JISSE
ISSN: 2636-4425

Journal of International Society for Science and Engineering
Vol. 4, No. 1, 21-30 (2022)

JISSE
E-ISSN:2682-3438

Punching Shear Behaviour of Flat Slabs Reinforced with U-Stirrups

Rasha Mabrouk[1*], Yehia Ahmed [2], and Hany Abdalla[1]

[1]*Structural Engineering Department, Faculty of Engineering, Cairo University, Egypt*

[2]*Faculty of Engineering, Cairo University, Egypt*

A R T I C L E I N F O

Article history:
Received:26-01-2022
Accepted:01-03-2022
Online: 01-03-2022

Keywords:
Punching
U-stirrups
Flat slabs

A B S T R A C T

Flat slabs have become one of the most efficient structural systems used in buildings. However, it has a very significant drawback which is the punching failure that could occur at the slab column connections. This research presents an experimental program that aims to study the effect of using simple U-stirrups to resist punching in flat slabs. In this experimental program, seven slab specimens were tested. These slabs included one control specimen with no punching shear reinforcement and six specimens with varying arrangements of shear reinforcement. The parameters considered were the bar diameter of the stirrups, their spacing and arrangement in the vicinity of the column region as well as the length of the perimeter covered. The specimens were studied in terms of initial cracking load, ultimate failure load, maximum deflection, maximum strain, load-deflection relationship, and cracking patterns. The experimental results were compared against those estimated using different design codes. The test results showed that using the U-shaped stirrups as punching shear reinforcement improved the ultimate capacity as well as the punching behaviour of flat slabs.

1. Introduction

Flat slabs are one of the most widely used structural systems in multi storey buildings. This is due to the many advantages they provide such as giving higher clear height, the flexibility of change with respect to the architectural design as well as the ease of installation of electrical or mechanical services. In the flat slab system, the slabs are directly supported on columns without using beams. Hence, loads in this case are directly transferred to the columns which lead to rather large shear stresses in the area surrounding them [1]. These large shear stresses pose a high risk as they may lead to a brittle sudden punching failure. There are many methods that can be used to improve the punching capacity of flat slabs such as using drop panels or introducing punching shear reinforcement.

Different types of shear reinforcement are studied in the literature such as stirrups, stud type or shearheads [2]. Yamada et al. [3] conducted an experimental program that consisted of thirteen specimens using two types of shear reinforcement: namely the hat type and the hook type. It was concluded that good anchorage of longitudinal top and bottom reinforcement bars is essential and that using hat type punching shear reinforcement effectively improved the punching shear capacity. Muttoni et al. [4] studied 16 square slabs having the same reinforcement ratio using two types of shear reinforcement: corrugated shear studs and cages of continuous stirrups. They concluded that punching shear reinforcement is very effective, and the crushing load depends on the anchorage properties, spacing and distance to the supported area. A system made of three vertical reinforcing bars welded via hooks onto a metal strip, was used for reinforcement against punching shear by Marko et al. [5]. Hegger et al. [6] tested 39 square and octagonal slabs with various shear reinforcement shapes. It was concluded that punching shear reinforcement has an important role in increasing the shear capacity and improving the ductility of flat slabs, and that the anchoring of punching shear reinforcement leads to higher punching shear resistance. Jang et al. [7] studied the effect of the ratios of flexural and shear reinforcement. They found that both values affect the behaviour of slabs in punching. Cantone et al. [8] proposed a novel system of large diameter double headed shear studs. They experimentally studied the efficiency of this system as well as theoretically through the critical shear crack

[*] Rasha Mabrouk, Structural Engineering Department, Faculty of Engineering, Cairo University, Cairo, Egypt, +201060884868, yrasha@yahoo.com

theory. Recently, Polo et al. [9] studied the effect of the arrangement of shear studs whether orthogonal or diagonal using large scale column slab specimens. The behaviour of the slabs tested was found to be similar in both cases.

Despite the large research efforts conducted on the different types of shear reinforcement, not many researchers investigated the simple U-stirrups or the hat type. This type of shear reinforcement can be easily applied on site during construction. It can also be an economical and practical reinforcing method to resist punching shear stresses. The ease of fabrication and installation of the shear reinforcement also plays an important role. Despite previous research showing that this type can be effective in resisting the punching stresses, yet it has not been widely used. Some of the design codes allows its usage where the ACI 318-19 [10] states that "simple-leg, simple-U, multiple-U, and closed stirrups shall be permitted as a shear reinforcement." However, other design codes such as the Egyptian code of practice ECP 203-2018 [11] recently allowed only the use of closed stirrups as punching shear reinforcement.

Design codes generally state that good anchorage between the shear reinforcement and top and bottom longitudinal reinforcement should be satisfied. However, this leads to difficulty in placing reinforcing bars especially in cases of slabs with small thicknesses and typically increases the cost as well as requiring a more skilled caliber of labor. An example of a simplified solution was presented in the form of spliced stirrups or the lattice girders which can be placed between the layers of flexural reinforcement by Beutel et al. [12]. The governing factor in all cases is not only the increase in the punching capacity but the gain that can be obtained in the ultimate capacity with respect to cost and ease of casting.

Based on the above, this research aims to investigate the behaviour of flat slabs with simple U-stirrups as shear reinforcement. The U-stirrups were designed to be simply cast between the top and bottom layers of reinforcement. The main objectives are to: 1) Study the effect of using U-stirrups on the ultimate capacity of the slabs, 2) Investigate the different parameters of the arrangement of the stirrups, 3) Evaluate the effect of the anchorage of the U-stirrups with the longitudinal reinforcement, and 4) Compare the experimental data with the predictions using different design codes.

