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Resisting Punching Shear of Flat Slab

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ABSTRACT: The flat slab system has gained popularity in many nations over the years, notably for multistory buildings such as offices and parking garages. Nowadays, a large number of flat slab buildings require punching resistance. There are a variety of reasons for this, including design or construction faults, low-quality materials, failure to comply with new code regulations, or an increase in vertical load. In this paper is to study and review the factors affected on punching shear and collect the most techniques to resist this phenomenon. Punching shear capacity is influenced by concrete strength, slab thickness, column dimensions, flexural steel and shear reinforcement. To improve the punching shear capacity of flat slab constructions, previous researches proposed using standard shear reinforcement, shear head steel, shear stud, helix reinforcement, and lattice reinforcement. Many recent studies have advised that steel-fiber-reinforced concrete (FRC) be used in the entire slab or a portion of the slab surrounding the column near the slab–column connection instead. This is based on a number of FRC flat slab test findings, including punching shear strength and deformation capacity.

KEY WORDS: Punching shear; Factors Affecting; Punching resisting; Codes Provision.

I. INTRODUCTION

Due to architectural freedom and construction speed, reinforced concrete slabs that are not supported by beams, also known as flat slabs, are the most popular floor system in the building projects [1].
Flat reinforced concrete (RC) slabs is the most cost-effective structural method for residential and commercial buildings supported by RC columns with span lengths ranging from 7.0 to 9.0 m and a live load of less than 5 kN/m2 [2]. Despite the economic benefits of this type of slab, punching failure has resulted in some tragic calamities [3]. Punching, in reality, can cause the slabs to gradually collapse, resulting in the entire collapse of a building.
Punching is one of the most common causes of brittle and sudden fracture in reinforced concrete buildings. During the transmission of loads from the slab to the columns, a punching effect occurs at the end-parts of the columns, and this effect is just as essential as the slab's resistance to bending [4]. Since the 1960s, the sensitivity of flat slabs to punching shear has been the topic of extensive experimental, theoretical, and analytical research [5].
If the punching failure occurred, the slab and column would have become physically separated. This will significantly disrupt the equilibrium of the structure established by such members. Then, due to weight redistribution to other components that were not meant to handle new loads, the entire structure may collapse. The punching failure occurred all at once because concrete is a brittle fracture material [6]. As a result, slabs that are supported directly by columns in the design stage should be given special consideration as shown in the Fig.1 [5].

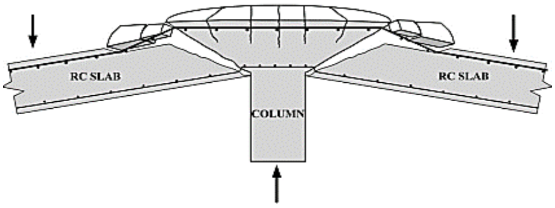

Fig1. In the slab column connection area, there was a punching failure [5].

As a result, the punching phenomenon has piqued the interest of various researchers [1], [6]–[9] with several scientific and technical papers devoted to the execution of experimental programs and the development of analytical and numerical models for a better understanding of this phenomenon.

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The punched shear capacity of flat slab-column connections under static load is influenced by a number of factors. Punching shear capacity is influenced by slab thickness, column dimensions, concrete strength, flexural reinforcing ratio and pattern, and shear reinforcement. The outcomes and supporting circumstances in experiments are influenced by the testing methods and conditions, such as the loading rate and scale of specimens. The following explanation is based on a few selected references pertaining to the aforementioned elements [10].
Although different methods can increase the punching shear capacity of reinforced concrete flat plates, their applicability is typically limited. For example, classical shear reinforcing using stirrups is only suitable to slabs with a depth larger than 150 mm, according to ACI Committee 318-14[11] and larger than 250mm in Egyptian codes [12].
The problem of punching failure is addressed in many ways by design codes. For example, the current Egyptian Code of Practice E.C.P. (203–2018) [12], the American code ACI318-14 [11], and the European Code Euro-Code 2 [13] ignore the effect of horizontal reinforcement. Furthermore, the location of the essential section of punching varies from half to double the effective slab depth measured from the column face, depending on the design standards.
Drop panels, shear reinforcement in the form of studs or stirrups, and bent up bars are used in a new way, however it takes a long time to build [14]. Instead of employing conventional shear reinforcement to boost the capacity of flat slabs, the newest construction material (technology) that can be employed in such instances is moderate or high strength self-compacted concrete [15].

