A Review on Flat Slab Punching Shear Reinforcement

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Abstract

Flat slab system is a concrete plate propped on columns without the existence of beams. During the former century, flat slabs have been used widely in different building types. In general, flat slabs are made from brittle materials and also have a finite depth; thus, flat slabs may undergo to fail due to punching shear or high deflections. Therefore, these criteria should be considered in the design of flat slabs and ignoring both of them had led to several crumbling down to many constructions in the past. To enhance the flat slab performance against failure due to punching and deflections, additional reinforcement should be supplied in the column region. In this paper, a review is presented to study the mechanism of punching shear in flat slabs and describe different types that used for reinforcement against punching shear.

Key words: Flat slab, Punching shear, Shear reinforcement.

1. Introduction

Flat sheet or plate is a rigid concrete slab with regular thickness, in generality, it can consider as one of the common applicable constructional systems on the globe, such as trading premises, residential buildings, hotels, office premises and hospitals. In flat slabs, the load has straight transmitted to the columns with no existence of panels or beams. See figure (1.A). Transforming of shear from the concrete plate toward columns are considered as the essential anxiety resulting from the dangerous of punching the column over the slab. Transforming of shear from the concrete plate toward columns are considered as the essential anxiety resulting from the dangerous of punching the column over the slab. Generally, when the live load becomes over 3 kN/m2, it is suitable to utilize falling panels at the position of columns, where the negative bending is relatively high, to enhance the capacity of negative flexural and minimize the hazard of shear failure at these locations, see figure (1.B). On the other hand, it is advisable to make heads for columns when live loads overrun 6 kN/m2, figure (1.C). However, for warehouse and industrial structures, the intensity of live loads may become over 10 kN/m2, in this situation, it should be used falling panels jointly by the heads of columns, see figure (1.D). [1]

A

B

C

D

Figure (1): Types of flat slabs (https://www.slideshare.net/satishhn/civil-structural-engineering-flat-slab-design)

Indeed, the construction system of flat slabs is a brilliant solution for the architects due to its flexibility to arrange partitions and columns without light hindering. The absence of beams in the flat slab systems brings many advantages such as simplicity in construction with low cost. Moreover, this type of construction provided an extra space over the floor height of the structure [2]. When using the flat slab system; the storey level could be depressed by minimizing the height of the partition and fenced cladding, it can save about 10 % from the height of members, and also, reduce the load on the foundation, see figure (2) [3].

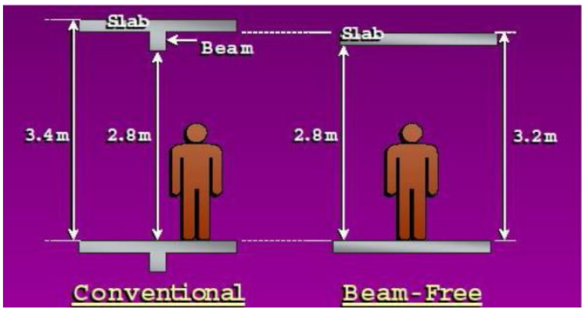

Figure (2): Height Savings by removing the beams [3]

1.1. Historical Background

Flat slab systems appeared at the last of the ninetieth century. It is used and developed in Europe and North America separately from each other. In these days, engineers established that it is beneficial to remove the beams that lay between columns, to simplify the construction operation of buildings and to reduce the whole story heights with equivalent use of the overall volume of the structure. The first flat slab system, designed by George M. H., was built and completed in the USA in 1901 [4].

At the period from 1905 to 1909; an engineer called Turner C.A. applied the flat slab concept to many buildings, it was considered as a major move to the widespread use of such sort of structures [5]. In the meantime, an engineer named Robert M. from Switzerland developed simultaneously the same constructional system, see figure (3). Through the years 1900 to 1908, Robert M. made an experimental study for slabs that applied directly on columns, he gained a patent in 1909 for his constructional system. In 1910, his design was applied in Zurich to a warehouse where the columns support directly a reinforced concrete plate [6].

