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Punching Shear Strength of Voided Slab: Literature Review and Evaluation of Design Codes

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Abstract

Voided slabs have been introduced to minimize self-weight by reducing the amount of concrete. Similar to flat slabs, voided slabs are subject to punching shear failure due to high concentrated load at column connections. Despite their advantages, the design equations for voided slabs and flat slabs against punching shear failure, as suggested by the current building codes, are derived from tests conducted on flat slabs. Previous tests on voided slabs, however, showed that the punching shear capacity of such slabs is different from that of flat slabs due to the differences in cross-sections. This paper reviews the previous works conducted to investigate the punching shear behavior of voided slabs. In addition, it evaluates the punching shear design provisions of the current building codes using the test results of voided slabs from literature. Comparisons between the tests result of voided slabs from previous studies and the predictions of the punching shear design equations of the current building codes revealed that the latter are inconsistent and widely scattered.

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Keywords: *Reinforced concrete, punching shear, voided slab, slab-column connection.*

الخلاصة: تم إدخال البلاطات المفرغة لتقليل الوزن الذاتي عن طريق تقليل كمية الخرسانة. على غرار الألواح المسطحة ، تخضع البلاطات المفرغة لفشل قص التثقيب بسبب الحمل المركّز عند وصلات العمود. على الرغم من مزاياها ، فإن معادلات التصميم للألواح المفرغة والألواح المسطحة ضد فشل القص ، كما هو مقترح في قوانين البناء الحالية ، مشتقة من الاختبارات التي أجريت على الألواح المسطحة. ومع ذلك ، أظهرت الاختبارات السابقة على الألواح المفرغة أن قدرة قص التثقيب لهذه الألواح تختلف عن قدرة الألواح المسطحة بسبب الاختلافات في المقاطع العرضية. تستعرض هذه الورقة الأعمال السابقة التي أجريت للتحقيق في سلوك القص التثقيب للألواح المفرغة. بالإضافة إلى ذلك ، يقوم بتقييم أحكام تصميم قص التثقيب في قوانين البناء الحالية باستخدام نتائج اختبار الألواح المفرغة من الدراسات السابقة. كشفت المقارنات بين نتائج اختبارات الألواح المفرغة من الدراسات السابقة وتنبؤات معادلات تصميم قص التثقيب الخاصة برموز البناء الحالية أن الأخيرة غير متسقة ومشتتة على نطاق واسع.

1. INTRODUCTION

Voided slabs are considered an attractive solution for long-span floors. They overpass solid flat slabs due to their economic advantages and the associated reduction in materials [1-7]. A voided slab consists of hollow plastic voids placed within the slab soffit between the tension and compression steel reinforcements, as shown in Figure1. Solid sections are introduced to allow for transmitting loads from a slab to a column.

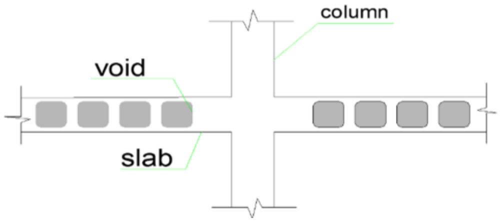


Figure 1. Voided slab.

Those voids are different shapes and sizes such as (Sphere, Donut, Cylinder, Hexahedron, Cuboid, and others). Previous studies found that the presence of such voids reduces the amount of concrete used in the construction of slabs by about 35% [8-9]. Similar to flat slabs, voided slabs are supported directly on columns. This situation imposed high shear stresses and bending moments at the column connections, and consequently, voided slabs are susceptible to local failure called punching shear. In which, a part of a slab attached to a column is pushed normally to the plane of a slab, leaving the rest of a slab rigid [10]. Despite all the advantages provided by voided slabs, limited experimental studies were conducted to investigate their punching shear behavior, and as a result, their punching shear design equations in the current building codes are those derived for flat slabs. The applications of these equations are therefore difficult because of the difference in the cross-section between flat slabs and voided slabs, which was found to affect the punching shear capacity. In this paper, the previous studies conducted to investigate the punching shear behavior of voided slabs are reviewed, and the punching shear design provisions in the current building codes are evaluated using the previous test results of voided slabs from literature.

2. RESEARCH SIGNIFICANCE

Despite being an attractive solution for long-span floors, the punching shear strength of voided slabs has received little attention, and the majority of the work was conducted to investigate the punching shear of flat slabs. As a result, the design codes have suggested equations, originally derived from tests on the flat slab, to design voided slabs. The use of these equations in construction is difficult and could lead to unsafe design. Particularly, when the solid section of voided slabs is relatively small, the punching shear capacity would be lower than that of a flat slab. The aim of this study is to review the previous studies conducted about the punching shear of voided slabs and highlight the shortage of the design codes in this regard.

3. LITERATURE REVIEWS

This section reviews the previous experimental works available in the literature that were conducted to study the punching shear behavior of voided slabs.

Schnellenbach-Held and Pfeffer in 2002[11], conducted experimental and numerical works to study the punching shear behavior of biaxial hollow slab. They tested six specimens in the experimental part. The test variables were the slab’s depth, the voids’ size, and the concrete compressive strength. The numerical simulations included nonlinear finite element methods to examine the influence of the flexural reinforcement ratio, the concrete compressive strength, and the yield strength of reinforcements. Their investigations showed that the failure mode of biaxial hollow slabs is similar to the failure mode of flat slabs. However, the punching shear capacities were lower than the flat slabs due to the reduced shear area resulting from the presence of voids. They, therefore, suggested to consider the reduced shear area provided by the presence of void in the calculation of punching shear capacity.

