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RESEARCH ARTICLE

Efficiency of shear studs manufactured from threaded bars on the punching behavior of flat slabs

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Abstract

Punching resistance in flat slab systems in reinforced concrete structures is often provided with drop panels or shear reinforcement around columns. Shear studs are effectively used in these structures as shear reinforcement. However, factory-made shear studs may not be available in all locations and small quantities for small projects. Therefore, cheap shear studs that can be manufactured from widely available materials in small quantities can be very useful in certain cases. In this study, shear studs manufactured from threaded bars, widely available in hardware stores, are used for providing punching resistance to flat slabs. Stud heads were formed with T-section nuts. Four slab specimens, two with shear studs and two without, were cast and tested under concentrated loads at their mid-point. The slabs had 2150×2150×150 mm dimensions and they were cast with two different longitudinal reinforcement ratios. Test results showed that manufactured shear studs significantly increased the load and deformation capacities of the slabs. Slabs with shear studs were able to show up to three times higher bending deformations and they were able to sustain up to 50% higher loads. The study has shown that these studs can be effectively used for punching strengthening purposes in flat plate systems or in other cases where punching resistance is needed.

1. Introduction

Slabs play an important role in the behavior of cast-in-place reinforced concrete structures [1]. Structures with flat slab systems have some advantages over beam-slab systems in terms of flexibility in architecture, ease of construction, and reduced structural mass. On the other hand, they may have some disadvantages regarding the flexibility of the structure under earthquake loads and susceptibility to punching shear around columns. As a remedy for punching shear in these structures, drop panels or shear reinforcement around columns are used in practice [2]. Punching shear reinforcement, either in the form of closed stirrups or headed shear studs, has been used effectively in these structures for the cases where drop panels were not preferred. Numerous studies were conducted in the literature and the efficiency of headed shear studs against punching failure has been experimentally shown [3-5]. Shear studs were also used for retrofitting and strengthening existing structures [6-9]. Although minimum standards for shear studs were defined in relevant design codes such as ACI 318-19 [10], there is no standard shear stud type and shape in the market and different commercial brands produce different kinds of shear studs under their trademark. Although these products

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were typically tested to show their efficiency and code compliance, they may not be available widely depending on the location or they may not be available in small volumes. Shear studs that can be produced from readily available materials on-site may be quite useful, especially when needed in small quantities in a small part of the structure, such as under footings of heavy machinery supported by a reinforced concrete slab. In this study, shear studs manufactured from widely available cold-formed threaded bars were tested to show their efficiency in the punching resistance of flat slabs. Studs were hand manufactured by cutting 6 mm diameter M6 threaded bars, which are commonly available in hardware stores, to the required length and screwing standard T-section nuts at both ends to form the stud heads for anchorage. Two slabs with different reinforcement ratios were cast using these studs, along with identical control specimens without shear studs. Slabs were tested under concentrated load at their mid-point. Results were compared and discussed.

2. Experimental program

Four slabs with 2150×2150x150 mm dimensions were cast for the experimental program. Slab specimens were grouped into two according to their longitudinal reinforcement ratio. Each group had a specimen with and without shear studs. Table 1 presents the names and details of the specimens. Slabs were reinforced with 8 mm diameter deformed bars at the top and bottom, equally spaced in both directions parallel to the slab edges. Bars were bent to form a U shape at the ends to provide sufficient anchorage. 25 mm clear cover was left at the top and bottom. Shear studs were manufactured by cutting 6 mm diameter threaded M6 bars into 150 mm length and placing two 19 mm diameter T-section nuts at both ends (Fig. 1). These studs were placed in three rows in both directions, centered at the center of the slab. Studs were spaced at 65 mm, approximately half the length of the effective depth of the slab, in the direction parallel to the edges. Additional 8 mm diameter bars were placed for mounting studs in the specimen. Details of the specimen reinforcement layout are given in Fig. 2 and a photo of the formwork prepared for specimens with shear studs is presented in Fig. 3.

