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Design of Punching Shear Of R.C. Footings Using American And European Codes: A Comparative Study

Amr El-said[1], Ahmed F. Deifalla[*2], Nehal M. Ayash[3] and Maged Tawfik[1]
[1]Department of Civil Engineering, The Higher Institute of Engineering
El Shrouk, Cairo 11837, Egypt
A.elsayed@sha.edu.eg
[2]Department of Structural Engineering and Construction Management, Faculty of Engineering, Future University in Egypt
New Cairo 11835, Egypt.
ahmed.deifalla@fue.edu.eg
[3] Civil Engineering Department, Faculty of Engineering at Mataria, Helwan University
Cairo 11718, Egypt
nehal82ayash@m-eng.helwan.edu.eg
[4]Department of Civil Engineering, The Higher Institute of Engineering
El Shrouk, Cairo 11837, Egypt
M.nashaat@sha.edu.eg.

Abstract **-**. The current study evaluate the various selected design codes using an intensive collection of reinforced concrete (RC) footings, which were tested under punching shear. Three design codes were selected including ACI 318-19, EC2, and second generation of Euro code (PrEC2). The effect of the main parameters on the safety of the punching shear capacity calculated using selected methods was examined. It was found that the PrEC2 strength predictions are the closer to measurements and the most reliable. The safety of the punching shear predicted using the ACI is directly proportional with the flexure reinforcement ratio While the safety predicted using the EC2, and PrEC2 design codes is inversely proportional. This is due to the EC2, and PrEC2 design codes considered the flexure reinforcement ratio while the ACI neglected its effect. The spring simulation of the subsoil, provide capacity compared to the sand box model with respect to those obtained experimentally.

Keywords**:** Column-footing, Punching shear capacity, EC2, PrEC2, ACI318-19

1. Introduction

The structural components, which are responsible for transferring the loads from the skeleton structure to the soil underneath, is the reinforced concrete (RC) footings. Therefore, they are simultaneously loaded by rection of the subsoil below and the forces from the elements of the super structure. These reaction forces are far more intense, thus it's important to include them when estimating punching capacity. The capacity of the footing is frequently limited by the punching shear failure. This failure is an undesired failure mechanism, with a brittle nature.

Due to the difficulties of the tests, the experimental investigation for the punching shear capacity of the footings has been difficult. As a result, the testing setups must consider a large number of influential factors that should be taken into consideration, as well as significantly higher costs. The punching shear capacity of footing depends on various parameters, such as the concrete's compressive strength, the flexural reinforcement ratio, the stiffness of the foundation-soil system, and the foundation's shear slenderness.

Numerous experimental and analytical studies had been conducted to investigate the punching shear capacity of footings and calibrate the various national and international design codes [1-14]. For the literature review, it was found that: (1) all selected design codes provide conservative estimates for the punching shear capacity of slender R.C. footings, while being less conservative for compact footings; (2) size effect and shear span to depth ratio are significant affecting the strength; and (3) the new Euro-code draft provides superior strength predication compared to all selected design codes. This study is a component of ongoing, in-depth research in the area of punching in column footings. This study's goal is to investigate how column footings without reinforcement for punching shear are designed for punching shear capability. The following international design codes were calibrated for determining the punching shear capacity of the footings: ACI 318-19, EC2 (2004), and PrEC2 (2020). A total of 195 footings without stirrups were included in the database. It looked at how design factors, such as the size of the footing, the material's characteristics, and the modelling of the soil beneath the footing, affected the punching shear capacity that was computed using these selected international design codes and standards.

2. Experimental tests of footings and selected design codes

A data base for a total of 195 specimens from the previous experimental works on column footings as collected from [1-14, 26-31]. These column footings connections have a wide variety of material and geometrical features with footing dimensions ranged between (800 – 3050 mm), the column widths (150 – 534 mm), the footing depths (82 – 760 mm), the shear slenderness ratios (0.44 – 10.48), the compressive concrete strength (7.92 – 47.6 MPa), the flexural reinforcement ratios (0.12% – 1.77%) and the yielding strengths of steel reinforcement (289 – 580 MPa).