2. Experimental Program

In this part, the details of all the specimens used as well as the design of the concrete mix and the testing procedures are discussed. Seven reinforced concrete flat slabs were tested under concentric loading up to failure.

2.1. Specimen details

Table 1 shows the details of the seven specimens used in this research. All the tested specimens were designed as half scale square slabs having the same dimensions of 1100 mm x 1100 mm and a total thickness of 120 mm. The concrete cover was taken as 20 mm, while the clear span was 1000 mm. A concentric column with dimensions 150 mm x 150 mm and a height of 200 mm was cast with each of the slabs. In addition, all the slabs had the same flexural reinforcement mesh of 10Y10/m+5Y12/m and compression reinforcement of 5Y10/m. The column was reinforced with 4Y12 and stirrups 10R8/m.

Table 1: Details of specimens

Specimen	Dimensions (mm)	S (mm)	N1	N2	N3	D (mm)	N	L (mm)
S1	1100x1100x120	No punching shear reinforcement was used						
S2		50	3	3	-	8	12	400
S3		25	5	5	-	8	20	400
S4		25	9	9	-	8	36	600
S5		25	16	16	-	8	64	1000
S6		25	7	7	7	8	56	600
S7		25	5	5	-	10	20	400

N1= Number of stirrups in the horizontal direction
N2 = Number of stirrups in the vertical direction
N3 = Number of stirrups in the diagonal direction
N = Total Number of Stirrups

One slab was designed as the control specimen and tested without punching shear reinforcement for comparison purposes. The other six slabs were provided with shear reinforcement in the form of simple U-stirrups. The parameters considered in this study were as follows:

- Spacing between stirrups (S)
- Arrangement of the stirrups whether in two orthogonal directions or with additional stirrups in the diagonal direction (N1 and N2 denote the number of stirrups in the orthogonal directions and N3 denotes the number of stirrups in the diagonal direction)
- Diameter of the stirrup bar (D)
- The length of the perimeter covered by the stirrups (L)

Figure 1 shows the typical details of the U-stirrups used, while Figures 2 and 3 show the details of the control specimen and the six slabs with shear reinforcement. The dimensions of the stirrups were chosen to satisfy the requirements of the ACI 318-19 [10] which states that the width of the stirrups should be larger than 12 D (D is the diameter of the stirrups bar). In this case, the width was taken as 100 mm. The distance between the column edge and the first U-stirrup was taken as 25 mm which is less than the maximum value of d/2 as stipulated by the ACI 318-19 [10] where d is the depth of the slab taken = 100 mm.

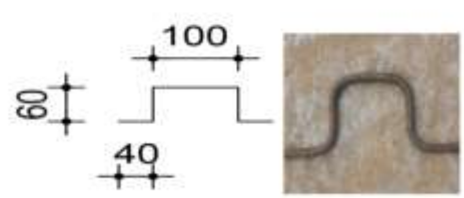
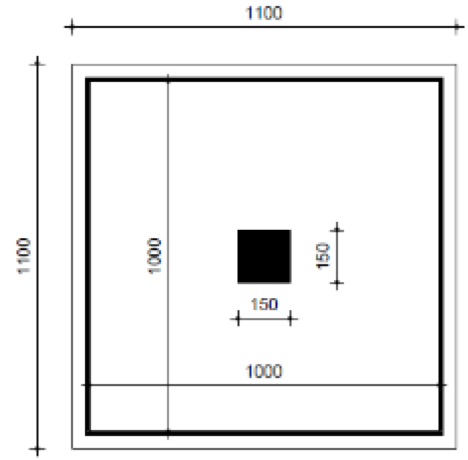
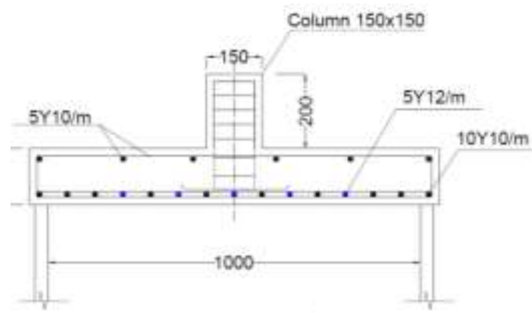


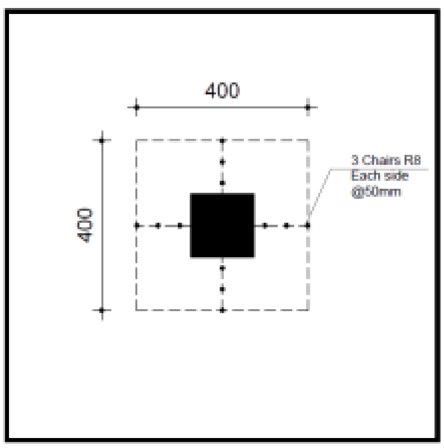
Figure 1: Typical U-stirrup reinforcement details. (All dimensions are in mm)



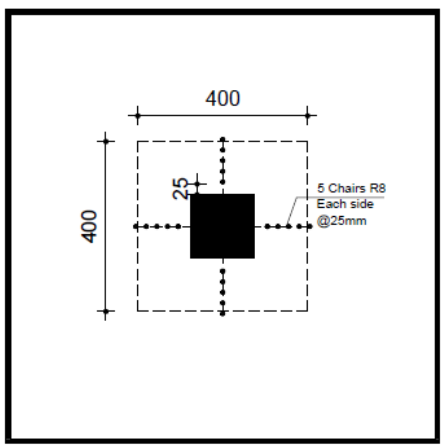


(a) (b)