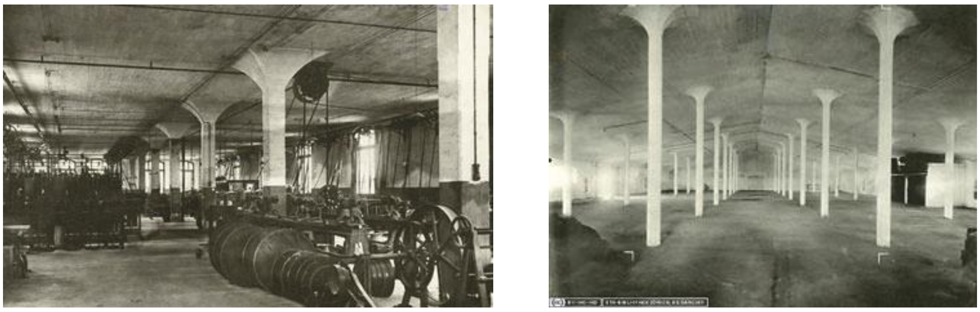

Figure (3): Robert Maillart's structures using a concept of flat slabs [7]

At the same period, another engineer called Arthur F. built many structures, in Russia, in which the concrete plates were supported by a system of columns. Therefore, he may consider as one of a few engineers who participated in improving and developing this sort of structures [8]. In spite of the fact that there were a few variations in the aforementioned designs; but they used columns with large size to transmit loads easily from concrete plates to the columns. Moreover, no consideration for a specific reinforcement was taken to resist punching failure for systems that used these days [9].

1.2. Punching shear

In flat slabs where no beams are used to interconnect columns that supporting the flat slabs; the loads have transmitted in a high concentration within a relatively tiny region. In this system, the slab-column connection zone becomes extremely critical due to shear stress concentration developed in this region, which may cause a punching failure for the slab. Therefore, punching shear can be defined as a failure of the slab in that area where the load is applied in high intensity, or due to shear stress at the column support region, see figure (4) [2].

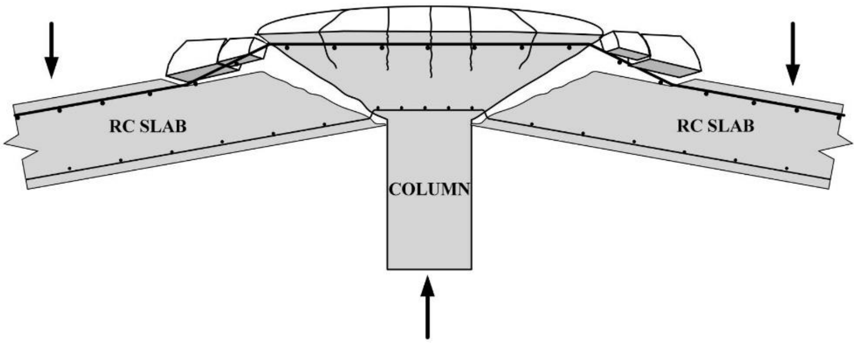

Figure (4): Punching failure in the slab columns connection area [2]

If the punching failure happened, the slab and column have physically disconnected from each other. This will cause a considerable disturbance of the equilibrium for structure created by such members. Then, collapse to the whole structure may be induced because of load redistribution to the other members that not designed to capable new loads. Because concrete is a brittle fracture material, the punching failure appeared all at once. Therefore, it should be taken into account with considerable attention the slabs that hold directly by columns in the design stage.

To obviate slabs brittle fracture caused by punching shear, it is crucial to reinforce slab regions adjacent to the column by different reinforce arrangements. Recent design regulations state that bent or straight reinforcement bars should be provided in the lower region of the slab to avoid progressive constructional breakdown producing from exceptional actions, even if the design computations demonstrate that punching shear reinforcement is not required, see figure (5).

