A Study of Punching Shear Capacity of RC Flat Slab Strengthening by Vertical Bolts

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ABSTRACT

This study aims at improving the punching shear capacity of reinforced concrete flat slabs by using post-installed vertical bolts. The focus was made on the case that the compressive strength of concrete was lower than specified, which could represent poor construction that needs remediation. Three full-scale specimens were investigated, i.e. control and two strengthened specimens. One was strengthened by installing vertical bolts in the slab around the column, while the other was strengthened with a greater number of vertical bolts together with steel plates on the top and bottom of the slab. The specimens were loaded monotonically until failure. The results showed that the strengthened samples with vertical bolts had higher punching shear capacity. However, the predicted punching shear capacity considering typical shear reinforcement given by ACI318-19 was significantly underestimated. The addition of steel plates could not only improve the strength of the flat slab but also improve the confinement around the column and thus making it more ductile.

Keywords: Strengthening, Punching shear, Flat slab

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Introduction

To improve the punching shear capacity of flat slabs, researchers have been looking for solutions that are able to enhance shear capacity. Several factors contribute to the need of these enhancements, like design or construction errors, an increase in load, or deterioration of materials [1-4]. There are several techniques in literature: installing steel bars, steel rods, shear bolts, steel jacketing, increasing column size, and installing column capitals.

The early work on improving punching shear capacity by shear bolts was conducted by El-Salakawy et al. [5]. The results showed that shear bars or shear bolts substantially improved the punching shear strength and could also change the mode of failure from punching to flexure. Said et al. [6] studied the shear strengthening-technique for lightweight concrete using steel bars, GFRP rods, and high-strength steel bolts with steel plates. It was found that the punching shear capacity was improved significantly.

Anchorage of the shear rods or bolts played a significant role, in whether the force can be fully developed. Strengthening with a FRP fan was a novel technique, in which, the FRP was anchored at their ends on a slab like a fan to provide sufficient anchorage [7]. There were reports that studied the efficiency of using shear bolts to strengthen RC flat slabs [8-9]. Nuts and washers were used to provide anchorage to post-installed shear bolts at both ends. The arrangement of bolts in Cartesian and radial arrangement was also investigated. It was found that the shear bolts could improve both punching shear capacity and post-failure ductility. There was an attempt to use external steel plates with bolts in strengthening shear capacity [10]. It was observed that by having steel plates installed with bolts, it behaved as a composite section, in which the steel plates increased the flexural strength and in turn improved punching shear.

While most of the previous works focused on using normal or high-strength concrete, in this study, the strengthening of punching shear for flat slabs having comparatively low compressive strength was experimentally investigated. This is to represent the situation where the quality of concrete in some cases, is lower than the design value. The strengthening was made by using shear bolts with washers and nuts at both ends were used together with different patterns of steel bearing plate.

Testing Programs

1. Details of the flat slab specimen

The test specimens were designed to represent a typical form of the RC flat slab-column connection. The dimensions of the slab are 1500x1500x100 mm with the 200x200 mm column at the center as shown in Figure 1. The compressive strength of the concrete was 15 MPa (standard ASTM cylinders and tested at 28 days), representing low-quality concrete. The top and bottom reinforcements, grade SD40 with the yield strength of 420 MPa, were DB10 with a spacing of 100 mm and DB10 with a spacing of 200 mm, respectively.

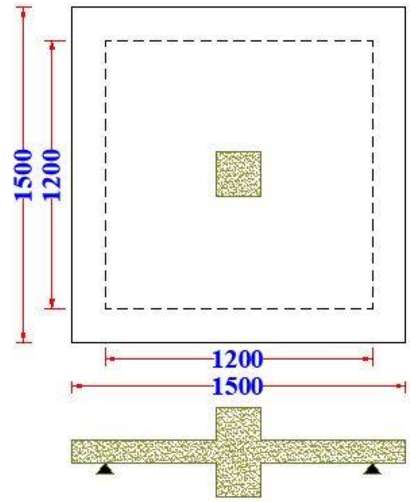


Figure 1 Controlled Specimen SP-0

2. Punching shear strengthening schemes

Specimen SP-1 and specimen SP-2 were strengthened with post-installed shear bolts having washers and nuts at both ends. The shear bolts are grade 8.8 steel bars (yield strength of 640 MPa) with a diameter of 12 mm as shown in Figure 2.

