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EVALUATION OF PUNCHING SHEAR CAPACITY OF TWO-WAY RC SLABS WITHOUT TRANSVERSE REINFORCEMENT ACCORDING TO DIFFERENT PROVISIONS

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Abstract

Currently, RC flat slabs are being used commonly because of their advantages. Punching shear failure is one of the governing failure modes of RC flat slabs without column capital and drop panels. In this paper, the provisions for predicting the punching shear capacity of two-way reinforced concrete (RC) flat slabs without shear reinforcement including ACI 318-19, Eurocode 2 and TCVN 5574:2018 provisions are reviewed by mean of considering the influences of the main parameters (effective depth, compressive strength of concrete, loaded area, reinforcement ratio). A total of 169 test results collected from the literature were used to compare with the provisions. The aim of this study was to evaluate the level of applicability of predicting the punching shear capacity of two-way RC flat slabs according to these provisions. The comparison results indicated that the Eurocode 2 provision provides the most accurate prediction of punching shear capacity of two-way RC flat slabs.

Keywords: punching strength capacity; two-way flat slabs; concrete; reinforcement; structural design.

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1. Introduction

In current years, reinforced concrete flat slab structure is widely used in the commercial building, parking zone, hotels, cinemas, etc. It consists of flat plates and columns without beams at the plate-column connections. Owing to the removal of beams, storey clear height can be increased whereas total building height can be reduced. This could lead to save construction cost. Another advantage of this type of RC structure is easy setting up of formwork and good slab's appearance. Punching shear failure is usually a governing problem for reinforced concrete flat slabs supported on columns. Under the high vertical loading, the diagonal cracks could occur inside the slab in the vicinity of slab-column connections. This phenomenon could lead to a progressive collapse of the overall structure [1]. In the past, the tests on RC two-way slabs were carried out by Elstner and Hognestad [2], Kinnunen and Nylander [3], Moe [4], Regan [5], Rankin and Long [6], Gardner [7], Guandalini and Muttoni [8], and the empirical expressions were proposed based on their own experimental data, which have

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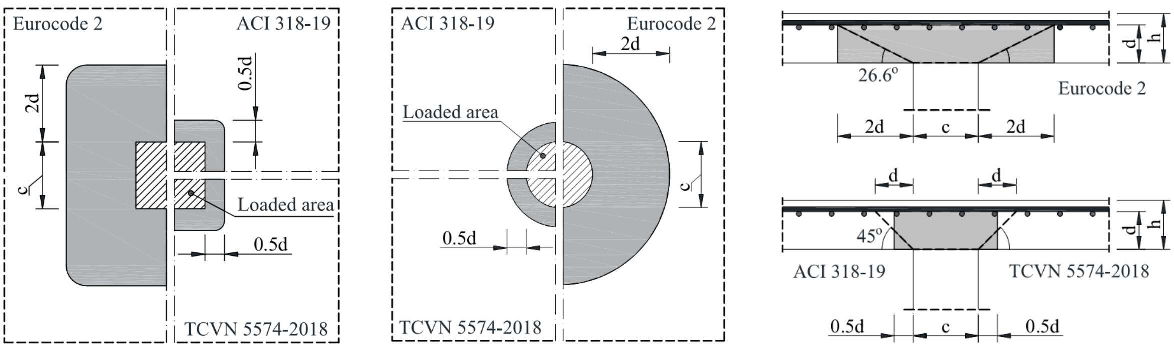
different geometric and material parameters. The studies had shown that the punching shear capacity depends on the parameters such as the effective depth of slabs, concrete compressive strength, and reinforcement ratio. The cracks propagate through the slab depth with an angle of 20 to 45 degree to the bottom of the slab [9]. Moreover, the maximum shear stress at failure of slabs significantly decreases with increasing effective depth that is the influence of size effect [10].

Currently, many design codes are used to estimate punching shear capacity of RC slabs. In this paper, the punching shear capacity of RC two-way flat slabs were calculated from the provisions of ACI 318-19 [11], Eurocode 2 [12], and TCVN 5574:2018 [13]. It was shown in the Fig. 1, the control section according to these models of two-way non-prestressed RC flat slab without shear reinforcement, column capital and drop panels. Due to neglecting low correlated parameters, the provisions are generally simple to apply in design. Their applicability was clarified by comparing to the existing experimental results. The parameters that affect the punching shear capacity of the slabs were considered as concrete strength, effective depth, reinforcement ratio, width column to effective depth ratio. Some existing experimental results of punching tests on interior column-slabs connections are used to compare these different provisions for the punching shear capacities of RC flat slabs without shear reinforcement, column capitals and drop panels.



(a) Square column (b) Circular column (c) Control section

Figure 1. Design Perimeters according to ACI 318-19, Eurocode 2, TCVN 5574:2018

2. Existing code provisions for punching shear capacity

In this section of the paper, the punching shear capacity of two-way reinforced concrete slabs is predicted by using the existing provisions of practice including ACI 318-19, Eurocode 2 and TCVN 5574:2018. The safety factors of these provisions were chosen as a value of 1.0 for justifiable comparison.

2.1. ACI 318-19

In ACI 318-19, the control section located at $d/2$ from the edges of loaded area, corresponding to a cracked angle of 45° (refer to Fig. 1). The design model considers the punching shear capacity depending on the concrete compressive strength, aspect ratio of loaded area, and size effect factor. Whereas, the flexural reinforcement ratio is neglected. In comparison with previous versions, the influence of size effect is considered in the current version. To calculate the punching shear strength of non-prestressed two-ways slabs, the ACI 318-19 code proposes the following expression:

$$V_c = \xi\lambda_s\lambda\sqrt{f_c'}b_o d \tag{1}$$

where $\xi = \min\left[0.17\left(1+2\beta^{-1}\right);0.083\left(2+\alpha_s d b_o{}^{-1}\right);0.33\right]$; V_c is the punching shear strength, in N; β is ratio of longer to the shorter dimension of the loaded area; d is the effective depth of slabs, in mm; b_o is the perimeter of the control section, in mm; $\lambda_s = \sqrt{\dfrac{2}{1+0.004d}} \leq 1$ is the size effect factor; $\lambda = 1$ is the factor for normal-weight concrete; f_c' is the cylinder compressive strength of concrete, in MPa (≤ 70 MPa); $\alpha_s = 40$ for interior columns.