Figure (5): Upper floor collapse of Wolverhampton parking (UK) [10]

2. Failure Mechanism

2.1. Rules of crack sliding model (CSM):

Basics of Crack Sliding Model for shear beam cases were developed by Zhang in 1997, further progressing for CSM was done in 2006 by Hoang, who conducts the punching shear of the slabs in the absence of shear reinforcement. The CSM has distinguished the yield lines that created in uncracked concrete from that initiated in rifted concrete. Yield lines may define as the lines of the displacement cut-out. Yield slipping stripe creates to the cracked concrete could be explained by Muttoni. In 1990, he presents an experimental study finding that the critical shear rift was developed perpendicularly to the crack surface [11].

When failure caused shear starts, a component of proportional displacement initiated by the crack will become in parallel with the crack. Then, the slipping resistance will be crowded straight with the crack, and it will convert to the sliding yield line. Significant yield line location can be specified, depending on the CSM, by integrating the criterion of the crack with the crack slipping criterion. To evaluate the required load for inducing a definite shear crack, the first norm should be used; however, for the estimation of crack sliding failure possibility, the next criterion must be used. If the cracking load becomes equal to the sliding resistance, a shear failure will happen instantly after the crack. In the meantime, if the slipping resistance becomes greater, the specified crack will not be crucial. In such status, there is a possibility of a further rise to the applied load, and more shear cracks will be initiated.

It is assumed that an axisymmetric reinforcement is provided to the slab, as shown in figure (6). It is a simply supported slab over a (D) circumference with a point load (P) applied at the centre. This force is applied to the slab via a circular column of do diameter. It is supposed that a considerable slab reinforcement is provided against bending and torsion. It presumed that the punching shear crack is developing in a circumferential shape and the mechanism of failure is so perfect as the truncated punch is an upward conical block.

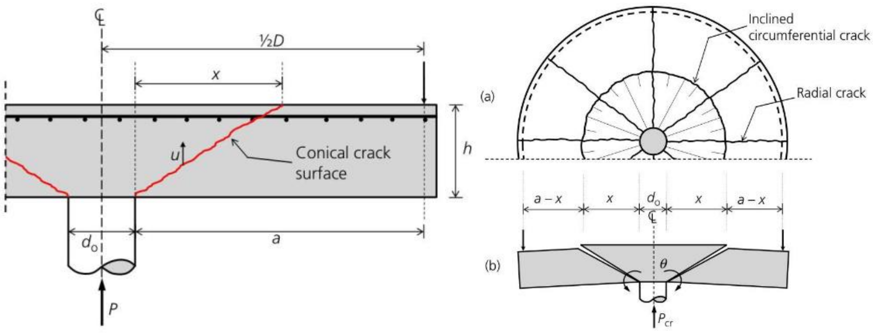

Figure (6): Mechanism of punching crack without shear reinforcement [11]

2.2. Critical Circumference

The strength of punching shear is measured at the critical perimeter zone, which is lying at a specified distance to the face of the column. According to the ACI, fib model code and Euro codes, this distance is varied from (1/2) to (2) the efficient slab depth, see figure (7). Therefore, the critical perimeter can be computed as follows [2]:

ACI 318: $u = 4 \times c + d \times \pi$ 1. a

ACI 318: $u = 4 \times c + 4 \times d$ 1. b

Fib Model code: $u = 4 \times c + d \times \pi$ 2

Euro code: $u = 4 \times c + 4 \times d \times \pi$ 3

In these expressions the taken cross-section of the column is square, (c) is the column side length, and d is the slab effective depth. However, least slab punching force will result from the minimum values of perimeter.

