An Experimental Investigation of Slab-Column Connection Strengthened with Steel Collar under Eccentric Load

Hanaa Abdulbaset Ali
Department of Civil Engineering, University of Baghdad, Iraq
hanaa.ali2001d@coeng.uobaghdad.edu.iq (corresponding author)

Mohannad H. Al-Sherrawi
Department of Civil Engineering University of Baghdad, Iraq
Dr.Mohannad.Al-Sherrawi@coeng.uobaghdad.edu.iq

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ABSTRACT

Slab-Column (SC) connections refer to concrete reinforcing slabs that have consistent thickness and directly transfer loads to the support column. The absence of beams makes these connections distinct and economical compared to other systems. The most common type of failure in flat slab systems is punching shear, therefore, strengthening the SC region is necessary. The current study introduces a practical methodology that aims to enhance the punching shear strength of concrete flat slabs using steel collars. Nine 9-square reinforced concrete slab specimens with dimensions of 1400×1400×100 mm were cast and investigated under static load. Three specimens were tested using the axial load procedure, while six slabs were tested deploying an eccentric procedure. This article has studied two parameters to characterize the shear strength resistance for this type of slab: the steel collar model and the eccentricity loading effect. The study outlines the load-deflection relationship, failure mode, ultimate capacity, stiffness, cracking load, and the value of the failure angle. The test results illustrate a reduction in ultimate load by 26% and 60% due to the influence of eccentric load and unbalanced moment in group I, while the ultimate load increased by 34% and 61% in specimens strengthened with steel collars under the same eccentric load applied, proving the efficiency of the steel collar in the connected area of the slab column on enhancing the shear strength of the slab exposed to eccentric load and moments.

Keywords-slab column; connection; eccentric load; flat slab; steel collar; steel angle

I. INTRODUCTION

Unequal spans, loading on the sides of a column, the presence of lateral loads, changes in material temperature, and differing shrinkage often lead to unbalanced moments and eccentric loads in buildings with flat plates. The unbalanced moment decreases the punching shear resistance of the flat slab. The design of the connected zone in the SC is typically the most crucial aspect in the concrete flat plate system. Punching shear failure may take place in this area due to high concentrations of loads and moments [1-6]. The critical zones of flat slab column members are the edges and corners which are usually exposed to eccentric loads and unbalanced moments, leading to shear failure. Briefly, these influences have been less experimentally investigated in comparison with flat slabs subjected to concentric loads. Most previous experiments were mostly applied to SC regions subjected to concentric loadings [7-12]. Decreasing the slab thickness leads to flat slab failure represented by punching due to significant stress near the column. This type of collapse is a complicated occurrence that depends on various factors, including the ratio of longitudinal reinforcement, compressive strength, slenderness of slab, and column dimensions. The complexity of this phenomenon increases when vertical and horizontal loads are combined [13-15]. Nowadays, the adoption of fiber-reinforced polymers to enhance the strength of structures is widely utilized. This serves as a second option for common methods of reinforcement, like external metal plates, concrete jacketing, or external prestressing [16-19]. The principal goal of the current study is to experimentally study the influence of the eccentric load and steel collar strengthening on the slab-column connection.

II. DESCRIPTION OF SLAB-COLUMN CONNECTION

The deployed practical methodology includes nine flat slabs, with overall dimensions of 1400 × 1400 × 100 mm and 1300 mm effective slab length, which were cast and prepared. The principal objective of this article is to describe the effect of eccentric load and steel collar on the structural behavior of flat slabs. Table I provides details of the slabs, with load applied with different eccentricities: SC_1 with load applied at the center, SC_2 with an eccentricity of 100 mm, SC_3 with an eccentricity of 150 mm, and s1 and s2 referring to the steel collar with thickness of 6 mm and 10 mm, respectively. The steel reinforcement distribution for all slabs is the same. The top fiber of each slab was reinforced with ϕ 10 mm rebars at 75 mm in both directions, adopting a reinforcement ratio of 1.45%. The bottom fiber was reinforced with ϕ 8 mm rebars, spaced at 150 mm in both directions with a reinforcement ratio of 0.43%. This design is intended for specimens without punching shear reinforcement. The cantilever column was reinforced longitudinally with four rebars of 16 mm and two ties of ϕ 8 mm. Figure 1 illustrates the reinforcement details.