In the followed parts, the determination of the punching shear capacity of footings according to ACI 318–19 [32], EC2 (2004) [33], and PrEC2 2020 [34], are presented as follow and summarized in Table (1). The area of the portion of the footing's contact surface inside the critical perimeter A0 varies on where it is and how it is shaped, and it is specified differently in the standards. Some codes do not distinguish between punching through flat slabs and foundations because the essential perimeters are employed in the same locations and shapes in both situations.

Table (1) Summary of design codes / standards / guidelines for punching shear.

Code provision	*Concrete strength factor*	*Reinforcement ratio factor*	*Geometry effect factor*
ACI 318	$\sqrt{f'_c}$	N/A-	$\lambda_s = \sqrt{\frac{2}{1+0.004d}} \leq 1, \left(2+\frac{\alpha_s d}{b_o}\right), \left(1+\frac{2}{\beta}\right)$
EC2	$\sqrt[3]{f_{ck}}$	$\sqrt[3]{\rho_l}$	$\lambda_s = \left(1+\sqrt{\frac{200}{d}}\right) \leq 2.0$
PrEC2	$\sqrt[3]{f_{ck}}$	$\sqrt[3]{\rho_l}$	$k_{pb} = 3.6\sqrt{1-\frac{b_0}{b_{0.5}}},\ a_{pb} = \sqrt{\frac{a_{p\,.\,d_v}}{8}}$

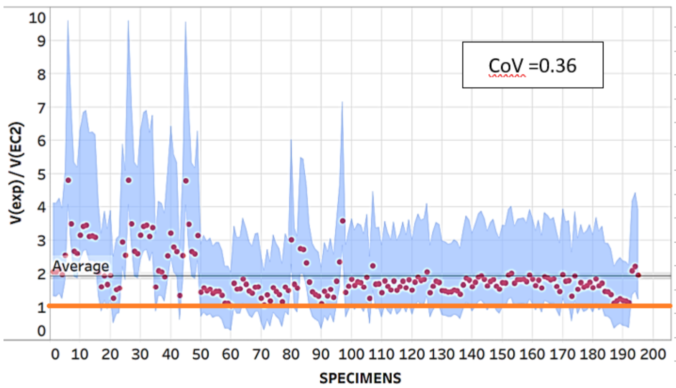
3 Evaluation of Different Codes Provisions:

195 previous test results of footings demonstrating punching failure were gathered in order to confirm the reliability of the existing design methodologies. ACI 318-19, EC2 (2004), and PrEC2 2020, were among the punching shear design equations. For each specimen in the database, the ratio of experimental outcomes to calculated results (Vexp /Vcalc) was determined as indicated in Figure (1). When comparing the values computed for punching-shear using all examined design codes to those obtained experimentally, it is noted that the values of (Vexp /Vcalc) are more than 1.0, this is meaning that there is underestimation of the calculated values of punching- shear using all studied design codes when compared with that obtained experimentally [4], [5], [7], [9], and [12]. The statistical findings for the ratio of the experimental to the analytical shear capacity (Vexp /Vcalc) utilizing different shear design equations are shown in Table (2). The statistical results provided the maximum, minimum, average, standard deviation, coefficient of variation, confidence limits, and intervals of the ratio for experimental to calculated punching shear capacity of examined footings to aid in evaluating the precision of the design punching shear. When applying the appropriate adjustment factors, the acquired statistical parameters are crucial. Less data allows the safety ratioto have lower values while still being valid, resulting in a more cost-effective design. The standard deviation determined how much a collection of numbers varied or were dispersed. High value means that there is depression with a wider range. The percentage measure of a probability distribution's dispersion is called the coefficient of variation. The chance that a sample is representative of the complete population from which it was drawn is referred to as the confidence limits are referred to the probability that a sample is true for the entire population from which it was sampled. The