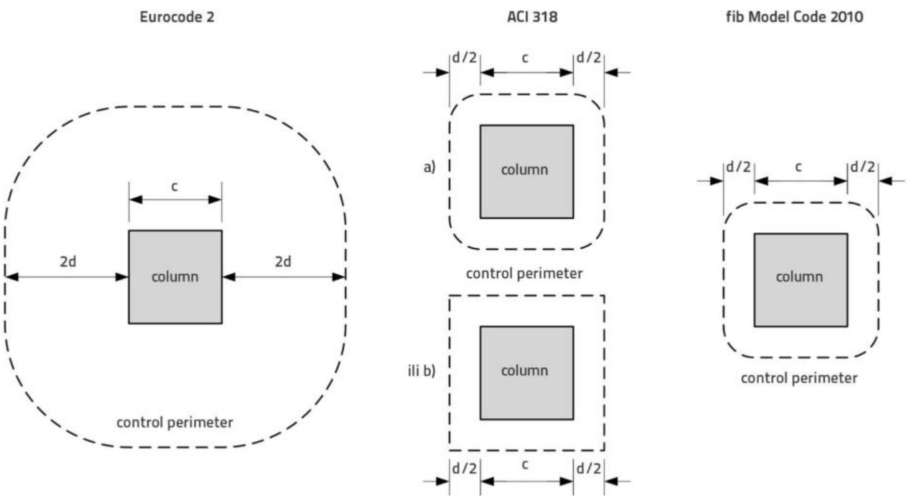

Figure (7): Critical circumference given in different codes [2]

3. Computation of slab punching force

3.1. Without shear reinforcement

The punching force is computed in Euro Code2 as follows [2]:

$$V_{cr} = 0.18. k(100. \rho. f_c)^{1/3}. u. d \quad 4$$

Where:

ρ: is the bending reinforcement ratio,

f_c: is the concrete compressive strength of the cylinder, and

k: is a dimensionless parameter, computed by the expression:

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2.0 \quad (5)$$

In ACI 318, the force of punching shear computed as:

$$V_{cr} = \frac{1}{3}\sqrt{f_c}.u.d \quad (6)$$

While, in referring to MC 2010, it is calculated as in the following expression:

$$V_{cr} = k_{\psi}\sqrt{f_c}.u.d \quad (7)$$

The rotation angle of the slab ψ is estimated experimentally or theoretically and as proposed in agreement with MC 2010 [12]. There are four approximations levels in the theoretical calculation depending on MC 2010. The approximation of the second level, it could be used in empirical analysis of the slab the punching shear, may be used in the whole of cases [13]:

$$\psi = 1.5\frac{r_s.f_y}{d.E_s}\left(\frac{V_u}{V_{flex}}\right)^{1.5} \quad (8)$$

Where:

r_s : separated radius of the slab punching shear,

f_y : reinforcement yield strength for bending,

E_s : steel reinforcement elastic modulus,

V_{flex}: *maximum* load over the test, and it is computed by equation (9), and

V_{flex}: failure force of bending reinforcement, above or below column region.

$$V_{flex} = \frac{4.m_R}{r_q\left(cos\frac{\pi}{8}+sin\frac{\pi}{8}\right)-c}.\frac{B^2-B.c-c^2/4}{B-c} \quad (9)$$

Where

r_q : the radius where reaction forces appear over the slab,

c : column side dimension (mm),

B : slab side length (mm), and

m_R : the slab extreme bending moment (N.mm), it is computed by following expression:

$$m_R = \rho.f_y.d^2\left(1-\frac{\rho.f_y}{2.f_c}\right) \quad (10)$$

3.2. With shear reinforcement

For slabs, which undergo to punching shear, all codes state that, there is share action between the shear reinforcement and the concrete, as mentioned in the following expression:

$$V_{rd} = V_{cr} + V_{rs} \quad (11)$$

In the same time, components that presented in equation (11) varied depending on the used Code, and the varying is strongly remarkable between the idea adopted in ACI 318 and Euro Code 2 with the concept of MC 2010 on another side. With regards to Euro Code 2, for slabs strengthen by shear reinforcement, the punching shear force is computed as follows:

$$V_{rd} = 0.75 \times 0.18.k.(100.\rho.f_c)^{1/3}.u.d + 1.5.\frac{A_{SW} \cdot f_{ywd,ef} \cdot d}{s_r} \quad 12$$

Where:

A_{sw}: the gross shear reinforcement area over single column circumference (mm^2),

s_r: the radial length for a singular shear reinforcement circumferences (mm), and

$f_{ywd,ef}$: the design stress which is permissible for shear reinforcement, and it is computed as follows:

$$f_{\ ywd,ef} = 250 + 0.25.d \le f_{ywd} \quad 13$$

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

$$V_{rd} = \frac{1}{6}\sqrt{f_c}.u.d + \frac{A_{SW} \cdot f_{yt} \cdot d}{s_r} \quad 14$$

