1}$	0,883	0,078
			V_{MC}/V_{exp}	$5{,}610\cdot10^{-1}$	$8{,}720\cdot10^{-1}$	$6{,}793\cdot10^{-1}$	$9{,}465\cdot10^{-2}$	0,882	0,076
			V_{BS}/V_{exp}	$7{,}160\cdot10^{-1}$	1,114	$8{,}677\cdot10^{-1}$	$1{,}208\cdot10^{-1}$	0,883	0,077
			V_{ACI}/V_{exp}	$7{,}670\cdot10^{-1}$	1,210	$9{,}272\cdot10^{-1}$	$1{,}355\cdot10^{-1}$	0,879	0,068

Continuation of Table 2

1	2	3	4	5	6	7	8	9	10
4	c=0,115; ρ=0,722; d=0,057; f_y=300	6	f_c	$2,640\cdot10^{1}$	$3,100\cdot10^{1}$	$2,908\cdot10^{1}$	$1,693\cdot10^{1}$	0,878	0,261
			V_{exp}	$8,180\cdot10^{-2}$	$9,390\cdot10^{-2}$	$8,575\cdot10^{-2}$	$5,278\cdot10^{-3}$	0,794	0,052
			V_{STR}	$5,180\cdot10^{-2}$	$5,470\cdot10^{-2}$	$5,347\cdot10^{-2}$	$1,060\cdot10^{-3}$	0,886	0,296
			V_{DIN}	$4,030\cdot10^{-2}$	$4,250\cdot10^{-2}$	$4,162\cdot10^{-2}$	$8,329\cdot10^{-4}$	0,856	0,177
			V_{EC2}	$3,980\cdot10^{-2}$	$4,200\cdot10^{-2}$	$4,107\cdot10^{-2}$	$8,066\cdot10^{-4}$	0,883	0,285
			V_{EC2Dr}	$6,160\cdot10^{-2}$	$6,500\cdot10^{-2}$	$6,363\cdot10^{-2}$	$1,268\cdot10^{-3}$	0,864	0,205
			V_{MC}	$4,100\cdot10^{-2}$	$4,300\cdot10^{-2}$	$4,250\cdot10^{-2}$	$8,367\cdot10^{-4}$	0,701	0,006
			V_{BS}	$5,500\cdot10^{-2}$	$5,800\cdot10^{-2}$	$5,667\cdot10^{-2}$	$1,033\cdot10^{-3}$	0,915	0,473
			V_{ACI}	$6,200\cdot10^{-2}$	$6,700\cdot10^{-2}$	$6,500\cdot10^{-2}$	$2,000\cdot10^{-3}$	0,823	0,094
			V_{STR}/V_{exp}	$5,821\cdot10^{-1}$	$6,595\cdot10^{-1}$	$6,253\cdot10^{-1}$	$3,013\cdot10^{-2}$	0,900	0,373
			V_{DIN}/V_{exp}	$4,528\cdot10^{-1}$	$5,129\cdot10^{-1}$	$4,863\cdot10^{-1}$	$2,341\cdot10^{-2}$	0,900	0,373
			V_{EC2}/V_{exp}	$4,472\cdot10^{-1}$	$5,066\cdot10^{-1}$	$4,804\cdot10^{-1}$	$2,313\cdot10^{-2}$	0,899	0,371
			V_{EC2Dr}/V_{exp}	$6,924\cdot10^{-1}$	$7,844\cdot10^{-1}$	$7,438\cdot10^{-1}$	$3,582\cdot10^{-2}$	0,899	0,371
			V_{MC}/V_{exp}	$4,620\cdot10^{-1}$	$5,230\cdot10^{-1}$	$4,958\cdot10^{-1}$	$2,363\cdot10^{-2}$	0,904	0,397
			V_{BS}/V_{exp}	$6,140\cdot10^{-1}$	$6,960\cdot10^{-1}$	$6,595\cdot10^{-1}$	$3,192\cdot10^{-2}$	0,901	0,383
			V_{ACI}/V_{exp}	$7,140\cdot10^{-1}$	$8,040\cdot10^{-1}$	$7,587\cdot10^{-1}$	$3,415\cdot10^{-2}$	0,950	0,739
5	c=0,115; ρ=1,625; d=0,057; f_y=300	6	f_c	$2,630\cdot10^{1}$	$3,130\cdot10^{1}$	$2,920\cdot10^{1}$	$1,815\cdot10^{1}$	0,950	0,743
			V_{exp}	$9,960\cdot10^{-2}$	$1,254\cdot10^{-1}$	$1,130\cdot10^{-1}$	$8,486\cdot10^{-3}$	0,961	0,829
