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Effective Use of Space Swimmer Bars in Reinforced Concrete Flat Slabs

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Abstract

One of the controlling factors in the design of reinforced concrete flat plates is the punching shear criteria. Engineers, in many cases, will be reluctant to increase the plate thickness, use column crown or drop flat plate in order to satisfy the punching shear criteria. This study introduces an effective use of space swimmer bars as punching shear reinforcement in flat plates. Swimmer bars are short inclined steel reinforcement bars welded to both top and bottom flexural reinforcement. In this study pyramid shape will be investigated since the punching shear takes the form of a truncated pyramid or a truncated cone. A counteract truncated pyramid or a truncated cone of reinforcement forming space three dimensional pyramid by swimmer bars will be employed to generate four inclined planes crossing the four inclined planes of the cracks. The number of truncated pyramid-crack interceptors may be increased for large applied punching shear forces. The experimental results showed substantial improvement in punching shear strength of reinforced concrete flat slabs that can be used effectively to eliminate the need for column crown or drop flat plate.

Keywords: Swimmer bars, concrete slabs, punching shear, flat plates, column crown.

Introduction

Reinforced concrete slabs are among the most common structural elements. Despite the large number of slabs designed and built, their details for the elastic and plastic behavior are not always properly implemented satisfactorily. This occurs partially because of the mathematical complexities of the elastic-plastic analysis of these plates, especially for support conditions which realistically approximate those in multi-panel building floor slabs. Reinforced concrete slab floors have taken many forms since their introduction. Some of these were clearly direct imitations of earlier floors made entirely of wood or of wood supported on steel beams. Others were just as clearly invented, with no recognizable ancestors, to suit the properties of the materials, steel bars and concrete (Park and Gamble 2000).

Slabs may be divided into two general categories: beamless slabs and slabs supported on beams located at sides of panels. Beamless slabs are described by the generic terms flat plates and flat slabs. The flat plate is an extremely simple structure in concept and construction, consisting of a slab of uniform thickness supported directly on columns, as shown in Figure 1. The flat plate is a direct development from the earlier flat slab structure, which was characterized by the presence of capitals at the top of the columns and usually also by drop panels or thickened areas of the slab surrounding each column. The basic form of the flat slab is shown in Figure 2.

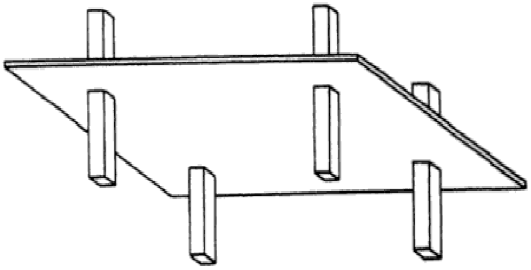


Figure 1: Flat plate

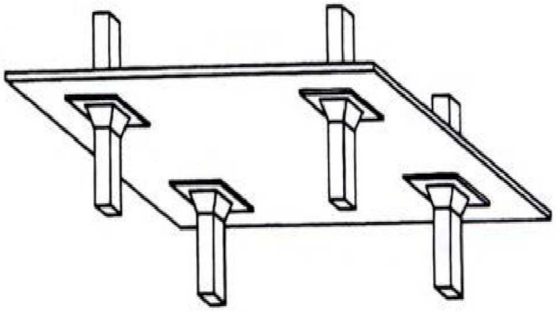


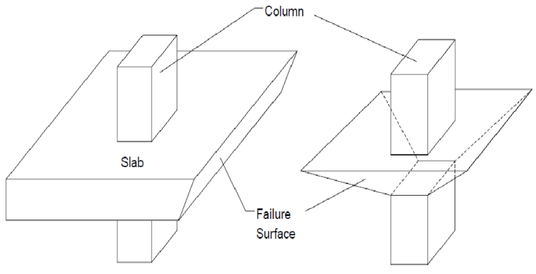
Figure 2: Flat slab

Reinforced concrete flat slabs are extensively used in buildings and parking garages. Their design is governed by deflection at the serviceability limit state and punching shear at the ultimate limit state. When no punching shear reinforcement is provided, failure develops in a brittle manner. Punching shear failure occurs with almost no warning signs, because deflections are small and cracks at the top side of the slab are usually not visible. Over the past decades, several structural collapses occurred due to punching shear failure resulting in human casualties and large damages. These collapses revealed some shortcomings in codes of practice and the necessity of reconsidering punching provisions (Macgregor and Wight 2005).

