

The experimental studies of punching shear behaviour of reinforced concrete flat slab with the inclusion of steel fibre: Overview

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Abstract. The application of flat slab in construction offers a good deal, whereby the elimination of beam could reduce the overall height of the building and self-weight of structure. However, a drawback is that a high concentration of shear forces and bending moments at the column peripheries are produced, which cause punching shear failure. Previous researches proved that an adequate mix composition of steel fibre reinforced self-compacting concrete (SFRSCC) has the ability to improve load carrying capacity and the energy absorption performance specifically in the slab-column connection. In view of this, this study reviewed parameters used by several previous experimental studies of the performance of steel fibre reinforced concrete in improving the punching shear strength of the flat slab. It was found that fibre volume fractions, preparation of material and size of specimen affect the efficiency of steel fibre in resisting the punching shear.

Keywords. Punching shear, steel fibre, self-compacting concrete, flat slab

1. Introduction

In recent decades, the use of fibre reinforcement for cementitious material, either as partial [1][2] or full replacement[3] for conventional reinforcement, have gained increasing popularity. In the field of industrial floor [4]and tunnel construction, the steel fibre reinforced concrete (SFRC) with the range of fibre volume fraction approximately 0.26% to 0.76% were used. It has been proved that the inclusion of steel fibre in the concrete matrix has ability to improve the ductility behaviour of fibre-reinforced specimens as compared to plain concrete[5]. The role of steel fibres in cement-based matrix is rather complex. With randomly distributed discontinuous fibres in large area, the efficiency of steel fibre may be reduced[6]. However, partial or full orientation in areas where steel fibres need to be most effective can also be achieved. Generally, steel fibre acts as crack arrestor, resisting the growth of cracks[7][8] and endowing a brittle plain concrete into a concrete of greater ductility and a distinctive post-cracking behaviour prior to failure[9] [10].

Due to this beneficial behaviour, the SFRC can be applied to solve punching shear failure in reinforced concrete flat slab. Flat slab is a simple and easy construction technique, where the slab is supported directly by column without the use of beam. However, a drawback of this situation is the production of a high concentration of shear forces and bending moments at the column peripheries, which cause the punching shear failure. Partial or complete replacement of conventional bar reinforcement with steel fibre reinforcement has great potential, as it could lead to further cost reduction



due to lower necessary manpower and working time for the placement of reinforcing bars[11][12]. Table 1 shows the summary of parameters that have been investigated and explored by previous researchers. The present manuscript aims to provide an overview of the previous study of punching shear behaviour of reinforced concrete flat slab with the inclusion of steel fibre.

Table 1. Summary of previous researches.

| Category | Parameters | Type of test | Researchers |
|----------|--|--|--|
| Material | Types of fibre, fibre volume fraction, fibre strength, fibre geometry, fibre aspect ratio, concrete grade, reinforcement ratio, casting method, water-powder ratio | Monotonical load | [13] [14] [15] [12] [6] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [3] [26] |
| | Fibre strength | Gravity load and lateral displacement reversal | [27] |
| Slab | Fibre volume fraction | Cyclic load | [15] |
| | Slab thickness, span-depth ratio, slab punching area, slab geometry | Monotonically load | [13] [11] [15] [12] [22] [23] [24] [3] [26] |
| Column | Dimension of loading area, column size | Monotonical load | [23] [15] [3] [26] |
| | Edge column | Cyclic load | [15] |

2. The mechanism of punching shear failure

Punching shear failure in flat slab occurred when the connection of flat slab and column is subjected to concentrated loads as shown in Figure 1. The punching shear failure is a brittle failure with low stiffness, while flexural failure is a ductile failure. The difference between the flexural failure and punching shear failure is shown by load deflection graph in Figure 2. In this load-deflection graph, it is shown that flexural failure had significantly decreased the load carrying capacity, while punching shear failure dramatically decreased the load carrying capacity[28]. Once punching shear failure occurred, the connection between slab and column failed, thereby preventing any development of yielding mechanism, and the resistance capacity of the structure is dramatically decreased.

