Shear behaviour of 0.6 % and 0.7 % steel fibre reinforced concrete beams without stirrups

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Abstract. Concrete is a brittle material and respectively weak in tensile strength and tensile strain. Concrete technology is applied at which concrete is reinforced with steel fibre, as known as steel fibre reinforced concrete (SFRC) to produce a versatile structural material to exhibit superior strength properties in terms of ductility, fracture energy, toughness, strength and durability. The introduction of short, discontinuous and randomly oriented steel fibres into conventional concrete mixes possesses a strong bond with the concrete matrix with high elastic modulus. The goal of this study is to create a standard foresight in determining the potentiality of steel fibre as secondary shear reinforcement to partially or fully replace shear stirrups in conventional concrete. For this purpose, the series of SFRC beam specimens without stirrups which have the same concrete mixing ratios were produced with the inclusion of 0.6 % and 0.7 % steel fibre by volume fractions and compared with conventional normal weight reinforced concrete (NWRC) beam with stirrups. After the beam specimens had attained the target concrete characteristic strength of C25/30, four-point bending test was conducted to investigate the shear behaviour of reinforced concrete beams. The structural performance of shear beams was evaluated in the response of load-deflection, load-steel strain, crack patterns and failure modes. Test results indicated that with incorporation of steel fibres, the compressive strength and splitting tensile strength were improved, ultimate shear strength was improved up to 36 % at addition of 0.7 % steel fibre content, but water absorption was reduced. Besides, NWRC beam with stirrup increased 43 % in ultimate shear strength which possessed better performance in ductility.

1. Introduction
Concrete is reinforced with fibre or meshes or steel bars to produce a versatile structural material which improves strength in bending, shear, torsion, tension and compression, unlike plain concrete which is only strong in compression. Use of steel is increasing in momentum due to its flexibility combined with its higher strength-to-weight ratio. Steel fibres possess a strong bond with the concrete matrix and high elastic modulus in augmenting the tensile strength and composite stiffness properties. Concrete with inclusion of steel fibres is known as steel fibre reinforced concrete (SFRC). Due to the flexibility in deforming and indenting of steel fibres, improvement of their anchorage increases their bonding strength and toughening capabilities [1]. SFRC has higher spalling resistance, toughness and ductility as the peak strain increased linearly with the increase of steel fibre volumetric percentage [2]. Application of steel fibre reinforcement could prospectively replace stirrup reinforcement by eliminating the shear size effect in beam depth and increasing shear strength [3]. Fibres act as a stress transfer medium to bridge these cracks effectively which tend to delay the coalescence and unstable growth of cracks [4]. Fibre bridging is favourable as it increases fracture resistance during crack growth. There was a changeability in crack
profile due to the addition of fibres whereby a lot of closely spaced microcracks formed and avert the occurrence of large cracks [5].

Hence, this study aims to analyse the shear behaviour of SFRC short beam in determining the potentiality of steel fibre as secondary shear reinforcement. The objectives of this study are to study the hardened properties of 0.6 % and 0.7 % steel fibres additions in concrete on compressive strength, splitting tensile strength and water absorption as well as to investigate the shear behaviour of 0.6 % and 0.7 % SFRC beams without shear stirrups as compared to conventional NWRC beam. Reference name for normal weight reinforced concrete beam without stirrups, normal weight concrete beam with stirrups, 0.6 % steel fibre reinforced concrete beam and 0.7 % steel fibre reinforced concrete beam were simplified as NWRC-without stirrups (W/OS), NWRC-with stirrups (W/S), SFRC-0.6 and SFRC-0.7 respectively.

2. Experimental procedures
The experimental program involved the concrete trial mix design process, collection, preparation and handling of raw materials and equipment, followed by mixing procedures of reinforced concrete. In addition, laboratory testing to obtain fresh state and mechanical properties of reinforced concrete included steel tensile test, slump test, compressive test, splitting tensile test, water absorption test and four-point loading bending test.