			V_{STR}	$6,780\cdot10^{-2}$	$7,190\cdot10^{-2}$	$7,018\cdot10^{-2}$	$1,491\cdot10^{-3}$	0,950	0,742
			V_{DIN}	$5,270\cdot10^{-2}$	$5,590\cdot10^{-2}$	$5,460\cdot10^{-2}$	$1,152\cdot10^{-3}$	0,944	0,691
			V_{EC2}	$4,940\cdot10^{-2}$	$5,230\cdot10^{-2}$	$5,112\cdot10^{-2}$	$1,065\cdot10^{-3}$	0,942	0,674
			V_{EC2Dr}	$8,070\cdot10^{-2}$	$8,550\cdot10^{-2}$	$8,352\cdot10^{-2}$	$1,747\cdot10^{-3}$	0,946	0,709
			V_{MC}	$5,400\cdot10^{-2}$	$5,700\cdot10^{-2}$	$5,567\cdot10^{-2}$	$1,033\cdot10^{-3}$	0,915	0,473
			V_{BS}	$7,200\cdot10^{-2}$	$7,600\cdot10^{-2}$	$7,417\cdot10^{-2}$	$1,472\cdot10^{-3}$	0,958	0,804
			V_{ACI}	$6,200\cdot10^{-2}$	$6,700\cdot10^{-2}$	$6,500\cdot10^{-2}$	$1,789\cdot10^{-3}$	0,933	0,607
			V_{STR}/V_{exp}	$5,731\cdot10^{-1}$	$6,808\cdot10^{-1}$	$6,234\cdot10^{-1}$	$3,782\cdot10^{-2}$	0,988	0,984
			V_{DIN}/V_{exp}	$4,457\cdot10^{-1}$	$5,295\cdot10^{-1}$	$4,849\cdot10^{-1}$	$2,943\cdot10^{-2}$	0,988	0,984
			V_{EC2}/V_{exp}	$4,174\cdot10^{-1}$	$4,959\cdot10^{-1}$	$4,541\cdot10^{-1}$	$2,756\cdot10^{-2}$	0,988	0,984
			V_{EC2Dr}/V_{exp}	$6,816\cdot10^{-1}$	$8,098\cdot10^{-1}$	$7,415\cdot10^{-1}$	$4,501\cdot10^{-2}$	0,988	0,984
			V_{MC}/V_{exp}	$4,540\cdot10^{-1}$	$5,400\cdot10^{-1}$	$4,943\cdot10^{-1}$	$3,018\cdot10^{-2}$	0,987	0,982
			V_{BS}/V_{exp}	$6,050\cdot10^{-1}$	$7,180\cdot10^{-1}$	$6,578\cdot10^{-1}$	$3,974\cdot10^{-2}$	0,988	0,984
			V_{ACI}/V_{exp}	$5,370\cdot10^{-1}$	$6,200\cdot10^{-1}$	$5,772\cdot10^{-1}$	$3,138\cdot10^{-2}$	0,963	0,845
6	c=0,402; ρ=0,37; d=0,356; f_y=309 – 515	16	f_c	$2,120\cdot10^{1}$	$2,870\cdot10^{1}$	$2,489\cdot10^{1}$	$2,195\cdot10^{1}$	0,963	0,721
			V_{exp}	1,837	2,309	2,114	$1,382\cdot10^{-1}$	0,948	0,461
			V_{STR}	1,065	1,178	1,122	$3,334\cdot10^{-2}$	0,957	0,613
			V_{DIN}	$8,280\cdot10^{-1}$	$9,160\cdot10^{-1}$	$8,728\cdot10^{-1}$	$2,593\cdot10^{-2}$	0,957	0,614
			V_{EC2}	$8,528\cdot10^{-1}$	$9,434\cdot10^{-1}$	$8,989\cdot10^{-1}$	$2,671\cdot10^{-2}$	0,957	0,610
			V_{EC2Dr}	1,314	1,45	1,385	$4,115\cdot10^{-2}$	0,957	0,613
			V_{MC}	$8,760\cdot10^{-1}$	$9,690\cdot10^{-1}$	$9,233\cdot10^{-1}$	$2,738\cdot10^{-2}$	0,957	0,607
			V_{BS}	1,181	1,307	1,245	$3,708\cdot10^{-2}$	0,958	0,626
			V_{ACI}	1,551	1,804	1,679	$7,449\cdot10^{-2}$	0,959	0,642
