SJESR: Vol. 2, No.4, 2024, 11-23

IRAQI Academic Scientific Journals

SAMARRA JOURNAL OF ENGINEERING SCIENCE AND RESEARCH

S.J.E.S.R

Rehabilitation and Improving of Punching Shear Strength of Flat Plates: A Review

Hanaa A. ALI [1*], Mohannad H. Al-Sherrawi [1]

1- Department of Civil Engineering, University of Baghdad, Iraq

Keywords

Slab- column connection, steel stiffener, steel collar, steel angle.

Corresponding Author

E-mail:
hanaa.ali2001d@coeng.uobaghdad.edu.iq

Abstract

At times, due to change in design, replace in the construction design, function and general mistakes, it led to heavier or additional loads. These reason caused a brittle failure known as a punching shear of flat plates may be occur under static or dynamics load. Many works have been carried the objectives of punching shear strength presence flat slabs and the behavior of repaired flat plates damaged due to punching shear. In addition to increase thickness of slab, increase dimension of column, there are many technics focuses on slab column connection strengthened with varies way such as carbon fiber reinforced polymer, steel stiffeners, steel angle and steel collar with a view to enhancement, the punching shear strength of flat slab appears. This paper shows comparison between the slabs strengthening with these ways.

1- Introduction:

The flat slab system content of uniform slab thicknesses supported directly on columns. Because of no beams attractive due to the advantages below shorter construction time, less cost of formwork, less total building height with more clear space and architectural design flexibility. While the disadvantage of flat slab systems is the punching failure risk at the region of slab-column connection because of the transfer of shear force and unbalanced moment, the define of punching shear is the local brittle failure occur at area of slab-column connection so as the column and a portion of the slab is pushed together through the slab. The vertical loads that acting on the slab and the moments transferred from the columns may create exaggerated shear stresses around the parameter of slab-column connection. The unbalanced moments occur naturally at edge of slab-column connections and corner. They may be occur at internal column connections with unequal vertical loads on adjacent spans, or at any connection due to combined vertical and lateral forces because of earthquake excitations or wind effects. as a rule, the most popular technique of strengthening and repairing for flat plates are the use of steel plates and steel bolts strengthening technique demonstrated that it is an useful way to improve the behavior of flat slab column connection in punching shear as it enhances the bearing capacity of such connections. Many papers deal with experimental studies on steel bolts many different type and as results, they have an acceptance effect on strengthening the bearing capacity against shear [1-6]. The way of the strengthening is mainly used when concrete structural element bearing capacity is not sufficient. The high cost of rebuilding deteriorated structures leads to strengthen these deficient buildings, to develop easy strengthening methods and economical ways. Selecting the better suitable strengthening method based on cause of deterioration [7, 8]. The compression region depth influences the punching shear strength of the flat slabs column connections. So that, the strengthening by fiber reinforced polymer (FRP) increases the tensile strength and the corresponding compression strength in the concrete increases the punching shear capacity [9]. The high strength concrete enhanced the load–deflection response directly, initial stiffness of the connections and punching shear capacity. These connections also evidenced fewer and narrower cracks compared to their counterparts cast with NSC. Increasing the moment-to-shear force ratio (M/V) for (normal and high strength concrete different compressive strength) connections evidenced significant punching shear stresses led to decreasing the strength and limits the deformation capacity with subsequent brittle punching shear failure [10-12]. Among the techniques of strengthening and repair flat slabs this paper illustrate the recent ways used and their properties, these properties help the designer to enhance the bearing capacity and punching strength with the same size of the construction member.

2- Design Punching Shear According to Structural Code Approaches

The main and important of three building codes (ACI 318M 2019, BS8110-97, Eurocode-2 2004) [13-15] for interior slab-column connections were reviewed in current part. The differences between these codes in calculated two-way shear stress were locations of critical perimeters, consideration of size effect and reinforcement ratio. The location of critical perimeter was (0.5d) in ACI code, (1.5d) in B.S and (2d) in Euro code as well as Both B.S and Euro code were considered the effects of column size and reinforcing ratio. The latest edition of (ACI 318-19) committee was considering the first effect while the ACI 318 previous versions did not considered this. The reinforcement ratio still out of accounting punching shear stress in ACI 318.

a. ACI 318M-19

Nominal strength for shear in structural parts designed as two-way class with and without reinforcement in shear sections can be determined by the following Equations:

$$vn = vc \quad (1)$$

$$vn = vc + vs \quad (2)$$

The rectangular perimeter around column resulted in a critical region for two-way members when they were without reinforcement of shear, it will be formed at d/2 as a length coming out of column interface Fig. 1.

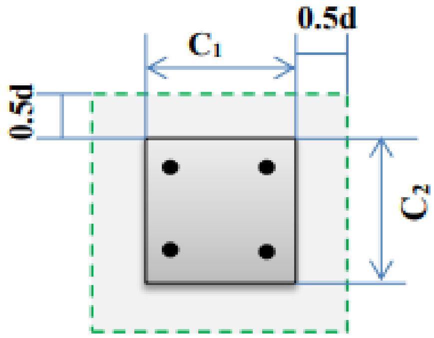


Fig. 1. Critical Slab Section without Shear Reinforcement for Punching Shear According to ACI Code.

