PUNCHING SHEAR BEHAVIOR OF RC SELF-COMPACTING CONCRETE FOOTINGS RESTING ON ELASTIC SPRINGS

* Zainab Talib Jaafar¹

Zinah Waleed Abass²

Shaimaa Hasan Fadhil³

- 1) Civil Engineering Department, Mustansiriyah University, Baghdad, Iraq.
- 2) Civil Engineering Department, Mustansiriyah University, Baghdad, Iraq.
- 3) Civil Engineering Department, Mustansiriyah University, Baghdad, Iraq.

Abstract: This research is conducted to study the effect of increasing footing thickness, flexural reinforcement ratios, and using funnel-shaped punching shear preventers (FSPSP) on the punching shear failure of self-compacting concrete (SCC) pad footing. Four reinforced concrete footing specimens were supported on a bed of steel (car)springs and loaded by vertical load till failure. The results showed that the ultimate load, the ductility, and the punching shear strength were improved by increasing footing thickness and using the FSPSP. The results also showed that the ultimate load increased with increasing of the flexural reinforcement ratio while the ductility and the deflection are decreased. It was found that the best results were obtained by using FSPSP, about 66% increasing in ultimate load.

Keywords: *Punching Shear; Footings; Reinforced Concrete SCC; Funnel-Shaped Punching Shear Preventers.*

1. Introduction

Footings can be defined as certain structural members that are utilized to support walls as well as columns for transmitting and distributing their loads to the supporting ground. Column footings (pad footings) are the main types of shallow foundations. Therefore, the check of punching of the column- footing is an important step of the design of the footings that are exposed to the high

concentrated forces by the columns. In general, punching shear failure is a brittle failure which appears at concentrated load or column support regions as a truncated cone in case of a circular column and a truncated pyramid in case of the rectangular column, with sides sloping outward at an angle of approximately 45°, tend to separate from the slab and move with the column due to the presence of simultaneous high vertical compressive stress at the top of the footing and lateral tensile stress at the bottom of footing [1]. also, it happens without visible signs before the occurrence of the failure. Therefore, Extensive studies [2-13] have been performed in the past decade about punching shear failure of the pad footing to enhance the punching shear strength of the footing-column connection. The basis test setup of pad footings which were used in the several studies are classified to 4 types which can be explained as; The first type referring to the footings which have been supported on a bed of steel (car) springs, also in which loaded by column stub [2,3], while the second type includes footings resting on the line or even the concentrated supports with the load applied through steel plate of column stub [4-7], third type test setup consists of applying uniform loading replicated through the use of a lot of load points [8-13], and the fourth type regarding these

*Corresponding author: zainab664@yahoo.com

test setups include footings that have been supported on the soil as well as being loaded through column [10-12].

Talbot (1913) [2] conducted the initial experimental investigations concerning the pad footings at Illinois University. Such tests have been conducted on 197 column footings models placed over a bed of springs to simulate the interaction between the footing and the soil. Investigations in Illinois about pad footing continued by Richart (1948) [3]. Richart tested 156 footings of various shapes and construction details by placing them on a bed of automotive coil springs, Cole (1966) [14] studied the basic mechanism of failure in shear of RC footings through the use of high strength gypsum plaster models were constructed and loaded to failure on a foundation of sand in the box.

Hallgren et al. (1998) [4] Studied the effect of the related to concrete strength, flexural reinforcement ratios, the reinforcement anchorage type, type as well as usage regarding shear reinforcements, approach to apply loading in addition to slabs' shapes on punching shear strength of 14 column footings that were loaded by uniform line loads and with uniform surface loads. Hegger et al. (2006) [10] also examined punching shear failure regarding five RC footings with different thickness and reinforcement ratios supported on the sand in the box. furthermore, Hegger et al. (2009) [12] investigated the punching shear behavior of footings supported on the sand and a column stub and a uniform surface load was applied over the footings with taking different parameters such as shear span to depth ratio (a/d), concrete compressive strength and punching shear reinforcement which consists of vertical stirrups with different diameters. Lee et al. (2014) [15] studied a new manner for improving ductility and strength of the footing through inserting steel funnel-shaped to act as Punching Shear Preventers (PSP) into the footing. Kueres et al. (2019) [16] investigated the punching shear behavior regarding the footings with no shear reinforcement and with traditional closed stirrups as shear reinforcement, and they were supported on a column stub and a uniform surface load was applied.