II. RESEARCH SIGNIFICANCE

The main goal of this paper is to study and review the factors affected on punching shear and collect the most techniques to resist this phenomenon.

III. FACTORS AFFECTING THE CONCRETE'S PUNCHING SHEAR STRENGTH

A. Slab Thickness: The thickness of a slab is related to the concrete's Punching Shear strength. Alhussainawe, etal.[16], proved that increasing the slab thickness increased the final punching shear strength while also lowering the section's flexural capacity and shear stress at d/2 distance. With increasing slab thickness, overall deformations decrease, and thicker slabs are more likely to fail due to punching shear [16].
B. Column's smallest lateral dimension: The column's smallest c/s dimension is proportional to the concrete's Punching Shear resistance [17], [18].
C. Column Shape: Rectangular and Square columns are more likely to fail. Punching Shear Failure is more resistant in circular columns [17]. The punching shear strength of slabs in rectangular columns can be lower than in square columns with the same control perimeter length. This is owing to the possibility of a shear force concentration along the control perimeter. Some, but not all, punching design calculations take into account this drop in strength by using empirical parameters that are solely expressed in terms of column geometry. In fact, the concentration of shear pressures is also influenced by the slab's deflected shape [19].
D. Column placement: This is determined by whether the column is an interior or exterior column. Prior to the Punching Shear failure, interior columns are more common than outside columns [17]. To determine the influence of increasing column dimensions on "flat slab" punching shear failure, Faris[20], uses two specimens the first is a "flat slab" with a span of (5 * 5) m, while the second has a span of (6 * 6) m. The interior, edge, and corner columns were analysed, with the interior column being the most threatening. It is found that increasing column diameters prevents punching shear failure in "flat slabs" and that adding a drop panel increases the area of the critical shear perimeter, preventing punching shear failure [20].
E. Concrete Grade: The Punching Shear Resistance of concrete is directly related to its grade [17]. The application of HSC enhances the punching shear resistance of the slab-column connection, allowing larger forces to be delivered through the slab-column connection. However, the increased brittleness of the system offsets this gain in shear resistance. In fact, when compared to normal-strength concrete members, HSC members demonstrate different failure processes in some cases, and extrapolating models and equations created for normal strength to HSC may result in unsafe designs [21].
F. Flexural Reinforcement: Punching shear capacity is affected by the strength of flexural reinforcement, reinforcing pattern and arrangement, and the amount of compression reinforcements. The punching shear resistance decreases significantly as the reinforcement ratio decreases, according to the parameters studied [22]. The value of the yield strength has no effect on the shear resistance of slabs if shear failure occurs before flexural yielding has started. Only if the flexural reinforcement was securely anchored would a concentration of reinforcement along the column result in an increase in punching shear strength; otherwise, the weakened bond of closely spaced reinforcing bars will not result in a rise in

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punching shear strength. it is suggested that the effective depth, not the slab thickness, dictates the shear and flexural behaviour of a slab [22].

G. Shear RFT: Shear reinforcements can be used to stop a punched shear crack from spreading. In general, shear reinforcement is a bar (or other shape) that crosses inclined fissures to prevent punching shear failure. If punching shear occurs, the bar should have sufficient tension strength, ductility, and anchoring to develop its strength. There are many types of shear reinforcements for new or existing reinforced concrete slabs [23].

Closed stirrups (Islam and Park, 1976) [24], bent-up bars (Hawkins, 1974) [25], shear studs (Dilger and Ghali, 1981) [26], and shear heads (Corley and Hawkins, 1968; 1974) [27]are some of the reinforcement techniques that have been used to increase the resistance of the punching shear of slabcolumn connections Fig.2.

