Testing setup to examine punching shear strength in Self-Compacting Fibre Reinforced Concrete (SCFRC) ribbed slabs

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Abstract. The punching shear resistance and behaviour of self-compacting fibre reinforced concrete (SCFRC) of flat slab were studied in the previous research. Currently, there is limited information available on the ribbed slab, without conventional reinforcement, and using SCFRC as the main material. The extensive convolution of the punching shear behaviour within the concrete and structure itself, and insufficient appropriate test method ascribed to the conventional reinforcement are being used. Hence, the testing setup, to examine the punching shear resistance and behaviour of the ribbed slabs by using SCFRC, was carried out. The substantial experiment on the SCFRC ribbed slabs, prone to punching shear failure, with the designed test arrangement was employed. The association between the punching shear load and the angle of the shear plane, the critical value of the basic control perimeter and the failure mode were studied and analysed from the results obtained. This research gives insight into the punching shear capacity of SCFRC ribbed slabs. The results exemplify and accentuate the advantages of using SCFRC, compared to the normal concrete in structural designs. The punching shear test presented here has established itself as a suitable procedure for testing SCFRC, and potentially, other fibre reinforcement composites.

1. Introduction

The continuous improvements of the technology of steel fibre reinforced concrete (SFRC), and the better knowledge on the characterisation of the mechanical behaviour of this composite are contributing to enhance the field applications of SFRC [1]. Adding steel fibre reinforcements to the self-compacting concrete (SCC) has the ability to be poured in place and filling the formwork corners and small voids between the reinforcement bars by means of its own weight without any compaction [2]. The punching shear failure is a more localised effect associated with thin slabs, when subjected to a highly concentrated load. The punching shear failure occurs when the principal stress across the critical surface of the section exceeds the tensile strength of the concrete, because of the applied loading, and failure occurs with limited warning [3].

2. Experimental studies

In this research, a series of cube and slab samples were cast and tested. The cubes were tested to obtain compressive strength at 28 days and 42 days. The slab samples were tested at 56 days, because the optimum compressive strength design for the self-compacting fibre reinforced concrete (SCFRC) is
achieved in 56 days. In this section, the development of punching shear testing method and the experimental studies are presented to determine the punching shear capacity of ribbed slab by using SCFRC.

2.1. Test development
A preliminary test was conducted to characterise the punching shear capacity with minimum influence of the bending stress. The trial test were performed and modified to develop the final test setup. This experiment was divided into two phases. The first phase was the identification of the size for the slab samples. The preliminary testing was carried out on the 2800 mm (length) x 1200 mm (width) rectangular slabs. The samples were loaded to enhance the possibilities of the punching shear failure [4]. In this phase, it was observed that the punching shear failure was present. However, the behaviour of the punching shear observed reacted close to the support; thus, the final size of the sample was chosen to be square with the dimension of 1200 mm x 1200 mm.

The second phase was identifying the thickness of the slab samples and variety of material distribution for the same. In the preliminary stage, the testing was carried out by using samples of 200 mm thickness, having the topping of 100 mm x 100 mm at the ribbed part. Thus, for further investigation, the thickness of the topping was designed for 120 mm to observe the behaviour of the punching shear failure towards different thickness of the slab samples.

2.2. SCFRC mix
The self-compacting concrete (SCC) used consisted of ordinary Portland cement, natural sand and crushed stone aggregate with minimum size of 10 mm. The SCC mix for the sample cast for this experiment was produced in the concrete plant and delivered to the laboratory. The steel fibre was added manually into the concrete truck at the end of the mixing process. The mix composition of SCFRC G30 is shown in table 1.

