Punching shear strength of flat slab strengthened with reinforced concrete column capital under bi-axial loading

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Abstract: The punching shear strength of reinforced concrete (RC) flat slab is the main concern in the structural behavior. This study presents a strengthening technique for improving punching shear resistance in RC two-way flat slabs using RC column capital. Two sizes of column capital were used (600x 600 and 800 x 800 mm), and the influence of column capital on the behaviours of two-way solid slabs under concentric and biaxial loading thus investigated. Six specimens were tested, with two slabs as reference specimens with concentric and biaxial loading, and four slabs with added column capital. The dimensions of the slabs were 1,600 x 1,600 x 100 mm, while the column dimensions were 200 x 200 mm. The eccentricity of the biaxially loaded slab was set to 150 mm in both directions. The results showed a considerable increase in punching shear capacity for flat slabs using column capital; further, as the column capital increased, the punching strength of the slab also increased.

Keywords: bi-axial load, column capital, flat slab, punching shear, strengthening.

1. Introduction
Reinforced concrete (RC) flat slabs are widely used due to their many benefits, including ease of working, reduced design loads, and cost-effectiveness. However, the sudden failure of a flat slab is a major problem for designers, as this may occur suddenly and without warning as a column punches the slab at the slab-column connection, which may cause the collapse of large parts of a building. The reason for such failure is the transmission of heavy shear loads and large moments through the column, and the sources of these large shear forces are numerous, including an increase in the number of floors due to a change in design or the weight of fresh concrete during construction. Unbalanced loads, unequal spans, creep, varying shrinkages, and wind can also generate unbalanced moments that causes brittle failure in slabs. Many methods have been used to avoid punching shear failure, including increasing the thickness of slabs, increasing the strength of concrete, or increasing flexural reinforcement and the use of the shear reinforcement. Sarsen and Hassan [1] and Johari and Amin [2] investigated the effects of increasing slab thickness on the punching shear behaviours, while Oukaili and Husain [3], Marzouk and Hussain [4], and Metwally et. al. [5] investigated the punching shear behaviours of flat slabs with high compressive concrete strength based on increasing slab thickness when subjected to concentric and eccentric loads. Ngo [6], Alwash and Habeeb [7], and Micael et al [8] experimentally investigated the punching shear strength of high compressive strength concrete with regard to strengthening flat slabs. Alam and Amanat [9], Elbakry and Allam [10], and Jang and Kang [11] tested specimens with high flexural reinforcement ratios to investigate the behaviours of slab-column connections with varying ratios of flexural reinforcement. Kruger et al [12] experimented with flat slab strengthening by using steel stirrups as shear reinforcement to study the behaviours of punching shear strength under eccentric loads. Jamal et al [13] studied the punching shear behaviours of flat slabs strengthened with single or
double steel shear heads under the effect of eccentric loads. Mauricio et al [14] investigated the effect of using shear studs as shear reinforcement in different arrangements and numbers on the punching shear behaviours of flat slabs. Abdelaziz et al [15] investigated the effect of strengthening flat slabs with different sizes of ultra-high strength concrete (UHSC) drop panels on punching shear behaviours when subjected to eccentric loads. Hassanzadeh and Sundqvist [16] investigated the effect of strengthening flat slabs with new shotcrete column heads, steel column heads, and new shear reinforcement insets on ultimate loads and deflections subjected to concentric loads. Lapi et al [17] discussed the effects of the enlargement of support by widening the column, casting a concrete capital, or post-installing a steel capital on the punching shear behaviours of flat slabs. This overview of the available literature suggests that the strengthening of flat slabs with reinforced concrete column capitals has had little previous attention, and few researchers have studied the effects of bi-axial loads on the punching shear behaviours of flat slab. This paper thus investigates the strengthening of two-way RC flat slabs with regard to punching shear strength by using RC column capital under concentric and bi-axial loads. The investigation of six flat slabs strengthened with RC column capital to enhance punching shear capacity is presented, and the effects of bi-axial loads on punching shear resistance with and without column capital thus presented. The effect of column capital size on punching shear strength of flat slabs was also investigated, and the technique was found to increase the performance of two-way slabs against punching.

