JISSE
ISSN: 2636-4425

Journal of International Society for Science and Engineering
Vol. 4, No. 3, 55-64 (2022)

JISSE
E-ISSN:2682-3438

Behavior of Lightweight Reinforced Concrete Flat Slabs Subjected to Punching Shear

Ashraf Adel Shawky [1], Abdel-Rahman Hazem[2,*]

[1] Associate Professor of Concrete Structures -Structural Engineering Department, Faculty of Engineering, Cairo University, Egypt

[2] PhD Candidate -Structural Engineering Department, Faculty of Engineering, Cairo University, Egypt

ARTICLE INFO

Article history:
Received: 11-04-2022
Accepted: 25-08-2022
Online: 25-08-2022

Keywords:
Flat slabs
Lightweight concrete slabs
Punching shear
shear reinforcement

ABSTRACT

Punching is one of the most important phenomena to be considered during the design of reinforced concrete flat slabs. This research investigates, experimentally, the behavior of interior slab-column connections consisted of lightweight concrete and special shear reinforcement. The experimental work included testing of five flat slabs with dimensions of 1100 x 1100 mm and thickness of 120 mm. The studied variables were the concrete type, the presence of shear reinforcement, and the column dimensions. The concrete type varies from normal weight concrete to lightweight concrete, while the column dimensions vary from 150 x 150 mm to 250 x 250 mm. The five specimens were loaded at the interior column with a single concentrated load until failure. The test results showed that using of lightweight concrete decreased the performance of slab behavior compared with the normal weight concrete and reduced the shear punching capacity. Also, The presence of shear reinforcement improved punching shear but without a remarkable percentage, while changing the column dimensions had a remarkable effect on the punching shear capacity.

1. Introduction

Lightweight concrete (LWC) has an ancient history in the Roman Empire from two thousand years ago [1]. Over the years, the marvelous use of LWC with including various types of natural aggregate in the Roman concrete has amazed the engineers [2]. The low density and high fire resistance are the main favorable characteristics of LWC [3-6]. LWC has several definitions in the different codes. ACI 213-14 [7] requires 17 N/mm^2 as a minimum cylinder strength, and density from 1120 to 1920 kg/m^3 for structural LWC, and requires density from 800 to 2240 kgLm^3 for LWC that has no strength requirement. LWC that has compressive strength more than and equal to 40 N/mm^2 is categorized as high strength LWC [7]. EN 206 [8] requires 8, and 9 N/mm^2 for the cylinder, and cube strengths, respectively, while EN 1992 [9] requests 12, and 13 N/mm^2 for the cylinder, and cube strengths, respectively. The LWC with fly ash or blast furnace cement has a low thermal conductivity which leads to a high exerted temperature in the core of the element [10] during the hydration process and could exceed the critical limit for the formation of delayed ettringite [11]. The effect of curing LWC is depending on the testing age and the type of specimen. No difference was observed when curing then testing concrete cylinders at 28 and 90 days, while the cube specimens were more affected with curing due to the corners' fast drying [12].

The most challenging applications for LWC are bridges [13], and offshore platforms [14]. LWC can be used for high and low stressed facades that require low material density [15]. Due to the low conductivity characteristic, LWC is increasingly used for thermal insulation as external walls or as a casted layer on the roof. The existing examples of structures with LWC are; bus station roof in Korbach, the Pedestrian bridge in Czech, a heavy lifter in the Netherlands, and several private houses in Germany [15].

A sudden punching collapse occurs in slabs without shear reinforcement leading to high losses [16-17]. The punching shear is affected by the effective depth [18], the ratio between the longitudinal main reinforcement, and characteristic compressive strength of concrete [19]. The crack propagation of punching is significantly different between the normal weight concrete (NWC) and LWC specimens [20]. The crack spread through the week aggregates led to smoother crack and less aggregate

* Abdel-Rahman Hazem, Structural Engineering Depart., Faculty of Engineering, Cairo University, Egypt , +201068604332, abdelrahman.hazem1@yahoo.com

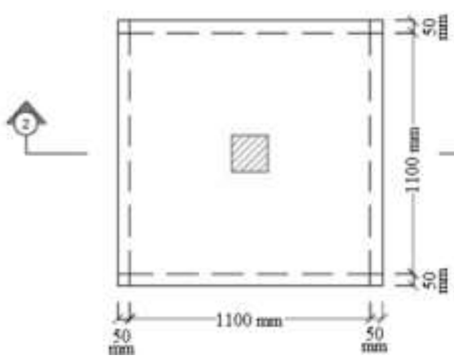
interlocking effect. By decreasing the density of concrete as in LWC, the ultimate strength and the rotation of the slab were decreased, which led to less ductile performance [21]. Goldyn M. et al [22] studied the effect of changing the ratio of longitudinal reinforcement for lightweight concrete slabs experimentally [22]. Using double headed studs in the reinforcement improved the ultimate load capacity from 19% to 44% for slab reinforcement ratios ranging from 0.5% to 1.2% [22]. Said M. et al [23] studied new strengthening techniques to improve the capacity of punching shear of LWC slabs. The highest punching capacity was achieved when strengthening slab by planting vertical steel bars inside the slabs [23]. This technique achieved 77% improvement ratio [23]. The performance of pre-stressed lightweight concrete slabs was investigated by Deifalla A. [24]. It was concluded that Eurocode 2 [9] was overly conservative, while MC [26] was the most accurate in calculating punching load [24, 27]. The researches which are studying the existence of vertical stirrups to improve punching capacity were minimum specially in the case of using lightweight concrete, so an experimental investigation had to be performed.