The steel fibre used for this research was hooked at the end steel fibres (Stahlcon HE 0.55/35) with the length (l_f) of 35 mm, diameter (d) of 0.55 mm and aspect ratio (L_f / d_f) of 65. The tensile strength of the steel fibres is at 1250 N/mm². The hooked end steel fibres were chosen to enhance the anchorage between the steel fibre and the surrounding concrete matrix. The greater friction was found from comparison matrix between the hooked end fibre and aggregates with straight fibres [5]. Similar results were obtained with higher toughness and residual strength [6, 7] and greater pull out forces [7]. The dosage of the fibre used for all slab samples was found to be 80 kg/m³, which is equivalent to 1% of the total mix volume. The volume fraction chosen was referred to the previous study findings [8]. While facilitating the distribution of fibre during casting and avoiding the balling effect, the fibres were glued into the bundles [8, 9, 10]. The type of fibres was confirmed according to the BS EN 14889-1 (2006).

| Cement CEM I 42.5R | Pulverised fly ash (Class F) | Course aggregates (10 mm) | Fine aggregates | Water | Water Cement Ratio | Steel Fibre content |
|-------------------|-----------------------------|---------------------------|-----------------|-------|-------------------|-------------------|
| 315 kg/m³         | 105 kg/m³                  | 830 kg/m³                 | 865 kg/m³      | 185 kg/m³ | 0.44             | 80 kg/m³         |

2.3. Specimen preparation
In this research, the dimension of the ribbed slab samples was set in the square form, which was 1200 x 1200 mm and the thickness was set to 200 mm. The two different topping thicknesses were 120 mm and 100 mm. These thicknesses were considered as the common size of precast slab produced by the local manufacturers, compared to the preliminary samples, that only have the thickness of 100 mm and the dimension of 2800 mm (length) x 1200 mm (width).

No vibration was applied to the SCC mix during the concreting process of the samples [11]. The gunny sacks were used in the curing process for 28 days. For better observation of the crack propagation pattern during the experiment, all the samples were being painted white. To measure the vertical
deflections of the samples, the linear variable displacement transducer (LVDT) were used, and the loads from the actuator were measure using the load cell. The LVDT and strain gauge arrangement are shown in figure 1 and figure 2, respectively. Table 2 shows the summary of the slab samples, and distribution of three different types of materials in the slabs is shown in figure 3. The N-S1 has full SCC, N-S2 has full SCFRC and N-S3 has SCC at the top and SCFRC at the ribbed part. The N-S1 is being reinforced by BRC A8 at the toping part and Y10 at the ribbed part.

**Figure 1.** LVDT arrangement at bottom of the slabs.  
**Figure 2.** Strain gauge arrangement at top of the slabs.  
**Figure 3.** Variation of materials in slab samples.

| Sample No.  | Topping Thickness | Topping Material | Rib Thickness | Rib Material |
|-------------|-------------------|------------------|---------------|--------------|
| N-S1-100 (P) | 100 mm            | SCC              | 100 mm        | SCC          |
| N-S2-100 (P) | 100 mm            | SCFRC            | 100 mm        | SCFRC        |
| N-S3-100 (P) | 100 mm            | SCC              | 100 mm        | SCFRC        |
| N-S1-100    | 100 mm            | SCC              | 100 mm        | SCC          |
| N-S2-100    | 100 mm            | SCFRC            | 100 mm        | SCFRC        |
| N-S3-100    | 100 mm            | SCC              | 100 mm        | SCFRC        |
| N-S1-120    | 120 mm            | SCC              | 80 mm         | SCC          |
| N-S2-120    | 120 mm            | SCFRC            | 80 mm         | SCFRC        |
| N-S3-120    | 120 mm            | SCC              | 80 mm         | SCFRC        |
2.4. Test setup

Figure 4 shows the preliminary testing setup for the punching shear. A constant rate of 0.01 mm/sec was subjected to the centre of the slab samples, by using hydraulic jack, with the dimension of load cell being 200 mm x 200 mm. For the deflection measurements, an LVDT was positioned under the slab samples in line with the centre of the load cell. Based on the observation in the preliminary testing setup, the behaviour of punching shear failure was shown successfully. However, the size of the sample can be modified to be in small scale, because of the sufficient crack elongation around the support area. The final testing setup is shown in figure 5.