2.2. Eurocode 2:2014

Eurocode 2 recommends a shear cracked inclination of 26.6° in the punching zone (refer to Fig. 1). Therefore, punching failures outside a control area of $2d$ are not considered. The code considers the parameters, including concrete cylinder compressive strength, flexural reinforcement ratio, size effect of the effective depth. The perimeter of control section of Eurocode 2 is larger than ACI 318-19. Due to a large control section, local shear stress concentrations in the surrounding of the column decrease away in the section. Therefore, the influence of the aspect ratio of loaded area are neglected. The punching shear capacity can be calculated as:

$$V_{Rd,c} = \left(\frac{0.18}{\gamma_c}k(100\rho_l f_{ck})^{1/3} + k_1\sigma_{cp}\right)b_o d \geq \left(v_{\min} + k_1\sigma_{cp}\right)b_o d \tag{2}$$

where $V_{Rd,c}$ is the punching shear strength, in N; γ_c is the partial safety factor for concrete; $k = 1 + (200/d)^{1/2} \leq 2.0$ is the size effect factor; $\rho_l = \left(\rho_{lx}\rho_{ly}\right)^{1/2} \leq 0.02$ is the mean flexural reinforcement ratio; f_{ck} is the cylinder compressive strength of concrete, in MPa (≤ 90 MPa); $k_1 = 0.15$ is an empirical factor; σ_{cp} is the horizontal component of the pre-stressing force, in MPa; b_o is the perimeter of the control section, in mm; d is the effective depth of slabs, in mm; $v_{\min} = 0.0035k^{3/2}f_{ck}^{1/2}$.

2.3. TCVN 5574:2018

The control section in TCVN 5547:2018 is the same dimension as ACI 318-19. The punching shear capacity of TCVN 5547:2018 depends on the concrete tensile strength, the effective depth of slab. In TCVN 5574:2018, the punching shear capacity was estimated by the following expression:

$$V_c = b_o d f_{ct} \tag{3}$$

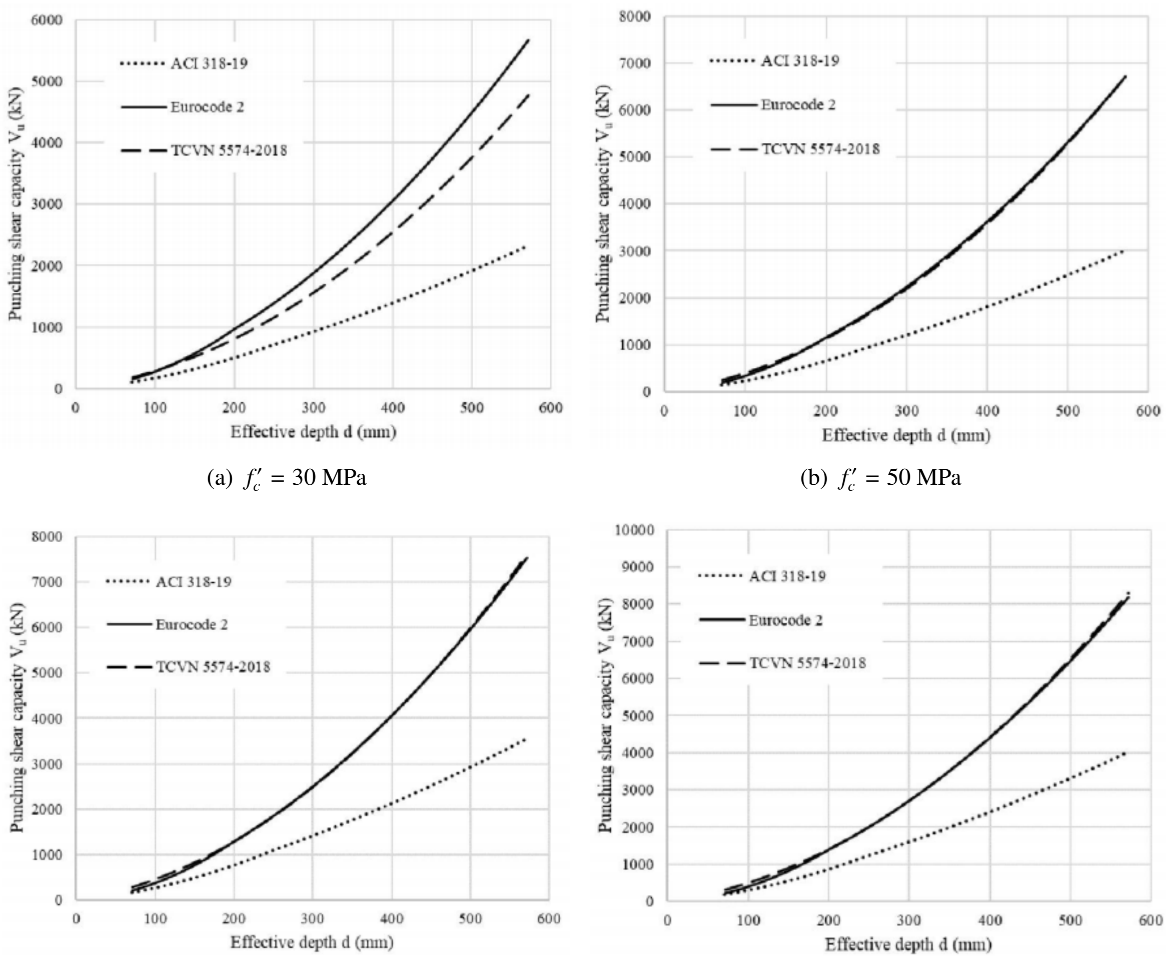
where V_c is the punching shear capacity, in N; b_o is the perimeter of the control section, in mm; d is the effective depth of slabs, in mm; f_{ct} is concrete tensile strength, in MPa. In this paper, The CEB-FIP 2010 formula was used to convert concrete compressive strengths to concrete tensile strength: $f_{ct} = 0.3(f_{ck})^{2/3}$ when $f_{ck} \leq 50$ MPa, and $f_{ct} = 2.12\ln(1 + 0.1(f_{ck} + 8))$ when $f_{ck} > 50$ MPa [14].

2.4. Comparison in different design codes

The punching shear capacity of two-way RC slabs was calculated by three code provisions to investigate the influence of the input parameters. In the section, each considered parameter increased from low to high, while other parameters remained constant. In addition, each considered parameter was calculated with the different magnitude of other constant parameters. For all the cases, the shear span length, yielding strength of reinforcement and the maximum size of coarse aggregate are 1500 mm, 365 MPa and 20 mm, respectively, and the shape of the loaded area is a square section. In this paper,

a. Effect of the effective depth

Fig. 2 presents the influence of the effective depth on the punching shear capacity at the concrete compressive strengths of 30 MPa, 50 MPa, 70 MPa, and 90 MPa. The constant parameters consist of the reinforcement ratio of 1.5%, the width column of 150 mm.