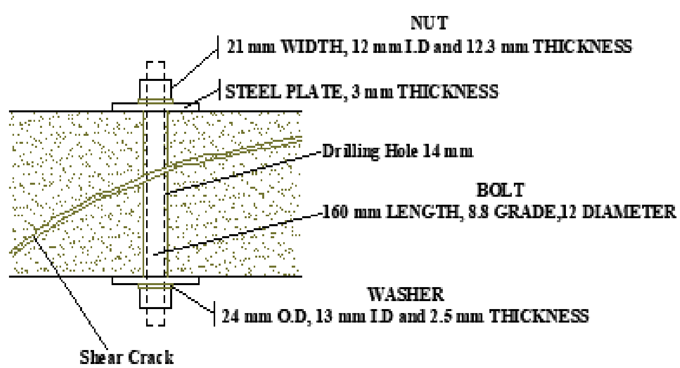


Figure 2 Post-installed Shear Bolt and Shear Crack

The arrangement of shear bolts for the specimen SP-1 was in a redial fashion having 12 groups of bolts around the column in a circular manner (Figure 3). To provide more anchorage to shear bolts and prevent concrete crushing at the end of bolts, steel plates of 60x132x3 mm were installed connecting each group of bolts.

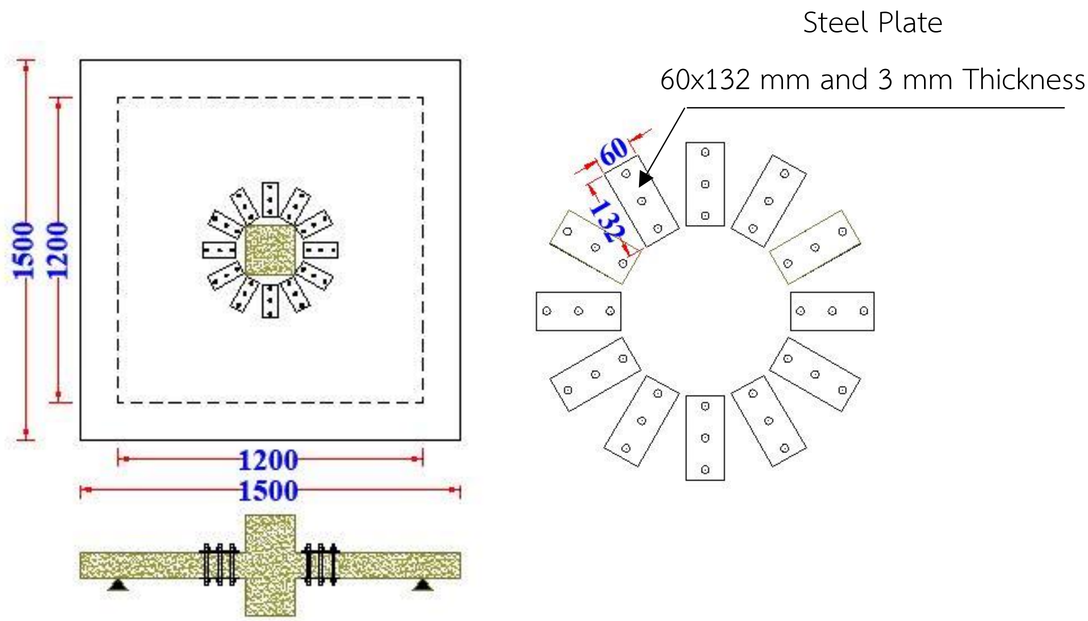


Figure 3 Strengthened Specimen SP-1

In the case of SP-2, bigger steel plates 580x580x3 mm shown in Figure 4 were used at the threaded ends as anchor plates for shear bolts. A total number of bolts was 68, almost double of the SP-1.