After each test was done, the failed slab samples were removed from the testing frame and checked visually to investigate, observe and measure the crack pattern. The failed slabs were cut in the middle into half to observe the punching shear cone and investigate the mode of failure. The distribution of steel fibres in the concrete of the slab samples can also be investigated.

3. Results and discussion

3.1. Load vs deflections

The test results obtained from this experiment are shown in table 3. It has been observed that the ultimate punching shear capacity are dependent on the span-to-depth and the thickness of the slab samples [4]. The preliminary samples displayed the higher loading capacity than the final samples; thus, the variance in size between the both played a major role in terms of sustaining the applied load and deflection. The relationship between the applied load and deflection at the centre of the samples for thickness of 100 mm of the preliminary, S1, S2 and S3 slabs and 120 mm thick slabs of S1, S2 and S3 are plotted in figure 6, figure 7 and figure 8, respectively. The load-displacement behaviour can be ascertained from the beginning of testing until the load achieves the peak value (failure load).

The observation of the crack development can be divided in two phases. The first phase is the first crack stage for the specimens. All thicknesses tested show that S1 and S2 sustained higher loading capacity compared to S3, except for the preliminary sample (P), because S1 and S3 (187.13 kN and 179.26 kN) are higher than S2 (135.68 kN). This is related to the preliminary sample size, that affects the application of steel fibre in the samples. For preliminary sample S1 (P), it was constructed with conventional method of steel bar and BRC, while for S3 (P), the preliminary sample was a combination of steel fibre at the ribbed part and BRC was applied to the topping. In terms of sustaining the loading capacity for preliminary samples, the higher or bigger size of structure is better to have the combination of steel reinforcement and steel fibre, rather than having fully steel fibre concrete S2 (P).

The first crack occurred on N-S1-100, once the load was achieved at 128.94 kN with ultimate load at 135.68 kN, and the displacement of 11 mm and 15 mm, respectively. For N-S2-100 and N-S3-100, the ultimate load value was 17% and 51% lower than S1, respectively. Nevertheless, both slabs managed
to preserve the load until final deflection of the specimens. The ultimate load recorded for N-S1-120 and N-S2-120 were 163.35 kN and 158.37 kN with the difference of 3%. Once the specimens achieved the ultimate load, the punching cone was formed.

Figure 6, figure 7 and figure 8 also show that, the increase in topping thickness remarkably affected the samples by increasing the ultimate load values of the ribbed slabs. It was observed from the control sample (S1), fully reinforced by steel fibres (S2) and steel fibres in the ribbed area with BRC at the topping area (S3). The occurrence is related to the lesser volume of steel fibres provided in samples, which was just within the ribs (tensile zone) without any provision of BRC in the toppings.

From the results, it is also observed that the ultimate load for 120 mm topping samples reached the stage of deflection earlier, compared to the 100 mm topping samples. It was reached at smaller displacement values implying that the flexural failure was experienced earlier for samples with higher topping thicknesses. Instead, S2 samples including S2 (P), has shown a contrast result comparing to S1 and S3, including S1 (P) and S3 (P), which shows that size and thickness of samples contribute to the load capacity resistance. The S2 and S2(P) samples demonstrate that, not only the size and thickness will affect the load carrying capacity, but also the volume of steel fibre inside the structure with the size and thickness as well will affect it [12].

Comparing the variation of steel fibre locations in each samples of S1, S2 and S3, the sample fully reinforced by steel fibre (S2), had the best performance by achieving slightly lower ultimate load, compared to the control sample (S1). Both N-S2-100 and N-S2-120 were observed showing these behaviours, which only varied in terms of topping thickness. Despite the fact that the ultimate loading values were slightly lower than the control samples, the load-displacement curve demonstrated better performance behaviour by displaying a deflection-softening curve after reaching the ultimate load. This behaviour shows that failure of N-S2 samples was gradual and avoided sudden structural failure.