TABLE I. MAIN CHARACTERISTICS OF THE SLABS

Group No.	Slab ID	Eccentricity from the center	Steel collar length	Steel collar thickness
I	SC 1	-	-	-
	SC 2	100	100mm	-
	SC 3	150	100mm	-
II	SC1 s1	-	100mm	6mm
	SC2 s1	100	100mm	6mm
	SC3 s1	150	100mm	6mm
III	SC1 s2	-	100mm	10mm
	SC2 s2	100	100mm	10mm
	SC3 s2	150	100mm	10mm

*I, II:-Group number, S:-Flat slab, C:- Column, s:- Steel collar

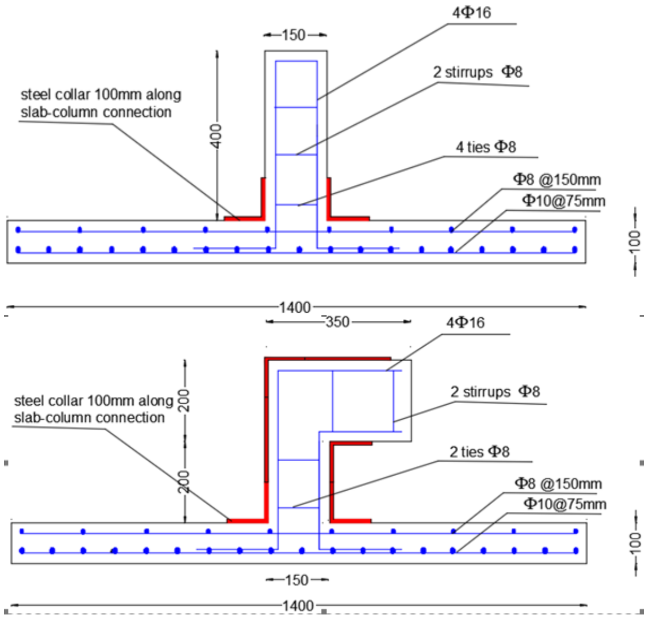

Fig. 1. Steel reinforcement of flat slab.

The slab connection region was reinforced using steel angle plates with two thicknesses, 6 mm and 10 mm, called steel collars. The total bonding consists of four angle plate pieces being cut at two angles, the top part in the column was cut at 90º and the bottom part in the slab was cut at 135º. The steel stress at the yield stage was 445 MPa and 485 MPa for plates with thicknesses of 6 mm and 10 mm, respectively. The concrete surface was roughened and cleaned to prepare the slab-column connection area for the attachment of the steel angles. The four steel angles were also attached to the four sides of the column using epoxy resin and were then welded longitudinally to form a complete collar around the slab-column connection region, as shown in Figure 2.

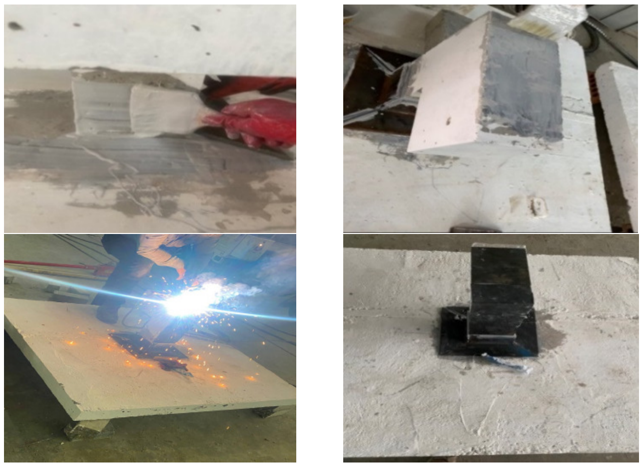

Fig. 2. Installation of steel collar on specimens.