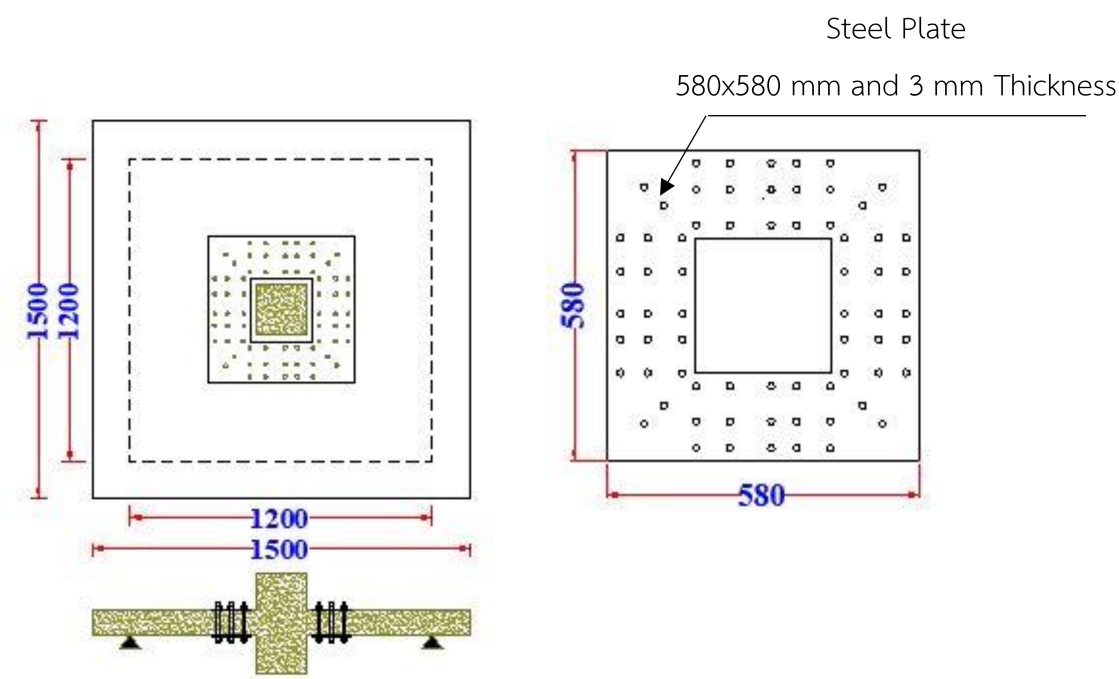
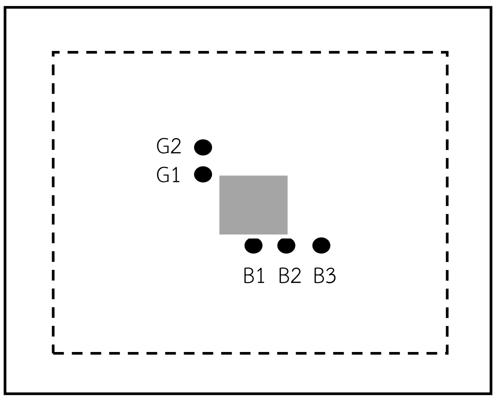


Figure 4 Strengthened Specimen SP-2

3. Instrumentations and test setup

The specimens were placed on a testing frame, supporting all four edges of the slab. The load was applied by hydraulic jack at the column, thus making the sample upside down. Load measurement was done by a load cell. Five displacement transducers were used to measure the slab deflection as shown in Figure 5. Strain gages of 5 mm gage length were attached along steel rebar at locations shown in Figure 6 to measure strain. The first gage was installed at the column face, while the next gage was installed at the distance d/2 from the column face. Data from all transducers and strain gages were simultaneously recorded by a data logger.



