

Research Article

Flexural Behavior of Steel Fiber Reinforced High-Strength Concrete Beams

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Abstract: In order to investigate the effect of longitudinal reinforcement ratio, volume dosage of steel fiber and the beam height on flexural behavior of steel fiber reinforced high-strength concrete beams, a parametric experimental study has been conducted. Four longitudinal reinforcement ratios, 4 steel fiber volume dosages and 4 different beam heights were used. Results reveal that the bearing capacity and the measured deflection of the steel fiber reinforced high-strength beams are much larger and the breaking of the compression zone is not too serious compared with the reinforced concrete beam. A considerable increase for the ultimate flexural capacity of the beams was observed by increasing the steel fiber volume dosage. Besides, the longitudinal reinforcement ratio has great effect on the ultimate flexural capacity of steel fiber reinforced high-strength concrete beams and the ultimate flexural capacity is increasing gradually with the increase of the longitudinal reinforcement ratio. Furthermore, the effect of the height of the reinforced concrete beam on the ultimate flexural capacity of the steel fiber reinforced high-strength concrete beam is significant and there is a tendency of increase in the ultimate flexural capacity with the increase of the height of the reinforced concrete beam.

Keywords: Flexural behavior, high-strength concrete, reinforced concrete beam, steel fiber

INTRODUCTION

Advances in the material technology have pointed out the addition of steel fibers in concrete to improve the main characteristics of concrete, such as, stiffness, toughness and ductility. Presently, steel fibers are the most commonly researched fiber type concrete. In the 1910s steel elements such as nails and metal chips, were considered as possible sources of reinforcement in concrete (Slater *et al.*, 2012). Through both research and experimental work, steel fibers were eventually introduced as an effective concrete reinforcement in the 1960s. Today, steel fiber reinforced concrete has been used at an increasing rate in various applications like: mine and tunnel linings, slabs and floors (especially those large slabs of factories on which there are great moving loads), rock slope stabilization, repair mortars, shell domes, refractory linings, dam constructions, composite metal decks, aqueduct rehabilitations, seismic retrofitting, repairs and rehabilitations of marine structures, fire protection coatings, concrete pipes and even conventional reinforced concrete frames because of improved toughness against dynamic loads (Altun *et al.*, 2007). Since its introduction, the use of Steel Fiber Reinforced Concrete (SFRC) has received much attention in concrete industry as more research is

being performed and more is being understood about its material properties and behavior (Slater *et al.*, 2012).

When steel fibers are added to high strength concrete, the increase in fiber volumetric ratio results in an increase in the compressive strength of the concrete and a considerable amount of increase in the tensile strength of the fiber reinforced specimens is observed in split cylinder tests (El-Niema, 1993; Febrillet *et al.*, 2000; Reis *et al.*, 2001; Okay and Engin, 2012). However, when this addition exceeds a certain volumetric level, the increase in the strength becomes less (Song and Hwang, 2004; Mohammadi *et al.*, 2008). Volumetric ratio of fiber also increases energy absorbing capacity in bending (Gao *et al.*, 1997). Wang and Lee (2007) experimentally demonstrated that steel fiber reinforced concrete jacketing significantly improves the ductility and flexural and shear strength of interior beam-column joints compared to that of regular concrete jacketing. As the volume content of the fiber increases, ductility under constant load increases in the diagrams. In other words, no difference is observed up to crack, but ductility increases afterwards with the increase in volume content of steel fibers (Craig *et al.*, 1986; Rao and Seshu, 2005). In a research study, the effect of steel fibers on cracks in reinforced concrete beams was investigated and it was concluded that a

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steel fiber dosage of 30-40 kg/m³ was appropriate to have an appreciable improvement on cracks (Altun *et al.*, 2007). Dupont and Vandewalle (2002) and Paine *et al.* (2002) studied the contribution of steel fibers of reinforced concrete beams and determined that a steel fiber dosage of 1-2% by absolute volume was ideal from that aspect. After having performed experiments on steel fiber reinforced concrete beams with steel fiber dosages of 0.5%, 1%, 1.5% by absolute volume, (Ganesan and Shivananda, 2002) developed expressions relating the flexural crack width to the steel fiber dosage. Gopalaratnam *et al.* (1991) studied the effects of dosage and texture as to whether dented or smooth, of steel fibers, as well as the effects of rate of loading and configuration of the setup on toughness of steel fiber reinforced concrete beams.