(a) $f_c' = 30$ MPa (b) $f_c' = 50$ MPa

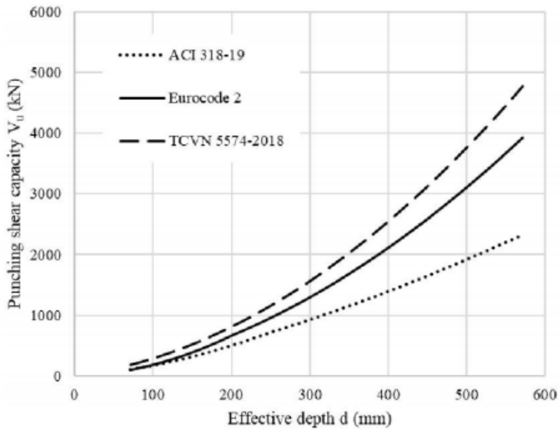
(c) $f_c' = 70$ MPa (d) $f_c' = 90$ MPa

Figure 2. Influence of the effective depth combined with concrete compressive strength

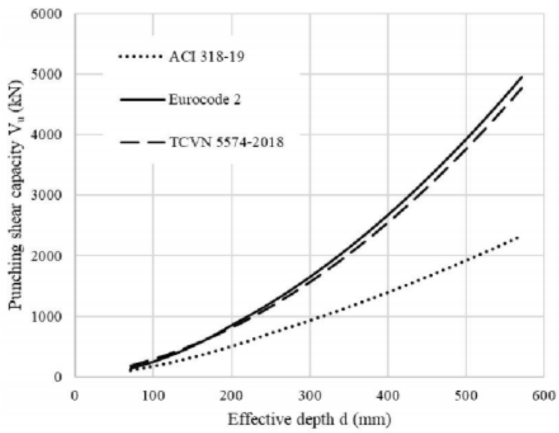
Obviously, when the effective depth increases, the punching shear capacity of slabs increase because of an increase in the control section area. However, this is not an increase in the nominal punching shear strength from different code provisions.

For the effective depth lower than 100 mm, the punching shear capacity estimated by ACI 318-19, Eurocode 2 and TCVN 5574:2018 has a slight deviation, while for the effective depth greater than 100 mm, the punching shear capacity according to Eurocode 2 gains the highest value with combining low concrete compressive strength. Moreover, for the higher concrete compressive strength, the deviation between the punching shear capacity according to Eurocode 2 and TCVN 5574:2018 decrease. The predictions of TCVN 5574:2018 and Eurocode 2 is equivalent with high concrete compressive strength.

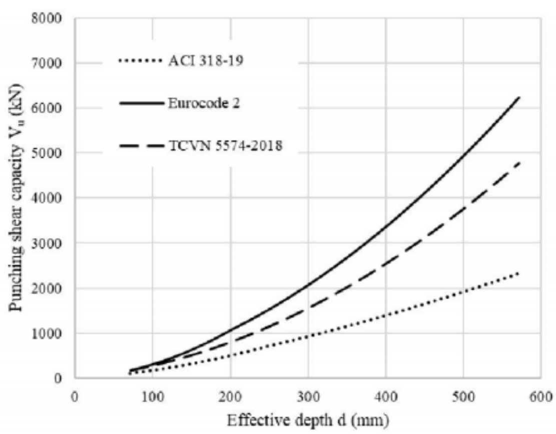
In Fig. 3, the reinforcement ratios of 0.5%, 1.0%, 2.0%, and 3.0% were designed to consider the influence of the effective depth on the punching shear capacity. The constant parameters include the concrete compressive strength of 30 MPa and the width column of 150 mm. From Fig. 3(a), the predictions of TCVN 5574:2018 are slightly higher than Eurocode 2 with the reinforcement ratio of 0.5%, and higher than ACI 318-19. Figs. 3(b), 3(c), 3(d) shows that for the higher reinforcement ratio, the deviations of the punching shear capacity according to Eurocode 2 and the other codes increase with increasing effective depth.