All tests were performed with a special test setup that restricts the displacement of the slabs at the edges but allows free rotation. Slabs were supported at 20 points, five points at each edge, separated 400 mm from each other. Steel rods passed through the holes left in the specimens and connected them to the test setup. These support points had load cells attached, which were bolted on circular shafts that allowed free rotation. The load was applied at the center of the slab from the bottom by a manually operated hydraulic jack. A 200 mm diameter circular steel plate was placed at the loading point to distribute the load evenly. A load cell was placed between the jack head and the specimen to measure the applied force. Photos of the test setup and loading jack are presented in Fig. 4. In addition to the load cells, the test setup was also equipped with Resistive Linear Position Transducers (RLPT's) to measure displacements. All data were captured by a data acquisition system.

Table 1. Test specimens

Specimen	Longitudinal Reinforcement (Bar diameter/spacing)	Shear Studs
D150s0	Φ8/150 mm	Not present
D200s0	Φ8/200 mm	Not present
D150s_Stud	Φ8/150 mm	Present
D200s_Stud	Φ8/200 mm	Present

(a) (b)

Fig. 1. Shear studs: (a) A single shear stud; (b) T-section nuts

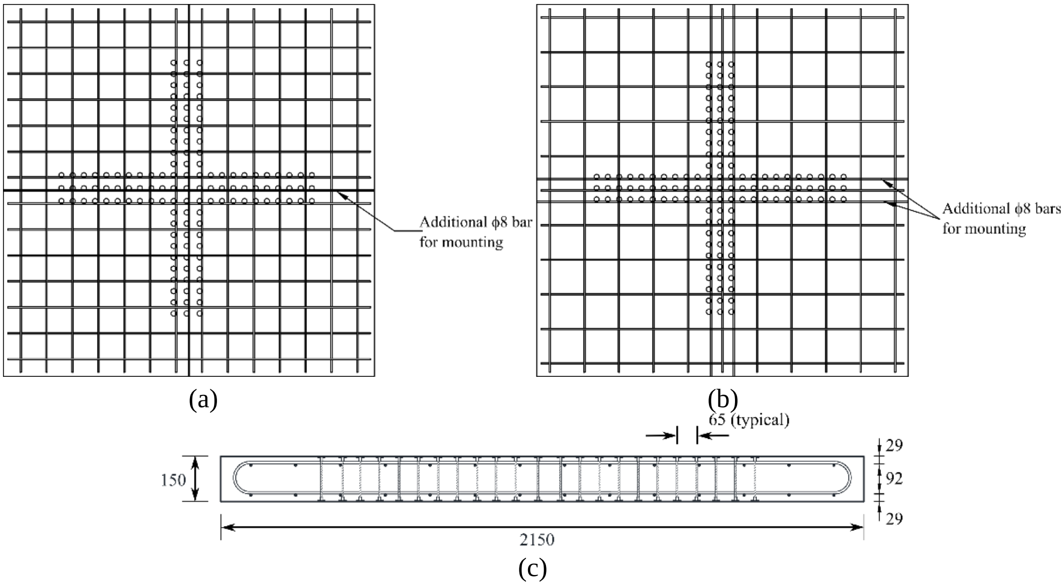


Fig. 2. Reinforcement layout for specimens with shear studs: (a) D150s_Stud; (b) D200s_Stud; (c) Typical slab cross-section. (All dimensions are in mm)

