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Punching shear resistance of reinforced concrete footings: evaluation of design codes

Resistência à punção de sapatas de concreto armado: avaliação de normas de projeto



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Abstract

Punching is a possible failure mode for slender footings and it may lead a structure to ruin through progressive collapse. Although footing present different geometric characteristics, their punching shear design is based on the empirical methods used for flat slabs. This paper uses experimental results from 216 tests to evaluate the performance of design code recommendations presented by ACI 318 (2014), ABNT NBR 6118 (2014) and Eurocode 2 (2010) to estimate the punching shear resistance of reinforced concrete footings. Great dispersion between theoretical and experimental results was observed, being evident that the test system affects the punching shear capacity of footings. The more complex method proposed by Eurocode 2 resulted in a better correlation with experimental results.

Keywords: punching shear, footings, reinforced concrete.

Resumo

A punção é um possível modo de ruptura para sapatas esbeltas e pode levar uma estrutura à ruína através do colapso progressivo. Apesar das sapatas apresentarem características geométricas diferenciadas, seu dimensionamento à punção é feito com base em métodos empíricos similares aos usados para ligações laje-pilar. Este artigo utiliza resultados experimentais de 216 ensaios para avaliar o desempenho das recomendações apresentadas pelas normas ACI 318 (2014), ABNT NBR 6118 (2014) e Eurocode 2 (2010) para a estimativa da resistência à punção de sapatas de concreto armado. Foi observada grande dispersão entre os resultados teóricos e experimentais, ficando evidente que o tipo de sistema de ensaio afeta a resistência à punção de sapatas. O método mais complexo proposto pelo Eurocode 2 resultou em uma melhor correlação com os resultados experimentais.

Palavras-chave: punção, sapatas, concreto armado.

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1. Introduction

Choosing the type of foundation is a fundamental step in the process of designing a structure. Failures at this stage can lead to either inadequate performance in service or represent risks to the safety of the building. The foundation elements are usually classified in two ways: shallow foundations and deep foundations. Footings are shallow foundations that transfer the loads from the structure to the soil through their base.

Punching shear is a possible failure mode for slender footings, that according to BROMS [1] is characterized by a shear-like crack, which extends from the ends of the column to the face of the footing base, but in a breakout cone shape. The punching shear resistance of reinforced concrete footings can be affected by different parameters, like the compressive strength of concrete, the flexural reinforcement ratio, the geometry, thickness and slenderness of the footing. Figure 1 illustrates an application of reinforced concrete footings with large dimensions as a foundation for a wind tower in the United Kingdom.

Figure 1
Examples of the use of footings as foundation in large structures

In cases where these elements have variable height, design codes like EUROCODE 2 [2] recommend that the punching shear resistance can be verified in failure planes with different inclinations, as shown in Figure 2. According to HEGGER *et al*. [3] and [4], in the case of footings, the angle of the failure plane is also affected by the ratio *a/d*, especially due to arch action, tending to be 45° for cases where $a/d \leq 1.25$ and less than 35° for cases where $a/d \geq 2$. The punching shear design of footings is based on empirical methods presented by design codes for concrete structures. These methods were developed based on available experimental evidences, which mostly refer to tests on slab-column connections. This paper presents an evaluation of the performance of design codes like ACI 318 [5], EUROCODE 2 [2] and ABNT NBR 6118 [6] in the prediction of the punching resistance of reinforced concrete footings without shear reinforcement. This is made through the analysis of the correlation between theoretical and experimental resistances using a database with 216 selected test results. A penalty criterion proposed by COLLINS [7] is used to evaluate the reliability of these design code recommendations. The composition of this database followed a selection methodology aiming to allow the evaluation of different parameters in the punching shear resistance of reinforced concrete footings. In these analyses, the compressive strength of concrete (f_c), the effective depth of the footing (d), the flexural reinforcement ratio (ρ), and the ratios between the column perimeter and the shear span-to-depth ratio of the footing (u_0/d e a/d) are considered. It is a relevant discussion that takes place in an international context, with recent contributions, such as the ones of SIMÕES *et al*. [8] and [9] and KUERES *et al*. [10].

2. Historical development of the punching shear study on footings

Footings are characterized by transferring loads directly to the soil through their base, and in these cases, the stress distribution depends on the type of the soil under which the footings are settled. According to MACGREGOR and WIGHT [11], a reinforced concrete footing supported by a sandy soil will have a stress distribution like the one in Figure 3a. In this case, the sand near the ends of the footing tends to move laterally when the footing is loaded, causing a decrease of soil stresses in this region. In case of footings under a clay soil base, the stress distribution is similar to what is presented

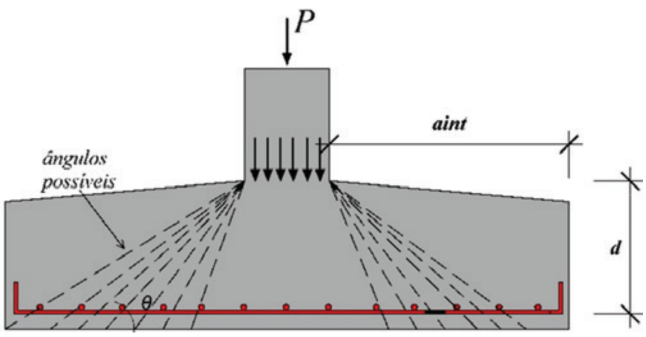


Figure 2
Punching shear failure in reinforced concrete footings without shear reinforcement

