ISSN: 2754-4990

Journal of Civil Engineering Research & Technology

Research Article Open Access

No More Drop Panels in the Design for Punching Shear in Flat Plates

Abdulqader S Najmi

Professor of Civil Engineering, The University of Jordan – Amman - Jordan

Abstract

Punching shear failure at column-slab connection occurs in a brittle manner, which involves the formation of a truncated cone or a truncated pyramid. A set-up of swimmer bars system takes the shape of truncated steel pyramids to counteract the potential truncated pyramids of cracks. Each counteract truncated steel pyramid is formed by swimmer bars will generate four inclined planes intercepting approximately perpendicularly the four inclined planes of the failure truncated pyramid. A reference to a testing program of four square slabs with a concentric column will be used; these were constructed with overall dimensions of 2000 mm by 2000 mm, 150 mm thickness and 140 by 140 mm column in the middle. The results obtained from testing has proved that the efficiency of using swimmer bars system in slab-column connections has increased their punching shear capacity to more than 250% and has decreased their deflection by increasing the stiffness of the slab in the vicinity of the concentrated loads, moreover, the nature of the punching shear failure becomes ductile instead of brittle and obviates sudden failure. The need for drop panels to resist the punching shearing forces becomes unnecessary. The ultimate strength of punching shear is limited by the compression shear failure, which was never measured for the case of punching shear. The gain in ductility can reach levels matching those in flexural behavior.

*Corresponding author: Abdulqader S. Najmi, Jordan University School of Engineering, Civil Engineering Department, Jordan. E-mail: najmi@ju.edu.jo

Received: February 10, 2020, **Accepted**: February 12, 2020, **Published:** February 15, 2020

Keywords: Welded Swimmer Bars, Truncated Steel Pyramid, Punching Shear

Introduction

Punching shear failure takes the form of a truncated pyramid or truncated cone. A counteract steel cage truncated pyramid using swimmer bars will generate four inclined planes intercepting at perpendicular angles approximately the four inclined planes of the failure. The swimmer bars themselves are a new type of shear reinforcement; these are short inclined bars welded to the steel squares (rectangles for rectangular columns) forming the base and the top of the truncated steel cage pyramid. The flat plate is an extremely simple structure in construction, consisting of a slab of uniform thickness supported directly on columns. Reinforced concrete flat slabs are extensively used in buildings and parking garages. 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 is usually invisible. The critical shear section in ACI Code is taken at d/2 from periphery of the column face [1].

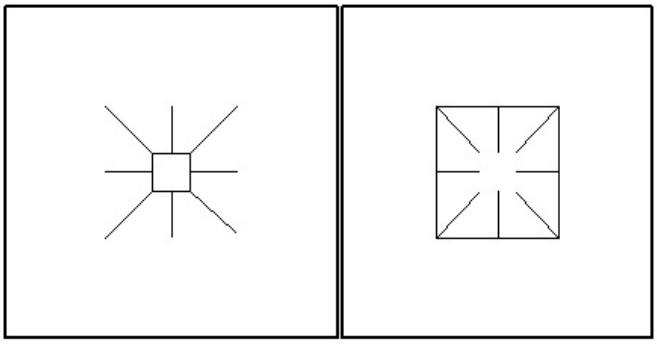


Figure 1: Pyramid shows its upper base and its lower base welded to 8 swimmer bars. Figures 1 and 2 show the set-up of the first shear reinforcement pyramid, counteracting the failure pyramid where 8 swimmer bars are welded to the landing bases of the pyramid. Both bases are welded to the flexural reinforcement of the slab.

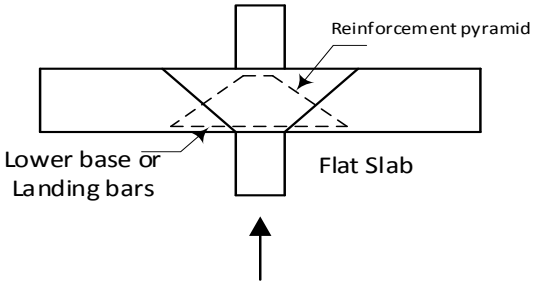


Figure 2: First reinforcement pyramid

Najmi who supervised a number of M.Sc. students to verify the concept experimentally started the topic of swimmer bars at the University of Jordan.