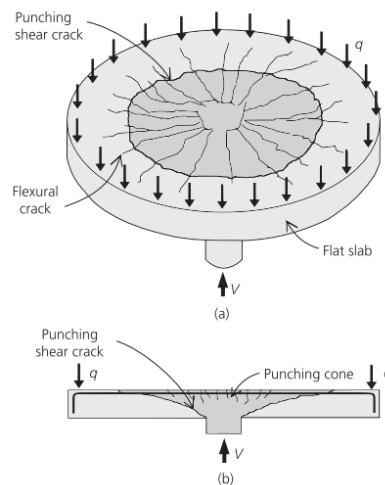


Figure 1. Punching shear failure at slab-column connection (a) isometric view and (b) cross-section view[29]

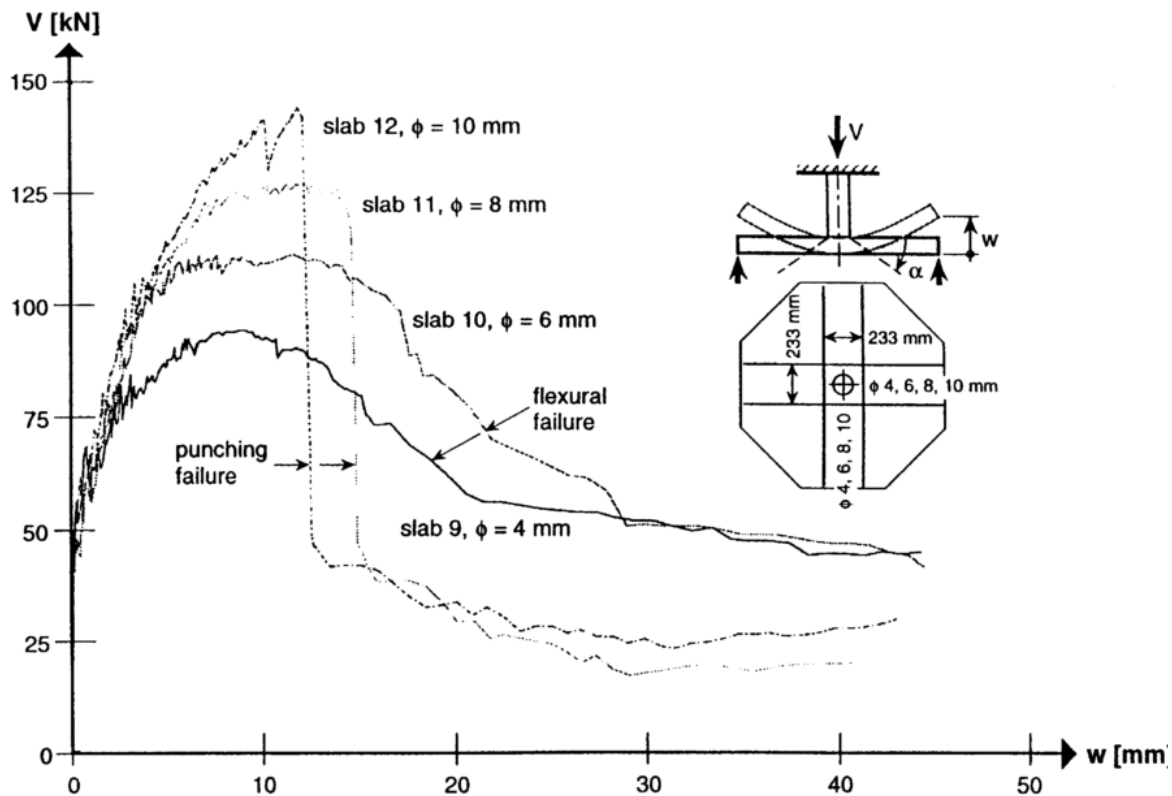


Figure 2. The comparison of load deflection behaviour between punching shear failure and flexural failure[28]