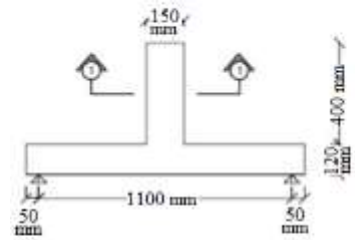
To achieve the objectives of the this research work, an experimental program was carried out. The experimental program includes testing five medium scale reinforced NWC and LWC with simple span two-way slabs under punching loading. The effect of different variables such as concrete type, and shear reinforcement type (vertical stirrups) was used to investigate the effect of using shear reinforcement on the punching shear capacity of NWC and LWC slabs.

2. Experimental work

2.1. Specimens details

The current study consists of five slab specimens that are denoted as S1 to S5. The five slabs were cast and tested under the axial compression loads at the reinforced concrete laboratory of the department of structural engineering at Cairo University. Each slab specimen has the same slab dimensions equal (1100 × 1100 × 120) mm, the column cross section is (150 × 150 × 400) mm except specimen (S5) has a cross section equal (250 × 250 × 400) mm as shown in Figures 1 and 2. All the details of the specimens are listed in Table 1. Reinforcement details of specimens are shown in Figure 3.

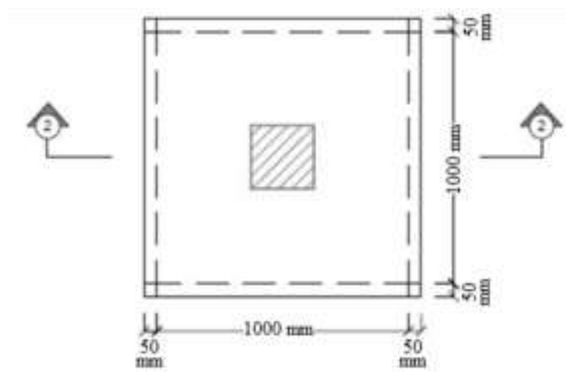


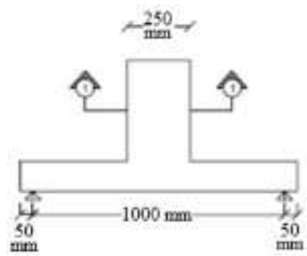


Section 2-2

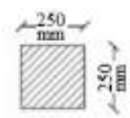
Section 1-1

Figure 1: Dimensions of test specimens except for specimen (S5)





Section 2-2

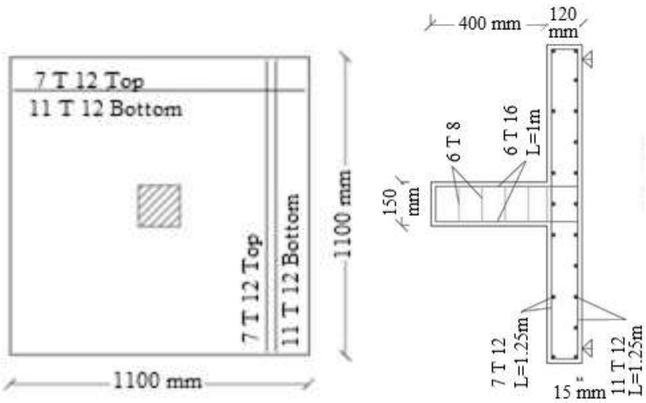


Section 1-1

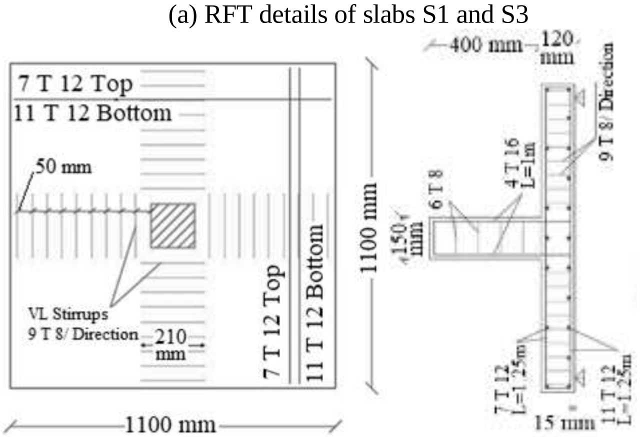
Figure 2: Dimensions of test specimen (S5)

Table 1: Details of slab specimens

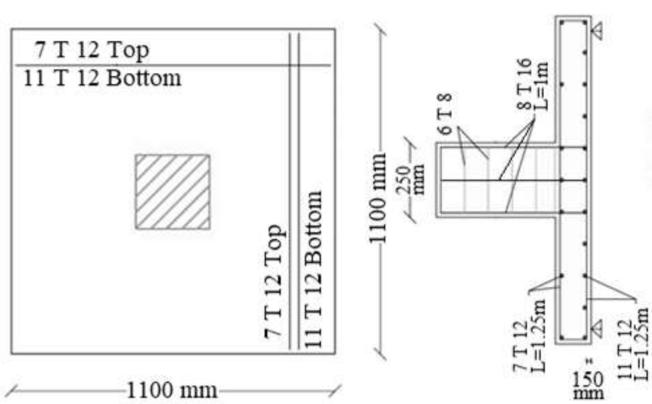
Slab	Type of Concrete	Column Dimension (mm)	Column RFT	Column Stirrups	Shear RFT
S1	N.W.C	150*150*400	4Ø16	6Ø8	…..
S2	N.W.C	150*150*400	4Ø16	6Ø8	VL.Stirrups 9Ø8/Direction @d/2
S3	L.W.C	150*150*400	4Ø16	6Ø8	…..
S4	L.W.C	150*150*400	4Ø16	6Ø8	VL.Stirrups 9Ø8/Direction @d/2
S5	L.W.C	250*250*400	8Ø16	6Ø8	…..



