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Experimental Investigation on the Effectiveness of Truss-Shaped Punching Shear Reinforcement in Flat Slab

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Highlights:

- At failure, the increase in deflection of the flat slabs with punching shear reinforcement was small.
- Punching shear capacity was increased in the range of 7.71% to 21.47%.
- The most efficient assembly was obtained by using more inclined members.

Abstract. The use of reinforced concrete flat slabs in building construction increases the floor-to-floor clearance, expedites site operations, and offers aesthetically rewarding features. However, punching shear failure in a flat slab is brittle in nature and can be potentially catastrophic. Many studies have been conducted to improve the punching shear capacity of flat slabs but some of the proposed punching shear reinforcements were complicated and costly. This research aimed to evaluate the effectiveness of a simple and cost-effective; truss-shaped punching shear reinforcement embedded in a 1200 mm × 1200 mm × 175 mm thick flat slab specimen. Three types of truss-shaped punching shear reinforcements were prepared. All specimens were supported at the edges and subjected to gravity load tests. The results showed that the introduction of truss-shaped punching shear reinforcement increased the punching shear capacity in the range of 7.71% to 21.47%. The maximum deflection of these specimens exhibited an insignificant increase compared to the control specimen, suggesting that punching failure governed the ultimate behavior. The additional strength offered by truss-shaped punching shear reinforcement makes flat slabs as a construction material more appealing because they allow them to withstand higher design loads.

Keywords: *crack formation; flat slab; punching failure; punching shear; shear reinforcement.*

1 Introduction

Flat slabs are reinforced concrete slabs supported directly by concrete columns without the use of beams. They are mostly applied in large industrial buildings

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and car parks. Construction with flat slabs offer several advantages over conventional slabs, such as elimination of beams, optimizing the ceiling height, and reducing the total building height as well as the corresponding material cost [1]. However, this type of structural member is subjected to high punching shear force and failure can be catastrophic when no early warning signs can be detected [2-5]. In the case where the total shear stress exceeds the shear resistance, the slab will be pushed down around the column. As a result, punching shear failure will occur when surface cracking has developed throughout the entire depth of the slab and the slab is separated from the supporting column [6]. Evidence of such catastrophic failures is shown in Figure 1.

(a) (b)

Figure 1 Flat slab failure worldwide: (a) Piper's Row Car Park, United Kingdom [7], (b) Sampoong Department Store, Seoul, Korea [8].

Many studies have been carried out to enhance the punching shear capacity of flat slabs by using punching shear reinforcement along with slab reinforcement, such as the shear-band system [9,10], a punching shear preventer [11], the Filigran system [12], and beam-type horizontal and vertical reinforcements [13]. Interestingly, the research pertaining to flat slabs also extends into the field of strengthening work using various approaches [14-16].

The research on punching shear slabs subjected to thermal load can be found in two works of Al Hamd, *et al.* [17,18]. Some of these punching shear assemblies may be difficult to produce, as they require a precise bend radius. In some cases, they may need to be placed at the junction between the slab and the column area where congestion of reinforcement can be expected. As such, further research on new types of punching shear reinforcements that are simple, cheap but effective should be explored. This study aimed to investigate the effectiveness of a truss-shaped punching shear reinforcement that offers easy installation and likely to be made by means of left-over reinforcement materials typically found at construction sites.

2 Specimen Details and Test Setup

Four types of reinforced concrete flat slabs of 1200 mm × 1200 mm × 175 mm thickness were prepared in this experimental work. It is worth mentioning that these were not scaled-down specimens. The selection of the size was based on the range of slab thicknesses used by other researchers in the available literature [10,19,20]. To apply a concentric punching shear load, a 200 mm × 200 mm × 150 mm column was constructed at the center of the slabs.

The top and bottom slab reinforcements for all specimens were set to be mesh A8 with a nominal yield strength of 485 N/mm^2. The control specimen (marked as C) was cast with only mesh A8. Specimen FS1 was equipped with an additional box truss without any incline member. Specimen FS2 was tested to study the effect of incorporating incline members into the box truss. In this case, two incline members at 27° from the bottom chord were introduced. In addition, specimen FS3 was developed to study the effect of having more incline members to resist punching shear force.

In Pilakoutas & Li [10] the provision of incline members was more effective than vertical members in resisting punching shear. In this case, the incline members were set at 14° from the bottom chord. All punching shear reinforcements were arranged radially at 45° to each other. Figures 2 and 3 show the details of the punching shear reinforcement and the orientation of the reinforcement in the flat slab, respectively.

