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The Effect of Steel Fibers on the Shear Behavior of High Strength Reinforced Concrete Beams

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Abstract: The objective of this research is to investigate experimentally the behavior of high strength steel fiber reinforced concrete beams in shear, for predicting the shear strengths of these structural members. In the experimental program, the volume fraction of fiber was considered in order to determine its effect on the specimen strength. The studied parameter includes volume fraction of fibers (0, 0.25, 0.5 and 0.75%) at shear span to depth ratio (a/d) of 1.5. The elastic behavior of tested beams at flexural zone was also investigated. Experimental results indicated that the shear strength of tested beams was significantly increased as the volume fraction of steel fibers increased. The number of the cracks increased by using discrete steel fibers and become finer. Moreover, the crack propagation and modes of failure may be changed by using discrete steel fibers. Finally, the discrete steel fibers increase ductility and failure loads of the tested beams.

INTRODUCTION

Addition of steel fibers to concrete makes it more homogeneous and isotropic and transforms it from a brittle to a more ductile material.

Steel fibers have some advantages over vertical stirrups or bent-up flexural steel. First, the fiber spacing is much closer than the practical spacing of stirrups, since, the former is randomly and more or less uniformly distributed throughout the concrete volume. Secondly, the first crack and the ultimate tensile strength of concrete are increased by the presence of steel fibers.

This results in an increase of the load necessary to produce shear cracking as well as the ultimate shear resistance of the beams. Thirdly, stirrups require a high labor input for cutting, bending and fixing and in thin webs, they can be impractical and difficult to fix. Lastly, in relatively shallow beams, the necessary development length of the stirrups may not be available because of the short distance between the mid-depth and the compression face of the member and therefore the use of stirrups may not be economical.

The methods recommended in codes of practice for calculating the ultimate shear strength of ordinary beams cannot be used for fiber concrete beams because of the different properties of the plain and fiber concretes. The considerable amount of experimental data is available on the shear strength of steel fiber mortar and concrete rectangular beams. Predictive equations for shear strength of fiber-reinforced concrete beams have also been suggested by some previous investigators. Some of these equations are generally based on tests of a particular type of steel fiber. The need for a generalized shear strength equation is therefore, obvious if steel fibers are to be used in actual structural members.

ACI Committee 544 showed that; for conventionally mixed Steel Fiber Reinforced Concrete (SFRC), high aspect ratio fibers are more effective in improving the post-peak performance because of their high resistance to pullout from the matrix[1]. A detrimental effect of using high aspect ratio fibers is the potential for balling of the fibers during mixing. Techniques for retaining high pullout resistance while reducing fiber aspect ratio include enlarging or hooking the ends of the fibers, roughening their surface texture or crimping to produce a wavy rather than straight fiber profile[2].

The European Standard EN 14889 1:2006[3] says that steel fibers are straight or deformed pieced of cold drawn steel wire, straight or deformed cut sheet fibers, melt extracted fibers, shaved cold drawn wire fibers and fibers milled from steel block which are suitable to be homogeneously mixed into concrete or mortar.

Nine beams have been tested by Lim and Oh[4] to investigate the influence of fiber reinforcement on the mechanical behavior of reinforced concrete beams in shear. The major test variables are the volume fraction of steel fibers and the ratios of stirrups to the required shear reinforcement. The test results show that the first crack shear strength increases significantly as fiber content increases and the improvement in ultimate shear strength was also achieved. The present study indicates that fiber reinforcement can reduce the number of shear stirrups required and that the combination of fibers and stirrups may meet strength and ductility requirements. The volume fraction of steel fibers was varied from 0-2% and the ratios of stirrups from 0-100% of the required shear reinforcement, the beams were tested under four-point loading condition and the load was applied to the test beams as two equal concentrated loads by means of steel spreader beam.