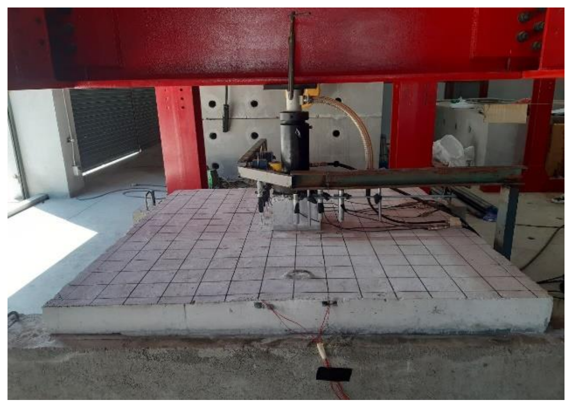


Figure 5 Positions of LVDT on Typical Specimen

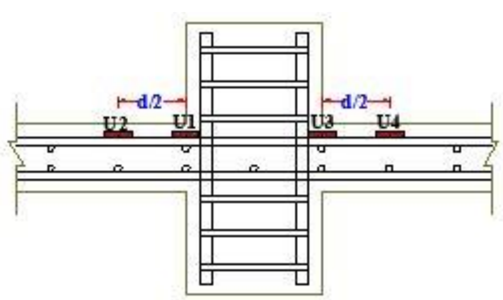


Figure 6 Positions of Strain Gauges on Steel rebars

Experimental results

1. Load carrying capacity

The load-deformation relations of the three specimens are shown in Figure 7. It can be observed that for the control specimen (SP-0), the stiffness of the slab decreased after the applied load reached 40 kN. It could carry a load up to 180 kN before failure, in which, distributed cracks were observed on the tension side of the slab and there was a crack around the column perimeter at the slab level (Figure 8). The strengthened sample SP-1 showed improved load capacity to 200 kN but with an initial crack at a lower load, which might be due to drill holes for the installation of shear bolts. The stiffness of the SP-1 was similar to that of the SP-0. It can also be observed that the sample SP-1 possessed higher deformation at maximum load.

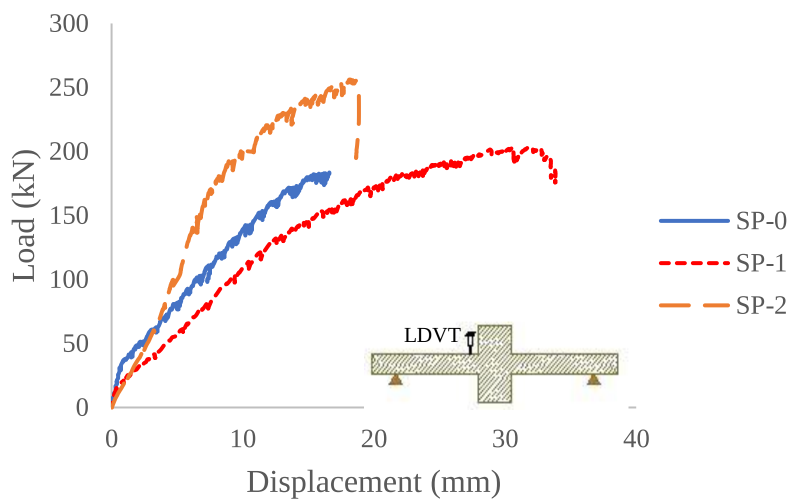
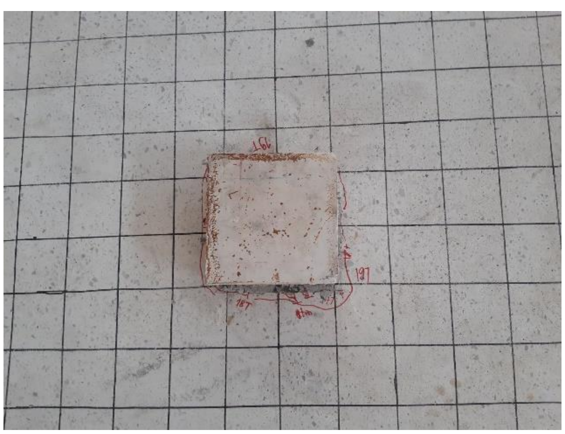
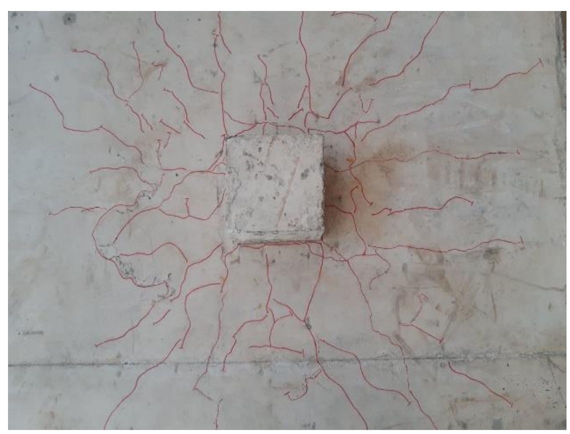