In Euro Code 2, both the Asw and Sr parameters having a similar sense, while the design stress that permissible for shear reinforcement is restricted at 414 MPa or 60 000 psi. Definite likeness can be noted when comparing equations (4) and (12), and (6) and (14). First of all, the concrete bearing capacity is reduced for both codes, as regarding of slabs without shear reinforcement and these which are reinforced for shear. The minimizing value becomes 25 % for Euro Code 2 and 50 % for ACI 318. With regard to ACI 318, the reduction of 25 % is allowed only for anchoring heads, headed studs (see figure (8)), shear reinforcement. The mentioned reduction comes from the wider shear cracks, which are assumed in slabs strengthened by shear reinforcement as compared with those that are not strengthened by shear reinforcement [14].

However, when the cracks become much wider, the capacity of shear transfer in concrete will be minimized due to the inefficient possibility of aggregate grain interlocking located on the both of shear crack sides. On the other hand, the addends that exist in equations (12) and (6) have a major comparable form, but the variance in the extent of design stress that allowed for shear reinforcement. This may be used as 1.5 in Euro Code 2, while in ACI 318, the ratio becomes 1.0. It should be mentioned that this ratio considers the efficiency of the shear reinforcement.

In MC 2010, the equation that states the bearing capacity contribution with the shear reinforcement for a slab undergoes to punching shear is given by:

$$V_{Rs} = \sum A_{SW}.k_e.\sigma_{SW} \quad 15$$

Where

ΣA_{sw}: the gross shear reinforcement area which is intersected with the possible shear crack (down to 45°) and this area is varied from (0.35.d) and (d)

k_e: the ratio which takes the column place (force eccentricity effect) and this ratio is 0.65, 0.7 or 0.9 for the corner, peripheral and central respectively, and

σ_{sw}: the shear reinforcement stresses which computed according to the following equation:

$$\sigma_{SW} = \frac{E_s \cdot}{6} \cdot \left(1 + \frac{f_{bd}}{f_{yw}} \cdot \frac{d}{\emptyset_w}\right) \leq f_{yw} \qquad 16$$

Where:

f_w: shear reinforcement bar diameter,

f_{yw}: yield of shear reinforcement, and

f_{bd}: the reinforcement bond strength, for practical uses it is equal to (3 MPa).

4. Shear Reinforcement Models For Punching Shear

1. Headed stud:

Steel hot-rolled studs, see figure (8), are used to enhance the shear resistance against punching failure, the studs yield strength raged from 526 to 591 MPa [5]. This solution is utilized effectively in Germany and North America. In general, the shear studs are welding over a strip of metal [15]. When shear studs are used, the strength will rise up to twice, while the capacity of rotation will be up to three times as compared with slabs of no shear reinforcement [9].

2. Deformed stud:

Due to the bond between concrete and deformed bars, there will be a relative rise in the stress of shear reinforcement. However, if the ratio of the flexural reinforcement rises, the function of the shear reinforcement quantity in the slab strength will be more obvious. As to the theoretical pattern, the shear reinforcement strains are larger for the same rotation, and thus, the deformed studs will increase the punching strength [16].

Figure (8): Shear reinforcement rail studs [15]

3. Stirrup:

Shear reinforcement stirrups made from cold-worked steel, see figure (9), with a yield strength varied from 536 to 550 MPa [5]. Stirrup shear reinforcement was first investigated by Graf (1938). The first investigation for stirrups was done in 1938 by Graf. In 1990, Broms examined experimentally eight samples with varied shear reinforcement types from bent bars to the ordinary stirrup. The outcomes of the test state that normal shear reinforcement in the case of open links which including tension flexural reinforcement only are insufficient to grant the required ductility for the flat slab. While the closed hoops are more efficient for shear reinforcements, but unfortunately, their installation requires reinforcement cages that built up by using individual bars. Therefore, the prices and the fixing time for reinforcement will be increased [15].