Wang et al. in 2008[12], tested nine square specimens to investigate the effect of the column’s size, the number of voids, the flexural reinforcement ratio, and the concrete compressive strength on the punching shear capacity of hollow slabs. The results showed that the punching shear capacity of the reinforced concrete hollow slab was increased with the concrete compressive strength, the tension reinforcement ratio, the column size, and the effective depth. The punching shear capacity was reduced with the increase in the size and number of voids. This would be expected due to the reduction in punching shear failure surface provided by the presence of voids.

Chung et al. in 2011[13], tested four full-scale specimens. One of them was a control flat slab, and the rest were voided slabs with various arrangements of voids around the column. Tests were prepared to examine the effect of voids within the critical section region on the punching shear capacity. The results showed that whenever the voids approach the face of the column the punching shear capacity decrease and vice versa. They also noticed that hollow slab specimens achieved a lower punching shear capacity by about 13%. They suggested that the shear area of the critical cross-section is a major contributor to the punching shear capacity of hollow slabs.

Ali et al. in 2014[14], realize numerical analysis using commercial finite element package (ANSYS 14.0) to investigate the stiffness and the structural capacities (flexural and punching shear) of the spherically voided biaxial slab (SVBS). The results showed that the punching shear strength of voided slabs was lower than that of flat slabs.

Han and Lee in 2014[6], tested five one-third scale hollow transfer slabs. One of them was a control flat slab specimen while the remaining four were voided slab specimens with various arrangements of voids around the column. All specimens were subjected to concentric load by hydraulic jack. The tests' variables were the location and number of voids. The results showed that the punching shear strengths of voided transfer slabs were lower than of the solid slab. They also discovered that the punching strength is influenced by the arrangement voids and their location with respect to the column. They, therefore, proposed that the critical section must be located at a distance smaller than half the effective depth of a slab (0.5 d) or center of each row of the voids.

Ahmed in 2014[15], performed an experimental work to study the punching shear mechanism of bubbled reinforced concrete slabs constructed with plastic spheres voids. His experimental program consisted of three squared slabs specimens: One of them was a control solid slab specimen while the remaining two were bubble slabs. The considered variables were the total depth of a slab and the flexural reinforcement ratio while the concrete compressive strength was kept constant. Results showed that the punching shear capacity of bubble slabs is less than flat slabs capacity by 10% for the same thickness.

Sakin in 2014[9], performed an experimental investigation to study the punching shear behavior of self-compacted concrete (SCC) in the presence of steel fibers. Her experimental program included five slab specimens. Four of them were constructed using SCC while one was a control specimen constructed from normal concrete. The volume ratio of steel fiver was the main test variable.

Valivonis et al. in 2017[16] tested six square voided slabs with various arrangements of voids around the column-slab connection while the thickness of specimens, the amount of flexural reinforcement, the numbers of voids, and the concrete compressive strength were kept constant. Results showed that the punching shear strength was reduced with the increase of voids in the critical section. Their test results were also compared to those from literature in the punching shear procedures of EC2, ACI 318-14. It was found that that their strength predictions were inconsistent. This would be expected since the punching shear provisions of these design codes were originally derived from the test results of flat solid slabs.

Jung et al. in 2017[17], conducted a numerical investigation using non-linear finite element analysis to investigate the punching shear behavior of voided slabs using the previous experimental and numerical investigations. Parameters considered were the distance between voids and the column's size. They also studied the ratio between the critical perimeter adopted in the ACI code and the ratio of the slab's effective depth (b^0 /d). Comparing the theoretical results with tests results of previous studies showed that large fluctuation between the tests results and the suggested shear strength value from ACI-318 code. Therefore, they proposed a method to evaluated the punching shear strength of voided slab as shown in Eq (1).

$$\frac{Vu}{0.083\sqrt{fck}\ bo\ d\ \ \alpha\, eff} = [0.1\ \alpha s\left(\frac{d}{0.1bo}\right)^2 + 2] \tag{1}$$

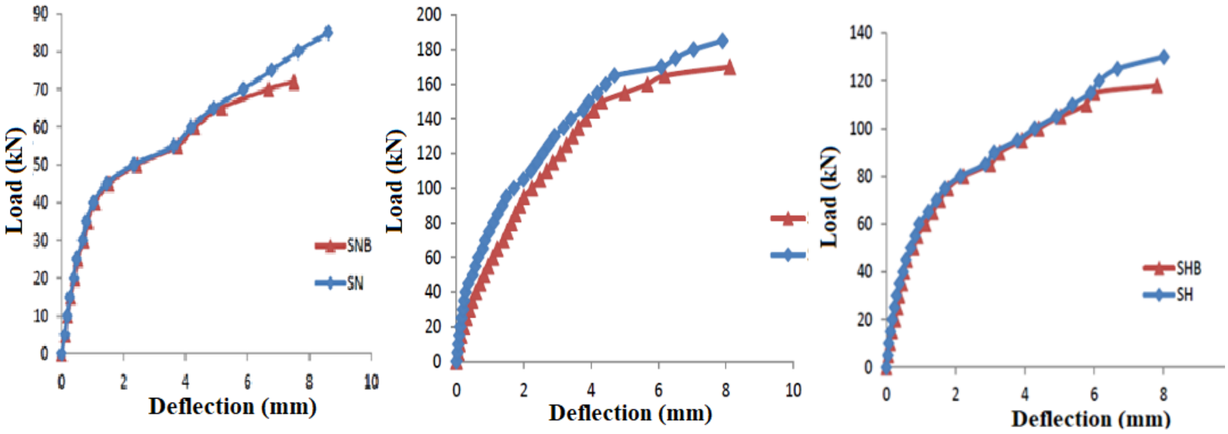
Mahmood and Dawood in 2017[18], tested nine specimens bubble slabs to study the punching shear behavior. Test variables of this study were: the type of concrete, bubbled plastic diameter, bubble's location, slab thickness, compressive strength, and solid slab section. Experimental results showed that the load-carrying capacity of the bubble slab was influenced by the location of bubbles. In addition, the punching shear capacity was increased when the bubbles located at a distance equal to two or three times the slab's effective depth (measured from the column face). The results also showed that the punching shear strength was influenced by the ratio of bubble diameter to slab thickness (D/t), in which the punching shear strength and deflection were increased by increasing (D/t).