The critical region for this type of slab, which is free of shear reinforcement, is located at a distance of d/2 from the column plate [20]. C1 and C2 are the column dimensions and the standard [20] considers a rectangular failure perimeter b_o around the column. All these details are depicted in Figure 3.

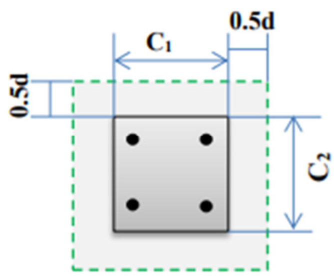

Fig. 3. Critical selection in slab without shear reinforcement according to ACI code for punching shear [20].

The concrete composition for the current work was obtained from a trail mix, using Portland type I cement, with a maximum coarse aggregate size of 12 mm, fine sand, an SP admixture ratio of 0.42%, and a water-to-cement ratio of 0.47. This is summarized as C:S:G (1:1.75:2.47). Based on ASTM C39/C39M21 and ASTM C496/C496M-17, three cylinders of concrete having dimensions of 150 × 300 mm, were cast and tested to measure the compressive strength, fc`, and the splitting strength, ft, respectively [21, 22]. To determine the modulus of concrete rupture, fr, three concrete prisms with dimensions of 400 × 100 × 100 mm were prepared and cast following ASTM C78/C78M-21 [23]. To estimate the modulus of elasticity for the concrete, the equation provided by [20] was used, $E_c = 4700\sqrt{fc`}$, based on the measured compressive strength, fc`. Table II portrays the mean outcomes for three samples.

TABLE II. STRENGTH OF CONCRETE

Group No.	Cylinder strength fc` (MPa)	Splitting tensile strength ft, (MPa)	Modulus of rupture fr, (MPa)	Modulus of elasticity Ec, (MPa)
I				
II	33.4	3.22	3.12	25254
III				

III. TEST SETUP

A total of nine specimens were tested according to a static procedure. The applied load (concentric and eccentric) was transferred from the column to the slab. The methodology for applying the eccentric load using load cells is similar to the approach followed in [24, 25]. Figure 4 displays the experimental column slabs, while Figure 5 shows the data logger and the Linear Variable Displacement Transducer (LVDT). Initially, all specimens were prepared, and located at the exact position, and the steel frame was placed on four sides and used as support. The data extraction strategy consisted of utilizing strain gauges and a LVDT. Thus, at the initial stages of loading, cracks were initiated, and as the loading increased, the cracks grew and developed in the tensile zone, and subsequently on the compression surfaces of the specimen. The punching angle and the punched zone perimeter or area were measured when the slab specimen collapsed.

(a) (b)

Fig. 4. (a) Concentric load, (b) eccentric load.

(a) (b)

Fig. 5. (a) Data logger, (b) LVDT.

IV. RESULTS AND DISCUSSION

A. Mode Failure of Slab

Most practical specimens, and particularly slabs without augmentation, underwent sudden punching shear failure. However, specimens with steel collar bolstering subjected to various types of load, either concentric or eccentric, collapsed gradually. The flat slabs reached failure gradually with growing cracks that extended from the crucial zone towards the center and the edges having been formed, resulting in an X-shape with decreasing load. The first cracks were equivalently initiated when the load ranged from 30 to 40 kN for all specimens. The former appeared on the slab extremes close to the column position when the specimens were subjected to concentric load, while they were located in the opposite direction of the load when the latter was eccentric. The cracks had the form of a circular region in the specimen without strengthening, while they formed a rectangular section when the specimens had collars. The applied eccentric load on the column led to the punching model creation that was obviously evident in three directions at the compression zone, whereas the crack pattern occurred less in the tension zone. Therefore, the mode of failure was considered as slightly brittle. Figure 6 illustrates these failure modes.