2. Experimental Programme
The experimental programme began with the fabrication of six RC flat slabs. The dimensions for all slabs were 1,600 x 1,600 mm, with thicknesses of 100 mm. A column with dimensions 200 x 200 mm was located at the centre of each slab. A column cap was used at the top of each column to avoid crushing of the columns and to highlight the bi-axial loads. The column cap dimensions were 500 x 500 mm, with 200 mm thickness. The average 28-day concrete compressive strengths were 33 MPa based on 150 x 150 x 150 cubes. The flexural reinforcement ratio ($\rho$) used in this research was 1.26. All slabs were reinforced with 9 Ø10 mm rebar in each direction, while the central column was reinforced with 4 Ø12 mm. For column caps, 4 Ø12 mm was used in each direction for the top and bottom reinforcement. All of these details were kept consistent throughout the research. A total of six slabs were tested, as shown in Table 1, with slabs grouped according to eccentricity and columns capital dimensions. The specimen nomenclature uses S for the Slab, E for eccentricity, and C for column capital. The numbers 0 or 1 following the letter E refer to concentric load ($e=$0) and biaxial load ($e=150$ mm), respectively, while the numbers 0, 6, and 8 following the letter C refer to the column capital dimensions (0, 600 mm, and 800 mm, respectively). Slab and reinforcement details are thus shown in Table 2 and Figure 1.

Table 1: Test Matrix

| Slab    | Thickness (mm) | Compressive strength (MPa) | Column capital dimension mm | Eccentricity (mm) | $\rho$ (%) | Type of load |
|---------|----------------|---------------------------|----------------------------|-------------------|------------|--------------|
| SE0C0   | 100            | 33                        | ----                      | 0                 | 1.26       | Concentric   |
| SE1C0   |                |                           | ----                      | 150               |            | Bi axial     |
| SE0C6   |                |                           | 600 x 600                 | 0                 |            | Concentric   |
| SE1C6   |                |                           | 600 x 600                 | 150               |            | Bi axial     |
| SE0C8   |                |                           | 800 x 800                 | 0                 |            | Concentric   |
| SE1C8   |                |                           | 800 x 800                 | 150               |            | Bi axial     |
Table 2: Reinforcement details

| Reinforcement | Details                      |
|---------------|------------------------------|
| A             | 9∅10 mm @190 mm c/c         |
| B             | closed stirrups 3∅12 mm @110 mm c/c |
| C             | 4∅12 mm                      |
| D             | 4∅12 mm with angle 45°       |
| E             | closed stirrups 2∅12 mm@100 mm |

Figure 1: Details of tested slabs

3. Experimental Tests
All slabs were simply supported along four edges on knife edges laid on steel frames. Testing was performed with a load-controlled hydraulic jack with a capacity of 1,000 kN with a constant loading rate of 5 kN per minute. The upper and lower faces of tested slabs were observed for the development of cracks, and three linear variable displacement transformers (LVDTs) were used to measure the deflection for the slabs. The first LVDT was attached at the centre of a slab, the second LVDT was placed on the compression region in the first third of the slab, and the third LVDT was placed on the tension region in the other third of the slab for comparison purposes. Three slabs were tested under
concentric loads and the other three slabs were tested under bi-axial loads, with 150 mm eccentricity in both x and y-directions. The tests were terminated when the column penetrated the slab. Automatic data acquisition devices were used to record the test results. The test setup for axially and bi-axially slabs is shown in Figure 2.

![Test setup](image)

(A) with axial load  (B) with bi-axial load

Figure 2: Test setup

4. Results and Discussion

4.1. Failure mode

All tested slabs in this research failed suddenly in punching shear, under the influence of either axial loads or bi-axial loads. The slabs failed due to increased cracks that expanded and propagated in several directions from the slab edges towards the centre, forming a V-shape when the load was increased. The first cracks appeared in the bottom surfaces of slabs, while cracks on the top surfaces appeared when the columns punched the slabs at ultimate load. These crack patterns had a circular shape when strengthening was not used, while for slabs strengthened with column capital, the crack patterns took on a rectangular shape and the failure became more ductile. The using of strengthening created a critical section near to the column capital face. When bi-axial loads were applied, the punching failure clearly occurred at three sides, and in the direction of the compression side, while in the tension side, the cracks were smaller, and the failure mode was less brittle. Failure modes for all tested slabs are shown in Figure 3.