Skuturna et al. in 2017[19], conducted an experimental study to investigate the punching shear capacity of biaxial voided slabs. Their experimental work consisted of testing six square specimens' slabs to study the effect of the slab's depth and voids arrangement around the column. The test results were then compared with the punching shear provisions of the EC2. The comparisons revealed that the design code provided inconsistent and scattered strength estimations.

Oukaili and Husain in 2017[20], investigated the punching shear behavior of bubble slabs using twelve square half-scaled specimens. Four of these specimens were control flat slabs and the rest were bubble slabs. Test variables were total slabs' depth, flexural reinforcement ratio, the bubbles' size, bubbles' location with respect to the column, and concrete compressive strength. Results showed a reduction in the load-carrying capacity of bubbled slabs in comparison with the solid slabs. The reduction was about (4.41-18) % for bubble slabs containing bubbles at distance (2d) from column faces and about (14.7-29.4) % for bubble slabs located at (d) from the column face. They, therefore, concluded that bubble slabs constructed with bubbles located at (2d) from column face have a similar load-carrying capacity of that of solid flat slab. This is due to the increase in punching shear failure surface within the solid section provided by the absence of voids.

Chung et al. in 2018[21], conducted an experimental and a numerical investigation to study the punching shear behavior of voided slabs. In their experimental part, they examined four slab specimens. One of them was a control flat slab specimen and the other three were voided slab specimens with various arrangements of voids around the column. They further examined the effect of voids' location with respect to the column on the punching shear capacity using numerical simulations. The results from experimental and numerical simulations showed that the arrangements of voids have a significant effect on the punching shear capacity and the latter was found to increase when voids were placed far from columns. They also proposed a design equation based on ACI-318-11 code. Their design equation achieved good agreements with their test results and those of previous studies.

Abbas and Jaafer in 2018[22], investigated the punching shear behavior of voided slabs by testing six square specimens' slabs. Three of these specimens were control specimens constructed without voids and the rest were voided slabs. Specimens were constructed with different concrete types: normal strength concrete (NSC), high strength concrete (HSC), and modified reactive powder concrete (RPC). The geometrical and material strength was kept constants for all specimens. The results showed that the type of concrete influenced the strength of slabs as shown in Figure2. In addition, the punching shear capacity of voided slabs was lower by (18, 8.8 and 10.2) % than those of flat solid slabs constructed using concrete types: normal strength concrete (NSC), high strength concrete (HSC) and modified reactive powder concrete (RPC), respectively.



A B C

Figure 2. Load –deflection of solid and voided slab using: A- high strength concrete, B- reactive powder concrete and C- normal concrete [23], where SH: high strength concrete solid specimen, SHB: high strength concrete voided specimen: modified reactive powder concrete solid slab, SMB: modified reactive powder concrete voided slab, SN: normal strength concrete solid slab, SNB: high strength concrete voided slab.

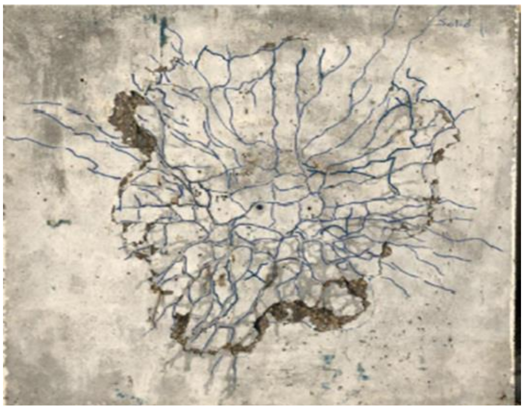


Figure 3 Failure pattern of voided HSC specimen [23].

Sagadevan and Rao in 2019[10], tested eight full-scale square specimens of voided slabs. One specimen was a control specimen and the rest were voided slabs. Test variables were slab depth, size and shape of plastic void (sphere and cuboid shape), and the arrangement and numbers of voids from the column faces. Comparing test's results with provisions in building codes (ACI 318, EN 1992and IS 456) and data collected from previous studies showed that the estimation of punching strength of voided slabs in standards (ACI 318, EN 1992and IS 456) is not satisfactory with result in this study where it is greatly overestimated by the provisions codes. Therefore, they proposed an effective area method to predict the punching shear strength of voided slab, it is reasonably fair in comparison with the test results of this study.