Although a lot of researches have been carried out on the properties of steel fiber reinforced concrete, the results of effect of longitudinal reinforcement ratio, volume dosage of steel fiber and the beam height on ultimate flexural capacity of steel fiber reinforced high-strength concrete beams are not completely appropriate for practical purposes. Therefore, the present study investigate the effect of longitudinal reinforcement ratio, volume dosage of steel fiber and the beam height on flexural behavior of steel fiber reinforced high-strength concrete beams, which has great instruction in the design and applications of steel fiber reinforced high-strength concrete beams.

MATERIALS AND EXPERIMENTAL PROGRAM

Raw materials: Ordinary Portland cement (Class 42.5R) made by Longyuan cement plant was used. The water to be mixed was local tap water. The steel fibers were made by Shanghai Harex Metal Products Co., Ltd., which belong to milling steel fibers. One side face of the steel fiber is very smooth and the other side face is coarse. The length and diameter of the steel fiber are 32.14 and 0.9 mm, respectively and the draw ratio of the steel fiber is 35.71. The milling steel fiber with a stern anchor at each end can be distributed easily without caking in the concrete mixture. On the other hand, the milling steel fibers have wonderful bond strength with the concrete matrix. The coarse aggregate used was composed of continuous gravel with different size of 5-20 mm. The fine aggregate was coarse river sand with the fineness modulus of 3.4. The longitudinal reinforcing steel bars are hot rolled ribbed thread steel bars. The plain bars with the diameters of 8mm and 10mm are adopted as the stirrup and auxiliary steel bars, respectively. The water reducer used is naphthalene formaldehyde water reducer.

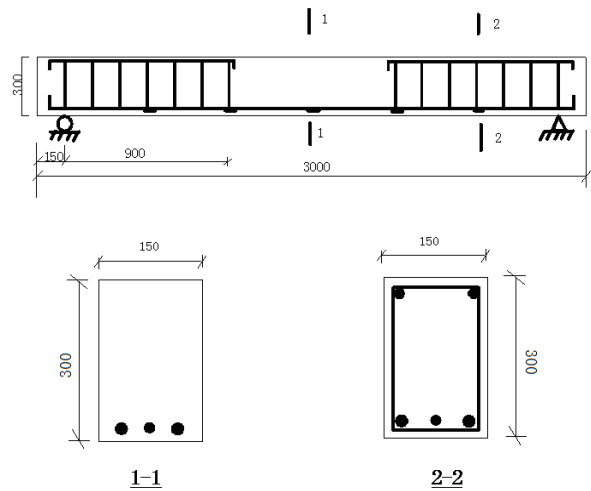


Fig. 1: Detail sizes of the beam (all dimensions are in mm)

Table 1: Design parameters of the specimen beams

Specimen no.	Longitudinal reinforcement ratio (%)	Steel fiber volume dosage (%)	Beam height (mm)
1	0.77	1.5	300
2	1.39	1.5	300
3	2.10	1.5	300
4	2.70	1.5	300
5	1.39	0	300
6	1.39	0.5	300
7	1.39	1.0	300
8	1.39	2.0	300
9	1.39	1.5	250
10	1.39	1.5	300
11	1.39	1.5	350

Design and production of specimens: In this study, 10 beams of steel fiber reinforced high-strength concrete and 1 beam of reinforced concrete were designed to investigate the flexural behavior of steel fiber reinforced concrete beams. The detail sizes of the beam can be seen in Fig. 1. When the beams were designed, the varying parameters of longitudinal reinforcement ratio, volume dosage of steel fiber and the beam height were considered. The design parameters of the specimen beams can be seen in Table 1. The compressive strength of the concrete was designed as 60 MPa.