Investigated the use of a single plane crack interceptor for shear in beams. The concept developed into the use of swimmer bars as, investigated the use of swimmer bars in reinforced concrete beams. The experimental test results showed substantial improvement in the shear performance of the reinforced concrete beams in comparison with the traditional stirrup system. The impact of using swimmer bars left a remarkable enhancement on the deflection of the beams. It was also noted that the width of the cracks in the beams that had swimmer bars were smaller by far than the beams reinforced with the traditional stirrup system [2-3].

Studied the effective use of space swimmer bars in reinforced concrete flat slabs as punching shear reinforcement [4]. The test results showed that the pyramid form of swimmer bars provided four plane crack interceptors, which increased the punching shear strength of the tested slabs. The use of swimmer bars as part of the pyramid steel cage could give the designer the option of reducing the slab thickness and consequently, reducing the cost. The deflection was also reduced and the tested slabs showed an increase in their flexural rigidity.

Punching Shear

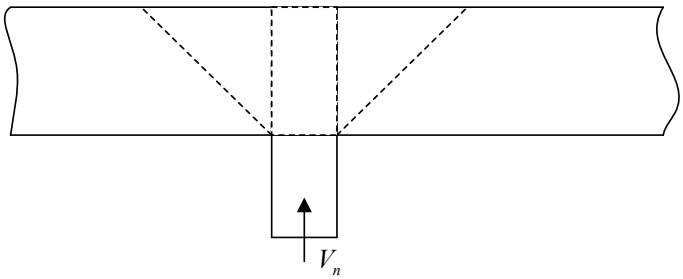


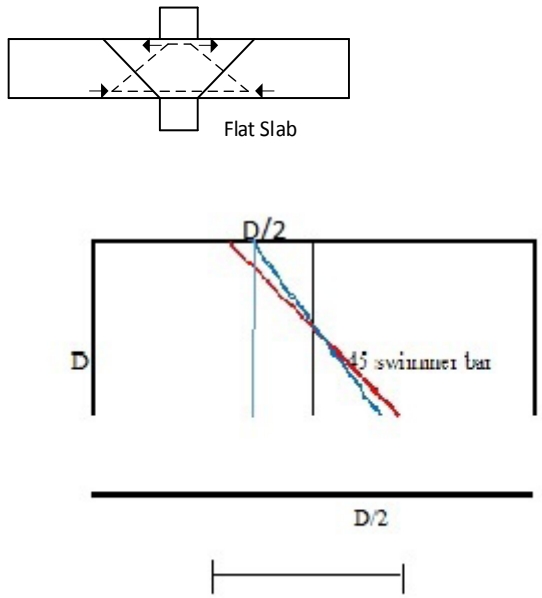
Figure 3: Punching shear failure

The slab that is under the effect of a punching load , will experience the formation of a failure bounded by four planes of a pyramid when the load is delivered through a square or a rectangular column. The volume of concrete between the column face and the four planes of failure is subjected to confinement. However, this confinement is limited, and a failure at the face of the column occurred when the shear resistance of the prismatic shape of the column itself did not withstand the punching shear, and the column dipped through the slab as observed by [5]. Figure 4 shows the column stub dipping the slab underneath. In order to prevent dipping of the column into the slab, the first pyramid should have its swimmer bars intersection the four faces of the column, the area needed is obtained from:

$$A_{s-dipping} = \frac{V_n - V_c(0)}{0.6 \times f_y}$$

Figure 4: Column Stub dipping the slab Underneath

The example given later will comprehensively provide all the details needed. Most important here, is guarantee that the nominal shear strength at the face of the column plus the needed reinforcement is larger than the nominal applied shear. The confinement available at the face of the column, could be considered by considering the design of the first pyramid will cover dipping as well.



$$d - 2 \times 0.001 \times \frac{d}{2} = 0.999d$$

Figure 5: Welded Swimmer Bars Deformed with Flexural Reinforcement

Being welded to the flexural reinforcement, the swimmer bars will deform at their ends the same deformation of the flexural bars. Figure 5 shows two cases, of swimmer bars, one inclined at an angle of 45 degrees. Simple analysis shows a very important result due to this welding. The swimmer bars at a flexural strain equals 0.1% top and bottom, will develop a compressive force in the swimmer bars, and the stress is of the order of 100MPa.

