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Flexural Behavior of RC Beams Strengthened with Steel Fibers

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Abstract

Steel fiber reinforced concrete (SFRC) is a conventional reinforced concrete to which steel fiber has been added. This process increases the tensile strength at first crack and ultimate crack, which is considered to represent resistance to cracking and crack propagation. SFRC can withstand shock or impact loading due to its energy absorption characteristics as well as the improvement of the brittle failure mechanism under tension. This paper presents the results of an experiment undertaken on six under-reinforced concrete (RC) beams to enhance the flexure behavior and ultimate strength capacities by using steel fiber at different depths. One beam was tested without any strengthening (control beam). Three beams were strengthened to half depth with the three steel fiber ratios 0.5%, 1%, and 2%, respectively. The two last beams were strengthened to the full depth with the two steel fiber ratios 1% and 2%, respectively. The primary aim of this paper is to determine the optimum percentage of steel fiber (SF) and its focus location. The ultimate loads, mid-span deflection, and crack patterns for all specimens were investigated and compared, using the results for the control beam to evaluate the flexural behavior of the SFRC beams. Based on the analysis of the results, SFRC beams were found to exhibit ductile behavior, have good crack control, and have effective flexure strengthening and significantly reduced mid-span deflection. The steel to fiber ratio and the distributed volume are directly proportional to the initial stiffness, cracking load, and failure load; however, they are inversely proportional to the steel strain, crack width, crack spacing, ductility, and mid-span deflection.

Keywords: Reinforced concrete beams, Flexure capacity, Steel fiber, Strengthening

1. INTRODUCTION

Reinforced concrete (RC) is the most widely used material in the construction field, thus its properties demand continuous upgrading. It is a brittle material with low tensile strength and cracking can occur at relatively low loads. The addition of steel fiber plays an important role in the improvement of the mechanical properties of RC, including tensile properties, crack control, strength, and ductility. Fiber can reduce the permeability of the concrete and reduce the bleeding of water, leading to greater impact, abrasion, and shatter resistance. There are a variety of fibers available, such as steel, natural fiber, and glass. Steel fiber is the most commonly investigated and most commonly used material. As steel fiber reinforced concrete (SFRC) is capable of energy absorption, it can be used for structures that are exposed to impact or dynamic forces under seismic or cyclic conditions. Several experimental studies have investigated the properties of concrete with added steel fiber. Khalil and Abdulrazq (2011) [1] and H. Alasmari (2019) [2] who studied the influence of steel fiber on the flexural behavior of rubberized hybrid RC beams in layered. They noted that hybrid rubberized concrete beams without steel fiber had reduced performance in terms of their characteristics compared to the others but improved the mechanical properties (compressive and tensile strengths, elastic modulus, and bending strengths). Esraa (2019) [3] studied the behavior and strength of steel-carbon-plastic hybrid fiber RC beams by adding the three materials to combine their advantages and make the mixture more economical. The results showed improvement in the ultimate load value. In addition, it has been found that fiber facilitates an internal stress redistribution, thereby increasing the strength of the specimens after the first crack has formed (Kaize Ma 2018) [4]. Adding fiber can partially reduce the high level of brittleness of concrete, which is caused flash and catastrophic failure, especially in structures subjected to earthquake, blast or suddenly loads (Kandasamy, 2011) [5]. Both the compressive and flexural strengths of SFRC increase with the inclusion of steel fiber. Furthermore, the cracking/failure pattern of SFRC specimens show improved ductility compared to plain concrete (Nafisa et al., 2018) [6]. The fiber provides effective bonding and increases the fracture strength of the concrete, and the improved fiber-matrix bonding and alignment of the steel fiber along the beam axis contribute to enhanced fracture resistance of fiber concretes as well as to the reduction efficiency of fiber concrete sections (Sivakumar, 2018) [7]. Hereby, the use of microfiber offers improved impact resistance compared to longer fiber (Rana, 2013) [8]. Prabhu (2018) [9] studied the flexural behavior of fly ash RC beams with steel fiber, whereby 40% of the cement content was replaced with fly ash; the results showed an increase in the load-carrying capacity with the addition of fiber to the beam. Furthermore, the stiffness of concrete was increased with the addition of steel fiber and fly ash (Khadake and Konapure, 2012) [10]. Steel fiber alignment has been shown to have a direct influence on the load-carrying capacity of fiber RC members

(Zile, 2013 and Abrishambaf, 2015) [11,12]. The distribution of steel fiber in small concrete sections also exhibited improved fracture properties compared to large concrete sections (Barnett, 2010) [13]. Meanwhile, the self-straining of steel fiber generated at high stresses can cause fiber pullout or fiber rupture (Thomas and Ramaswamy, 2007) [14]. Adding steel fiber to RC improves capacity, ductility, tensile strength, static and dynamic energy absorption, decreases the final cracking, and leads to better fatigue behavior (Pramod and Abhijit, 2017; Rai and Joshi, 2014) [15, 16]. The modulus of rupture of polypropylene fiber RC is less than that of SFRC (Chandu and Supriya, 2015) [17]. The volume of the fiber slightly affects the compression strength of the concrete (Rizzuti, Bencardino 2014; Marčiukaitis et al., 2011) [18,19]. The addition of binding wire as a steel fiber to concrete is directly proportional to the flexural and tensile strengths; however, it is inversely proportional to the compressive strength (Shweta and Kavilkar, 2014) [20]. Alani and Aboutalebi (2013) [21] concluded that the compressive and tensile strengths of concrete are nearly the same for both synthetic and steel fibers, but steel fiber showed more ductility. The slump of silica fume concrete with steel fiber is inversely proportional to the increase in the silica fume and steel fiber being used (Madheswaran et al., 2014) [22]. An improvement in bond strength for all concrete mixtures has been observed with increasing percentages of the fiber volume fraction (Challoob and Srivastava, 2013) [23]. Inmaculada (2017) [24] studied the flexural behavior of layered SFRC beams and noted that the flexural load capacity of all the series of beams is similar, but the there were fewer deflections of layered beams compared to monolithic beams.

All of the above-mentioned studies were unable to thoroughly investigate the deformation and destruction processes of SFRC. Hence, in the present study, steel fiber was randomly distributed at different depths of under-reinforced beam specimens to study the effect of steel fiber on the behavior of RC beams. The primary objective of this study was to observe the flexural strength behavior of SFRC beam specimens based on different fiber ratios and different distributed depth areas. Deflection, crack patterns, and load capacity were recorded for the SFRC beams and compared to a control specimen beam that did not contain steel fiber.

2. EXPERIMENTAL METHODOLOGY

2.1 Materials

The process of manufacturing was very similar to the conventional method of concrete manufacture. The properties of the Portland cement used were determined through laboratory testing at initial and final setting times of 75 minutes and 216 minutes, respectively. The compressive strength after 28 days was 55.63 MPa. The well-graded aggregate used was obtained from locally available crushed dolomite, with a specific gravity of 2.85. The fine aggregate used was natural river sand with a specific gravity of 2.63 and a fineness modulus of 3.28. Normal potable water free from any harmful amounts of oils, alkalis, sugars, salts, and organic materials was used for the mix proportioning and curing of the RC specimens. The mix proportion of the concrete used is presented in Table 3. Cubes with the dimensions 150x150x150mm were taken from each concrete mix in order to determine the compressive strengths. The specimens and the beams were cured using the water sprinkling method until the date of testing. After 28 days, the average concrete strength of the standard cubes of casting was tested to be 25 MPa. High-tensile ribbed steel bars of 12 and 10 diameters were used for the beams. Mild smooth steel 8 mm in diameter was used as the stirrups in all beams. The properties of the reinforcement used in the experiment are given in Table 2.