In the present study, four beams specimens of size 100×150×1200 mm at shear span ratio (a/d) of 1.5 were prepared to investigate the shear behavior of HSRC beams with steel fibers. The volume fraction of fibers used was 0.25, 0.5 and 0.75% (FB0.25, FB0.5, FB0.75%). The required materials were thoroughly mixed in a drum type mixer machine and the Super Plasticizer (SP) was added along with 50% of the water. Since, the work ability was reduced with the addition of steel fibers, the dosage of SP was adjusted to obtain a constant work ability of compaction factor of 0.9.

MATERIALS AND METHODS

Experimental program

Description of test specimens: The present study includes twelve specimens, divided to three groups, the first group of specimens contains four specimens which are identified as (A-0), (A-1), (A-2) and (A-3). The beams have constant span equal 1500 mm and rectangle cross section 250 mm depth and 120 mm width as listed in Table 1. The shear span to depth ratio (a/d) was (1.5). Using numbers (0), (1), (2) and (3) in the specimen's names indicate the volume of a fraction of fiber in specimens by weight are equal to 0, 0.25, 0.5 and 0.75%, respectively. The volume of fraction percentage can be defined as:

$$v_f = v_{sf} / v_c$$

Where:

v_{sf} = The volume of steel fiber
v_c = The volume of the specimen

The dimensions of the tested beams are shown in Fig. 1, the tested beams represented about half-scale models of prototype structural beam in the building. They have Rec-section, consisted of 250 mm in thickness and 120 mm width and its supporting length was 1500 mm. Table 1 present beams dimension and details of reinforcement.

Reinforcement steel: The steel used in this research was high tensile steel (36/52) for longitudinal reinforcement. It has 3600 kg cm^{-2} yield stress. The bars used for reinforcement were 12 and 16 mm diameter deformed bars. Tests were carried out of the Egyptian standard specifications. Table 2 presents a summary of tests performed on the steel to determine its properties.

Properties of steel fiber used: The steel fiber with length 60 mm, diameter 0.75 mm, aspect ratio 80, density 78.5 kN m^{-3}, an ultimate tensile strength of 1100 MPa, and an ultimate tensile strain of 2.2% (based on the manufacturer) were used (Fig. 2).

Table 1: Specimens detail

Group No.	a/d	Dimension	Specimens	Fiber content (%)	Vertical stirrups (m)	Main Steel	Compres. St. (mm)
A	1.5	120×250	A-0	0	7Φ8as	2D16	2D12
		120×250	A-1	0.25	7Φ8	2D16	2D12
		120×250	A-2	0.50	7Φ8	2D16	2D12
		120×250	A-3	0.75	7Φ8	2D16	2D12