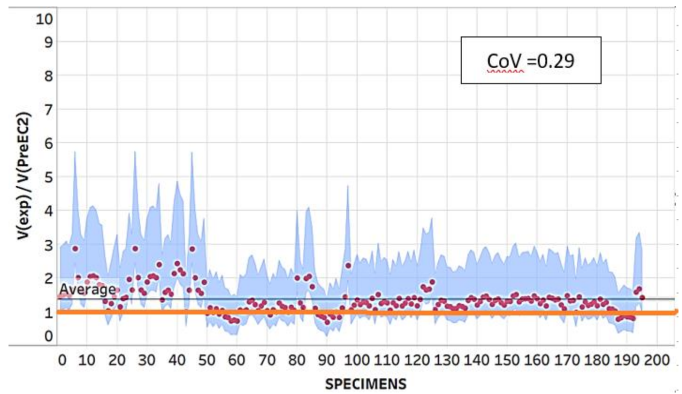
confidence intervals show the range with an upper bound and a lower bound in which the true value is likely to fall within. It is calculated as follow:

$$\text{Mean of samples} \mp \textit{standard deviation} * \frac{\text{Confidence Level}}{\sqrt{\text{sample size}}}. \quad (1)$$

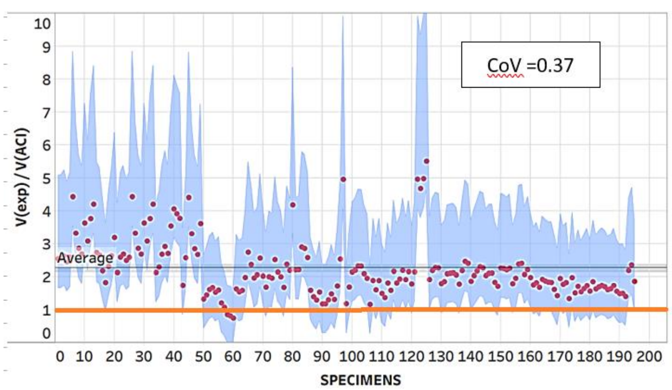
From Table (2), when EC2 and PrEC2 design codes are compared, it is found that PrEC2 has a lower factor of modification and is regarded as being more dependable than EC2 [1]. Compared to EC2, PrEC2 has 70% lower averages, standard deviations, and lower and upper 95% confidence limits. This is due to the fact that PrEC2 included enhancement factors for estimating punching shear, and they are based on the perimeter at a distance of 0.5 effective depths from the edge of the loaded region and the length of the column periphery, which produces less conservative findings than EC2.



(a) EC2



(b) PrEC2



(c) ACI

Figure (1) Safety ratio for studied design codes compared to confidence intervals 95%.

Table (2) Statistical measures of safety ratio

Design code	*EC2 2004*	*prEC2 2020*	*ACI-318 (2019)*
Average	1.91	1.37	2.25
Coefficient of variation (COV)	36%	29%	37%
Lower limit 95% Confidence	1.81	1.88	2.13
Minimum	1.03	0.69	0.12
Maximum	4.8	2.87	5.5

4 Effect of Parameters on Safety Factors

For the analysis of the influence of individual characteristics of the footing on its punching capacity as a function of applied load with respect to the predicted capacity from different design codes was considered. For additional parametric research, the examined design codes are EC2, PrEC2, and ACI. Any chart can utilize a trendline to show the trend in the data that has been plotted. This makes it easier to determine if the data values have increased or decreased. To further explore the effect of each variable on the performance of each method; thus, several categories were selected as appropriate to each variable.

4.1 Effect of Compressive strength of Concrete

When EC2 and PrEC2 design codes are compared to the other investigated codes, there is a modest difference in the safety ratio when the compressive strength of concrete is increased. This is due to the fact that the square roots of concrete's compressive strength are utilized in other examined codes equations, whereas the cubic root of concrete's compressive strength is employed in equations of the EC2 and PrEC2 design codes. The variance in the safety ratio when using PrEC2 is substantially lower than that when using EC2, i.e., the accuracy of PrEC2 code is unaffected by changes in concrete compressive strength. It is evident that the safety ratio decrease as concrete's compressive strength increases.