Because the strength of steel fiber reinforced concrete mainly depends on the strength of the coarse aggregate and the reinforcing effect of the steel fibers, the quality of the raw materials should be controlled strictly. Before the concrete mixture was mixed, the gravel with the diameter beyond 25 mm should be removed away and the coarse aggregate should be washed out. All the mixes were mixed in the mixing plant. In order to distribute the steel fibers uniformly and prevent them caking, a forced mixing machine was adopted. Fibers were dispersed by hand in the mixture

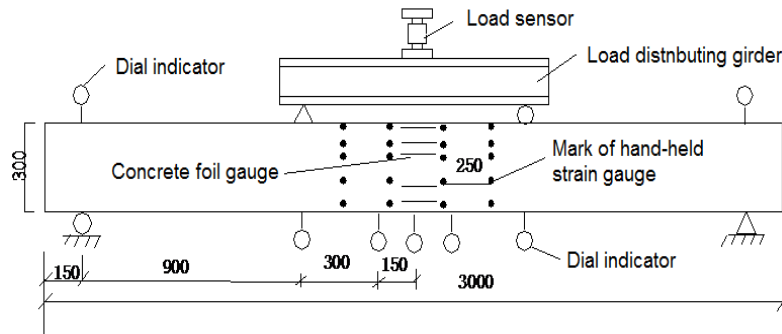


Fig. 2: Sketch map of testing apparatus (all dimensions are in mm)

to achieve a uniform distribution throughout the mixture. The mixing procedure, which was designed by trial and error, was chosen as follows: the coarse aggregate and fine aggregate were mixed initially for 2 min and the cement and steel fibers were mixed for another 2 min. Finally, the water reducer agent and water were added and mixed for 3 min. After casting, all the beams were finished with a steel trowel. Immediately after finishing, the beams were covered with plastic sheets to minimize the moisture loss from them. All the beams were stored at temperature of about 23°C in casting room. They were demoulded after 24 h and then cured at 100% relative humidity and controlled temperature ($21 \pm 2^\circ\text{C}$) before testing.

Experiment method: At the end of the curing period of 28 days, the beams were taken out from the curing room and were prepared for the test of flexural behavior. Three-point bending beam method was employed in this study. This study was carried out at the Key Laboratory of Engineering Material and Hydraulic Structure of Henan Province. The experiment was carried out on a hydraulic pressure testing machine according to the Chinese Standard CECS13-89 (National Standard of China, 1989), whose measure range of the load transducer is 0-500 kN. The sketch map of testing apparatus is presented in Fig. 2. The strain of reinforced bars was by foil gauge with the size of 5×3 mm. The strain of concrete was by foil gauge with the size of 80×5 mm. The strain data acquisition was carried out by an automatic data acquisition instrument. After the strain of concrete was beyond the ultimate tensile strain of the concrete foil gauges, the foil gauges will be in failure when the load was increased to a certain value. Therefore, besides foil gauges, a hand-held strain gauge was used to measure the deformation of the beams. The deflection of the beams was measured by dial indicators. In order to inspect the reliability of the experiment devices and insure that the specimen can contact with the loading devices closely, preloading should be carried out to each of the specimens for 2-3 times in advance. The

load in the preloading was a tenth of the calculated ultimate load and it also should less than 70% of the cracking load. After preloading, the specimen beam was loaded in 5 steps and each step of load was not more than 20% of the calculated ultimate load.

RESULTS AND DISCUSSION

Mechanics characteristic of steel fiber reinforced high-strength concrete beam: Figure 3 presents the typical relation curve between each step load and the deflection of steel fiber reinforced high-strength concrete beam. From the figure, it can be seen that both of the strain of concrete and the reinforcing bar was very low at the beginning of loading stage. The strain was linearly increased gradually and the beam was in a linear elastic stage. When the load was increased to 25% of the ultimate load, the strain of the tension zone of the concrete reached the ultimate tensile strain and the 1st crack appeared in the weaker section in the tension zone of the concrete. With the further increase of the load, the tensile stress born in the cracking concrete was transferred to the reinforcing bars, which made the stress of the reinforcing bars in cracking concrete section increase abruptly. Before the reinforcing bars yielded, the number and length of the cracks on the beam surface was becoming larger. Compared with the reinforced concrete beam, there are more little cracks on the surface of the steel fiber reinforced high-strength beam, while the crack length and width are much less. When the reinforcing bars yielded, the stress of reinforcing bars was kept constant, while the strain and the deflection of the beam were increasing rapidly. There was a wide crack in the concrete section where the reinforcing bars yielded and this crack developed towards the beam top to form the critical crack. The beam can still bear load until the compression zone of the concrete is in failure. Compared with the reinforced concrete beam, the bearing capacity and the measured deflection of the steel fiber reinforced high-strength beam are much larger and the breaking of the compression zone is not