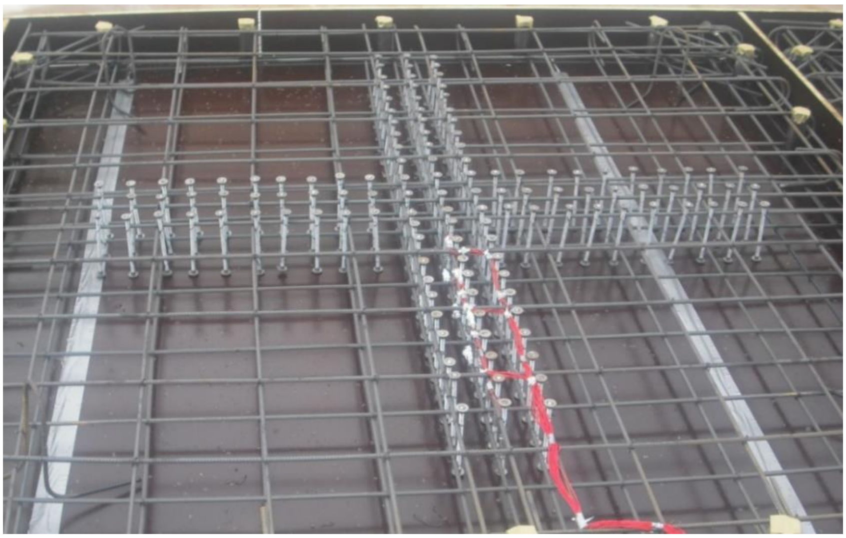


Fig. 3. Formwork for specimens with shear studs

(a)

(b)

Fig. 4. Test setup: (a) Test setup; (b) Hydraulic jack and load cell

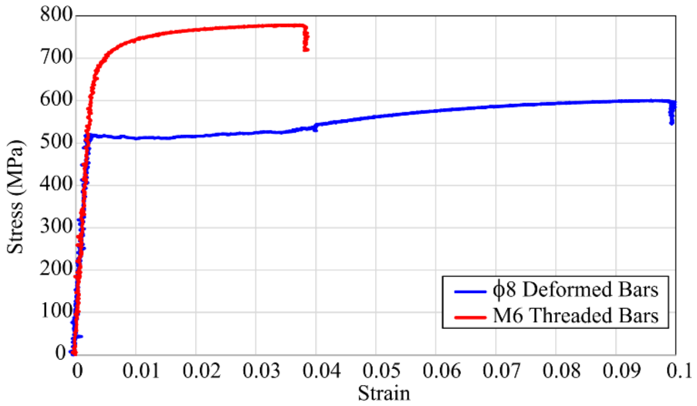


Fig. 5. Stress-stress curves for reinforcement

Table 2. Test specimens

Specimen	Peak Load (kN)	Displacement at Peak Load (mm)
D150s0	184	35
D200s0	161	43
D150s_Stud	250	109
D200s_Stud	241	118

The concrete used for the specimens was obtained from a local ready-mix concrete plant. Specimens with and without shear studs were cast separately. Standard 150 mm diameter 300 mm high cylinder samples were taken from concrete batches and tested around the day of slab tests to determine their compressive strengths. Average compressive strength of 27.1 MPa and 30.2 MPa were obtained for specimens with and without shear studs, respectively.

8 mm diameter deformed steel bars and 6 mm diameter threaded M6 bars were tested under tension according to ASTM A370-22 [11]. Stress-strain curves obtained from these tests are presented in Fig. 5. Note that M6 threaded bars were cold-formed bars, so they did not have a definite yield plateau as deformed bars had. Manufactured shear studs were also tested to confirm that the failure was due to the breaking of the rod, not the slippage of the nut at both ends. Tests confirmed this and studs failed under tension from the rods before the slippage of nuts.

3. Test results and discussions

Testing of D150s0 and D200s0 was conducted as a part of another study [12]. Load-midpoint displacement curves obtained from all tests are presented in Fig. 6. Peak loads and corresponding midpoint displacements measured in these tests are also summarized in Table 2.