(a) RFT details of slabs S1 and S3



(b) RFT details of slabs S2 and S4



(c) RFT details of slab S5

Figure 3: RFT details of the tested slabs

2.2. Materials

The cement used in this research was ordinary Portland cement (OPC). Tests of cement were carried out according to the Egyptian Code No. 373/1991. The reinforcement steel used in this research study was high tensile steel (36/52) for longitudinal reinforcement. It had a yield strength of 360 N/mm^2, The deformed bars used for reinforcement were 12 mm and 16 mm in diameter, and used for column reinforcement and flexure reinforcement. The reinforcement steel used for shear and column reinforcement was mild tensile steel (24/36), had a yield strength of 240 N/mm^2, and the deformed bars used for reinforcement were 8 mm.

Silica fume was utilized as a mineral admixture in the design of the concrete mix. In the ferrosilicon alloy and silicon metal industries, silica fume is a by-product of induction furnaces [28]. 586 kg/m^3 is the average bulk density. The primary concern with employing silica fume is that the water demand increases unless using a proper dosage of super plasticizer. Silica fume is highly pozzolanic and reacts quickly with calcium hydroxide due to the hydration of cement to produce high strength calcium silicate hydrates [28].

Silica fume consists of extremely small particles with a surface area of 20000 m^2/kg. During the hydration process of cement, silica fume combines with the lime to generate a stable cementitious compound due to its high fineness and silica content. The high-range water-reducing admixture facilitated the utilization of silica fume in concrete as a part of the cementitious component to produce high strength concrete. The normal silica fume ranges from 5 to 20 percent of Portland cement content. Sika ViscoCrete® -3425 [28] was used as a super plasticizer in the mixture. Polystyrene foam is a type of plastic produced foam styrene as shown in Figure 4. It is a lightweight, rigid cellular that was used in the concrete mix. Polystyrene foam has excellent resistance to moisture, imperviousness to rot, and mildew and corrosion. Polypropylene MasterFiber®012 [29] was used to restrict small cracks formations that occur during plastic shrinkage and premature drying to provide hardened cementitious material.

Two concrete mixes were selected from several-trial mixes to casting the tested specimens for LWC and NWC specimens. The target compressive strength of the two mixes was 30 N/mm^2 at the age of 28 days. In order to produce the lightweight concrete with bulk density of 18.2 kN/m^3, several trial mixes were done. Silica fume, polystyrene foam, and super plasticizer were utilized in the mix. The concrete mixture included natural sand as the fine aggregate, fine crushed stone with 10 mm of maximum nominal size as the coarse aggregate, ordinary Portland cement, polypropylene fiber, and tab water. Mixing of the concrete was performed in a conventional rotating mixing in the concrete Research Laboratory at Cairo University. Mix proportions for the concrete mix used in this study to produce LWC and NC are shown in Tables 2 and 3, respectively.

Figure 4: Polystyrene Foam

Table 2: Mix proportion of LWC

Water (Liter)	Cement (kg)	Sand (kg)	Coarse Agg. (kg)	Foam* (Liter)	Silica fume (kg)	Super Plasticizer (Liter)	Fiber** (kg)
135	500	630	630	400	40	20	0.9

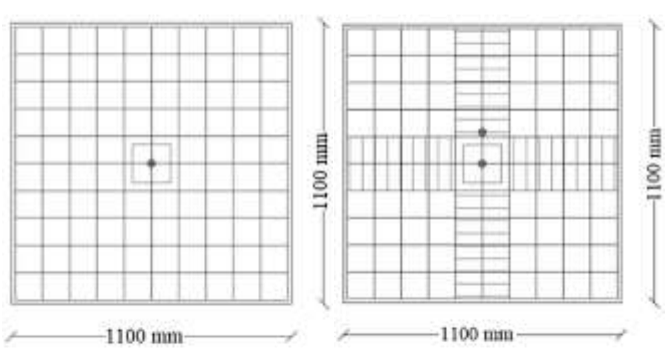
* Indicate to Polystyrene foam, ** Indicate to Polypropylene fibers

Table 3: Mix proportion of NC

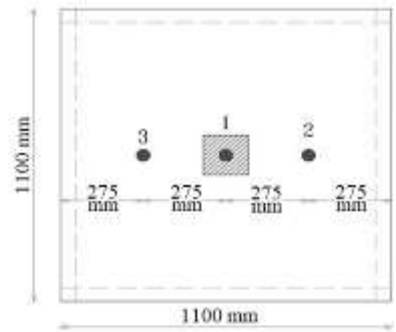
Water (Liter)	Cement (kg)	Sand (kg)	Coarse Agg. (kg)
135	500	630	630

2.3. Test Setup

The testing of specimens was conducted at the concrete research laboratory of Cairo University. The strain gauges are used to record the strain of the bottom main steel and shear reinforcement. The strain gauges for the bottom main reinforcement were located at the slabs center under the center of the column for all slabs, and on the shear vertical stirrups in specimens S2 and S4. The vertical displacement of the slab was measured using three LVDTs. These LVDTs were located at the center and the quarter of the slab on the bottom side. After curing the slabs, all specimens were prepared for punching test under the rigid loading frame which is provided with steel bracing. The slabs were tested using a hydraulic jack with 50 ton capacity. The loading rate was adjusted to be increased incrementally by 0.50 ton till the occurrence of the first crack then the loading rate was incrementally increased by 1.00 ton. Figures 5-a and 5-b presenting the locations of strain gauges and LVDTs, respectively. Figure 6 shows the loading setup of the slab specimen.