The investigations of these collapses showed that the collapse initiated from a local punching failure and propagated throughout the structure, in a progressive collapse. The term progressive collapse refers to the spreading of an initial local failure triggered by the loss of one or more load carrying members and leading to partial or total collapse of the structure in a manner analogous to the chain reaction (Nilson 2010).

Two types of shear failures have been observed in slabs, of slab-column framed systems. The first is a “one-way” or “beam-type” shear failure, as shown in Figure3a, which involves an inclined crack extending across the entire width of the slab. The other failure mode, which often governs the slab design, is referred to as a “two-way” or “punching” shear failure, shown in Figure 3b. This failure involves a truncated cone or pyramid-shape surface around the column. In regular concrete slabs, the angle of inclination of the truncated pyramid-shape surface with the slab failure plane typically ranges between 20 and 45 degrees.

Based on research work on two-way shear action reported by ACI Committee 326 (ACI Committee 326, 1962), a critical shear area corresponding to that of a vertical section of depth d that follows the column periphery at a distance d/2 from the column faces is recommended, where d is the slab effective depth. This concept is incorporated in ACI 318-11 Section 11.11.1.2 (2011 ACI Building Code), which requires that, for interior connections of slab-column frames, shear stresses be investigated at a “critical section” located at d/2 from the periphery of the concentrated load.



(a) One-Way Shear Failure (b) Two-Way Shear Failure

Figure 3: Shear failure of slabs

Increasing the slab thickness or using drop panels or column capitals is often not an economical and/or practical option. Increasing slab thickness results in a cost and weight increase, while changes in slab cross section and formwork, when using drop panels or column capitals, take away some of the major advantages of slab-column systems over beam-column frames as uniformity in slab bottom surface and increased clear story heights. Therefore, methods to increase punching shear resistance without modifying the slab thickness is often preferred (Nilson 2010).

In 2003, (Bin Mu and Christian) conducted several tests on concrete slabs including circular specimens with a diameter of 127 mm and thickness of 19 mm were cast. The specimens were supported on a simple ring with a diameter of 101.6 mm and tested under a central patch load. The test setup, testing machine, and loading rate were similar as in the two-way bending tests. The slab specimens were reinforced either with randomly distributed short fiber-reinforced glass or with continuous fiber mesh with equal fiber volume ratios. Many parameters were studied in the test including the effect of fiber type, form and volume ratio in the two bending behavior and punching shear capacity of the glass concrete slabs. One of the conclusions of the study was that for two-way bending, fiber mesh was very efficient as reinforcement. Short randomly distributed fibers improve the flexural strength and ductility of glass concrete slabs, but do not change their failure modes. Another conclusion of the study was that the fiber mesh position and restrained boundary condition do not significantly influence the shape of the punching shear failure cone.

El-Salkawy, Polak and Soudki, (2003) tested six edge slab column connections strengthened by shear bolts drilled through the slab thickness. The specimens were subjected to vertical load through the column stub and unbalanced moment through two equal opposite horizontal loads applied at the column ends.

The slabs were simply supported on stiff supports along the three edges. Steel sections bolted to the supports held the corners of the slab in position. They observed that shear bolts can increase the capacity and ductility of slab column edge connections, and can change the failure mode from punching shear mode to a favorable flexural mode. Al-Nasra and Wang (1994) studied the shear strength of concrete on floor slabs. Asha, Al-Nasra, and Najmi (2012) investigated the use of swimmer bars in reinforced concrete beams. They showed an improvement in shear strength of reinforced concrete beam by using several swimmer bars.