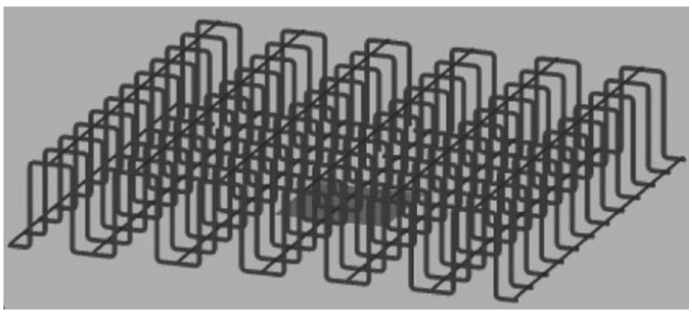

Figure (9): Cages of continuous stirrups [5]

4. Swimmer bars:

Swimmer bars is a modern shear reinforcement form, see figure (10); they are consisting of sloping short bars welded in rectangles of steel which figure the top and bottom for the truncated pyramid steel crate. The required sets of steel crate depending on the concrete slab thickness, the concrete class, and the punching force magnitude. The punching capacity of the slab could be enhanced by 17 % when using swimmer bars as a shear reinforcement as compared by the base sample by changing the failure pattern from brittle to ductile [17].

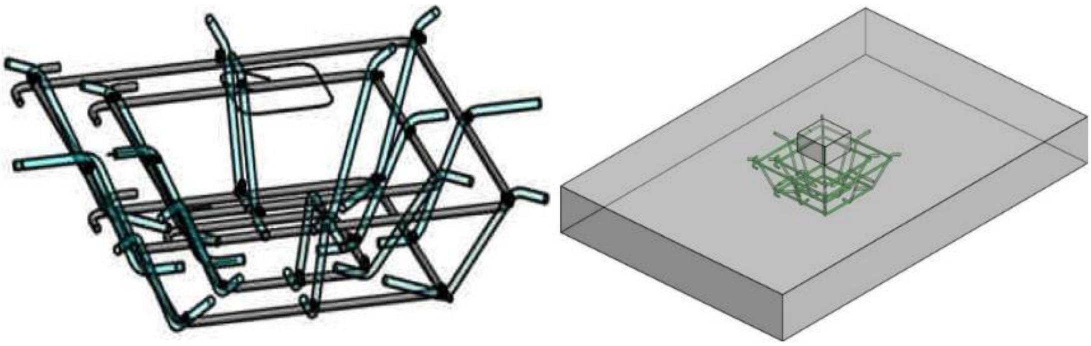

Figure (10): Cage view [17]

5. Shear bond reinforcement:

The system of shear-band reinforcement has made from high ductile steel strips, see figure (11) [18]. The advantages of these strips are the possibility of bent into several forms that are not ripped to the top slab surface. This may occur when the whole reinforcement of flexural is laying into a small cover loss. The benefits of the shear-band regulation can be stated as follows [4]:

a. Improves flat slab ductile and prohibits failure due to brittle punching.
b. The flat slabs capacity of punching shear will be raised even if the flexural capacity of the slab not increased.
c. Lightweight, easily fabricated, and the placement of reinforcement is soft and efficient.

Figure (11): Shear-bands specimens [18]

6. Post-installed shear reinforcement via mechanical anchorage:

This process is suitable for the consideration of the post-installed particularities of the shear reinforcement, as shown in figure (12). In the design stage, it is possible to consider the impact of the slab mechanical and geometrical parameters, such as concrete strength, reinforcement ratio, etc., while for post-installed bars, the taken parameters are anchorage failures, bond strength, bar strength, etc. The post-installed design of the shear reinforcement depends on the critical shear-crack theory (CSCT) [9]. Up to now, the CSCT theory is applied successfully to numerous systems of shear reinforcement that install previously for the concrete slab. Also, it is suitable to estimate the strength and post-installed behaviour of shear reinforcement. The outcomes of experimental and theoretical studies based on CSCT show the following:

a. It is an economical procedure and sloped punching shear bars are an efficient manner to the slabs.
b. Results of experimental work revealed that both the deformation capacity and the strength can be increased safely at the collapse for slabs with nil shear reinforcement.
c. In this system, the shear rupture of reinforced slabs may expand due to concrete struts crushing and punching outside or outside the region of shear reinforcement.
d. The concept of consistent depends on the CSCT provided in this system. It considers a variety of failure patterns and permits considering the impact of anchorage dimensions, bond, and the slab rotations on the member strength in the time reinforcing.