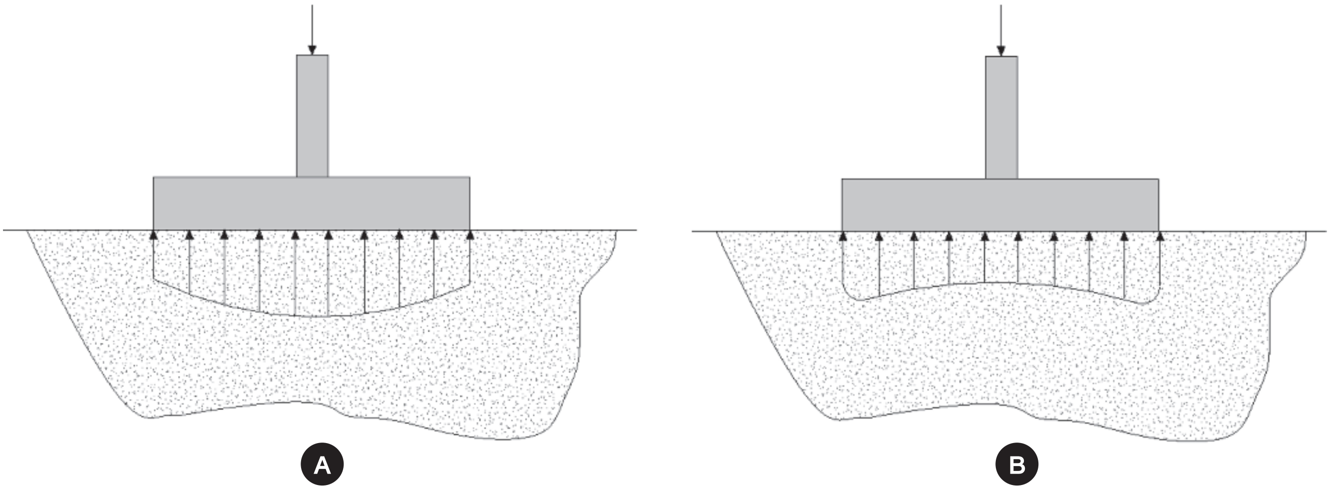


Figure 3
Stress distribution as a function of the soil type. a) sandy soil; b) clayey soil. (MACGREGOR e WIGHT [11])

in Figure 3b. It is possible to notice that as the footing is loaded, the soil deforms in a cup shape, relieving stresses in the central region of its base. For structural design purposes, it is common to assume that soil stresses are distributed steadily in the base.
HEGGER *et al*. [3] say that in case of footings *a/d* significantly influences punching shear resistance. According to these authors, the influence of this parameter is greater than from those usually considered in design, such as the compressive strenght of concrete (f_c) and the flexural reinforcement ratio (ρ), since in these cases the inclination of the failure plane is directly related to this ratio. EUROCODE 2 [2] is the only design code that recommends the consideration of this parameter when estimating punching shear resistance of reinforced concrete footings. Figure 4 illustrates the variation of the critical shear span (a_{crit}) to punching shear resistance for reinforced concrete footings in accordance to Eurocode in function of the effective depth of the footing.

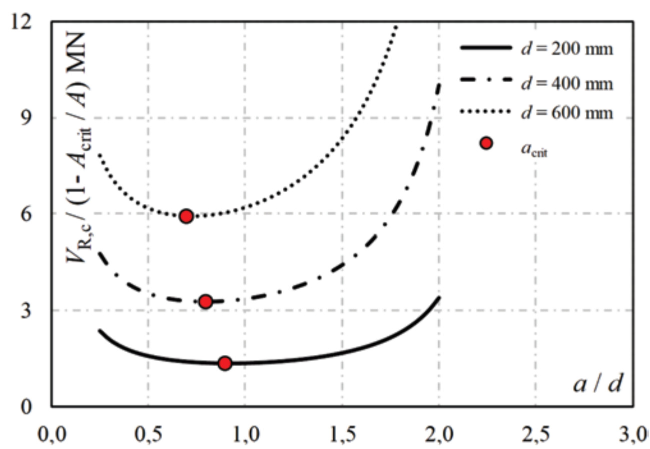


Figure 4
Variation of a_{crit} according to Eurocode 2 in function of the footing thickness.
Assumed: c = 300 mm, ρ = 1%, f_c = 25 MPa, u = c + 4d

Historicaly, the first study on punching shear was published in 1913 by TALBOT [12], who performed a long series of tests on reinforced concrete footings, simulating the interaction between the footing and the soil through steel springs. After him, many researchers contributed to the study of punching shear on footings, evaluating different simulation methods of the soil reaction. DIETERLE and STEINLE [13] and DIETERLE and ROSTÁSY [14] used a system with many hydraulic cylinders driven together to simulate the application of a uniformly distributed load through the base of the footing, being a reference to future studies like the one from HALLGREN *et al*. [15], who tested footings with uniformly distributed loading systems and also radially concentrated reaction ones, similar to the procedure used for testing slab-column connections locally.
HEGGER *et al*. [3] and [4] used a test system with a sandbox to simulate the soil effect, having as one of the variables the sand degree of compaction, which varied from loose to dense. Later, BONIĆ and FOLIĆ [16] also performed tests of this type, but using a mixture of sand and river gravel. Figure 5 shows some of the different systems used to test punching shear resistance of footings. It is important to highlight that the variety of test systems used to compose the existent experimental database for punching shear on footings can be constructed on a variable capable of influencing the quality and reliability of these results.