As seen in Fig. 6, specimens with shear studs significantly improved the ultimate load capacity of the slabs. Studs increased the ultimate capacities of D150s0 by 36% and D200s0 by 50%. It also affected the ultimate displacement capacities of D150s0 by %211 and D200s0 by %174. All specimens showed flexural deformations first, followed by the formation of a punching cone developed around the loading point. A sudden drop in the load and hence the failure of the specimens came with punching. However, shear studs significantly affected the observed behavior, which can be seen on the final crack profiles of the specimens, as given in Fig. 7. As seen in this figure, diagonal flexural cracks in the specimens with no shear studs were less pronounced. These specimens were not able to develop significant flexural deformations before failure and a punching cone, evidenced by circular cracks around the loading point, developed at the early stages of loading. These punching cracks further widened under increased deformations, which finally failed the specimen. Specimen with a smaller longitudinal reinforcement ratio, D200s0, developed wider diagonal flexural cracks before failure since it had a smaller bending capacity. On the other hand, specimens with shear studs were able to sustain higher loads and deformations before failure. Diagonal flexural cracks were much wider in these specimens and circular cracks developed very close to the center point with a much smaller diameter compared to specimens without shear studs. In other words, shear studs successfully prevented the punching in these specimens and allowed the specimens to bend under flexure. Final punching failure developed in these specimens around a smaller punching surface, which was almost equal to the diameter of the loading plate. This suggests that the punching surface was almost perpendicular to the specimen surface, and it was only able to develop at a surface for which shear studs were ineffective since they were parallel.

Calculating the theoretical capacities of the specimens can help examine the observed behavior. Yield line theory can be used to calculate the flexural capacities of the slabs. This method depends on the estimation of a failure mechanism with compatible boundary conditions and computation of the ultimate load using the principle of virtual work. For a square slab simply supported at the edges, a failure mechanism consisting of yield lines extending from the center to the corners can be assumed (Fig. 8). For a virtual displacement δ at the center under load P, work done by internal and external forces are given in the left and right side of Eq. (1), respectively, where L is the length of one side of the square slab and m is the yielding moment of a unit strip. Note that these specimens had identical positive and negative moment capacities since they had identical reinforcement at the top and bottom. The ultimate load P_{flex} that causes a flexural failure depending on the ultimate moment capacity mu is given in Eq. (2).

$$4mL\frac{2\delta}{L} = P\delta \tag{1}$$

$$P_{flex} = 8m_u \tag{2}$$

To calculate m_u, a sectional analysis for the ultimate bending moment capacities of the slabs for a unit strip of 1000 mm was conducted according to ACI 318-19. For the ultimate concrete compressive strain, ε_{cu} = 0.003 was assumed. An equivalent rectangular stress block was assumed for concrete under compression, with a uniform compression stress of $0.85f_c'$ over a depth of the cross-section $\beta_1 c$, where f_c' is the compressive strength of concrete, c is the depth of neutral axis and β_1 is a factor defined in the code depending on f_c' The yield strength of longitudinal steel bars was taken as f_y = 512 MPa according to test results presented in Fig. 5. No strength reduction factors were used. Accordingly, ultimate moment capacities were calculated as m_u = 23.5 kNm/m for D150s0, and m_u = 17.5 kNm/m for D200s0. Substituting these values into Eq. 2 yields P_{flex} = 188 kN for D150s0, and P_{flex} = 140 kN for D200s0.

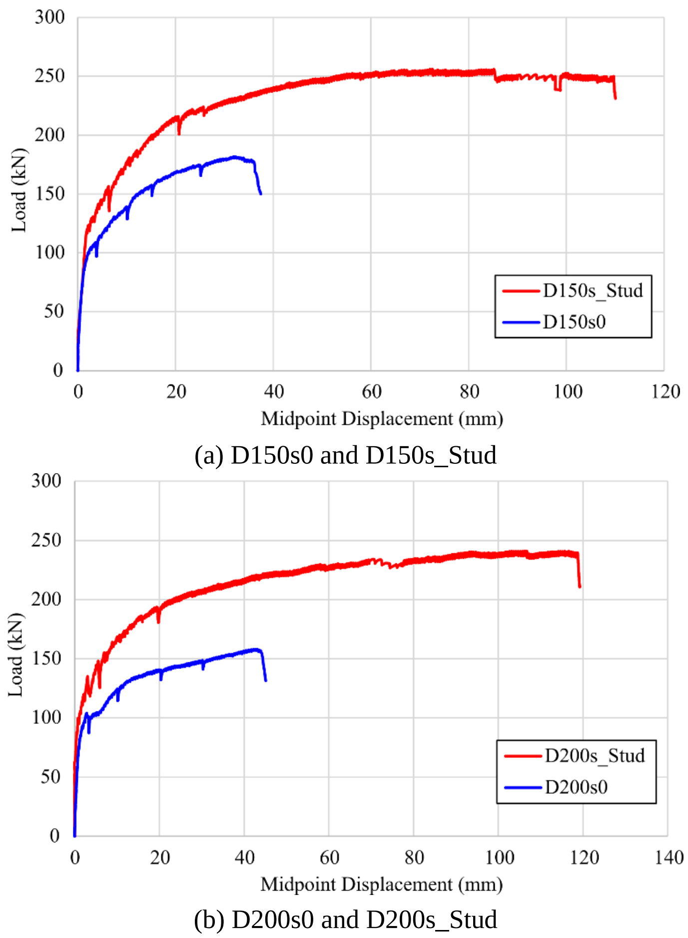
The punching capacities of the slabs can be calculated using ACI 318-19, which was selected since it also has provisions for shear studs. According to ACI 318-19, nominal punching strength V_n of slabs without shear studs can be calculated as the lowest value calculated from the series equations given in Eqs. (3a-c).