This study focused on strengthening of shear resistance of footing supported on the bed of springs (car). Four samples are constructed and tested to study the influence of thickness of footing, Percentage of steel reinforcement (ρ), and using the funnel-shaped punching shear preventers (FSPSP) as shear reinforcement.

2. Experimental Work

Four square reinforced concrete footing models were constructed and tested until the failure. All specimens had a square shape with a side length of 1000 mm. The axial load is applied by the solid square steel column of dimensions of 150*150 mm over the center of the footing as shown in Fig.1.

Figure 1. Dimensions and reinforcement layouts of the test specimens.

All the footings were cast at the same time and had the same compressive strength by about 21.2 MPa. The type of concrete that used in this study

is self-compacting concrete (SCC) of mix proportion (cement 290 kg/m³, water 160 liters/m³, sand 814 kg/m³, gravel 910 kg/m³, limestone 190 kg/m³ and superplasticizer 1% from (cement+ limestone)). Specimens S₁ and S₂ are specified to study the effect of the increase of the footing thickness 120 and 140 mm while S₁ and S₃ are employed to study the influence increasing of flexural reinforcement ratio as of (36 and 57)% respectively as shown in the Fig.1. The fourth specimen S₄ are employed to study the effect of using of four funnel-shaped punching shear preventers (FSPSP) as a shear reinforcement. The FSPSP made of galvanized metal and a smooth surface inclined by 45° as well as had four holes (diameter of the holes was 10 mm) which enhancement the full bond between the FSPSP and the concrete as shown in the Fig.2. the yield stress, ultimate strength, and modulus of elasticity of galvanized metal as (208, 364, and 106*10³) MPa respectively.

Figure 2. Funnel –Shape Punching Shear Preventers (FSPSP).

All the FSPSP installed around the column at critical shear zone as shown in the Fig.3. The size of the FSPSP as namely (the top diameter “d_t” * the bottom diameter “d_b” * height “h”) as

(120*40*40) mm and thickness of 1mm. Table 1 shows the detail of the footing specimens .

Figure 3. Location of the FSPSP.

Table 1. Footing Specimens Details.

Specimen symbol	Thickness of specimens mm	Flexural reinforcement ratio	FSPSP		
			Number	d _t *d _b *h (mm)	Thickness (mm)
S ₁	120	0.0036	none	None	-
S ₂	140	0.0036	none	None	-
S ₃	120	0.0057	none	None	-
S ₄	120	0.0036	4	120*40*40	1

It is worth pointing out here that the specimens are supported on a bed of springs and loaded concentrically which is applied by using a universal testing machine of the type (EPP300MFL system) with a capacity of 3000kN as shown in the Fig.4, applying the load in steps 5kN. The bed of springs consist of nine car springs, which each spring works separately from the other. The springs are held between two steel plates which thickness of each was 10mm. In addition, a ring of rubber was put at the top and bottom of each spring to install it and to prevent the friction between the springs and the plates.

The springs have a modulus of elasticity equal to 3.3×10^5 MPa as tested in the structural laboratory of the civil engineering department/ college of engineering / Mustansiriyah University

Figure 4. Test setup.

During the experiments, the strains of the reinforcing bars and vertical displacements at the quarter of the span of footings were measured with every load step. Strain gauge type (KFH-20-120-C1-11L1M2R 120 20) which is used in the test is installed at the bottom of the flexural reinforcement bar as shown in Fig. 5.

Figure 5. Location of strain gauge.