In 2006, (Hegger and Sherif) tested 17 footing specimens changing several parameters including span to depth ratio (a/d), concrete compressive strength, punching shear reinforcement and the soil-structure interaction. Two series of testing specimens were investigated; the first series were tested by supporting the specimens on column stub and applying a uniform load. Second series were tested on sand. The failure shear cracks seems to be mainly influenced by a/d and not by the concrete strength. The punching shear resistance decreased with increasing a/d and the footings supported on sand showed a higher punching shear resistance than that are uniformly loaded.

In 2010 (Yang, Yoon and Cook) studied the punching shear behavior of slabs reinforced with high-strength steel reinforcement as shows, and compared the behavior with that of slabs reinforced with conventional steel reinforcement. The high-strength steel selected for the research conformed to ASTM A1035-07. The influences of the flexural reinforcement ratio, concentrating the reinforcement in the immediate column region, and using steel fiber-reinforced concrete (SFRC) in the slab on the punching shear resistance, post-cracking stiffness, strain distribution, and crack control were investigated. They observed that using high-strength steel reinforcement and SFRC increased the punching shear strength of slabs, and concentrating the top mat of flexural reinforcement showed beneficial effects on post cracking stiffness, strain distribution, and crack control.

Behavior of thick concrete plates that are used for offshore and nuclear containment concrete walls were investigated by (Rizk, Marzouk and Hussein-2011). In this research, five thick concrete slabs with a total thickness of 300 mm to 400 mm were tested under concentric punching loading. Four specimens had no shear reinforcement, whereas the remaining one included T-headed shear reinforcement consisting of vertical bars mechanically anchored at the top and bottom by welded anchor plates. The main conclusion was that all specimens without shear reinforcement exhibited brittle shear failures. The addition of T-headed shear reinforcement with a shear reinforcement ratio of approximately 0.68% by volume changed the failure mode to ductile flexural failure. The test results revealed that increasing the total thickness from 350 mm to 400 mm resulted in increased punching capacity and at the same time resulted in a small increase in ductility characteristics.

When a reinforced concrete flat slab column structure is subjected to large concentrated load, punching shear cracks occur inside the slab at the column vicinity. They propagate at 20 ~ 50 degree angles through the slab thickness, so that truncated conical or pyramid failure surface around the column forms. Many factors affect the punching shear capacity of flat slab-column connections under static loads. Slab thickness, column dimensions, concrete strength, flexural reinforcing ratio and pattern, and shear reinforcement are all the parameters influencing punching shear capacity. In experiments, the testing methods and conditions, such as the loading rate and scale of specimens, also influence the results, and supporting conditions.

Several reinforcement alternatives for increasing punching shear resistance of slab-column connections have been used including; bent-up bars, closed stirrups, shear heads, and shear studs. The main objective of this research is to evaluate the potential of using new style of steel bent-up bars (called swimmer bars) in slab-column connections for increasing their punching shear strength and deformation capacity when subjected to concentrated loads. These swimmer bars will form a shape like a pyramid or a cone around the column in the opposite direction of the failure surfaces.

Punching Shear Design Requirements in ACI

ACI 318M-11 (ACI 2011) requires that the factored shear force V_u at the critical section (the perimeter at a distance $\frac{d}{2}$ from column face) should be no more than the product of nominal shear force V_n times the shear strength reduction factor which is $\emptyset = 0.75$ as shown in Eqn. 1.

$$V_u \leq \emptyset V_n \qquad (1)$$

The requirement of ACI code for using bent up bars will be considered as follows:

a) Shear force (V_s) to be resisted by shear reinforcement consists of a single bar or a single group of parallel bar, all bent up at the same distance from the support according to Article 11.4.7.5 of ACI (ACI 2011)

$$V_s = A_v f_y \sin\alpha \quad \text{in} \quad \text{kN} \tag{2}$$

But not greater than $0.25\sqrt{f'_c}b_o\, d$,
where α is angle between bent-up reinforcement and longitudinal axis of the member, A_v is the area of shear reinforcement, f_y is the yield strength of reinforcement, and f'_c is the compressive strength of concrete.