2.1. Materials and mix proportion
Composite raw materials used for the study consists of cement, fine aggregate, coarse aggregate, water and steel fibres. The “Orang Kuat” cement manufactured by YTL Cement (M) Sdn. Bhd. with strength class of 52.5, branded Ordinary Portland Cement (OPC) which complied with Type 1 Portland cement in accordance with ASTM C 150 [6] was used in this study. Besides, aggregates were prepared in the saturated surface dry condition in compliance with ASTM C 33 [7]. Crushed stone coarse aggregates with maximum size of 20 mm and fine aggregate with particle diameter of 56 % passing through 600 μm was employed in this study. The water used in this study was direct from municipal water tap in compliance with ASTM C 1602 [8] in the production of hydraulic cement concrete. The water-cement ratio applied in this study was 0.60 by referring to the Department of Environmental (DOE) method in achieving target strength. Hooked-end steel fibres with 0.55 mm in diameter and 35 mm in length in accordance with BS EN 14889-1:2006 and MS 2388: 2010 under Group 1 type made of cold drawn wire was used in this study as shown in Figure 1.

Figure 1. Short hooked-end steel fibre with an aspect ratio of 63.34.

Moulds for specimens or fastenings in compliance with ASTM C 470/ C 470M [9] were reusable steel cubic and cylinder moulds. For aggregate size equal to or exceeding 20 mm, the cubic and cylindrical mould dimensions used in conforming to the specifications are 150 mm (Width × Depth × Length) and 100 mm (Diameter) × 200 mm (Length) respectively. The concrete ingredients mix proportion is in terms of ratios of cement, water, coarse and fine aggregates.

The amount of fibres incorporated in the concrete mix was measured as 0.6 % and 0.7 % in the volume fraction of the composite of fibre reinforced concrete in this study. Table 1 shows the mix proportion of each concrete mix where NWRC is indicated as Mix 1 while; SFRC-0.6 and SFRC-0.7 are indicated as Mix 2 and Mix 3 respectively.
Table 1. Concrete mix design.

| Raw Materials (kg/m³) | Control Variables |
|----------------------|-------------------|
|                      | Mix 1 (NWRC) | Mix 2 (SFRC-0.6) | Mix 3 (SFRC-0.7) |
| Cement               | 341.67        | 341.67          | 341.67          |
| Fine aggregate       | 748.47        | 748.47          | 748.47          |
| Coarse aggregate     |               |                 |                 |
| 4.75 mm-10 mm        | 359.02        | 359.02          | 359.02          |
| 10 mm–20 mm          | 718.04        | 718.04          | 718.04          |
| Water                | 205           | 205             | 205             |
| Steel Fibre          | -             | 46.8            | 54.6            |

2.2. Design details and fabrication of beams

Figure 2 and Figure 3 show the structural beam detailing with and without stirrups respectively at dimensions of 125 mm (Width) × 200 mm (Depth) × 800 mm (Length) under four-point loading. The effective depth was to be 163 mm. By justification, the steel reinforcements used for the top and bottom rebar were 2R8 and 2H8 respectively; R8 was used for the shear link with a spacing of 100 mm, indicated in R8-100. However, shear links were not applied to the full span of beams but only located at shear span to avoid the delay of concrete crack at the flexure zone. This allowed the steel to yield first before crushing of concrete.

Preparations of concrete formwork panels, reinforcement cage and strain gauge installation were performed in advance before the casting of RC beam specimens. The chosen steel strain gauge was the FLK-6-11 type, TML load cell. It was attached at the bottom part of rebar located at the beam’s mid-span. The hardened RC beams were painted in white so that cracking propagation is more evident. Besides, 50 × 50 mm grid indication was drawn on the concrete beam surface to ease the coordination of cracking.
2.3. Testing methods
Cubical and cylindrical specimens were left to set after casting and demoulded after 24 hours. They were then cured to undergo hydration process for curing periods of 7 days and 28 days in accordance with ASTM C511 [10]. Whereas the beam specimens were left to set after casting and demoulded after 7 days and were fully covered with wet gunny bags for at least 7 days. In accordance with ASTM E 8 [11], the direct steel tensile test was carried out to determine the yield strength and ultimate tensile strength of the steel reinforcement bar by using Instron Universal Testing Machine. Besides, the slump test was carried out in accordance with ASTM C 143 [12] to determine the workability of fresh concrete. The concrete cube specimens were tested for its compressive strength when the required testing age had been achieved in accordance with BS EN 12390-03 [13]. Generally, the split-tension test was to measure the concrete tensile strength according to ASTM C 496 [14] by applying a diametric compressive force. The standard water absorption test method for density, absorption and voids in hardened concrete was performed in accordance with ASTM C 642 [15]. The mass of the surface-dried specimens after curing was determined and the specimens were oven-dried for 24 hours at a temperature of 100 to 110 °C to calculate the water absorbed. The four-point bending shear test was carried out on a simple beam according to ASTM D 6272 [16]. Three LVDTs were placed at three different locations at the midspan with 150 mm spacing. The shear strength was determined in term of shear stress.