Figure 7 Load Displacement Relationships of Slab Specimens



a) Top view



b) Bottom view

Figure 8 Crack Pattern and failure mode of specimen SP-0

The sample SP-2 showed a similar reduction in initial stiffness. However, as the load increased, the stiffness of the specimen did not change and was comparatively higher than SP-0 and SP-1. The maximum load-carrying capacity increased up to 260 kN with comparable deformation with the controlled sample (SP-0). It was observed that the shear cracks appeared at the edge of the steel plate.

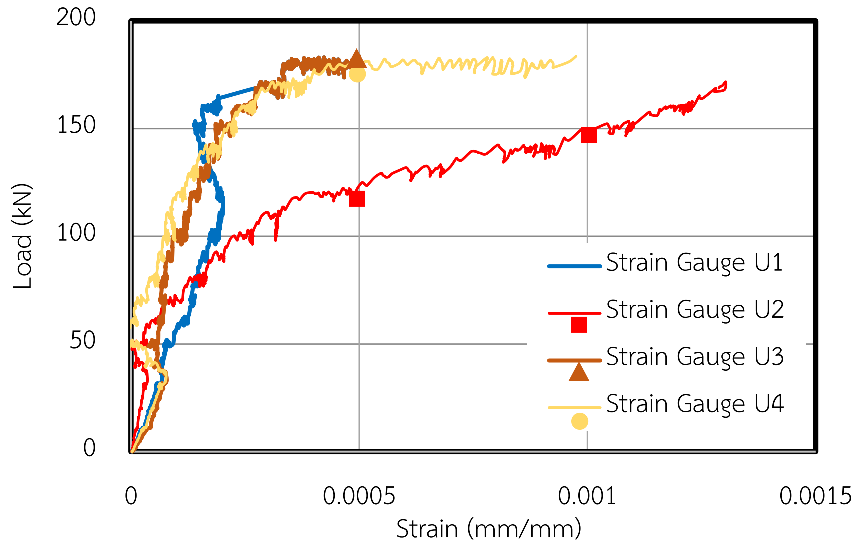


Figure 9 Load and longitudinal strain at the column faces (U1, U3) and at d/2 from the column faces (U2, U4) of the controlled specimen SP-0

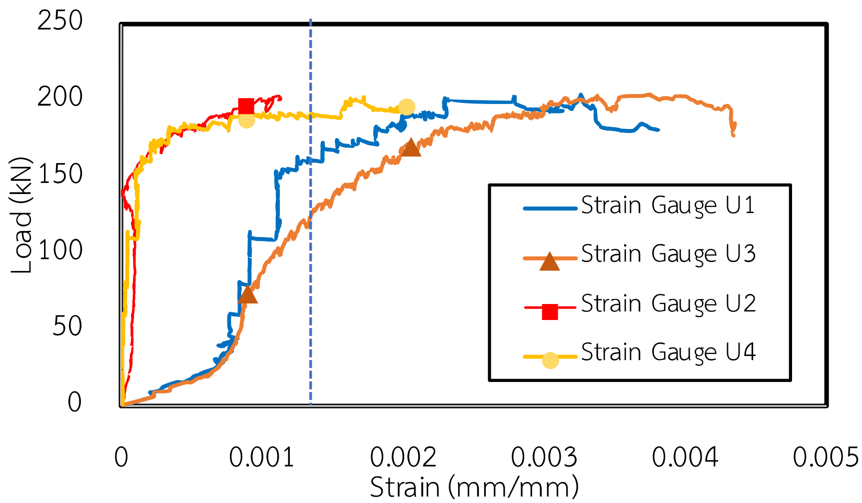


Figure 10 Load and longitudinal strain at the column faces (U1, U3) and at d/2 from the column faces (U2, U4) of strengthened specimen SP-1

The maximum load capacity of the samples is compared to the predictions by ACI code [11] and shown in Table 1. Although the prediction given by the ACI approach could reflect the gain in punching shear strength due to post-installation of shear studs, It was observed that the punching shear capacity of the reinforced concrete slab predicted by the ACI code was significantly underestimated. A similar observation was also reported by Elbakry et al. [10]. Additionally, the effects of steel plates have not yet been included in prediction.

