Shear Performance of Pretensioned Prestressed Concrete Beam with Steel Fibre

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Abstract. The use of steel fibre has proven to be effective in enhancing the performance of concrete structure. However, its application in the prestressed concrete is not fully understood. Therefore, this study presents the application of steel fibre in the prestressed concrete beam. An investigation on the crack pattern and load-deflection relationship of prestressed concrete beam filled with steel fibre was carried out and a comparison is made with the prestressed concrete beam without the steel fibre. A total of three configurations of beams with size of 150 × 200 × 1200 mm were employed. Steel fibres were added with two different volume fractions of 3% and 5%. Experimental results showed that the control beam experienced shear crack pattern, while the other two beams experienced the flexural-shear crack. In comparison between two different percentages of steel fibre in the beam configurations, more cracks were observed in the prestressed beam that filled with 3% steel fibre compared to the prestressed beam filled with 5% of steel fibre.

1. Introduction
Prestressed concrete members have been used in building structures and infrastructure facilities since the 1960s due to their advantages such as high quality, and durable aesthetic [1] Prestressed concrete is known to have better performance compared to normal reinforced concrete. The application of prestressing concrete benefit the construction as it able to provide more strength for longer span. Reinforced concrete is known with its ability to utilise full-strength capacity in resisting the load directly while prestressing concrete is capable in resisting shear stress due to its pre-compression behavior.

For reinforced concrete beam, shear failure would occur when the length of the beam is three times of the effective depth. Failure mode of shorter spans is due to combination of three elements; shear, crushing, and splitting. For longer spans (plain reinforced concrete beam), the crack occurred easily due to flexural tensile stresses[2]. By prestressing the concrete, the pre-compression are introduced in the structural elements which is subjected to tensile stresses and can be kept under compression during its service time [3]. The external load will generate tensile stresses which is nullified by the pre-compression and could also be a residual compression. Hence, the cracking problem in structure can be avoided and the cross-section can be fully utilised in transferring the load. The used of prestressed concrete could avoid plain concrete’s shear failure which commonly happened with sudden collapse and failed without earlier signage [4].
A pull-out behaviour of prestressing strands in reinforced concrete incorporated with steel fibre showed that the addition of the steel fibre into concrete was capable to modify shear performance of the concrete [5]. Yoon and Nishiyama [6] have conducted a test investigating shear failure of deep fibre reinforced concrete beams and found that the shear crack was reduced when utilising a significant content of steel fibre in the element. Furthermore, the additional of steel fibre in concrete was capable to eliminate the occurrence of the concrete spalling as the steel fibre could hold the concrete during the cracking stages [7]. In addition, post cracking response of concrete structural was reported better than conventional element [8]. The claim is strongly supported by Liu et al. [9] with experimental works conducted and demonstrated that the volume of the steel fibre utilised has contributed to the increment of the beam shear strength. As for the use of steel fibre in prestressed concrete beam, with 0.3 and 0.5 percent of additional steel fibre, Yoon and Nishiyama [6] have concluded that the increment amount of steel fibre has led to more crack’s appearance. This finding however contradicts the effect of steel fibre in ordinary reinforced concrete beam as reported by previous researchers.

Uncertainty finding of prestressed beam performance with steel fibre has led this study to be initiated. This study is investigating the shear performance of prestressed concrete with additional of steel fibre in the prestressed concrete beam. Therefore, three beams configurations were tested to investigate the shear behaviour and the effect of additional steel fibre to the prestressed concrete beam performance against shear failure. Additional volume fracture of 3% and 5% steel fibres were used in this study and the shear failure was observed and compared with the reinforced concrete beam specimen without steel fibre (control specimen).

2. Methodology

2.1. Specimen Materials
Two main materials used in this study were concrete and steel fibre. The concrete compressive strength was calculated based on the standard BS EN 12390 [10]. Concrete grade 40 MPa was used for all specimens in this study. 0.6% of plasticiser from the weight of cement was added into the concrete mixture for the workability of the mixture. In avoiding concrete segregation, the usage of plasticiser should not be added with maximum amount [11]. While for steel fibre, hooked-end type was used as depicted in Figure 1. The length of the steel fibre is 60 mm and the diameter is in the range of 0.5 mm – 1.0 mm. The proportions of steel fibre used were 3% and 5% of its volume.