4.1. Effect of biaxial load (SE0C0 and SE1C0)

From Figure 4, the moment resulting from the application of bi-axial load clearly affected the behaviours of flat slabs, with the capacity of slabs subjected to bi-axial loads reduced by about 15.57% compared to that of concentric loaded slabs. Table 3 shows that the deflection for SE0C0 was higher by approximately 18.77% than that of SE1C0. The initial stiffness of SE0C0 is also higher than that of SE1C0 due to the lack of moment, though both slabs fail in a brittle manner with a sudden loss of resistance.
Figure 3: Modes of failure

Figure 4: Effect of biaxial load
Table 3: Test results

| Slab     | First crack kN | First deflection mm | Ultimate load (P_u) kN | Deflection mm | P_u slab/ P_u reference |
|----------|----------------|---------------------|------------------------|---------------|-------------------------|
| SE0C0    | 28             | 0.678               | 122                    | 18.31         | ----                    |
| SE1C0    | 21             | 0.643               | 103                    | 15.42         | ----                    |
| SE0C6    | 55             | 1.436               | 230                    | 26.82         | 1.885                   |
| SE1C6    | 45             | 2.239               | 186                    | 23.64         | 1.805                   |
| SE0C8    | 39             | 0.565               | 258                    | 33.74         | 2.115                   |
| SE1C8    | 52             | 1.440               | 231                    | 30.83         | 2.242                   |

4.2. Effect of column capital with axial loading (SE0C6 and SE0C8)

Table 3 also shows that the strengthening with column capital improves the punching shear capacity for concentrically loaded flat slabs compared to that seen in the reference slab. It is also clear that an increase in the size of the column capital leads to an increase in the ultimate load, with load capacity for SE0C6 and SE0C8 increased by 88.5% and 112 %, respectively, as compared to SE0C0. From Figure 5, it is also clear that the wider column capital (SE0C8) showed a stiffer response than SE0C6, and the deflections at ultimate load for SE0C8 and SE0C6 were increased by 46.5% and 84.2%, respectively as compared to SE0C0.

![Figure 5: Effect of column capital on concentric slabs](image)

4.3. Effect of column capital with bi-axial loading (SE1C6 and SE1C8)

Figure 6 shows that, even in the case of bi-axial loading, strengthening with column capital improves the punching shear resistance. The increase in the size of the column capital also increased the ultimate loads, with the percentage increases for SE1C6 and SE1C8 as compared to SE1C0 being 80.6% and 125%, respectively. It Table 3 shows that the moment resulting from bi-axial loading reduced the punching shear capacity even in the presence of the column capital as compared to that experienced by the slabs under concentric loading, however. The punching shear capacity for SE0C6 was increased by about 24% compared to SE1C6, and while for SE0C8 compared to SE1C8, the increase was about 12%. Figure 7 shows a comparison between the slabs with column capital under concentric and bi-axial loading. The SE1C8 slab showed a stiffer response prior to failure compared to SE1C6, while the deflection at ultimate load for SE1C8 was higher than that of SE1C6 by 30%.

![Figure 7: Comparison of slabs with column capital under concentric and bi-axial loading](image)
5. Conclusions
This paper presented an experimental investigation of strengthening with column capitals with two different sizes for six flat slabs under concentric and bi-axial loading. The behaviours of the flat slabs examined includes punching shear capacity, crack patterns, and deflection. The primary findings and conclusions of this research were as follows:

1- All tested flat slabs failed in punching shear failure.
2- The moment resulting from the bi-axial loading decreased the ultimate loads by about 16% for the reference slab and by 19% and 11% for slabs strengthened with column capitals with dimensions of 600 x 600 mm and 800 x 800 mm, respectively.
3- Strengthening with column capitals was effective in enhancing the punching shear capacity for all slabs. For concentric loads, the increases in the punching shear capacities for SE0C6 and SE0C8 were about 89% and 112%, respectively. For bi-axial loads, the increases in the punching capacities for SE1C6 and SE1C8 were 81% and 125%, respectively.
4- The increase in column capital size from 600 x 600 mm to 800 x 800 mm increased the punching shear capacity by about 13% for slabs under concentric loads and by about 25% for slabs under the effects of bi-axial loading. This increase occurred because of the increase in the critical section of the column, which increases the area resisting the stress transfers through the column.
5- The increase in column capital size from 600 x 600 mm to 800 x 800 mm increased the mid-slab deflection by about 26% for slabs under concentric loads and by about 30% for slabs under bi-axial loading.

6- The failure mode for flat slabs strengthened with column capital was more ductile under both concentric or bi-axial loads than that of the reference slab.

7- Strengthening with column capitals changed the resulting crack patterns from circular to rectangular shapes.

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