(a) Strain Locations



(b) LVDTs Locations

Figure 5: Locations of Strains and LVDTs

Figure 6: Loading Setup

3. Results and Discussion

The tested specimens were categorized into five groups referring to the three variables that the research aimed to investigate. Group (1) includes specimens S1 and S2, to study the effect of shear reinforcement. Group (2) includes specimens S3 and S4, to observe the effect of shear reinforcement. Group (3) includes specimens S1 and S3, to examine the effect of the concrete type. Group (4) includes specimens S2 and S4, to evaluate the effect of the concrete type. Group (5) includes specimens S3 and S5, to investigate the effect column dimension. The control specimen (S1) failed suddenly with extensive spalling of concrete cover, while all the other specimens had a punching shear failure with extensive spalling of concrete cover and achieved a gradual and higher ultimate load. The crack began at the tension side of the slab forming a diagonal shape coincident with the loaded area perimeter. As the applied load increased, the cracks became wider and new cracks developed and began to propagate in several directions towards the slab edges forming a van shape. Figure 7 shows crack patterns of the examined slabs. It was observed from Figure 8 that the highest cracking load was obtained when increasing the columns' dimensions as in S5. On the other hand, the lowest cracking and ultimate loads are achieved by slab S3 when using LWC without using vertical stirrups as shear reinforcement. The highest ultimate load was recorded in the control specimen S2 with shear reinforcement due to the existence of shear reinforcement and the higher strength of NWC than LWC.

(a) S1

(b) S2

(c) S3

(d) S4

(e) S5

Figure 7: Crack patterns of slab specimens

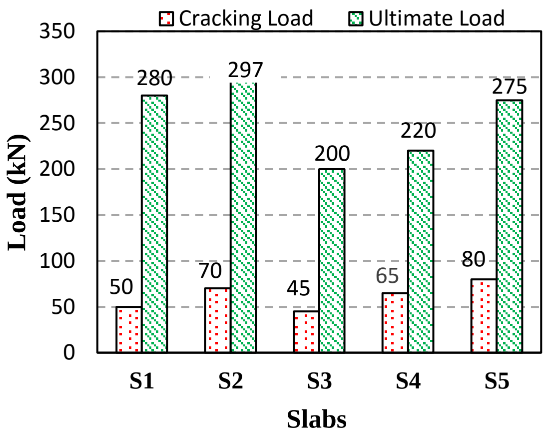
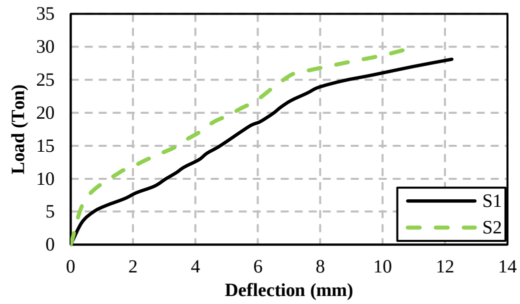


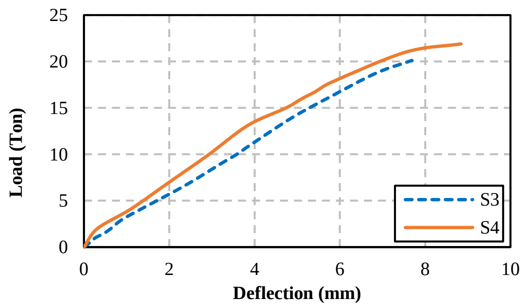
Figure 8: Cracking and ultimate loads of slab specimens

3.1. The effect of shear reinforcement

From Figure 9-a, the specimen (S2) had an ultimate load value higher than the control specimen (S1). At the first crack, the applied load for the control specimen (S1) with associated deflection of 0.74 mm under the column and 1.66 mm at 0.25L was 50 kN while the applied load for the specimen (S2) with associated deflection of 0.48 mm under the column and 0.7 mm at 0.25L was 70 kN. For the control specimen (S1) at an ultimate load level equal to 280 kN, the recorded deflection was 12.22 mm under the column and 11.28 mm at 0.25L. While specimen (S2) at ultimate load level equal 297 kN, the recorded deflection was 10.84 mm under the column and 9.63 mm at 0.25L. The ultimate load of the specimen (S2) was 6 % higher than the control specimen (S1) due to the stiffening action which is resulted from the existence of shear reinforcement, while the deflection at the ultimate load level for the specimen (S1) was 35.7% higher than the specimen (S2) under the column and 41% higher at 0.25L at same loading level. The ultimate load of the specimen (S4) recorded 220 kN and it was 10% higher than the specimen (S3) with a value of 200, while the deflection at the ultimate load level for the specimen (S3) was 14.8% higher than the specimen (S4) under the column and 8.67% higher at 0.25L at same loading level as shown in Figure 9-b.



