Mechanical behaviour of Steel fibre reinforced concrete beams: a review

Al-Khwaja Aysar Fares Amin¹, Choong Kok Keong¹* and Tan Geem-Eng²

¹School of Civil Engineering, Universiti Sains Malaysia
14300 Nibong Tebal, Pulau Pinang
² RIVO Precast SDN. BHD.
41050 Klang, Selangor, Darul Ehsan, Malaysia

*E-mail: cekkc@usm.my

Abstract. Concrete is one of the most widely utilized material in the world. It is mainly used in construction due to its capability to be formed to any required shape. This because of the good workability of the fresh concrete. However, concrete is still a brittle material that makes it tends to fail under tension. Thus, a material with high tensile strength needs to be included in the mixture such as steel rebars and steel fibres (SF). This review paper summarizes previous studies that investigated the effect of SFs addition on the mechanical properties of reinforced concrete (RC) beams. Researchers in all previous studies agreed that the addition of fibres in RC beams can noticeably improve the mechanical properties, serviceability, and durability of RC beams. Generally, the effect of SFs on the RC beams was dependent on various factors such as aspect ratios, volume percentages, and type of SFs. It was confirmed that the optimum SFs content ranged from 0.75 to 1.5 V.%, depending on the strength of concrete. However, more studies are required to further understand the effect of fibres on the properties of concrete in beams with different cross-sectional shapes.

1. Introduction
One of the most valuable properties of the SFs is the excellent resistance to crack propagation and cracking. Commonly, SFs with reinforced concrete were used to monitor the cracks that happened due to both plastic and drying shrinkage. Due to the ability to arrest cracks, SFs tend to enhance the tensile strength of the concrete mixture only when the SF modulus of elasticity is larger than the mortar binder or concrete, also it can hold the concrete matrix even after wide cracking [16,20]. SFs not only improve the tensile strength, but also can enhance the extensibility of the concrete, at both ultimate and first crack, under flexural loading [4,16]. Another important factor that affect the concrete mix is the aspect ratio of SFs (length/diameter of SFs). Generally, the aspect ratio of SFs is proportional to the toughness and the flexural strength of concrete. However, sometimes too long SFs tend to form “ball” in the concrete mix, creating workability problems [20]. The inclusion of SFs not only improve the strength and toughness of concrete, but it can also lower the permeability of the RC. The reduced permeability of concrete can also lead to reduction in the water bleeding [19,20]. Several types of SFs generate larger shatter resistance, abrasion, and impact in concrete. The net results of the majority of studies that have been performed on the steel-fibres-reinforced concrete (SFRC) have agreed that inclusion of SFs have the ability to alter the character of the SFRC from brittle to ductile material. This changing will basically
increase some characteristics of the SFRC. For instance, the energy absorption and its ability to resist repeatedly applied, impact or shock loading [1].

2. Effect of SFs on the mechanical properties of concrete

2.1. Effect on compressive strength

The inclusion of SFs has been shown to improve compressive strength of concrete. However, the improvement in the compressive strength of concrete is influenced by the volume content of the SFs. For example, Van Chanh et al. (2004) studied the inclusion of 1% SFs by volume which corresponds to 78.6 kg/m³, and they indicated that this content slightly increased the compressive strength from 0 to 25% [16]. Similarly, 20% improvement in the concrete compressive strength was observed by Mello et al. (2014) when 2.3% SF was used in the concrete mixture [10]. Figure 1 shows the effect of SFs content on compressive strength. It can be noticed from Figure 1 that the inclusion of 3% fibre content enhanced the compressive strength of plain concrete by around 15%. These findings with regards to the improvements in compressive strength by Mello et al. are in agreement with other investigations [16]. Moreover, Olivito and Zuccarello, (2010) studied the effect of SFs on the compressive strength. Results showed that the concrete cube specimens did not fail. They maintained their integrity until the end of the test. This is attributed to the fibres bridging effect on the specimens. They have further observed that the compressive failure of the SF reinforced samples was significantly altered from fragile to the ductile state [12]. In addition, Jang and Yun, (2018) have investigated the combined effects of coarse aggregate size and SFs on flexural and compressive strength of high-strength-concrete. Their results showed that both aggregate size and SF volume fraction have little effect on the modulus of elasticity and compressive strength of Steel-Fibre-Reinforced-Concrete. Furthermore, their results showed that the increase of fibre volume fraction can improve the toughness, post-peak behaviour, peak strain of Steel-Fibre-Reinforced-Concrete under compression [6].