Table 1. Mix proportioning of the concrete

Ingredients	Grade 25 MPa
w/c ratio	0.56
Mixed water	230
Portland cement	410
Fine aggregate (sand)	902
Coarse aggregate (max size=16 mm)	833

Table 2. Properties of the reinforcement used in the experiment

Properties	Ø 8	Φ 10	Φ 12
Yield stress (MPa)	280	395	392
Ultimate stress (MPa)	410	590	582
Actual area (mm^2)	50	78	201

2.1.1 Steel fiber

Wirand Fiber-FF3 type steel fiber, with both ends hooked and glued, was used in the study. Throughout the investigation, the steel fiber volume used in the concrete mixes was 0.5%, 1% and 2% of the total volume of the concrete. The properties and a snapshot of the used steel fiber are given in Table 3 and Figure 1, respectively.

Table 3. Properties of the steel fiber used in the experimental work

Diameter	0.75 mm
Length	50 mm
Strain at failure	less than 4%
Tensile strength	tensile strength

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Figure 1. Hooked-end shaped steel fiber used in this study

2.2 Laboratory specimens

The specimen beam size was 1800 mm long, 150 mm wide and 200 mm thick. All beams had identical reinforcement details, including longitudinal reinforcement in the form of 2Φ12 at the tension side and 2Φ10 at the compression side. All beams were under-reinforced with a 0.9% reinforcement ratio. The transverse reinforcement, i.e. stirrups, was 5 Ø 8/m, as shown in Figure 2.

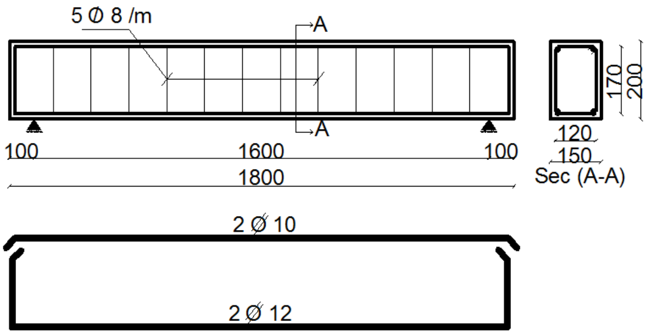


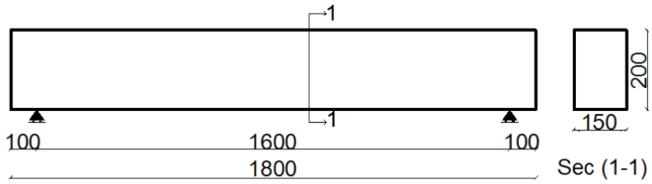
Figure 2. Typical beam specimen dimension and reinforcement details

2.3 Experimental program

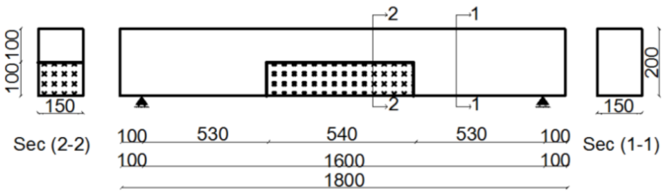
Six specimens of under-reinforced concrete beams were tested to failure in this study to evaluate the influence of the steel fiber ratio and the position of the steel fiber in the whole beam depth. The strength behavior and ductility of the beam were also studied. One specimen (B1) did not use steel fiber and was used as a reference, but the remaining five specimens were strengthened with steel fiber. Three specimens (B2, B3, and B5) were strengthened with steel fiber to the half of the beam depth on the tension side in the middle third of the span using the ratios 0.5%, 1%, and 2% by volume, respectively. Specimens B4 and B6 were strengthened with full steel fiber to the middle third of the span by the ratios of 1% and 2% by volume, respectively. The details of the specimens are shown in Figure 3. Table 4 outlines the testing program.

Table 4. Test program and specimen details

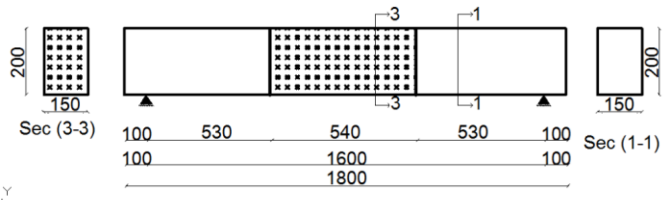
Beams	Tension RFT	Compression RFT	Stirrups	SF Ratio	SF Location
B1	2Ø12	2Ø10	5Ø8/m	0%	
B2	2Ø12	2Ø10	5Ø8/m	0.5%	0.5d
B3	2Ø12	2Ø10	5Ø8/m	1%	0.5d
B4	2Ø12	2Ø10	5Ø8/m	1%	d
B5	2Ø12	2Ø10	5Ø8/m	2%	0.5d
B6	2Ø12	2Ø10	5Ø8/m	2%	d



a. Beam B1 reference beam details



b. Beams B2, B3, and B5 details



c. Beams B4 and B6 details

Figure 3. Details of the steel fiber locations in the tested specimens

2.4 Test setup and instrumentation

A very rigid steel frame consisting of horizontal and vertical I-sections was used as a base to support the beam specimens. The tests were carried out in the reinforced concrete laboratory at the Faculty of Engineering, El-Mataria, Helwan University. The specimens were simply supported and loaded under one-point loading at the mid-span of the specimen using a hydraulic oil jack. All beams were tested with a clear span of 1700 mm. The load was applied in successive increments and the loading speed was kept constant during the testing of all specimens. Two electronic displacement transducer (LVDTs) vertical gauges were used under the beams at the mid-span as well as at the third of the span between the two supports in order to measure the vertical deflection. One electrical strain gauge was fixed to the mid-length of the longitudinal reinforcement bar of each beam in order to measure the steel strain. The development of cracks and deflection was observed during loading and recorded after each increment until failure.

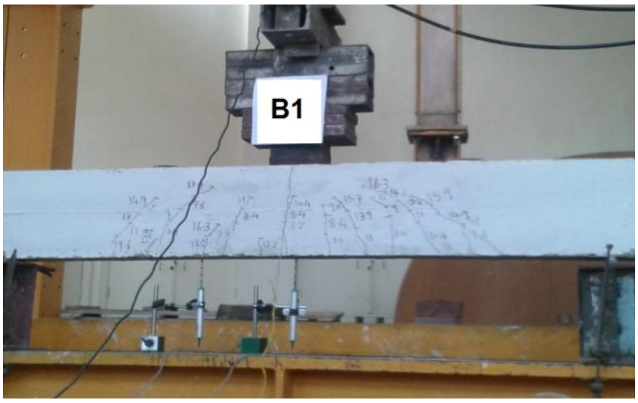


Figure 4. Test setup and LVDT arrangement

3. TEST RESULTS AND DISCUSSION

The crack pattern, initial stiffness (Pcr/ Δcr), failure mode, load deflection, failure loads, and ductility (deflection values at ultimate load) were obtained from the experimental specimens and are presented comparatively. The obtained results and the experimental program were conducted to study the behavior of under-reinforced beams strengthened with steel fiber.