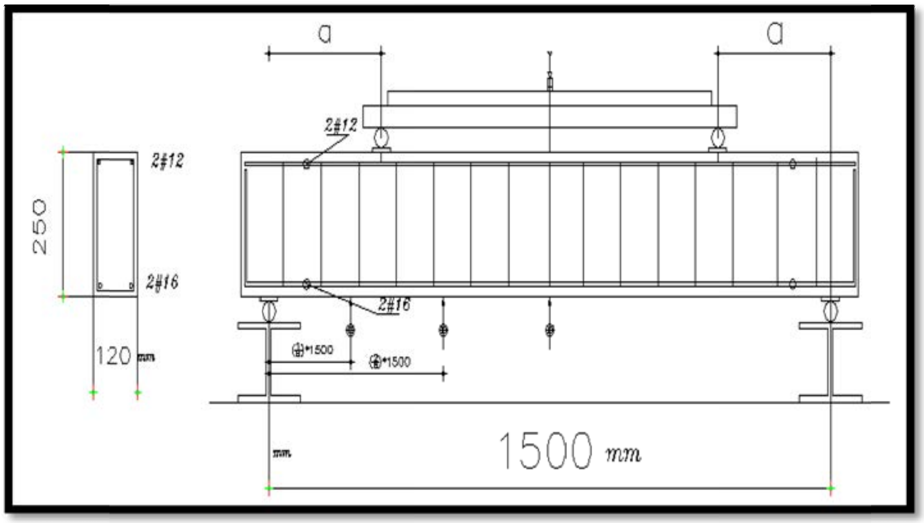

Fig. 1: Beam dimensions

Fig. 2: Fiber shape

Reinforcement details of specimens: Figure 3 shows the reinforcement details of the specimen (A-0) as an example for the reinforcement of the specimens. The main longitudinal reinforcement of the beam was the same in all test specimens. It was approximately 1.34% of the cross-sectional area of the beam, it was 2 bars of 16 mm diameter deformed steel, the secondary reinforcement was 2 bars of 12 mm diameter deformed steel and For all specimens, shear reinforcement (stirrups) was 7φ8 m^{-1}. All reinforcement bars were provided with adequate anchorage lengths at their ends. In all specimens, the clear concrete cover was 25 mm[5].

Compressive strength: Table 3 represented compressive strength for specimens after 28 days from casting, after 7 days, six cubes and four cylinders of these specimens were tested and the remains specimen (six cubes and four cylinders) were tested after 28 days. Figure 4 and 5 represented the standard cubes and cylinders failure.

Test setup: The beam shear tests were performed using four points loading. The beams were tested after removal from water, to avoid the development of shrinkage cracks and a consequent reduction in the tensile strength of the specimens. Digital Load cell of capacity 550 kN with an accuracy of 0.1 kN was adopted to measure the applied load. The value of loads was recorded from the monitor connected to the load cell. The beams were tested using an incremental loading procedure. The vertical displacement of the beams was recorded using three electric dial gauges. One at the middle of beams, the other at distance equal to half of the beam depth from the support and the third near support as shown in Fig. 6.

Figure 6 shows a sample of specimens before testing and the positions of dial gauges. During tests, the applied load was kept constant at each load stage for measuring and observing.

Table 2: Properties of steel used in the experimental work

Properties	Φ 12	Specification
Yield stress (MPa)	380	360
Ultimate stress (MPa)	615	520
Weight per meter length	0.601	0.587-0.649
Ultimate stress/yield stress	1.5	1.05
Elongation	14	12

Table 3: Results of testing concrete specimens cubes and cylinder

Specimens No.	Fiber content (%)	Average compressive strength (MPa)
0	0	51
1	0.25	53
2	0.50	55.8
3	0.75	68.9

The behavior of tested beams: This section describes the most important results observed after testing of the specimens. The effect of changing the fraction volume of steel fiber on the shear resistance are presented in the shown tables and figures.

Beam (A-0): The beam has rectangular-section, of 250 mm in height and 120 mm width and its length was 1500 mm as mentioned before. The beam consisted of two 16 mm bars used as tension reinforcements and

Fig. 3: Reinforcement details of beam

Fig. 4: Standard cube failure shape

Fig. 5: Standard cylinder failure shape

vertical stirrups 7φ8 m^{-1}. The shear span-to-depth ratio for this beam was (1.5). The behavior of this beam can be summarized as follows:

- First shear cracks were initiated at 118 kN
- At a load of about 129 kN another shear cracks appeared
- The flexural cracks did not appear in this specimen
- Shear failure took place at a load of 145 kN; this failure was sudden and loud. The crack patterns and load-deflection diagram of this beam are shown, respectively in Fig. 7 and 8

Figure 9 indicates the deformed shape of beam deflection along beam length at various values of loads 60, 100 and 145 kN.

Beam (A-1): The beam has rectangular-section, of 250 mm in height and 120 mm width and its length was 1500 mm as mentioned before. The beam consisted of two 16 mm bars used as tension reinforcements and vertical stirrups 7φ8 m^{-1}. The shear span-to-depth ratio for this beam was 1.5 with fiber content (0.25%). The behavior of this beam can be summarized as follows:

- First shear cracks were initiated at 145 kN
- At a load of about 150 kN flexural cracks appeared
- The first flexural shear crack initiated at a load of about 150 kN. At this stage propagation of the flexural crack was also observed
- Shear failure took place at a load of 165 kN. This failure was sudden and loud. The crack patterns and load-deflection diagram of this beam are shown in Fig. 10 and 11, respectively

Figure 12 indicate the deformed shape of beam deflection along beam length at various values of loads 60, 110 and 140 kN.