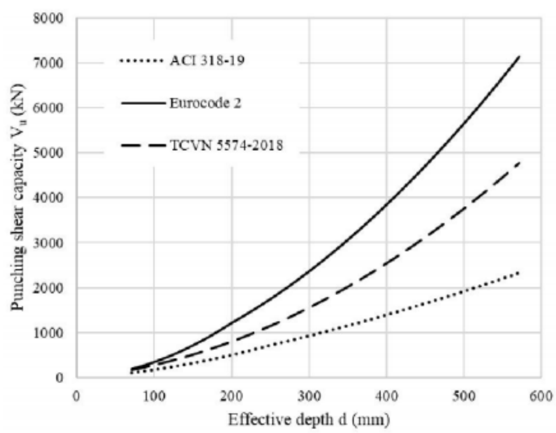
(a) ρ = 0.5%



(b) ρ = 1.0%



(c) ρ = 2.0%



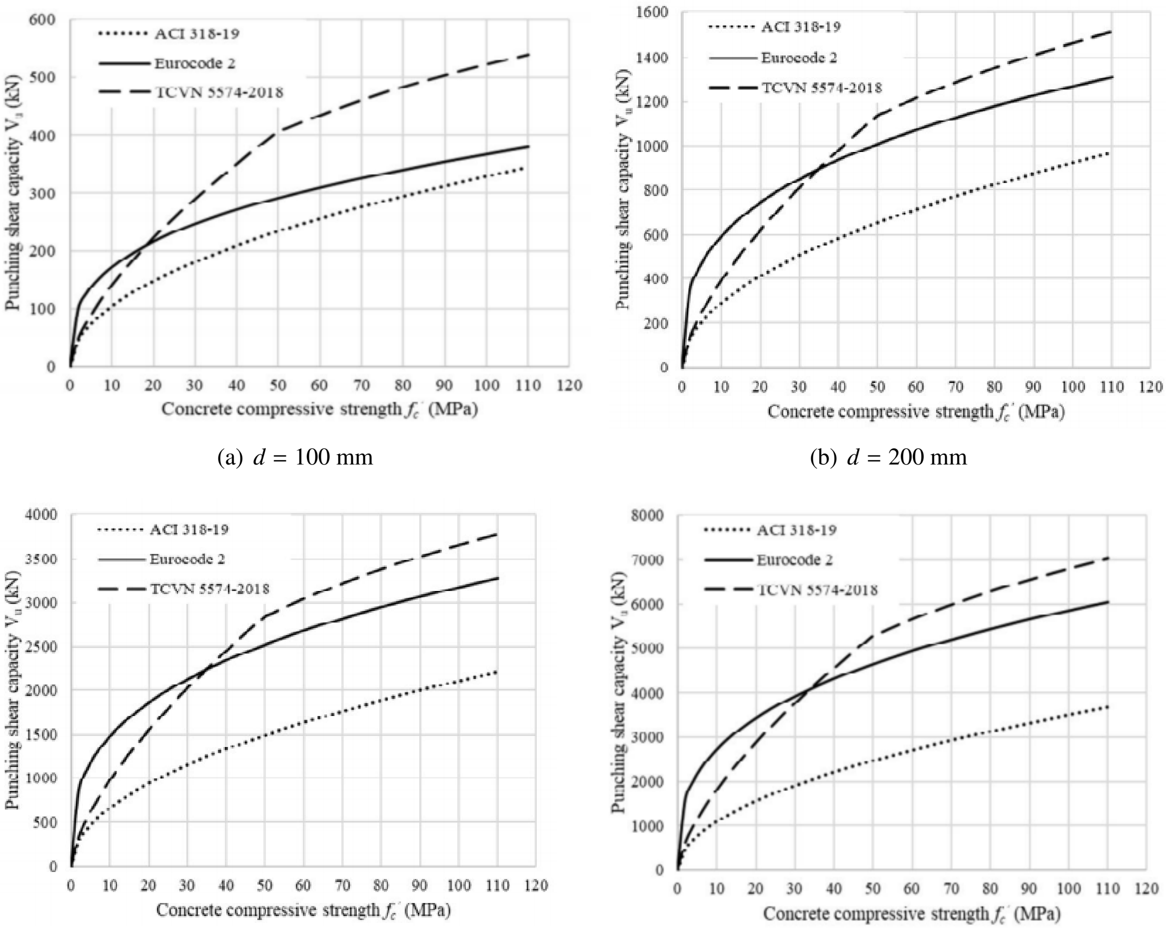
(d) ρ = 3.0%

Figure 3. Influence of the effective depth combined with reinforcement ratio

b. Effect of the concrete compressive strength

In all of the code provisions, the punching shear capacity are proportional with concrete compressive strength, this was also mentioned by Metwally et al. [15]. Figs. 4, 5 present the influence of the compressive strength of concrete on the punching shear capacity. The different magnitudes of the effective depth and the reinforcement ratio were designed to calculate (refer to Figs. 4, 5). The constant parameters consist of the width column of 150 mm, the reinforcement ratio of 1%, and the effective depth of 200 mm. The punching shear capacity estimated by ACI 318-19 is lowest in all of the cases.

With the higher concrete compressive strength, the punching shear capacity estimated by TCVN 5574:2018 is higher than the punching shear capacity estimated by other provisions. From Figs. 4(b), 4(c), 4(d), the deviation between Eurocode 2 and ACI 318-19 is approximately constant. However, the punching shear capacity estimated by Eurocode 2 could be higher than the values estimated by ACI 318-19 with combining the large effective depth and the high compressive strength of concrete (refer to Fig. 4). Fig. 5 shows that the influence of the compressive strength of concrete on the punching shear capacity estimated by Eurocode 2 with the small reinforcement ratio is lower than the capacity with the large reinforcement ratio.



(a) d = 100 mm

(b) d = 200 mm

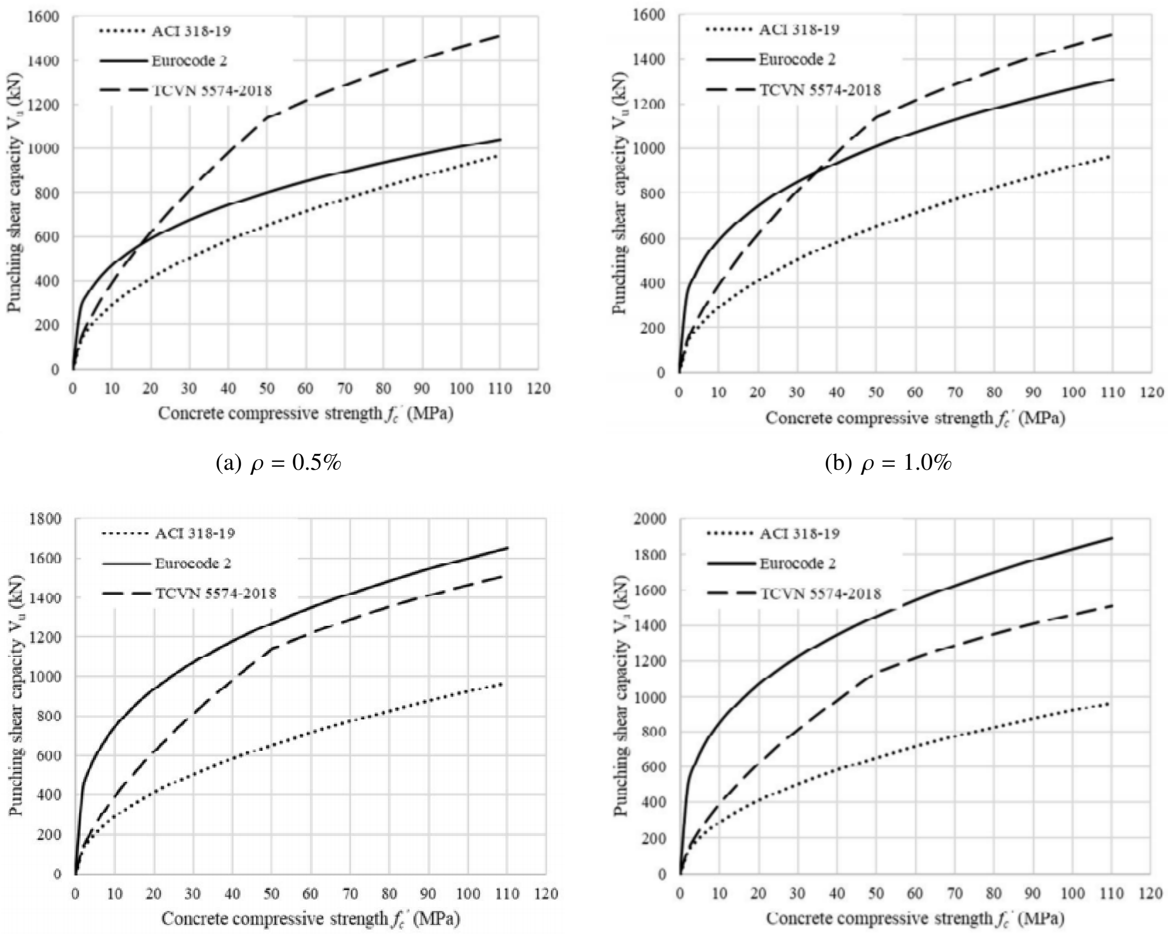
(c) d = 350 mm

(d) d = 500 mm

Figure 4. Influence of the concrete compressive strength combined with effective depth

c. Effect of the dimension of the column section

To consider the influence of the ratio of the dimension of loaded area to the effective depth, the edge length of the column (c) were selected to consider. The constant parameters consist of the effective depth of 200 mm and the reinforcement ratio of 1.0% for combining with the compressive



(a) $\rho = 0.5\%$

(b) $\rho = 1.0\%$

(c) $\rho = 2.0\%$

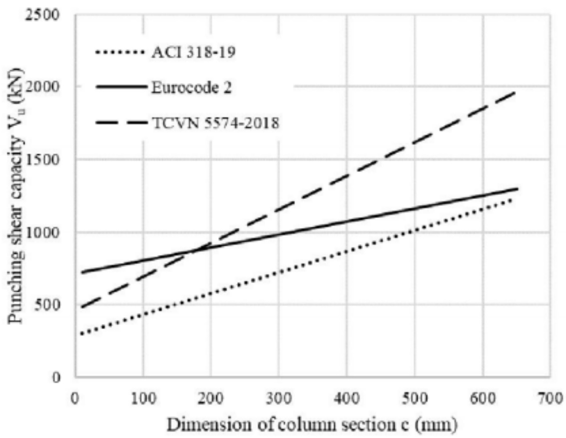
(d) $\rho = 3.0\%$

Figure 5. Influence of the concrete compressive strength combined with reinforcement ratio