b) Where shear reinforcement consists of a series of parallel bent-up bars or groups of parallel bent-up bars at different distances from the support V_s shall be computed by Eqn. 3 according to Article 11.4.7.6 of ACI (ACI 2011)

$$V_s = \frac{A_v f y(\sin\alpha+\cos\alpha)d}{S} \quad = \quad \frac{A_v}{S} = \frac{V_s}{d f_y(\sin\alpha+\cos\alpha)} \tag{3}$$

Where S is the spacing between shear reinforcement in mm

c) Where more than one type of shear reinforcement is used to reinforce the same portion of a member V_s shall be computed as the sum of the values computed for the various types of shear reinforcement according to Article 11.4.7.8 of ACI (ACI 2011)

d) V_s shall not be taken greater than $0.66\sqrt{f'_c}b_o d$ according to Article 11.4.7.9 of ACI (ACI 2011)

e) The factored shear force to be resisted by concrete (V_c) of the critical section without shear reinforcement is also mentioned in Article 11.11.2.1 of ACI (ACI 2011) as shown in Eqn. 4:

$$V_c = min.\left\{\begin{matrix} 0.33\lambda\sqrt{f'_c}b_o d \\ 0.17\lambda\sqrt{f'_c}\left(1+\frac{2}{\beta_c}\right)\, b_o d \\ 0.083\lambda\sqrt{f'_c}\left(2+\frac{\alpha_s d}{b_o}\right)b_o d \end{matrix}\right\} kN \tag{4}$$

Where β_c is the ratio of the long side to short side of the column, b_o is the perimeter length of the critical section. λ= 40, 30, 20 for interior, edge, and corner column, respectively. The nominal shear strength can be expressed according to Article 11.11.2.1 of ACI (ACI 2011) as follows

$$V_n = V_c + V_s \tag{5}$$

Where V_n is the nominal shear force in kN

Specimens Characteristics

Two specimens were tested in this study, 2 m x 2 m and 0.17 m thick each. The first one (P1) is regular flat plate with no swimmer bars, which is used as control sample, and the other one, PSW8-8, is reinforced with two layer of pyramids made of φ 8 mm swimmer bars. The two specimens are reinforced by 10 Φ10 mm in the direction parallel to the supports, and 10 Φ12 mm in the direction perpendicular to the supports. The steel reinforcements of the column located at the center of the slab was reinforced by 4ϕ12mm.The first specimen which has no swimmer bars (P1), was made by top and bottom of flexural reinforcements with column at the middle of slab.

The second specimen, PSW8-8, was reinforced by eight swimmer bars; four swimmer bars were welded at the intersection of transverse bars and other four bars were welded at the middle distance between of these crosses as shown in Figure 4 and Figure 5. The flexural steel bars were cut and fixed to form a steel cage, transverse bars and swimmer bars were connected to flexural reinforcement by welding. All specimens were cast with concrete from the same mix. All specimens were tested by a single point load from hydraulic jacks at the age of 28 days. The uni-axial compressive strength of concrete was determined using standard cubes tested at 3 days, 7 days, 14 days and 28 days. The average 28-day concrete compressive strength was calculated to be 40.74 MPa. The steel used in this experiment is of 420 MPa yield strength.

Figure 4: Steel cage used in the second specimen, PSW8-8, showing the swimmer bars.

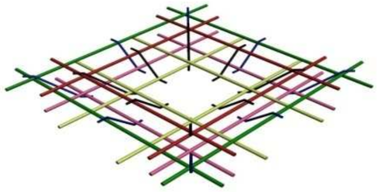


Figure 5: Three dimensional modeling of transverse bars and Swimmer bars used in PSW8-8

Test Procedure

The test started by mounting the square flat plates of 2mx2m on two steel beams. Each beam has a cross section composed of two channels back to back. The centerlines of these beams were located 100 mm from the edge of the concrete flat plate, making the center- to- center support distance to be 1.8 m. The load was applied on the column that is located at the middle of concrete plate by hydraulic jack. The load was transferred to the specimen by two steel plates of 30 mm thick located underneath the jack's head. There is a stub column that is 250 mm by 250 mm located at the middle of concrete plate as shown in Figure 6.