			V_{STR}/V_{exp}	$4,675\cdot10^{-1}$	$6,297\cdot10^{-1}$	$5,329\cdot10^{-1}$	$3,919\cdot10^{-2}$	0,956	0,590
			V_{DIN}/V_{exp}	$3,636\cdot10^{-1}$	$4,898\cdot10^{-1}$	$4,145\cdot10^{-1}$	$3,048\cdot10^{-2}$	0,956	0,589
			V_{EC2}/V_{exp}	$3,745\cdot10^{-1}$	$5,045\cdot10^{-1}$	$4,269\cdot10^{-1}$	$3,139\cdot10^{-2}$	0,956	0,586
			V_{EC2Dr}/V_{exp}	$5,768\cdot10^{-1}$	$7,771\cdot10^{-1}$	$6,576\cdot10^{-1}$	$4,837\cdot10^{-2}$	0,956	0,590
			V_{MC}/V_{exp}	$3,850\cdot10^{-1}$	$5,180\cdot10^{-1}$	$4,386\cdot10^{-1}$	$3,219\cdot10^{-2}$	0,955	0,581
			V_{BS}/V_{exp}	$5,190\cdot10^{-1}$	$6,990\cdot10^{-1}$	$5,914\cdot10^{-1}$	$4,340\cdot10^{-2}$	0,955	0,570
			V_{ACI}/V_{exp}	$6,810\cdot10^{-1}$	$9,560\cdot10^{-1}$	$7,973\cdot10^{-1}$	$6,466\cdot10^{-2}$	0,930	0,244
7		31	f_c	$2,210\cdot10^{1}$	$2,980\cdot10^{1}$	$2,526\cdot10^{1}$	$1,838\cdot10^{1}$	0,973	0,601
			V_{exp}	1,668	2,669	2,202	$2,136\cdot10^{-1}$	0,973	0,598
			V_{STR}	1,099	1,214	1,148	$2,784\cdot10^{-2}$	0,973	0,610
			V_{DIN}	$8,544\cdot10^{-1}$	$9,440\cdot10^{-1}$	$8,929\cdot10^{-1}$	$2,164\cdot10^{-2}$	0,973	0,618
			V_{EC2}	$8,698\cdot10^{-1}$	$9,610\cdot10^{-1}$	$9,090\cdot10^{-1}$	$2,204\cdot10^{-2}$	0,973	0,617
			V_{EC2Dr}	1,35	1,498	1,417	$3,436\cdot10^{-2}$	0,973	0,616
			V_{MC}	$9,040\cdot10^{-1}$	$9,980\cdot10^{-1}$	$9,445\cdot10^{-1}$	$2,287\cdot10^{-2}$	0,973	0,603
			V_{BS}	1,219	1,347	1,274	$3,098\cdot10^{-2}$	0,973	0,608
7	c=0,402; ρ=0,39; d=0,356; f_y=309 – 515	31	V_{ACI}	1,583	1,838	1,691	$6,155\cdot10^{-2}$	0,974	0,624
			V_{STR}/V_{exp}	$4,470\cdot10^{-1}$	$6,626\cdot10^{-1}$	$5,258\cdot10^{-1}$	$5,015\cdot10^{-2}$	0,954	0,195
			V_{DIN}/V_{exp}	$3,477\cdot10^{-1}$	$5,153\cdot10^{-1}$	$4,090\cdot10^{-1}$	$3,900\cdot10^{-2}$	0,954	0,195
			V_{EC2}/V_{exp}	$3,539\cdot10^{-1}$	$5,246\cdot10^{-1}$	$4,163\cdot10^{-1}$	$3,970\cdot10^{-2}$	0,954	0,197
			V_{EC2Dr}/V_{exp}	$5,516\cdot10^{-1}$	$8,176\cdot10^{-1}$	$6,488\cdot10^{-1}$	$6,188\cdot10^{-2}$	0,954	0,196
			V_{MC}/V_{exp}	$3,680\cdot10^{-1}$	$5,450\cdot10^{-1}$	$4,326\cdot10^{-1}$	$4,134\cdot10^{-2}$	0,953	0,190
			V_{BS}/V_{exp}	$4,960\cdot10^{-1}$	$7,350\cdot10^{-1}$	$5,833\cdot10^{-1}$	$5,560\cdot10^{-2}$	0,954	0,197
			V_{ACI}/V_{exp}	$6,470\cdot10^{-1}$	$9,580\cdot10^{-1}$	$7,745\cdot10^{-1}$	$7,367\cdot10^{-2}$	0,966	0,406