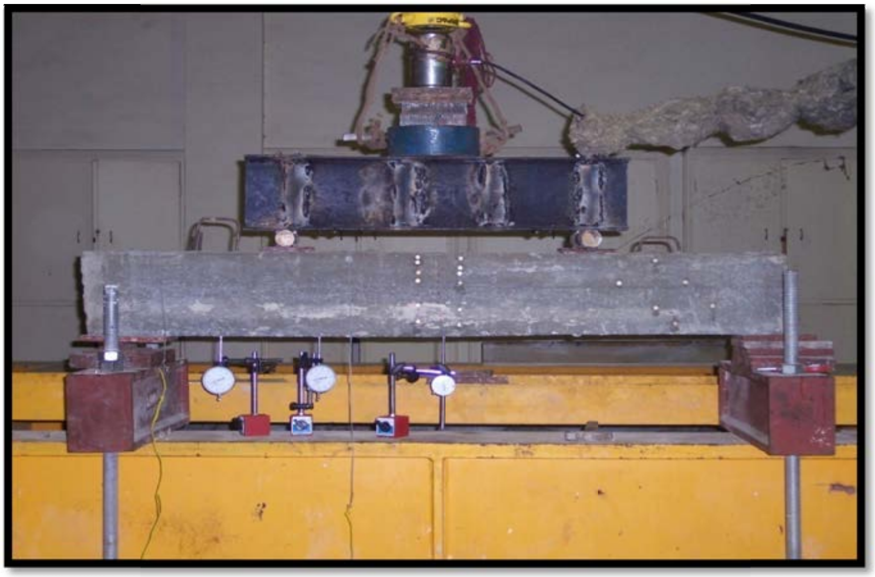

Fig. 6: Specimen before testing

Fig. 7: Crack patterns for specimen (A-0)

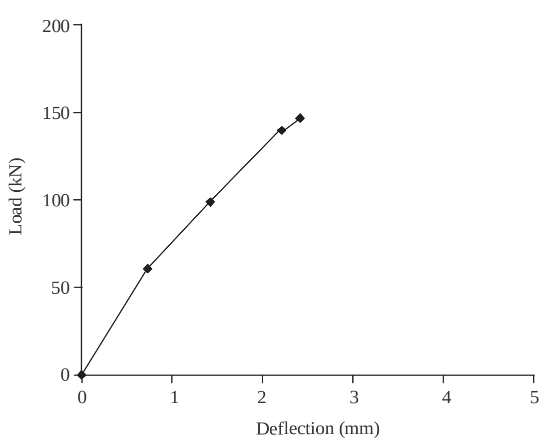

Fig. 8: Load-deflection curve for specimen (A-0)

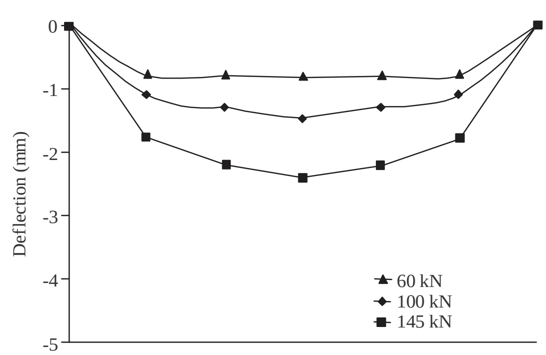

Fig. 9: Deformed shape for specimen No (A-0)

Beam (A-2): The beam has rectangular-section, of 250 mm in height and 120 mm width and its length was

Fig. 10: Crack patterns for specimen (A-1)

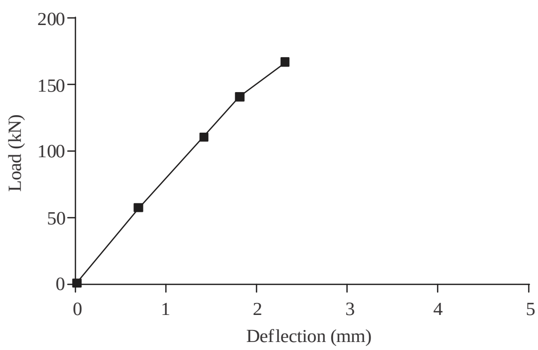

Fig. 11: Load-deflection curve for specimen (A-1)