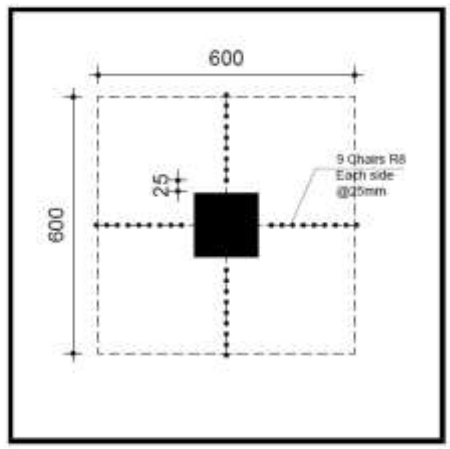
Figure 2: Details of control Specimen S1; (a) concrete dimensions in plan (b) typical reinforcement details in cross section elevation. (All dimensions are in mm)



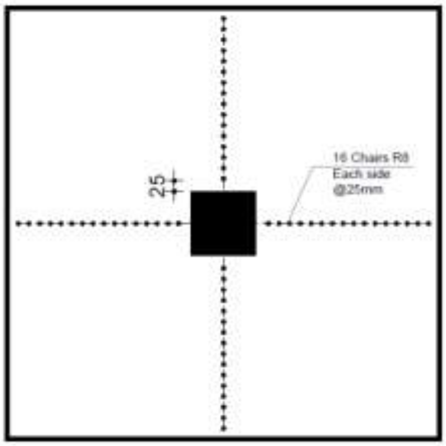
(a) Specimen S2



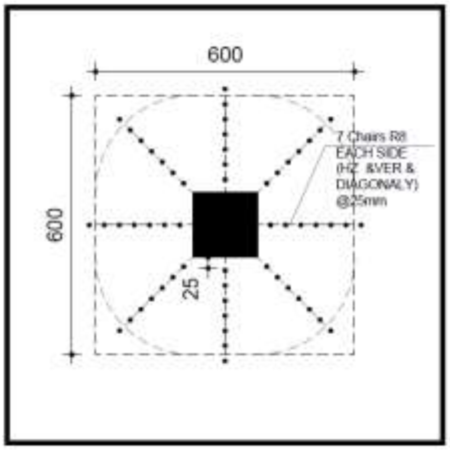
(b) Specimen S3



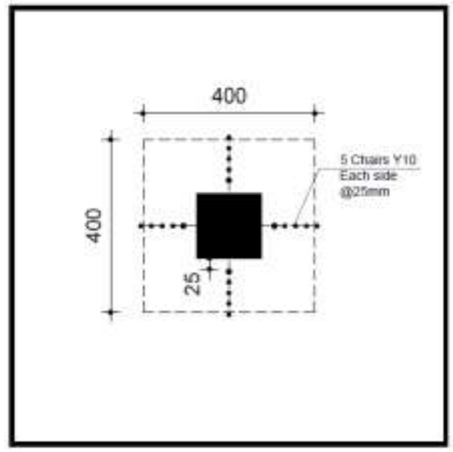
(c) Specimen S4



(d) Specimen S5



(e) Specimen S6



(f) Specimen S7

Figure 3: Details of Specimens S2 to S7. (All dimensions are in mm)

Specimens S2 and S3 were used to study the effect of the longitudinal spacing between the U-stirrups, where for S2 the maximum allowable spacing of d/2 (50 mm) was used, while for S3 this value was halved and taken as 25 mm. For S3 to S5, the spacing and properties of the stirrups were kept constant, while only the length of the perimeter covered by the U-stirrups herein denoted by L was changed from 400 mm to 1000 mm. Previous research [13] indicated that the critical punching zone extends between d/2 to 2d from the face of the column which leads to values for the perimeter length L ranging between c+ d to c+ 4d (c is the column width). Based on this, the values of length of the parameter were chosen as c+2.5d, c+4.5d, and the total length of the specimen. In specimen S6, the arrangement of the stirrups was changed from orthogonal to diagonal. In this case, the number of stirrups was taken as only 7 instead of 9 to maintain the perimeter surrounding the column with length 600 mm while having reinforcement in the diagonal direction. On the other hand, for S7 the diameter of the stirrups was taken as 10 mm instead of 8 mm.

To ensure punching failure of the tested specimens, a preliminary design using ACI 318-19 [10], ECP 203-2018 [11] and the Eurocode EC2 [14] was performed to check that the flexure failure load was larger than the expected maximum punching load. This preliminary design yielded a flexural capacity of 423 kN for all specimens using a reinforcement ratio of 1.35% which is represented by the mesh value stated earlier.

The reinforcement bar sizes used were 8 mm, 10 mm and 12 mm. Mild steel 24/35 (denoted as R) with the yield stress of 240 N/mm^2 and ultimate stress of 350 N/mm^2 was used for the 8 mm column stirrups as well as the 8mm U-stirrups. High grade steel 36/52 (denoted as Y) with the yield stress of 360 N/mm^2 and ultimate stress of 520 N/mm^2 was used for the other reinforcement bars. The values of yield stress and ultimate stress were obtained from the manufacturer's data. Figures 4 and 5 show the reinforcement details of specimens S5 and S6, respectively. The stirrups required in each direction were welded to a transverse steel bar and installed between the top and bottom longitudinal reinforcement. This way, the longitudinal reinforcement can be easily placed independent of the shear reinforcement. Anchorage is not well achieved in this case, but this was intentionally decided to investigate the effectiveness of anchorage with the longitudinal reinforcement.