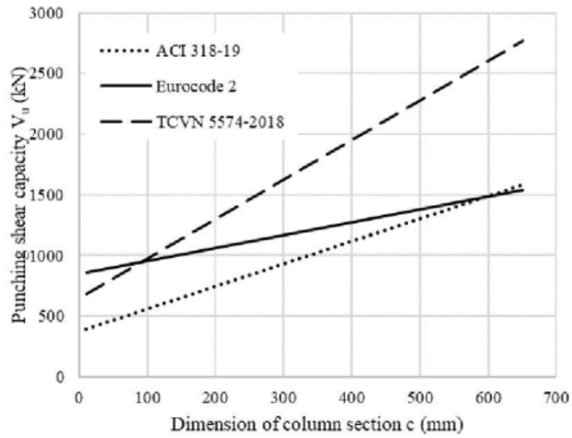
strength of concrete in Fig. 6, and the effective depth 200 mm and the concrete compressive strength of 30 MPa for combining with the reinforcement ratio in Fig. 7.

Fig. 6 shows that the punching shear capacity significantly increases when the loaded section area increase. With the large dimension of column section, TCVN 5574:2018 predicts the punching shear capacity higher than the other provisions. Moreover, the level of influence of dimension of column section on the punching shear capacity according to Eurocode 2 is lower than the other provisions, shown by the slope of the lines in Fig. 6.

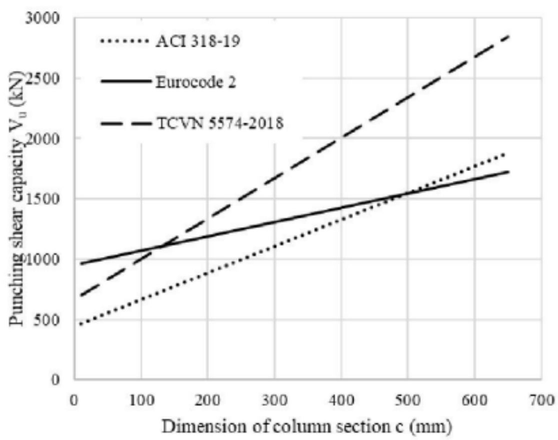
On the other hand, the effect of the dimension of columns on the punching shear capacity estimated by Eurocode 2 is lower than the punching shear capacity estimated by TCVN 5574:2018 when combining with the small reinforcement ratio (refer to Fig. 6). For the large reinforcement ratio, the effect of the dimension of columns on the punching shear capacity is approximate for Eurocode 2 and ACI 318-19, which were represented by three parallel lines in Fig. 7.



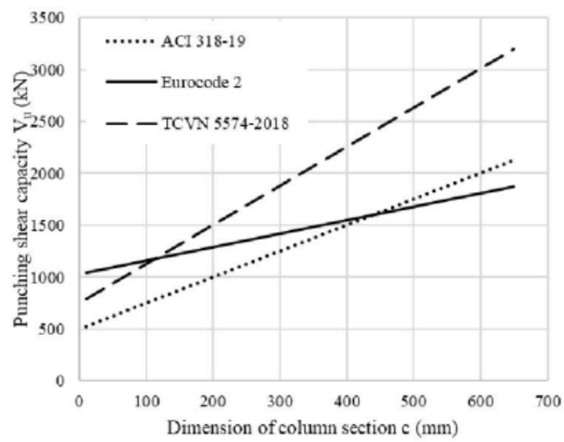
(a) f'_c = 30 MPa



(b) f'_c = 50 MPa

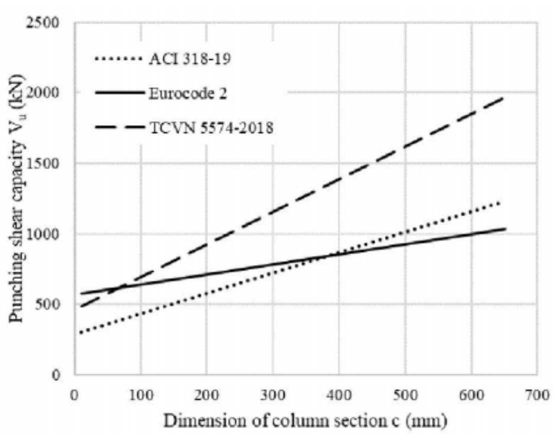


(c) f'_c = 70 MPa

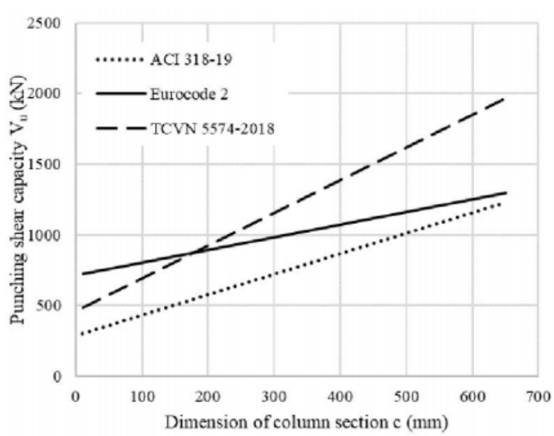


(d) f'_c = 90 MPa

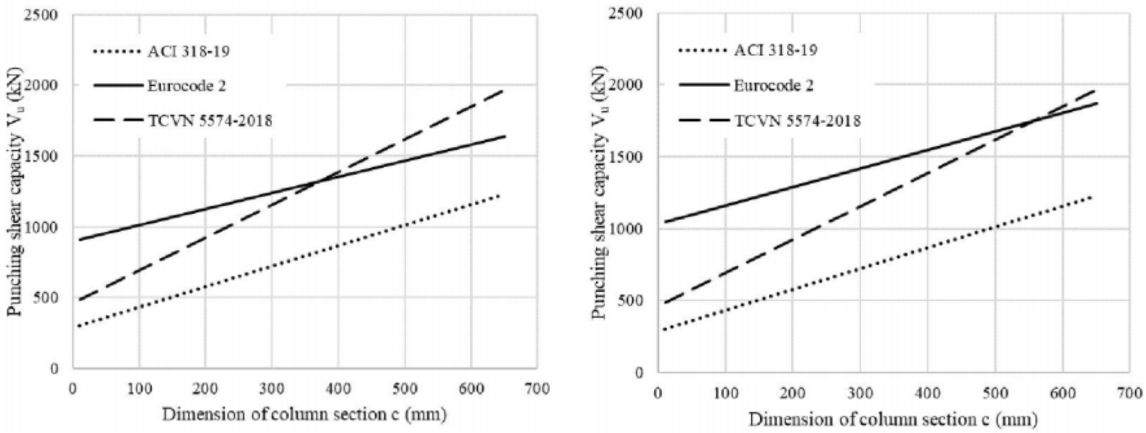
Figure 6. Influence of the column width combined with compressive strength



(a) ρ = 0.5%



(b) ρ = 1.0%



(c) ρ = 2.0% (d) ρ = 3.0%

Figure 7. Influence of the column width combined with reinforcement ratio

d. Effect of the reinforcement ratio

The effect of the reinforcement ratio was considered with remaining the other constant parameters (refer to Fig. 8). Dilger et al. [16] and Gardner [17] defended that the punching shear capacity of slabs increased as the reinforcement ratio increased. However, while Eurocode 2 provision recognizes the influence of the reinforcement ratio, ACI 318-19 and TCVN 5574:2018 are completely neglected. With low reinforcement ratio, the punching shear capacity predicted according to Eurocode 2 is lower than TCVN 5574:2018.