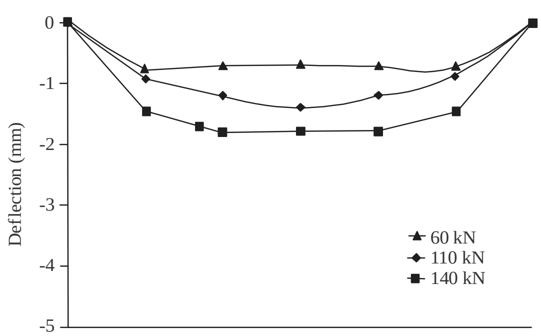

Fig. 12: Deformed shape for specimen No. (A-1)

1500 mm as mentioned before. The beam consisted of two 16 mm bars used as tension reinforcements and vertical stirrups 7φ8 m^{-1}, shear span-to-depth ratio for this beam was 1.5 with fiber content (0.5%). The behavior of this beam can be summarized as follows:

- First shear cracks were initiated at 155 kN
- At a load of about 170 kN, the first flexural crack was initiated
- The shear crack propagated until a load of about 175 kN which the second flexural shear crack initiated, at this stage propagation of flexural crack and initiation of three minor flexural cracks observed
- Shear failure took place at a load of 180 kN. This failure was sudden and loud. The crack patterns and load-deflection diagram of this beam will show in Fig. 13 and 14, respectively

Figure 15 indicate the deformed shape of beam deflection along beam length at various values of loads 60, 90 and 140 kN.

Beam (A-3): The beam has rectangular-section, of 250 mm in height and 120 mm width and its length was 1500 mm as mentioned before. The beam consisted of two 16 mm bars used as tension reinforcements and vertical stirrups 7φ8 m^{-1}. The shear span-to-depth ratio for this beam was 1.5 with fiber content (0.75%). The behavior of this beam can be summarized as follows:

- First shear cracks were initiated at 165 kN
- At a load of about 180 kN first flexural crack was initiated
- The shear crack propagated until a load of about 195 kN which the second flexural shear crack initiated at this stage propagation of flexural crack and initiation of three minor flexural cracks was observed
- Shear failure took place at a load of 215 kN. This failure was sudden and loud. The crack patterns and load-deflection diagram of this beam are shown in Fig. 16 and 17, respectively

Figure 18 indicates the deformed shape of beam deflection along beam length at various values of loads 50, 90 and 140 kN.