3. Material test results and discussion
The properties of the material which determined from the experimental raw data of testing were presented followed by discussion on data analysis.

3.1. Steel tensile test
Table 2 shows the summary of mechanical properties computed from the tensile testing of the H8 and R8 steel bars based on the experimental data. The yield strain of the steel bar was determined by elastic tensile stress divided by modulus of elasticity.

| Steel Bar with Notation | Yield Strength (MPa) | Ultimate Tensile Strength (MPa) | Modulus of Elasticity (MPa) | Yield Strain (με) |
|-------------------------|----------------------|---------------------------------|-----------------------------|------------------|
| Longitudinal tensile steel bar | H8 485.33 | 568.25 | 214 980.30 | 2257.56 |
| Longitudinal compressive steel bar | R8 511.16 | 546.12 | 203 231.74 | 2515.16 |
| Transverse stirrups | R8 511.16 | 546.12 | 203 231.74 | 2515.16 |

3.2. Fresh concrete testing method-slump test
The fresh properties of the produced NWRC, SFRC-0.6 and SFRC-0.7 were obtained to determine the mixture workability. Table 3 shows the slump test results for plain concrete, 0.6 % and 0.7 % steel fibre additions in concrete. From the test results, it is shown that slump loss occurred with the increase of fibre percentage in the concrete mix. The reason for the lower slump is that the introduction of steel fibres can form a network structure in concrete, which can restrain mixture flow. Besides, increased fibre percentage cause more cement pastes to be absorbed and coated around due to the larger surface area, the mixture presents a much stiffer consistency and the increase of the viscosity of mixture contributes to the slump loss.
Table 3. Slump value recorded for each fresh concrete mix batch.

| Reference Name of Concrete Mix | Volume Fraction of Steel Fibre, $V_f$ (%) | Slump (mm) | Variation as Compared to Control (%) |
|--------------------------------|------------------------------------------|------------|-------------------------------------|
| NWRC (Control)                | 0                                        | 63         | -                                   |
| SFRC-0.6                      | 0.6                                      | 54         | -14.29                              |
| SFRC-0.7                      | 0.7                                      | 52         | -17.46                              |

3.3. Destructive hardened concrete mechanical strength test

For each batch of beam specimens, there were at least three concrete cubes for compressive strength test and three cylindrical specimens for splitting tensile test were casted from the same batch of concrete mix during casting of the beam. The main destructive tests on hardened concrete are the compressive test and splitting tensile test.

3.3.1 Compressive strength test. Figure 4 shows the average compressive cube strength taken from the result of three cube specimens after 7 days of curing and 28 days of curing.

![Figure 4](image)

**Figure 4.** Average compressive cube strength of concrete specimens at 7 days and 28 days curing periods.

Figure 4 shows a direct proportionality of compressive strength to curing age. Typically, the compressive strength of concrete at 7 days curing age reached around 70 % to 80 % of the compressive strength of concrete at 28 days curing age. The compressive strength of concrete specimens with the inclusion of 0.6 % and 0.7 % increased by 6.93 % and 10.23 % respectively as compared to plain concrete. As mentioned in Kumutha and Vijai [17], there would have an insignificant increase in compressive strength with the addition of steel fibre in concrete mixture beyond 0.5 % volume fraction.

Normal concrete easily fails when subjected to compression as stress block at 45 degree in angle is heavily sheared due to its brittleness. This is due to reduced shear stress in concrete against this shear plane due to introducing fibres. Besides, concrete with the inclusion of steel fibre is likely to be confined and take slightly more load. Figure 5 illustrates the crack patterns of a plain concrete cube specimen and a steel fibre concrete cube specimen respectively. It can be observed that the crack width of the plain concrete cube is much larger than that of the steel fibre concrete cube and there is serious crushing and spalling of the plain concrete as compared to the steel fibre concrete. The plain concrete also developed major cracks on the surface as compared to the steel fibre concrete. This is due to the bridging effect provided by the steel fibres in the latter specimen that distributing the stress among concrete cracks to limit the propagation of cracking or breaking of concrete.
Figure 5. Crack pattern of concrete cube specimens under compressive test: (a) plain concrete; (b) steel fibre concrete.

