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Flexural behavior of lightly and heavily reinforced steel fiber concrete beams

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HIGHLIGHTS

- Flexural behavior of steel fiber reinforced concrete beams was studied.
- Fibers slightly increased load capacity of lightly and heavily reinforced beams.
- Ultimate deflection of SFRC specimens was greater than that of CC specimens.
- Flexural toughness of SFRC specimens was greater than that of CC specimens.
- Load–deflection relationships can be estimated using the available equations.

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ABSTRACT

Flexural behavior of lightly and heavily reinforced steel fiber concrete beams was investigated. The test series consisted of 20 singly reinforced beams having $180 \times 250 \times 3500$ mm dimensions. The main parameters in the testing program were the type of concrete and the amount of longitudinal reinforcement. Ten different longitudinal reinforcement ratios (with a minimum of 0.2% and a maximum of 2.5%) covering the range from under-reinforced to over-reinforced beam behavior were used in the testing program. Two specimens were cast for each longitudinal reinforcement ratio, one specimen using conventional concrete (CC) and another specimen using steel fiber reinforced concrete (SFRC). Load–deflection behaviors were obtained and evaluated in terms of ultimate load, ultimate deflection, service stiffness, post-peak stiffness, and flexural toughness. The results indicate that the use of SFRC increases the ultimate load and service stiffness of the beams slightly compared to that of CC specimens. As reinforcement ratio increases, the ultimate deflection of SFRC specimens becomes significantly greater than that of CC specimens. For over-reinforced sections, the post-peak stiffness of the SFRC specimens is observed to be significantly lower than that of CC specimens. The flexural toughness of SFRC specimens is greater than that of CC specimens with the difference being significantly larger for over-reinforced sections. Experimental load–deflection relationships were also compared to the load–deflection curves obtained from sectional analyses based on strain compatibility and best fit stress–strain relationships for SFRC in tension and compression.

1. Introduction

Steel and synthetic fibers have been used to enhance the properties of concrete in practice for many years. However, commercial use of fibers in concrete begun in 1970's particularly in Europe, Japan and the USA. Extensive research has been conducted worldwide on the use of other types of fibers in addition to steel. Nowadays, a wide range of engineering materials including ceramics, plastics, and steel is being used to enhance composite properties of concrete.

In structural applications, concrete behaves as a brittle material with low tensile strain capacity and with some softening post-peak behavior in compression essentially due to the transverse strain capacity. By adding steel fibers, the micro- and macro-cracking in concrete matrix is controlled, and this results in improvements in mechanical properties. The use of adequate amount of steel fibers with appropriate shape increases the tensile strength and the ductility behavior of concrete matrix [2].

When fibers are used in concrete, they tend to act in a variety of ways. They can reduce the formation and development of cracks

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due to early-age plastic settlement and drying shrinkage. They may also provide a degree of post-cracking load-carrying capacity [2]. Steel fibers generally reduce the brittle nature of concrete matrix, but they do not have significant effect on the compressive behavior [7]. However, the ductility and flexural toughness characteristics of concrete are considerably improved as a function of the volume fraction, aspect ratio, and type of the fiber used [2].

Various analytical expressions have been proposed to model the compressive stress–strain behavior of steel fiber reinforced concrete (SFRC) [20,11,16,8,23] and tensile [14,15,23,19]. By using these available models, the load–deflection behavior of flexural members may be obtained numerically.

Many tests have been performed to evaluate the effect of steel fibers on flexural behavior of SFRC beam specimens ([14,18,22,4,10,3,9,21,12,17,13]).

Based on the results of load tests on concrete beams reinforced with a combination of steel bars and steel fibers, Henager and Doherty [14] stated that the presence of steel fibers improved the flexural behavior by increasing the ultimate load capacity and post-cracking stiffness and by decreasing the crack width and crack spacing. Qian and Patnaikuni [18] also reported improvement in stiffness and post-peak load resisting ability with no significant effect on the number and length of cracks. Altun et al. [3] reported that reinforced concrete beams with steel fibers had more favorable behavior in terms of the initiation, size, and propagation of flexural cracks as compared to the beams with conventional concrete. Their experimental results indicated a minor increase in ultimate moment capacity and a major increase in flexural toughness of reinforced concrete beams with the addition of steel fibers. Abdul-Ahad and Aziz [1] tested T-shaped reinforced concrete beams with various amounts of steel fibers and concluded that the addition of steel fibers resulted in an increase in the ultimate load capacity of both under-reinforced and over-reinforced beams. Based on the results of experimental and numerical studies, they stated that over-reinforced concrete beams may be used by providing steel fibers in the compression zone. Dancygier and Savir [10] investigated the behavior of concrete beams with steel fibers and with minimum amount of steel reinforcement. The experimental results indicated that the addition of fibers reduced the ductility of lightly reinforced beams. Based on this observation, an increase in minimum flexural reinforcement ratio was proposed for concrete beams with steel fibers in order to achieve a sufficient level of ductility. Campione and Mangiavillano [9] studied the monotonic and cyclic behavior of reinforced concrete beams with steel fibers. In addition to the previously mentioned improvements in the monotonic behavior, the presence of fibers also improved the cyclic behavior of beams by reducing the extent of cover concrete spalling and pinching.