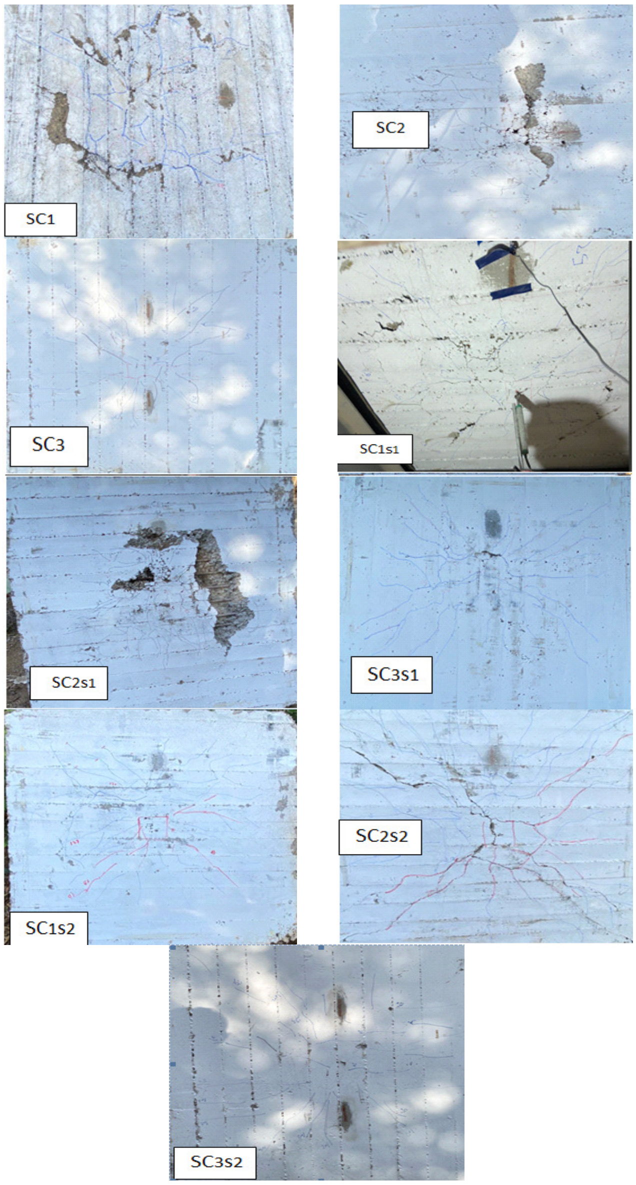

Fig. 6. Modes of failure of slab-column connection.

B. Load-Deflection Relationship

The load-deflection responses of the structural members are highly significant at all loading stages for both the slab and the strengthened slab. Figure 7 outlines these relationships.