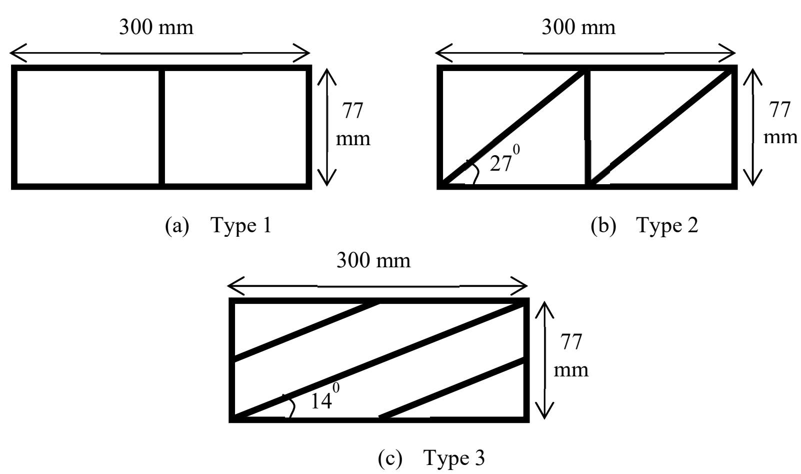
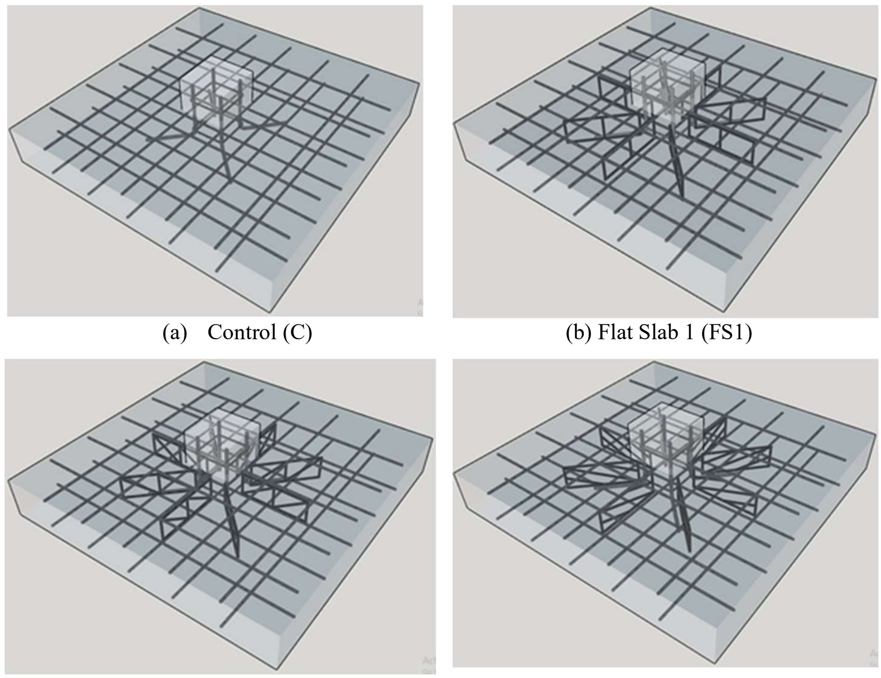


Figure 2 Details of the punching shear reinforcement: (a) only vertical and horizontal bars, (b) same as Type 1 with two additional inclined bars, (c) same as Type 1 (excluding middle vertical bar) with three additional inclined bars.



(a) Control (C)

(b) Flat Slab 1 (FS1)

(c) Flat Slab 2 (FS2)

(d) Flat Slab 3 (FS3)

Figure 3 Assembly of reinforcement for all specimens.

The truss-shaped punching shear reinforcements were constructed by spot welding an 8 mm diameter mild steel bar (nominal yield strength 250 N/mm^2). In this study, a concrete compressive strength of 25 N/mm^2 was used. The concrete cover for the reinforcement in the flat slab was set at 25 mm.

All specimens were rested on square hollow steel sections at four edges following the recommendation from Mabrouk, *et al.* [21] and Girish & Lingeshwaran [22]. This type of experimental work provides direct measurement of the punching shear capacity base on the failure load. In order to measure the maximum deflection, a linear variable transducer (LVDT) was placed at the center of the slab. Additionally, a load cell was secured to the hydraulic jack for measuring the applied force.