3.1 Failure mode

The failure modes were dependent on the test variables, the different steel fiber ratios, and the different distributed depth areas, as shown in Figure 5. The development and propagation of cracks were recorded on the surface of the specimens during the test. The presence of steel fiber in the concrete was seen to reduce cracking width and spacing. The first crack due to flexure occurred at the mid-span region when the applied load reached about 30-40% of the ultimate load; thereafter, the cracks propagated up to the mid-depth section of the beam. Diagonal cracks appeared as the load reached approximately 50-80% of the ultimate load. The flexural cracks at the mid-span expanded gradually until they caused flexural failure. The initial stiffness increased as the steel fiber ratio increased; it increased by about 4% and 9% for the steel fiber ratios 1% and 2%, respectively, distributed to the half depth of the beam. However, it increased by approximately15% and 16% for the steel fiber ratios, 1% and 2 %, respectively, distributed to the full depth of the beam. All beam specimens finally failed due to flexure failure. The failure occurred at the tension zone for the control beam (B1) at load levels of approximately 141.5 kN The failure loads were 142.5, 138.5 and 145 kN for beams B2, B3, and B4, respectively. These beams were strengthened with steel fiber to half of the beam depth on the tension side in the middle third of the span using steel fiber ratios of 0.5%, 1%, and 2% by volume, respectively. An improvement in the failure load was observed that was on average 0.7% and 2.5% higher in comparison to the control beam. From the test results, it can be seen that strengthening through steel fiber use to half of the beam depth on the tension side in the middle third of the span slightly affects the failure load. However, the failure load was 150 and 153.5 kN for beams B5 and B6, respectively, which were strengthened with steel fiber to the full depth of the beam in the middle third of the span by ratios 1% and 2% by volume, respectively. An improvement in the failure load was observed that was on average 5.5% and 8.5% higher in comparison to that of the control beam. Hence, as the steel fiber content or the volume distribution increased, the ductility decreased. Strengthening the beam with steel fiber to its full depth had a significant effect on failure loads. The complete test results are presented in Table 5. According to previous results, the addition of steel fiber improves the performance of the cracking load, yielding load, and ultimate load of RC beams.

Table 5. Test results

Beams	SF ratio	SF location	P_{Crack} *(KN)*	Δ_{Crack} *(mm)*	$P_{Ultimate}$ *(KN)*	*Initial stiffness (KN/mm)*	$\Delta_{Ultimate}$ *(mm)* At 130 KN
B1	0%	Control beam	40	0.94	141.5	42.55	11.7
B2	0.5%	0.5d	45.7	1.057	142.5	43.24	6.9
B3	1%	0.5d	47.9	1.083	143.5	44.23	5.856
B4	2%	0.5d	48.8	1.05	145	46.48	4.5
B5	1%	d	50	1.02	150	49	5.1
B6	2%	d	56.8	1.155	153.5	49.18	4.71

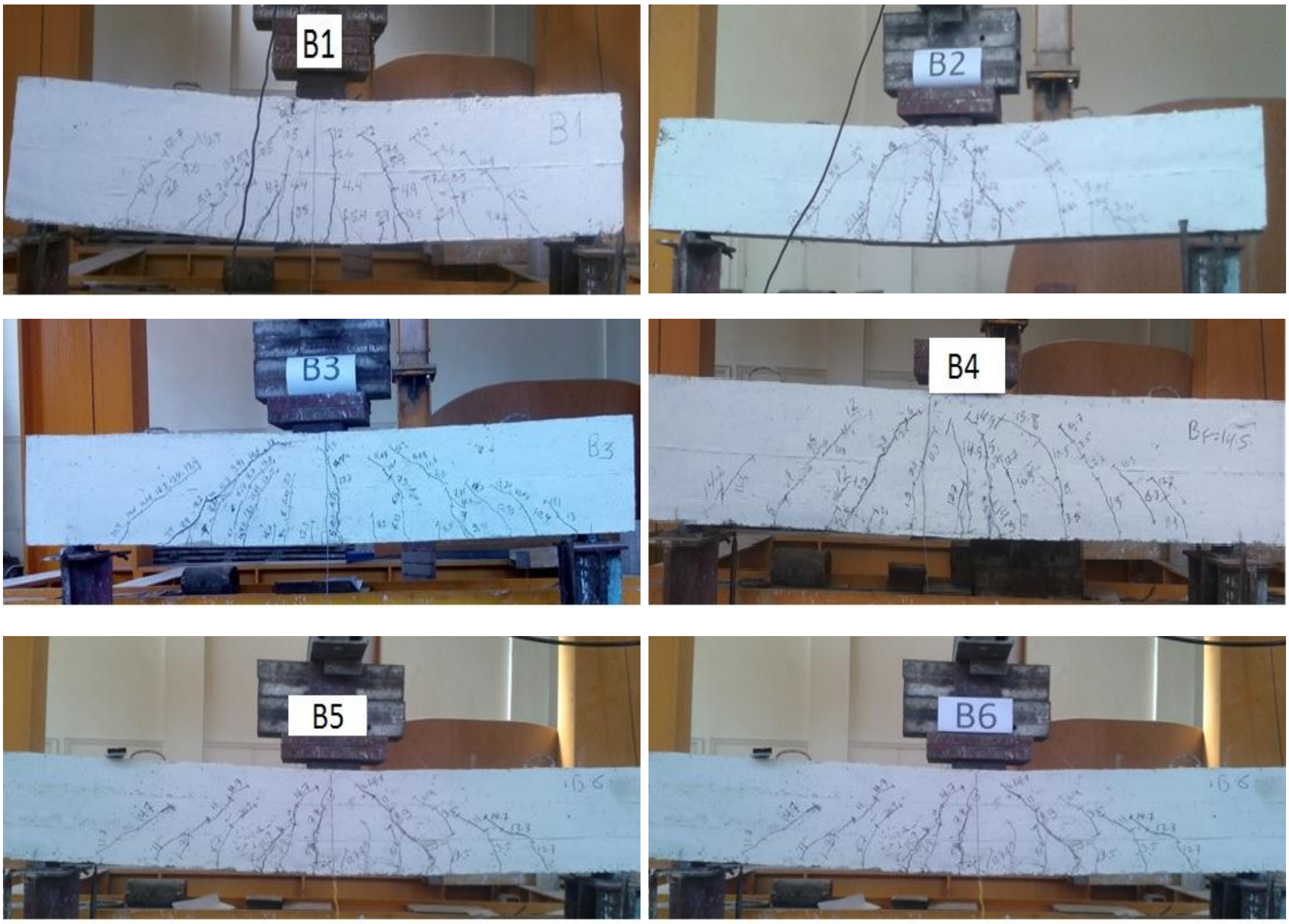


Figure 5. Failure mode of all tested specimen beams

Figures 6 and 7 show the influence of the steel fiber ratio on the cracking and failure loads, respectively, at different distribution depths.