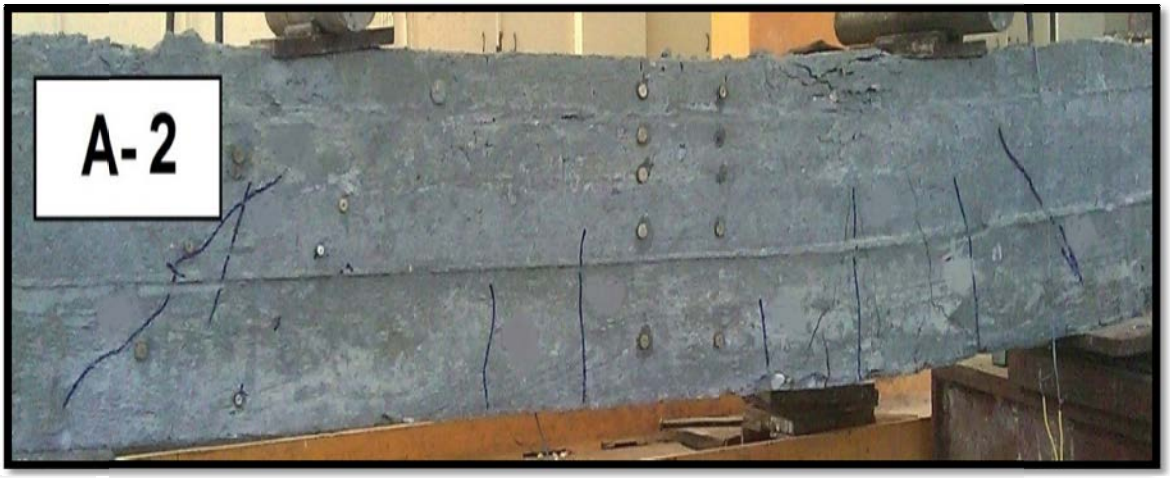

Fig. 13: Crack patterns for specimen (A-2)

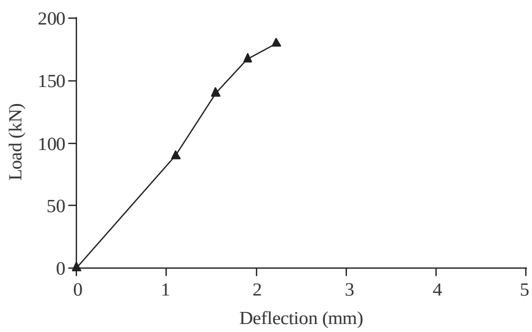

Fig. 14: Load-deflection curve for specimen (A-2)

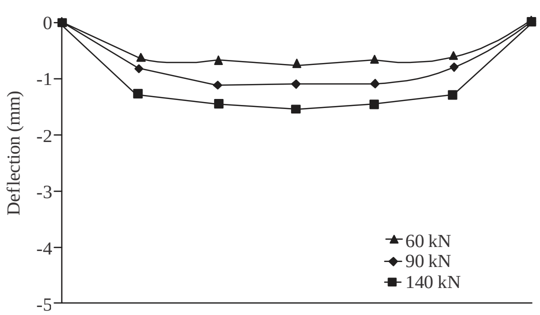

Fig. 15: Deformed shape for specimen No. (A-2)

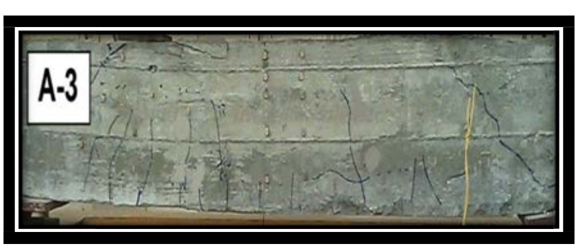

Fig. 16: Crack patterns for specimen (A-3)

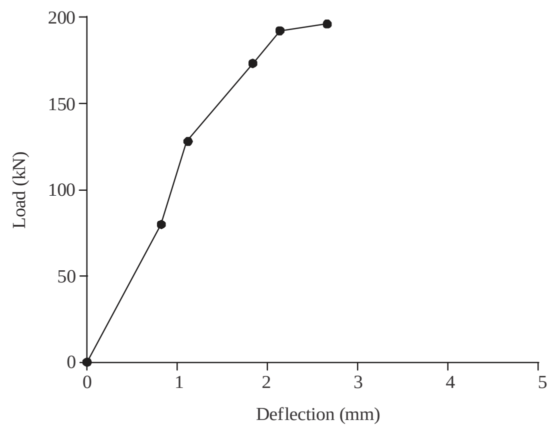

Fig. 17: Load-deflection curve for specimen (A-3)

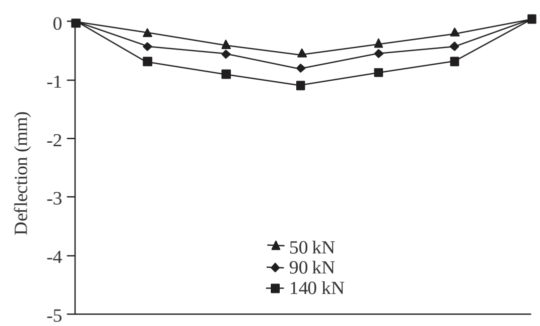

Fig. 18: Deformed shape for specimen No (A-3)