Table (3) Statistical measures for safety versus compressive strength of concrete.

fc (Mpa)	Safety factor		
	ACI	EC2	PrEC2
	Average		
10-20	2.49	2.16	2.38
20-30	1.99	1.63	1.77
30-40	2.40	2.14	1.97
>40	2.03	2.32	2.31
	Coefficient of variation		
10-20	0.71	0.76	0.91
20-30	0.74	0.31	0.68
30-40	0.95	0.92	0.64
>40	0.93	0.59	1.25

4.2 Effect of flexural reinforcement yielding strength

Compared to the other examined codes, the PrEC2 design code exhibits less fluctuation in the safety ratio when the yielding strength of reinforcement increases. The fluctuation in the safety ratio when using PrEC2 is substantially lower than that when using EC2, i.e., the accuracy of the PrEC2 code is unaffected by changes in the reinforcement's yielding strength. It can be noted that the safety ratio rise as the steel yielding strength does. It has been found that all design codes ignore the fact that flexural reinforcement yielding strength has a significant impact on anticipated punching shear capacity.

Table (4) Statistical measures for safety versus yield strength of reinforcement.

fy (Mpa)	Safety factor		
	ACI	EC2	PrEC2
	Average		
< 500	2.06	1.79	1.86
> 500	2.77	2.25	2.31
	Standard deviation		
< 500	0.73	0.60	0.72
> 500	0.96	0.82	0.82

4.3 Effect of flexural reinforcing ratio

Table (5) shows that, for all analyzed design codes, standards, and guidelines, there is strong convergence between experimental and calculated punching-shear capacity with less conservative values of predicted capacity as the reinforcement ratio is less than 0.4. While the calculated values of punching-shear capacity have substantial variability that are spread out and tend to be distant from the mean in cases where the reinforcement ratio is between (0.4 and 1.0), these variations are minimized when the reinforcement ratio is greater than 1.0. This suggests that as the reinforcement ratio is increased, the punching-shear values computed using these design codes decrease. As the flexural reinforcing ratio rises, these design algorithms forecast higher punching-shear values; nevertheless, the safety ratio in the EC2, and PrEC2 are reduced [3, 10]. This resulted from the fact that the EC2, and PrEC2 design codes did not take the reinforcement ratio into account in their methods. Comparing PrEC2 to the other examined codes, there is less fluctuation in the safety ratio as the reinforcement ratio is increased. Because PrEC2 uses safety ratio that vary much less than EC2 does, PrEC2 code correctness is unaffected by changes in the reinforcement ratio.

Table (5) Statistical measures for safety versus reinforcement ratios.

ρs	Safety factor		
	ACI	EC2	PrEC2
	Average		
< 0.4	1.60	1.69	1.63
0.4-1	2.46	2.02	2.13
> 1	2.31	1.70	1.82
	Standard deviation		
< 0.4	0.44	0.51	0.78
0.4-1	0.88	0.74	0.77
> 1	0.58	0.44	0.33

4.4 Effect of effective depth

As can be shown in Table (6), there is a stochastic prediction of the punching shear capacity with the maximum factor of modification for effective depths less than 200 mm. While in situations of the effective depth in between 200-300 mm in all examined codes, the anticipated values of the punching shear capacity, and factor of modification, are less conservative (excellent convergence between the experimental and computed punching- shear capacity). When the effective depth of footing is greater than 300 mm, the stochastic prediction of the punching shear capacity is once more observed [14]. The effective depth rises, the safety ratio for each design code also decreases. As the effective depth is increased, the computed values of punching-shear using all investigated design codes increase and get closer to the experimental data [10]. When compared to the other design codes, PrEC2's design code exhibits a little variance in the safety ratio as the effective depth increases. When utilizing PrEC2, safety ratio vary substantially less than when using EC2, i.e., the accuracy of PrEC2 code is less affected by changes in effective depth.

4.5 Effect of shear slenderness ratio

As shown in Table (7), it is clear that for all examined codes and for the shear slenderness ratio between 2.0 and 3.0, a stochastic prediction of the punching shear capacity with the highest factor of modification—underestimation of the computed values of punching shear—is shown. While there is good convergence between the experimental and estimated punching-shear capacities with less conservative values of the punching-shear capacity and factor of modification, there are circumstances when shear slenderness ratios are less than 2 or more than 3. The punching shear capacity of column footings accordance with shear slenderness ratio in existing design standards are showed in Figure (11). The trend lines in all of the analyzed design codes show that the safety ratio rise as the shear slenderness ratio does. As the shear slenderness ratio rises, the projected punching shear forces drop and move further away from the experimental results [11, 13]. When employing PrEC2, the variation in the safety ratio is substantially less than when using EC2.