Table 3. Results of verifying hypothesis (8)

Sample number	Sample variables	t	$t_{\alpha/2}$	H_0
2	V_{STR}	–11,090	2,306	rejected
	V_{DIN}	–16,742	2,365	
	V_{EC2}	–18,477	2,365	
	V_{EC2Dr}	–6,792	2,306	
	V_{MC}	–16,670	2,365	
	V_{BS}	–11,177	2,306	
	V_{ACI}	–8,848	2,262	
3	V_{STR}	–4,293	2,160	rejected
	V_{DIN}	–10,055	2,179	
	V_{EC2}	–11,918	2,179	
	V_{EC2Dr}	0,116	2,160	
	V_{MC}	–9,983	2,179	
	V_{BS}	–4,355	2,160	
	V_{ACI}	–2,560	2,160	
4	V_{STR}	–14,689	2,571	rejected
	V_{DIN}	–20,231	2,571	
	V_{EC2}	–20,499	2,571	
	V_{EC2Dr}	–9,980	2,447	
	V_{MC}	–19,824	2,571	
	V_{BS}	–13,246	2,571	
	V_{ACI}	–9,005	2,447	
5	V_{STR}	–12,178	2,571	rejected
	V_{DIN}	–16,709	2,571	
	V_{EC2}	–17,729	2,571	
	V_{EC2Dr}	–8,340	2,571	
	V_{MC}	–16,433	2,571	
	V_{BS}	–11,049	2,571	
	V_{ACI}	–13,562	2,571	
6	V_{STR}	–27,910	2,110	rejected
	V_{DIN}	–35,311	2,120	
	V_{EC2}	–34,532	2,120	
	V_{EC2Dr}	–20,234	2,101	
	V_{MC}	–33,809	2,120	
	V_{BS}	–24,295	2,110	
	V_{ACI}	–11,100	2,069	
7	V_{STR}	–27,260	2,040	rejected
	V_{DIN}	–33,967	2,040	
	V_{EC2}	–33,543	2,040	
	V_{EC2Dr}	–20,226	2,037	
	V_{MC}	–32,609	2,040	
	V_{BS}	–23,961	2,040	
	V_{ACI}	–12,798	2,030	

Analysis of the accuracy of calculation methods

Further this article analyses which methods allow to make the most accurate calculations of punching shear force. $\overline{V_{calc}/V_{exp}}$ ratios as well as error bands of these rations are given in Table 4. The confidence intervals of means are calculated by using t test. The value of significance level is 0,05. The ratio difference calculated with different methods:

$$\overline{V_{calc}/V_{exp}} - \overline{V_{calc1}/V_{exp}}, \tag{11}$$

here $\overline{V_{calc1}} \in \left\{\overline{V_{STR}}, \overline{V_{DIN}}, \overline{V_{EC2}}, \overline{V_{EC2Dr}}, \overline{V_{MC}}, \overline{V_{BS}}, \overline{V_{ACI}}\right\}$ and $\overline{V_{calc}} \neq \overline{V_{calc1}}$ can be statistically insignificant. That is why to verify the significance of the difference H_0 hypothesis is put against a competing hypothesis H_1:

