Experimental Investigation of the Flexural Behavior of Steel Fiber Reinforced Concrete

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Abstract. This research study is conducted to investigate the flexural behaviour of steel fiber reinforced concrete (SFRC) prisms incorporating different types and volume fractions of steel fibers, various grades of concrete, and different specimen depths, all tested under displacement control mode using four-point loading configuration. Two types of steel fibers (hooked end and straight) were incorporated into the concrete mixes at two different dosages (1% and 2%). Concrete mixes with compressive strengths of 40, 50, and 70 MPa were used to cast the samples. Specimen depth was also among the test variables, where prisms of depth 100, 150 and 200 mm were tested to study the size effect on the flexural behaviour of SFRC. Test results indicated that for the straight-end steel fibers, the increase in the fiber volume fraction from 1 to 2% had a noticeable effect on both flexural strength (or Modulus of Rupture, MOR) and associated prism mid-span deflection. However, for the hooked end steel fibers, there was only a limited increase in the same measured values due to reduced workability of the SFRC fresh mix. The test results also have shown that the increase in the concrete compressive strength had only a limited increase in the same measured values due to reduced workability of the SFRC fresh mix. The test results also have shown that the increase in the concrete compressive strength had only a modest effect on the average MOR value, but a noticeable effect on average mid-span deflection at peak load. The latter was attributed to the relatively long length and the hooked end geometry of the steel fibers. Finally, test results revealed that specimen depth had an impact on the measured flexural strength, where increase in specimen depth was associated with reduced MOR values, a phenomenon that is commonly referred to in the literature as size effect.

1. Introduction

Concrete is a widely-used construction material due to its excellent overall mechanical properties and economical benefits. However, concrete is also known for its low tensile strength, quasi-brittleness, and low fracture toughness. These drawbacks lead to the cracking of concrete and subsequent deterioration of reinforced concrete structures due to corrosion of steel reinforcement when exposed to aggressive environments. To overcome these issues, several studies focused in the past decades on improving the tensile properties of concrete through the use of discontinuous metallic and synthetic fibers in the concrete mix, resulting in what is commonly known as Fiber Reinforced Concrete (FRC) [1]–[3].

Currently, there are different types of discontinuous fibers available in the market, such as steel, polyethylene, polypropylene, and carbon. These fibers come in different geometrical shapes or cross-sections (such as rectangular, circular, and irregular), with deformed or fully-straight ends, and can be either short or long length [2, 4]. Steel Fiber Reinforced Concrete (SFRC) is among the most commonly used FRC material and is produced by randomly distributing macro steel fibers into the fresh concrete mix during mixing. SFRC has been used in several applications such as tunnel lining, slabs on grade,
pavements, slope stabilization, composite metal decks, concrete pipes, dam construction, rehabilitation of marine structures, etc. [1].

The addition of steel fibers in concrete has shown the ability to improve the tensile/flexural properties, fracture energy, and cracking behaviour of an otherwise a quasi-brittle material. However, the compressive strength of the concrete material is not particularly affected by the addition of steel fibers to the mix. In tensile/flexural members, steel fibers act as crack arrestors by bridging the crack surfaces and restrict the propagation of cracks. This mechanism results in an improved energy absorption capacity and toughness of the FRC materials, ranging from subtle to substantial, depending on a number of factors, including fiber type, fiber properties, fiber dosage, and grade of concrete [2,5-7].

The present study aims to contribute further to the existing literature on the flexural behaviour of SFRC and how it is affected by the steel fiber type, the fiber volume fraction, the concrete compressive strength and the specimen depth. The research presented herein is part of a larger study that incorporates the development of a predictive analytical model of the flexural strength of SFRC using a fracture mechanics approach. The experimental program in the present research involves flexural testing of 27 SFRC prisms of varying depths (100, 150, and 200 mm), where different dosages (1% and 2%) of steel macro fibers (hooked end and straight end) were used to reinforce concrete of varying compressive strengths (40, 50, and 70 MPa). The test results will be discussed in terms of the prisms load-mid-span deflection response, the measured flexural strength, and the cracking behavior and how these are affected by the fiber type, the fiber volume fraction, and the compressive strength and specimen depth.

2. Experimental Program

2.1. Materials and Specimens Preparation
The FRC prisms used in this study (Figure 1), were cast from two types of steel fibers (hooked end and straight end) of two different aspect ratios of fibers \( \frac{L_f}{d_f} = 55, \) and 65) and two dosages of steel fibers (1% and 2%). Three different concrete compressive strengths (40, 50, and 70 MPa) and three different specimen depths (100, 150, and 200mm) were used to cast these FRC prisms. Tables 1 and 2 show the specifications of the macro steel fibers and the concrete mix design used, respectively.