3.3.2. Splitting tensile strength test. Figure 6 shows the average tensile strength taken from the result of three-cylinder specimens after 7 days curing and 28 days curing. The splitting tensile strength of concrete at 7 days curing age reached around 80 % of the splitting tensile strength of concrete at 28 days curing age. The tensile strength of concrete specimens with the inclusion of 0.6 % and 0.7 % increased by 13.98 % and 17.92 % respectively as compared to plain concrete. This is due to the fibre-bridging mechanism possessed by fibres within the concrete matrix that act as a multi-dimensional reinforcement. There was a uniform distribution of applied load throughout the concrete specimen instead of a local concentration of load on one region.

Figure 6. Average splitting tensile strength of cylinder specimens at curing periods of 7 days and 28 days.

Figure 7 and Figure 8 depict the crack patterns of a plain concrete cylinder specimen and steel fibre concrete cylinder specimen respectively. The indirect tensile stress induced the splitting of the plain concrete cylinder into two halves during the loading. However, the steel fibre concrete cylinder was held in position and remained intact with smaller crack width. This was due to strong interlocking force between the concrete matrix and steel fibres contributes in transferring stress and distributing load uniformly to region around, hence increase the splitting tensile strength.

Figure 7. Crack pattern of plain concrete cylinder specimen: (a) plan view of concrete cylinder; (b) side elevation of concrete cylinder.
3.4. Durability concrete testing-water absorption test

The water absorption test was performed by submerging the concrete cube specimens in water until the weight became constant. Figure 9 shows the average water absorption taken from the result of three concrete cube specimens after 7 days and 28 days.

![Figure 8. Crack pattern of steel fibre concrete cylinder specimen: (a) plan view of concrete cylinder; (b) front elevation of concrete cylinder.](image)

![Figure 9. Average water absorption of cube specimens at curing periods of 7 days and 28 days.](image)

From the result shown, the water absorption of the concrete specimen with the inclusion of 0.6 % and 0.7 % decreased from 2.82 % and 6.50 % respectively as compared to plain concrete. It can be concluded that steel fibre concrete shows improved durability in water absorption as compared to normal concrete. The same steel fibre influence on water absorption in concrete was investigated in the experimental research conducted by Velayutham and Cheah [18] in studying the durability of steel fibre reinforced high strength concrete subjected to normal curing. Steel fibre concrete has lower water absorption and permeability than plain concrete as steel fibre in concrete resist movements, hence reduce permeability. Steel fibre concrete is able to limit pore connectivity and reduce porosity of the concrete mix since it is coated by cement paste and it does not absorb moisture.

4. Shear strength beam test results and discussion

During the four-point bending test, tested beams were subjected to two-point loads which were applied in uniform increments and deflections were imposed. The applied load, the beam deflection and longitudinal rebar strain were recorded continuously up to failure and plotted as load-deflection curves and load-steel strain curves. A comparison between the shear beam test results was studied to investigate the effect of variables on beam behaviour in conjunction with crack pattern and failure mode.

4.1. Shear strength beam test subjected to four-point loading

Table 4 shows the peak shear load applied on each beam specimens at ultimate failure, ultimate shear strength and failure mode on tested beams. The ultimate shear capacity was computed for NWRC which can be resisted by the concrete strut as well as SFRC.
Table 4. Tested beams details.

| Type of Beam (Reference Name) | Ultimate Load Applied, $P$ (kN) | Experimental Ultimate Shear Strength, $v_{\text{ULT,exp}}$ (MPa) | Computed Ultimate Shear Strength, $v_{\text{ULT,cal}}$ (MPa) | Shear Strength Ratio, $\frac{v_{\text{ULT,exp}}}{v_{\text{ULT,cal}}}$ | Failure Mode |
|------------------------------|---------------------------------|---------------------------------------------------------------|-------------------------------------------------------------|----------------------------------------------------------|--------------|
| NWRC-W/OS                    | 88                              | 2.16                                                          | 2.02                                                        | 1.07                                                     | Shear        |
| NWRC-W/S                     | 126                             | 3.09                                                          | 2.38                                                        | 1.30                                                     | Shear        |
| SFRC-0.6                     | 116                             | 2.85                                                          | 3.01                                                        | 0.95                                                     | Shear        |
| SFRC-0.7                     | 120                             | 2.94                                                          | 3.18                                                        | 0.92                                                     | Shear        |