$$V_n = 0.33\lambda_s\lambda\sqrt{f_c'}b_0 d \tag{3a}$$

$$V_n = 0.17\left(1 + \frac{2}{\beta}\right)\lambda_s\lambda\sqrt{f_c'}b_0 d \tag{3b}$$

$$V_n = 0.083\left(2 + \frac{\alpha_s d}{b_0}\right)\lambda\sqrt{f_c'}b_0 d \tag{3c}$$

$$\lambda_s = \sqrt{\frac{2}{1 + 0.004d}} \leq 1.0 \tag{3d}$$



(a) D150s0 and D150s_Stud

(b) D200s0 and D200s_Stud

Fig. 6. Load-midpoint displacement curves obtained from tests

where d is the effective depth of the section, and b_0 is the critical section perimeter, defined as the perimeter $d/2$ away from the column face. λ is a factor to account for the weight of concrete, taken as 1.0 for normal-weight concrete. λ_s is a size effect factor as given in Eq. (3d). α_s is a location factor, given as 40 for interior columns, the case which reflects the testing conditions. β is defined as the ratio of the long to short sides of the column, which is taken as 1.0 since a circular loading plate was used in the tests. For these specimens, d is 121 mm and b_0 is calculated as the circumference of a circle $d/2$ away from the 200 mm diameter loading plate, which is $b_0 = 2\pi\,(100+121/2) = 1008$ mm. When V_n values were calculated from Eqs. (3a-c), the lowest V_n was calculated as 221 kN for specimens without shear studs from Eq. (3a).

ACI 318-19 requires that headed shear stud reinforcement shall conform to ASTM A1044 [13], which requires that the area of the head of headed shear stud reinforcement be at least 10 times the area of the bar used as a stud. For the shear studs manufactured from threaded bars in this study, the diameter of the T-section nuts used was 19 mm, which results in a 10 times larger area compared to 6 mm diameter M6 threaded bars. In addition, ACI 318-19 requires the overall height of the shear stud assembly to be at least the thickness of the slab minus the clear cover for the top longitudinal reinforcement, which is satisfied with the 150 mm long shear studs used in this study. Therefore, shear studs used conform with ACI 318-19, and provisions of this code can be used to calculate the nominal punching strength of slabs with shear studs. For specimens with shear studs, nominal punching strength V_n can be calculated using Eq.4 according to ACI 318-19.

$$V_n = V_c + V_s \tag{4}$$

where V_c is taken as the lowest value calculated from Eqs. (5a-c), and V_s is calculated according to Eq. (6).

$$V_n = 0.25\lambda_s\lambda\sqrt{f_c'}b_0 d \tag{5a}$$

$$V_n = 0.17\left(1 + \frac{0.33}{\beta}\right)\lambda_s\lambda\sqrt{f_c'}b_0 d \tag{5b}$$