![Figure 1. Stress-Strain curves in compression for SFRC [16].](image)

The compressive behaviour of fibre reinforced concrete with end hooked SFs has been investigated [9]. Lee et al. (2015) performed uniaxial compression tests on 48-cylinder specimens with dimensions of 150 mm and 300 mm for diameter and height, respectively. The variables that they considered are length to diameter (fibre aspect ratio), fibre volumetric and concrete compressive strength. Their results revealed that the SF volume content and the SF aspect ratio can influence the compressive strength and the slump of SFRC; for instance, the compressive strength increased slightly when the fibre volume content increased for the aspect ratio of 45, while the compressive strength of the aspect ratio of 65 decreased when increasing the fibre content.
2.2. Effect on tensile strength
The effect of SFs addition on the tensile strength of concrete has been studied by several authors [10,12]. Generally, the investigations showed that the addition of SFs can significantly improve the tensile strength. However, the increment percentage was influenced by the volume content of the fibres; for instance, Olivito and Zuccarello (2010) have investigated the tensile strength of Steel-Fibre-Reinforced-Concrete by performing a direct tensile test on eight different prismatic specimens which have dimensions of 30 × 80 × 350 mm with only one type of SFs but different lengths (22 mm and 30 mm) with only 1% of fibre content. The experimental study revealed that the maximum tensile strength for the 22 mm and 30 mm SFs is 3200 N and 5800 N, respectively. The results mean that the improvement of the maximum tensile strength was enhanced up to 44% of the maximum tensile strength for the 22 mm fibres specimens, whilst for 30 mm fibres specimens showed higher ultimate strain compared with 22 mm fibres specimens [12]. In addition, these results were in agreement with study conducted by Mello et al. (2014) where they indicated that the addition of SF content up to 3% resulted in a significant increase in the tensile strength of concrete from null to 121.5% [10].

2.3. Effect on flexural behaviour
Several studies have investigated the flexural behaviour of SFRC. Jang and Yun, (2018) investigated the flexural behaviour by performing a three-point bending test on three prismatic specimens (300×100×100 mm). Each specimen was fabricated using different SF percentages (0.5, 1.0, 1.5, and 2.0 V.%.) and different aggregate sizes (8, 13, and 19 mm) in the concrete mixture by following American standards. The findings showed significant improvement in the equivalent flexural strength ratio; for instance, the flexural load ranged between 50 – 55 kN with the use of 2% SFs, while the maximum flexural load for 0.5% SF ranged between 20 – 37 kN under conditions of different aggregate sizes. Similarly, the maximum flexural load ranged between 50 to 52 kN with the use of 1.5% SF under conditions of different aggregate sizes. The improvement that occurred to the flexural performance of SFRC is mainly related to the volume fraction of SFs in the tension zone of the prismatic specimen. Therefore, it was suggested to use 1.5% volume fraction of hooked SFs since it is more economical and efficient. On the other hand, the results showed that the use of small aggregate size has a small effect on mechanical properties compared to SFs volume fraction. But small aggregate size with a high percentage of SFs was found to help the SFs to be distributed homogeneously within the concrete mix [6].