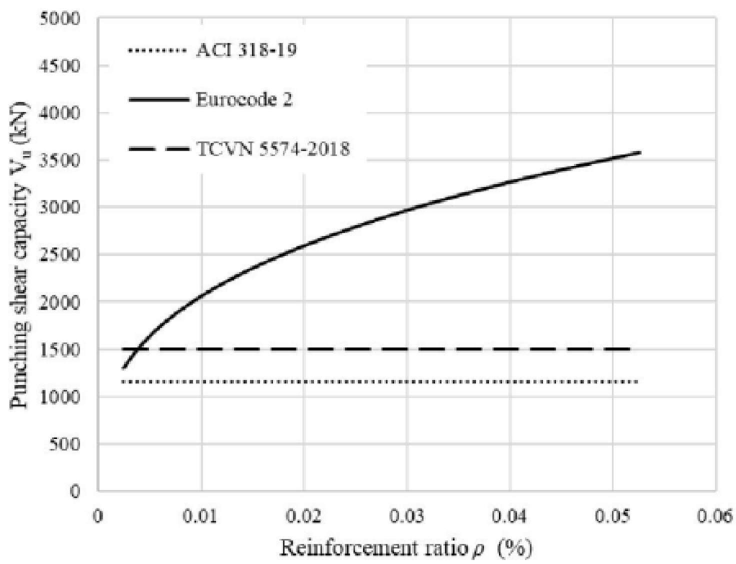
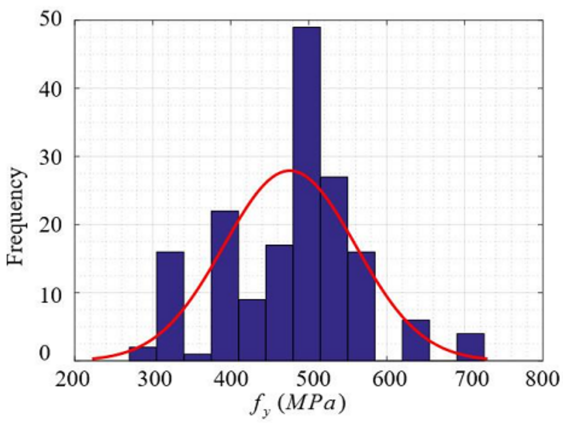


Figure 8. Influence of the reinforcement ratio

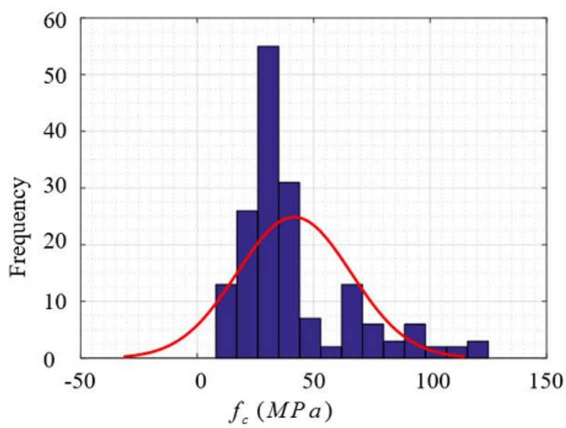
3. Database of experiment

A total of 169 experimental data of non-prestressed two-way reinforced concrete slabs subjected to concentric punching force were collected from the literature [2–8, 18–22]. In this database, the slabs had square and circular columns. The reinforced concrete slab-column connections of all test samples were no column capital, drop panels and shear reinforcement. The effective depth of the slab ranges from 35 to 500 mm, the width of the column section ranges from 51 to 520 mm, the cylinder compressive strength of concrete (f_c') ranges from 12.3 to 124.5 MPa, the reinforcement ratio (ρ) ranges from 0.22 to 5.01%, and the yield strength of reinforcement (f_y) ranges from 294 to 718 MPa. In some experiments, the concrete compressive strength was measured by different specimen types. The L'Hermite's formula was used to convert concrete compressive strengths between cylinder and cube strength, $f_c' = \left[0.76 + 0.2\log_{10}\left(\dfrac{f_{cu}}{19.6}\right)\right] f_{cu}$, in MPa [23].

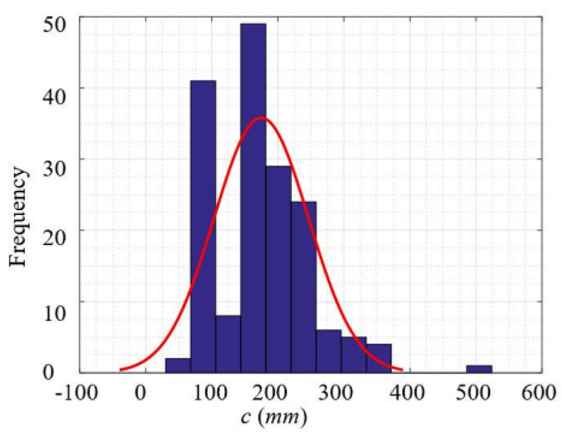
Fig. 9 shows the distribution of each parameter in the experimental data. The relationship between the punching shear capacity and five input parameters by the correlation plot is shown in Fig. 10. It can be observed that there is pairwise relationship between parameters with corresponding correlation coefficients for each indicator. As shown in Fig. 10, the parameters including the effective depth,