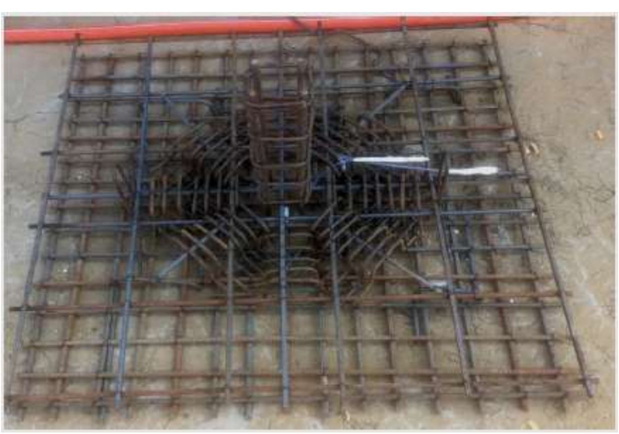


Figure 4: Layout of reinforcement details of Specimen S5.

Figure 5: Layout of the reinforcement details of Specimen S6.

The specimens were cast using ready concrete mix with a design characteristic compressive strength of 40 N/mm^2. Six concrete cubes with standard dimensions (150mm x 150mm) were cast during mixing and cured until the day of the compression testing. Compression test was performed on three cubes after seven days, and the other three cubes were tested after 28 days. The average compressive strength obtained after 28 days was 40.3 N/mm^2. All beams were cured until the test day according to the recommendations of the ECP 203-2018 [11].

2.2 Testing procedure

All specimens were supported on a steel frame base with dimensions 1000mm x 1000mm thus giving the clear span required. The specimens were mounted in an upside position where the flexural stresses will be recorded at the bottom side of the slabs. Figure 6 shows the typical loading setup used for the seven specimens. The specimens were concentrically loaded using a steel plate placed on top of the short columns cast with the slabs. Vertical load was applied through a jack and a 1000 kN load cell was used to measure its value throughout the test. Deflections were measured using three linear variable displacement transformers (LVDTs). The first LVDT was attached to the midspan of the slab directly under the loading point, while the other two were attached to the quarters of the span as shown in Figure 7. Strain gauges were attached to each specimen: one was attached to the flexure reinforcing bar located at the centre of each specimen which is expected to yield the maximum strain. For the specimens with punching shear reinforcement, a second strain gauge was attached to the vertical branch of the U-stirrups located at a distance (d/2) from the edge of the column where the punching shear crack is most expected to occur. The strain and deflection data were automatically recorded using a data acquisition system.

Figure 6: Loading test setup for the seven specimens.

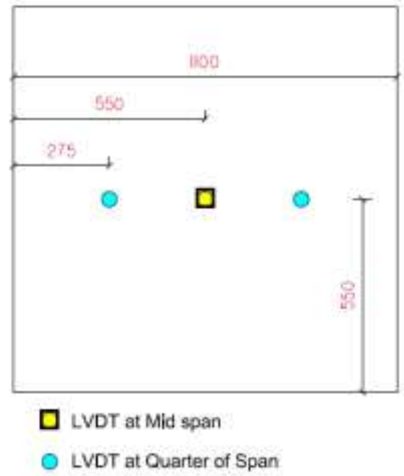


Figure 7: Locations of LVDTs used with all the specimens.

Table 2: Test results for the slab specimens.

Specimen	First Crack load (kN)	Failure Load (kN)	Deflection at Failure load (mm)		Strain at failure (μ strain)		Energy absorption (kN.m)		Ductility Energy Index (μ_E)	Mode of Failure
			Mid-Span	Quarter-Span	longitudinal reinforcement	U-Stirrups	E_{total}	$E_{0.75}$		
S1	40	280	6.0	4.5	2118	-	814.47	444.71	1.83	Punching
S2	40	300	8.0	6.6	4816	630	1267.42	631.13	2.01	Flexure-Punching
S3	40	310	8.8	6.0	2080	110	1592.51	704.16	2.26	Punching
S4	50	340	9.9	6.6	2448	120	1294.48	954.32	2.02	Punching
S5	50	340	11.3	6.3	4809	1134	2012.43	1078.38	1.87	Flexure-Punching
S6	60	360	14.2	12.0	1830	167	2914.72	1497.83	1.95	Punching
S7	50	330	9.8	8.1	2594	61	1720.42	847.31	2.03	Punching

3 Experimental Results

This section presents the test results obtained for the seven specimens in terms of the cracking patterns, load – deflection curves, ultimate loads, reinforcement strains and types of failure. Table 2 shows the test results obtained for all the specimens.

3.1 Crack patterns

Figure 8 shows the cracking pattern obtained for specimen S1, while Figure 9 shows the patterns for specimens S2 through S7. For slab S1, flexural cracks first appeared under the column at the bottom of the slab then radial cracks started to appear from the location below the column edge and extended towards the slab edges. Then, the cracks propagated in parallel lines along one diagonal axis of the slab. Later, circular concentric cracks formed around the column until it finally failed by punching with the punching cone clearly visible as shown in Figure 8.

Figure 8: Cracking patterns for slab specimen S1.

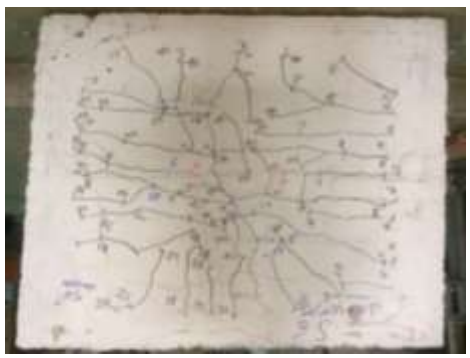
A different behaviour was observed for the slabs with shear reinforcement. Slabs S2 through S7 showed similar cracking patterns where radial cracks appeared at the bottom of the slab starting from the column edge. However, the cracks then propagated radially toward the slab edges along the four diagonal axes of symmetry of the slab clearly showing the effect of punching stresses. Following that, circular concentric cracks developed around the column and increased with the loading till failure. Based on the shape of the cracking patterns, punching failure occurred in all the specimens. However, slight differences were observed where specimen S5 with the largest perimeter length covered by the shear stirrups showed more cracks closely spaced and extending further than specimen S3 and S4 with shorter perimeter. Similarly, S6 with the diagonal arrangement of stirrups and S7 with the larger diameter showed more uniformly dispersed crack patterns covering larger area of the bottom slab surface than S4 and S3 respectively.