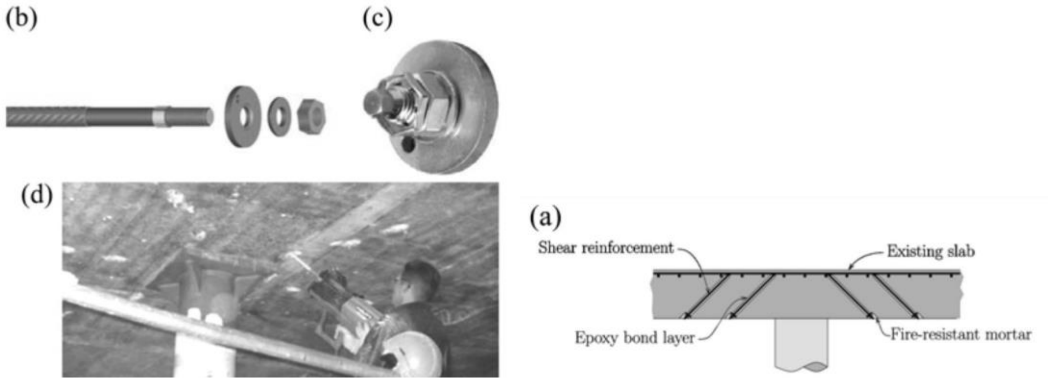

Figure (12): Post-installed shear reinforcement: (a)exemplary cross-section; (b) view bar, washers, and nut; (c) anchor head; and (d) inclined holes drilling. [18]

7. Shear reinforcement:

This type of reinforcement is formed from steel flat strip of high strength, the width and thickness of the are 25.4 mm and 0.8 mm respectively, as shown in figure (13). These strips were punched with circular holes in 8 mm diameter along the strip central line with two holes at both ends in the form of a semi-circle. A test on these holes is done by Li in 1995 and revealed that their presence in the strip is important to preserve suitable characteristics of the embedment anchorage in short strip lengths. It is found that it is convenient to bend the strip with an inclined angle, so that, the shear reinforcement becomes perpendicular to the possible crack caused by shear**.** The required shear reinforcement amount was found according to BS 8110 (1985) requirements to prevent the failure due to punching shear. The reinforcement is spanned just in a single direction; therefore, a single depth of shear stalks is required. Actually; this is crucial to facilitate matters on location; also, it is very effective because of the upper layer of reinforcement will be anchored. Moreover, this manner provides further anchorage to the compression zone reinforcement [15].

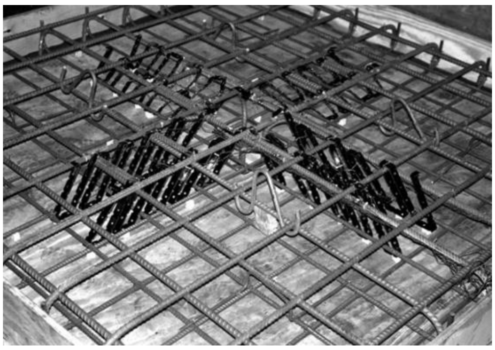

Figure (13): Reinforcement in slab Punching Shear Slab [15]