(a)

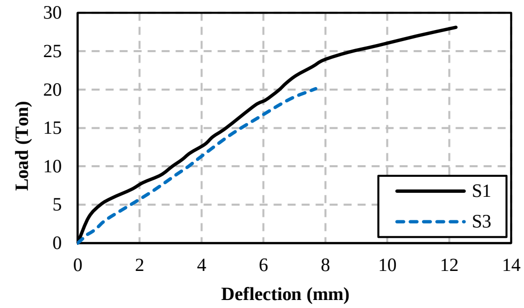


(b)

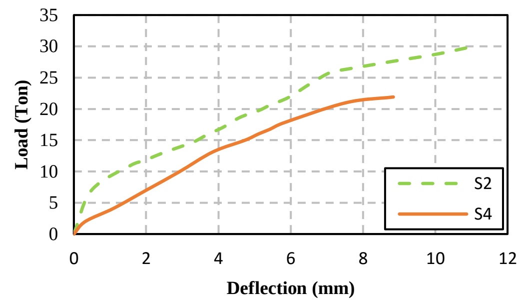
Figure 9: Load-Deflection curves to study the effect of shear reinforcement

3.2. The effect of concrete type

The control specimen (S1) had an ultimate load value higher than the specimen (S3) as shown in Figure 10-a. At the first crack, the applied load for the control specimen (S1) with associated deflection of 0.74 mm under the column and 1.66 mm at 0.25L was 50 kN while the applied load for the specimen (S3) with associated deflection of 1.6 mm under the column and 1.41 mm at 0.25L was 45 kN. For the control specimen (S1) at an ultimate load level equal to 280 kN, the recorded deflection was 12.22 mm under the column and 11.28 mm at 0.25L. While specimen (S3) at ultimate load level equal 200 kN, the recorded deflection was 7.69 mm under the column and 6.52 mm at 0.25L. The ultimate load of the control specimen (S1) was 40 % higher than the specimen (S3), while the deflection at the ultimate load level for the specimen (S3) was 18.85% higher than the specimen (S1) under the column and 8.67% higher at 0.25L at same loading level. . The ultimate load of the specimen (S2) achieved 297 kN and it was 35 % higher than the specimen (S4) with a value of 220 kN, while the deflection at ultimate load level for the specimen (S4) was 48.57% higher than the specimen (S2) under the column and 86.6% higher at 0.25L at same loading level as shown in Figure 10-b.



(a)



(b)

Figure 10: Load-Deflection curves to study the effect of concrete type

3.3. The effect of changing column dimensions

The specimen (S5) had an ultimate load value higher than the specimen (S3). At the first crack, the applied load for the specimen (S3) with associated deflection of 1.6 mm under the column and 1.41 mm at 0.25L was 45 kN while the applied load for the specimen (S5) with associated deflection of 2.75 mm under the column and 2.51 mm at 0.25L was 80 kN. For specimen (S3) at an ultimate load level equal to 200 kN, the recorded deflection was 7.69 mm under the column and 6.52 mm at 0.25L. While specimen (S5) at ultimate load level equal 275 kN, the recorded deflection was 9.43 mm under the column and 7.967 mm at 0.25L. The ultimate load of the specimen (S5) was 37.5 % higher than the specimen (S3), while the deflection at the ultimate load level for the specimen (S3) was 11.28% higher than the specimen (S5) under the column and 15.8% higher at 0.25L at same loading level as shown in Figure 11. From those observations, it was concluded that by increasing the size of column, the punching capacity and deflection are increased.

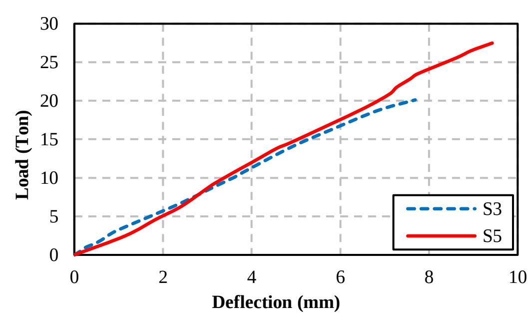


Figure 11: Load-Deflection curves to study the effect of changing column dimensions

3.4. Comparison between test results and ECP, ACI, BS, and EN codes

A comparison between the ultimate shear stress obtained from the experimental investigation and the calculated stresses from the codes is carried out. The punching shear resistance for the RC flat slab is achieved by considering the provisions of various codes. These provisions are showed as empirical equations. The most commonly used design equations are in the Egyptian code (ECP 203-2017), American Concrete Institute (ACI 318-14), BS 8110 -1997, and Eurocode-2.

3.4.1. ECP-203-2018 punching shear

The Egyptian Code [30] considered that the punching shear stress is not to be resisted by concrete only but also by shear reinforcement (vertical stirrups). The Egyptian Code recommends that the critical section for punching shear in slab is at a distance d/2 around the circumference of the concentrated load. The ultimate punching shear stress (q_{up}) for flat slabs must be less than the maximum ultimate shear strength:

$$q_{up} = \frac{Q_{up}}{b_o.d} \leq q_{cup} \quad (1)\ [30]$$

Where q_{up} is the ultimate punching shear stress, Q_{up} is the ultimate shear force, b_o is the critical shear perimeter at distance d/2 from column face, d is the effective depth of the slab, and q_{cup} is the concrete punching shear strength that be calculated by using the smallest value of the following equations:

$$q_{cup} = 0.8\left(\frac{\alpha\ x\ d}{b_0} + 0.2\right)\sqrt{\frac{F_{cu}}{\gamma_c}} \quad (2)\ [30]$$

$$q_{cup} = 0.316\left(0.5 + \frac{a}{b}\right)\sqrt{\frac{F_{cu}}{\gamma_c}} \quad (3)\ [30]$$

$$q_{cup} = 0.316\sqrt{\frac{F_{cu}}{\gamma_c}}\ (N/mm^2) \leq 1.7\ (N/mm^2) \quad (4)\ [30]$$