3. Methods to estimate punching shear resistance

3.1 ACI 318

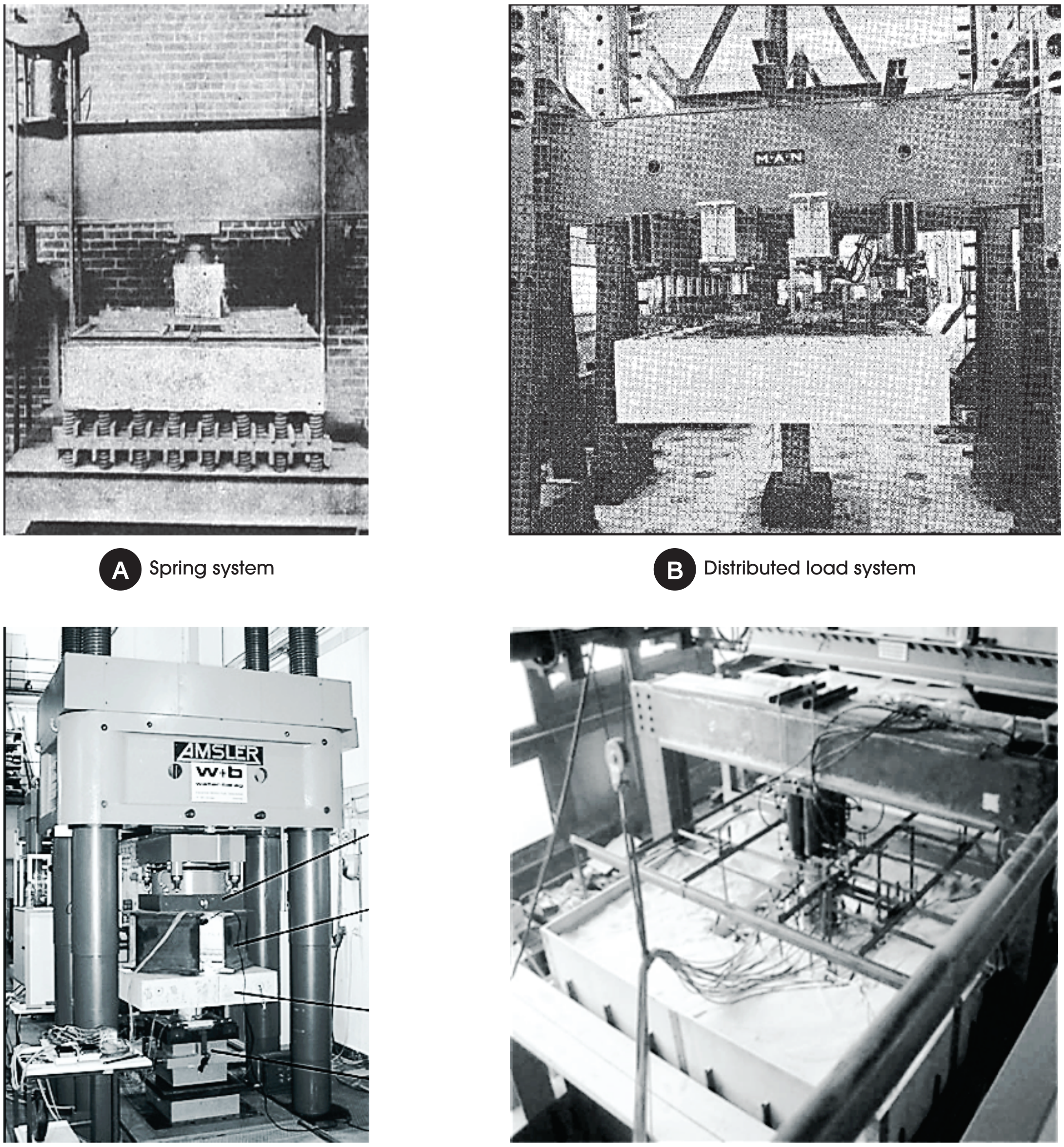
According to ACI 318 [5], the verification of punching shear resistance on footings shall be done by verifying shear stresses in a control perimeter *d/2* away from the faces of the column or from the ends of the loaded area, as shown in Figure 6. In these cases, the shear stress (v_u) shall be less than the shear strength provided by concrete (v_c), as expressed below.

$$v_u < \phi v_c \quad (1)$$

$$v_u = \frac{V}{u_1 d} \quad (2)$$

$$v_c = min\begin{cases} \left(1+\frac{2}{\beta_C}\right)\frac{1}{6}\sqrt{f_c} \\ \left(\frac{\alpha_s d}{u_1}+2\right)\frac{1}{12}\sqrt{f_c} \\ \frac{1}{3}\sqrt{f_c} \end{cases} \quad (3)$$

Where:
v_u is the maximum shear stress acting around the control perimeter u_1;
v_c is the shear strength;
ϕ is a safety factor, assumed in this paper as 1.0;
V is the shear force in the footing;
u_1 is a control perimeter *d*/2 away from the face of the column;
β_c is the ratio between the largest and the smaller dimension of the column;
f_c is the compressive strength of concrete in MPa ($f_c \leq$ 69 MPa);
α_s is a constant that assumes value of 40 for the case of internal columns, 30 for edge column and 20 for corner column;
d is the effective depth of the footing.



A Spring system

B Distributed load system

C Concentrated load system

D Sandbox system

Figure 5
Different test systems used to evaluate punching shear resistance of footings

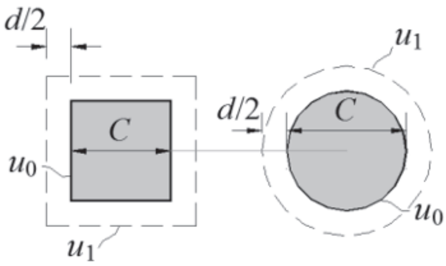


Figure 6
Control perimeter according to ACI 318 [5]

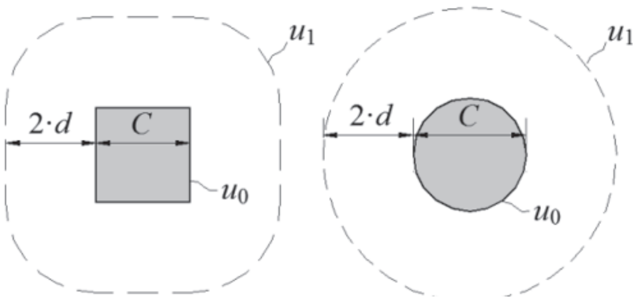


Figure 7
Control perimeter according to Eurocode 2 [2] and ABNT NBR 6118 [6]