Al-Gasham et al. in 2019[23], conducted an experimental and a theoretical study to investigate the punching shear behavior of voided slabs. In their experimental part, five half-scale square specimens' slabs were tested: one of them was a control solid slab specimen and the other were voided slabs. All specimens were constructed with a length of (1000) mm and a total depth of (90) mm. They were loaded at the center with central square column (120 mm). FE analysis used ABAQUS program to perform a parametric study. The results of the experimental and thermotical investigations indicated that punching shear strength of voided slab was lower than that of solid, see figure 4.

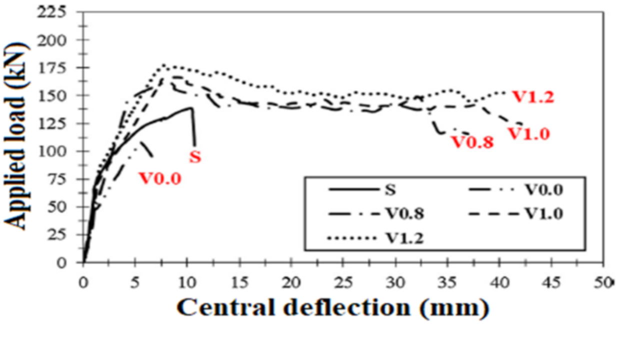


Figure 4. Load- deflection of tested specimens [24].

Khouzani et al. in 2020[24], tested four full-scale specimens biaxial voided slabs to study the punching shear capacity. Two specimens were considered for the one-way shear behavior with the dimension of (3500 × 1200 × 200) mm, and the other specimens were two-way shear behavior with the dimension of (2300 × 2300 × 200) mm. They also used vertical rods steel cages to evaluate the effectiveness of steel cages on the shear strength. Experimental results were compared with punching capacity according to the ACI-318-19 code and showed that the punching shear strength of voided slab was less than the solid slab.

4. DESIGN PROVISION OF RHE PUNCHING SHEAR OF FLAT SLAB WITHOUT SHEAR REINFORCEMENT

The punching shear provisions in the current design codes are based on the control surface approach. The punching shear strength is estimated using the algebraic sum of all the uniformly distributed shear stresses on the critical section. The critical section is an imaginary plane located at a specified distance from the column faces. Each design code has adopted a specific location and shape. In addition, each design code has adopted a specific shear stress equation.

4.1.The ACI – 318-19 [25]

The critical section for punching shear strength is located at 0.5d from the column face as shown in Figure5. The punching shear capacity of the slab without shear reinforcement is considered a function of effective depth and compressive strength as shown below:

$$\mathrm{V}_{\mathrm{ACI}}= vc\ \ bo\ \ \ d \tag{2}$$

Where

$VACI$: Ultimate punching shear load.

d: mean effective depth of a slab.

bo: Perimeter of critical section,

$$bo = 2(C1 + d) + 2(C2 + d) \tag{3}$$

vc: Concrete punching shear strength taken as the minimum values of the followings:

$$vc = \left(0.17 + \frac{0.33}{\beta}\right) \lambda \mathrm{s} \sqrt{fc} \tag{4}$$

$$vc = \left(0.17 + \frac{0.083\alpha s\ d}{\mathrm{bo}}\right) \lambda \mathrm{s} \sqrt{fc} \tag{5}$$

$$vc = 0.33\ \lambda \mathrm{s} \sqrt{fc} \tag{6}$$

βc: Ratio of long side to short side of the column (equal 1 for square column).

fc: Cylinder concrete compressive strength.

αs: Factor for internal, edge, and corner is taken 40, 30 and 20, respectively.

λs: Size effect factor

$$\lambda \mathrm{s} = \left(\frac{2}{21 + 0.004\mathrm{d}}\right)^{0.5} \le 1 \tag{7}$$

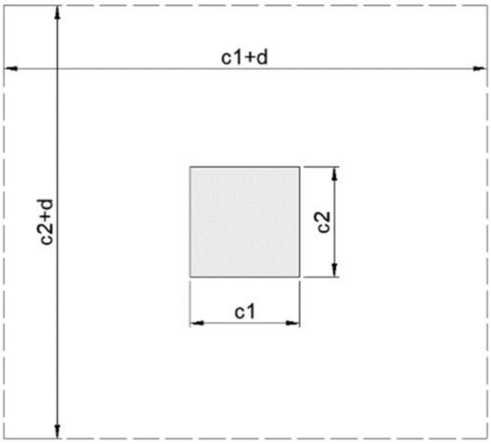


Figure 5. Critical Perimeter of an Interior Column for ACI

4.2.The EC2 [26]

The critical section for punching shear strength is located at 2d from the column face as shown in Figure 6. The punching shear capacity of slab without shear reinforcement is a function of slab's effective depth, amount of tension reinforcements, and compressive strength as shown below:

$$\mathrm{V\ EC2} = 0.18K(100\ \ \rho\ \ \mathrm{fc})^{0.33}\quad u\quad d \tag{8}$$

Where

$VEC2$: Ultimate punching shear load.

u: Perimeter of critical section

$$u = 2C1 + 2C2 + 4\,\pi\,\mathrm{d} \tag{9}$$

d: Effective depth of a slab.

C1, C2: Column dimensions.

k: Size effect factor

$$K = 1 + \left(\frac{200}{\mathrm{d}}\right)^{0.5}\quad \leq 2 \tag{10}$$

ρ: Ratio of tension steel reinforcement, where $\rho \leq 2\%$

fc: Cylinder concrete compressive strength.