The welding of swimmer bars to both bottom and top steel in the slab, will enable them to carry stresses once the loads are applied, this is very different behavior from all other shear reinforcement. The welding is essential and cannot be replaced by anchorage length. The welding has the purpose of integrating these swimmer bars to the flexural reinforcement to form the "skeleton reinforcement" instead of the "cage reinforcement". The strain in the swimmer bar is equal

to:
$$\varepsilon = \frac{\sqrt{d^2 + (0.999d)^2} - d\sqrt{2}}{d\sqrt{2}} = -5 \times 10^{-4}$$
$$\sigma = \varepsilon \times E_s = -100\text{MPa}$$

In spite of the large compressive forces sustained by the swimmer bars, their buckling length is so small and is compared to the crack width of the surrounding concrete, hence buckling of swimmer bars is unlikely. Reported that the cracks were still invisible in specimens provided with swimmer bars shear reinforcement, compared to the reference specimen without shear reinforcement. Proved experimentally, that the use of swimmer bars system has increased the capacity of slabs against shear failure by about 272% compared to the traditional slabs [6-7]. It was also proved that the use of swimmer bars system has reduced the deflection up to 24% compared to traditional slabs.

The slab (flat plate) has two main characteristics

1. The Ultimate capacity is characterised by the compression shear failure, and as in the case of over-reinforced beams is associated with brittle failure, and in order to avoid such a failure, designers limit the tensile reinforcement using different approaches.
2. The ultimate capacity in punching shear is attainable, when the maximum tensile reinforcement is provided to prevent all modes of diagonal shear failure. Once this reinforcement area is calculated, it becomes possible to choose the area of swimmer bars. This area is distributed among a number of swimmer bars. Each pyramid can have 8, 12, 16, 20, 24, bars each.

Design of Swimmer Bars

In conventional design, shear reinforcement is isolated, and not connected to the flexural reinforcement. The swimmer bars are essentially welded to the flexural reinforcement, and in flat plates it is welded to both layers of reinforcement through the landing bars (pyramid bases). Without shear reinforcement, the diagonal shear failure occurs at a load equals 1/5 the load required for diagonal compression failure. As given in ACI-14 Eqn. 22.5.1.2

$$V_{n-\max} = \left(\frac{\sqrt{f_c^{'}}}{6} + \frac{2}{3}\frac{\sqrt{f_c^{'}}}{6} \right)\left(\frac{c}{2} + x \right) \times 2 \times 4 \times d$$

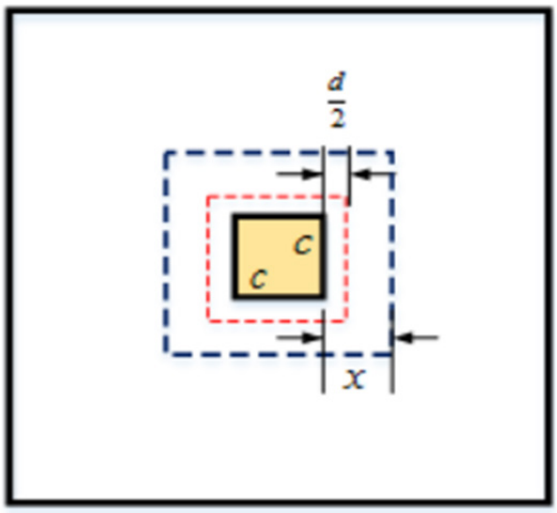


Figure 6: Dimensions related to Punching Shear

Where $V_c = \frac{1}{6}\sqrt{f_c^{'}} b_w d$

For two-way shear,

$$V_{u-\max} = \phi \left(V_c + \frac{2}{3}\sqrt{f_c^{'}} b_o d \right)$$

Design of Swimmer Bars

The thickness of the plate should meet the requirements to resisting punching shear, flexural strength and deflection. If only the concrete strength is considered in resisting punching shear, the failure of the punching shear takes the form of a pyramid (diagonal tension failure on four sides). Diagonal tension failure equals 1/5 of the shearing force for diagonal compression failure in accordance with Eqn. 22.5.1.2 – ACI-14. If the slab was strengthened by steel reinforcement (swimmer bars), the diagonal failure will not occur, and further shearing load will be accompanied by a transformation in the failure of the slab itself, the failure begins to behave in a ductile manner.