Yoo et al. (2018) have studied the influence of employing SFs on the flexural behaviour of RC beams with low reinforcement ratio. In their study, they incorporated four different fibre volume content of 0.25%, 0.50%, 0.75%, and 1.00% into the concrete mixture. A control specimen without the addition of fibres was also cast. Furthermore, the SF influence on flexural behaviour of RC beams was also evaluated using different low reinforcement ratios of 44%, 66%, 78%, and 100% of $\rho_{\text{min}}$. The results indicated an improvement in the flexural performance of RC beams, including the cracking behaviour, post cracking flexural stiffness, deflection capacity and flexural strength with the increment of the reinforcement ratio up to minimum reinforcement; for instance, the ultimate load reached 70 kN for 44% reinforcement ratio of $\rho_{\text{min}}$ and 0.5% SF content. However, ultimate load up to around 120 kN was observed when using 1.0% SF content and 100% reinforcement ratio of $\rho_{\text{min}}$[19]. A similar study that investigated the effect of SF content on the flexural behaviour of concrete reported that the addition of 2.3% of SF improved the flexural strength up to 80.7%. However, a further increase in SF volume content to 3% led to a decrease in the flexural strength from 80.7 to 67.9 % (Mello et al., 2014) [10]. This clearly shows that the increase of SF content does not necessarily improve the flexural strength of concrete. Therefore, further studies are required to determine the optimum SFs percentage that can give maximum flexural strength. Additionally, the employment of SFs resulted in an improvement of the post cracking stiffness, cracking performance, yield loads and initial cracking. However, the effect on the ultimate load-carrying capacity was found to be low. The utilization of high fibre volume content with low reinforcement ratios has led to lower ductility indices. It was concluded that discontinuous SFs could not be used as a replacement of longitudinal steel reinforcements at moderate volume content ($V_f = 1\%$) in terms of flexural strength, ductility and ultimate load carrying capacity margin[18].
2.4. Effect on shear behaviour

Several authors investigated the effect of replacement of transverse reinforcement with SFs on shear behaviour. Dinh, (2009) studied the shear behaviour of RC beam with hooked-end SFs as a replacement for stirrups. Twenty-eight simply supported beams with a shear span-to-depth ratio of 3.5 were cast. The specimens were subjected to concentrated load. Two parameters were used in the investigation which include fibre types and fibre volume content between 0.75% to 1.5%. Three types of DRAMIX hooked-end SFs were used. The first two types had the same length of 30 mm with different aspect ratios of 55 and 80, while the third had a length of 55 mm with aspect ratio of 80. The results indicated that the employment of 0.75% of fibre volume content or greater led to a significant improvement in shear strength; for example, the shear capacity for the 0.75% SF content reached 220.45 kN, while 270.63 kN shear capacity was observed when using 1.5% fibre content at the same fibre aspect ratio of 55. However, for fibre aspect ratio of 80, there was a slight difference of 17% higher than the 55 aspect ratio with 0.75% fibre content [4]. It can be concluded that there is a proportional relationship between the aspect ratio, fibre content, and shear capacity. Moreover, it was also observed by Dinh that hooked-end SFs can be employed as a minimum shear reinforcement in reinforced-concrete beams cast with normal strength concrete as well as within the considered depth range [4]. It is worth mentioning that these observations are in agreement with the ACI Code Section 11.4.6 [1], which states that the usage of hooked-end SFs in volume contents greater than or equal to 0.75% can replace the minimum shear reinforcement in normal-strength concrete beams as long as Vu lies down between the range of 0.5ȹVc ≤ Vu ≤ qȹVc (318-08, 2008) [1]. In addition to the abovementioned statements, the volume content of 0.75% has been proven to be the most recommended fibres ratio to be used as replacement for minimum reinforcement. Parra-Montesinos(2006) investigated the shear strength of 250 mm SFRC beams. The SFs (hooked end and deformed) replaced the minimum shear reinforcement in the beams completely. The obtained data showed that the addition of 0.75% of deformed or hooked SFs has shown to be the optimum volume fraction [13]. Moreover, it has been also indicated by Dinh that the utilization of fibres volume content had a greater effect on the shear strength of SFRC beams compared with effective beam depth and longitudinal reinforcement ratio. They further claimed that the increase in shear strength receded when the employment of fibres volume fraction was more than 1%. The abovementioned studies have investigated the effect of hooked-end SFs with normal concrete on the shear behaviour. High strength concrete has also been employed and investigated in past studies. For example, a recent study claimed that the addition of 0.75% of hooked fibres as a replacement for the minimum shear reinforcement with high strength concrete resulted in an acceptable alternative [19].

Further studies have also investigated the effect of fibres on shear behaviour [2]. Cucchiara et al. (2004) studied the effect of hooked-end SFs on rectangular simply supported beams with and without stirrups. Fibres length with 30 mm with an equivalent diameter of 0.5 mm (aspect ratio 60) and nominal tensile strength of 1115 MPa were used. Fibre contents corresponding to 1% and 2% of the volume of concrete were included in the mix. The results indicated that the use of a sufficient percentage (1-2%) of SFs can change the brittle shear mechanism to a ductile flexural mechanism. Furthermore, the changing from brittle shear mechanism to a ductile flexural mechanism would allow large dissipation of energy. They also claimed that the use of SFs as an alternative to transverse reinforcements in simply supported beam produce a similar performance in traditional simply supported beam in terms of ultimate strength while using SFs and shear reinforcement together would be more suitable because stirrups allow a larger deformation capacity beyond the elastic limit.