Members had reinforcing rebar's for shear on critical section needed to examine at d/2 from front of column plus this crucial region must checking about d/2 coming out of the point where shear reinforcement was stopped which formed with polygon shape around column Fig. 2.

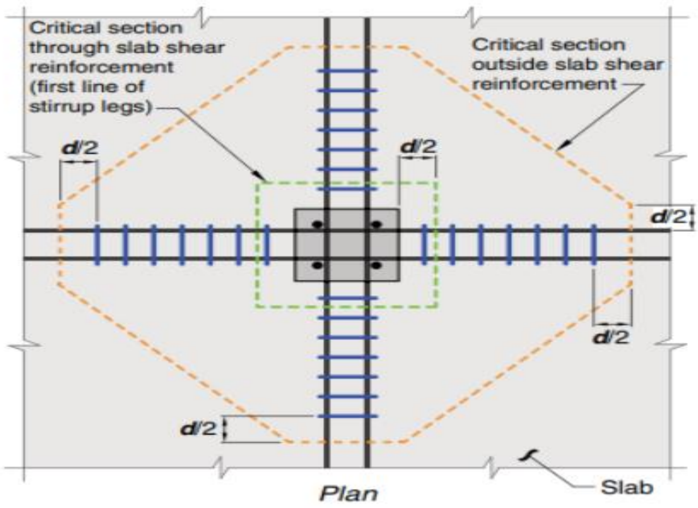


Fig.2. Critical Sections for Punching Shear in Slab with Shear Reinforcement According ACI Code.

To calculate v_c shear resistance in reinforced two-way concrete members without reinforcing rebars shear region used the minimum value of Equation (3) which illustrated below: -

$$v_c = \text{minimum of} \begin{cases} 0.33\lambda\lambda_s\sqrt{f_c'} \\ 0.17\left[1+\dfrac{2}{\beta_c}\right]\lambda\lambda_s\sqrt{f_c'} \\ 0.083\left[1+\dfrac{\alpha_s d}{b_0}\right]\lambda\lambda_s\sqrt{f_c'} \end{cases} \quad (3)$$

Where: -

λ: - 1 for concrete normal weight.

λ_s:- Modification factor for size effect $\sqrt{\frac{2}{1+0.004d}} \leq 1.0$

β_c: - Ratio resulted by dividing longest to the shortest column width

α_s: - Constant value classified according to column position within slab plate: for corner (20), for edge (30) and for interior (40).

b_o:- Length taken as perimeter for critical section=2(c1+c2+2d).

The structural members were designed by two-way concrete system with shear reinforcement (stirrups or headed studs), v_c for member reinforced with stirrups calculated by Equation (4) and for member reinforced with headed studs v_c needed to check at d/2 coming out of column interface used Equation (5) or at d/2 behind outer perimeter line of shear bolstering adopting the following Equation (6).

$$v_c)_{\text{stirrups}} = 0.17\lambda\lambda_s\sqrt{f_c'} \leq \phi 0.5\sqrt{f_c'} \quad (4)$$

$$v_c)_{\text{headed stud}} = \text{minimum of} \begin{cases} 0.25\lambda\lambda_s\sqrt{f_c'} \\ 0.17\left[1+\dfrac{2}{\beta_c}\right]\lambda\lambda_s\sqrt{f_c'} \leq \phi 0.66\sqrt{f_c'} \\ 0.083\left[1+\dfrac{\alpha_s d}{b_o}\right]\lambda\lambda_s\sqrt{f_c'} \end{cases} \quad (5)$$

$$v_c)_{\text{neadedstud}} = 0.17\lambda\lambda_s\sqrt{f_c'} \leq \phi 0.66\sqrt{f_c'} \quad (6)$$

Where: -

ϕ represents decreasing factor equal 0.75. The shear resistance for stirrups and headed stud vs ($v_s = \frac{A_v f_{yt}}{b_0 s}$).

A_v represents steel area of stirrup legs or shear stud, while symbol s considers the spacing reinforcing steel stirrups.

b. B.S. 8110-97

This standard codes identifies the shear strength v by nominal design value that can be calculated using the Equation (7) as follows:

$$v = \frac{V}{ud} \quad (7)$$

Where: -

V: Applied load.

u: Perimeter of critical concrete region that positioned at (1.5 d) outing of column outer face which equals = 2(6d+c1+c2), as shown in Fig.3` .

d: Effective depth.

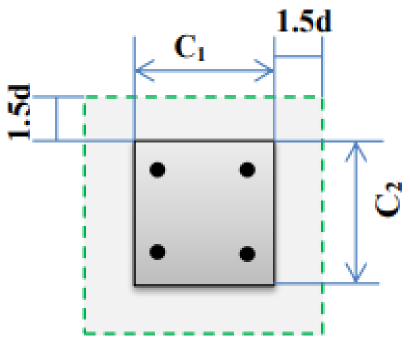


Fig. 3. Critical Section for Punching Shear in Slab without Shear Reinforcement According B.S. 8110-97.