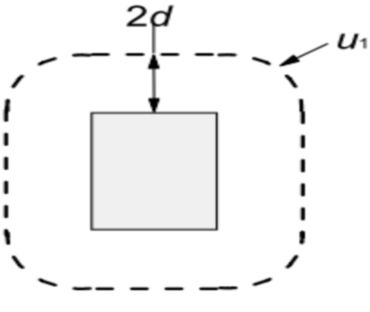


Figure 6. Critical Perimeter of an Interior Column for EC2 [26]

4.3.The BS 8110 [27]

The critical section for punching shear strength is located at 1.5d from the column face as shown in Figure7. Similar to EC2, the punching shear strength is made of function of slab's effective depth, amount ρf tension reinforcements, and compressive strength as shown below:

$$VBS8110 = 0.79(\rho fcu)^{0.33}\left(\frac{400}{\mathrm{d}}\right)^{0.5} \quad u \quad d \tag{11}$$

Where:

u: Perimeter of critical section,

$$u = 2(C1 + 3d) + 2(C2 + 3\mathrm{d}) \tag{12}$$

d: Effective depth of a slab.

C1, C2: Column dimensions.

ρ: The ratio of the tension steel reinforcement, where $\rho \leq 3\%$.

fcu: Cube concrete compressive strength, $fcu \leq 40\ MPa$.

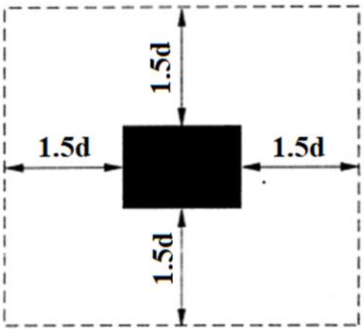


Figure 7. Critical Perimeter of an Interior Column for BS – 8110[27]

4.4.The CSA A23.3-04 [28]

The critical section for punching shear strength is located at 0.5d from the column face where d is the effective slab thickness. In the absence of shear reinforcements, the punching shear strength is made a function of concrete compressive strength:

$$\mathrm{V\,CSA} = vc\ bo\ \ d \tag{13}$$

Where

bo: Perimeter of critical section,

$$bo = 2(C1 + d) + 2(C2\ \mathrm{d}) \tag{14}$$

d: Effective depth of a slab.

C1, C2: Column dimensions.

VC: Concrete punching shear strength, which is the smallest of the values obtained from equations below:

1- $$Vc = 0.79\left(1+\frac{2}{\beta c}\right)^{0.2} \lambda\ \varphi c(\mathrm{f'c})^{0.5} \tag{15}$$

2- $$Vc = \left(\alpha s\frac{\mathrm{d}}{\mathrm{bo}} = 0.2\right) \lambda\ \varphi c(\mathrm{f'c})^{0.5} \tag{16}$$

3- $$Vc = 0.4\,\lambda\ \varphi c(\mathrm{f'c})^{0.5} \tag{17}$$

Where βC, is the ratio of long side to short side of the column.

λ = 1 for normal weight concrete and λ = 0.85 for semi lightweight concrete.

Φc =0.65 is the resistance factor for concrete.

f'c: is the concrete cylinder compressive strength. αs = 4 for interior columns.

5. TEST DATA

Table1. presents details of tested hollow slabs from literature. These slabs were collected to evaluate the accuracy of the punching shear of the current building codes (ACI-318-19, EC2, BS81109, and CSA) in the application of hollow slabs. All hollow slabs were tested at internal column situation, and they failed by punching shear. The collected voided slabs cover a wide range of test variables. The concrete compressive strength ranged from 20 MPa to 0 MPa, the flexural reinforcement ratio ranged from 0.306% to 1.803 %, the total depth of voided slabs ranged from 55.5 mm to 370.25 mm, and the column dimensions ranged from 100 to 350 mm.

Table 1. Details and experimental results of voided slab specimens of other researchers

Source	No. of slabs	Sample ID	V test (kN)	d (mm)	ρ(%)	fc'(MPa)	Column size(C) (mm)
Han and Lee (2014)[6]	4	V1	1297	370.25	0.716	33	267
		V2	1071	370.25	0.716	33	267
		V3	1111	370.25	0.716	33	267
		V4	944	370.25	0.716	33	267
Valivonis et al. (2017)[16]	6	BP1-1	772.7	233.9	0.306	31.01	350
		BP1-2	800.5	232.5	0.307	31.01	350
		BP2-1	443.1	225.70	0.317	32.07	350
		BP2-2	450.9	236.25	0.303	32.07	350
		BP3-1	630.4	231.05	0.31	30.38	350
		BP3-2	658.4	233.9	0.306	30.38	350
Schnellenbach-Held and Pfeffer (2002)[11]	6	D1-24	520	190	1.803	35.52	300
		D2-24	580	190	1.803	40.64	300
		D3-24	525	190	1.803	37.36	300
		D4-45	935	380	1.06	23.68	300
		D5-45	990	380	1.06	30.32	300
		D6-45	1180	380	1.06	32.4	300

Table 1. Details and experimental results of voided slab specimens of other researchers (continued)