3.2 Eurocode 2

EUROCODE 2 [2] defines that shear stress in reinforced concrete footings without shear reinforcement and with concentric load shall be calculated by Equation 4, where the control perimeter is determined as shown in Figure 7.

$$v_u = \frac{V_{red}}{u_1 d} \quad (4)$$

Where:
V_{red} is the reduced shear force to consider the soil-structure interaction;
u_1 is the control perimeter $d/2$ away from the faces of the column;
d is the effective depth of the footing.
In case of punching shear on footings, this design code allows that the soil reaction contained within the region of the control perimeter be considered for the reduction of the shear force in the footing. The reduced shear force V_{red} can be calculated by Equation 5, while the punching shear resistance of footings can be calculated by Equation 6.

$$V_{red} = V\left(1 - \frac{A_{crit}}{A}\right) \quad (5)$$

$$v_c = C_{Rd,c} k (100 \rho f_c)^{1/3} \frac{2d}{a_{crit}} \geq v_{min} \frac{2d}{a_{crit}} \quad (6)$$

$$v_{min} = 0.035 k^{3/2} f_c^{\ 1/2} \quad (7)$$

Where:
A_{crit} is the area within the control perimeter, measured at a a_{crit} distance from the face of the column;
A is the contact area with the soil of the footing;
$C_{Rd,c}$ is a constant determined by the each country's national annex, recommended by Eurocode as being 0.18;
$k = 1 + \sqrt{200/d} \leq 2.0$, with d in mm;
$\rho = \sqrt{\rho_x \cdot \rho_y} \leq 2.0$ is the flexural tensile reinforcement ratio of the footing, where ρ_x and ρ_y are the ratios in *x* and *y* directions, respectively. In calculations, the bars shall be considered within a region *3d* away from the faces of the column;
f_c is the compressive strength of concrete, which according to EUROCODE 2 [2], shall be less than 90 MPa, but respecting the established limits by each country's annex;
a_{crit} is the distance from the face of the column to the considered control perimeter, determined by an interactive process.
This design code also recommends that the shear stress in the perimeter of the column (u_0) shall be limited to:

$$v_{max} = 0.24 f_c \left(1 - \frac{f_c}{250}\right) \quad (8)$$

3.3 ABNT NBR 6118

ABNT NBR 6118 [6] defines that the verification of punching shear resistance on footings shall be done considering the same recommendations used for designing slab-column connections, as expressed below.

$$v_u = \frac{V}{u_1 d} \quad (9)$$

$$v_c = 0.182 \left(1 + \sqrt{\frac{200}{d}}\right) (100 \rho f_c)^{1/3} \quad (10)$$

$$v_{max} = 0.27 f_c \left(1 - \frac{f_c}{250}\right) \quad (11)$$

Where:
V is the shear force in the footing;
u_1 is the control perimeter $d/2$ away from the faces of the column, with the geometry recommended by Eurocode;
d is the effective depth of the footing.
$\rho = \sqrt{\rho_x \rho_y}$ is the flexural tensile reinforcement ratio, calculated analogously to what is presented by Eurocode;
f_c is the compressive strength of concrete. On its current version, the Brazilian code allows the design of structures with concretes that have compressive strength up to 90 MPa.
In case of Equation 11, the Brazilian code allows v_{max} to be increased by 20% in case of internal columns when the spans that reach this column do not differ by more than 50% and there are no openings near the column. These are the rules for use in the verification of slab-column connections, but that have been assumed to be valid for the footings in this paper since they were concentric loaded.

4. Database

4.1 Data collection methodology

A total of 335 tests on reinforced concrete footings were found in the literature. These results were collected and filtered in function of the following parameters: compressive strength of concrete; geometry and thickness of the footing; usage of shear reinforcement. Table 1 presents the criteria used to filter the tests that composed the database.

Current design codes specify that the minimum compressive strength of concrete for use in structures and foundations is 20 MPa, but in the past, much lower values were used. In these analyses, it was established that test results on footings with f_c < 15 MPa would be discarded. In relation to the geometry of the footings, all specimens that had no circular or square base were discarded because *a*/*d* would be different in *x* and *y* directions. Regarding the effective depth, it was considered that any test on footings with effective depth less than 100 mm is not representative of the actual characteristics of these structural elements. All tests on footings with shear reinforcement were discarded, as well as two of the footings tested by BONIĆ and FOLIĆ [16], whose results were much far from the theoretical predictions of all design codes, though the specimens had physical characteristics similar to the other ones.

After collecting and filtering the data, a total of 216 footings remained, which composed a database for the analysis of the normative methods, as indicated in Table 2. Aiming to evaluate the

Table 1
Summary of the process of filtering and composition of the database

Authors	N° of Tests	Filtering criterion					Used tests
		f_c < 15 MPa	Square Geom.	d < 100 mm	Shear reinf.	Low reliability	
Talbolt [12]	69	50	–	–	–	–	19
Richart [17]	140	3	12	–	–	–	125
Rivkin [18]	9	–	–	9	–	–	0
Kordina and Nölting [19]	11	–	11	–	–	–	0
Dieterle and Rostásy [14]	25	–	3	–	4	–	18
Hallgren *et al.* [15]	14	1	–	–	3	–	10
Timm [20]	10	–	–	–	7	–	3
Sundquist and Kinnunen [23]	8	–	–	–	–	–	8
Hegger *et al.* [3]	5	–	–	–	1	–	4
Hegger *et al.* [4]	17	–	–	–	4	–	13
Bonić and Folić [16]	6	4	–	–	–	2	0
Urban *et al.* [21]	9	–	–	–	–	–	9
Siburg and Hegger [22]	12	–	–	–	5	–	7
Total n° of obtained tests	335						
Total n° of filtered tests	119						
Total n° of used tests	216						