The results show that the ultimate shear strength increased from 2.85 MPa to 2.94 MP, where the performance was improved by 31.94 % and 36.11 % when 0.6 % and 0.7 % of steel fibres were introduced respectively. However, the results show that the NWRC-W/S increased the shear strength of NWRC-W/OS beam up to 45.15 %. NWRC-W/S beam can sustain a higher load as compared to the beams with the inclusion of steel fibres content at 0.6 % and 0.7 %. The inclusion of steel fibres in the concrete matrix can exhibit the ductile tensile behaviour even after cracking during the load resisting phase due to the bridging mechanism of the fibre pull-out behaviour. The steel fibres that intersect in the cracking plane absorb the residual stress and improve the post-crack compressive behaviour.

4.2. Load-displacement response

The deflection was measured at midspan of the tested beam until failure and plotted as load-midspan deflection curves. Figure 10 illustrates the midspan deflection behaviour of the NWRC-W/OS, NWRC-W/S, SFRC-0.6 and SFRC-0.7 beams subjected to the applied load. Table 5 shows the results of first crack failure with the increase of steel fibres content. The first crack strength determined the FRC behaviour up to the onset of cracking in the concrete composite, whereas toughness indices characterize the toughness up to specified end-point deflections [19].

![Figure 10. Load-deflection behaviour of beam specimens at midspan.](image-url)
Table 5. Summary of First Crack Strength, First Crack Deflection and Stiffness Indices of Bending Beam Specimens.

| Type of Beam (Reference Name) | First Crack Strength | First Crack Deflection | Stiffness Indices |
|-------------------------------|----------------------|-------------------------|------------------|
|                               | $v_{cr}$ (MPa)       | $\Delta$ (%) | $\delta_{cr}$ (mm) | $\Delta$ (%) | $\frac{P_{cr}}{\delta_{cr}}$ (kN/mm) | $\Delta$ (%) |
| NWRC-W/OS                     | 1.01                 | -             | 3.63              | -              | 11.29                     | -             |
| NWRC-W/S                      | 1.25                 | 23.76         | 4.03              | 11.02          | 12.66                     | 13.13         |
| SFRC-0.6                      | 1.06                 | 4.95          | 2.73              | -24.79         | 15.75                     | 39.50         |
| SFRC-0.7                      | 1.10                 | 8.91          | 3.36              | -7.44          | 13.39                     | 18.60         |

According to the graphic in Region A, as the fibre volume increased, the first cracking load increased. Notably, introduction of steel fibre can sustain higher first cracking load than control beam without stirrups but lower first cracking load than beam with stirrups. Stiffness reflects the resistance of an elastic body to deformation or deflection when subjected to the applied force. SFRC-0.6 possessed the highest degree of stiffness indices where improvement of stiffness was up to almost 40%. However, NWRC-W/S possessed highest first crack deflection which showed that beam with stirrup improved the pre-cracking behaviour by delaying the appearance of the first cracks for flexure shear cracks due to its high efficiency in energy absorption. Besides, the toughness of concrete beams can be determined from the area under the load-deflection curve. It indicates the energy absorption capacity of reinforced concrete beams which is significant for behaviour after the onset of cracking before rupturing.

As shown in Figure 10, when fibre volume fraction increased, the toughness of beam specimens increased significantly as compared to NWRC-W/OS beam. The addition of a volume fraction of hooked steel fibre as shear reinforcement imparts ductility and substantially increases the shear strength of a concrete beam. However, it can be seen that NWRC-W/S beam still has the highest first cracking strength with the improvement of 23.76 % as compared to NWRC-W/OS as well as toughness with the highest shear resistance as stirrups help in energy absorption and high ductility.

By referring to the later stage in Region B based on Figure 10, the corresponding maximum midspan deflection were 9.23 mm (at 88 kN), 11.65 mm (at 126 kN), 10.91 mm (at 116 kN) and 10.98 mm (at 120 kN) for NWRC-W/OS, NWRC-W/S, SFRC-0.6 and SFRC-0.7 beams respectively. With the inclusion of 0.6 % and 0.7 % steel fibres, the deflection had increased by 18.2 % and 19 % respectively. The maximum deflection in SFRC beams was found to be increased with the increase in the fibre content, which infers that the steel fibre addition in a beam improves the post-peak ductility and maintains the ultimate load through further deflection. Steel fibres improve the bendability of the concrete structures and improve the effective stiffness of the beam after the occurrence of diagonal tensile cracking and decrease the beam deflection [20]. This can be explained when steel fibres act as a medium in bridging existing macrocracks by limiting them from extending in the opening and improving the post-cracking strength. The mechanism works when steel fibres take up a large portion of tensile stress, allow the beam structure to sustain the higher ultimate load.