Table (6) Statistical measures for safety versus effective depth.

d (mm)	Safety factor		
	ACI	EC2	PrEC2
	Average		
< 200	2.96	2.85	2.55
200-300	1.86	1.65	1.88
300-400	2.09	1.65	1.78
> 400	2.36	1.72	1.83
	Standarad deviation		
< 200	0.92	0.86	0.87
200-300	0.50	0.32	0.80
300-400	0.81	0.21	0.60
> 400	0.84	0.57	0.53

Table (7) Statistical measures for safety versus shear slenderness ratios.

a /d	Safety factor		
	ACI	EC2	PrEC2
	Average		
< 2.0	1.95	1.68	1.71
2.0-3.0	2.64	2.22	2.30
> 3.0	2.17	1.90	2.06
	Standard deviation		
< 2.0	0.65	0.43	0.63
2.0-3.0	1.03	0.87	0.82
> 3.0	0.31	0.51	0.80

4.6 Effect of column periphery to effective depth ratio

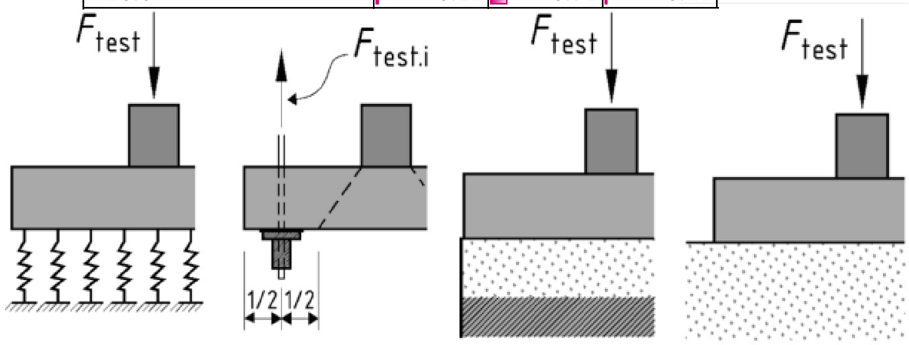
As can be shown in Table (8), there is good convergence between experimental and predicted punching-shear capacity for column periphery related to the effective depth between 2.0 and 6.0, with less conservative choices of the punching-shear capacity and factor of modification. While a stochastic forecast of the punching shear capacity with the highest factor of modification, i.e., an underestimating of the computed values of punching- shear, is found in circumstances where the column periphery related to the effective depth is less than 2.0 mm or more than 6.0. Figure (12) illustrates the punching shear capacity of column footing specimens based on column periphery related to the effective depth (b0/d) in current design codes. The trend lines in all the analyzed design codes show that the safety ratio get smaller as the column dimension gets bigger. As the column periphery related to the effective depth (b0/d) increases, the predicted punching shear forces rise and approach those observed experimentally. When employing PrEC2, the variation in the experimental-to-predicted shear strength ratio s is substantially less than when using EC2. When compared to the other investigated codes, PrEC2 design code shows less fluctuation in the safety ratio as the column periphery related to the effective depth (b0/d) is increased.

4.6 Effect of sub- soil simulation

There are different types of subsoil simulation collected from previous studies, such as elastic springs, line support, on soil and on sand box. The springs (Figure 2a) represents perfectly elastic subsoil. The line supports (Figure 2b) were usually placed at half distance between the end of a footing and section where the critical shear crack crosses bending reinforcement. The on-soil simulation (Figure 2c) consists of multi-layer soil which is the more realistic configuration of the tests because non-uniform ground pressure. This subsoil model uses in-situ ground. The sand box model (Figure 2d) consists of layer of sand confined in a stiff box. This setup creates conditions for uniform ground pressure development under a footing.

Table (8) Statistical measures for safety versus column periphery to effective depth ratio (b0/d).