8. Fibre-Reinforced Polymers (FRP) System:

FRP is an abbreviation to fibre-reinforced polymers which could be used in the connection of the slab with the column to enhance the resistance of punching shear. It is considered as a new technology used in the construction, the materials of FRP could solve the problems that may be caused due to durability. The concrete shear capacity of slabs strengthen by FRP rebar could be computed as in the next equations:

a- ACI 440.1R-15 [19]:

$$V_c = 0.8\sqrt{f_c'}b_o k d \tag{17}$$

$$k = \sqrt{2\rho_f n_f + \left(\rho_f n_f\right)^2} - \rho_f n_f \tag{18}$$

$$n_f = \frac{E_f}{E_c} \tag{19}$$

$$E_c = 4750\sqrt{f_c'} \tag{20}$$

b- El-Ghandour, et al., 2003 [20]:

$$V_c = 0.79\left[100\rho_f.\frac{E_f}{E_s}.\frac{0.0045}{\varepsilon_y}\right]^{1/3}\left(\frac{f_{cu}}{25}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4} b_o d \tag{21}$$

c- Ospina et al., 2003 [21]:

$$V_c = 2.77\left(\rho_f f_c'\right)^{1/3}\left(\frac{E_f}{E_s}\right)^{1/2} b_o d \tag{22}$$

d- El-Gamal et al., 2005 [22]:

$$V_c = 0.33\sqrt{f_c'}b_o d\alpha \tag{23}$$

$$\alpha = 0.5\left(\rho_f E_f\right)^{1/3}\left(1 + \frac{8d}{b_o}\right) \quad (E_f \text{ in GPa}) \tag{24}$$

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 had made between values of punching shear capacity that gained from the literature of past work, with data estimated from ACI 440.1R-15 supplies, see table (1). A remarkable note that appeared from the mentioned table states that the values estimated via the ACI 440.1R-15 were highly conservative [23].

Table (1): comparing the punching shear capacity between the test and the estimated values [23]

Reference	Specimen	FRP Type	V_{test}	V_{test}/V_{pred}
Hassan et al. [24-25]	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.[26]	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.[20]	SC1	CFRP	229	2.23
	SC2		317	2.15
El-Gamal et al.[22]	C-S1		674	2.08
	C-S2		799	1.87
Zaghloul A. [27]	ZJF5		234	1.38
Bouguerra et al.[28]	C175N		530	2.01

5. Conclusion

Previously, a brief review of the flat slab and punching shear problem has conducted.

1. In the past, there is no consideration for the punching shear problems, and therefore, many catastrophic collapses in buildings have happened.
2. Recently, modern technologies have been used to improve the resistance of slab to punching shear; while there is still a huge gap to construct buildings with low cost and high performance.
3- Shear reinforcement are used in many forms such as headed and deformed studs, strips and shear bond reinforcement.
4- When swimmer bars are used, it is probably that the capacity of punching shear increased by 17 % comparing with flat slab without specified reinforcement for punching.
5- Shear reinforcement could be used in the post- installed form by a mechanical anchorage, an experimental test shows that this method is economic, but unfortunately, the slab shear failure may develop due to struts crushing of concrete and punching in the outside region of shear reinforcement.
6- The fibre-reinforced polymers could be considered as the new type of shear reinforcement that used to enhance the punching resistance, also, FRP materials solved problems induced by durability.

Conflicts of Interest

The author declares that they have no conflicts of interest.

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مراجعة حول تسليح البلاطات المستوية ضد القص الثاقب

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الخلاصة:

يتكون نظام البلاطة المسطحة من صفيحة خرسانية مثبتة على أعمدة دون وجود عتبات. خلال القرن الماضي، استخدمت البلاطات المسطحة على نطاق واسع في أنواع مختلفة من المباني. بشكل عام، تصنع البلاطات المسطحة من مواد هشة ذات عمق محدود؛ وبالتالي، قد تخضع للفشل بسبب قوى القص أو انحرافات عالية. ولذلك، يجب اخذ هذه المعايير بعين الاعتبار عند تصميم البلاطات المسطحة وان تجاهل اي منهما قد يؤدي إلى انهيار العديد من المباني كما حصل في الماضي. لتحسين أداء البلاطة المسطحة ضد الفشل نتيجة قوة الاختراق والانحرافات، لا بد من توفير تسليح إضافي في منطقة العمود. في هذا البحث، سيتم تقديم مراجعة لدراسة آلية قص الاختراق في البلاطات المسطحة ووصف أنواع التسليح المختلفة التي تستخدم في التعزيز ضد قص الاختراق.

الكلمات الدالة: البلاطة المسطحة، قص الاختراق، تسليح القص.