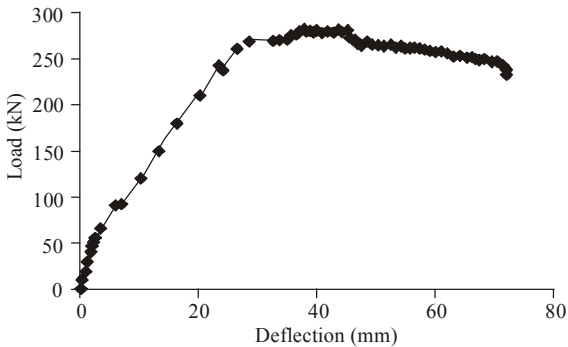


Fig. 3: Typical relation curve between each step load and the deflection

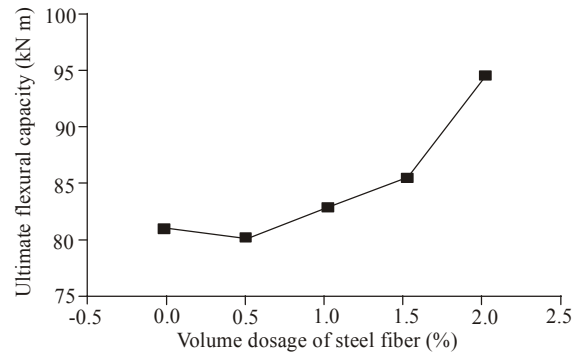


Fig. 5: Ultimate flexural capacity versus steel fiber volume dosage

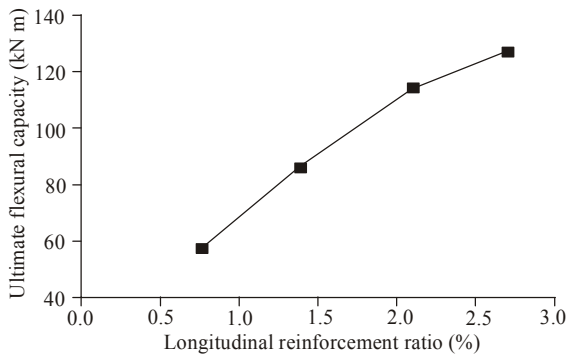


Fig. 4: Ultimate flexural capacity versus longitudinal reinforcement ratio

too serious, which reflects the improvement of reinforcing and toughening of steel fibers.

Effect of longitudinal reinforcement ratio on ultimate flexural capacity: The effect of the longitudinal reinforcement ratio on the ultimate flexural capacity of steel fiber (with volume dosage of 1.5%) reinforced high-strength concrete beams, with the beam height of 300mm, is presented in Fig. 4. From the figure, it can be seen that the longitudinal reinforcement ratio has great effect on the ultimate flexural capacity of steel fiber reinforced high-strength concrete beams. The ultimate flexural capacity is increasing gradually with the increase of the longitudinal reinforcement ratio. As the longitudinal reinforcement ratio is increased from 0.77 to 2.7%, the ultimate flexural capacity increases 121% from 57.15 KN·m to 126.00 KN·m. When the longitudinal reinforcement ratio is less than 2.7%, the increasing rate of the ultimate flexural capacity is lower with the increase of the longitudinal reinforcement ratio, while the increasing rate is much higher when the longitudinal reinforcement ratio is beyond 2.7%. From the variation rule above mentioned, it can be seen that the longitudinal reinforcement ratio is the main factor influencing the ultimate flexural capacity of steel fiber

reinforced high-strength concrete beams. Therefore, the larger longitudinal reinforcement ratio should be chosen in the actual applications of steel fiber reinforced high-strength concrete beams.