Table 4. Values of $\overline{V_{calc}/V_{exp}}$ ratios

Sample number	Sample variables	$\overline{V_{calc}/V_{exp}}$ values	$\overline{V_{calc}/V_{exp}}$ the lowest limit	$\overline{V_{calc}/V_{exp}}$ the highest limit
1	V_{STR}/V_{exp}	0,777	0,223	0,728
	V_{DIN}/V_{exp}	0,604	0,396	0,567
	V_{EC2}/V_{exp}	0,588	0,412	0,551
	V_{EC2Dr}/V_{exp}	0,911	0,089	0,854
	V_{MC}/V_{exp}	0,607	0,393	0,569
	V_{BS}/V_{exp}	0,821	0,180	0,769
	V_{ACI}/V_{exp}	0,636	0,364	0,597
2	V_{STR}/V_{exp}	0,694	0,657	0,730
	V_{DIN}/V_{exp}	0,540	0,511	0,568
	V_{EC2}/V_{exp}	0,493	0,467	0,518
	V_{EC2Dr}/V_{exp}	0,813	0,770	0,855
	V_{MC}/V_{exp}	0,542	0,513	0,570
	V_{BS}/V_{exp}	0,692	0,656	0,728
	V_{ACI}/V_{exp}	0,747	0,711	0,783
3	V_{STR}/V_{exp}	0,870	0,795	0,945
	V_{DIN}/V_{exp}	0,677	0,618	0,735
	V_{EC2}/V_{exp}	0,615	0,561	0,668
	V_{EC2Dr}/V_{exp}	1,019	0,931	1,107
	V_{MC}/V_{exp}	0,679	0,620	0,738
	V_{BS}/V_{exp}	0,868	0,793	0,943
	V_{ACI}/V_{exp}	0,927	0,843	1,011
4	V_{STR}/V_{exp}	0,625	0,598	0,653
	V_{DIN}/V_{exp}	0,486	0,465	0,508
	V_{EC2}/V_{exp}	0,480	0,459	0,502
	V_{EC2Dr}/V_{exp}	0,744	0,711	0,777
	V_{MC}/V_{exp}	0,496	0,474	0,517
	V_{BS}/V_{exp}	0,660	0,630	0,689
	V_{ACI}/V_{exp}	0,759	0,727	0,790
5	V_{STR}/V_{exp}	0,623	0,589	0,658
	V_{DIN}/V_{exp}	0,485	0,458	0,512
	V_{EC2}/V_{exp}	0,454	0,429	0,479
	V_{EC2Dr}/V_{exp}	0,742	0,700	0,783
	V_{MC}/V_{exp}	0,494	0,467	0,522
	V_{BS}/V_{exp}	0,658	0,621	0,694
	V_{ACI}/V_{exp}	0,577	0,548	0,606
7	V_{STR}/V_{exp}	0,533	0,511	0,555
	V_{DIN}/V_{exp}	0,414	0,397	0,432
	V_{EC2}/V_{exp}	0,427	0,409	0,444
	V_{EC2Dr}/V_{exp}	0,658	0,631	0,685
	V_{MC}/V_{exp}	0,439	0,421	0,457
	V_{BS}/V_{exp}	0,591	0,567	0,616
	V_{ACI}/V_{exp}	0,797	0,761	0,833
8	V_{STR}/V_{exp}	0,526	0,506	0,546
	V_{DIN}/V_{exp}	0,409	0,393	0,425
	V_{EC2}/V_{exp}	0,416	0,400	0,432
	V_{EC2Dr}/V_{exp}	0,649	0,624	0,674
	V_{MC}/V_{exp}	0,433	0,416	0,449
	V_{BS}/V_{exp}	0,583	0,561	0,606
	V_{ACI}/V_{exp}	0,774	0,745	0,804

$$\begin{cases} H_0: \overline{V_{calc}/V_{exp}} = \overline{V_{calc1}/V_{exp}}, \\ H_1: \overline{V_{calc}/V_{exp}} \neq \overline{V_{calc1}/V_{exp}}, \end{cases} \tag{12}$$