The shear stress (v) checking at distance 1.5d coming out of the column outer side. If capacity shear in concrete (vc) Equation (8) greater than (v) no need shear reinforcement:

$$v_c = \left[0.79\sqrt[3]{\frac{f_{cu}}{25}}(100\rho)^{1/3}\left(\frac{400}{d}\right)^{1/4}\right]\left(\frac{1}{\gamma_m}\right) \quad (8)$$

fcu ≤ 40 MPa, 400/d ≥ 1, ρ is the ratio of flexural reinforcement which can be taken the value of 3% as maximum limit while γ_m represents the safety factor for material and can be taken as 1.25.

Accordingly, if design is integral with shear reinforcement, two limitations must be regarded at least on region, which had a punching shear failure. First is that reinforcement steel should be located at 0.5d from the loading line, and required reinforcement area should be provided within the failure zone, that must be at less 40% of estimated area. This is the second, and all details are included in Fig. 4.

There is another limitation about spacing of reinforcement perimeter, it must not exceed 0.75 of diameter rebar while shear reinforcement spaced around any perimeter within a distance not greater than 1.5 of diameter. Then shear stress must be checking for successive perimeters at intervals limits by 0.75d until the perimeter reached a case which does not need reinforcing the shear.

The shear reinforcements calculated from the Equation (9) below:

$$\sum A_{sy}\sin\alpha \geq \frac{(v-v_c)ud}{0.95f_{yw}}$$
$$\sum A_{sy}\sin\alpha \geq \frac{5(0.7v-v_c)ud}{0.95f_{yv}} \quad (9)$$
$$\sum A_{sy}\sin\alpha \geq \frac{0.4ud}{0.95f_{yw}}$$

Where:

f_{yv}: is the specific resistance of shear reinforcement (N/mm^2)

Σ A_{sv}: is a shear reinforcing area (in mm^2).

α: is a measured angle between slab plane and shear bolstering.

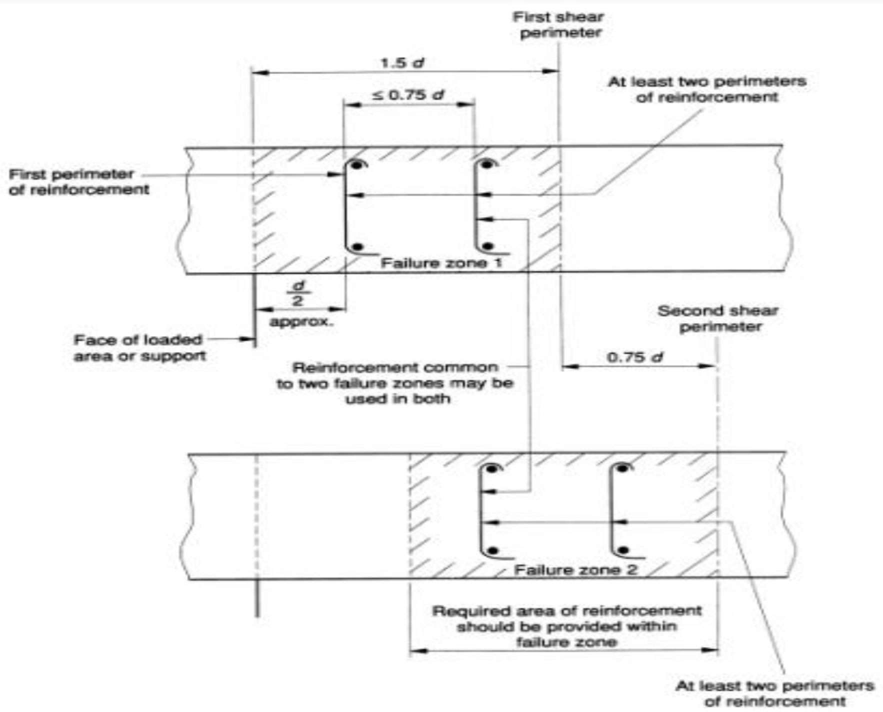


Fig. 4. Zones for Punching Shear Reinforcement According to B.S. 8110-97.

c. Eurocode2 (2004)

The design shear stress (V_{Ed}) calculated as following:

$$v_{ED} = \frac{V_{ED}}{u_1 d} \qquad (10)$$

Where: -

V_{ED} : Applied shear force

u_1: A critical perimeter positioned at (2d) from column face (Fig.5.`) which equals = 2(c1+c2+2πr)

d: Effective depth

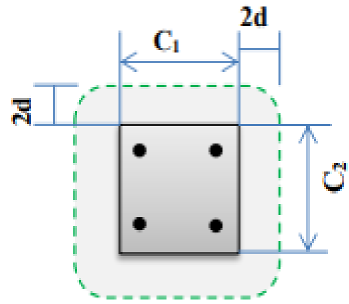


Fig. 5. Control Perimeters around Loaded Areas According to Euro code 2.

The shear punching strength for this type of slabs without shear bolstering may be computed through the Equation below: -

$$v_{Rd.c} = 0.18K^3\sqrt{f_{ck}}\,(100\rho 1)^{1/3} \geq v_{min} \qquad (11)$$

Where: -

f_{ck}:- strength of concrete in MPa.