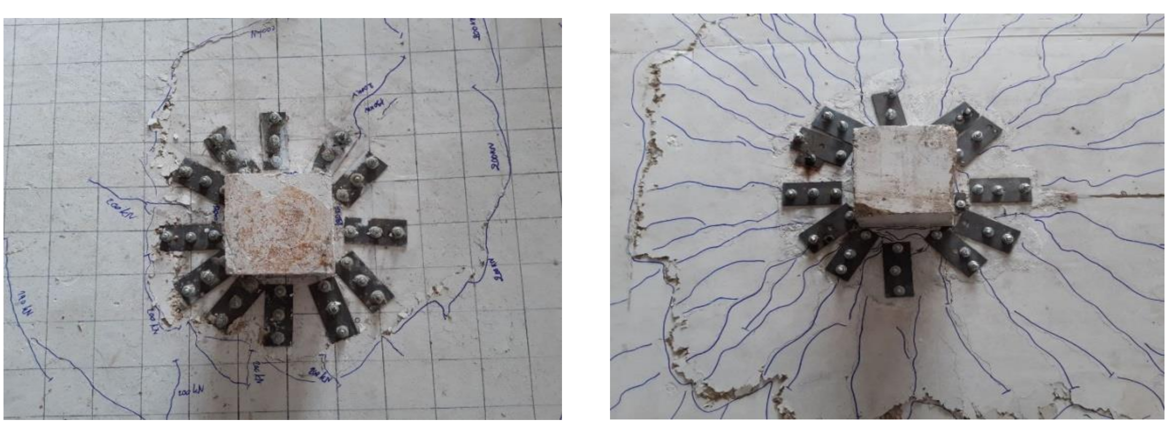
Table 1 Comparison of the experimental results with ACI318-19

Specimen	SP-0	SP-1	SP-2
P_{ACI} (kN)	75.6	97.8	141
P_{exp} (kN)	182	202	256
P_{ACI}/P_{exp}	0.41	0.48	0.55

2. Mode of failure

For the controlled specimen (SP-0), it was observed that the specimen failed under punching shear right at the column faces as shown in Figure 8. The strain in the longitudinal rebar is much lower than the yielding strain (0.002 mm/mm) when the slab failed at the ultimate load (Figure 9). This indicated that the specimen might fail under punching shear, as the cracks associated with the failure were right at the column perimeters.

In the case of the strengthened specimen (SP-1), the longitudinal rebars yield right at the column faces, as indicated by strain at U1 and U3 reaching yielding strain (Figure 10). The slab could carry additional load until the maximum load at 200 kN, showing improvement compared to the SP-0. This indicated the change in failure mechanism from the shear failure at the column edge to punching shear with a larger shear perimeter, thus, improving shear capacity as shown in Figure 11.



a) Top view b) Bottom view

Figure 11 Crack pattern and failure mode of specimen SP-1

For the specimen SP-2, in which steel plates were placed both above and below the slab connected by bolts, it was found that the longitudinal rebars yielded at the ultimate load (Figure 12). However, the specimen failed in shear, as the punching shear crack was observed around the perimeter of the steel plates as shown in Figure 13. The perimeter of the shear crack was larger than that of the specimen SP-1, resulting in higher shear capacity. As the concrete around the column was confined by steel plates and bolts, the integrity of the slab around the column at failure was improved.