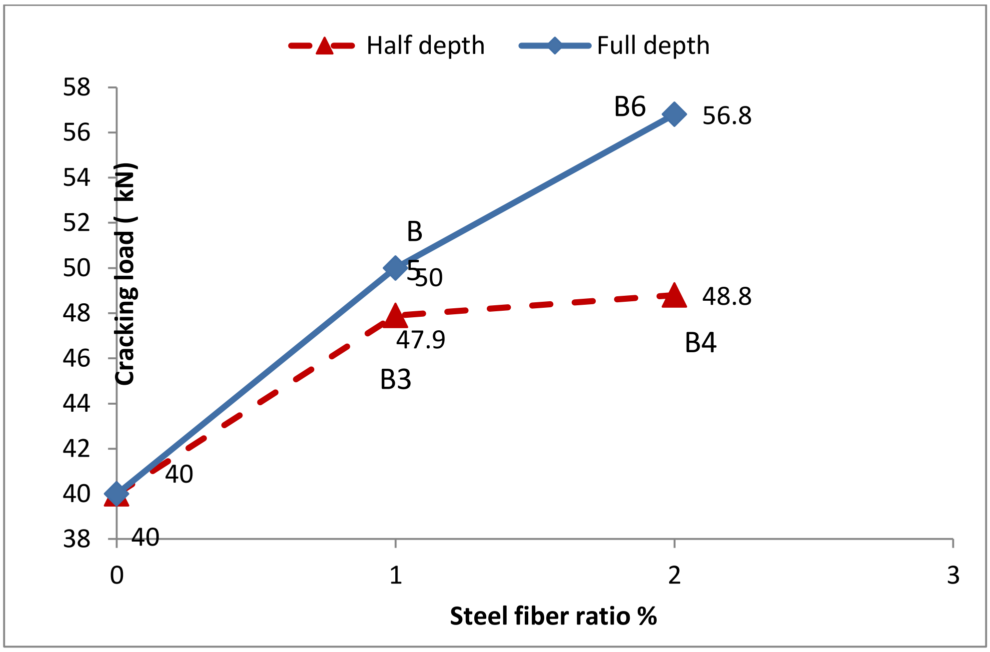


Figure 6. Influence of the steel fiber distribution depth and ratios on the cracking load.

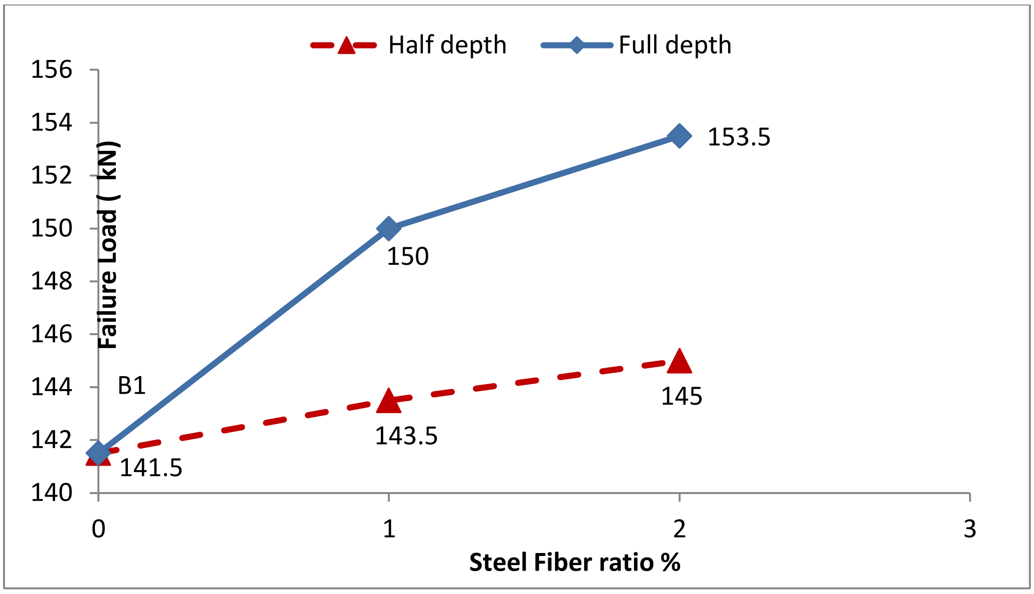


Figure 7. Influence of the steel fiber distribution depth and ratios on the failure load.

3.2 Load-deflection relationship

Figure 8 shows the relationship between the applied load and the mid-span deflection at different load stages for the specimens B1, B2, B3, and B4. Different steel fiber ratios were distributed to half beam depth in the tension zone in each case. Increasing the steel fiber ratio increased the stiffness and flexural capacity of the beams in each case. Figure 9 shows that the same trend was also observed in beams B5 and B6, which distributed different steel fiber rations to full beam depth. According to the maximum deflection value at the ultimate load, increasing the steel fiber enhanced the ductility of the beam. The beams with steel fiber distributed to full depth showed the relatively highest toughness (area under curve). The steel fiber delayed the propagation of cracks, whereby it may be the case that the fiber bridges these cracks and restrains their widening, thus improving their ductility and energy absorption capacity. Figures 10 and 11 show that increasing the distributed areas of the steel fiber with different ratios from half to full depth had a slight effect on the stiffness and flexural capacity of the beams. Figures 12, 13, 14, and 15 show the beam's deformed shape at about 30% and 65% of the average failure loads of the tested beams (i.e. at 40 kN and 100 kN) in all cases. Furthermore, the beams with steel fiber exhibited the lowest deflection values at the different load stages. The mid-span deflections corresponding to the yielding point and ultimate point substantially decreased with the increase of the steel fiber contents, in all cases. This may due to the increased bonding between the steel rebar and the concrete matrix caused by the confining effect of the steel fiber. It was also observed that beam B1 (the control beam with no added steel fiber) exhibited the greatest values of deflection at different load stages.

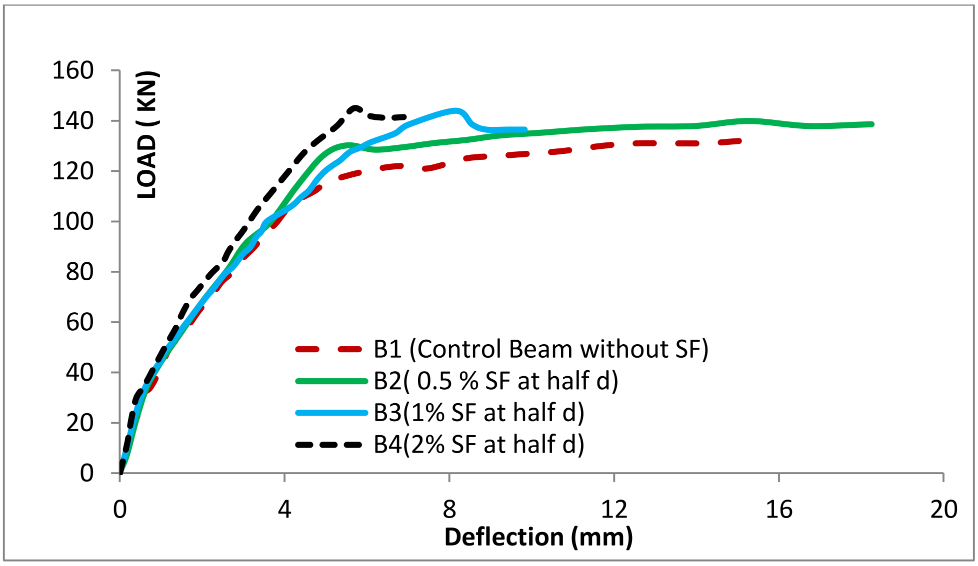


Figure 8. Load deflection curve for specimens with different steel fiber ratios at half depth