$\rho 1$:- $(\rho ly, \rho lz)^{\frac{1}{2}}$ ≤ 0.02, ρly, ρlz longitudinal tension reinforcement in each direction of slab which calculated in area equals the cross-section of column plus (3d) each side.(K= $1 + \sqrt{\frac{200}{d}} \leq 2$), and ($v_{min}$= 0.35$K^{2/3}\sqrt{f_{ck}}$).

Slabs having reinforcing in shear, the strength of punching shear for this type of slabs can obtain from the following formula:

$$v_{ED} = \frac{V_{ED}}{u_1 d} \qquad (12)$$

Where: -

A_{sw}: Area that resulted for one perimeter of reinforcing in shear column rounded (mm^2).

s_r: Radial spacing for perimeters of reinforcing in shear column (mm).

$f_{ywd,ef}$: Effective strength must be designed for reinforcing in shear related with punching failure, it is also the effective value which can be calculated in term of: $f_{ywd,ef}$ = 250 + 0.25 d ≤ f_{ywd} (MPa)

α: Concluded angle between shear reinforcement and plane of slab.

The outer perimeter for reinforcing in shear must be located at a length not exceed the value of *kd* which was recommended to take about 1.5 as explains in Fig.6.

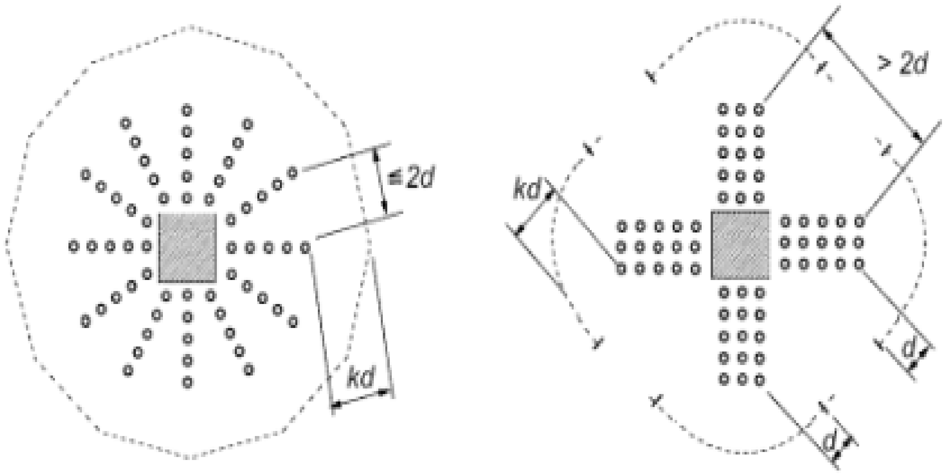


Fig. 6. Control Perimeter According to Euro code 2 for Slabs with Shear Reinforcement.

3- Review of Strengthening and Rehabilitating of flat plates

The system of strengthening is improved continuously since its appear in the 1970s the researchers beginning to performed tests to strengthening and retrofitted of column-slab connection by using different mechanisms and materials. Many solutions have been depended to solve punching-shear problems for connected region between column and slab, by increasing slab thickness, (by supplying a drop panel or column-capital or formed the column with high dimensions, using high concrete compressive grade or supplying more shear capacity by shear reinforcement like: shear studs, stirrups forms, shear bands or shear heads.

a. Strengthening by using steel stiffeners

The using of steel stiffeners is widely known nowadays as a mechanism to strengthen the flat slab to obtained a better structural behavior expressing by load-displacement relationships, failure mode and crack propagation. [16] investigated the influence of various numbers of steel stiffeners and their locations on the strength punching shear. This investigation consisted of two parts, steel plates dimensions were classified to three types according to slabs: (SS_3 300×300mm), (SS_2 200×200mm), and (SS_1 100×100mm), as shown in Fig.7` . SS1 slab had one stiffener placed at each side of column, SS2 have two stiffeners placed at each side of column and three stiffeners placed in SS3. Strengthening with steel stiffeners extended from the region of column to the slab represented column capital case, also numerical investigation studied the effects of column cross section and steel stiffeners size. The outcomes referred to impact of failure parameter around the column by increasing the number and size of the steel stiffeners, it was increased when increasing these parameters. The punching shear capacity increased when used circular columns instead of square column, as shown in Fig. 8. In addition, increasing the number of steel stiffeners widely improved the punching shear strength.