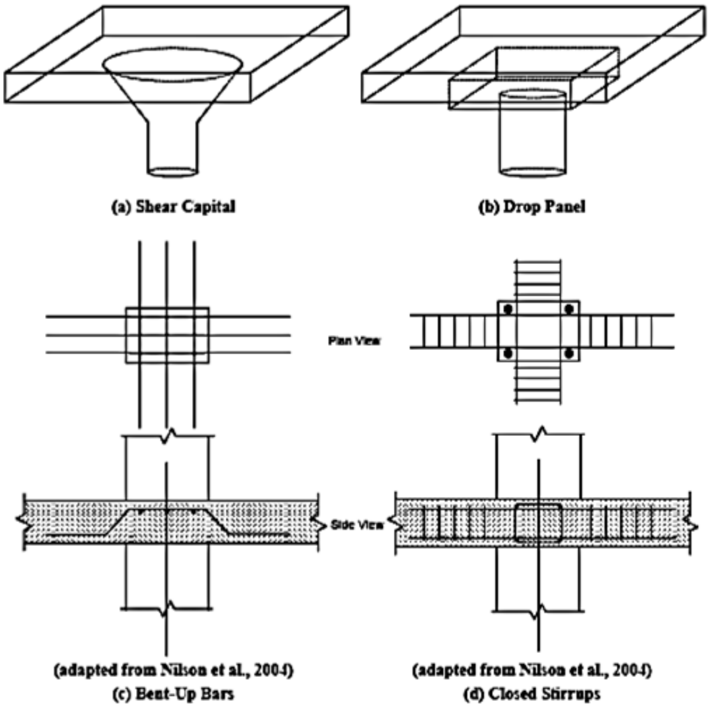

Fig2. Several Techniques for Improving Punching Shear Resistance (a, b, c & d)

IV. CODE PROVISIONS

A. Without shear RFT

In the current major codes, there are substantial differences in the methodologies utilised to analyse shear resistance of RC slab-column connections. In general, all design codes use a simple "shear on a particular critical perimeter" method that only includes the most significant data. The critical section for checking punching shear is typically located 0.5 to 2.0 times the effective depth (d) from the loaded area's edge. The critical section for punching shear in Egyptian Code Practice ECP 203-2018 [12], and American code ACI 318-14 [11] is d/2 from the column face, and the effect of flexural reinforcement is not taken into account when calculating punching shear capacity. For British Standards Institution, 1997 (BS 8110-97 [28]critical section 1.5d and DIN 1045-1 (2001)[29], and 2d for Eurocode 2, 2004 (EC2-2004)[13] as shown in Fig. 3. The way they express the effect of concrete compressive strength $(f\,'c)$ on punching shear capacity is another significant distinction among codes. The critical perimeter can be computed as follows :

-ACI 318-08, ECP 203-2018: $b_o = 4(c + d)$ (1)

-BS 8110-97: $b_o = 4(c + 3d)$ (2)

-EC2-2004: $b_o = 4(c + \pi d)$ (3)

-DIN 1045-1: $b_o = 4c + 3\pi d$ (4)

The taken cross-section of the column is square, (c) is the column side length, and d is the slab effective depth in these formulas. The minimal perimeter values, on the other hand, will result in the least slab punching force.

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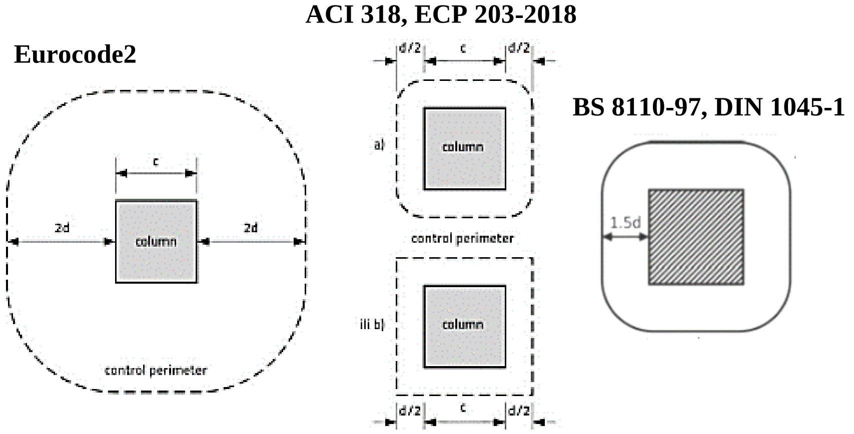