RESULTS AND DISCUSSION

Analysis of experimental results

Analysis the results of the beams (A) included beam (A-0), beam (A-1), beam (A-2) and beam (A-3): All the beams failed as it was expected. The values of ultimate shear, failure modes and percentage of load increase

Table 4: Effect of fiber on specimens Group A

Group	a/d	Specimen No.	v_f (%)	Failure load (kN)	Increase ratio	Mode of failure
A	1.5	A-0	0	145	Control	Shear failure
		A-1	0.25	165	13.80 (%)	Shear failure
		A-2	0.50	180	24.13 (%)	Shear failure
		A-3	0.75	215	48.20 (%)	Shear failure

based on the ultimate load of control beam are given in Table 4. As shown in this Table, the discrete steel fiber increased the ultimate capacity of R.C beams. The percentage of increase reached to about 48.2% when the fiber ratio was increased to 0.75% for the same span to depth ratio.

Crack pattern and failure mode for beams with and without steel fiber are shown in Table 4. The failure of concrete without steel fiber showed a brittle failure behavior compared to specimens with steel fiber. The higher the fibers ratio, the brisker failure of specimens.

The cracking pattern and failure mode of the beams were closely observed. When the loads applied to beams with steel fiber, vertical cracks appeared in the mid-span region. Initially, the cracks were of small width and concentrated in the mid-span region with angles vertical.

However, with further increase of load, the depth and width of cracks increased. The angles of cracks became small and turned diagonal. The change in the angle of cracks can be attributed to the cantilever action of the cracked concrete restrained by the longitudinal reinforcement in the tension zone. When the load was further increased, the depth of some of the diagonal cracks further enhanced and crossed into the compression zone of the beams which ultimately caused the failure of the beams as the cracks extended further towards the point of application of loads. This kind of failure is also called "diagonal tension" failure which was observed in the beams having the fiber of 0, 0.25%. For beams having the fiber (0.5, 0.75%), the failure has been observed predominantly due to shear cracks which are also called the shear failure. Here, the flexural cracks are dominant in the middle third region and the angle of failure is large.

Load deflection curves: Figure 19 shows the relationship between the applied load and mid-span deflection for different steel fiber ratio. While increase ratio of steel fiber enhances the stiffness of beam when beam (A-0) start cracking at load equal 118 kN the deflection of the beam at this load equal 1.8 mm while beam (A-3) cracks at load 165 the deflection was 1.5 mm. Moreover, it is clear that the increase of steel fiber ratio decreases the ultimate deflection as shown in Fig. 19 and in turn, increases shear capacity of beams and increase stiffness as shown on Table 5.

Energy absorption capacity: Energy absorption capacity of all the specimens was calculated as area under load-deflection curve. Table 6 shows the results and it can be observed that as fiber content increased, the energy absorption capacity increased and for 0.75% fiber, an increase of 42.6% was found. This can be attributed to the effect of fibers in bridging the crack and hence enhancement in energy absorption capacity.

Table 5: Initial stiffness for beams

Group	a/d	Specimen No.	Increase ratio (kN/mm)	Stiffness
A	1.5	A-0	65.56	Control
		A-1	70.45	7.40 (%)
		A-2	97.06	48.00 (%)
		A-3	110.00	67.70 (%)

Table 6: Energy absorption capacity for the beams

Group No.	Specimen No.	v_f (%)	Energy absorption capacity (kN-mm)
A	A-0	0	6.4×10^2
	A-1	0.25	8×10^2
	A-2	0.5	8.6×10^2
	A-3	0.75	11.2×10^2