The maximum punching shear capacity of any area around the column distanced (x) from the column face to resist diagonal compression failure is:

$$V_{n-\max} = \left(\frac{\sqrt{f_c^{'}}}{6} + \frac{2}{3}\sqrt{f_c^{'}} \right)\left(\frac{c}{2} + x \right) 8 \times d$$

but this load on concrete can only be achieved in the presence of shear reinforcement (swimmer bars). $V_{n-\max}$ At $x = \frac{d}{2}$ is a plate-column property and should be used to examine if their dimensions can resist the actual shearing force.

Area of swimmer Bars

It is necessary to estimate the area of reinforcement (area of swimmer bars), this area, can be later assigned to a number of reinforcing bars. As a pyramid can have 8, 12, 16, 20, 24, bars each.

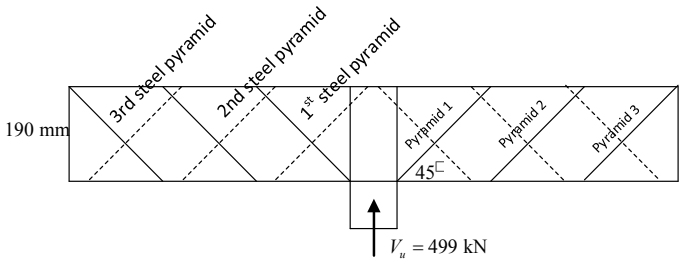


Figure 7: 45 degrees inclined swimmer bars

Figure shows the use of swimmer bars inclined 450, the first pyramid shown in Figure will have its position or location from inside the column, to prevent dipping of the column, as reported by. This is presented here by assuming that the critical perimeter is at a distance

$$x = \frac{d}{2}$$

The behaviour of any slab becomes dependent on the amount of shear reinforcement installed.

1. For no reinforcement, the punching shear takes place at the vicinity of the column, and designers choose to increase the slab depth, use better concrete grade to resist the punching shear failure. This failure is brittle, and dangerous.
2. The added shear reinforcement in terms of using steel pyramids, will promote the ductile behaviour.

In order to build a procedure for the design of swimmer bars, an example taken from Darwin's textbook [8].

Example (Darwin's 15th Edition)

A flat plate has thickness mm and is supported by 450 mm square columns spaced 6m on centers each way. The floor will carry a total factored load of 14.0 kN/m2. Check the adequacy of the slab in resisting punching shear at a typical interior column, and provide shear reinforcement, if needed, using swimmer bars. An average effective depth mm may be used. Material strengths are f_y = 420MPa, and $f_c^{'}$ = 28 MPa

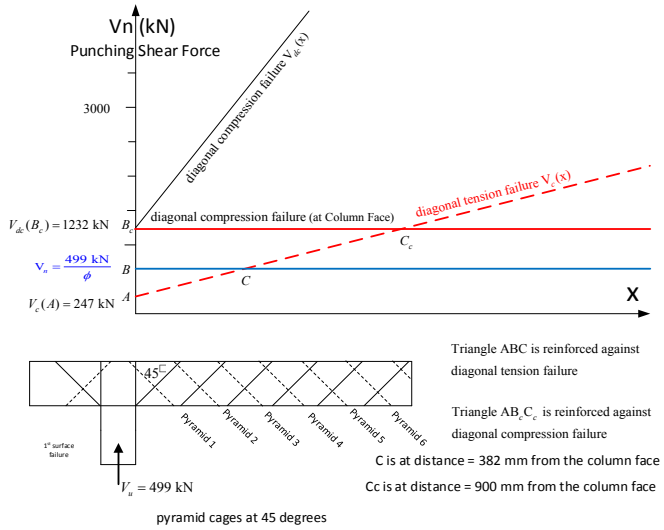
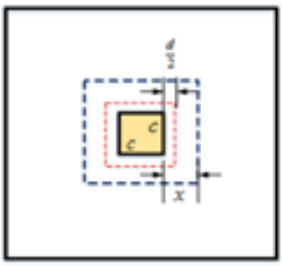


Figure 8: Design of Swimmer Bars

$$V(x) = \frac{\sqrt{}}{6} \times \left(\frac{}{2} + x\right) \times 8d$$

Where:



$V_c(x)$ = nominal shear strength in diagonal tension (as a function of x)

$f_c^{'} =$

$c =$

$d =$

$V_c(x)$ Is a linear function in x and shown on Figure

$$V_{dc}(x) = \frac{5 \times \sqrt{f_c^{'}}}{6} \times \left(\frac{c}{2} + x\right) \times 8d$$

$V_{dc}(x) =$ Nominal shearing strength in diagonalcompression

Although the relationship is linear in x, but the design of concrete slabs uses only one point on this line, which is at the face of the column.