Source	No. of slabs	Sample ID	V test (kN)	d (mm)	ρ(%)	f_c' (MPa)	Column size(C) (mm)
Sagadevan and Rao (2019)[10]	7	V1	239.8	119	1.13	22.48	300
		V2	240.4	119	1.13	22.48	300
		V3	574.4	205	0.8	21.36	300
		V4	548.9	205	0.8	21.36	300
		V5	657.2	221	0.43	20	300
		V6	672.3	221	0.43	20	300
		V7	653.6	221	0.43	20	300
Skuturna et al. in (2017)a,[19]	6	BPR1-1	600.2	234.6	0.487	26.51	350
		BPR1-2	600.1	234.8	0.486	26.51	350
		BPR2-1	776.3	232.9	0.493	28.95	350
		BPR2-2	704.5	235	0.485	28.95	350
		BPR3-1	385.4	152.9	0.403	27.96	350
		BPR3-2	428.1	150	0.416	27.96	350
Chung et al. (2018)[13]	3	PD-N-0	556.4	217	0.8	21.4	300
		PD-N-4	515.7	217	0.8	22.2	300
		PD-N-8	480.2	217	0.8	26.8	300
Oukaili and Husain (2017)[20]	8	BD1	140	75.5	0.748	30	100
		BD3	205	102.5	1.09	30	100
		BD5	120	75.5	0.748	30	100
		BD7	190	102.5	1.09	30	100
		BD9	180	75.5	0.748	60	100
		BD11	325	102.5	1.09	60	100
		BD13	170	75.5	0.748	60	100
		BD15	290	102.5	1.09	60	100
Sakin (2014)[9]	1	S3	195	55.5	0.504	31	100
Al-Gasham et al. (2019)[23]	1	V0.0	162.6	74	0.84	28.2	120

[a] The contribution from presence of shear reinforcement is not considered as it is not significant in comparison with observed failure load[10,19].

6. EFFECT OF TEST VARIABLES

6.1 Concrete compressive strength

Figure.8. Present the effect of concrete compressive strength on punching shear strength using the test results of voided slab of (Oukaili and Husain (2017) [20] and Schnellenbach-Held and Pfeffer (2002)[11]). Similar to flat slabs, the punching shear strength was found to increase as the concrete compressive strength increased.

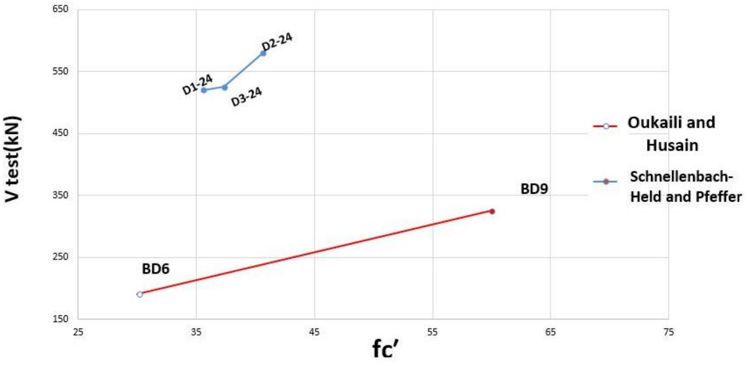


Figure 8. Effect of compressive strength

6.2 Flexural reinforcement ratio

Figure9. shows the effect of flexural reinforcement ratio on the punching shear capacity of slabs using the test results of voided slabs reported by (Oukaili and Husain(**2017)[20]**]). It was concluded from this figure that the punching shear strength was increased as the flexural reinforcement ratio increased. The influence of flexural reinforcement is identical to that on flat slabs.

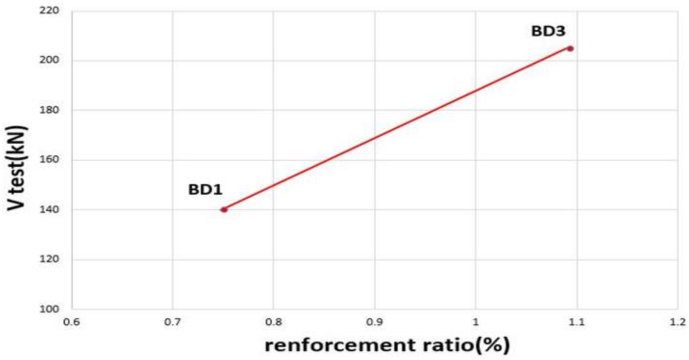


Figure 9. Effect of reinforcement ratio**(%).**

6.3 Effective depth

Fig.10.demonstrates the influence of effective depth (d) on the punching shear capacity slabs using the test results of voided slabs reported by (Sagadevan and Rao (2019)[10] and Skuturna et al. in (2017)[19]). This figure indicates that the shear strength was increased with the slab's effective depth.