Verification of (12) hypothesis is done similarly as for hypothesis (8) applying (9) and (10) formulas, only instead of $\overline{V_{\text{exp}}}$ and $\overline{V_{calc}}$ we use $\overline{V_{calc}/V_{exp}}$ and

$\overline{V_{calc1}/V_{exp}}$, and instead of $S_{\exp}$ and S_{calc} we use $S_{calc/\exp}$ and $S_{calc1/\exp}$. Here $\{S_{calc/\exp}, S_{calc1/\exp}\} \in \{S_{STR/\exp}, S_{EC2Dr/\exp}, S_{MC/\exp}, S_{BS/\exp}, S_{ACI/\exp}\}$, $S_{STR/exp} - S_{ACI/exp}$ are estimates of standard V_{calc}/V_{exp} deviations given in Table 2. Due to abundant data *t* values and $t_{\alpha/2}(k)$ critical value in verifying the hypothesis (12) are not provided. Table 5 provides the final results of the verifying hypothesis (12).

This Table also shows the theoretical methods used to calculate the punching shear force ranged by the proximity of the obtained punching shear values to the experimentally received punching shear values. First in a row are the methods where calculated punching shear force is the least different from the punching shear force obtained experimentally.

Column 3 in Table 5 shows the methods adequate to ranges 1, 2 etc. Column 4 shows the methods where the mean of the ratio between the theoretical punching shear values and the experimental punching shear values is insignificantly different from the mean of the ratio of the theoretical and experimental punching shear values of the method given in column 3, ie here hypothesis (12) H_0 is in force.

As the results given in Table 5 show almost in all cases the punching shear force calculated by the EC2Dr method is the closest to the results obtained experimentally.

The $\overline{V_{EC2Dr}/V_{exp}} - \overline{V_{calc}/V_{exp}}$ difference in samples 1, 2, 5 is statistically significant in all methods except for ECDr. The $\overline{V_{EC2Dr}/V_{exp}} - \overline{V_{ACI}/V_{exp}}$ difference in samples 3 and 4 is statistically insignificant. Therefore, in this case we can state that ACI and EC2Dr methods similarly accurately calculate the punching shear force in respect to experimental results.

Punching shear force calculated by the ACI method is the closest to the experimental punching shear results obtained in samples 6 and 7. Besides, the $\overline{V_{ACI}/V_{exp}} - \overline{V_{calc}/V_{exp}}$ difference is statistically significant when V_{calc} is calculated applying all the methods except ACI. These samples are special because reinforcement of slabs is minimal. It is known that in a minimally reinforced slab punching shear cone is 45°, which corresponds to the punching shear angle in ACI method. In limited reinforcement the shear force taken over by the longitudinal reinforcement is not big. Most part of the shear force is taken over by the concrete which is in the area of the punching shear cone. Therefore, absence of evaluation of reinforcement ratio ρ in ACI method does not cause a significant calculation error.

In this case, therefore, experimental results confirm the theoretical presumptions. This allows to make a conclusion that ACI method is the best to calculate the punching shear force in slabs. It is possible to notice from the data provided in Table 5 that, when the reinforcement percentage is high calculation results of punching shear strength by applying the ACI method are less correct than applying other methods if compared to experimental results. This is clearly seen from comparison of samples 1and 5 $\overline{V_{ACI}/V_{exp}} - \overline{V_{calc}/V_{exp}}$ (the Table 5). When the amount of reinforcement is approximately 1 %, the ACI

Table 5. Results of verifying hypothesis (12)