2.5. Effect on crack behaviour

Addition of SFs have also been shown to positively affect the crack behaviour of concrete elements. Soulioti et al. (2011) have fabricated plain and fibre reinforced concrete specimens with 0.5, 1, and 1.5 V.% SF content. Their results showed that the fibre reinforced concrete samples noticeably retained the post cracking ability, unlike plain concrete samples which failed significantly by a single crack [14]. Several authors found that the cracking behaviour of RC beams has been improved by the addition of SFs. Olivito and Zuccarello(2010) stated that using higher fibre content of 1% as well as fibre length of
30 mm resulted in the increment of the ductility and tenacity of the SFRC[12]. Moreover, the study showed that this phenomenon occurs due to the high energy absorption and high deformability nature of SFRC. The study also showed that different fibre length can affect the post-cracking behaviour. Short fibres caused softening behaviour, while long fibres resulted in hardening behaviour. It is worth to mention that long fibres not only influence the post-cracking behaviour, but it can also increase the maximum load carrying capacity of the member. Furthermore, they observed that increase of fibre content resulted in increase in flexural strength, first crack strength, and ductility. The study also showed that SFRC has higher bending stiffness and different cracking style compared with those of normal concrete[12].

In addition, the effect of beam depth on the crack behaviour in the case of replacing the minimum transverse reinforcement with SFs content of 0.75% has also been investigated; for example, Dinh(2009) concluded that wider spacing between inclined cracks when larger beam depths were utilized. Generally, beams with larger spacing between cracks exhibited lower shear strength compared to beams with small crack spacing. The influence of hooked-end SFs with different lengths on the crack behaviour has also been studied by Dinh(2009). As a result, fibre lengths of 60 mm allowed a larger inclined crack opening before the occurrence of complete failure compared to the type of failure observed with beams having a fibre length of 30 mm. However, the consolidation of long fibres was unfavourable. In addition, Dinh suggested the use of fibres with length less than the clear spacing between longitudinal bars to achieve reasonable consolidation[4]. As have been discussed before, SFs intend to change the character of the concrete from brittle to ductile as shown in Figure 2. Figure 2 shows the effect of using long and short straight SFs on the concrete cracks. Short straight SFs were used to bridge or links the microcracking but long straight SFs were used to close the macrocracks of the concrete[3].

![Figure 2. Effect of SFs on concrete characteristics and effect of long and short SFs on the cracks][3].

### 3. Orientation and distribution of SFs

SFs reinforcement can be employed as a three-dimensionally randomly distributed form in structural elements. This, as a result can enhance the shear resistance and crack control of the structural member. In addition, SFs can also act as a tensile layer that covers the steel reinforcement in the structural element. It is found that the efficiency is better if two-dimensional orientation of SFs occurred in the structural element [16, 20]. Several researchers intensively investigated the orientation and distribution behaviour of SFs in hardened concrete. It was stated in research studies [7, 8] that the orientation of SFs resulted from a series of stages where these stages starts from the mixing of the concrete until the hardening of the concrete inside the formwork. In addition, the boundary conditions related to each stage
of the fabrication process and the actions imposed, such as external vibration, gravity and wall effect
can encourage many interaction stages where the orientation of SFs is modified. The orientation and
distribution of SFs in SFRC specimens were also studied in [5,15] where the results obtained revealed
that compaction process has a significant effect on the orientation of the SFs. During the compaction
process, a phenomenon called wall effect occurred. They explained that this phenomenon of SFs
orientation tends to make SFs orientated parallelly to the surface of the formwork. However, this
phenomenon has shown to only affect the concrete that is in contact with the surface of the formwork.
In the case of using long SFs in thin elements, the wall effect can be significant (see Figure 3).

Figure 3. Illustration of wall effect inside formwork [15].