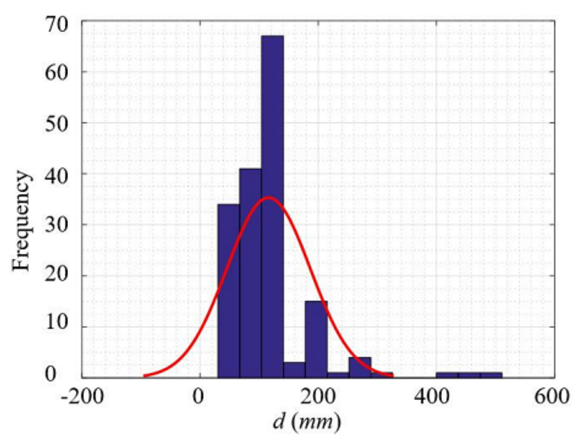
(a) Tensile strength of reinforcement



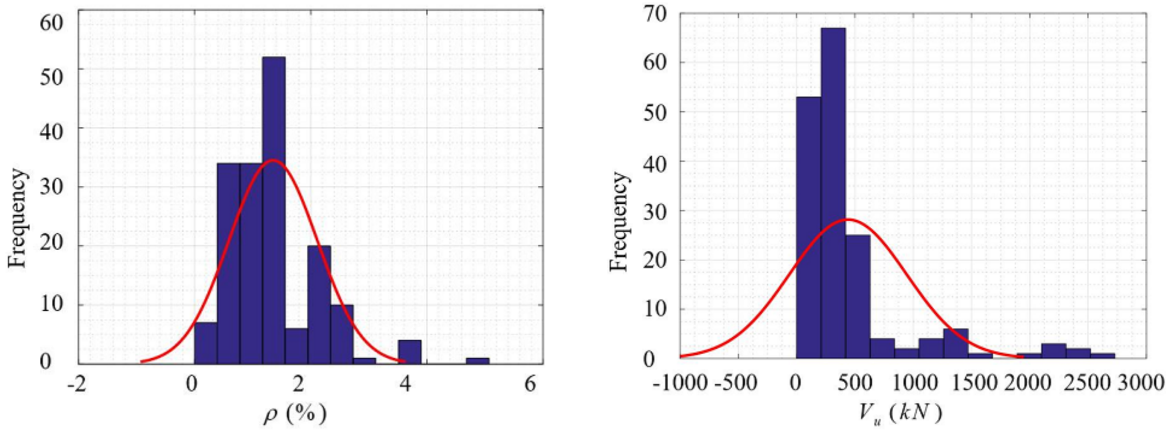
(b) Compressive strength of concrete



(c) Width of column section



(d) Effective depth



(e) Reinforcement ratio

(f) Punching shear strength

Figure 9. Histogram of the input parameters of the database

the compressive strength of concrete and the loaded area are highly correlated with the punching shear capacity. However, the reinforcement ratio and the tensile strength of reinforcement are lowly correlated with the punching shear capacity.

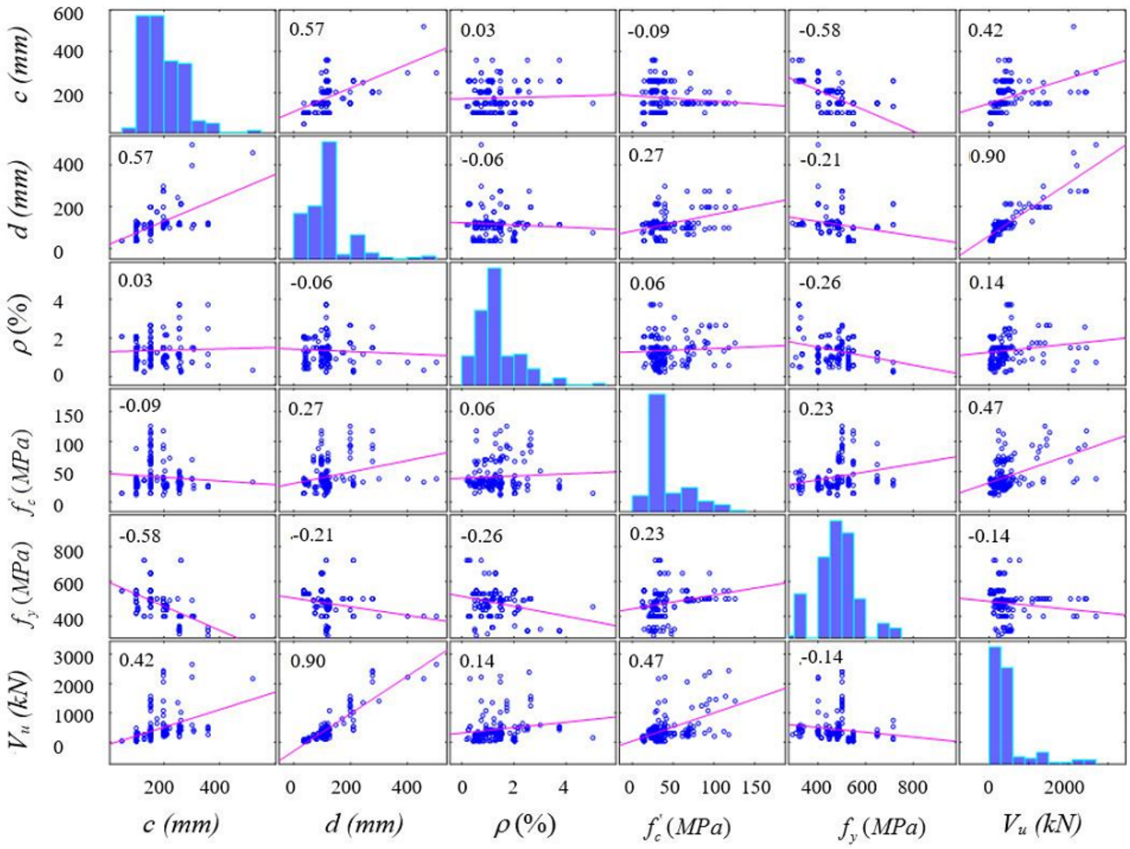


Figure 10. Correlation matrix of the database

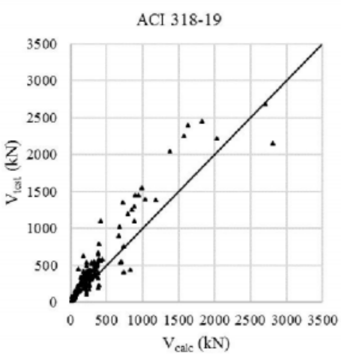
4. Comparison between the code provisions and the database

Values of the punching shear capacity of the tests were calculated by using the different provisions presented in the section 2. All safety factors of these provisions were chosen as a value of 1.0 and values of material strengths were mean values for justifiable comparison. The ratio between the experimental value and the predicted value in accordance the different code provisions (V_{test}/V_{calc}) was used to assess the applicability [24]. Table 1 summarized the statistical measurement of comparison of the punching shear capacity of slabs between these code provisions and the database. The mean value for the Eurocode 2 for estimating the experimental results equal 1.133 while the mean value for the ACI 318-19 is 1.523. This indicates that the estimated values in accordance with ACI 318-19 are more conservative, while Eurocode 2 predictions are fit the experimental results. The coefficient of variation shows the scale of the variability in comparison to mean value. The coefficient of variation of Eurocode 2 is smallest that indicates a minimized level of scatters in the results.