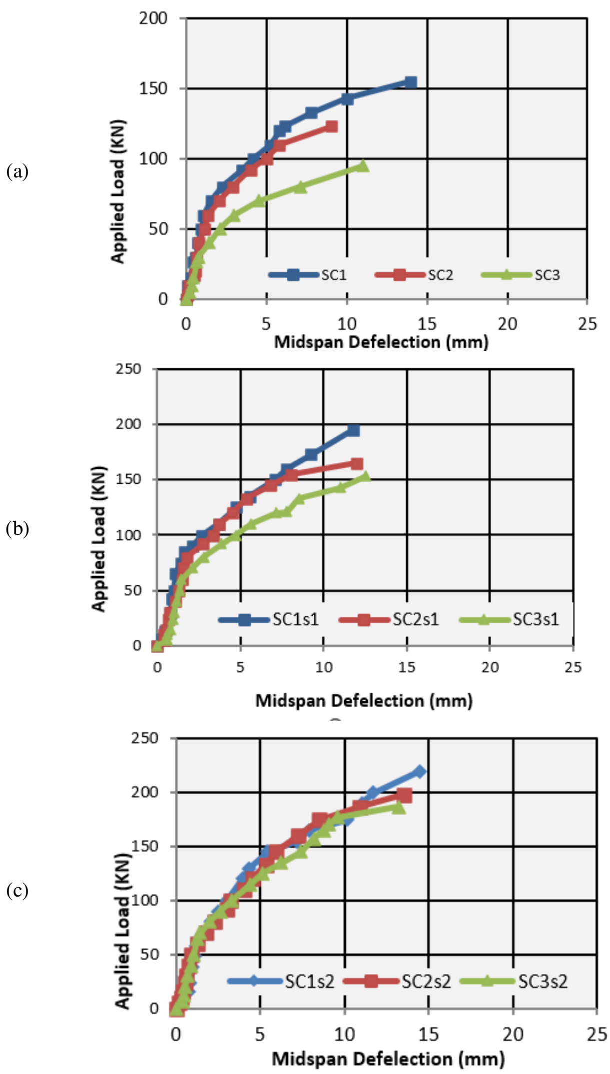

Fig. 7. (a) Class I, (b) class II, (c) class III.

The behavior of the tested slabs with eccentricities of 100 mm and 150 mm, respectively, (SC2, SC3, group I) demonstrated a decrease in the applied load compared to the reference slab SC1. The second group displayed an augmentation by using a steel collar compacted on the connected zone of the slab column for the slabs SC1s1, SC2s1, and SC3S1. The improvement compared to group I was about 26%, 34%, and 61%, respectively. Group III showed high load capacity due to the increase in the thickness of the steel collar by 10 mm, with improvements of about 46%, 60%, and 90% compared to group I. The crack load was slightly different across all specimens.

C. Load Strain of Steel Reinforcement

The strain was measured at the center of the column-slab connection when the reinforcement reached its yielding limit. Figure 8 depicts the load-strain relationship in the longitudinal reinforcements of all specimens. The failure mode of most slabs were very similar. When the specimens fail before the steel reinforcement reached its yielding limit, the failure is called punching shear failure, and when a failure occurs after longitudinal steel yielding, it is known as flexural failure. It was obvious that the slabs SC3, SC2, and SC3s2 failed in pure punching shear mode, SC1, SC3s1, and SC2s2 failed in flexural shear mode, and SC1s1, SC2s1, and SC1s2 failed in flexural mode. The strain value is within the normal range, whereas the strain values in slabs decrease with increasing steel collar thickness.

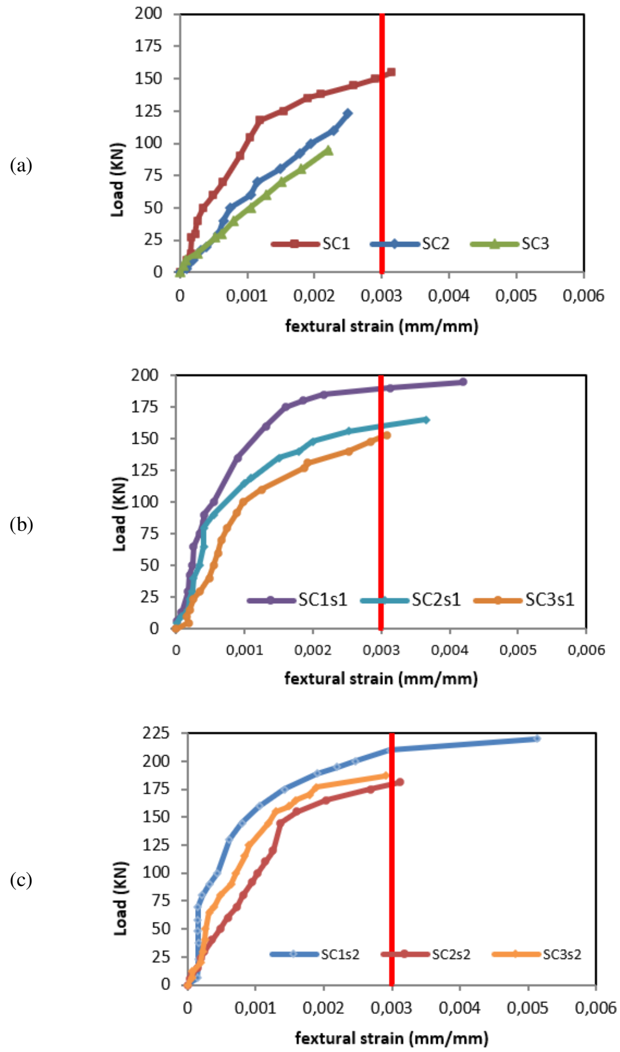

Fig. 8. (a) Class I, (b) class II, (c) class III.