Sample number	Range of calculation method	Calculation method	Methods when (6) H_0 hypothesis is accepted
1	2	3	4
1	1	EC2Dr	
	2	BS	STR
	3	STR	BS
	4	ACI	DIN; EC2; MC
	5	MC	DIN; EC2; ACI
	6	DIN	EC2; MC; ACI
	7	EC2	DIN; MC; ACI
2	1	EC2Dr	
	2	ACI	
	3	STR	BS
	4	BS	STR
	5	MC	DIN
	6	DIN	MC
	7	EC2	
3	1	EC2Dr	ACI
	2	ACI	EC2Dr; STR; BS
	3	STR	BS; ACI
	4	BS	ACI; STR
	5	MC	DIN; EC2
	6	DIN	MC; EC2
	7	EC2	DIN; MC
4	1	ACI	EC2Dr
	2	EC2Dr	ACI
	3	BS	STR
	4	STR	BS
	5	MC	DIN; EC2
	6	DIN	MC; EC2
	7	EC2	MC; DIN
5	1	EC2Dr	
	2	BS	STR
	3	STR	BS
	4	ACI	
	5	MC	DIN
	6	DIN	EC2; MC
	7	EC2	DIN
6	1	ACI	
	2	EC2Dr	
	3	BS	
	4	STR	
	5	MC	EC2
	6	EC2	MC; DIN
	7	DIN	EC2
7	1	ACI	
	2	EC2Dr	
	3	BS	
	4	STR	
	5	MC	EC2
	6	EC2	MC; DIN
	7	DIN	EC2

and the ECDr methods are equally good to calculate the punching shear force.

Analysis of the results given in Table 5 also clearly shows that when reinforcement is strong, ie samples 1 and 5 in the second position, according to $\overline{V_{calc}/V_{exp}}$ proximity to 1, is V_{calc} values calculated by the BS method, and the third in a row is the STR method. Since $\overline{V_{BS}/V_{exp}} - \overline{V_{calc}/V_{exp}}$ and $\overline{V_{STR}/V_{exp}} - \overline{V_{calc}/V_{exp}}$ differences are statistically insignificant, it is possible to state that, when reinforcement is bigger than 1,6 %, BS and STR methods are second in a row to make an accurate calculation of punching shear. When reinforcement is small, better results than ACI and EC2Dr are obtained by applying the BS method, which is clearly seen from samples 6 and 7 (Table 5).

Punching shear values obtained using EC2 and DIN methods are the most different from the experimental results. This is clearly seen in Table 5.

4. Conclusions

Generally, the difference of the punching shear force in slabs calculated applying STR; DIN; EC2; EC2Dr; MC; BS; ACI methods from the punching shear force in slabs obtained experimentally is statistically significant. This shows that none of the analysed methods allows an accurate calculation of punching shear force.

Generally, the method allowing the most accurate calculation of punching shear force is EC2Dr method.

When reinforcement is minimal, less than 0,5 %, ACI is the best to make an accurate calculation of punching shear force.

When reinforcement is $\rho \geq 1{,}6$ %, BS and STR methods are second in a row to calculate punching shear accurately.