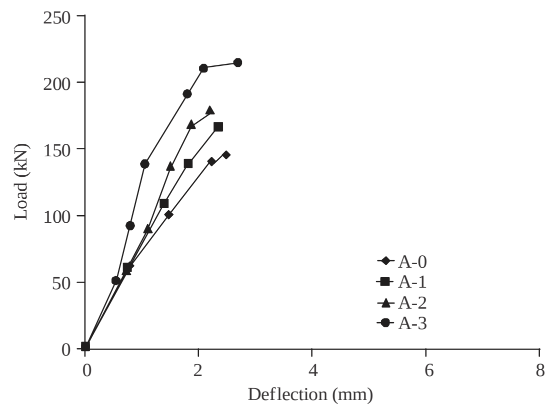

Fig. 19: Load-deflection curves for the beams

Effect of variable changing of fraction's volume on the beams behavior: Table 7 shows the test result of ultimate load. It can be observed that as the fiber content increases the ultimate load gradually. The ultimate load increased due to the addition of fibers, at the same shear span-depth ratio of 1.5 ultimate load increased by 48.2 from changing fiber ratio to 0.75%.

Fiber volume has a significant influence on plasticity and compression zone of the element. With small v_f, normal crack destroys compression zone in nearly the same manner as in the concrete element. With the increase of v_f, compression zone plastic hinge was formed like one in simple bending beam. Besides, fiber volume has significant influence on the height of compression

Table 7: Effect of fiber on all specimens

a/d	Specimen No.	v_f (%)	Fcu (MPa)	Failure load (kN)	Increase ratio
a/d = 1.5	A-0	0	51	145	Control
	A-1	0.25	53	165	13.80 (%)
	A-2	0.50	55.8	180	24.13 (%)
	A-3	0.75	68.9	215	48.20 (%)

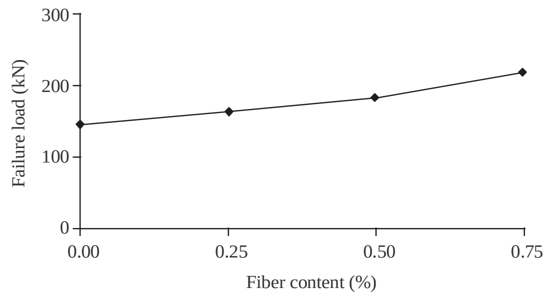

Fig. 20: Effect of fiber content

zone. Experiments show that the average height of compression zone for a/d = 1.5 was equal to 75-84 mm in the conventional concrete element. In SFRC beams it was noticeably greater: the average height of compression zone, at fiber volume 0.75% was equal to 95-102 mm.

In conclusion, the influence of shear stresses on principal stresses and fiber volume effect on the height of compression zone are the main factors determining load capacity.

The addition of fiber displays an increased number of both flexural and shear cracks at closer spacing than the corresponding beams without fibers. As showed on beam (A-3) clearly because of the fiber spacing were much closer, fibers bridging cracks like aggregate role.

Steel fibers beneficially and substantially improve the crack and deformational behavior as well as the ultimate strength because steel fibers enhance the post cracking behavior of beams. It can be noted that the fibers provide increased stiffness after cracking. Reduction of deflections was due to more effective control of cracking, regardless of the value of the modulus of elasticity which increased with addition of fibers.

The addition of fibers increases the work of fracture (represented by the area under the stress crack opening curve). The fiber contributes to dissipate energy thanks to: matrix fracture and matrix spalling, fiber matrix interface deboning, post deboning friction between fiber and matrix (fiber pullout), fiber fracture and fiber abrasion and plastic deformation (or yielding) of the fiber.

Figure 20 shows the influence of steel fiber content on the shear strength of beams with different shear-span depth ratios. It can be seen that the shear strength increases with the increase of fiber content for each shear span-depth ratio.

CONCLUSION

Adding of fibers to high strength concrete increases the first crack load and the ultimate load. For 0.75% volume fiber, the ultimate load increased by 48.2%.

Adding of steel fibers to the concrete mix improves the shear strength of RC beams and tends to increase initial and post-cracking stiffness of beam.

The combination of stirrups and steel fibers demonstrates a positive hybrid effect on the mechanical behavior and is one of the optimal choices for improving the shear capacity.

Test results show that plasticity, cracks propagations and load capacity of elements are greatly influenced by steel fiber volume added. Steel fibers work as a splice which help the matrix to exhibit fewer cracks and increases the stiffness.

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