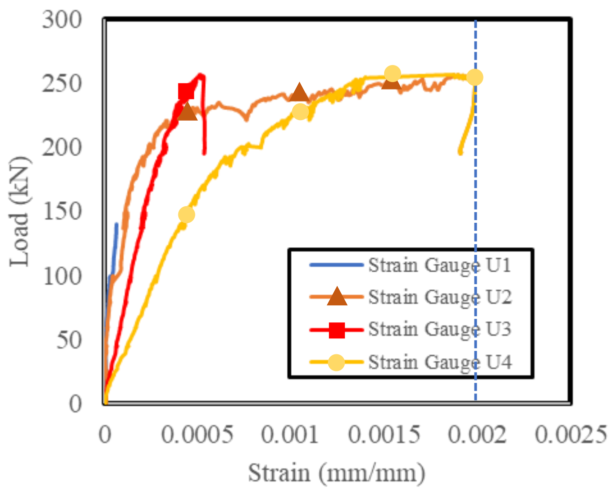
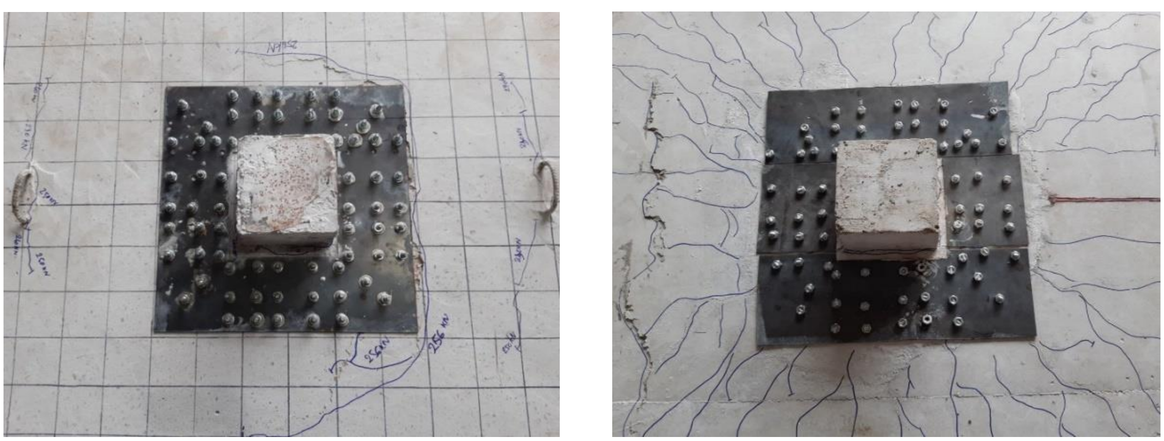


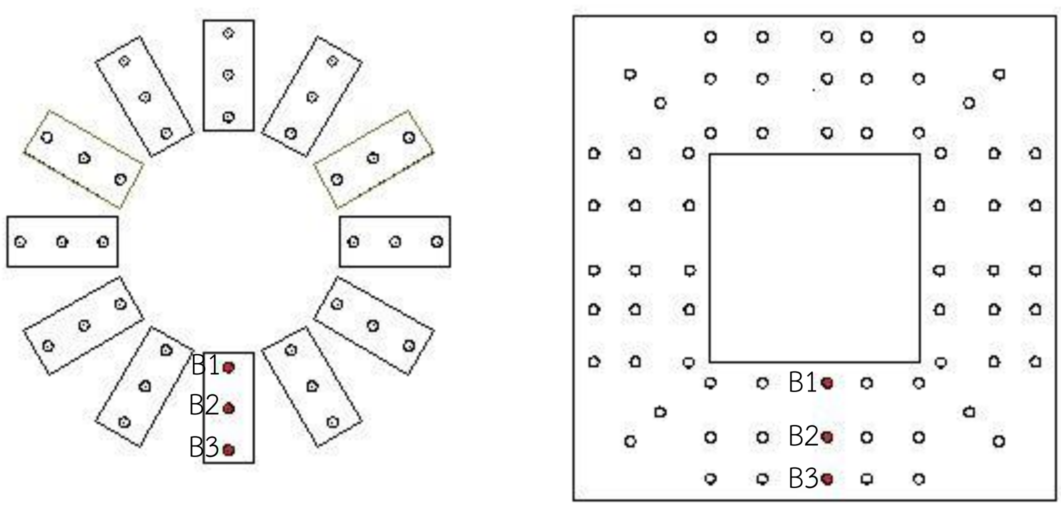
Figure 12 Load and Longitudinal Strain at the column faces (U1, U3) and at d/2 from the column faces (U2, U4) of the specimen SP-2