| Sample No. | Ultimate Load, $P_{\text{exp}}$ (kN) | Deflection (mm) |
|------------|-------------------------------------|-----------------|
| N-S1-100 (P) | 187.13 | 13.85 |
| N-S2-100 (P) | 135.68 | 4.25 |
| N-S3-100 (P) | 179.26 | 11.90 |
| N-S1-100 | 135.68 | 15.10 |
| N-S2-100 | 112.77 | 18.23 |
| N-S3-100 | 80.20 | 22.37 |
| N-S1-120 | 169.38 | 10.61 |
| N-S2-120 | 158.37 | 8.99 |
| N-S3-120 | 110.30 | 15.25 |

**Table 3. Test result for punching shear and the deflection.**

![Figure 6. Load-displacement curve S1.](image-url)
3.2. Failure behaviour

The crack patterns for both testing setups at the bottom surface of the slab samples are similar. The crack pattern at the bottom of the slab type N-S1 was more severe compared to that of the N-S2 slabs. The development of the crack was observed carefully during the experiment. The width of the crack lines was expected to increase with the increased load. A series of crack patterns were formed at the centrally loaded area. The N-S2 slab sample, showing the crack lines, propagated from the centre ribbed close to the loading area.

The characteristic of punching shear failure was like the brittle failure, that occurred near the loading, followed by the development of the punching cone [13]. Typically, these failures can be observed on the tensile face, which is at the bottom of the slab, as shown in figure 9.

With the increase of load, the failure occurred with the flexural cracks at the bottom part of the specimens, near the loading position, and the cracks propagated towards the end of the slab. The slab S1 was found to have larger failure mode with damage on the tensile face compared to S2 and S3, while S2 and S3 displayed a similar crack pattern, because both ribbed part was filled with SCFRC. The higher punching shear resistance was found on both S2 and S3. The introduction of steel fibre in the slab showed that, better punching shear resistance was achieved compared to the slab without steel fibre, and it reduced the crack line development as well [14].

Table 3 shows that, the result achieved by S2 final sample is greater compared to the S3 final sample, having a combination of SCC and SCFRC in the slabs. The crack was observed initially on the loading area and then disseminated to the edge of the slabs. The steel fibre inside the sample has helped it to resist the crack development and sustaining the load and force merely to control the sample performance [15]. The N-S2-100 can resist about 18% different ultimate loads from N-S1-100, and N-S2-120 can resist about 7% different ultimate loads from N-S1-120.
4. Conclusions

This study has used various parameters among the slabs, with the variation of steel fibre distribution and the various thickness of topping, to observe the performance and effect through crack patterns and load-deflection behaviour. From here it can be concluded that, by introducing the steel fibres, the punching shear resistance will increase for the ribbed slab, while having a similar load capacity with the reinforcement slab of about 7% - 18%. The SCFRC has proven that it has the ability to slow down and resist the crack development under concentrated load.

The samples, fully reinforced by steel fibres (N-S2-100 and N-S2-120), have displayed the best performance by achieving an ultimate load slightly lower than control sample (S1), while exhibiting enhanced flexural behaviour. Nevertheless, when achieving ultimate load, these samples displayed deflection-softerning behaviour, and with the load carrying capacity gradually decreasing, it has avoided a sudden brittle failure, similar to the control samples. For the samples, that were only reinforced with steel fibres in the ribbed area and had the provision of BRC in topping (N-S3-100 and N-S3-120), showed similar behaviour as the fully reinforced samples (S1), with the load-displacement curve pattern being almost the same and decreasing gradually towards the final failure.

Comparing the topping thickness of 100 mm and 120 mm samples—the thicker the topping, the higher the ultimate load achieved. Among the types of the samples, the best performance was obtained by the S2 in resisting the punching shear failure and the crack development and having almost equal load carrying capacity with S1. Even though the preliminary samples S1 (P), S2 (P) and S3(P) have shown much better performance, in terms of load carrying capacity, resisting punching shear failure and developing cracks, the sample used for this research was selected and used, because of the study done on the preliminary slab, that shows the crack pattern from the punching shear failure only occurring around and near the loading area.
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