In detail, the failure develops along inclined faces of a truncated cone or pyramid in the slab column connection due to the combination of flexural and shearing stress in a slab. At first, the shear force is carried by the concrete. After the crack has fully developed across the slab depth, the shear is resisted by the combination of the following components: vertical component of aggregate interlock (V_a), the dowel shear force developed by the longitudinal reinforcing bars crossing the crack (V_d), and the shear force developed in the concrete compression zone (V_c). As a result, shear resistance of a slab (V_r) without shear reinforcement is given by the following equation.

$$V = V_c + V_a + V_d \dots\dots\dots (1)$$

In the conventional concrete slab - column connection, the shear resistance at slab-column connection is provided by the intact concrete in compression zone[30]. Thus, it differs from the fibre slab-column connection, where the shear strength is the sum of contributions of the compression and tension zone[31]. Generally, the punching shear strength of flat slab can be expressed as follows:

$$V_{sf} = V_c + V_a + V_d + V_{sf} \dots\dots\dots (2)$$

3. Parameters of study in punching shear capacity of steel fibre reinforced concrete flat slab

The punching shear capacity and inclination of the punching shear crack at the slab-column connection is governed by the amount of shear carried through the cracked interface and the stress distribution in that region. These factors were influenced by the geometry of the structure (slab thickness) and structural parameters (material strength, aggregate size etc.). In SFRC flat slab, the properties of steel fibre also has crucial impact on determining the material strength. Thus, in this section, the following were discussed:

3.1 *Effects of Geometry, volume fraction, aspect ratio and location of steel fibre*

Many types of steel fibre were tested for their performance, such as flat, undulated, crimped, twisted and the most used is hooked-end steel fibres. Cheng and Parra-Montesinos [25] compared the performance of twisted and hooked end types of steel fibres. The findings showed that the increment were 11% and 50% for twisted and hooked end fibre, respectively, as compared to the control specimen without any fibre. This hooked steel fibre has better ability to enhance the punching shear capacity of reinforced concrete flat slab. Hooked end types were the most preferred in structural study [32] because the hook of fibres, rather than depending solely on the chemical adhesion, static friction, developed mechanical interlocks that strengthen the bond between the fibres and concrete matrix [33][34].

The replacement of conventional reinforcement with steel fibre was reported to have ability to enhance the punching shear resistance in reinforced concrete (RC) flat slabs. Previous researches proved that by using an adequate mix compositions of steel fibre reinforced concrete (SFRC), steel fibres can act a shear reinforcement by improving the load carrying capacity and the energy absorption performance of the slab-column connection[21]. The ultimate load capacity and ductility of slab can be significantly enhanced with the inclusion of more than 0.4% of steel fibres[12]. In fact, the addition of 0.4% to 0.75% steel fibre is sufficient to resist crack and improve the performance of SFRC flat slab[24][20]. Nguyen et al. [6] showed that the SFRC with 0.8% steel fibre inclusion have more effective fibre distribution as compared to the SFRC with 1.6% of steel fibre content. However, to replace the conventional reinforcement that resist flexural loading and shears fibre volume fraction of SFRC flat slabs must be at least 1% [35][3][11].

In addition, Abdel-Rahman et al.[15] proved that by providing the steel fibre in areas where the area is equivalent to the slab thickness was sufficient to increase the load capacity and ductility behaviour of slab. This method will help to minimize the cost, however, the bonding between two types of concrete, the plain concrete and fibre concrete, will be questionable. In other study conducted by Cheng and Parra-Montesinos[25], where the steel fibre is provided only in central square region, no failure or distress were detected at the bond between the fibre concrete and plain concrete. In this method, the construction cost could be minimized by providing the steel fibre at the needed region only.

The application of SFRC in flat slab has ability to enhance the load capacity, change the brittle failure into ductile failure, and lastly the ability to reduce the perimeter of critical section, where the critical section of SFRC slab is closer to the column face as compared to the plain concrete slab as shown in Figure 3. Due to the benefits in inclusion of steel fibre in the concrete mix, many researches attempted to increase the steel fibres volume content. This matter resulted in enhancement in terms of energy absorption capacity of the concrete mix and the ability to develop higher post crack residual tensile strength. However, the high amount of steel fibre content would not guarantee the higher increment in punching shear resistance. This is because the combination of both high steel fibre content and steel reinforcement would increase the tendency for fibre blockage, which will reduce the efficiency of fibre in the concrete as shown in Figure 4.