4.3. Load-steel strain response

Figure 11 illustrates the full behaviour of load-steel strain in midspan steel reinforcement bar for all four tested beams. As shown in Figure 11, NWRC-W/OS beam had its first crack at 41 kN and led to the sudden elongation of the bottom concrete. The bottom steel reinforcement in NWRC-W/OS tended to deform under higher strain as the tensile stress was solely restrained by steel reinforcement which transferred from concrete. Upon further loading, the steel strain of NWRC-W/OS beam at ultimate load of 88 kN was 2185 $\mu$e. Since yield strain equals to 2257 $\mu$e, the failure of the beam was not due to excessive yielding of the steel reinforcement but rather the excessive crack in the concrete. As compared
to NWRC-W/OS beam, SFRC-0.6 and SFRC-0.7 beams have higher steel strain value of 2297 με and 2304 με with an increment of 5.13 % and 5.45 % respectively. This is due to tensile stress in the concrete was shifted to the steel fibres instead of being transferred directly to the steel reinforcement, thus the elongation of steel reinforcement had been delayed when steel fibres started to withstand the stress immediately in preventing radical deflection of beam as compared to NWRC-W/OS beam which improve the tensile stress capacity in concrete.

![Load-steel strain curve of beam specimens](image)

**Figure 11.** Load-steel strain curve of beam specimens.

For NWRC-W/S beam, the steel strain value achieved was 2352 με at the load level of 126 kN. Except for NWRC-W/OS beam which failed due to crushing of concrete before the yielding of steel, NWRC-W/S, SRFC-0.6 and SFRC-0.7 were failed due to both excessive cracks in concrete and yielding of the steel reinforcement. Shear failure was expected as steel reinforcement had not yielded in excess. Steel fibres used in the reinforced concrete beam act as a secondary reinforcement and can improve post-cracking tensile resistance and prevent instantaneous crack width development after the yielding of reinforcement. NWRC-W/S had a steeper gradient in load-steel strain prior to failure as compared with SFRC-0.6 and SFRC-0.7. NWRC-W/S beam has better properties in energy absorption and higher load bearing capacity as compared to SFRC-0.6 and SFRC-0.7.

### 4.4 Crack pattern and failure mode

Figure 12 and Figure 13 illustrate distinctive cracks development between NWRC-W/OS, NWRC-W/S, SFRC-0.6 and SFRC-0.7 at first crack loading and ultimate failure loading. The first crack formation which occurred near the region of the applied load cell indicated that the development of moment by the loading was greater than the moment capacity of cracking of the beams. Figure 12 depicts the first tension crack of both NWRC beam specimens as a flexural-shear crack and about 100 mm from the midspan. Besides, the initial crack of the SFRC-0.6 and SFRC-0.7 beams formed later at 43 kN and 45 kN respectively as compared to NWRC-W/OS beam.

As referred in Figure 13, flexural-shear cracks were spread throughout the shear span as loading was incremented continuously. Those cracks were extended from past flexural cracks. The presence of steel fibres which bonded at the tensile surface of the concrete beam helped in arresting the macro-cracks from propagating whereas the stirrups in the RC beam absorbed energy and distributed the stress induced. Besides, the diagonal cracks started from the last flexural-shear crack turned to be more inclined under shear loading. NWRC-W/S, SFRC-0.6 and SFRC-0.7 beams were able to exhibit several major inclined cracks prior to a complete failure. With splitting cracks developed along with the upper
compression layer, the NWRC-W/S, SFRC-0.6 and SFRC-0.7 beams are said to approach a combination failure mode of diagonal tension and shear compression failure.