Table 2
Summary of the database footings characteristics

Authors	N° of tests	Test type	b (mm)	d (mm)	ρ (%)	c (mm)	Sect.	f_c (MPa)	V_u (KN)
[12]	19	Springs	1524	178 – 254	0.33 – 0.62	305	S	15.0 – 20.2	549 – 1483
[17]	125	Springs	2134	203 – 356	0.20 – 1.23	305 – 356	S	15.0 – 34.8	1326 – 2713
[14]	18	Dist.	1500	290 – 760	0.14 – 0.86	150 – 450	S	20.1 – 30.6	859 – 5338
[15]	10	Con./Dist.	850 – Φ960	232 – 250	0.25 – 0.66	250	C	19.5 – 40.0	622 – 1363
[20]	3	Con.	760 – 1080	172 – 246	1.18 – 1.25	175 – 250	C	32.8 – 40.7	668 – 1060
[23]	8	Con.	1730 – 2300	160 – 240	0.37 – 0.58	500 – 1000	C	24.6 – 35.4	875 – 1763
[3]	4	Sand	900	150 – 250	0.62 – 1.03	150 – 175	S	17.6 – 24.5	530 – 1251
[4]	13	Sand/Dist.	1200 – 1800	250 – 470	0.85 – 0.88	200	S	19.0 – 38.1	1203 – 3037
[21]	9	Con.	1200	118 – 318	0.29 – 0.86	200	C	26.2 – 32.5	270 – 2000
[22]	7	Dist.	1200 – 2700	400 – 590	0.12 – 0.40	200 – 300	S	19.6 – 53.3	1548 – 5392

Table 3
Demerit scale, according to the criterion of COLLINS [7]

V_u/V_{teo}	Classification	Penalty
< 0.50	Extremely dangerous	10
[0.5 – 0.65]	Dangerous	5
[0.65 – 0.85]	Low safety	2
[0.85 – 1.30]	Appropriate safety	0
[1.30 – 2.00]	Conservative	1
≥ 2.00	Extremely conservative	2

reliability and performance of theses codes, a weighted system of classification based on penalties was applied, presented by COLLINS [7], called "Demerit Points Classification" (DPC), that takes into account aspects of safety, accuracy and economy. Table 3 presents the demerit scale proposed by Collins, where a penalty is assigned to each interval from V_u / V_{teo}, and the total penalty defines the performance of each design code. The higher the value of the total sum, the worse the normative process is considered.

5. Results

Figures 8, 9 and 10 present a comparison between the experimental results from the database and the theoretical ones obtained according to ACI 318 [5], EUROCODE 2 [2] and ABNT NBR 6118 [6], taking as variables the following parameters: compressive strength of concrete; flexural reinforcement ratio of the footing; effective depth of the footing; and the u_0/d ratio. For all design codes, it is possible to observe a strong dispersion between the experimental results and the theoretical estimates in function of the evaluated parameters. In case of ACI, it is important to highlight that the results indicate that the use of its recommendations can lead to estimates against safety of punching shear resistance for thick footings, once its equations do not present any term that considers the size effect.

Figure 11 shows the influence of *a/d* in the estimates of punching shear resistance of footings according to EUROCODE 2 [2]. The red dashed line marks the results range below $0.85 \cdot V_u/V_{teo}$, which are considered to be against safety results by COLLINS [7]. The blue dashed line shows results above $1.30 \cdot V_u/V_{teo}$, assumed by COLLINS [7] as conservative. In general, it is seen that the parameter *a/d* affects the punching shear resistance of footings. Nevertheless, the interactive method proposed by Eurocode was dispersed.

Still analyzing Figure 11, it is important to note that most of the performed tests using test systems with concentrated forces at the ends of footings, in an arrangement similar to what is made for tests on slab-column connections, presented against safety resistance estimates for Eurocode. On the other hand, tests performed with spring and sandbox systems, which best represent the real situation, presented mostly conservative predictions of resistance using Eurocode. Figure 12 presents general dispersion graphics of design codes, noticing that Eurocode 2 was slightly less dispersed and conservative, when compared to ACI 318 and NBR 6118. The same is evident from Figure 13.

Table 4 and Figure 14 present a summary of the normative results classification according to the criterion of COLLINS [7]. According to this criterion, the design code that best performed was Eurocode 2, which had the highest number of results classified in

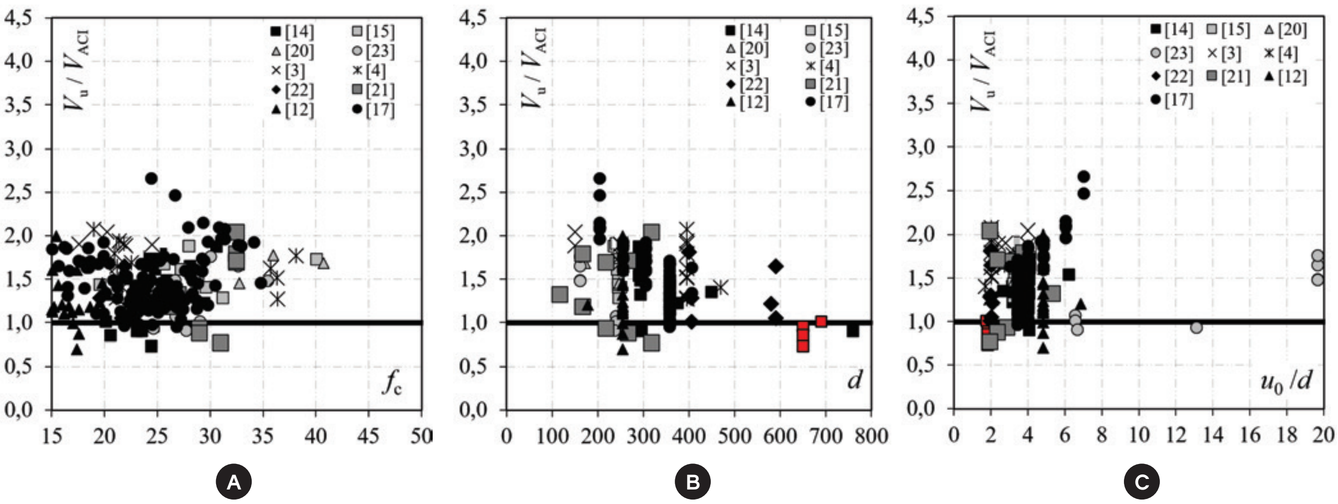


Figure 8
Comparison between experimental results and the recommendations of ACI 318 [5]