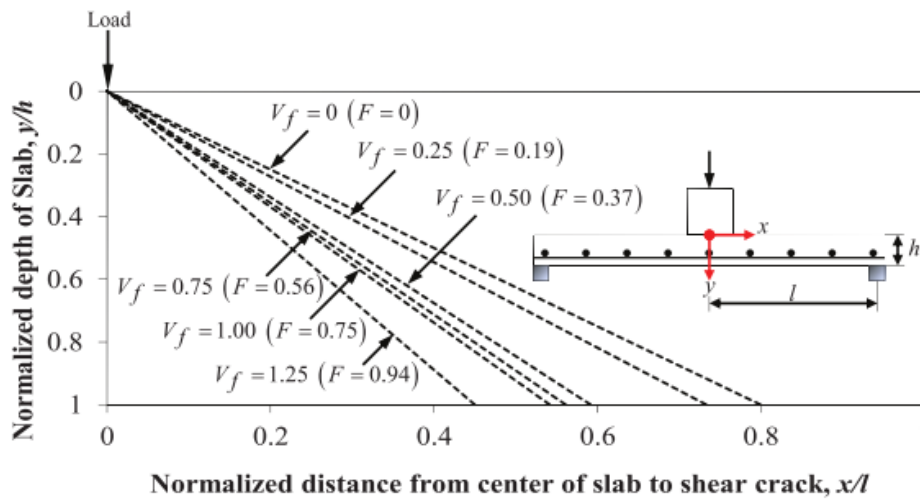


Figure 3. The comparison of propagation of cracks between plain concrete slab and SFRC slab (Narayanan and Darwish,1987)[36]

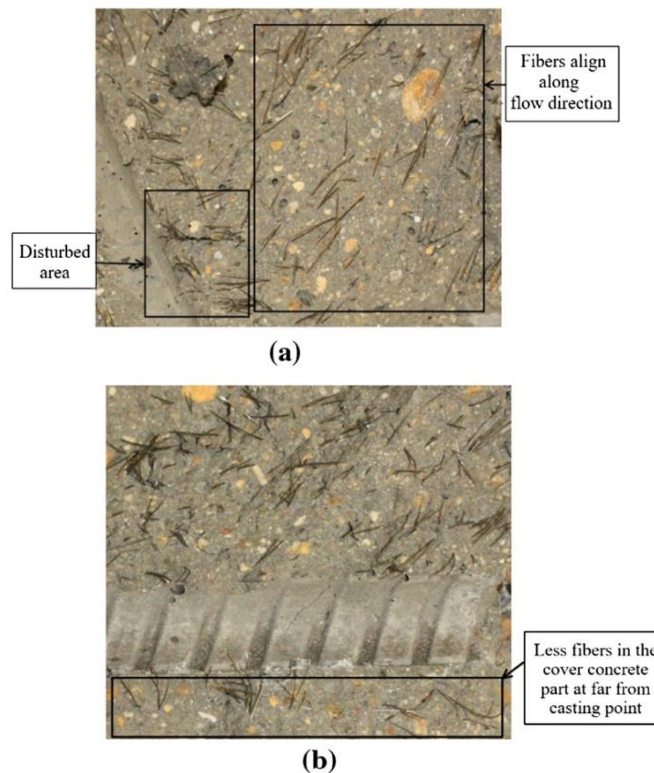


Figure 4. The distribution of fibre in disturbed area[6]

In previous researches, the aspect ratio of fibre that was typically used were in the range of 60 to 100. M. Harajli et al. [13] reported that the aspect ratio of steel fibre has no significant effect on the punching shear capacity and failure mode of flat slab. This is in line with the study by A. Khaloo and M. Afshari[35], the fibre with larger aspect ratio shows only slight increment in energy absorption capacity, which is about 1.2 times higher than the fibre with small aspect ratio. This is in contrast with the finding from Teixeira et al. [17] and De Hanai and Holanda[26], where the use of steel fibre with high aspect ratio contributed to the high fracture energy, as well as high load capacity.