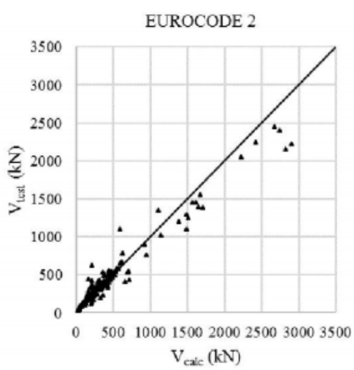
Table 1. Statistical results of the different code provisions

	Test/ACI 318-19	Test/Eurocode 2	Test/TCVN 5574:2018
Mean	1.523	1.133	1.206
Standard deviation	0.524	0.314	0.617
Coefficient of variation	0.344	0.277	0.512

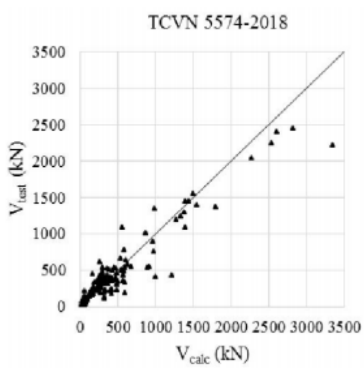
Fig. 11 shows the correlations between the calculated values according to the different code provisions and the experimental values. It is clear, the punching shear capacity estimated by Eurocode 2 has the highest correlations compared to CEB-FIP 2010, ACI 318-19 and TCVN 5574:2018.



(a) ACI 318-19



(b) Eurocode 2



(c) TCVN 5574:2018

Figure 11. Comparison between the code provisions and experimental data

5. Conclusions

The punching shear capacity of slabs according to these design provisions were presented in this paper, including ACI 318-19, Eurocode 2 and TCVN 5574:2018. The parametric study was carried out to consider the influence on the punching shear strength according to three provisions. The predictions of the provisions on the punching shear capacity of slabs were compared with the experimental database. The following conclusions were summarized below:

For two-way non-prestress RC flat slabs without transverse reinforcement, column capitals and drop panels, ACI 318-19, Eurocode 2 and TCVN 5574:2018 provisions consider the influence of the main parameters similarly, excepting the influence of the reinforcement ratio. In comparison to the ACI 318-19 and TCVN 5574:2018, the punching shear capacity estimated by Eurocode 2 predicts a larger value when considering the influence of effective depth. This tendency is for TCVN 5574:2018 with the larger dimension of loaded area combined with small reinforcement ratio or the high compressive strength of concrete.

The ACI 318-19, Eurocode 2 and TCVN 5574:2018 provisions predict a conservative value of the punching shear capacity of two-way RC flat slab without transverse reinforcements, column capitals and drop panels. The Eurocode 2 code provision predict the punching shear capacity of the slab more accurate than the other provisions. The mean values of V_{test}/V_{calc} were 1.133, 1.523 and 1.206 for the Eurocode 2, ACI 318-19 and TCVN 5574:2018 respectively, and the coefficient of variation for the Eurocode 2 was 0.277.

References

[1] Adom-Asamoah, M., Kankam, C. K. (2008). Behaviour of reinforced concrete two-way slabs using steel bars milled from scrap metals. *Materials & Design*, 29(6):1125–1130.

[2] Elstner, R. C., Hognestad, E. (1956). Shearing Strength of Reinforced Concrete Slabs. *ACI Journal Proceedings*, 53(7):29–58.

[3] Kinnunen, S., Nylander, H. (1960). *Punching of concrete slabs without shear reinforcement*, page 112. New York: Elander.

[4] Moe, J. (1961). *Shearing strength of reinforced concrete slabs and footings under concentrated loads*. Portland Cement Association, Research and Development Laboratories.

[5] Regan, P. E. (1984). The dependence of punching resistance upon the geometry of the failure surface. *Magazine of Concrete Research*, 36(126):3–8.

[6] Rankin, G. I. B., Long, A. E. (1987). Predicting the punching strength of conventional slab-column specimens. *Proceedings of the Institution of Civil Engineers*, 82(2):327–346.

[7] Gardner, N. J. (1990). Relationship of the Punching Shear Capacity of Reinforced Concrete Slabs With Concrete Strength. *ACI Structural Journal*, 87(1):66–71.

[8] Guandalini, S., Burdet, O., Muttoni, A. (2009). Punching Tests of Slabs with Low Reinforcement Ratios. *ACI Structural Journal*, 106(1):87–95.

[9] Phong, N. H. (2010). Method of strengthening the shear resistance of reinforced concrete beams with continuous fiber cable. *Journal of Science and Technology in Civil Engieering (STCE) - NUCE*, 4(2).

[10] Bažant, Z. P., Cao, Z. (1987). Size Effect in Punching Shear Failure of Slabs. *ACI Structural Journal*, 84 (1):44–53.

[11] ACI 318-19 (2019). *Building code requirements for structural concrete (318-19) and commentary (318R-19)*. American Concrete Institute, Farmington- Hills, Michigan.

[12] Eurocode 2 (2004). *Design of concrete structures. Part 1-1: General rules and rules for buildings*.

[13] TCVN 5574:2018. *Design of concrete and reinforced concrete structures*. Ministry of Science and Technology, Vietnam.

[14] FIB MC (2010). *Model code 2010-final draft*, volume 1. Bulletins: Lausanne, Switzerland.

[15] Metwally, I. M., Issa, M. S., El-Betar, S. A. (2008). Punching shear resistance of normal and high strength reinforced concrete flat slabs. *Civ Eng Res Mag*, 30(3):982–1004.

[16] Dilger, W., Birkle, G., Mitchell, D. (2005). Effect of flexural reinforcement on punching shear resistance. *Special Publication*, 232:57–74.

[17] Gardner, N. J. (2011). Verification of Punching Shear Provisions for Reinforced Concrete Flat Slabs. *ACI Structural Journal*, 108(5):572–580.

[18] Marzouk, H., Hussein, A. (1992). Experimental Investigation on the Behavior of High-Strength Concrete Slabs. *ACI Structural Journal*, 88(6):701–713.

[19] Tomaszewicz, A. (1993). *High-Strength Concrete-SP2-Plates and Shells, Report 2.3*. Punching Shear Capacity of Reinforced Concrete Slabs, Norway.

[20] Ramdane, K. E. (1996). Punching shear of high performance concrete slabs. In *Proceedings of the fourth international symposium on utilization of high-strength/high performance concrete*, volume 3, 1015–1026.

[21] Li, K. K. L. (2000). *Influence of size on punching shear strength of concrete slabs.* Doctoral dissertation, McGill University, Montreal, Québec.

[22] Timm, M. (2003). *Punching of foundation slabs under axisymmetric loading*. PhD dissertation, Institute for Building Materials, Concrete Structures and Fire Protection of the Technical University Braunschweig.

[23] Neville, A. M. (1995). *Properties of concrete*, volume 4. Longman London.

[24] Lapi, M., Orlando, M., Angotti, F., Spinelli, P. (2016). Comparison of recent code provisions for punching shear capacity of R/C slabs without shear reinforcement. In *Conference on Italian Concrete Days*, 113–132.