COLUMN periphery /depth (bo/d)	Safety factor		
	ACI	EC2	PrEC2
	Average		
< 2.0	4.41	1.75	3.82
2.0-4.0	2.09	1.62	1.74
4.0-6.0	2.20	2.03	2.00
6.0-10.0	2.50	2.36	2.33
> 10.0	2.22	2.56	2.07
	Standard deviation		
< 2.0	4.41	1.75	3.82
2.0-4.0	0.63	0.38	0.47
4.0-6.0	0.82	0.79	0.79
6.0-10.0	0.78	0.72	0.73
> 10.0	0.12	0.71	0.11



(a) (b) (c) (d)

Figure (2) Subsoil model types: a) springs; b) line support; c) on-soil and d) sand box

Compared to the EC2 design code, the PrEC2 design code offers fewer modifications to forecast the punching shear capacity for different types of sub-soil simulations. Table (9) illustrate the punching shear capacity of column footing specimens based on soil modeling in current design codes. The trend lines for each design code show that all of them produce good convergence values for punching shear capacity that are close to those discovered experimentally when using the spring simulation of subsoil. On the other hand, because the sand box model assumes uniform soil pressure beneath the footing, the divergence values for punching shear capacity are very different from those discovered experimentally. In terms of forecasting the factor of modification, the on-soil model is superior to the sand box model. In comparison to the spring model, the line model of soil is less accurate in predicting the factor of modification, although it is more accurate than the on-soil and sand-box models.

Table (9) Statistical results of the Safety ratio categorized based on sub-soil models.

soil type	Safety factor		
	ACI	EC2	PrEC2
	Average		
springs	2.07	1.67	1.81
line	1.32	1.44	1.21
on soil	2.43	2.19	2.19
sand box	2.75	2.00	2.29
	Standard deviation		
springs	0.72	0.23	0.65
line	0.43	0.29	0.39
on soil	0.87	0.90	0.84
sand box	0.81	0.58	0.61

5 Conclusions:

The punching shear capacity of the examined footings was determined in the current study using design codes from 195 RC columns footing experimental works that were collected from earlier investigations. The chosen design codes, standards, and recommendations to forecast punching shear capacity are ACI 318-19, EC2 (2004), and PrEC2 (2008). Selected design codes assess how design characteristics affect punching shear capacity. The following summarized the main findings.

- In comparison to experimentally measured punching shear capacity, all chosen design codes significantly understate the calculated punching shear capacity. Additionally, the second generation of the Eurocode (PrEC2) is the most accurate and dependable.
- The PrEC2 is more accurate and less conservative (about 70%) than EC2. This is due to the introduction enhancement factors which are based on the length of the column perimeter in PrEC2.
- The experimental-to-predicted shear strength ratio (Safety.) of the predicted capacity using all chosen methods is inversely proportional to effective depth, concrete compressive strength, and column dimensions; that is, the predicted capacity increases with increasing these parameters, whereas it is directly proportional to reinforcement yielding strength and shear slenderness ratio; the predicted capacity decreases with increasing these parameters. Although this parameter has a substantial impact on the outcomes, all design codes do not take reinforcement material properties into account.
- When comparing the EC2 and PrEC2 design codes to the other investigated codes, the experimental-to-predicted shear strength ratio s with increasing concrete compressive strength (fc') vary slightly. This is because other research codes utilize the square roots of fc', while EC2 and PrEC2 design codes use the cubic root of fc'.
- The safety of the estimated punching shear capacity utilizing the ACI is directly related for the flexure reinforcement ratio. When safety is calculated using the EC2, and PrEC2 design codes, it is inversely proportional to that. This is because the reinforcement ratio was taken into account in the design codes EC2, and PrEC2, whereas ACI ignored its impact.
- When using the spring simulation of the subsoil, all design codes provide punching shear capacity values that are close to those obtained experimentally. On the other hand, because the sand box model assumes uniform soil pressure beneath the footing, the divergence values for punching shear capacity are very different from those discovered experimentally. In terms of forecasting the factor of modification, the on-soil model is superior to the sand box model. In comparison to the spring model, the line model of soil is less accurate in predicting the factor of modification, although it is more accurate than the on-soil and sand-box models.

- Compared to the EC2 design code, the PrEC2 design code offers fewer modifications to anticipate the punching shear capacity for different types of sub-soil simulations.

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