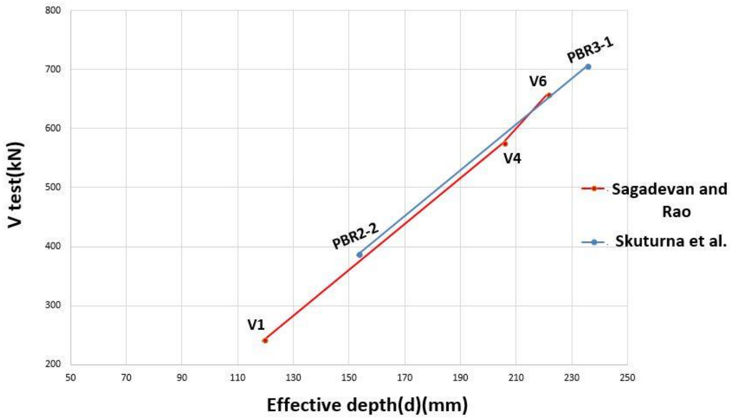


Figure 10. Effect of effective depth**.**

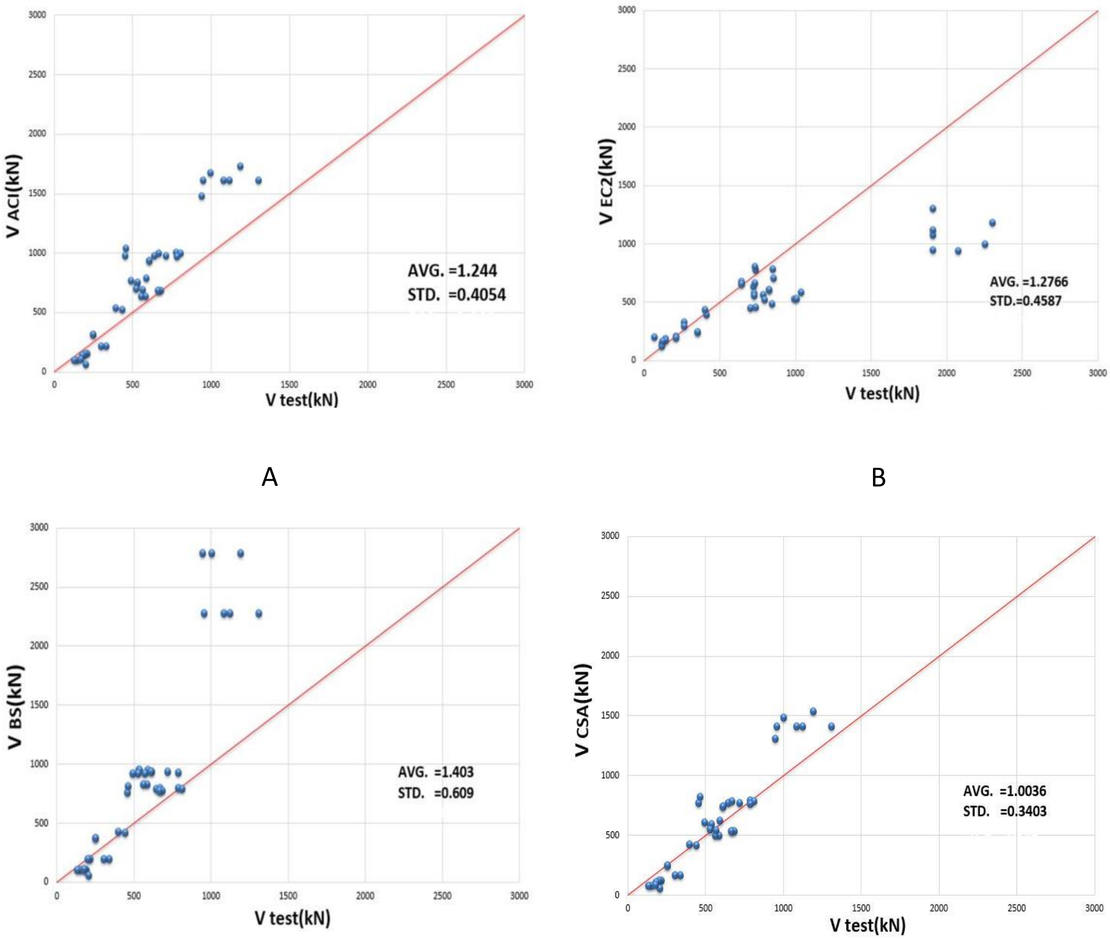
6.4 Effect of void arrangement

Current codes determined the critical section of shear in flat slab, with a variation in the dimensions of this region for each of the codes. It was noted that the presence of voids within these critical regions affects their tolerance to the shear force.

7. EVALUTION OF THE CURRENT CODES

Fig.11. compares between test results of hollow slabs and the predicted punching shear strength of design codes. It can be seen from these figures that the punching shear equations of design codes are inconsistent with the test results and widely scattered because punching shear equations do not distinguish between hollow slabs and flat slabs. Therefore, they do not consider the differences that exist in terms of cross-section and subsequently punching shear capacity. As a result, the equations of the codes are unsafe, especially when the voids are close to the column, see Table 2.

Table.2. compares between the test results of the voided flat slabs failed by internal punching shear and the punching shear design predicted in the current building codes (ACI-318-19, EC2, BS8110, and CSA). The average punching shear strength to tests of the ACI-318-19, EC2, BS8110 and CSA were (1.2441, 1.2766, 1.4034, 1.0036), respectively. The standard deviation of punching shear strength to tests, of the (ACI-318-19, EC2, BS8110, and CSA) were (0.4054, 0.4587, 0.6099, 0.3403), respectively.



A B

C D

Figure11. Comparison of punching shear capacity of voided slab specimens obtained from experiments and various standards: A- ACI, B-EN, C-BS and D-CSA.

Table 2. Punching shear capacity of voided slabs calculated by various standards.