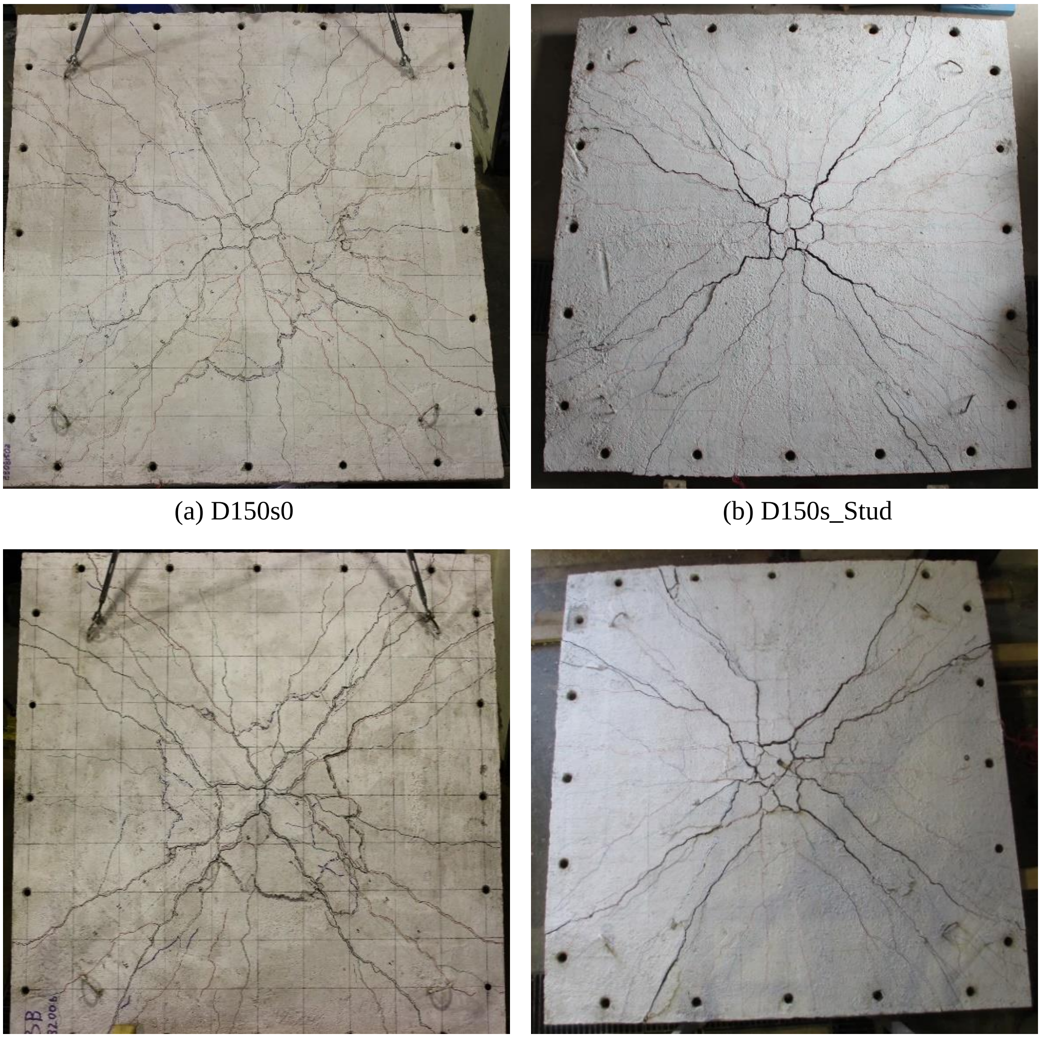
$$V_n = \left(0.17 + \frac{0.083\alpha_s d}{b_0}\right)\lambda_s\lambda\sqrt{f_c'}b_0 d \tag{5c}$$

$$V_s = \frac{A_v f_{yt}}{s}d \tag{6}$$

In Eq.6, A_v is the sum of the area of all legs of reinforcement on one peripheral line that is geometrically similar to the perimeter of the column section. Since there were 12 shear studs on the peripheral line with 6 mm diameter studs, A_v can be calculated as 12×28.3 = 340 mm^2. s is the spacing of the peripheral lines of shear reinforcement in the direction perpendicular to the column face, which was 65 mm for these slabs. f_{yt} is taken as 707 MPa, which was found from the intersection of the stress-strain curve of the threaded bars with a line drawn parallel to the elastic phase at a 0.002 strain offset. Substituting these values into Eqs. (4)-(6), the nominal punching strength of specimens with shear studs can be found as 606 kN. All these found results are summarized in Table 3 along with test results.