References

1. Albrecht, U. Design of flat slabs for punching – European and North American practices. *Cement & Concrete Composites*, 24, 2002, p. 531–538.
2. Vainiūnas, P.; Popovas, V.; Jarmolajev, A. Punching shear behavior analysis of RC flat floor slab-to-column connection. *Journal of Civil Engineering and Management*, 8(2), 2002, p. 77–82.
3. Vainiūnas, P.; Popovas, V.; Jarmolajev, A. Non-linear 3d modelling of RC slab punching shear failure. *Journal of Civil Engineering and Management*, 10(4), 2004, p. 311–316.
4. Šalna, R.; Marčiukaitis, G.; Vainiūnas, P. Estimation of factors influencing the punching shear strength of RC floor slabs. *Journal of Civil Engineering and Management*, 10, Suppl 2, 2004, p. 137–142.
5. CEB-FIP Model Code 1990. London: Thomas Telford Ltd, 2001. 307 p.
6. E DIN 1045-1: Tragwerke aus Beton und Stahlbeton und Spannbeton, Teil 1: Bemessung und Konstruktion, 1999.
7. Eurocode 2: Design of concrete structures - Part 1: General rules and rules for buildings. European Committee for Standardization. Pr-EN 1992-1 (Final draft), October 2001. 230 p.
8. Eurocode 2: Design of concrete structures - Part 1: General rules and rules for buildings. European Committee for Standardization. ENV 1992-1-1, December 1991. 254 p.
9. BS 8110 (1985) Structural Use of Concrete, Part 1: Code of Practice for Design and Construction. British Standards Institution. London, 1985.
10. ACI Committee 318: Building Code Requirements for Reinforced Concrete. Detroit. American Concrete Institute, 1999.
11. STR 2.05.05:2005: Design of concrete and reinforced concrete structures (Betoninių ir gelžbetoninių konstrukcijų projektavimas). 2005 (in Lithuanian).
12. Nölting, D. Das Durchstanzen von Platten aus Stahlbeton – Tragverhalten, Berechnung, Bemessung. Heft 62, Technische Universität Braunschweig, 1984. 174 p.
13. Piel, W. Zur Erhöhung der Durchstanztragfähigkeit von Flachdeken mit Stahlverbundsystemen. Dissertation, Bergischen Universität Wuppertal, 2004. 277 p.
14. Lemeshko, B. Yu.; Lemeshko, S. B. Comparative analysis of goodness of fit tests for normal distributions. *Metrology (Метрология)*, No 2, 2005, p. 3–24 (in Russian).
15. Stepnov, M. N.; Shavrin, A. V. Statistical methods for analysis of observations data of mechanical tests. Handbook. (Статистические методы обработки результатов механических испытаний. Справочник). Moscow: Mashinostrojenije, 2005. 400 p.
16. Sheskin, D. J. Handbook of parametric and nonparametric statistical procedures. Boca Raton, Chapman & Hall/CRC, 2000. 982 p.

KOLONOS-PLOKŠTĖS JUNGTIES BE SKERSINIO ARMAVIMO VEIKIANT SUTELKTAJAI APKROVAI PRASPAUDŽIAMOJO STIPRIO NORMATYVINIŲ SKAIČIAVIMO METODIKŲ STATISTINĖ ANALIZĖ

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S a n t r a u k a

Darbe nagrinėjamas gelžbetoninių plokščių praspaudžiamojo stiprio skaičiavimo normatyvinių metodikų STR 2.05.05:2005, E DIN 1045-1, ENV 1992-1-1 EC 2, prEN 1992-1 [Final draft] EC 2, Model Code CEB-FIP 1990, BS 8110, AC 318 atitikimas eksperimentiniams duomenims. Išanalizuota, ar pagal šias metodikas apskaičiuotų ir eksperimentiškai nustatytų praspaudžiamojo vidutinių stiprio reikšmių skirtumas statistiškai reikšmingas, kai reikšmingumo lygmuo yra 0,05. Vidurkių skirtumo reikšmingumo analizei naudotas Stjudento *t* kriterijus. Išnagrinėta, pagal kurias metodikas apskaičiuotos stiprio reikšmės mažiausiai skiriasi nuo eksperimentinių duomenų. Tuo remiantis metodikoms priskirti rangai. Taikant Stjudento *t* kriterijų, išanalizuota, pagal kurias metodikas apskaičiuotų praspaudžiamojo stiprio reikšmių santykis su eksperimentiškai nustatytomis praspaudžiamojo stiprio reikšmėmis statistiškai nereikšmingas. Reikšmingumo lygmuo imtas 0,05.

Nustatyta, kad beveik visais atvejais skirtumas tarp eksperimentiškai ir teoriškai apskaičiuotų praspaudžiamojo stiprio reikšmių statistiškai reikšmingas. Taip pat nustatyta, kad tiksliausiai praspaudžiamąjį stiprį galima apskaičiuoti pagal prEN 1992-1 [Final draft] EC 2 metodiką.

Reikšminiai žodžiai: gelžbetoninių plokščių praspaudžiamasis stipris, gelžbetoninių plokščių projektavimo normos, praspaudžiamojo stiprio statistinė analizė.

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