Specimen ID	Vtest (kN)	ACI318-19		EC2 1992		BS8110		CSA	
		VC (kN)	VC/Vtest	VC (kN)	VC/Vtest	VC (kN)	VC/Vtest	VC (kN)	VC/Vtest
V1	1297	1606.34	1.238	1896	1.461	2273.79	1.753	1409.59	1.086
V2	1071	1606.34	1.499	1896	1.77	2273.79	2.123	1409.59	1.31
V3	1111	1606.34	1.445	1896	1.706	2273.79	2.046	1409.59	1.268
V4	944	1606.34	1.701	1896	2.008	2273.79	2.408	1409.59	1.49
BP1-1	772.7	1003.9	1.299	726.78	0.94	795.2	1.029	790.95	1.02
BP1-2	800.5	995.5	1.243	721.32	0.90	787.7	0.984	784.33	0.977
BP2-1	443.1	971.2	2.192	688.22	1.553	756	1.706	765.26	1.72
BP2-2	450.9	1035.2	2.296	723.8	1.605	806.6	1.788	815.7	1.809
BP3-1	630.4	976.7	1.549	708.3	1.123	781.7	1.24	769.5	1.22

Table 2. Punching shear capacity of voided slabs calculated by various standards (Continued)

Specimen ID	Vtest (kN)	ACI318-19		EC2 1992		BS8110		CSA	
		VC (kN)	VC/Vtest	VC (kN)	VC/Vtest	VC (kN)	VC/Vtest	VC (kN)	VC/Vtest
BP3-2	658.4	993.95	1.509	717.9	1.090	795.5	1.208	783.1	1.18
D1-24	520	732.4	1.408	980.4	1.88	948.10	1.823	577.0	1.109
D2-24	580	783.4	1.350	1025.3	1.767	948.1	1.634	617.3	1.067
D3-24	525	751.16	1.430	997.05	1.899	948.1	1.805	591.8	1.127
D4-45	935	1478.6	1.581	2062.6	2.205	2785.4	2.977	1307.7	1.398
D5-45	990	1673.19	1.690	2239.5	2.262	2785.46	2.813	1479.7	1.494
D6-45	1180	1729.6	1.465	2289.5	1.940	2785.46	2.360	1529.6	1.296
V1	239.8	312.1	1.301	339.1	1.413	369.2	1.539	245.8	1.0258
V2	240.4	312.1	1.298	339.1	1.410	369.2	1.5351	245.86	1.022
V3	574.4	631.5	1.099	712.7	1.24	826	1.438	497.59	0.866
V4	548.9	631.5	1.150	712.7	1.29	826	1.504	497.59	0.906
V5	657.2	679.7	1.034	632	0.961	766.9	1.166	535.5	0.814
V6	672.3	679.7	1.011	632	0.940	766.9	1.140	535.5	0.796
V7	653.6	679.7	1.039	632	0.967	766.9	1.173	535.5	0.819
BPR1-1	600.2	932.1	1.552	815	1.35	933.2	1.554	734.3	1.22
BPR1-2	600.1	933.2	1.555	815.5	1.35	933.9	1.55	735.2	1.22
BPR2-1	776.3	964.1	1.242	835.8	1.076	925.1	1.191	759.6	0.977
BPR2-2	704.5	976.3	1.385	842	1.19	934.7	1.32	769.2	1.09
BPR3-1	385.4	536.7	1.392	397.7	1.032	422.9	1.097	422.8	1.097
BPR3-2	428.1	523.45	1.225	390.1	0.911	414.14	0.967	412.4	0.963
PD-N-0	556.4	685.06	1.231	774.1	1.39	913.05	1.641	539.7	0.970
PD-N-4	515.7	697.75	1.353	783.6	1.519	913.05	1.770	549.7	1.06
PD-N-8	480.2	766.6	1.596	480.2	1.7388	913.05	1.901	604	1.25
BD1	140	95.79	0.684	140	0.7371	97.70	0.697	75.4	0.539
BD3	205	150.0	0.732	205	0.9776	192.4	0.938	118.23	0.576
BD5	120	95.79	0.798	120	0.8629	97.70	0.814	75.4	0.628
BD7	190	150.06	0.789	190	1.04798	192.482	1.013	118.2	0.621
BD9	180	135.47	0.752	180	0.729	97.74	0.549	106.7	0.593
BD11	325	212.22	0.65	325	0.778	192.2	0.595	167.20	0.51
BD13	170	135.4	0.796	170	0.765	97.704	0.575	106.7	0.627
BD15	290	212.2	0.731	290	0.832	192.482	0.664	167.2	0.576
S3	195	63.4	0.325	195	0.280	50.107	0.252	49.9	0.256
V0.0	162.6	100.6	0.618	162.6	0.66	104.087	0.645	79.2	0.487
AVG.		1.24		1.276		1.403		1.003	
MIN.		0.32		0.280		0.256		0.256	
MAX.		2.296		2.26		2.979		1.809	
STD.		0.405		0.45		0.609		0.3403	

8. CONCLUSION

The aim of this study was to investigate the applicability of the available punching shear design equations on the reinforced concrete hollow slabs. A total of 42 reinforced concrete slab specimens constructed with a wide range of test variables were collected from the literature and they were used to examine the applicability of the punching shear equations of ACI 318-19, EC2, BS8110, and CSA (A23.3-04) to design the punching shear of voided slabs. All these slabs have failed by punching shear. Comparisons with the test results showed that the punching shear predictions of these codes were inconsistent and widely scattered due to the fact that hollow slabs are different from those flat slabs in terms of cross-section and the current codes do not consider such differences. Hence, the application of these equations to design hollow slabs is inappropriate and it might lead to unsafe predictions especially when the solid section is relatively narrow and the location of voids is close to the column.

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