the appropriate safety range. However, it is important to highlight that it presented some results in the low safety and dangerous range, most of them referring to tests on footings performed with systems of concentrated forces at the ends. Both ACI 318 and NBR 6118, which present simpler theoretical calculation methodologies than Eurocode, presented somewhat more dispersed and conservative results, which led to greater penalties, worsening its performance according to the criterion of Collins.

6. Conclusions

This paper presents a review of available experimental evidences on punching shear resistance of reinforced concrete footings without shear reinforcement, which are foundation elements widely used in small and large structures. The detailed review of the literature allowed the collection and selection of tests results forming a wide database with 216 tests on footings. These results were used to evaluate the performance of ACI 318 [5], EUROCODE 2 [2] and ABNT NBR 6118 [6]. The performed and presented analyses lead to following conclusions:

1. The results show that the test system type used to simulate, in lab, the real behavior of footings, influences significantly the punching shear resistance and the conclusions about the suitability and precision of design codes.
2. Eurocode 2, which presents a more complex interactive method of calculation than those presented by ACI and the Brazilian code, was slightly less dispersed than those from other design codes, showing a better correlation with experimental tests and a better performance according to the criterion of COLLINS [7].

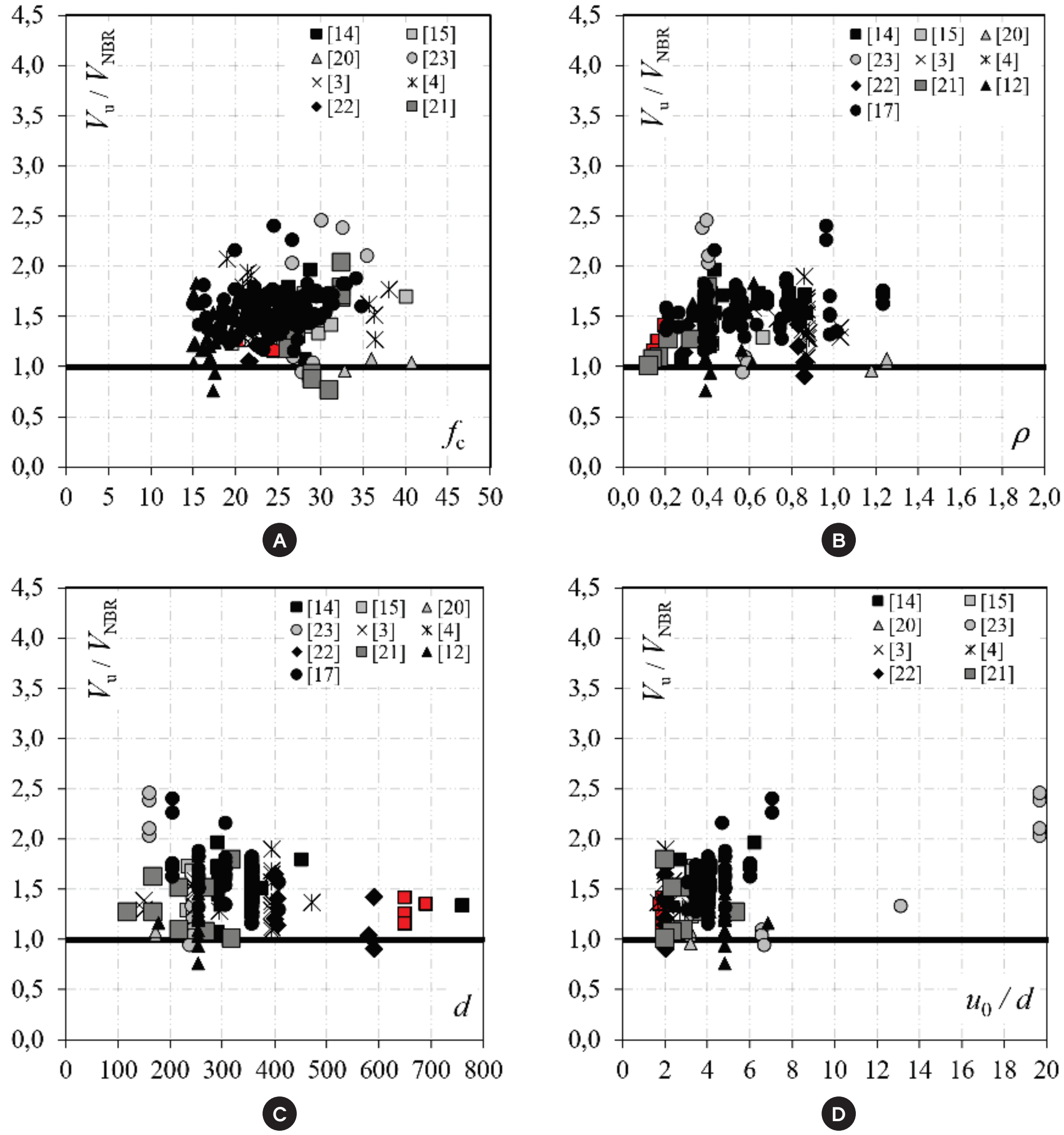


Figure 9
Comparison between experimental results and recommendations of NBR 6118 [6]

3. For thick footing, ACI 318 showed a strong tendency of unsafe prevision for the punching resistance. In all other cases, ACI was in general conservative.
4. ABNT NBR 6118 was the design code that presented the worst performance according to the criterion of COLLINS [7] due to the exaggerated number of conservative results.