![First Crack Comparison](image1)

**Figure 12.** Comparative first crack.

![Ultimate Failure Mode](image2)

**Figure 13.** Comparative ultimate failure mode.

The beams with the inclusion of steel fibres and stirrups which assisted in energy absorption, enabling it to resist additional loading after the formation of inclined cracks. However, NWRC-W/S beam had a better serviceability performance in controlling crack formation. The principal stresses were redistributed along the homogeneous concrete beam and the principle compressive stresses within the beam was imposed in an arch form, whereas tensile stresses took the form of a curve assumed by a cord or suspended chain [21]. The bending stresses were dominant with minimum shear at the midspan of the beam, hence the stresses direction was more likely to counterpart to the beam axis. Since the shearing forces were greater at supports, the principle stresses were more likely to be inclined and the diagonal cracking was formed near the supports due to tensile stresses subjected to shear. Hence, greater shear force imposed a greater inclination angle.

When the load was sufficient to impose a diagonal tension greater than the concrete tensile strength, a critical inclined crack occurred and followed by immediate failure of beam. It can be noted that the last critical crack developed fully. NWRC-W/S beam sustained the highest ultimate shear load at a load level of 120 kN, followed by SFRC-0.6, SFRC-0.7 and lastly the control beam, NWRC-W/OS at 120
kN, 116 kN and 88 kN respectively. Besides, much of the true shear cracks have also occurred at the lower half region of the beam especially for SFRC-0.6 and SFRC-0.7 beams where the tensile stress was distributed uniformly, minimizing crack width as well as reducing the crack spacing between two adjacent cracks. As compared with NWRC-W/OS beam, both SFRC-0.6 and SFRC-0.7 beams have higher shear strength, as steel fibres manage to transfer tensile stress across the surfaces of crack, which is known as crack-bridging stress [20]. Besides, prior to beam collapse, a significant deformation was detected where the cracks appeared on beams with the incorporation of fibres substantially increased in number and were more closely spaced. The cracking pattern demonstrated the increased energy absorption capacity where the shear failure mode was gradual enough in dissipating sufficient energy before fracture [22]. The behaviour was explained with aggregate bridging zone which initiated the fibre-matrix debonding zone from matrix-micro cracking. The shear failure mode of all beams was similar with the diagonal failure modes with about 45 degree of inclined diagonal crack. Hence, there is a combination of diagonal tension failure and shear compression failure at the shear crack tip when there is crushing of concrete in the compression zone.

5. Conclusion
This research study presented a comprehensive experimental program for studying the shear behaviour of 0.6 % and 0.7 % steel fibre reinforced concrete beams without stirrups. The main objectives of this study are to study the hardened properties of SFRC-0.6 and SFRC-0.7 on compressive strength, splitting tensile strength and water absorption; to investigate experimentally the shear behaviour of SFRC-0.6 and SFRC-0.7 beams without stirrups; and to study the shear behaviour of SFRC-0.6 and SFRC-0.7 beams as compared to conventional normal weight reinforced concrete beams.

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It has been observed that the compressive strength of concrete specimens with the inclusion of 0.6 % and 0.7 % were 32.01 MPa (increment of 6.93 %) and 33 MPa (increment of 10.23 %) respectively as compared to plain concrete with 29.94 MPa in compressive strength. The splitting tensile strength of concrete specimens SFRC-0.6 and SFRC-0.7 were 3.18 MPa (increment of 13.98 %) and 3.29 MPa (increment of 17.92 %) respectively as compared to normal concrete with 2.79 MPa tensile strength. It was found that there was a reduction of 2.82 % and 6.50 % in water absorption of SFRC-0.6 and SFRC-0.7 respectively. The ultimate shear strength of 0.6 % and 0.7 % SFRC beams had increased 31.82 % and 36.36 % respectively as compared to the NWRC beam without stirrups, whereas NWRC beam with stirrup increased 43.18 % in ultimate shear strength which possessed better performance in ductility. Inclusion of steel fibres also reduced the beam deformations substantially at all load levels, controlled dowel bar, delay crack formation, shear cracking by controlling the crack width and length in propagation. It can be noted that SFRC fibres possessed more cracks, but they were smaller than in plain concrete and the crack spacing was also narrower. All of the tested beams possessed an arch action in a shear-transfer mechanism where the shear was transmitted directly to the support through a compression strut that would develop between two adjacent web-shear cracks formed in a member. The beams approached a combination failure mode of diagonal tension and shear compression failure. Overall, the steel fibres that intersected in the cracking plane absorb the residual strength improving the post-crack compressive behaviour. Hence, steel fibres can improve the tensile strain capacity as well as the flexural stiffness in resisting deflections and the behaviour at serviceability limit state as they are able to permit effective stress transfer using bridging mechanism and reduce crack width and crack spacing.

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