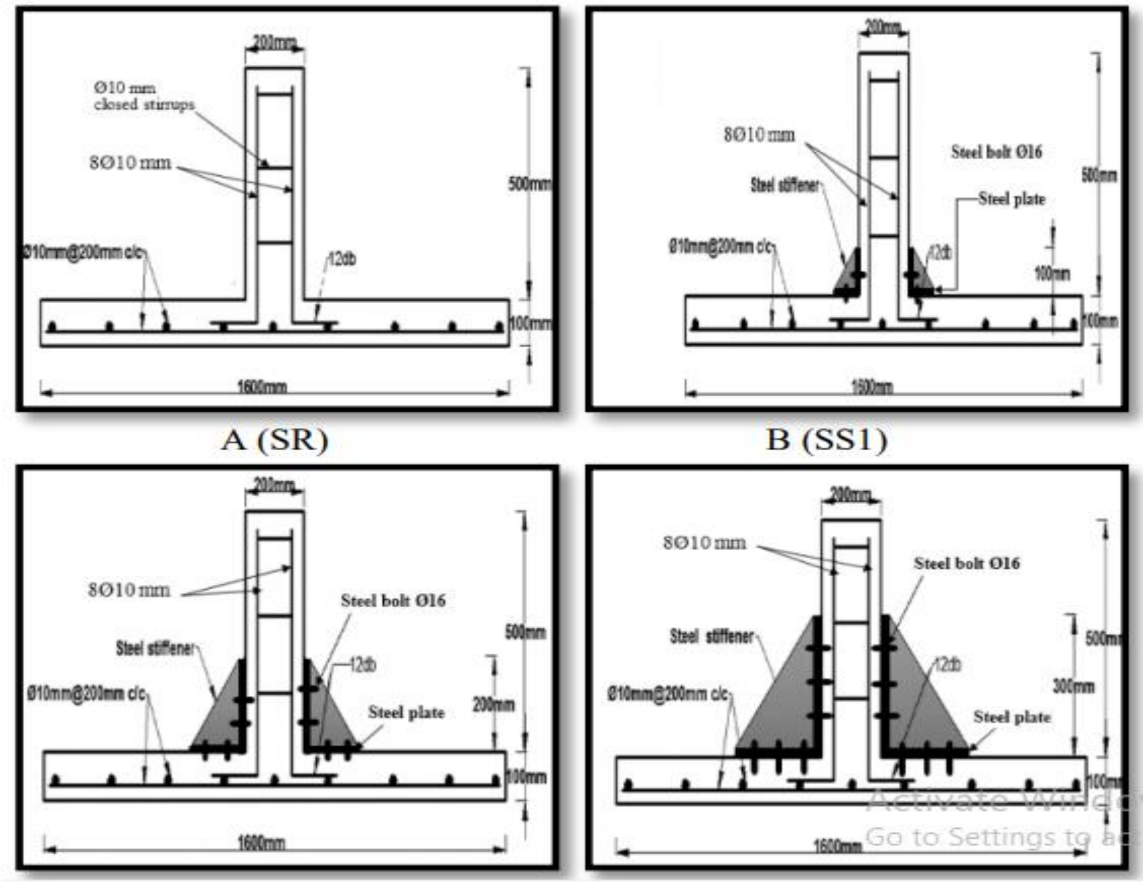
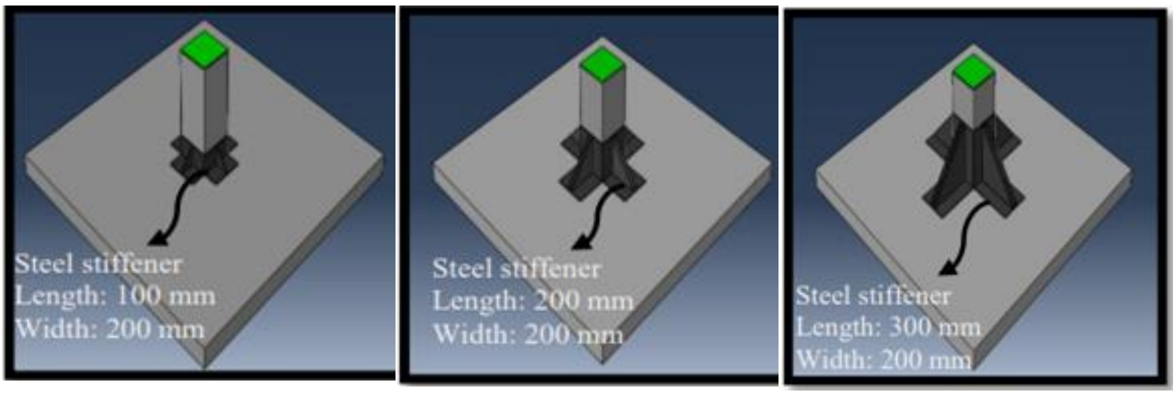


Fig. 7. Details of specimens [16].



a ***b*** ***C***

Fig. 8. The steel stiffeners the effect on column's shape (rectangular and circular) [16].

The investigation retrofitting feasibility of the damaged flat slabs due to punching utilizing steel stiffeners application by [17], as shown in Fig.9. Experimental work consisted of four flat plats with square shape, three of them were placed as steel plates include stiffeners, there was a parametric study concluded studying the influences of compressive strength and steel reinforcing percentage on the shear behavior or punching strength for column- slab connection.