3.2 Effects of casting method

Mechanical vibration could cause fibre to segregate at the bottom of slab, which will affect the homogeneity of the concrete mix. This will cause inconsistent results as it is could not be controlled. Therefore, using self-compacting concrete (SCC) has been a better alternative to avoid uneven dispersion of fibres. In fact, the fibre dispersion and orientation influence the resistance of concrete at before and after post-cracking[37]. Furthermore, an extensive experimental study confirming the aforementioned results was conducted by Nguyen et al.[6] on casting direction (as shown in Figure 5) and casting method effects the punching shear capacity of flat slab. The findings concluded that casting direction that began at the centre (position A) of formwork gave the smallest punching cone size when the slabs failed in punching shear failure, as compared to the slabs that were casted at the corner or along one side of the mold as shown in Figure 6.

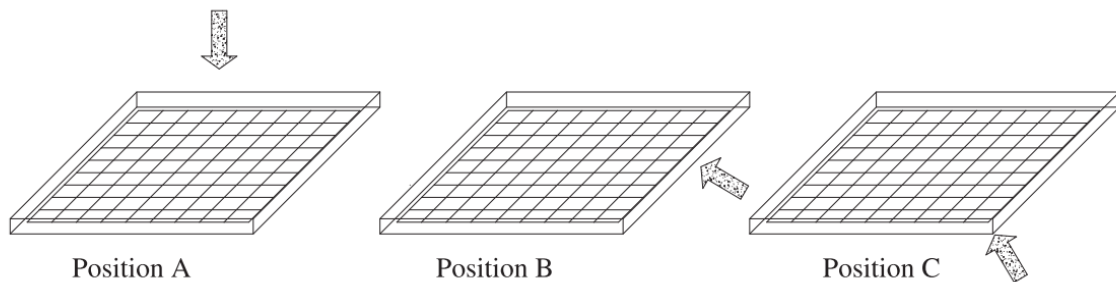


Figure 5. The casting direction of concrete

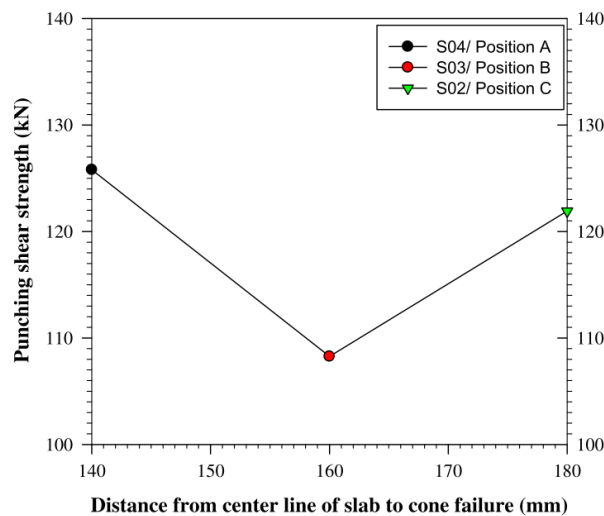


Figure 6. The influence of casting direction on the punching shear strength and punching cone size[6]

3.3 Size effect

Generally, the increment in the slab thickness will increase the ultimate capacity of the flat slab[22]. It could be concluded that the size of specimens has directly proportional relationship with the bearing capacity of the slab. However, Michels et al. [11] found that increase in thickness of slab has negative effects on the fibre dispersion, where the thick specimen has less pronounced fibre and curve angle after having passed the peak force. In order to prove the importance of fibre dispersion and orientation in determine the capacity of the structure, J. Michels et al. [38] compared the post cracking behavior between small scale beams and large scale plates. It was reported that the decrement in fracture energy

in full-scale plate are greater as compared to small-scale beam due to the less pronounced fibre orientation.