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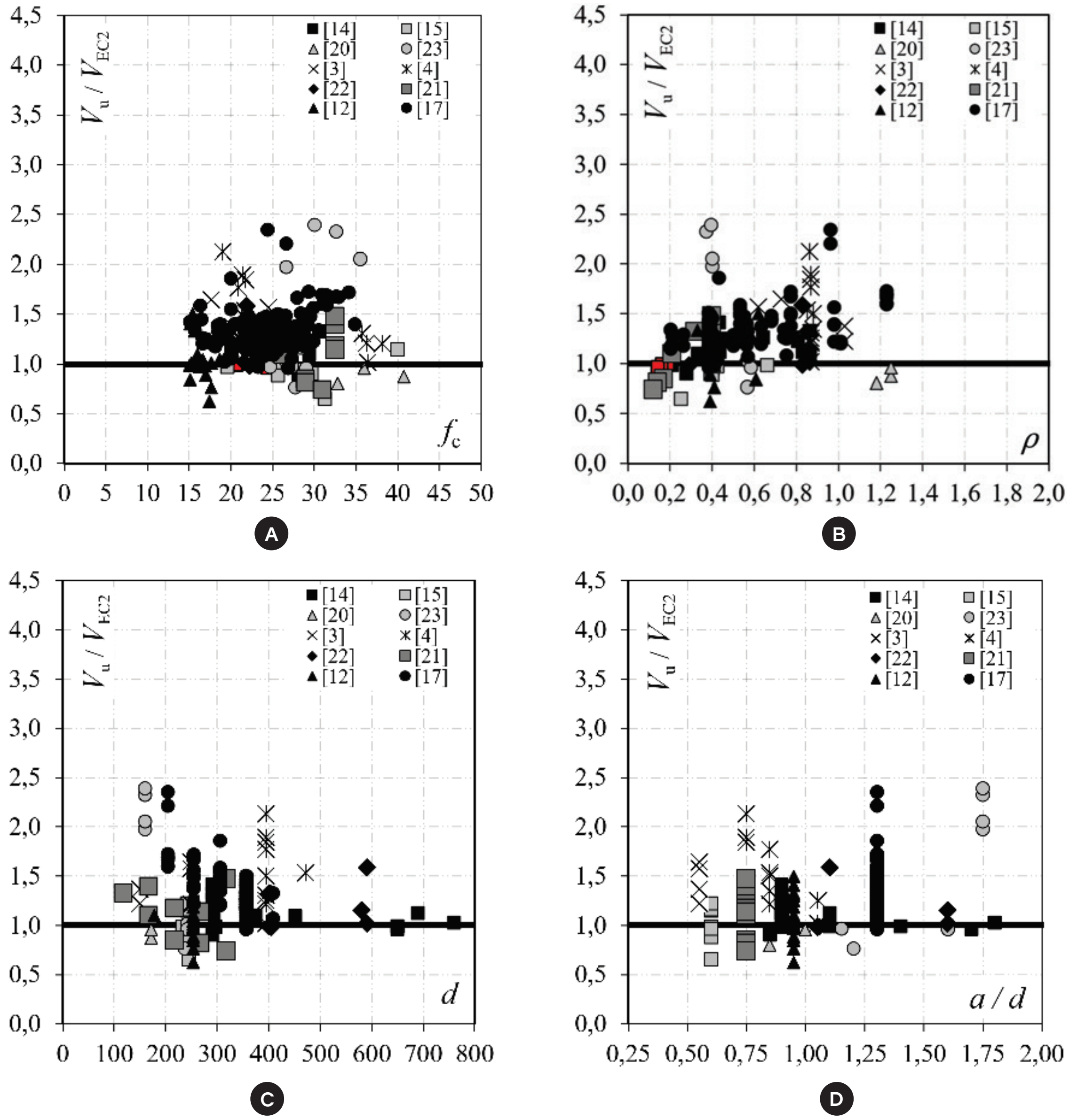

Figure 10
Comparison between experimental results and recommendations of Eurocode 2 [2]

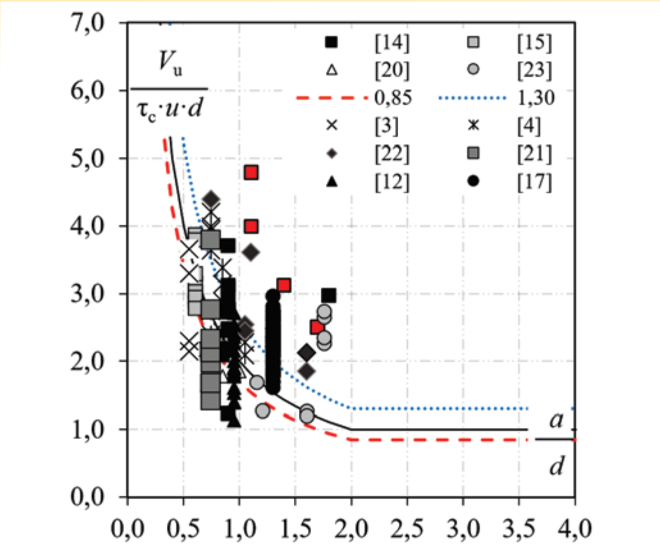

Figure 11
Influence evaluation of a/d on Eurocode 2 resistance estimates [2]