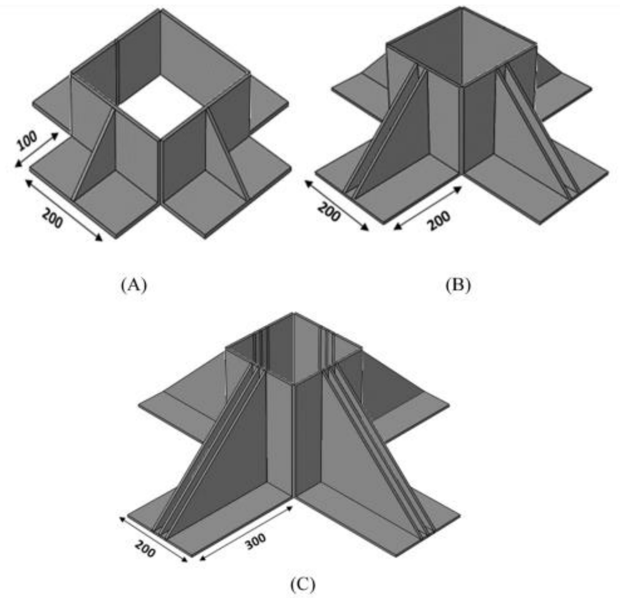


Fig. 9. steel stiffeners [17].

Conclusions of this work were increasing the failure perimeter of slab when increasing the number of steel stiffeners and its size (failure perimeter as they determine the crushed area around the column). The slabs repaired with steel stiffener were stiffer than these without strengthening expressed by load displacement curves. The punching shear strength and mode of failure and crack propagation also appear [17].

b. Strengthening by using FRP

The academic article presented by [18] dealt with studying six specimens of square slab column connection included a column located at the center, the goals of this paper was investigating the structural behaviour of punching shear for connected region between column and slab when strengthened the bonded region using fan shape of CFRP composite materials. Four specimens were performed, cast and tested with strengthening CFRP fan sections using without instillation them, one instilled by shear studs while reference specimen was without strengthening, reinforcement details was same for all slabs. The findings proved that strengthening technique enhanced the strength values of punching shear and the slab ductility compared with slabs without strengthening [18].

Salama, et. al [19] studied the effectiveness of the GFRP (glass fiber reinforcement polymer) stirrup extension and type on the punching strength of flat-plates. Four specimens were tested and exposed to both of vertical load and unbalanced moment. Fig. 10. illustrates the geometry of slabs and reinforcing profiles. Findings showed the importance of GFRP stirrups when using them as a reinforcement material located on the zone of punching-shear. They were obivesly enhancing structural performance of this type of slabs.

The parameters such as extension, amount, and type of shear reinforcing, have a clear effect on the deformation response and strength of shear-reinforced slabs. Increasing extension of GFRP stirrup from 1.75 times of the diameter (d) to 4.25 times of the diameter (d) resulted a significant improvement in punching strength and deformations up to the final failure of the stirrup, despite of utilized a spiral or closed GFRP reinforcing in shear zone. Composite GFRP stirrups provided adequate performance and strengthening to regulate distribution of vertical strain in the vertical stirrups legs.

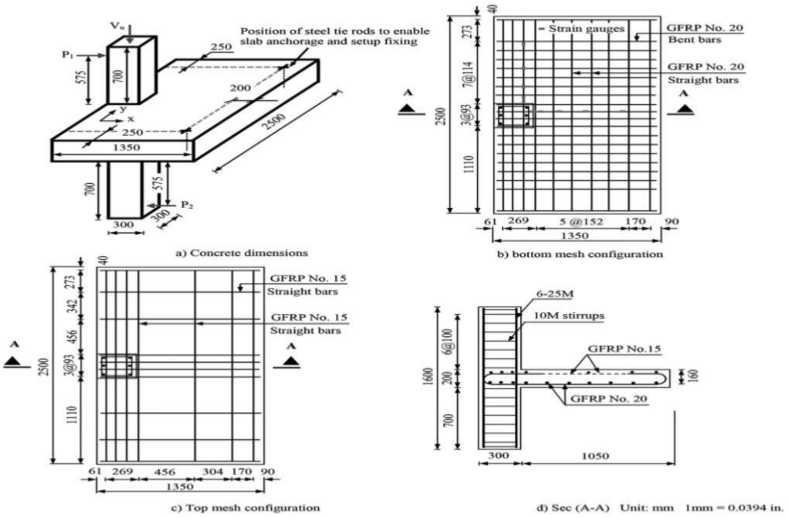


Fig. 10. The Typical Geometry of Slabs and Their Reinforcement [19].

The effect of fabricating an opening around the column area (vicinity) and the influence of bolstering using (CFRP) sheets on the punching shear resistance for reinforced concrete bubbled slabs were studied by [20]. Hence, 14 slab were casted and tested up to failure with dimension of (2000×2000×230 mm). The parameters of experimental program included: 1- position, geometry, and opening distance to the column; 2- position of bubbles vicinity related with critical two-way shear section; 3- augmenting punching resistance using CFRP sheets and its impact to the connection region between column and slab on behavior of bubbled slabs. Fig. 11 displays load deflection curves on centre slabs.