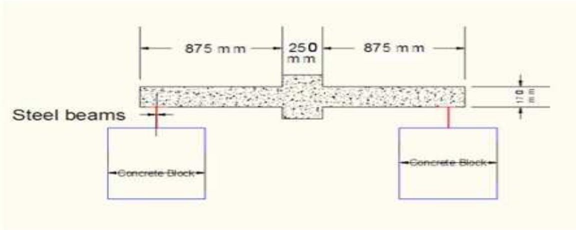


Figure 6: Specimen setup

Strain and deflection measurements of the specimen were recorded after each load increment, until failure by punching shear. The punching shear tests of all specimens were carried out by using a 730-kN test frame (TONI-MFL).The frame was connected to data acquisition system displaying a record of the load during test.

Two linear variable displacement transducers (LVDT), as shows in Figure 7, were used to measure the deflection at 300 mm from face of column in both direction parallel and perpendicular to the support. These transducers have 0.01 mm accuracy. Strain gauge transducers were installed on the side face and the top surface of specimen to measure the concrete strain with an accuracy of 0.002 mm as shown in Figure 8.

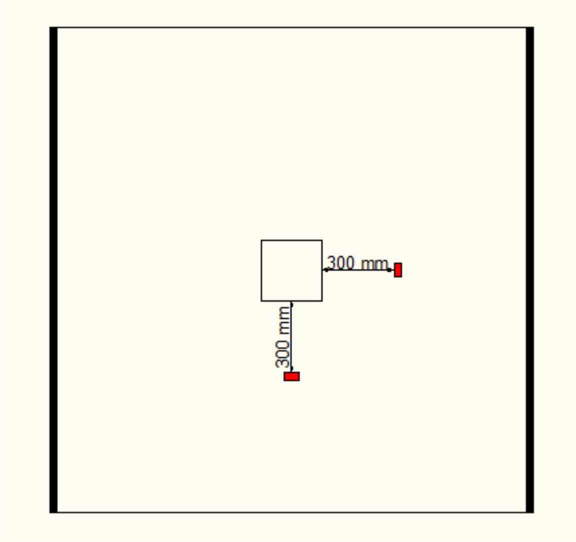
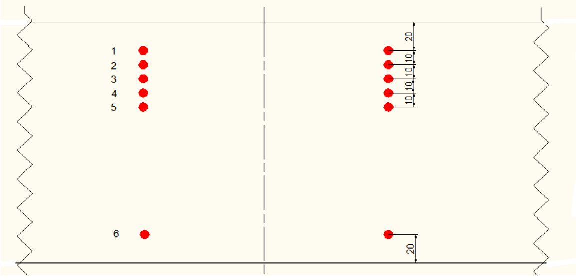


Figure 7: LVDT layout



Test Results

The first specimen P1, that has no swimmer bars and the one which is used as control sample was tested first. For P1, loading started at 20 kN, when loading reached 100 kN hair cracks appeared at the side perpendicular to the supports. By the increase of the applied load gradually, cracks appeared and increased in width at the side and bottom face of specimen. Finally, punching shear failure occurred at the load of 501.6 kN. For the second specimen, PSW8-8, loading started at 100 kN and hair cracks appeared at the side perpendicular to the supports. When increasing the load, cracks appeared and increased in width at the side and bottom face of specimen. Finally, punching shear failure occurred at the load of 543.2 kN. Figure 9 shows the mode of failure for the sample PSW8-8, which is similar to the mode of failure of sample P1, the control sample without swimmer bars.

Figure 9: Mode of failure of PSW8-8.