Fig3.Comparison of Major Code Provisions

The punching force is computed in BS 8110-97 as follows [2]:

$$V_c = 0.79(\frac{400}{d})^{1/4}(100\rho)^{1/3} b_o d \quad (5)$$

The value of V_c shall be multiplied by $\sqrt[3]{f_{cu}/25}$ for $fcu > 25$ MPa.
The value of $\sqrt[4]{400/d}$ not be less than 1.0.
The upper limit of $f_{cu} = 40$ MPa has been ignored
where f_{cu} = characteristic cube strength (MPa)
ρ = average steel ratio within $1.5d$ of column face =0.5 $(\rho_x + \rho_y)$
In ACI 318-08 [11] can be computed the punching shear by:

$$V_c = \frac{1}{3}\sqrt{f_c'} b_o d \quad (6)$$

f_c'= specified cylinder strength (MPa)
The upper limit of f_c' = 35 MPa has been ignored
b_o= critical shear perimeter
d = average effective depth
c = column width or diameter
Punching shear in EC2-2004 [13] calculated by:

$$V_c = \frac{0.18}{\gamma}[1 + \sqrt{\frac{200}{d}}](100\rho f_{ck})^{1/3} b_o d \quad (7)$$

f_{ck} = characteristic cylinder strength (MPa)
ρ = flexural steel ratio = $\sqrt{\rho_x \rho_y}$
γ_c = partial safety factor = 1.5 (taken as 1.0)
$(1 + \sqrt{200/d}\,)$ = size factor ≤ 2.0
While DIN 1045-1 [29] by:

$$V_c = 0.14[1 + \sqrt{\frac{200}{d}}](100\rho f_{ck})^{1/3} b_o d \quad (8)$$

f_{ck} = characteristic cylinder strength (MPa)
ρ = flexural steel ratio =$0.5(\rho_x + \rho_y) < 0.4 f_{cd}/f_y < 0.02$
$f_d = 0.85 f_{ck}$
f_v = yield strength of flexural steel (MPa)
$(1 + \sqrt{200/d}\,)$= size factor ≤ 2.0
In ECP 203-2018 [12] can be computed the punching shear by:

$$V_c = 0.316\sqrt{f_c/\gamma_c} b_o d \quad (9)$$

-f_c= compression strength (MPa)

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-b_o= critical shear perimeter
-d = average effective depth
-c = column width

B. With shear RFT

All codes stipulate that there is a share action between the shear reinforcement and the concrete in slabs that are subjected to punching shear, as stated in the following expression [1]:

$$V_{rd} = V_{cr} + V_{rs} \quad (10)$$

At the same time, the components in equation (10) differed depending on the employed Code. According to ECP203-2018 [12], the punching shear force for slabs reinforced by shear reinforcement is calculated as follows:

$$q_{up}(cracked) = 0.12\sqrt{\frac{f_{cu}}{\gamma_c}} + q_{sup} \leq q_{up-max} \quad (11)$$

$$q_{sup} = \frac{A_{st}\, f_y}{s.u\,.\gamma_s} \quad (12)$$

A_{st}: is The area of all the branches of the stirrups placed on the perimeter of the critical section.
s: is the distance between stirrups.
u:is the perimeter of the critical section as shown in the Figure 4.