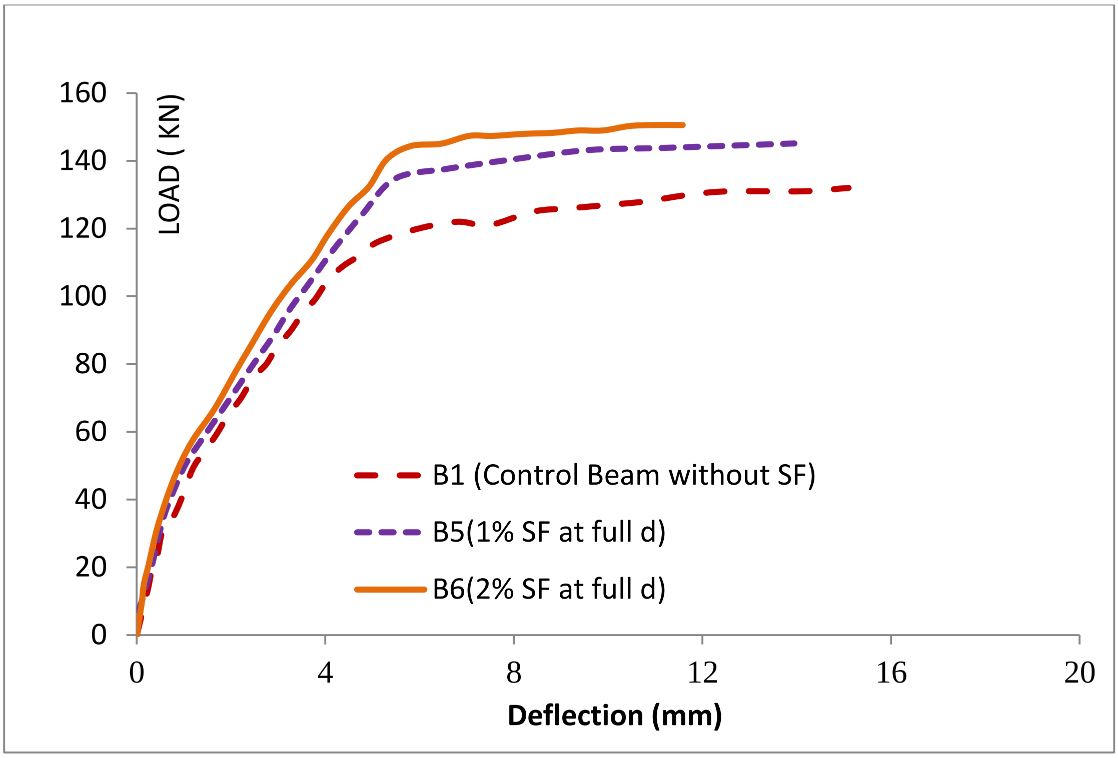


Figure 9. Load deflection curve for specimens with different steel fiber ratios at full depth

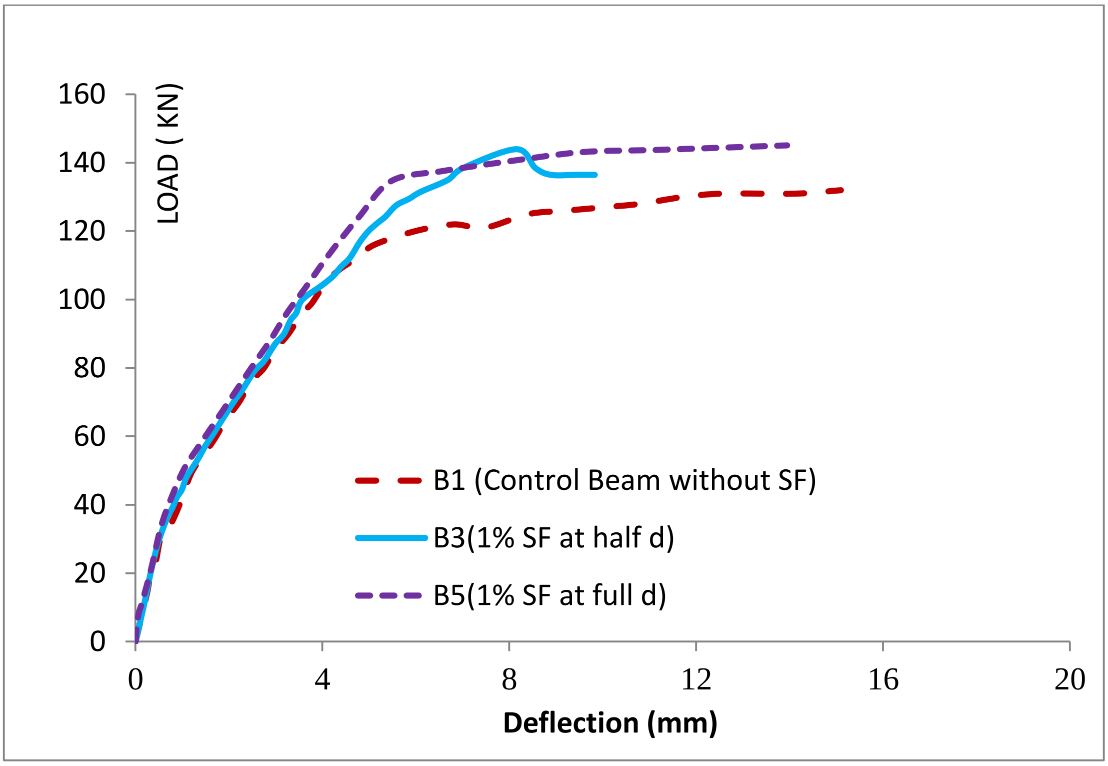


Figure 10. Load deflection curve for specimens with a 1% steel fiber ratio at half and full depths