![Figure 1](ZP305.png) (a) ZP305
![Figure 1](OL13/0.2.png) (b) OL13/0.2

**Figure 1** – Photo of steel fibers dispersed in concrete mix

![Figure 2](Figure_2.png)

**Figure 2** – Experimental setup for four-point flexural tests

| Fiber Type | Length \( L_f \) (mm) | Diameter \( d_f \) (mm) | Aspect ratio \( \frac{L_f}{d_f} \) | Fiber tensile Strength (MPa) | Fiber density Kg/m\(^3\) |
|------------|----------------------|------------------------|-----------------|-----------------------------|------------------------|
| **ZP305**  | 30                   | 0.55                   | 55              | 1100                        | 7.850                  |
| **OL13/0.2** | 13                   | 0.2                    | 65              | 2600                        | 7.850                  |

Table 1 - Specification of the steel fibers
Table 2 - Mix design of concrete mixes

| Compressive cube strength (MPa) | Cement Qty | Coarse aggregate-cement ratio | Fine aggregate-cement ratio | W/C ratio |
|--------------------------------|------------|-------------------------------|----------------------------|-----------|
| 40                             | 1          | 1.74                          | 2.36                       | 0.58      |
| 50                             | 1          | 1.46                          | 1.90                       | 0.49      |
| 70                             | 1          | 0.925                         | 1.09                       | 0.37      |

2.2. Test Setup

Four-point deflection controlled flexural tests were carried out to determine the load–mid-span deflection response and the flexural strength of the various beams (prisms) according to ASTM C1018 [8] as shown in Figure 2. The SFRC prisms were tested under displacement control using an initial constant loading rate of 0.1mm/min, which was later increased to 0.3mm/min after the peak load is reached. The loading was terminated once the load on the specimen dropped to 2 kN.

3. Results and Discussions

A summary of the experimental results is presented in Table 3. For each test parameter, four identical test samples are tested and the corresponding load-deflection (P-Δ) curves are plotted in a single graph, which also shows a calculated average modulus of rupture (MOR). Each test sample is identified with a label showing the depth of the sample, type of fiber, the fiber dosage, and ends with the compressive strength of the sample. For example, test sample 100-ZP-1-40 represents a specimen of a depth of 100 mm, having fiber type ZP305, fiber volume fraction of 1% and cast with 40 MPa compressive strength concrete.

Table 3 – Summary of experimental results

| Specimen index | Fiber Type | V_t (%) | Depth, d (mm) | Cube concrete strength, f_{cu} (MPa) | Average flexural strength, MOR (MPa) | Mid-span deflection at peak load Δ_u (mm) |
|----------------|------------|---------|---------------|--------------------------------------|--------------------------------------|--------------------------------------|
| 100-0-40       | -          | 0       | 100           | 40                                   | 4.70                                 | 0.25                                 |
| 100-OL-1-40    | OL13/0.2   | 1       | 100           | 40                                   | 5.45                                 | 0.35                                 |
| 100-OL-2-40    | OL13/0.2   | 2       | 100           | 40                                   | 7.85                                 | 0.45                                 |
| 100-ZP-1-40    | ZP305      | 1       | 100           | 40                                   | 5.69                                 | 1.0                                  |
| 100-ZP-2-40    | ZP305      | 2       | 100           | 40                                   | 5.82                                 | 1.2                                  |
| 150-ZP-1-40    | ZP305      | 1       | 150           | 40                                   | 4.59                                 | 1.0                                  |
| 200-ZP-1-40    | ZP305      | 1       | 200           | 40                                   | 3.56                                 | 1.4                                  |
| 100-ZP-1-50    | ZP305      | 1       | 100           | 50                                   | 5.63                                 | 1.0                                  |
| 100-ZP-1-70    | ZP305      | 1       | 100           | 70                                   | 6.62                                 | 1.8                                  |

Figure 3. Observed crack patterns in sample test specimens
The tested SFRC prisms in this study failed after forming single or double cracks as shown in figure 3 with an observation, in some of the samples, of initial crack propagation not starting at the middle length of the prisms, i.e. cracks were initiated within the constant-moment region but away from the mid-span. Some of the tests prisms exhibited dual crack initiation and propagation as shown in Figure 3b. However, as the load increased, only one of the cracks propagated further until failure. This is in line with the assumption that single crack will propagate until failure.