Effect of fiber volume dosage on ultimate flexural capacity: The variations of the ultimate flexural capacity of steel fiber reinforced high-strength concrete beams with the beam height of 300 mm versus the steel fiber volume dosage, with the longitudinal reinforcement ratio of 1.39%, are illustrated in Fig. 5. A considerable increase for the ultimate flexural capacity of the steel fiber reinforced high-strength concrete beams was observed by increasing the steel fiber volume dosage. Compared with the reinforced high-strength concrete beams without steel fiber, the increase was determined as 16.7% for 2% steel fiber volume dosage. As seen from the variation curve, the increasing speed of the ultimate flexural capacity of the steel fiber reinforced high-strength concrete beams is very low before the steel fiber volume dosage is less than 1.5% and the increasing speed of the ultimate flexural capacity becomes higher with the steel fiber volume dosage increasing beyond 1.5%. However, there is an inflection point in the varying curve when the steel fiber volume dosage is 0.5%. The main reason of steel fibers can improve the ultimate flexural capacity of the high-strength concrete beams is that the steel fibers have good bond performance with the high-strength concrete matrix and the steel fibers in the tension zone of the beam were pulled out and the fibers were all broken when the concrete beam was eventually in failure. During the course of the steel fibers were being pulled out or being broken, a certain amount of energy was consumed, which prolonged the loading time of the beam. Therefore the ultimate flexural capacity of the high-strength concrete beams was improved. Meanwhile, the failure of the steel fiber reinforced high-strength concrete beams presents some

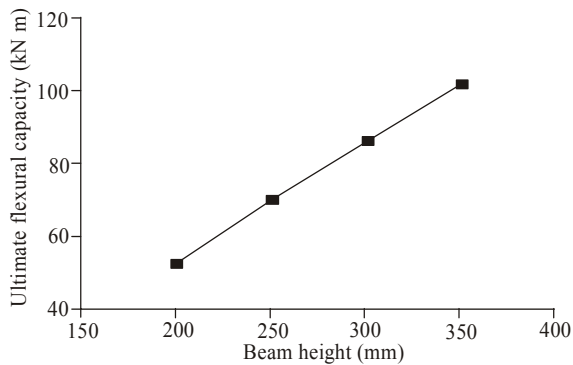


Fig. 6: Ultimate flexural capacity versus height of the reinforced concrete beam

characteristic of plastic failure. The main reason why the ultimate flexural capacity of the steel fiber reinforced high-strength concrete beam with 0.5% fiber volume dosage is less than that of the reinforced concrete beam without steel fiber may be that the amount of steel fibers bridging the cracks is much smaller when the steel fiber volume dosage is too little. Therefore the reinforcement of steel fibers on the high-strength concrete structure elements is unobvious and instead, the addition of steel fibers increases the defect zones inside the beam.

Effect of beam height on ultimate flexural capacity:

The relation between the ultimate flexural capacity of the steel fiber reinforced high-strength concrete beam and the height of the reinforced concrete beam, with the longitudinal reinforcement ratio of 1.39% and the steel fiber volume dosage of 1.5%, is given in Fig. 6. As can be seen from the relation curve, the effect of the height of the reinforced concrete beam on the ultimate flexural capacity of the steel fiber reinforced high-strength concrete beam is significant. There is a tendency of increase in ultimate flexural capacity of the steel fiber reinforced high-strength concrete beam with the increase of the height of the reinforced concrete beam. As the height of the reinforced concrete beam is increased from 200 to 350 mm, the ultimate flexural capacity of the steel fiber reinforced high-strength concrete beam increases 94% from 52.2 kN·m to 101.25 kN·m. From the variation rule above mentioned, it can be seen that the height of the reinforced concrete beam is another main factor influencing the ultimate flexural capacity of steel fiber reinforced high-strength concrete beams.

CONCLUSION

This study reported experimental results of investigate the effect of longitudinal reinforcement

ratio, volume dosage of steel fiber and the beam height on flexural behavior of steel fiber reinforced high-strength concrete beams. The following conclusions can be draw from the results presented in this study:

- Compared with the reinforced concrete beam, the bearing capacity and the measured deflection of the steel fiber reinforced high-strength beam are much larger and the breaking of the compression zone is not too serious, which reflects the improvement of reinforcing and toughening of steel fibers. A considerable increase for the ultimate flexural capacity of the steel fiber reinforced high-strength concrete beams was observed by increasing the steel fiber volume dosage
- The longitudinal reinforcement ratio has great effect on the ultimate flexural capacity of steel fiber reinforced high-strength concrete beams. The ultimate flexural capacity is increasing gradually with the increase of the longitudinal reinforcement ratio
- The effect of the height of the reinforced concrete beam on the ultimate flexural capacity of the steel fiber reinforced high-strength concrete beam is significant. There is a tendency of increase in ultimate flexural capacity of the steel fiber reinforced high-strength concrete beam with the increase of the height of the reinforced concrete beam

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