Figure 4 shows the overall test setup. For each type of flat slab, three specimens were tested, and the average results were extracted for discussion The tests were conducted at Heavy Structure Lab, Universiti Sains Malaysia.

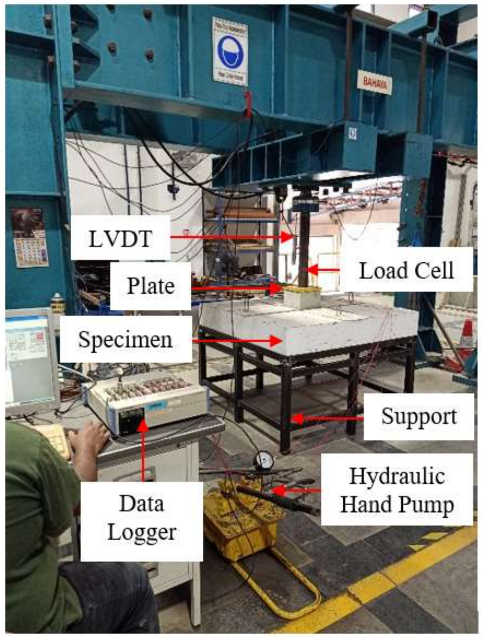


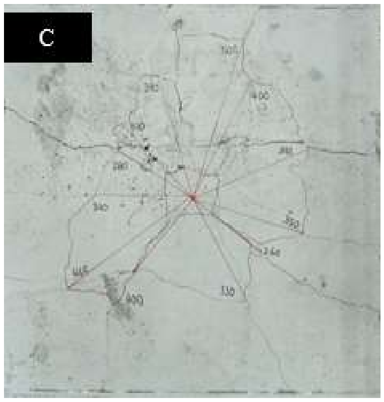
Figure 4 Punching shear test setup.

3 Results and Discussions

The experimental results and discussion of the punching shear test for flat slab are presented in the following sections.

3.1 Crack Patterns

Figure 5 shows the crack lines observed on the tension side of the slab for each type of specimen. It can be seen that all slabs failed in the form of punching shear failure, manifested by the formation of circular cracks that radiated from the center of the slab. The cracking was initiated near the column and propagated diagonally to the edges of slab. As the load was increased, both the number of cracks and the crack width also increased. Finally, quasi-circular cracks were developed at the tension side, penetrating towards the column [23]. Similar results have been reported by Alwash & Naser Al-Mamoori [24]. The average crack measured from the center of the specimen for C, FS1, FS2 and FS3 was recorded to be in the range of 300 mm to 365 mm. In addition, specimens with punching shear reinforcement showed more distributed finer cracks compared to the control specimen (C).



(a) Control

(b) Flat Slab 1

(c) Flat Slab 2

(d) Flat Slab 3

Figure 5 Punching shear crack patterns.

3.2 Maximum Deflection

The applied load versus maximum displacement for all types of flat slabs is shown in Figure 6. In general, similar patterns were observed for all cases. Although three specimens were tested for each type of flat slab, for ease of discussion, only one result for each test is presented. Typically, the graph can be divided into a linear phase and a hardening phase prior to failure of the specimen. Also noted in the graph is the high similarity in terms of load deflection relationship between control and FS1. This phenomenon can be associated with the large distance between the vertical reinforcement and the incapability of the vertical reinforcement to resist incline shear force. The punching shear force at the end of the linear phase was recorded to be approximately 53 kN, 61 kN, 95 kN and 115 kN for C, FS1, FS2 and FS3, respectively. As a result, FS1, FS2 and FS3 showed stiffer behavior compared to the control specimen. The results also showed that at failure, an insignificant difference in terms of maximum deflection was observed between the control specimen and the specimens with punching shear reinforcement. In this case, the recorded maximum deflection at the center of slabs C, FS1, FS2 and FS3 was 17.65 mm, 20.10 mm, 20.12 mm and 20.65 mm, respectively. This phenomenon indicates that the presence of punching shear reinforcement did not introduce any bending failure that significantly extended the deformation of the specimen.