Where a = column smaller dimension, b = column bigger dimension, f_{cu} = compressive strength of concrete in N/mm^2, and α = factor for column position (interior = 4, edge = 3, and corner = 2). To calculate the punishing shear capacity when involving shear reinforcement, the following equation is used.

$$q_{up} = 0.12\sqrt{\frac{F_{cu}}{\gamma_c}} + q_{sup} \leq q_{up(max)} \quad (5)\ [30]$$

Where A_{st} is the total area of shear reinforcement (vertical stirrups), S is the center to center spacing (spacing between stirrups < d/2), and $q_{up(max)}$= maximum ultimate punching shear strength and must be less than the following:

$$q_{up(max)} \leq 0.45\sqrt{\frac{F_{cu}}{\gamma_c}} \quad (6)$$
[30]

3.4.2. ACI 318-14 punching shear

The punching shear capacity that specified in ACI 318-08 is calculated on the perimeter of a distance d/2 from the column face for all sides in square or rectangular columns. The ultimate shear strength of concrete slabs (V_{uo}) is the smallest of the following equations [31]:

$$V_{uo} = 0.17\left(1 + \frac{2}{\beta_c}\right)\lambda\sqrt{f_{c'}}\ ud \quad (7)$$
[31]

$$V_{uo} = 0.083\left(\frac{\alpha_s\ d}{u} + 2\right)\lambda\sqrt{f_{c'}}\ ud \quad (8)$$
[31]

$$V_{uo} = 0.33\ \lambda\sqrt{f_{c'}}\ ud \quad (9)$$
[31]

Where:

V_{uo} is the ultimate shear strength of slabs, $f_{c'}$ is the cylindrical compressive strength (N/mm^2), α_s is the constant value of the column position, (interior = 40, edge = 30, and corner = 20), β_c is the ratio of larger side to shorter side of the column, λ is a factor for the density of the concrete (1.0 For Normal Weight Concrete, 0.85 For low weight concrete, and 0.75 For all-light- weight concrete), u is the perimeter of the critical shear at distance d/2 from column face, and d is the slab effective depth [31]. To calculate the strength of the design punching shear that using shear reinforced, the following equations is used:

$$\phi\ V_n \geq V_u \quad (10)$$
[31]

$$V_n = V_c + V_s \leq V_{max} \quad (11)$$
[31]

$$V_c = 0.17\sqrt{f_{c'}}\ ud \quad (12)\ [31]$$

$$V_s = \frac{A_{sv}\ F_{sy}\ d}{S} \quad (13)$$
[31]

$$V_{max} = 0.5\sqrt{f_{c'}} \quad (14)$$
[31]

Where V_n is the nominal shear strength, V_u is the applied shear force that calculated at the critical perimeter, ϕ = 0.75 (constant factor), V_c is the concrete punching shear resistance, V_s is the punching shear resistance by using shear reinforcement, A_{sv} is the total area of shear reinforcement (vertical stirrups), and S is the center to center spacing (spacing between stirrups < d/2) [31].

3.4.3. BS 8110 -97 punching shear

The punching capacity is calculated on the perimeter with a distance of 1.5d or more from the loaded area. The failures of punching occur on the inclined sides of the pyramid or truncated cones, depending on the loaded area shape.

The ultimate shear strength (V_{cd}) will be calculated by using the following equation:

$$V_{cd} = 0.79\times(100\rho)^{1/3} \times (400/d)^{1/4} \times (F_{cu}/25)^{1/3} \times (u_o d/\gamma m) \quad (15)$$

[32]

Where γm is the factor of the material partial ($\gamma m = 1.25$), F_{cu} is the compressive strength of concrete, (N/mm^2), $\rho = \frac{\rho x+\rho y}{2} < 0.03$, in which ρx and ρy are the ratio of the flexural reinforcement in both directions, $(400/d)^{1/4}$ is the factor of the size $(400/d)^{1/4} \leq 1$, and u_o is the perimeter of the critical shear at distance 1.5d from column face [32]. The punching shear strength of flat slabs that using shear reinforcement is calculated by using the following equation.

$$V_{sd} = V_{cd} + 0.87\, A_{sv}\, F_{sy} \sin\alpha \quad (16)$$

[32]

Where, A_{sv} is the area of one row of shear reinforcement (spacing $\leq$ 0.75d), F_{sy} is the yield strength of the shear reinforcement, (N/mm^2), α is the angle between shear reinforcement and plane of the slab. The angle α=90° when the shear reinforcement used will be normally taken vertical links [32]. The maximum shear stress (v_{max}) must not to exceed 0.8 $\sqrt{F_{cu}}$ or 5 N/mm^2 if less. The v_{max} will be calculated by using the following equation:

$$v_{max} = \frac{V}{u_o d} \quad (17)$$

[32]

Where V is the design ultimate value of the applied load.