a) Top view b) Bottom view

Figure 13 Crack pattern and failure mode of specimen SP-2

Figure 14 Strain gage attached on shear bolts



a) SP-1 b) SP-2

Figure 15 Locations of strain gages on shear bolts

3. Strain in the Shear Bolts

Strain gages were also attached to the shear bolts as seen in Figure 14. The location of bolts with strain gages installed was depicted in Figure 15 for both SP-1 and SP-2. B1 represents the shear bolt closest to the column, while B3 for the furthest bolt. It could be observed from strains measured in shear bolts of the specimen SP-1 (Figure 16) that the shear bolt located closer to the column resisted more shear force the most. The shear force resisted by shear bolts reduced gradually as it was further away from the column. In the case of SP-2, the strain in shear bolts closest to the column was highest; similar to that of the SP-1 (Figure 17). However, the bolts in the second and third rows have significantly lower strain. This could be attributed to the confinement provided steel plate covering on the top and bottom of the slab. When the concrete was confined, the shear strength could be improved. Furthermore, as the steel plates on top and bottom of the slab were connected, it could also provide extra shear resistance.

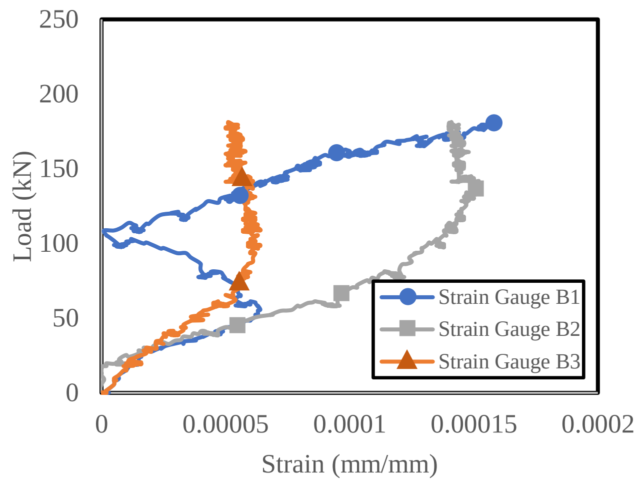


Figure 16 Load and Strain Relationship in Anchor Rods of Strengthened Specimen SP-1

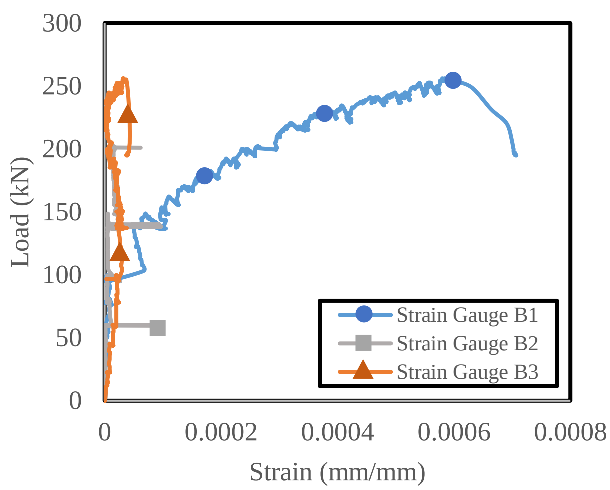


Figure 17 Load and Strain Relationship in Anchor Rods of Strengthened Specimen SP-2

Conclusions

This study showed the application of post-installation of shear bolts for strengthening punching shear for flat slabs, especially in the case of low compressive strength of concrete. The post-installation of the shear bolt for strengthening the flat slab against punching was experimentally investigated. The predictions of punching shear given by ACI318-19 were significantly underestimated compared to the experimental results. The installation of separated shear bolts (SP-1) could slightly improve the punching shear capacity of the flat slab specimen. With added steel plates (SP-2), which connect shear bolts together, the punching capacity of the flat slab was significantly improved. The added steel plates acted as a confining element to keep the concrete not spalling and play a significant role in improving the punching shear capacity as it confines concrete around the perimeter of the column.

Acknowledgment

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