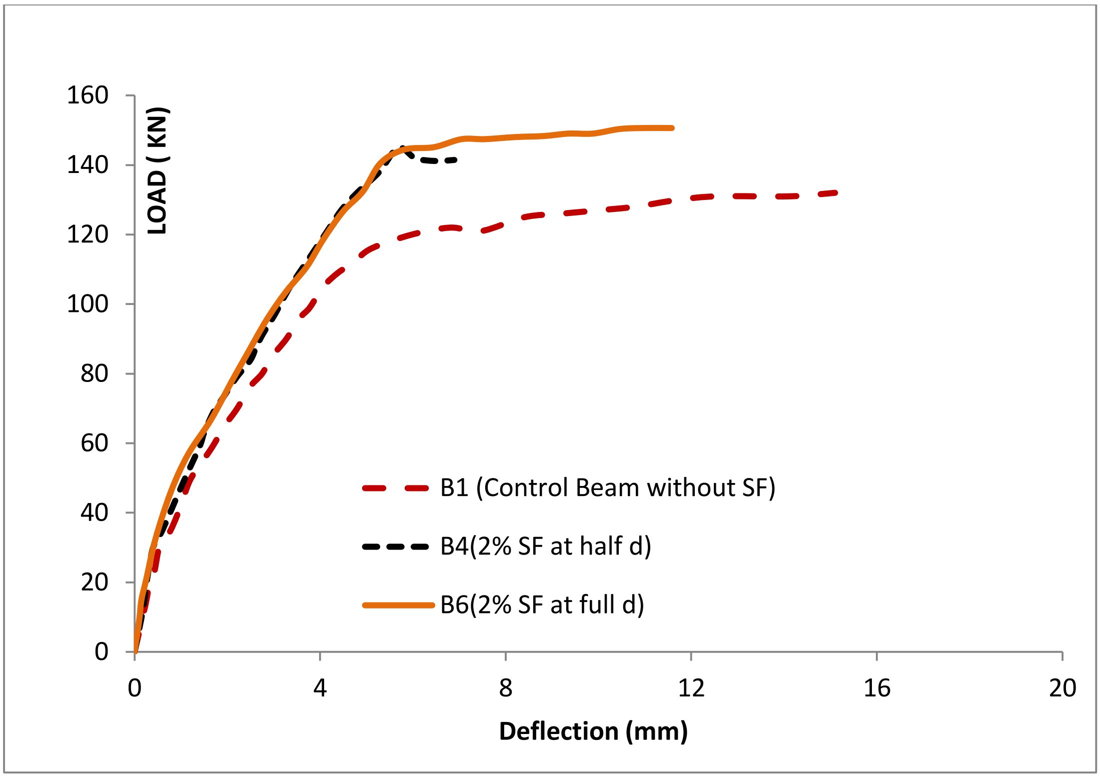
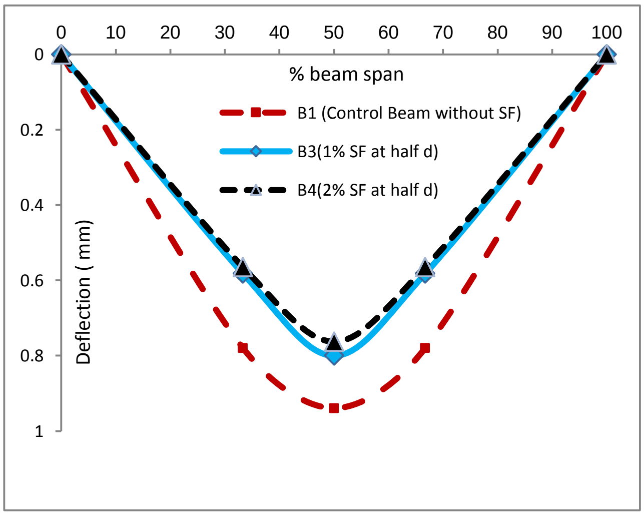
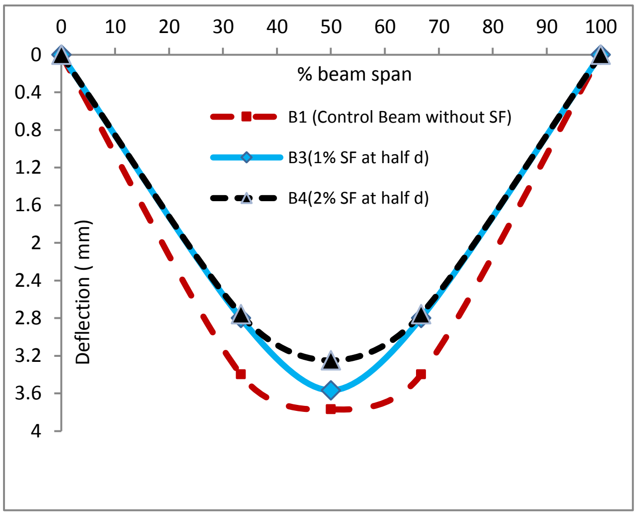


Figure 11. Load deflection curve for specimens with a 2% steel fiber ratio at half and full depths

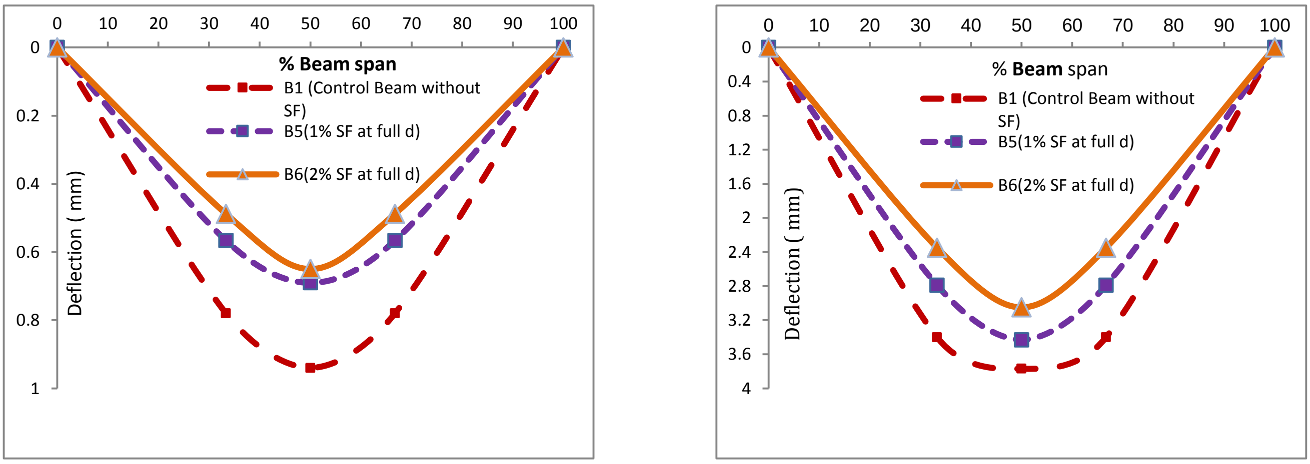


a) At 40 KN



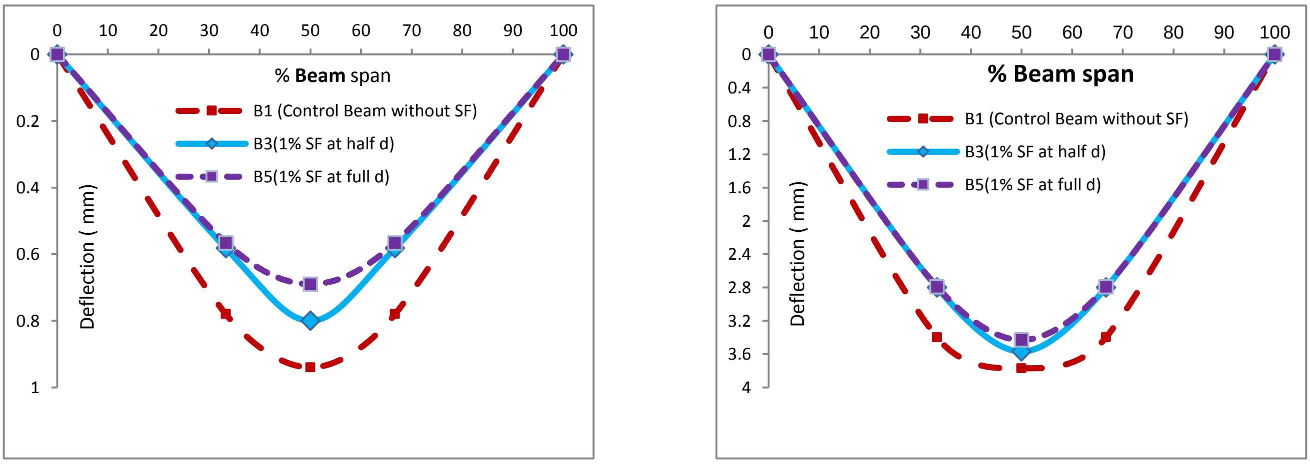
b) At 100 KN

Figure 12. Beam deformation shape with a different steel fiber ratios at half depth