Figure 1. Steel Fibre
2.2. Casting of Beams

All three beam specimens were casted in a formwork of 2250 mm length prestressing bed (Refer to Figure 2). One of the specimens was reinforced concrete beam with four numbers of 12 mm reinforcement bar diameter. The ultimate tensile load for 12.7 mm tendon is 186 kN. For pre-tensioned prestressed concrete, the tendon is tensioned up to 50% from its tendon strength that is approximately 93 kN (2900 Psi). The tendon tensioning was conducted using manual hydraulic jack with 70 mm elongation. The fresh concrete was then placed into the formwork in the prestressing bed and cube moulds. Compacted process was done by hand-rammed and vibrating table. The prestressed concrete specimens were then left for seven days before the formwork was removed. The stressed in the presetressing wires were released from the anchorage ends before the specimens removed from the formwork and they were kept in the laboratory under controlled room temperature. All beams and cubes specimens were tested after a curing period of 28 days. Two-point load testing was carried out for beams and compressive strength test for the cubes.

![Pre-tensioning Process](image1)

**Figure 2.** Pre-tensioning Process

2.3. Testing Set-Up

The shear test was conducted using two-point load test method [12]. The load-deflection result of the testing was recorded to differentiate the stiffness of every specimen. The specimen was tested until it reached the ultimate failure. From this study, three linear variable differential transducers (LVDT) were used; left (LVDT 1), middle (LVDT 2) and right (LVDT 3) side of the beam. A 20 mm LVDT was employed. The Figure 3 shows the setting up of two-point load shear testing and the placement of the LVDTs.

![Testing Set-Up of Two Point Bending](image2)

**Figure 3.** Testing Set-Up of Two Point Bending
3. Results and Discussion

3.1. Concrete Cube Compression Test
Concrete cube compressive strength of 7, 14 and 28 days were recorded for all beam specimens; reinforced concrete beam, prestressed beam with 3% of steel fibre and 5% of steel fibre (refer to Table 1).

| Days | Concrete Cube Compressive Strength (N/mm$^2$) |
|------|---------------------------------------------|
|      | Control Concrete  | 3% Steel Fibre | 5% Steel Fibre |
| 7    | 28.0             | 28.9           | 29.5           |
| 14   | 33.1             | 35.4           | 37.0           |
| 28   | 41.0             | 43.7           | 45.7           |

3.2. Load-Deflection Behaviour
Load-deflection was measured until the beam was failed. The typical load-deflection curves for reinforced concrete beam, prestressed beam with 3% steel and prestressed beam with 5% steel fibre were presented in Figure 4, Figure 5(a) and Figure 5(b), respectively. From the Figure 4, it shows that when load was increased, the deflection is also increased. The highest displacement experienced was recorded by LVDT 3 which was placed at the right support of the specimen where the first crack was observed.

![Figure 4. Load-Deflection for Reinforced Concrete Beam](image)

The highest value of the deflection was recorded by LVDT 2 which it was placed at the middle of the beam for beam specimen with 3% of steel fibre (Figure 5(a)). This maximum deflection recorded was 14.02 mm when a 34.32 kN load was applied. Maximum load recorded in the study was 37.58 kN, also by LVDT 2. From Figure 5(b), it shows that, LVDT 2 gave the highest value of deflection compared to the LVDT 1 and LVDT 3. The deflection was higher at the middle position of the beam specimen. The ultimate load experienced by the beam specimen with 5% steel fibre was 44.60 kN.
Table 2 shows the results of ultimate load and displacement with percentages difference comparison of each specimen group for the ultimate displacement. The ultimate load for reinforced concrete beam is slightly higher (0.4%) compared to prestressed beam with 5% steel fibre while prestressed beam with 3% steel fibre is recorded lower (18.53%) than reinforced concrete beam specimen. This has showed additional of steel fibre to prestressed beam did not contribute to the strength enhancement of the beam. The ultimate displacement comparison of each LVDTs showed LVDT 1 (left side) experienced the highest increment for prestressed beam with 5% steel fibre (14.24 mm) compared to reinforced concrete beam (2.84 mm). This can be observed from the crack failure happen for prestressed beam with 3% and 5% were more to the left side of the beam. The result contradict with ultimate displacement experienced by LVDT 3 (right side) which reflecting reinforced concrete beam crack failure can be seen at the right side of the specimen.