3. Discussion of Experimental Result

3.1. Cracking Characteristics

To examine the influence of footing thickness on the punching shear behavior, two specimens are available S_1 and S_2 with the same reinforcing bar layout. The test results showed that the first cracks started to appear in S_1 , and S_2 at 64.2 and 57.5% of the ultimate failure load respectively. Table 2. Illustrates test results of the tested footings.

Table 2. Test Results of the Footings.

Specimens symbol	ρ	FSPSP number	First crack load P_{cr} (kN)	Ultimate load P_u (kN)	Difference of P_u %	Deflection at ultimate load $\Delta \mathbf{u}$ (mm)	Ductility ($\Delta \mathbf{u} / \Delta \mathbf{cr}$)
S ₁	0.0036	-	63	98	-	1.51	2.96
S ₂	0.0036	-	65	113	+15.3	1.62	3.44
S ₃	0.0057	-	80	120	+22.4	1.10	2.50
S ₄	0.0036	4	73.5	163	66.3	1.83	10.28

Also, it can be noted that the increase of the thickness of the specimens lead to increase the ultimate load by about 15.30% relative to reference specimen S_1 . As well as, ductility [deflection at ultimate load (Δu) to the deflection at observed first crack load (Δcr) [17,18]]. This was already observed in previous experimental investigations on reinforced concrete footings [13,16,19,12].

While in the case of increasing of flexural reinforcement ratio from 36% to 57% for specimen S_3 , the ultimate load reached 22.44% over reference specimen S_1 . In contract, the increasing of the flexural reinforcement ratio led to reduce ductility and deflection at the ultimate load and this indicates that the model becomes more brittleness, this behavior is an agreement with [19-21].

Furthermore, inserting FSPSP to the specimen S_4 causes considerable improvement in the ultimate load which reached 66.32 % and improvement of the ductility in the footings with FSPSP compared to that results of the specimen without FSPSP, these results are a good agreement with [15].

At all specimens, the propagation of cracks was appeared and spread without stopping the load applying till the pattern of the final crack was mapped in the tension face as shown in Fig.6.

Figure 6. Crack Patterns of the Footings S_1 , S_2 , S_3 , and S_4 (bottom face).

3.2. Load-Deflection Characteristic

Generally, Fig. 7 shows the relationship between load and deflection at the quarter of the footing specimens. For each specimen, general relation between deflection as well as load with regard to specimens has been, primarily almost linear elastic behaviors with regard to low loading stages has been indicated. Gradually, the load has been increasing up to the failure, where after cracking the load and deflection curve is significantly changed.

As can be noted from the load-deflection curve, at an equivalent load, the deflection decreased by about 19.2% by increasing thickness of S₂ relative to the reference concrete specimens S₁. While the toughness value [area under the load-deflection curve, i.e. absorbed energy] is increased with increasing of the footing thickness.

From Fig.7 it can be observed that the gradient of the load-deflection curve increases with the increasing of flexural reinforcement ratio in the specimen S₃ as well as at a certain load, the deflection decreased by about 52.16 % for S₃ respectively relative to the reference concrete specimens S₁.

Also, it can be noted that the gradient of the load-deflection curves were increased with inserting FSPSP to the footing. And the toughness increase with the addition of FSPSP to the footings. While the deflection at a certain load decreased by about 78.47 for S₄ relative to the reference S₁.

Figure 7. Load-Deflection Relationship of the Footings.

3.3. Failure Characteristics

There are two different types of The punching failure; the first type is called shear failure, which often occurs in the footings with a lot of flexural reinforcement ratios as well as it is occurring suddenly with a little deflection. In contract, the second type considered as flexural failure that occurs when the flexural reinforcement ratio is little and the footings are failed by the yielding of the reinforcement bars [15, 22, 23].

Therefore, in order to know the type of failure of the specimens, the ultimate strain in the flexural reinforcing bar has been evaluated from strain gauges that are glued at the bottom flexural reinforcement bar as shown in the Table 3. Table 3 showed that the ultimate strains of flexural reinforcement bar of S₂ increase with increasing the footing thickness but did not reach the yield strain. While, increasing flexural reinforced ratio lead to decrease the ultimate strain of flexural reinforcing bars, so all specimens are failed by punching shear.