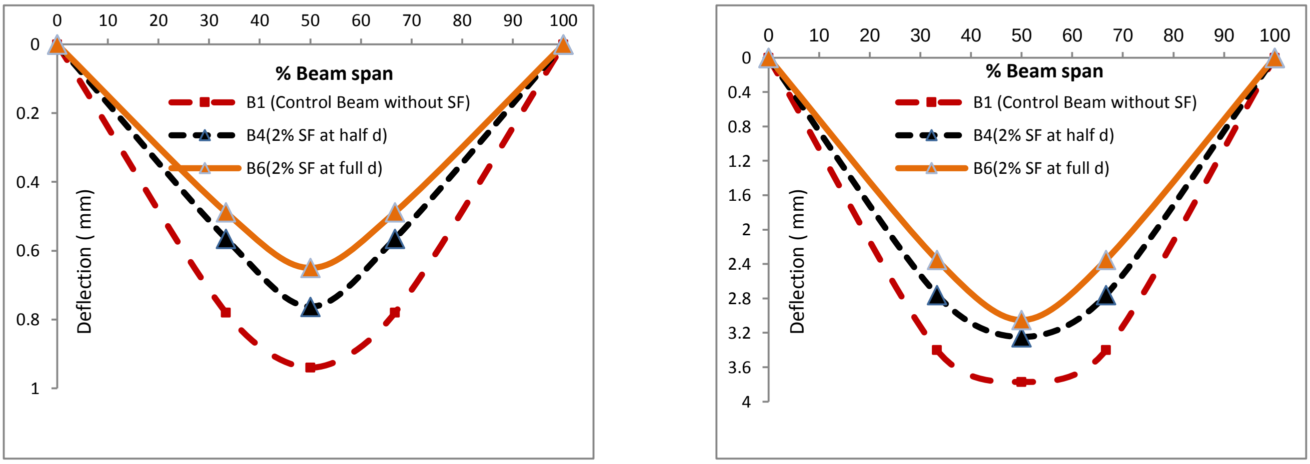
a) At 40 KN b) At 100KN

Figure 13. Beam deformation shape with a different steel fiber ratios at full depth



(a) At 40 KN b) At 100KN

Figure 14. Beam deformation shape with a 1% steel fiber ratio at half and full depths



a) At 40 KN b) At 100KN

Figure 15. Beam deformation shape with a 2% steel fiber ratio at half and full depths

3.3. Load strain curve

The steel reinforcement strains were measured continuously at the mid-span of the main flexural reinforcement throughout the entire testing procedure. Some of the strain gauges were damaged before reading. The readings for different load levels are presented in Figures 16 to 19.

The addition of steel fiber had an unnoticeable effect on the steel reinforcement strain prior to the RC beam cracking. The strain in the longitudinal reinforcement was greatly reduced due to the presence of steel fiber compared to the control beam. As the steel fiber ratios increased, the steel reinforcement strain decreased at the same loading level. At the load level of 100 KN, the steel reinforcement strains decreased by about 20% and 24% for the steel fiber ratios 1% and 2%, respectively, distributed to the half depth of the beam. This decrease in the steel strain ratio increased to 25% and 55% for the steel fiber ratios 1% and 2%, respectively, distributed to the full depth of the beam. In the initial loading before the cracking stage, the effect of the steel fiber on the behavior of the concrete was limited. After the cracking stage, the steel fiber may have crossed the cracks to transfer the load together with the longitudinal reinforcement, thus decreasing the steel reinforcement strain.

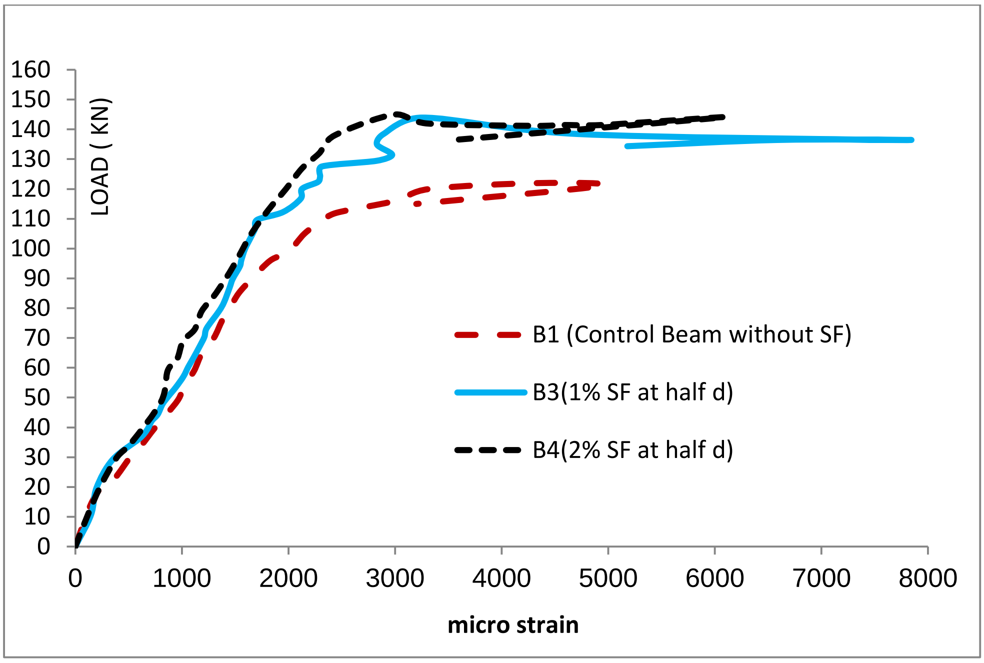


Figure 16. Load strain curve for specimens with different steel fiber ratios at half depth