D. Load-Strain of Concrete

The strains of concrete in the compression and tension zones were measured using two strain gauges placed on the extreme outer faces of the slab (top and bottom), at a distance of 4d from the face of the column. The compressive values at the top were slightly greater than the tensile strain at the bottom surface in most of the specimens, because concrete is weak in the tension zone, which causes the neutral axis to rise toward the compression zone of the concrete.

E. Strain in Steel Collars

Four pieces of steel with a length of 10 mm and thickness values of 6 mm and 10 mm were placed on the connected sector of the slab-column, which was bonded by epoxy adhesive. During the failure of the specimens, no deformation and no separation occurred in the steel collars due to the high stiffness of the steel angles. Especially in specimens with a thickness of 10 mm, except SC1s2 where simple deformation occurred due to the high ultimate load, small values of steel collar strain were noticed in all specimens.

F. Stiffness

The stiffness is calculated from the load and deflection values at the uncracked and ultimate stages [26-27]. Table III exhibits the estimation of a flat slab by dividing the difference in loads by the difference in deflection. The initial stiffness was estimated from the load and deflection values at the uncracked stage. Generally, a similar behavior can be observed in stiffness and initial stiffness, being considerably affected by the use of a steel collar of 6 mm and 10 mm thickness. This significantly increased the stiffness of the slabs in group II by (21%-31%), and in group III by (40%-34%) compared to group I, even when the eccentricity affected the good agreement of the strengthening of the steel collar at both stages, the initial and the ultimate. The reduction in stiffness values in slabs SC2, SC3, SC2s1, SC3s1, SC2s2, and SC3s2 was less than in specimens SC1, SC1s1, and SC3s2 due to the eccentricity effect.

TABLE III. RESULTS OF THE TESTED SLABS

Slab ID	Load crack P_{cr} (kN)	Displacement at load crack Δcr	Ultimate load P_u (kN)	Displacement at ultimate load Δu (mm)	Perimeter of failure area (mm)	Angle of failure	Enhancement ratio of P_u (%)	Initial stiffness $\frac{Pcr}{\Delta cr}$	Ultimate stiffness $\frac{Pu-Pcr}{\Delta u-\Delta cr}$
SC_1	32	1.75	155	12.50	2650	13.50	Reference	18.29	11.44
SC_2	30	2.12	123	10.00	1540	11.50	Reference	14.15	11.80
SC_3	24	2.10	95	9.00	1210	10.00	Reference	11.43	10.29
$SC_1 s_1$	35	1.80	196	12.00	2850	17.50	26	19.44	15.00
$SC_2 s_1$	31	2.40	165	13.00	2630	15.20	34	12.92	12.04
$SC_3 s_1$	30	2.65	153	12.50	2115	13.20	61	11.32	12.40
$SC_1 s_2$	39	1.98	220	14.20	3580	12.50	41	19.70	15.21
$SC_2 s_2$	35	1.89	198	13.56	3120	15.20	60	18.52	13.97
$SC_3 s_2$	35	2.25	187	13.21	2602	13.30	96	15.56	13.36

V. CONCLUSIONS

This work investigated the strengthening of the punching shear region under concentric load, in contrast to most researches which deal with flat plates subjected to concentrated load. It also explored the effectiveness of maintaining and rehabilitating construction by using steel collars. This solution is considered useful and economical, especially for high-rise buildings, where it may enhance the punching shear resistance on the performance of concrete flat-plates. Many remarks concerning the augmentation of the flat plate bonding and the eccentric load influence can be made:

- The most useful way to strengthen the slabs, in both load types, was by utilizing a steel collar, especially when the latter's thickness increased, having led to efficiently extending the perimeter of the failure area so that the failure mechanism (punching shear) shifted away from the critical region.
- The failure of specimens using steel collar strengthening did not occur suddenly, it gave gradual warnings by increasing the crack width, thereby, increasing the perimeter of the failure zone, because the presence of the collar leads to increased shear strength.
- The tested specimens with eccentric load exhibited decreased ultimate load capacity due to the unbalanced moments.
- The cracks were positioned more to one side of the slabs due to the effect of eccentricity.
- The slabs are stiffer when steel collars are used, the value of stiffness in flat slabs with eccentricity is less than in specimens with concentric load.

REFERENCES

[1] N. Oukaili and L. Husain, "Punching Shear in Reinforced Concrete Flat Plates Under Eccentric Loads: Experimental Investigation," in *APFIS2017 - 6th Asia-Pacific Conference on FRP in Structures*, Singapore, Jul. 2017.

[2] E.-S. I. M. Ismail, "Non-linear finite element analysis of reinforced concrete flat plates with opening adjacent to column under eccentric punching loads," *HBRC Journal*, vol. 14, no. 3, pp. 438–449, Dec. 2018, https://doi.org/10.1016/j.hbrcj.2018.01.001.

[3] A. A. Abdulhussein and M. H. Al-Sherrawi, "Experimental and Numerical Analysis of the Punching Shear Resistance Strengthening of Concrete Flat Plates by Steel Collars," *Engineering, Technology & Applied Science Research*, vol. 11, no. 6, pp. 7853–7860, Dec. 2021, https://doi.org/10.48084/etasr.4497.

[4] H. S. Askar, "Usage of prestressed vertical bolts for retrofitting flat slabs damaged due to punching shear," *Alexandria Engineering Journal*, vol. 54, no. 3, pp. 509–518, Sep. 2015, https://doi.org/10.1016/j.aej.2015.05.013.

[5] H. R. Taresh, M. Y. M. Yatim, and M. R. Azmi, "Punching shear behaviour of interior slab-column connections strengthened by steel angle plates," *Engineering Structures*, vol. 238, Jul. 2021, Art. no. 112246, https://doi.org/10.1016/j.engstruct.2021.112246.

[6] M. Zahid and S. Al-Zaidee, "Validated Finite Element Modeling of Lightweight Concrete Floors Stiffened and Strengthened with FRP,"

Engineering, Technology & Applied Science Research, vol. 13, no. 4, pp. 11387–11392, Aug. 2023, https://doi.org/10.48084/etasr.6055.

[7] D. Vargas, E. O. L. Lantsoght, and A. S. Genikomsou, "Flat Slabs in Eccentric Punching Shear: Experimental Database and Code Analysis," *Buildings*, vol. 12, no. 12, Dec. 2022, Art. no. 2092, https://doi.org/10.3390/buildings12122092.

[8] A. A. Abdulhussein and M. H. Al-Sherrawi, "Experimental study on strengthening punching shear in concrete flat plates by steel collars," *AIP Conference Proceedings*, Mar. 2023, Art. no. 020026, https://doi.org/10.1063/5.0130802.

[9] H. A. Ali and M. H. Al-Sherrawi, "Steel Collar Strengthening of a Slab-Column Connection under Eccentric Load," *Engineering, Technology & Applied Science Research*, vol. 14, no. 3, pp. 14677–14684, Jun. 2024, https://doi.org/10.48084/etasr.7391.

[10] P. G. Fernández, A. Marí, and E. Oller, "Theoretical prediction of the punching shear strength of concrete flat slabs under in-plane tensile forces," *Engineering Structures*, vol. 229, Feb. 2021, Art. no. 111632¸https://doi.org/10.1016/j.engstruct.2020.111632.

[11] A. Hameed, H. Husain, and M. Al-Sherrawi, "Analysis of Corner Column-Slab Connections in Concrete Flat Plates," *East African Scholars Journal of Engineering and Computer Science*, vol. 2, no. 1, pp. 37–46, Jan. 2019.