(a) Specimen S2

(b) Specimen S3

(c) Specimen S4

(d) Specimen S5



(e) Specimen S6

(f) Specimen S7

Figure 9: Cracking patterns for slab specimens S2 to S7.

3.2 Load deflection relationship

Figure 10 shows the load deflection curves for the tested slabs. The load deflection relationships exhibited a linear pattern up to failure except for slab S3 and slab S6 where a nonlinear and a bilinear behaviour were observed, respectively. This shows that decreasing the spacing between stirrups or using diagonal arrangement improved the load deflection behaviour of the slabs. The effect of the spacing between the U-stirrups can be seen through specimens S1, S2 and S3 in Figure 10(a). Using slab S1 as a reference, the ultimate load for specimen S2 increased by 7.1 % while in case of specimen S3 it increased by 10.7 %. The first crack load was not affected. Specimen S2 and S3 showed improvement in the values of the deflection over S1 where the mid-span deflection increased by 33.33 % for S2 and the increase for S3 was 46.66 %.

Figure 10(b) shows the effect of the length of the shear reinforcement perimeter (L). An increase in the failure load with a ratio of 10.7% for S3, and a ratio 21% for both S4 and S5 compared to control specimen S1 was obtained. These results also confirm that the critical punching zone extends to 2d from the column edge. In case of extending the punching shear reinforcement outside this perimeter as per S5, there was no observed effect on the punching shear strength. This is due to the fact that for the orthogonal arrangement used, as the perimeter increases the distance between the stirrups in the circumferential direction increases and thus causes the extended stirrups to be not fully effective in resisting the punching shear stresses. However, the value of the deflection at mid span increased as the length of the stirrup's perimeter increased considerably where S3, S4 and S5 showed an increase over S1 of 47%, 65%, and 88%, respectively.

Using diagonal arrangement for the U stirrups in addition to the orthogonal ones slightly increased the failure load with a ratio of 7% for S6 compared to S4. This agrees with previous research [9], [15-17] which stated that using diagonal arrangement of shear reinforcement did not show much difference over the orthogonal one.

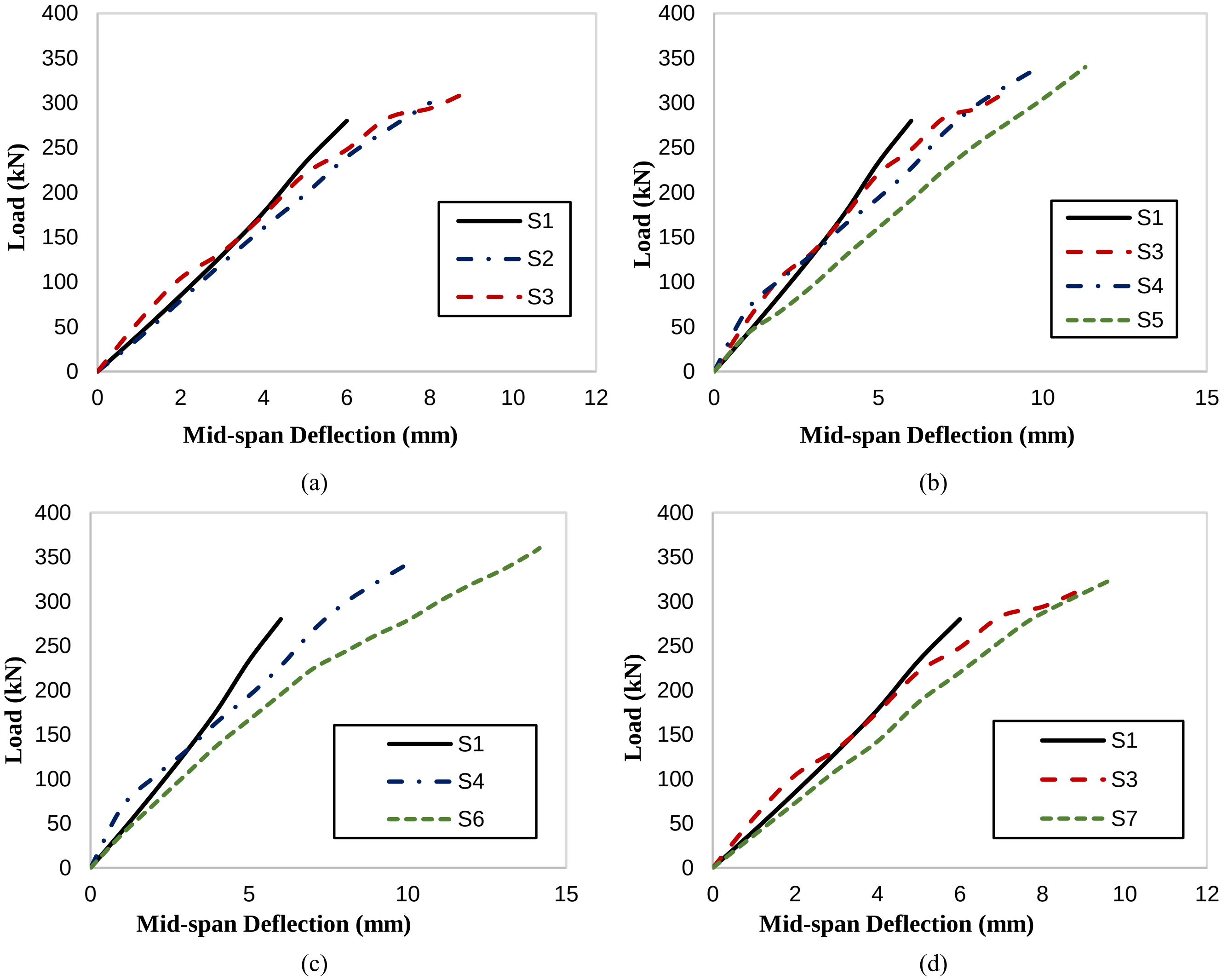


Figure 10: Load deflection curves at mid span.