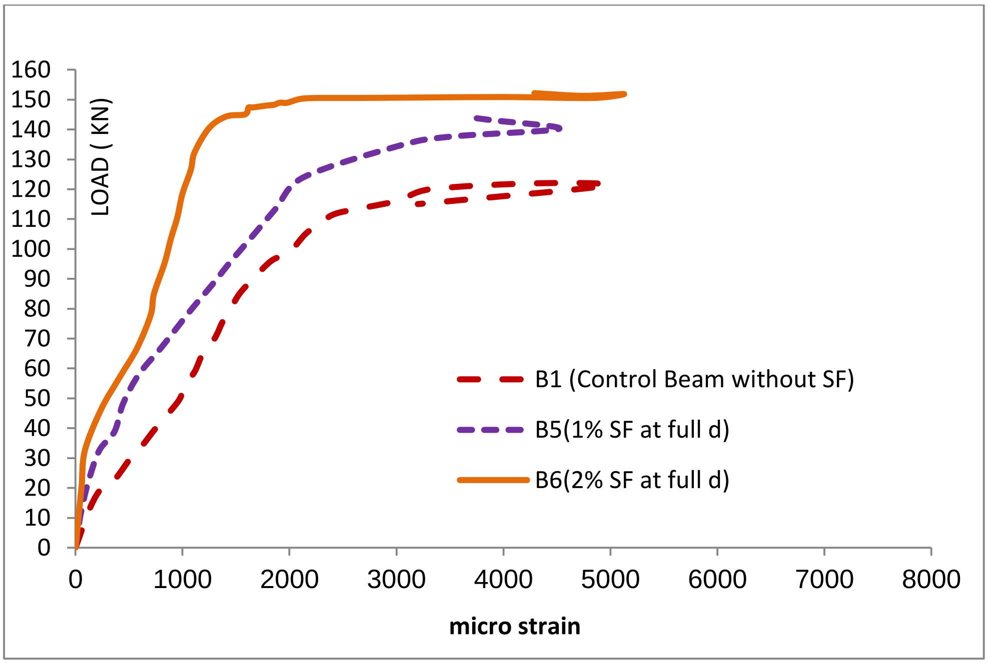


Figure 17. Load strain curve for specimens with different steel fiber ratios at full depth

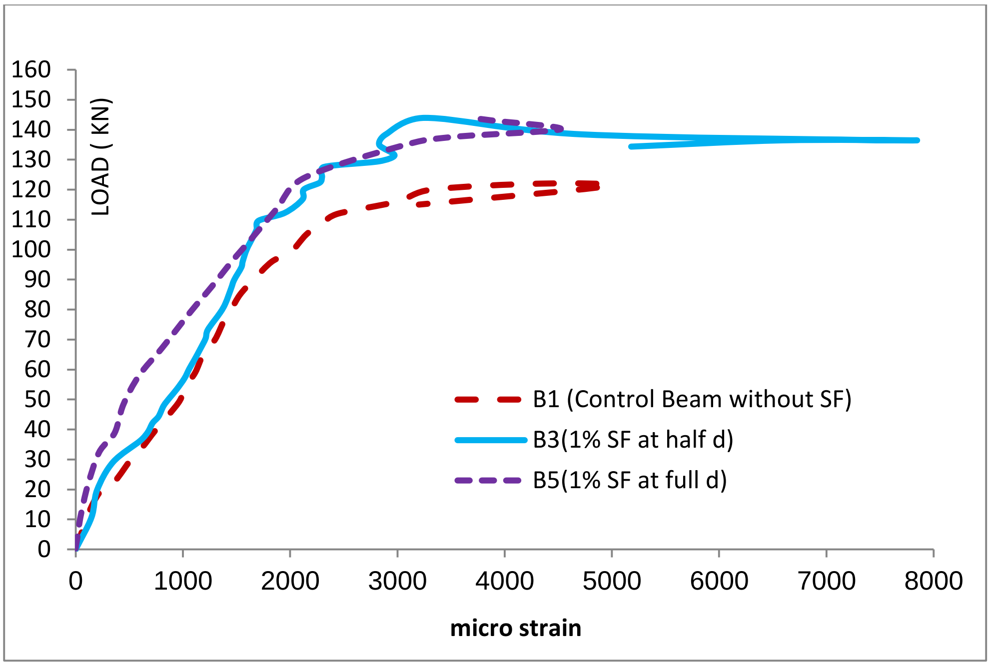


Figure 18. Load strain curve for specimens with a 1% steel fiber ratio at half and full depths

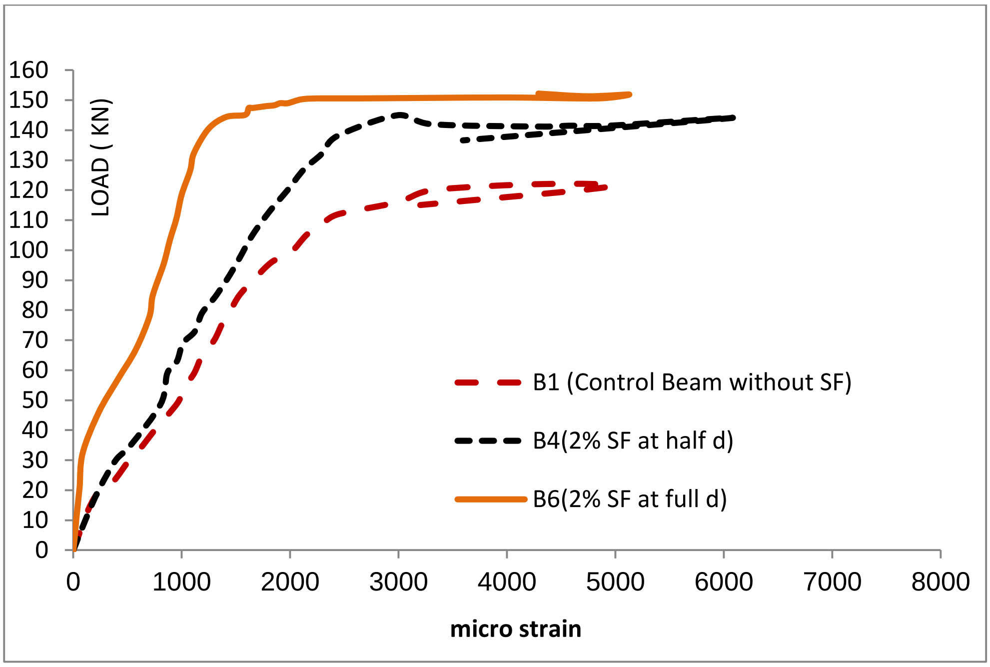


Figure 19. Load strain curve for specimens with a 2% steel fiber ratio at half and full depths

CONCLUSIONS

This study has reported on the experimental results of adding different steel fiber ratios at different depths on the flexural behavior of RC beams. The following conclusions can be drawn from the study.

1- The addition of steel fiber was found to be effective in controlling crack separation and width.

2- The experimental results show that the addition of steel fiber enhances the load-deflection relationship, first crack load, and ultimate load for the tested beams when compared to the control beam.

3- As the steel fiber ratio increased, an improvement was noted in the bonding between the fiber and concrete mixture, which led to an increase in the ultimate flexural strength, ultimate load, and toughness due to a bridging effect.

4- The initial stiffness increased by approximately 4%

and 9% for the steel fiber ratios at 1% and 2%, respectively, distributed to the half depth of the beam. However, stiffness increased by approximately 15% and 16% for the steel fiber ratios at 1% and 2 %, respectively, distributed to the full depth of the beam.

5- The steel fiber ratio and the distributed volume were directly proportional to the initial stiffness, cracking load, and failure load; however, they were inversely proportional to the steel strain, crack width, crack spacing, ductility, and mid-span deflection.

6- The ultimate flexural capacity of the tested beams strengthened with steel fiber distributed to full depth was observed to increase considerably, compared to the control beam, by approximately 5.5% and 8.5% for the steel fiber ratios at 1% and 2%, respectively.

7- The failure load of the tested beams strengthened with steel fiber distributed to the half depth was approximately 1.4% and 2.5% higher for the steel fiber ratios at 1% and 2%, respectively, compared to the control beam.

8- Increasing the steel fiber ratio had an insignificant effect on the steel reinforcement strain before cracking. However, after cracking, it reduced the steel reinforcement strain at the same load level compared to the control beam without steel fiber.

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