In the same studies, it was also reported that the vibration (180 Hz) of concrete can trigger the alignment
and rotation of the SFs preferentially in a specific direction[5, 15]. The SFs tend to be orientated
perpendicular to the direction of the external vibration. Studies have shown that the most significant
factor affecting the SFs distribution and orientation is casting method, in particular for self-consolidation
SFRC[17, 19]. According to the results, the required distribution and orientation of SFs in the
construction site can be achieved by carefully controlling the casting method. However, Laranjeira et
al, (2011) [7] showed that the existence of coarse aggregate does not allow the SFs to line up parallel to
the direction of shear crack and random distribution and orientation of SFs is achieved instead. Yoo et
al. (2016) have recommended the following methods to overcome this issue: (i) the inclusion of SFs
slowly in the fresh concrete (dosage) and mixing again of fresh concrete and (ii) the casting of the fresh
concrete parallel to the direction of the element length [17]. In another study, Michels et al. (2012)
investigated the orientation of SFs in RC slab. The result revealed that increasing the slab thickness will
reduce the orientation at cracked state [11].

A summary of the findings on the effect of SFs on mechanical properties of RC beam is shown in Table 1.

| Studies behaviour | SF content (V.%) | Findings | Ref. |
|------------------|-----------------|----------|-----|
| Compressive strength | 2.3% | Addition of 2.3% SFs improved compressive strength up to 20% for plain concrete. | [10] |
| | 3% | 3% SF RC enhanced compressive strength to 16%. | [16] |
| Tensile strength | 1% | The 30 mm fibres specimens showed higher ultimate tensile strength of 44% compared with 22 mm fibres specimens. | [12] |
| | 3% | Tensile strength was improved up to 121% comparing with the control sample. | [10] |
| Flexural strength | 0.5, 1.5, and 2% | The maximum flexural load for the 0.5, 1.5, and 2% ranged between 20-37, 50-52, 50-55 kN, respectively. The 1.5% found to be the optimum fibre content. | [6] |
| | 0.5 and 1% | The ultimate load reached 70 kN for the reinforcement ratio of 44% of the $\rho_{\min}$ and 0.5% fibre content. While, ultimate load 120 kN for 1% fibre content and 100% reinforcement ratio of the $\rho_{\min}$. | [18] |
2.3 and 3% The flexural strength was increased up to 80.7% when using 2.3% fibre content. However, the improvement percentage reduced to 67.9% when using 3% fibre content. [10]

Shear strength 0.75 and 1.5% Shear stress reached 220.45 kN for the 0.75% fibre content. While, 270.63 kN shear stress was observed when using 1.5% fibre content, at the same aspect ratio (55). However, at aspect ratio of 88, a slight difference of 17% in the shear stress was observed when using 0.75% fibre content. [4]

Crack behaviour 0.5, 1, and 1.5% Results showed that the fibre RC samples retained the post cracking, unlike plain concrete, which failed significantly by a single crack. [14]

1% Study showed improvement in the ductility and tenacity of the SFR when increasing the fibre volume percentage and length. [12]

0.75% Fibres having longer length (i.e. 60 mm) allowed larger inclined crack opening, compared with the shorter fibre length (30 mm). However, the consolidation of long fibres was unfavourable. [4]

Orientation and distribution - Results showed that compaction and vibration methods can significantly influence the orientation and distribution of fibres. [5,15]

- The study revealed that casting method can also affect the orientation and distribution of SFs in the concrete mixture. [17,19]

- The existence of coarse aggregates will not allow the SFs to line up parallel to the direction of the shear cracks. However, it can lead to random distribution and orientation of fibres. [7]

4. Conclusion
SFRC can be defined as a combination between normal concrete and thousands of small discontinuous discrete fibre distributed randomly in the concrete during mixing. SFs (SF) has become a promising material that can be employed in different structural elements to improve mechanical properties of concrete. Inclusion of fibres has shown to improve compressive strength, tensile strength, and shear behaviour. In addition, this material can resist repeatedly applied, impact or shock loading. The addition of SFs has shown to alter the characteristics of concrete from brittle to ductile as well as increase the ultimate strength of concrete. Further, it was found that the orientation and distribution of SFs are influenced by casting, vibration, and compaction methods. A review of the past studies have shown that inclusion of 0.75 V.% of SF in RC beams can fully replace shear links. Furthermore, it has been observed that hooked-end SF are the most suitable type of SF to be included with normal strength concrete, while straight SF resulted in better results if used with high strength concrete due to the high tensile strength of straight SF.

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