Table 2. Summary of Results

| LVDTs Position | Ultimate Loads (kN) | Ultimate Displacement (mm) | Ultimate Displacement (Different-%) |
|----------------|---------------------|-----------------------------|-----------------------------------|
|                | Reinforced Concrete Beam (RCB) | Prestressed Beam with 3% Steel Fibre (PBSF3) | Prestressed Beam with 5% Steel Fibre (PBSF5) | Reinforced Concrete Beam (RCB) | Prestressed Beam with 3% Steel Fibre (PBSF3) | Prestressed Beam with 5% Steel Fibre (PBSF5) | RCB - PBSF3 | RCB - PBSF5 | PBSF3 - PBSF5 |
| LVDT 1         | 46.4                | 37.8                        | 44.4                              | 2.84                      | 11.18                       | 14.24                        | 293.0       | 401.41      | 27.37       |
| LVDT 2         | 10.74               |                             | 13.37                             | 16.58                     |                             | 24.49                        | 54.38       | 24.00       |
| LVDT 3         | 17.24               | 6.52                        | 7.43                              | 62.18                     | 56.90                       | 13.96                        | 26.18       | 56.90       |

3.3. Cracking Pattern

The first crack was observed to occur at the support of the beam. It started from the beam soffit and propagated to the top of the beam. The crack started at 60 mm from the end of the support and continued until 294 mm distance from the support. Figure 6 (a) shows the crack pattern of the control beam which appeared at the right side of the beam.

Crack pattern for specimen with tendon and 3% of steel fibre can be seen in Figure 6 (b). The crack started to form at 390 mm from the right end of the support. From the observation, the crack was categorised as flexural-shear crack as the crack was large and sudden. The crack pattern formed from this specimen is as what has been recorded by Narayanan and Darwish [13]. The study conducted by
Narayanan and Darwish [13] was using un-tensioned reinforcement in the prestressed beam with the 0.75 fraction of steel fibre.

Figure 6 (c) is showing crack pattern formed for prestressed concrete beam with 5% steel fibre. This crack pattern was at 420 mm from the nearest support at left side of the beam and it occurred at the section between the flexural and shear zones. The crack failure mode observed in this beam was categorised as the flexural-shear failure. This beam specimen experienced a sudden crack with wider crack opening. This beam demonstrated more cracks as compared to the prestressed beam filled with 3% of steel fibre. This is due to shear crack increased significantly as the fibre content increased [7]. Increment amount of steel fibre will increase the strength of the beam as the steel fibre will act as bonding material in the concrete. This has been mentioned as well by Yusof et al. [14] whereby when the steel fibre concrete beam was loaded, the steel fibre will perform a bridging effect to the cracks.

![Figure 6. Crack Pattern of Prestressed Beam; a) Reinforced Concrete Beam b) 3% Steel Fibre c) 5% Steel Fibre](image)

4. Conclusion

From this study there are several findings that can be concluded:

i. Reinforced concrete beam specimen in this study has failed in shear crack while for prestressed beams with 3% and 5% steel fibre, the beams failed in flexural-shear crack manner. The reinforced concrete beam showed shear crack failure because it consists of reinforcement bar which resisted the flexural load applied. The prestressed beams with steel fibre showed flexural-shear crack behaviour with large crack occurred and the failure occurred at a very sudden rate compared to the reinforced concrete beam.

ii. More cracks were observed in the prestressed beam with 3% steel fibre compared to the prestressed beam with 5% of steel fibre. This due to 5% steel fibre prestressed beam have higher strength compared to the prestressed beam with 3% of steel fibre.

iii. The ultimate load for reinforced concrete beam is 46.38 kN while for prestressed concrete beam with 3% and 5% steel fibres, the ultimate load recorded were 37.22 kN and 44.63 kN, respectively.

iv. Prestressed concrete beam with 5% steel beam has achieved almost the similar compressive strength as the reinforced concrete beam with 4% differences which shows the existence of 5% steel fibre is sufficient to replace reinforcement in beam and can result in lowering the possibility of shear failure.

5.0 References

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