The ultimate punching shear is V_u = 499kN, which is translated to $V_n = 665\text{kN}$ which is calculated as follows:

The first critical section for punching shear is at a distance x = d/2 = 75 mm from the column face,

$$V_{dc}(0) = \left(\frac{\sqrt{f_c^{'}}}{6} + \frac{2}{3}\sqrt{f_c^{'}}\right)\left(\frac{c}{2} + x\right)8 \times d = 1232\text{kN}$$

Therefore, the slab can be designed with the same thickness. Capacity of concrete alone:

$$V_c(x) = \frac{1}{3}\sqrt{f_c^{'}} \times \left(\frac{c}{2} + x\right)8 \times d = 493\text{kN} \quad < 665\text{kN}$$

However, when shear reinforcement is used, the concrete contribution is reduced.

$$V_c(x) = \frac{1}{6}\sqrt{f_c^{'}} \times \left(\frac{c}{2} + x\right) \times 8d$$

$V_s = \frac{V_u - \phi V_c(x)}{\phi} = V_n - V_c(x)$, and for zero shear reinforcement:

$$V_c(x) \geq V_n$$

For the pyramids, it can be seen that only a single pyramid is used at each critical perimeter, hence the pyramid reinforcement acts as a step function.

First Pyramid

$V_u = w_u(6^2 - 0.6^2) = 498.96$ kN

$V_n = 665\text{kN}$

At $x = 75\text{mm}$

$$V_c(x) = \frac{1}{6}\sqrt{f_c^{'}} \times \left(\frac{c}{2} + x\right) \times 8d = 328.6\text{kN}$$

$$V_{s1} = V_n - V_c(x) = 336.4\text{kN}$$

$$A_{s1} = \frac{V_n - V_c(x)}{0.6 \times f_y} = 1335\text{mm}^2$$

, for 8 bars, diameter of the swimmer bar =14.6 mm
Use 8 swimmer bars in the first pyramid of diameter = 16 mm.

In order to cover dipping, the steel reinforcement needed is obtained from the following equation:

$$A_{s-dipping} = \frac{V_n - V_c(0)}{0.6 \times f_y}$$

$$V_c(0) = \frac{1}{3}\sqrt{f_c^{'}} \times \left(\frac{c}{2}\right) \times 8d = 493\text{kN}$$

$A_{s-dipping} = 682\ \text{mm}^2$ Hence, the shear reinforcement area of the first pyramid can cover the problem of dipping.

Second Pyramid:

$$x = \frac{3d}{2} = 225\ \text{mm}$$

$$V_u = w_u(6^2 - 0.9^2) = 493\ \text{kN}$$

$$V_n = \frac{V_u}{0.75} = 657\text{kN}$$

$$V_c(x) = \frac{\sqrt{f_c^{'}}}{6} \times \left(\frac{c}{2} + 225\right) \times 8d = 493\text{kN}$$

$$V_{s2} = V_n - V_c(225) = 164\ \text{kN}$$

For 8 bars, diameter of the swimmer bar =10.2 mm.
A pyramid of 8 swimmer bars can be used, diameter of the swimmer bar is taken = 12 mm.

Third Pyramid

$$x = \frac{5d}{2} = 375\text{mm}$$

$$V_u = w_u(6^2 - 1.2^2) = 484\ \text{kN}$$

$V_n = \frac{V_u}{0.75} = 645\text{kN}$ (About 97% of the value taken for pyramid 1), hence, one can ignore the reduction in the value of ultimate shear with the distance x

$$V_c(375) = \frac{\sqrt{f_c^{'}}}{6} \times \left(\frac{c}{2} + 375\right) \times 8d = 657\text{kN}$$

$$V_{s3} = V_n - V_c(375) = -12\text{kN}$$

No need for a third pyramid.