3.4.4. EUROCODE 2 punching shear

According to Eurocode 2 [9], the critical section should be at distance 2d from the loaded area face for interior, edge and corner column and should be considered to minimize its length. But in case of using shear reinforcement, the recommended section is 1.5d. The design process for punching shear is based on several checking at the column face and at the shear perimeter. If shear reinforcement is required, a new perimeter where shear reinforcement is no longer required should be found. The design values for the punching shear capacity of a slab without shear reinforcement, the punching capacity of a slab with shear reinforcement, and the maximum punching capacity along the reference section, are denoted as v_{Rdc}, v_{Rdcs}, and v_{Rd} max, respectively. The applied shear stress is calculated by applying the following equation:

$$v_{ED} = \frac{V_{ED}\times\beta}{u\times d} \quad (18)$$

[9]

Where V_{ED} is the applied punching force, u is the length of the reference perimeter being considered, d is the effective depth of the slab, and β is the factor that takes the effect of the eccentricity recommended values (β = 1.5, 1.4, and 1.15 for the corner, edge, and interior columns, respectively) [9]. The design punching shear resistance (N/mm^2) for Slabs without Punching Shear Reinforcement is calculated as follows:

$$V_{Rd,c} = C_{Rd,c} \times K(100\rho_1 f_{ck})^{1/3} + K_1\sigma_{cp} \geq (v_{min}+K_1\sigma_{cp}) \quad (19)\ [9]$$

Where, f_{ck} is in N/mm^2, $K=1+\sqrt{\frac{200}{d}} \leq 2$, d in mm, $C_{Rd,c}$ is 0.18/γc, for v_{min} is given by Expression (6.3N) that for k1 is 0.l, and

$$\rho_1= \sqrt{\rho ly.\rho lz} \leq 0.02 \quad (20)\ [9]$$

Where ρly and ρlz are related to the bonded tension steel in y- and z- directions respectively [9]. The design punching shear resistance for slabs with shear reinforcement is calculated as follows where shear reinforcement is required:

$$v_{Rdcs} = 0.75\, v_{Rdc}+1.5(d/S_r)A_{sw}\, f_{ywd,ef}\, (1/(u_1 d))\sin\alpha \quad (21)$$

[9]

Where, d is the average of the effective depths in the vertical directions (mm), A_{sw} is the area of one branch of shear reinforcement around the column (mm^2), S_r is refer to the radial perimeter spacing of shear reinforcement (mm), $f_{ywd,ef}$ is the effective strength of the punching shear reinforcement, α is the angle between the plane of the slab and the shear reinforcement (α = 90° and sin α = 1 for vertical stirrups), and v=0.6(1-fcd/250) [9].

Table 4 shows the calculated values from ECP 203-2018, ACI 318-14, BS 8110-97, and Eurocode 2 in comparison with the experimental results. From Table 4, the ratios between the experimental ultimate load and the calculated load from all mentioned codes were greater than one, which indicate that they lie in a safe side and conservative. The highest conservative code was the ACI 318-14 with the largest differences from the experimental results.

Table 4: The ultimate punching capacities of the experimental results and the design codes.

Slab	P_{test}	P_{ECP}	P_{test} / P_{ECP}	V_{ACI}	P_{test} / V_{ACI}	V_{BS}	P_{test} / V_{BS}	V_{EN}	P_{test} / V_{EN}
S1	280	182	1.54	173	1.62	242	1.15	221	1.26
S2	297	171	1.73	191	1.56	284	1.04	242	1.22
S3	200	182	1.1	130	1.54	194	1.03	177	1.13
S4	220	171	1.28	168	1.31	215	1.02	209	1.05
S5	275	253	1.09	181	1.52	235	1.17	214	1.28

4. Conclusions

According to the experimental investigation results, the following conclusions could be derived:

1. The slab specimens made by lightweight concrete had a decrease in the resistance of punching shear for slab-column joints up to 40%. So, it is advised not to use lightweight concrete in flat slabs, because it has low effect on the resistance of punching shear for slab column joints.
2. The slab specimens that were provided by shear reinforcement (vertical stirrups) had an increase in the resistance of punching shear for slab column joints up to 6% in normal strength concrete and up to 10% in lightweight concrete.
3. Increasing the supporting column dimension from 150 x 150 mm to 250 x 250 mm increased the resistance of punching shear for slab-column joints up to 37.5%.
4. The national and international codes that have been selected to study in research gives conservative estimate for the punching shear strength of tested slab. According to the BS code provision, adding the top main flexural reinforcement steel factor (ρ) in the design code equations will led to maximize the resistance of the punching shear of the slab-column connections. The ACI and ECP codes show lower resistance of the punching shear than the BS, and Eurocode as they do not take into consideration the main reinforcement in their design equations.
5. Using shear reinforcement (vertical stirrups), increasing the number of the stirrups distribution per meter, and adding the top main and additional reinforcement to the design equation, will maximize the resistance of the punching shear up to 6%, and 10% for normal strength concrete and lightweight concrete, respectively.

It's suggested for future studies to investigate the effect of changing spacing between the stirrups, the diameter of reinforcing bars, and to conduct a finite element models to represent the behavior of lightweight concrete slabs and to create design equations taking into consideration all affecting parameters.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] Thienel, K. C., Haller, T., & Beuntner, N. "Lightweight concrete—From basics to innovations." Mater. 13(5), 2020, 1120. DOI: 10.3390/ma13051120

[2] Lamprecht, H.-O. Opus Caementitium: Bautechnik der Römer, 5th ed.; Beton-Verlag GmbH: Düsseldorf, Germany, 1996; p.264. ISBN 3-7640-0350-2.

[3] Cavalline, T.L.; Castrodale, R.W.; Freeman, C.;Wall, J. "Impact of Lightweight Aggregate on Concrete Thermal Properties." ACI Mater. J. 114, 945–956, 2017.