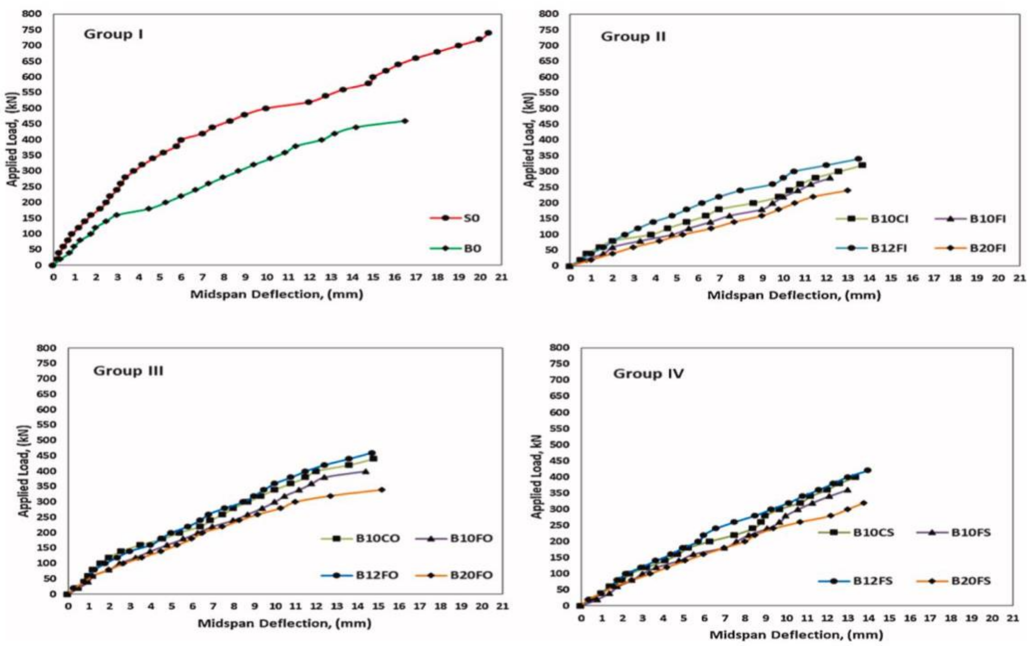


Fig. 11. Load Def. Of Center Slabs [20].

Upon test, it was observed that failure occurred when a crack width was started then quickly advanced on specimen surface exactly on compression sector. Cracks formed generally on the connected interfaced zone between which called slab-column connection regions caused by applied loading on column and penetrated into the depth of slab. Therefore, it is not recommended to design RC bubbled slabs near columns. For optimal structural integrity, the addition of a single layer of CFRP sheets to bubbled slab specimens with an aperture got a significant increment on shear resistance, compared with specimens of slabs without CFRP. As well as during the service load, the displacement of bubbled slabs increased and the post-cracking stiffness which increased in slabs with the CFRP strengthened bubbled compared to those without strengthening. Reduction capacity of shear in bubbled slabs due to absence of openings in vicinity loaded parts [20].

c. Strengthening by using plate angle

Taresh et al. [21] studied the behavior of interior slab-column connections strengthening with steel plates as angle and bolts (with high strength). These steel sections were placed on the extreme column surface using bolts. The shorter leg treated to column capital while longer one was placed in a mode of drop panel. The mechanism of enhancement had effectiveness converted the failure mode from punching shear to flexure failure included punching deformation exterior of strengthening zone, also enhanced the ultimate load, stiffness, deformation capacity and energy absorption.

d. Strengthening by steel collar

The punching shear strength slab-column connection strengthen with steel collars by Abdulhussein and Al-Sherrawi [22], 14 square reinforced concrete flat plates were subjected to concentrated load at the column that located in central of slabs. Parameters of the study were the thickness of steel collars, the legs length of steel collars, stiffeners in steel collars and the used partial pattern of steel angles with different length. The ultimate load of strengthened specimens with partial pattern decreased with respect to the strengthened specimen with collar pattern. The steel collars increase the perimeter of failure zone therefore the shear strength increases. The effectiveness of using steel collar on connected region between slab and column to convert the failure mode from punching to punching flexural. The strengthened slabs give enhancement in strain of reinforcement steel and concrete that led to more stiffness [22].

4- Conclusions

From previous works of deferent ways of strengthening slab-column connection like use steel stiffeners, steel collar, steel plate and FRP led to this conclusion.

1- A stiff behaviour of load deflection relationship at a circular column compared with specimens of square cross section. (the shape of the column is affected variables on the ultimate load capacity

2- The steel stiffeners strengthening slab-column connection were efficient in extending the perimeter of critical shear so that, the failure mechanism did not change just shifted away from the face of the column.
3- Increasing the number of CFRP strengthening fans from increased the shear capacity and doubling the area of CFRP from single string to double string with the same fans number not only enhances the punching shear capacity but also increases the ductility.
4- Strengthening with one layer of CFRP sheets resulted in an improvement of the shear capacity of the bubbled slab specimens with an opening compared with bubble slab (with opening) without strengthening.
5- The strengthening with steel angles has indeed changed the mode of failure from a pure punching shear to flexure-induced punching.
6- When strengthening slab-column with steel collar the collapse did not appear suddenly but it gave warning by the increased width and number of cracks.