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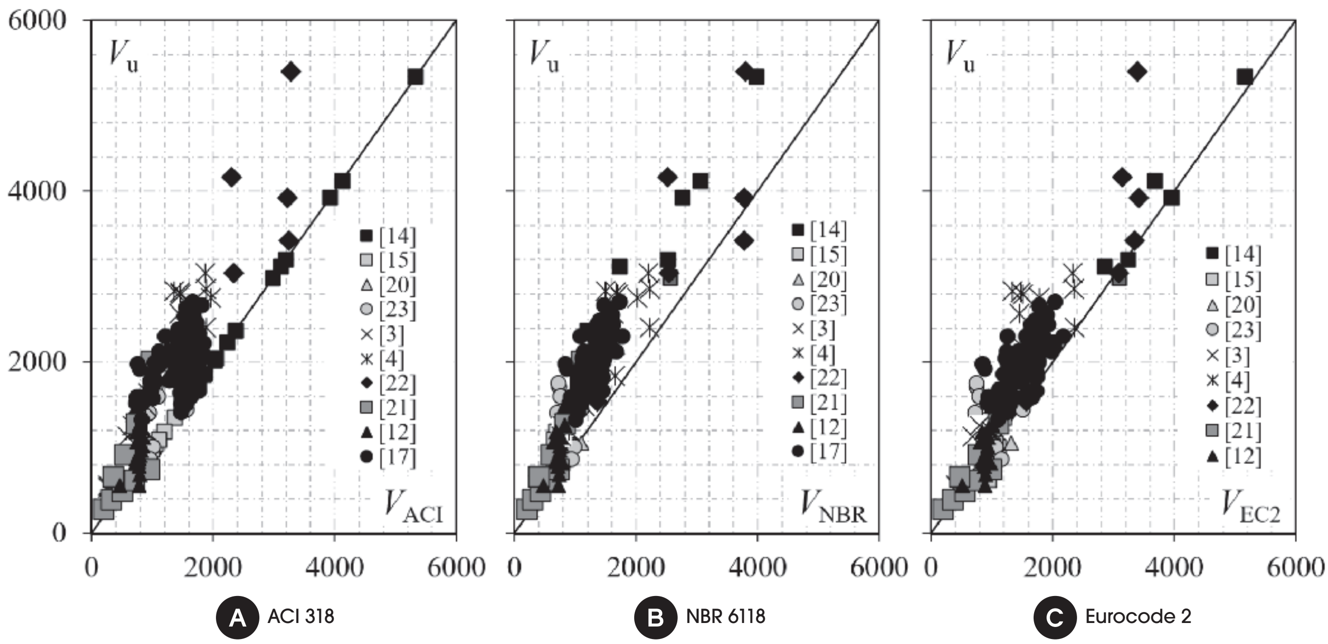

Figure 12
Comparison between experimental and theoretical results

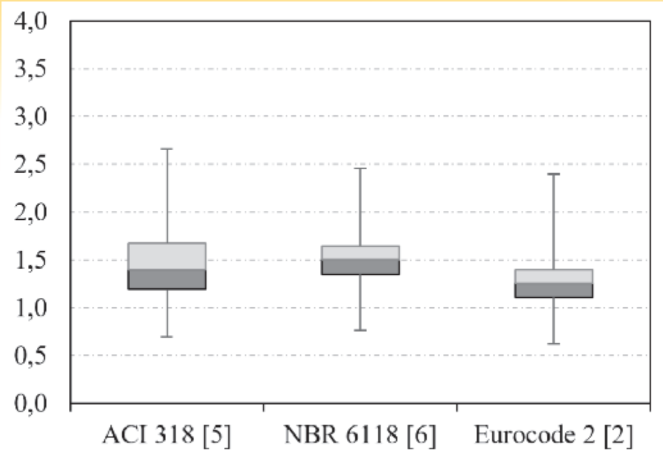

Figure 13
Evaluation of theoretical and experimental results precision

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Table 4
Classification according to the criterion of COLLINS [7]

V_u/V_{teo}	V_u/V_{teo}	<0.50	[0.50-0.65]	[0.65-0.85]	[0.85-1.30]	[1.30-2.00]	>2.00	Total
ACI [5]	N° of test	0	0	3	80	123	10	216
	Penalties	0	0	6	0	123	20	149
NBR [6]	N° of test	0	0	1	44	164	7	216
	Penalties	0	0	2	0	164	14	180
EC 2 [2]	N° of test	0	1	7	118	84	6	216
	Penalties	0	5	14	0	84	12	115

Design code	Average	SD	CV
ACI 318 [5]	1.43	0.33	0.23
NBR 6118 [6]	1.49	0.27	0.18
Eurocode 2 [2]	1.28	0.28	0.22

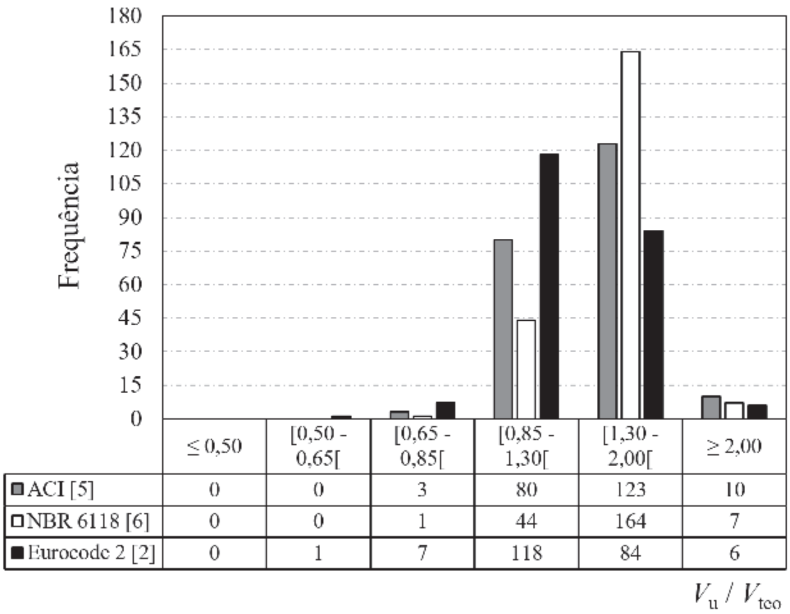

Figure 14
Comparison between experimental and theoretical results