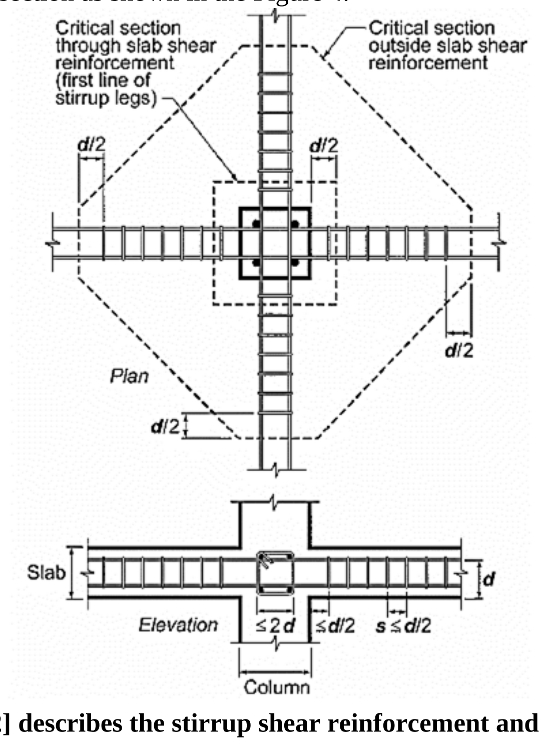

Fig4. ECP203-2018 [12] describes the stirrup shear reinforcement and edge column arrangement.

The distance between the face of the column and the first line of stirrup legs that encircle it must not exceed $d/2$. In the first line of shear reinforcement, the spacing between adjacent stirrup legs must not exceed $2d$ measured in a direction parallel to the column face. As indicated in Fig. 4, the distance between successive lines of shear reinforcement that encircle the column must not exceed $d/2$ in a direction perpendicular to the column face [12].

According to Euro Code 2 [13], the punching shear force for slabs reinforced by shear reinforcement is calculated as follows:

$$V_{rd} = 1.35.k \cdot .\rho \cdot (f_c)^{1/3} \cdot u \cdot d + 1.5 \cdot \frac{A_{SW} \cdot f_{ywd,ef} \cdot d}{S_r} \quad (13)$$

A_{sw}: the gross shear reinforcement area over single column circumference (mm2),
s_r: the radial length for a singular shear reinforcement circumferences (mm).
$f_{ywd,ef}$: the design stress which is permissible for shear reinforcement, and it is computed as follows:

$$f_{ywd,ef} = 250 + 0.25.d \leq f_{ywd} \quad (14)$$

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However, the ACI 318 recommendation for slabs strengthen by shear reinforcement, the punching load is found as the following equation:

$$V_{rd} = \frac{1}{6}\sqrt{f_c} \cdot u \cdot d + \frac{A_{sw} \cdot f_{yt} \cdot d}{s_r} \quad (15)$$

V. SYSTEM OF FIBRE-REINFORCED POLYMERS (FRP)

FRP stands for fibre-reinforced polymers, which could be utilised at the connection between the slab and the column to improve punching shear resistance. The materials of FRP might alleviate the problems that may be produced by durability. It is regarded a novel technology employed in construction. The following equations can be used to calculate the concrete shear capacity of slabs reinforced using FRP rebar according to ACI 440.1R-15 [30]:

A. ACI 440.1R-15 [30]:

$$V_c = 0.8\sqrt{f_c'}\,b_o k d \quad (16)$$

$$k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f \quad (17)$$

$$n_f = \frac{E_f}{E_c} \quad (18)$$

$$E_c = 4750\sqrt{f_c'} \quad (19)$$

B. El-Ghandour, et al., 2003 [31]:

$$V_C = 0.79[100\rho_f \cdot \frac{E_f}{E_s} \cdot \frac{0.0045}{\varepsilon_y}]^{1/3}(\frac{f_{cu}}{25})^{1/3}(\frac{400}{d})^{1/4} b_o a \quad (20)$$

C. Ospina et al., 2003 [32]:

$$V_c = 2.77(\rho_f f_c')^{1/3}(\frac{E_f}{E_s})^{1/2} b_o d \quad (21)$$

D. El-Gamal et al., 2005 [33]:

$$V_c = 0.33\sqrt{f_c'}\,b_o d\alpha \quad (22)$$

$$\alpha = 0.5(\rho_f E_f)^{1/3}(1 + \frac{8d}{b_o})(E_f \text{ in GPa}) \quad (23)$$

Where,
f_c' = specified concrete compressive strength.
b_o = perimeter of the critical section at (d/2) from the concentrated load.
d = distance from extreme compression fiber to the centroid of the tension reinforcement.
A comparison was done between punching shear capacity values obtained from previous research literature and data estimated from ACI 440.1R-15 [30] supplies see table. 1. The values computed using the ACI 440.1R-15 [30] were excessively conservative [34], [35], according to a notice that appeared in the table 1.