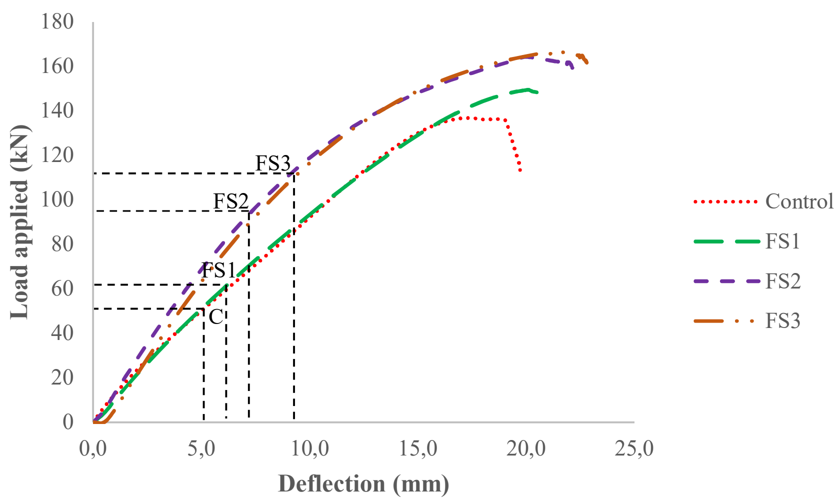


Figure 6 Load-deflection relationship for all types of flat slab.

3.3 Maximum Punching Shear Capacity

The maximum load at failure for all specimens is shown in Figure 7. As expected, the specimen without provision of punching shear reinforcement showed the lowest average punching shear capacity compared to the specimens with punching shear reinforcement. The average punching shear capacity for C, FS1, FS2 and FS3 was recorded to be 140.03 kN, 150.82 kN, 161.43 kN and 170.09 kN, respectively. The increase in punching shear capacity was calculated to be 7.71 % for FS1, 15.29 % for FS2 and 21.47 % for FS3. Specimen FS1 showed the lowest improvement, as only horizontal and vertical members were present to intercept the punching shear cracks. With the introduction of incline members as in FS2, the punching shear capacity was increased approximately 10%. This finding shows that the presence of incline members can effectively intercept radial cracks. In this case, the tensile strength of the incline members is mobilized to enhance the punching shear capacity. By replacing the vertical members in the truss assembly with more incline members, as in FS3, the punching shear capacity showed further improvement. This phenomenon is particularly true because after the development of incline cracks, the punching shear reinforcement transfers most of the shear force across the shear cracks, which in turn delays further widening of the shear cracks. As a result, the punching shear capacity is enhanced [10].

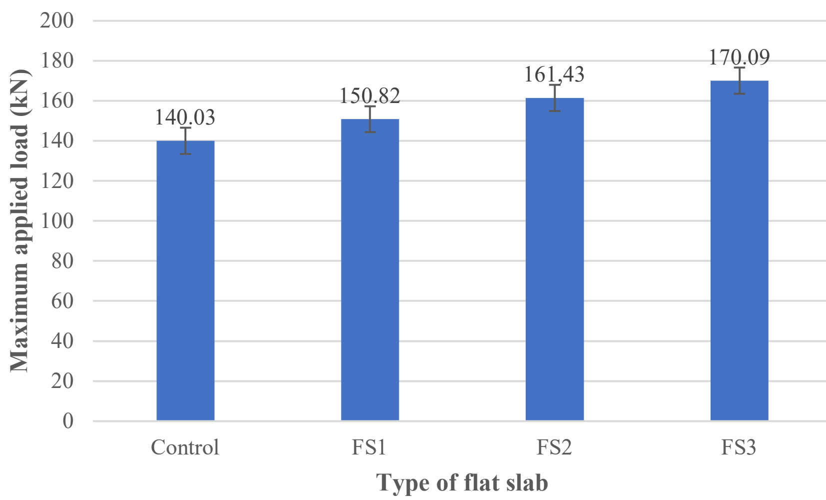


Figure 7 Maximum punching shear capacity for all specimens.

4 Conclusions

A total of twelve flat slab specimens were tested in order to study the effectiveness of several novel truss-shaped punching shear reinforcements. Based on the results, the effectiveness of the punching shear reinforcements was found to be significant when inclined members were incorporated in the assembly. In this case, the enhancement in the punching shear capacity was recorded to be approximately 21.47% compared to 7.71% when using non-incline members. These promising results show that the truss-shaped punching shear reinforcement can be further developed for use in the construction of flat slabs. Moreover, this type of punching shear reinforcement also offers easy installation and cost effectiveness. In order to have a broader spectrum of results, the study on the proposed punching shear reinforcement could be extended to columns on a raft foundation and transfer slab. Considering the actual weight and the high cost for producing the flat slab specimens, further works are strongly recommended using numerical simulation where parametric studies can be performed.

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