Two pyramids are needed, the first one, which is nearest to the face of column has a total steel area for the 8 swimmer bars equal to double the area needed for the second pyramid. It is important to point out that in Figure 8, the distance BC can be obtained from the equation:

$$BC = \frac{V_n - V_c(0)}{\frac{4}{3} \times \sqrt{f_c^{'}} \times d}$$

Whereas the distance is obtained from the equation:

$$B_cC_c = \frac{V_{dc}(0) - V_c(0)}{\frac{4}{3} \times \sqrt{f_c^{'}} \times d}$$

The number of swimmer bars need not be the same for all pyramids, and therefore, the designer can choose numbers like 8, 12, 16, and 20. The planes themselves should be identical as they represent plane crack interceptors.

Conclusions

1. Nominal maximum strength of a solid slab for punching shear, reinforced by the swimmer bar system is obtained from:

$$V_{n-\max} = \left(\frac{5}{6}\sqrt{f_c^{'}}\right)\left(\frac{c}{2}\right)8 \times d$$

2.. The use of swimmer bars inclined by 45 degrees represent an efficient detailing system.
3. The first pyramid of reinforcement must have the lines of its swimmer bars intersecting the four faces of the column to prevent dipping as shown in Figures 2 and 7.
4. Notation

A_s = area of swimmer bars

A_{s1} = area of swimmer bars of first pyramid

A_{s2} = area of swimmer bars of second pyramid

A_{s3} = area of swimmer bars of third pyramid

b_o = Perimeter of punching area, mm

b_w = Width of beam, mm

c = Square column dimension

d = depth of slab

E_s = modulus of elasticity of steel reinforcement

x = Distance from face of column to the perimeter of punching shear, mm

$f_c^{'}$ = specified compressive strength of concrete, MPa

V_c = specified yield strength for nonprestressed reinforcement, MPa

$V_c(x)$ = nominal shear strength provided by concrete, N

$V_{dc}(x)$ = nominal shear strength at a distance x from the column face provided by concrete, N

V_n = nominal shearing strength in diagonal compression, N

$V_{n-\max}$ =nominal shear strength, N

V_s = Maximum nominal shear strength, N

V_u = nominal shear strength provided by shear reinforcement, N

V_u = factored shear force at section, N

w_u = The ultimate load per square meter. kN/m2

ε = normal strain

σ = normal stress

Acknowledgement

The author wishes to thank the Deanship of Academic Research at the University of Jordan for providing financial support of this research during the sabbatical year.

References

1. ACI 318M-14, Building Code Requirements for Structural Concrete and Commentary (ACI 318M-14), American Concrete Institute, Farmington Hills, MI, 2014.
2. Najmi (2013) Improved Shear Performance of Bent-Up Bars in Reinforced Concrete Beams, International Journal of Engineering Sciences & Research Technology, IJESRT, 2: 1264-1268.
3. Moayyad M Al-Nasra, Naem M Asha, Abdul Qader S Najmi (2013) Investigating the Use of Swimmer Bars as Shear Reinforcement in Reinforced Concrete Beams, International Refereed Journal of Engineering and Science (IRJES), Vol 2: 40-49.
4. Duweib, Al-Nasra, Najmi, (2013), Investigating the Use of Space Swimmer Bars as Punching Shear Reinforcement of Reinforced Concrete Flat Plates, International J. of Engg. Research & Indu. Appls. Vol 6: 127-139.
5. Rauof Basim Al-Natour (2013) Swimmer Bars as Shear Reinforcement for Punching Shear of High Strength Concrete Flat Plates, M.Sc. thesis, The University of Jordan, Amman, Jordan.
6. Najmi, Marahlah, (2015), Swimmer Bars as Shear Reinforcement in Reinforced Concrete Flat Slabs, International Journal of Engineering and Advanced Technology Volume 4: 4.
7. Al-Maitah S Z (2017) Optimizing the Role of Swimmer Bars to Resist Punching Shear in Flat Plates, M.Sc. thesis, The University of Jordan.
8. Darwin, Dolan, Nilson (2016), Design of Concrete Structures, Fifteenth Edition, McGraw Hill.