3.1. Effect of Volume Fraction of Fibers (Vf) on the load-deflection Response

3.1.1. OL13/0.2 Fibers (Straight End):
Figures 4a and 4b show the load-deflection curves for two series of specimens (Series 1 and Series 2); each consists of three duplicate 100 mm-prisms cast using 40 MPa concrete; incorporated 1 and 2 % of OL13/0.2 straight end fibers, respectively. For both series, one or two significant cracks had formed on the prism tensile face within the constant moment region and continued to propagate towards the compression face with an increased mid-span deflection. This crack propagation was initially associated with an increase in applied load until a peak value was reached, and then started to drop as the crack continued to propagate and the mid-span deflection continued to increase. At the peak load, the measured flexural strengths (MOR) and associated mid-span deflection (\(\Delta_u\)) were 5.45 MPa and 0.35 mm for Series 1, and 7.85 MPa and 0.45 mm for Series 2, respectively. It is evident in this case that by increasing the fiber volume fraction from 1 to 2%, the MOR and \(\Delta_u\) had increased by 44% and 30%, respectively.

\[
\text{Average MOR} = 5.45\text{MPa} \\
\Delta_u = 0.35\text{mm}
\]

\[
\text{Average MOR} = 7.85\text{MPa} \\
\Delta_u = 0.45\text{mm}
\]

Figure 4. Effect of volume fraction of OL13 fibers on the load-deflection response of the specimens

3.1.2. ZP305 Fibers (Hooked End):
Figures 5a and 5b show similar curves for other two series of specimens (Series 3 and Series 4) that incorporated 1 and 2 % of a longer length (30 mm) ZP305 hooked-end steel fibers, respectively. For these series of tests, the observed crack initiation and propagation and its impact on the peak load and associated mid-span deflection were similar to those discussed earlier for Series 1 and 2. However, for the former Series (3 and 4), the increase in the fiber volume fraction had a minimal impact on the measured MOR, but a definite impact on the measured mid-span deflection \(\Delta_u\). This behavior was attributed to the relatively long length of the ZP305 fibers and the geometry of the end of the fibers (hooked end) which resulted in reduced workability of the SFRC fresh mix and hence reduced fiber-reinforcing efficiency in terms of limited increase in the measured MOR. The longer length of the ZP305 fibers has, on the other hand, a contribution to bridging major crack and thus allowing the specimen to sustain high load levels while increased mid-span deflections. This resulted in the apparent strain hardening behavior shown in Figure 5b for Series 4. The measured increase in \(\Delta_u\) for Series 4 compared to Series 3 was 20%.
3.2. Effect of Concrete Strength on the load-deflection Response

Figure 6 shows the load-deflection response of specimens of concrete strength of 50 MPa and 70 MPa. When comparing these figures with Figure 5a, it can be observed that with an increase in concrete strength, the specimens were able to sustain a higher load over an increased mid-span deflection. For specimens with concrete strength of 50MPa (Figure 6a), the load started to decrease when the deflection reached about 1 mm. However, for specimens with higher concrete strength (70 MPa), the specimens were able to sustain the applied load for a larger deflection of around 1.8 mm as shown in Figure 6b.

This indicates that with the increase of concrete compressive strength (achieved with reduced w/c ratio), the bonding between the fibers and the concrete matrix has increased as well. Published data in the literature [9] suggest that the reduction of w/c ratio does indeed lead to increased fiber/matrix bond strength. This increase had probably enhanced the crack arrest mechanism of the steel fibers, and thus, increased the capability of the specimens to sustain higher loads for larger deflections. Compared to the 40 MPa SFRC, the 70 MPa SFRC showed a corresponding increase of 16% and 80% in the average MOR and associated mid-span deflection values, respectively.

3.3 Effect of Depth on the load-deflection Response

Figure 7 shows the load-deflection response of ZP305 fibers specimen of (1%) but with increased depth from 100 mm (shown earlier in Figure 5a), to depths of 150 and 200 mm. Upon comparison, it can be observed that with the increase of the specimens depths from 100 to 200 mm, the specimens showed higher peak loads but lower MOR values over an increased deflection (around 1.4mm). This decrease in the measured MOR with increased specimen depth is indicative of the increased apparent brittleness of the SFRC prisms associated with the increased specimen depth. This is what is commonly referred to in the literature as the size effect [4].
4. Conclusions
In this study, 27 SFRC prisms were cast and tested under a four-point flexural loading configuration. The parameters investigated were the type and volume fraction of steel fibers used, the compressive strength of the concrete, and the depth of specimens. Two types of steel fibers (hooked end and straight end) were used in two different dosages in the concrete mix.

Test results showed that the increase in the volume fraction of OL13/0.2 steel fibers (straight end) from 1% to 2% resulted in 44% and 30% increase in the average MOR and the associated mid-span deflection values, respectively. However, for the longer, hooked-end ZP305 steel fibers, there was very little increase in the average MOR value and only a 20% increase in the associated mid-span deflection was observed. This was attributed to the reduced workability of SFRC concrete mix related to the longer length of the fiber and due to the hooked end geometry. For the same fiber (ZP305), test results has also shown that that the concrete compressive strength had a modest effect on the average MOR value (only 16% increase), but a noticeable effect on the average mid-span deflection at peak load; with an increase of about 80% between the 40 MPa and 70 MPa concrete strength. As for the effect of specimen depth on the flexural behaviour of the SFRC, test results had shown that by increasing the SFRC specimen depth to 150 mm and 200 mm (original length 100 mm), the average MOR values has reduced by 19% and 37%, respectively.

5. References
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