When test results and calculated capacities were examined, it can be seen that all specimens had higher punching strength than their flexural strength. Therefore, flexural failure could be expected from all specimens. D150s0 failed almost at its flexural capacity. Its failure load was also close to its punching capacity, which explains its smaller deformation capacity before failure. For this specimen, flexural and punching failure came almost at the same time. D200s0 failed at a value that is slightly higher than its flexural capacity. The punching and flexural capacities of these specimens were more apart from each other for this specimen, so it had a clearer flexural deformation, which was also visible from wider flexural cracks, compared to D150s0. Specimens with shear studs had much higher punching strengths. These specimens failed at loads higher than their flexural capacities but lower than their punching capacities. Shear studs indirectly contributed to the flexural strength of these specimens by delaying the formation of the punching cone and allowing the section to deform into the strain-hardening phase of the longitudinal steel bars which increased the ultimate flexural strength and deformation capacity. Wider diagonal flexural cracks observed in these specimens support this idea.

It has to be noted that punching formulae given in the code do not consider the reduced punching stress due to excessive bending deformations and cracking in this zone, since they were used for design purposes and excessive bending was prevented by other clauses in the code. Therefore, under these testing conditions of these specimens, punching strength is reduced under excessive deformations and final failure comes due to the punching, not bending. That is the reason for the sudden punching failure at the end for all specimens at a load that was significantly lower than their punching strengths.



(a) D150s0 (b) D150s_Stud

(c) D200s0 (d) D200s0_Stud

Fig. 7. Final crack profiles of specimens after tests

Table 3. Calculated capacities of specimens

Specimen	Flexural Strength (kN)	Shear Strength (kN)	Test Result (kN)
D150s0	188	221	184
D200s0	140	221	161
D150s_Stud	188	606	250
D200s_Stud	140	606	241

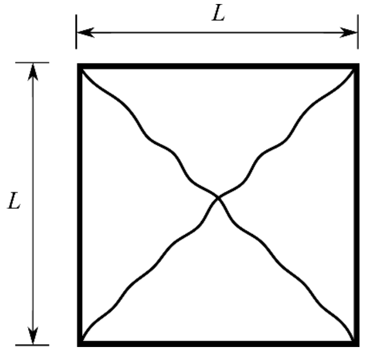


Fig. 8. Assumed yield line mechanism for the slabs

4. Conclusion

An experimental study involving the use of shear studs manufactured from widely available threaded bars was presented. Results of the tests revealed that these shear studs performed effectively in increasing the punching strength of reinforced concrete slabs. Slabs cast with shear studs had significantly higher load and deformation capacity compared to their twin cast without shear studs. Studs were effective in delaying the punching of the slabs and allowing higher flexural deformations in the slab. These shear studs were hand manufactured from widely available, cost-efficient, threaded bars and T-section nuts. Therefore, they can be used in small projects where commercial products are not available or costly to provide. On the other hand, their probable use for cases where moment transfer occurs between the column and slab needs to be investigated. In addition, the suitability of these studs for retrofitting purposes on existing structures needs further research. It also has to be noted that the test specimens used in this study had a constant number of identical shear studs (12 shear studs around the peripheral line). These studs can be optimized in number, diameter, and spacing for design purposes to provide sufficient punching strength to enable flexural behavior. This point also needs further investigation.

Conflict of interests

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Author contributions

Selçuk Saatcı: Conceptualization, Methodology, Validation, Resources, Writing-Original Draft, Writing-Review & Editing, Supervision, Project Administration, Funding Acquisition. Yonca Yaşayanlar: Formal Analysis, Investigation, Data Curation, Visualization.

Data availability statement

The data presented in this study are available upon request from the corresponding author.

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