Deflection

Two dial gauges were used to measure the deflection at 300 mm from face of column in both direction parallel and perpendicular to the support. These gauges are of 0.01 mm accuracy. The applied load is increased incrementally. The deflection is measured at each increment of load. The load deflection is plotted for the tested samples as shown in Figure 10 and Figure 12. Figure 12 shows an increase in slab rigidity due to the use of the swimmer bars. Also strain gages mounted on the side of the slab were used to measure deformation. Figure 11, and Figure 13 shows the deformation across the thickness of the slabs (the one without swimmer bars P1, and the one with swimmer bars, PSW8-8).

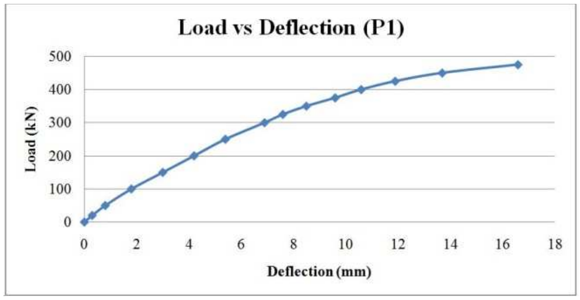


Figure 10: Load – Deflection curve of the sample P1.

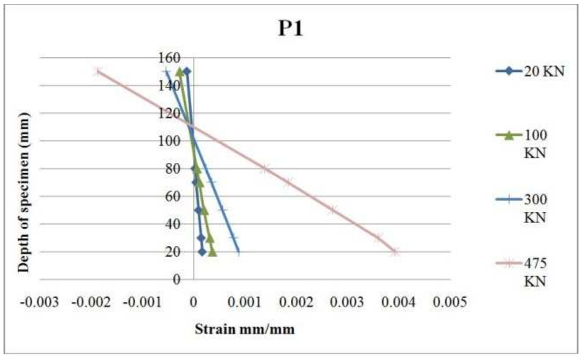


Figure 11: Concrete strain vs. slab depth of specimen P1

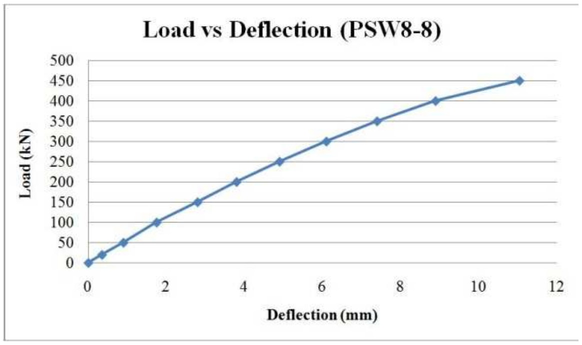


Figure 12: Load vs. Deflection of specimen PSW8-8

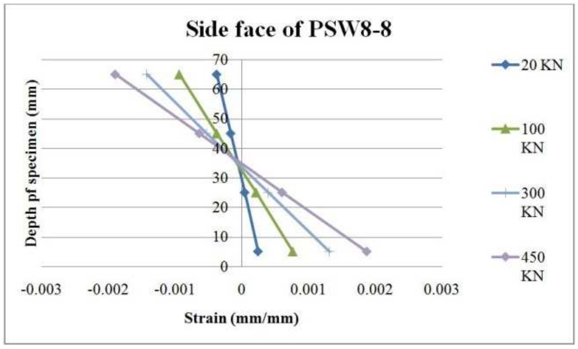


Figure 13: Concrete strain vs. slab depth of specimen PSW8-8

Conclusions

The experimental results showed 8.3% increase in punching shear strength of reinforced concrete plates by using space swimmer bars. Adding swimmers bars improved the punching shear performance and increased the slab rigidity. The use of swimmer bars as three dimensional pyramid cages can give the designer the ability to reduce the slab thickness and consequently reduce the cost. Also the added punching shear strength by using this type of reinforcement may give the designer options to avoid using drop panels. The punching shear strength can be increased by increasing the diameter of the swimmer bars used.

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