[4] Fares, H.; Toutanji, H.; Pierce, K.; Noumowé, A. "Lightweight Self-Consolidating Concrete Exposed to Elevated Temperatures." J. Mater. Civil Eng. 27, 04015039, 2015

[5] Roberz, F.; Loonen, R.C.G.M.; Hoes, P.; Hensen, J.L.M. "Ultra-lightweight concrete: Energy and comfort performance evaluation in relation to buildings with low and high thermal mass." Energy Build. 138, 432–442, 2017

[6] Samson, G.; Phelipot-Mardelé, A.; Lanos, C. "A review of thermomechanical properties of lightweight concrete." Mag. Concr. Res. 69, 201–216, 2017.

[7] ACI Committee 213. ACI 213R-14 Guide for Structural Lightweight-Aggregate Concrete; American Concrete Institute: Farmington Hills, MI, USA, p. 53, 2014

[8] DIN EN 206. Concrete-Specification, Performance, Production and Conformity; Beuth Verlag: Berlin, Germany, p. 96, 2013.

[9] DIN EN 1992-1-1. Eurocode 2: Design of Concrete Structures-Part 1-1: General Rules and Rules for Buildings; Beuth-Verlag: Berlin, Germany, p. 241, 2011.

[10] Held, M. Hochfester Konstruktions-Leichtbeton. Beton 46, 411–415, 1996.

[11] Taylor, H.F.W. Cement Chemistry, 2th ed.; Thomas Telford Ltd.: London, UK, p. 459, 1997. ISBN 9780727725929.

[12] Herrnkind, V.; Scholz, S.G. Berücksichtigung des Einflusses der unterschiedlichen Lagerungsarten „trocken" und „feucht" auf die Ergebnisse der Druckfestigkeitsprüfungen. Beton 58, 164–167, 2008.

[13] Raithby, K.D.; Lydon, F.D. Lightweight concrete in highway bridges. Int. J. Cem. Compos. Lightweight Concr. 3, 133–146, 1981.

[14] Helland, S.; Aarstein, R.; Maage, M. ln-field performance of North Sea offshore platforms with regard to chloride resistance. Struct. Concr. 11, 15–24, 2010.

[15] Thienel, K.-C. Application of Lightweight Concrete. In Nordic Mini-Seminar: Structural Lightweight Aggregate Concrete; Øverli, J.A., Zivkovic, J., Eds.; Nordic Concrete Federation: Trondheim, Norway, 6–9, 2019. ISBN 978-82-8208-066-8.

[16] Mitchell D, Devall RH, Saatcioglu M, Simposn R, Tinawi R, Tremblay R. Damage to concrete structures due to the 1994 Northridge earthquake. Can J Civ Eng 22, 361–377, 1995.

[17] Gardner NJ, Huh J, Chung L. Lessons from the Sampoong department store collapse. Cement e Concrete Composites 24, 523–529, 2002.

[18] Dönmez A, Bazant ZP. Size effect on punching shear Strength of Reinforced Concrete Slabs Without and With Shear Reinforcement". July-Aug., 876–886, ACI Struct J 114(4), 2017. https://doi.org /10.14359/5168 9719.

[19] Urban T, Goldyn M, Krawczyk L, Sowa L. Experimental investigations on punching shear of lightweight aggregate concrete flat slabs. Eng Struct 197, 2019. https://doi.org/10.1016/j.engstruct.2019.109371.

[20] Wille K, Dehn F. Fracture mechanical behaviour of lightweight aggregate concrete. Material Sciences 2003. https://doi.org/10. 1680/rocisd .32477.0051.

[21] Deifalla, A. "Strength and ductility of lightweight reinforced concrete slabs under punching shear." Struct. 27, 2020.

[22] Goldyn, M., Krawczyk, L., Ryżyński, W., & Urban, T. "Experimental investigations on punching shear of flat slabs made from lightweight aggregate concrete." Arch. Civ. Eng., 64 (4/I), 2018.

[23] Said, M., Adam, M. A., Arafa, A. E., & Moatasem, A. "Improvement of punching shear strength of reinforced lightweight concrete flat slab using different strengthening techniques." J. Build. Eng., 32, 101749, 2020.

[24] Deifalla, A. "Evaluation for the Punching Shear Design of Concrete Slabs Subjected to Compressive Forces." In International Conference on Advanced Technologies for Humanity, Springer, 474-481, 2021. https://doi.org/ 10.1007/978-3-030-94188-8_42

[25] MC: Fib model code for concrete structures 2010. Ernst & Sohn, 2013.

[26] Halvoník, J., Kalická, J., Majtánová, L., & Minárová, M. "Reliability of models aimed at evaluating the punching resistance of flat slabs without transverse reinforcement." Eng. Struct., 188, 627-636., 2019.

[27] Sika Egypt (2017), https://egy.sika.com/en/documents/pds-english.html. (accessed April 2022).

[28] Master Builders, https://www.master-builders-solutions.com/en-ae/products/ masterfiber/masterfiber-012. (accessed April 2022).

[29] ECP 203-2017, "Egyptian code of practice for design and construction of reinforced concrete structures". Housing and Building Research Centre, Cairo, (2017).

[30] ACI 318-14, "Building Code Requirement for Structural Concrete and Commentary (ACI 318-14)". American Concrete Institute, Farmington Hills, Mich.

[31] BS 8110 (1997), "Structural use of Concrete", Part 1: Code of practice for design construction, British Standards, London.