Comparing slabs S3 and S7, using larger cross section area of shear reinforcement had a slight increase on the punching capacity and a noticeable increase in the deflection. It should be noted that all slabs with punching shear reinforcement showed an enhancement in their punching capacity even though good anchorage was not ensured with the longitudinal reinforcement.

3.3 Reinforcement Strains

The values of the strain in the longitudinal reinforcement and the branches of the shear reinforcement can be seen in Table 2. Figure 11 shows the load strain curves for the longitudinal reinforcement in the flexure side at mid span.

Slabs S1, S3, S4, S6 and S7 showed a linear load strain relationship up to failure and no yielding occurred in the longitudinal bars based on the values of strain measured in the longitudinal reinforcement confirming the punching failure mode. As for specimen S2 and S5 a bilinear curve was observed with rather large values of strain in the longitudinal reinforcement indicating that yield occurred. However, this contradicts with the preliminary design conducted on all the slabs where they were designed to fail in punching and the fact that the punching cone was clearly observed indicating a punching failure. One possible explanation is that the strain gauges were attached to only one bar at mid span and thus the strain measured through the strain gauge is greatly affected by its location relative to the cracks recorded. In addition, this steel bar may have reached its yield strain while the rest of the reinforcing bars in the mesh possibly have not. So, the flexural failure did not fully develop. In this case, it can be said that flexural punching failure was observed.

For the U stirrups, they did not reach their yield strains in all the slabs with shear reinforcement. The values of strains observed in the branches of the stirrups were rather low except for slab S2 and S5 where they exhibited a rather higher strain values compared to the rest of the specimens. As the case with the flexural reinforcement, the location of the strain gauge relative to the cracks greatly affects the values of the strains measured. That could explain the high variations in the values measured in the stirrups among the six specimens. One more explanation for the high strain value in the stirrups in slab S2 can be attributed to the larger value of spacing which was taken as 50 mm leading to a small number of stirrups resisting shear and thus higher stresses and strains developing in each stirrup.

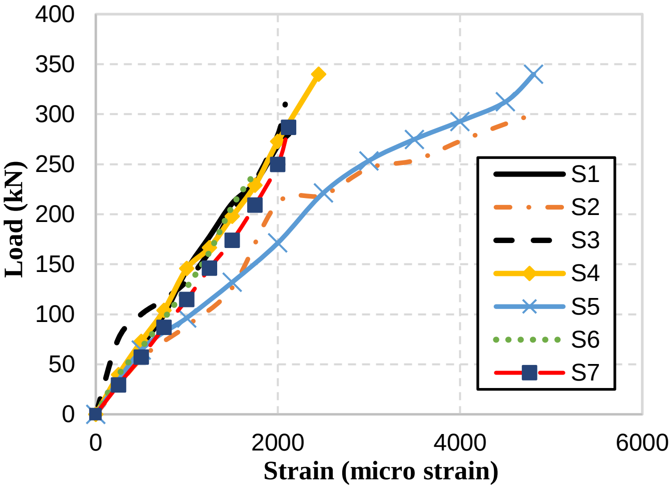


Figure 11: Load strain curves for the flexure longitudinal reinforcement at mid span.

3.4 Ductility

Ductility of reinforced concrete slabs can be measured using several methods such as the displacement ductility factor or the ductility energy index [18, 19]. In this research, specimens failed in shear without the main flexural reinforcement fully reaching its yield strain and thus the displacement ductility factor will not be applicable in most of the specimens. Hence, the ductility energy index will be used where ductility can be expressed in terms of energy absorption. The energy ductility index is the ratio of the total energy absorption up to failure to the energy absorption up to 75% of the failure load [16] and can be calculated using Equation (1). The value of the energy absorption for each specimen can be obtained by calculating the area under the load deflection curve. This area was calculated using Simpson's rule as shown in Equation (2).

$$\mu_E = \frac{E_{total}}{E_{0.75}} \qquad \text{Equation (1)}$$

Where; μ_E is the ductility energy index, E_{total} is the total energy absorption up to failure load and $E_{0.75}$ is the energy absorption up to 75% of the failure load.

$$A = \frac{P_i+P_{i+1}}{2} * (\Delta_{i+1}-\Delta_i) \qquad \text{Equation (2)}$$

Where; A denotes the area under the load deflection curve, P_i is the applied load at the i^{th} step and Δ_i is the mid-span deflection corresponding to the i^{th} step.