Majority of the tests available in the literature on flexural behavior of reinforced concrete beams with steel fibers are conducted with a fixed amount of longitudinal reinforcement. However, it is a well known fact that the behavior of flexural specimens varies based on the amount of longitudinal reinforcement present in the cross section. In other words, there are two main groups of cross sections based on the flexural behavior, namely under-reinforced and over-reinforced cross-sections. Therefore, there is a need to evaluate the behavior for various longitudinal reinforcement amounts covering the whole range of flexural behavior.

2. Research significance

The objective of the study is to investigate the flexural behavior of lightly and heavily reinforced (i.e., under-reinforced and over-reinforced) steel fiber concrete beams. Load tests were conducted on pairs of SFRC and conventional concrete (CC) beams with increasing amount of reinforcement. The investigated reinforcement amounts ranged from a considerably light reinforcement of $\rho = 0.2\%$ to a relatively heavy reinforcement of $\rho = 2.5\%$. The test results were evaluated based on load carrying capacity, ultimate deflection, service stiffness, post-peak stiffness, and flexural toughness characteristics. Some of the stress–strain models available in the literature for tension and compression behavior of SFRC were used to estimate the flexural load–deflection behavior of the tested SFRC beams for a comparison of the measured and predicted response.

3. Experimental program

The experimental program consisted load testing of 20 reinforced concrete beams having 180 × 250 mm rectangular cross section and 3300 mm span length. The main parameters in the testing program were the type of concrete (CC and SFRC) and the amount of longitudinal reinforcement. Ten different longitudinal reinforcement ratios, ranging between 0.2% and 2.5%, covering the range from under-reinforced to over-reinforced beam behavior were used in the testing program. Two specimens were cast for each longitudinal reinforcement ratio, one specimen with CC and another specimen with SFRC. Details of the test specimens are presented in Table 1.

Schematic general and cross-sectional views of the test specimens are shown in Fig. 1. Two-point loading was applied, producing a constant moment region of 500 mm in the middle of 3300 mm clear span. Transverse reinforcement in the form of 8 mm diameter stirrups spaced at 100 mm was used within each shear span located on either side of the constant moment region. Two 10 mm diameter hanger bars (i.e., compression reinforcement) were also used in the shear-spans. No transverse reinforcement and hanger bars was used in the 500 mm long mid-span region of the specimens. Consequently, any confinement effect due to the transverse reinforcement at the compression zone of the beams was eliminated. The longitudinal and transverse reinforcements used in the specimens were deformed reinforcing steel bars with a nominal yield strength of 420 MPa.

The materials for the two concrete mixture used in this research included ordinary Portland Cement (PC 42.5), clean tap water, superplasticizer (Glenium ACE 30), crushed sand of 0.44 mm size, fine aggregate of size ranging from 4 to 16 mm, and coarse aggregate of size ranging from 15 to 25 mm. The proportions of these materials for the CC and SFRC mixes are presented in Table 2.

Dramix ZP 305 type steel fibers were added in the concrete mixture for the SFRC specimens. The geometric properties and the manufacturer specified mechanical properties of the steel fibers are shown in Table 3. A photograph of the fibers is shown in Fig. 2.

3.1. Test method and test set-up

Four-point bending tests were conducted on beam specimens. Rollers were placed at both ends of the beam and the loading was applied with a 300 kN capacity hydraulic jack. Monotonically increasing displacement loading was applied on

Table 1
Details of the test specimens.

Specimen	Concrete type	Bar diameter (mm)	Number of bars	Reinf. area (mm^2)	Reinf. ratio (%)
CC0.20 SFRC0.20	CC SFRC	10	1	78.5	0.20
CC0.30 SFRC0.30	CC SFRC	12	1	113.1	0.30
CC0.40 SFRC0.40	CC SFRC	14	1	153.9	0.40
CC0.53 SFRC0.53	CC SFRC	16	1	201.1	0.53
CC0.81 SFRC0.81	CC SFRC	14	2	307.9	0.81
CC1.06 SFRC1.06	CC SFRC	16	2	402.1	1.06
CC1.60 SFRC1.60	CC SFRC	16	3	603.2	1.60
CC2.02 SFRC2.02	CC SFRC	18	3	763.4	2.02
CC2.13 SFRC2.13	CC SFRC	16	4	804.0	2.13
CC2.50 SFRC2.50	CC SFRC	20	3	942.5	2.50