References

1- Fernández, P. G., Marí, A., & Oller, E. (2021). Theoretical prediction of the punching shear strength of concrete flat slabs under in-plane tensile forces. Engineering Structures, 229, 111632. https://doi.org/10.1016/j.engstruct.2020.111632.
2- Jia, Y., & Luin, J. C. C. (2023). Finite element analysis of reinforced concrete slab-rectangular column connections using ABAQUS. In Advances in Frontier Research on Engineering Structures (pp. 33-44). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-19-8657-4_4.
3- Abdel-Rahman, A. M., Hassan, N. Z., & Soliman, A. M. (2018). Punching shear behavior of reinforced concrete slabs using steel fibers in the mix. HBRC journal, 14(3), 272-281. https://doi.org/10.1016/j.hbrcj.2016.11.001.
4- Majeed, M. M., & Abbas, A. N. (2019). Punching shear strength characteristics of flat plate panels reinforced with shear-head collars: Experimental investigation. Civil Engineering Journal, 5(3), 528-539. http://dx.doi.org/10.28991/cej-2019-03091265.
5- Ali, H. A., & Al-Sherrawi, M. H. (2024). Steel Collar Strengthening of a Slab-Column Connection under Eccentric Load. Engineering, Technology & Applied Science Research, 14(3), 14677-14684. https://doi.org/10.48084/etasr.7391.
6- Ngab, A. S., & Shahin, M. S. A (2021) Simple Equation for Predicting the Punching Shear Capacity of Normal and High Strength Concrete Flat Plates.
7- Jaafer, A. A., AL-Shadidi, R., & Kareem, S. L. (2019). Enhancing the Punching Load Capacity of Reinforced Concrete Slabs Using an External Epoxy-Steel Wire Mesh Composite. Fibers, 7(8), 68. https://doi.org/10.3390/fib7080068.
8- El-Kashif, K. F., Ahmed, E. A., & Salem, H. M. (2019). Experimental investigation of strengthening slab-column connections with CFRP fan. Ain Shams Engineering Journal, 10(3), 639-650. https://doi.org/10.1016/j.asej.2019.02.005.
9- Askar, H. S. (2015). Usage of prestressed vertical bolts for retrofitting flat slabs damaged due to punching shear. Alexandria Engineering Journal, 54(3), 509-518. https://doi.org/10.1016/j.aej.2015.05.013.

10- Abdulrahman, B. Q., & Aziz, O. Q. (2021). Strengthening RC flat slab-column connections with FRP composites: A review and comparative study. Journal of King Saud University-Engineering Sciences, 33(7), 471-481. https://doi.org/10.1016/j.jksues.2020.07.005.
11- Salama, A. E. (2019). Punching Shear Behavior of GFRP-RC Edge Slab Column Connections with and without Shear Stirrups Reinforcement (Doctoral dissertation, PhD thesis, University of Sherbrooke, Sherbrooke, QC, Canada).
12- Lapi, M., Ramos, A. P., & Orlando, M. (2019). Flat slab strengthening techniques against punching-shear. Engineering Structures, 180, 160-180. https://doi.org/10.1016/j.engstruct.2018.11.033.
13- ACI Committee. (2019). "Building code requirements for structural concrete" (ACI 318-19) and commentary. American Concrete Institute.
14- Euro code 2, Design of Concrete structures —Part 1-1, General Rules and Rules for Buildings, EN1992.
15- BS 8110 Standard, Structural Use of Concrete: Code of Practice for Design and Construction, Part 1, BS 8110. British Standard Institution, UK, 1997
16- Kadhim, S. S., & Ammash, H. K. (2019). Steel stiffeners for enhancement of slab-column connections. Al-Qadisiyah Journal for Engineering Sciences, 12(4), 199-206. https://doi.org/10.1016/j.engstruct.2018.11.033.
17- Ammash, H. K., Kadhim, S. S., & Dhahir, M. K. (2022). Repairing half-loaded flat slabs against punching shear using steel stiffeners. Case Studies in Construction Materials, 16, e01032. https://doi.org/10.1016/j.cscm.2022.e01032.
18- El-Kashif, K. F., Ahmed, E. A., & Salem, H. M. (2019). Experimental investigation of strengthening slab-column connections with CFRP fan. Ain Shams Engineering Journal, 10(3), 639-650. https://doi.org/10.1016/j.asej.2019.02.005.
19- Salama, A. E., Hassan, M., & Benmokrane, B. (2019). Effectiveness of Glass Fiber-Reinforced Polymer Stirrups as Shear Reinforcement in Glass Fiber-Reinforced Polymer-Reinforced Concrete Edge Slab-Column Connections. ACI Structural Journal, 116(5).
20- Oukaili, N. K., & Merie, H. D. (2021). CFRP strengthening efficiency on enhancement punching shear resistance of RC bubbled slabs with openings. Case Studies in Construction Materials, 15, e00641. https://doi.org/10.1016/j.cscm.2021.e00641.
21- Taresh, H. R., Yatim, M. Y. M., & Azmi, M. R. (2021). Punching shear behaviour of interior slab-column connections strengthened by steel angle plates. Engineering Structures, 238, 112246. https://doi.org/10.1016/j.engstruct.2021.112246.
22- Abdulhussein, A. A., & Al-Sherrawi, M. H. (2021). Experimental and Numerical Analysis of the Punching Shear Resistance Strengthening of Concrete Flat Plates by Steel Collars. Engineering, Technology & Applied Science Research, 11(6), 7853-7860. https://doi.org/10.48084/etasr.4497.