VI. FIBROUS REINFORCED CONCRETE

The use of fibres to improve punching shear resistance and fracture management in slab-column connections has yielded positive results Steel fibres have also shown to be beneficial in constructions subjected to lateral stresses (i.e. seismic) due to their ability to absorb energy dissipation. There have been several formulas offered for estimating the punching shear capacity of SFRC [37].

$$V_n^{sf} = V_c + V_a + V_d + V_{sf} \quad (24)$$

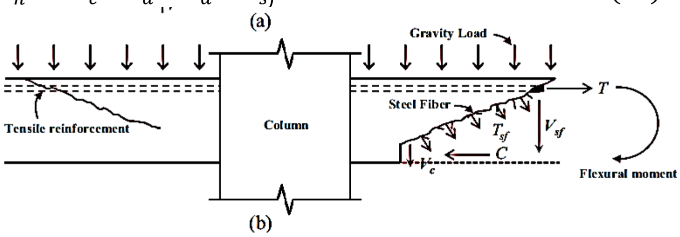

Fig5.shear resistance mechanism. of SFRC Flat Slab of the[37]

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The shear contribution of the uncracked concrete in the compression zone (V_c), the aggregate interlock at the crack interface (V_a), the dowel force transmitted across the crack by the flexural reinforcement (V_d), and the shear force resisted by the steel fibres at the crack interface make up the shear transfer mechanism of the SFRC flexural member without shear reinforcement, as shown in Fig. (5a) (V_{sf}). 22 As a result, the punching shear strength (V_n^{sf}) of SFRC flat plate slabs without shear reinforcement can be written as follows [37]:

Table1. Punching shear capacity results [36]

Reference	Specimen	FRP Type	V_{test}	V_{test}/V_{pred}
Hassan et al. [36]	G(0.7)30/20	GFRP	329	2.08
	G(1.6)30/20		431	1.90
	G(1.6)30/20-H		547	1.98
	G(1.2)30/20		438	1.91
	G(0.3)30/35		825	2.59
	G(0.7)30/35		1071	2.30
	G(1.6)30/35		1492	2.12
	G(0.7)30/35-H		1600	2.00
	G(0.7)30/20-B		386	2.36
	G(1.6)45/20-B		400	1.74
	G(1.6)45/20		511	1.67
	G(0.3)30/35-B		781	2.37
	G(0.7)30/35-B-2		1195	2.45
	G(0.3)45/35		911	2.08
	G(1.6)30/20-B		451	2.09
	G(1.6)45/20		504	1.74
	G(0.7)30/35-B-1		1027	2.38
	G(0.3)45/35-B		1020	2.59
	G(0.7)45/35		1248	2.30
Elgabbas et al. [35]	S2-B	BFRP	548.3	1.53
	S3-B		664.6	1.86
	S4-B		565.9	1.64
	S5-B		716.4	1.67
	S6-B		575.8	2.23
	S7-B		436.4	1.69
El-Ghandour et al. [31]	SC1	CFRP	229	2.23
	SC2		317	2.15
El-Gamal et al. [33]	C-S1		674	2.08
	C-S2		799	1.87

VII. CONCLUSION

A quick review of the flat slab and punching shear problem was undertaken previously.

1. In the past, there was little concern for punching shear difficulties, resulting in numerous disastrous building collapses.
2. Modern technologies have recently been employed to increase slab resistance to punching shear; nonetheless, there is still a significant gap in the ability to design buildings that are both low-cost and high-performance.
3. Shear reinforcement comes in a variety of shapes and sizes, including deformed and headed studs, strips, and shear bond reinforcement.
4. Stirrups are used in the traditional shear reinforcing method, although this method is ineffective for slabs with shallow depths of less than 150 mm.
5. Construction of headed-studs takes a long time.
6. Fibre-reinforced polymers (FRPs) can be thought of as a new type of shear reinforcement that can be used to improve punching resistance and solve durability issues.
7. The utilisation of fibres in slab-column punching shear resistance and fracture management

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