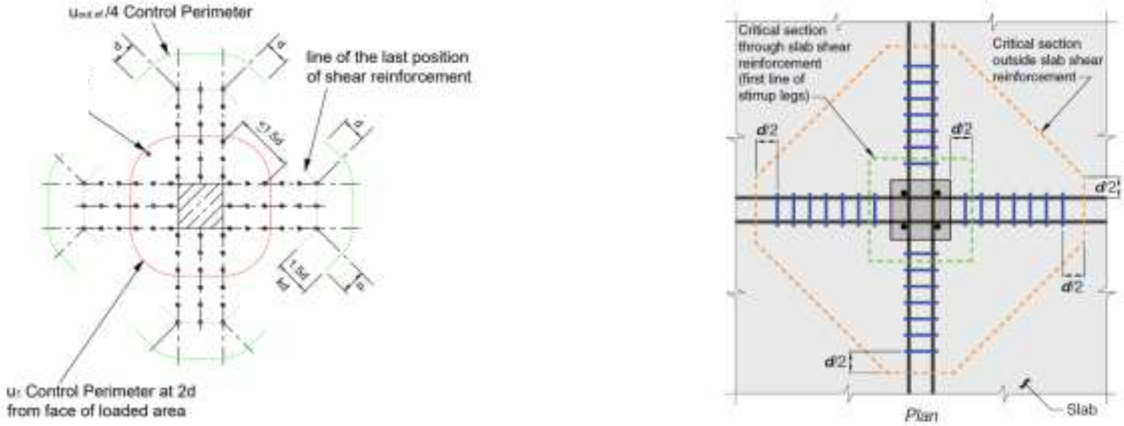
The values of the energy ductility index for the seven specimens are shown in Table 2. It can be seen from the results that the ductility generally improved for the specimens with shear reinforcement compared to the control specimen S1.

Comparing the values for the specimens with shear reinforcement to the control specimen, ductility significantly improved with a ratio of 23.5% for specimen S3 with the smaller spacing between stirrups (S=25 mm) compared to 10% for S2 (S=50 mm). Regarding the length of the perimeter covered by the stirrups (L), specimen S3 with stirrups extending c+2.5d showed the highest ductility increase while the ductility was improved by 10% when the stirrups extended to c+2.5d and an insignificant 2% when extended up to the edge of the specimen. Using diagonal arrangement for the stirrups in Slab S6 caused a slight reduction in the ductility index compared to S4 while using a higher cross section in specimen S7 caused a noticeable reduction of 11% in the value of the ductility index compared to S3.

3.5 Comparison with the design codes

In this section, the experimental results are compared to those calculated values using three different design codes namely, ECP 203-2018 [11], ACI 318-19 [10] and EC2 [14]. Table 3 summarizes the results of experimental data versus that calculated using the above design codes. For the control specimen S1 with no shear reinforcement, the calculated values using the design codes were underestimated with the ratios between experimental and calculated values equal 1.4 and 1.47 for ACI 318-19 [10] and ECP 203-2018 [11] respectively and 1.2 for EC2. Both the ACI 318-19 [10] and ECP 203-2018 [11] use the same approach for calculating the punching shear capacity with shear reinforcement. They both stipulate that shear stresses do not exceed that allowed using shear reinforcement at an inner critical section at d/2 from the face of the column. At the same time shear stresses should not exceed that allowed by concrete at a minimum outer perimeter at d/2 from the outermost stirrups used. While for EC2 [14], the critical control perimeter is evaluated at the distance (2d) from the loaded area and the outer perimeter at 1.5 d from the last row of shear reinforcement used. Figure 12 shows the location of the inner and outer perimeters for the three design codes.

For the values obtained at the inner critical section, the valued from ECP 203-2018 [11] and the ACI 318-19 [10] were very close to each other and within a reasonable margin from the experimental data for S2 and S3. However, when the extended perimeter was increased the two code values were rather underestimated as well as for the diagonal arrangement. This is because the codes do not take the effect of the perimeter into consideration where calculation is done at a perimeter located at d/2 from the face of the column. For the values obtained using the EC2 [14] design code, it generally overestimated the punching shear capacity of the specimens with a ratio of up to 25%. This means that EC2 [14] can lead to unsafe design in the cases under study in this research. However, the formulas stated in the design codes assume full anchorage between the shear reinforcement and the flexural reinforcement which is not satisfied in the slabs tested and thus could lead to the overestimated values calculated.



(a) According to EC2 [14]

(b) According to ACI 318-19 [10] and ECP 203-2018 [11]

Figure 12: Inner and outer critical perimeters for an interior column.

Table 3: **Comparison between experimental and calculated values for ultimate load**

Specimen	Pu (Exp) (kN)	Pu (Calc) Calculated using design codes (kN)						Pu (Exp)/ Pu (Calc)		
		At inner critical section			At Outer critical section			At inner critical section		
		ECP*	ACI*	EC2	ECP	ACI	EC2	ECP	ACI	EC2
S1	280	201	190	235	--	--	--	1.40	1.47	1.20
S2	300	269 (286)	288 (284)	466 (402)	302	285	297	1.05	1.06	0.75
S3	310	462 (286)	480 (284)	755 (402)	302	285	297	1.08	1.09	0.77
S4	340	462 (286)	480 (284)	755 (402)	416	392	297	1.19	1.20	0.85
S5	340	462 (286)	480 (284)	755 (402)	462**	553**	297	1.19	1.20	0.85
S6	360	848 (286)	866 (284)	1334 (402)	441	416	349	1.26	1.27	0.90
S7	330	767 (286)	785 (284)	1212 (402)	302	285	297	1.15	1.16	0.82

* Values in parenthesis represent the allowable maximum values set by the code provisions.
** The values are calculated at the edge of the slab.

The values calculated based on the outer perimeter using ECP 203-2018 [11] and ACI 318-19 [10] were slightly underestimated for the value of the shear reinforcement perimeter L = 400 mm while for the other specimens it was largely overestimated. Using EC2 [14] the values at the outer critical perimeter was rather underestimated for all the slabs. Slab S6 with the diagonal arrangement showed the closest calculated value relative to the experimental data.

It should be noted that the governing values for calculating the punching capacity among the estimated values was the maximum value set by the respective design codes and these values were used for calculating the ratios between the experimental data and the calculated values.

4 Conclusions

An experimental program was conducted on seven half scale flat slabs to study their behaviour in punching using simple U-stirrups. The following points can be concluded from the experimental results obtained.