[12] L. Secci, M. Lapi, E. Teoni, A. P. Ramos, and M. Orlando, "Eccentric punching strength of continuous flat slabs—Analysis of different experimental setups," *Structural Concrete*, vol. 22, no. 2, pp. 1183–1204, 2021, https://doi.org/10.1002/suco.202000267.

[13] H. A. A. Al-Katib, H. H. Alkhudery, and A. A. A. Al-Katib, "Flat Slab–Column Modeling Using Finite Element with Eccentric Loading Effects," *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, vol. 44, no. 2, pp. 513–521, Jun. 2020, https://doi.org/10.1007/s40996-019-00249-z.

[14] S. S. Kadhim and H. Ammash, "Steel Stiffeners for Enhancement of Slab-Column Connections," *Al-Qadisiyah Journal for Engineering Sciences*, vol. 12, no. 4, pp. 199–206, Dec. 2019, https://doi.org/10.30772/qjes.v12i4.621.

[15] ACI Committee 440, *State-of-the-art Report on Fiber Reinforced Plastic (FRP) Reinforcement for Concrete Structures: ACI 440R-96*. MI USA: ACI, 1996.

[16] N. K. A. Oukaili and H. D. Merie, "CFRP strengthening of bubbledecks with openings," in *9th International Conference on Fibre-Reinforced Polymer (FRP) Composites*, Paris, France, Jul. 2018, pp. 774–781.

[17] A. Torabian, B. Isufi, D. Mostofinejad, and A. P. Ramos, "Shear and flexural strengthening of deficient flat slabs with post-installed bolts and CFRP composites bonded through EBR and EBROG," *Structural Concrete*, vol. 22, no. 2, pp. 1147–1164, 2021, https://doi.org/10.1002/suco.202000236.

[18] N. K. Oukaili and H. D. Merie, "CFRP strengthening efficiency on enhancement punching shear resistance of RC bubbled slabs with openings," *Case Studies in Construction Materials*, vol. 15, Dec. 2021, Art. no. e00641, https://doi.org/10.1016/j.cscm.2021.e00641.

[19] ACI Comittee 318, *Building Code Requirements for Structural Concrete*. MI USA: ACI, 2019.

[20] *ASTM C39/C39-21, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. West-Conshohocken, PA, USA: ASTM International, 2021.

[21] *ASTM C496/C496M, Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. West-Conshohocken, PA, USA: ASTM International, 2017.

[22] *ASTM C78/C78M-21, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. West-Conshohocken, PA, USA: ASTM International, 2021.

[23] A. M. Abdel-Rahman, N. Z. Hassan, and A. M. Soliman, "Punching shear behavior of reinforced concrete slabs using steel fibers in the mix," *HBRC Journal*, vol. 14, no. 3, pp. 272–281, Dec. 2018, https://doi.org/10.1016/j.hbrcj.2016.11.001.

[24] M. I. Badawi, M. H. Makhlouf, G. Ismail, and A. H. A. Kreem, "Efficiency of (GFRP- Steel) Stirrups in Reinforcing the Punching of Slab-Column Connections subjected to Eccentric Load," *MSA Engineering Journal*, vol. 2, no. 2, pp. 566–595, Mar. 2023, https://doi.org/10.21608/msaeng.2023.291903.

[25] A. H. Jasim and H. K. Ammash, "Effect of using column capital on the punching shear strength of flat slab-edge column connection under eccentric loading," *Journal of Physics: Conference Series*, vol. 1895, no. 1, Feb. 2021, Art. no. 012060, https://doi.org/10.1088/1742-6596/1895/1/012060.

[26] M. M. Majeed and A. N. Abbas, "Punching Shear Strength Characteristics of Flat Plate Panels Reinforced with Shearhead Collars: Experimental Investigation," *Civil Engineering Journal*, vol. 5, no. 3, pp. 528–539, Mar. 2019, https://doi.org/10.28991/cej-2019-03091265.