After adding FSPSP to specimens S₄, it can be noted that the strain of the flexural reinforcement bar of S₄ could override the yield strain as well as prohibit occurs the brittle punching shear failure through redistributing the applied load onto flexural reinforcement bars.

The punching failure form is generally as a truncated pyramid shape and making angle (θ) with the footing's bottom face. The failure angels and area of the punching failure zones are measured by AutoCAD software and their values are illustrated in Table 3 and Fig.8. The test results show that when the footing thickness increases in S₂, the size of the failure zone is increasing confirm the previous conclusion obtained by [19,24] and the angle of failure becomes steeper as 46 degrees respectively which is previously observed by [16,25].

While increasing flexural reinforcement ratios lead to a decrease in the failure zone size as well as an increase in the angle of failure. Also, the use of the FSPSP showed a decrease the failure

size zone and considerably increase of the angle of failure.

Table 3. Failure characteristics of the footings.

Specimens	Ultimate Strain in Reinforcing Bar $\times 10^{-6}$	Yield Strain (ϵ_y) $\times 10^{-6}$	Mode of Failure	Measured Failure area (mm^2)	Angle of Failure (θ°)
S ₁	1851		Shear	363840	42°
S ₂	2004		Shear	374500	46°
S ₃	1100	2885	Shear	268400	58°
S ₄	4650		Flexure	335040	74°

Figure 8. Angle of failure of the specimens.

3.4. Experimental Results and ACI Design Code

Depending on the ACI318-14[26], the resistance force of punching shear which developed in the concrete footings that undergo a column of the square shape, it can be calculated as

$$V_c = 0.33\sqrt{f'_c}\lambda b_0 d \quad (1)$$

Where d is the effective depth of the slab or the footing, b_0 is the control perimeter and it is located at $0.5d$ from the loaded area, λ which is the factor of modification that take to account the

influence of the lightweight concrete. However, λ for the normal weight concrete is 1.

The corresponding punching shear force is calculated and presented in the Table 4. As shown in the Table 4 ACI-318 formulas generally give shear strength higher than the experimental method.

Table 4. Comparison with ACI design code.

Specimens	Ultimate load (P_u) (kN)	Effective depth (mm)	b_0 (mm)	V_c (kN)	P_u/V_c
S ₁	98	96	984	143.5	0.68
S ₂	113	116	1064	187.5	0.60
S ₃	120	96	984	143.5	0.84
S ₄	163	96	984	143.5	1.13

4. Conclusions

The conclusions from this investigation can be summarized as the following clauses:

1. The increase of specimen thickness from 120 to 140 mm does not have a significant effect on the value of the first cracking load that is observed at 57.5% of the ultimate load respectively. While increasing it leads to improvement of the ultimate load by about 15.30%, as well as lead to an increase of the ductility, deflection at ultimate load, and angle of failure.
2. Increasing the flexure reinforcement ratio by 58.3 % lead to an increase of first crack load and ultimate load by 26.98%, 22.44% respectively relative to the reference specimen, slightly increase of the angle of failure, and decreasing of ductility and the

deflection at equivalent load. Furthermore, increasing the flexural reinforcement ratio lead to make the footing more brittleness and failed by shear.

3. The footings that contain FSPSP showed an increase of the ultimate load, first crack load, ductility, deflection at the ultimate load, and angle of failure. The results also showed that the use of the FSPSP. lead to increasing of the ultimate load as 66.32% relative to reference specimen without FSPSP as well as lead to an increase of the ductility and angle of failure, also it leads to decrease all the deformations at all stages of loading.
4. The best result obtained by using FSPSP, which led to the highest rate of increase in ultimate load, ductility, and angle of failure, in addition to reducing deformation at all stages of loading.

Conflict of interest

The authors confirm that the publication of this article cause no conflict of interest.

5. References

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