Fibre alignment plays a crucial role in determining the fibre efficiency; steel fibres favorably aligned with respect to the tensile stress will be effective in resisting tension, whereas a perpendicular orientation would not offer any strength contribution as shown in Figure 7. Therefore, the differences in structural geometry and size had significant influence on the strength of structure. This problem arises because of the three-dimensional fibre orientation had a more significant effect in larger specimens than in small-scale specimens. The ‘wall effect’ or three-dimensional fibre orientation was considered because the fibre can rotate freely in all directions. Furthermore, Stahli et al. [39] confirmed the result that the moulded and smaller in size prism shows higher bending stresses as do the geometrically specimens cut off from bigger cast specimens. The so called ‘wall effect’ has been proven to be affected when there is huge difference in sizes, or two different structural elements.

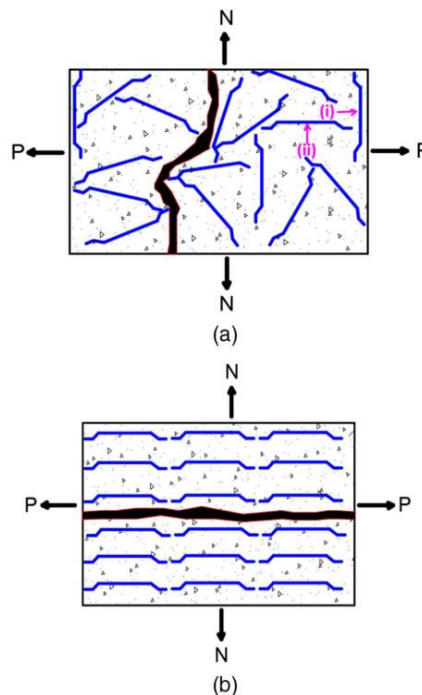


Figure 7. The orientation of fibre: (a) three-dimensional fibre orientation and (b) unidirectional distribution[33]

3.4 Effects of flexural reinforcement ratio

Punching shear failure in reinforced concrete flat slab is dominated by flexural deformation due to its large span to depth ratio[31]. Few studies show that fibre reinforcement has ability to replace all the conventional reinforcement in structural element with high internal redundancy such as slabs on grade[40]. However, Facconi et al. [12] proved that the use of steel fibre as the only reinforcement in slab was limited to slabs that are used only for light load. Therefore, to eliminate all the conventional reinforcement in slab was risky. This study is in line with the study conducted by Tan and Venkateshwaran[22], in which the flat slab with steel fibre as only reinforcement failed prior to flexural failure. Furthermore, the combination of both fibre and steel reinforcement still permit 25% saving in total steel content[12]. Cheng and Parra-Montesinos compared two flexural reinforcement ratio which are 0.83% and 0.56%. The slabs with 0.83% reinforcement ratio showed better in initial stiffness and ultimate load because the punching shear failure occurred prior to the flexural yield[25]. It could be concluded that the increment in flexural reinforcement ratio only influence the stiffness of the slab, not the punching shear behaviour of the slab[20]. Generally, in the studies of punching shear of flat slab,

researchers tend to use high flexural reinforcement ratio, in range between 1.0% to 1.5% to ensure the failure in punching.

4. Conclusion

This paper has presented parameters of study in punching shear behavior of reinforced concrete flat slab with the inclusion of steel fibre. This manuscript is limited by the scopes of discussion in experimental studies, without further discussion on theoretical parts. Therefore, based on the review and discussion, the following conclusions can be drawn:

- i. The high concentration of steel fibre leads to two different outcomes: either enhance or deteriorate the punching shear capacity of flat slabs. It is due to the efficiency of steel fibre in the concrete matrix. The effectiveness of steel fibre to resist and bridge the cracks in structural element is dependent on the fibre orientation and distribution. Therefore, there is limitation in increasing the fibre volume fraction in the concrete mix.
- ii. The use of self-compacting concrete would avoid uneven dispersion of steel fibre and the casting direction effects the punching shear cone size.
- iii. The application of steel fibre in the thin slab was more practical in order to maximize the efficiency of steel fibre.
- iv. The flexural reinforcement ratio only effected the stiffness of the specimen, therefore increasing of flexural reinforcement ratio did not really affect the punching shear behavior or capacity of flat slab.

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