1. Improvement in punching load capacity can be obtained with minimal anchorage between shear reinforcement and longitudinal reinforcement.
2. The use of the U-stirrups showed an increase in the values of the ultimate punching capacity ranging from 7% to 28% over the control specimen without shear reinforcement.
3. Using shear reinforcement in the form of U-stirrups generally improved the ductility of the slabs.
4. Using smaller spacing between the U-stirrups lead to a slight increase in the punching capacity but also lead to a noticeable improvement in the ductility of 23% compared to the control specimen.
5. Arrangement of the shear reinforcement on a perimeter with length exceeding a distance 2d from the face of the column does not lead to any increase in load capacity or a significant improvement in the ductility of the slabs.
6. Doubling the shear reinforcement in the same punching perimeter with adding diagonal distribution of stirrups causes a slight enhancement in the punching shear strength

and an increase in the deformation but no noticeable effect on the ductility is obtained.

7. Using larger cross section area of shear reinforcement had a slight increase on the punching capacity and a noticeable decrease in the ductility of 11%.
8. Comparing the calculated values using three design codes with the experimental results of the control specimen that had no punching shear reinforcement, it was found that EC2 gave slightly lower results while the values using ACI 318-19 and ECP 203-2018 were largely underestimated. On the other hand, for specimens with shear reinforcement, the EC2 results were very unconservative, while the values from the ACI 318-19 and ECP 203-2018 gave a closer estimate with a difference of 5% to 26% depending on each specimen.

Based on the above, the use of simple U-stirrups (hat type) as punching shear reinforcement presents a simple way that can be applied in practice to give reasonable enhancement to the punching shear capacity. To achieve reasonable improvement in strength and ductility, the U-stirrups need to be installed using small spacing and extending a distance up to 2d from the face of the column.

Conflict of Interest

The authors declare no conflict of interest.

References

1. L. Nguyen-Minh, M. Rovnak, T. Tran-Quoc, K. Nguyen-kim, "Punching Shear Resistance of Steel Fiber Reinforced Concrete Flat Slabs" Procedia Engineering, **14**, 1830–1837 (2011)
2. Y. Ahmed, *Punching shear behaviour of flat slabs reinforced with special shear reinforcement*, M. Sc. Thesis, Faculty of Eng., Cairo Univ. (2017)
3. Yamada, T., Nanni, A., Endo, K, "Punching Shear Resistance of Flat Slabs: Influence of Reinforcement Type and Ratio" ACI Struct. J., **88(4)**, 555-563 (1992).
4. A. Muttoni, M.F. Ruiz, S. Lips, "Experimental Investigation on Punching Strength and Deformation Capacity of Shear-Reinforced Slabs" ACI Struct. J., **109(6)**, 889-897 (2012).
5. B. Marko, D. Domagojm, D. Ivan, "Punching strength of flat slabs with and without shear reinforcement" Gradevinar, **67**, 771-786 (8/2015).
6. J. Hegger, A.G. Sherif, D. Kueres, C. Siburg, "Efficiency of Various Punching Shear Reinforcement Systems for Flat Slabs" ACI Struct. J., **114(3)**, 631-642 (2017).
7. J. Jang, S. Kang, "Punching Shear Behaviour of Shear Reinforced Slab–Column Connection with Varying Flexural Reinforcement" Int J. Concr. Struct. Mater., **13(29)** (2019)
8. R. Cantone, M. Ruiz, J. Bujnak, A. Muttoni, "Enhancing Punching Strength and Deformation Capacity of Flat Slabs" ACI Struct. J., **116(5)**, 261-274 (2019)
9. G. Polo, O. Bayrak, T. Hrynyk, "Shear-Resisting Performance of Reinforced Concrete Flat Plates with Different Headed Stud Layouts" ACI Struct. J., **118(1)**, 5-16 (2021)
10. ACI Committee 318, *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary,* (2019).
11. Egyptian Code Committee, *Egyptian Code for the Design and Construction of concrete Structures*, ECP-203, Cairo: Housing and Building Research Centre (2018)
12. R. Beutel R, J. Hegger, "The effect of anchorage on the effectiveness of the shear reinforcement in the punching zone" Cement & Concrete Composites, **24(6),** 539–549, (2002)
13. D. Heinzmann, S. Etter, S. Villiger, T. Jaeger, "Punching Tests on Reinforced Concrete Slabs with and without Shear Reinforcement" ACI Struct. J., **109(6)**, 787-794 (2012).
14. Euro-Code 2, *Design of Concrete Structures, Part 1-1: General Rules and Rules for Buildings,* CEN, EN 1992-1-1, Brussels, Belgium. (2004).
15. G. Birkle, W. H. Dilger, "Shear Strength of Slabs with Double-Headed Shear Studs in Radial and Orthogonal Layouts," Thomas T.C. Hsu Symposium: Shear and Torsion in Concrete Structures, SP-265, (2009).
16. J. Einpaul, F. Brantschen, M. Fernández Ruiz, M., A. Muttoni, "Performance of Punching Shear Reinforcement under Gravity Loading: Influence of Type and Detailing," ACI Struct. J., 113(4), 827-838 (2016).
17. T. X. Dam, J. K. Wight, G. J. Parra-Montesinos, "Behavior of Monotonically Loaded Slab-Column Connections Reinforced with Shear Studs," ACI Struct. J., 114(1), 221-232, (2017).
18. P. Mendis, D. Kovacic, "Spacing of stirrups for high-strength concrete columns in ordinary moment resisting frames" Australian Journal of Structural Engineering, 2(2/3), 95–104 (1999).
19. M. Hason, A. Hanoon, S. Saleem, F. Hejazi, A. Zand, "Characteristics of experimental ductility energy index of hybrid-CFRP reinforced concrete deep beams" SN Applied Sciences 3:200 (2021).