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Response of steel fiber reinforced high strength concrete beams: Experiments and code predictions

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ABSTRACT

The shear-flexure response of steel fiber reinforced concrete (SFRC) beams was investigated.

Thirty-six reinforced concrete beams with and without conventional shear reinforcement (stirrups) were tested under a four-point bending configuration to study the effectiveness of steel fibers on shear and flexural strengths, failure mechanisms, crack control, and ductility.

The major factors considered were compressive strength (normal strength and high strength concrete up to 100 MPa), shear span-effective depth ratio ($a/d = 1.5, 2.5, 3.5$), and web reinforcement (none, stirrups and/or steel fibers).

The response of RC beams was evaluated based on the results of crack patterns, load at first cracking, ultimate shear capacity, and failure modes.

The experimental evidence showed that the addition of steel fibers improves the mechanical response, i.e., flexural and shear strengths and the ductility of the flexural members.

Finally, the most recent code-based shear resistance predictions for SFRC beams were considered to discuss their reliability with respect to the experimental findings. The crack pattern predictions are also reviewed based on the major factors that affect the results.

1. Introduction

A promising solution for improving the mechanical performance of RC beams is to employ steel fiber-reinforced concrete [1,2]. It is well recognized that randomly distributed discontinuous steel fibers in a concrete matrix bridge tension cracks and enhance the overall response. In particular, experimental investigations have established that a suitable amount of steel fibers added to the concrete matrix significantly improves the shear and flexural strengths and ductility of steel fiber reinforced concrete (SFRC) flexural members [3,4]. As a consequence, fibers can potentially be used to replace conventional shear reinforcement, as shown in Refs. [5–13]. Despite the significant increase in concrete mix costs, the use of steel fiber reinforced concrete could be of interest to provide a design alternative for the shear reinforcement. Experimental investigations have been conducted to study the shear behavior of SFRC beams in the past [1,2,4–16]. In those papers, the effect of certain factors, such as shear span-effective depth ratio, fiber volume content, concrete strength, and longitudinal reinforcement ratio on the shear strength of SFRC members have been discussed. Although several experimental studies have been conducted to date to evaluate the shear capacity of SFRC beams, few studies are available on the shear strength of high strength SFRC members [14–16]. Hence, further experiments are needed to assess the response of high strength SFRC beams, especially with reference to more recent code provisions. Indeed, the influence of steel fibers in enhancing the shear strength of reinforced concrete (RC) members has been recognized in the fib Model Code for Concrete Structures 2010 (MC2010) and ACI 318 [17,18]. In the MC2010 [17], fiber reinforced concrete is considered as a material for structural members. The shear resistance of FRC members without shear reinforcement is defined as an extension of the shear strength suggested by Eurocode 2 [19]; an additional term that included the toughness properties of FRC is introduced by modifying the longitudinal reinforcement ratio. The ACI 318-11 Code allows a partial replacement of the minimum shear reinforcement with a fiber amount greater than 0.75% of the volume in the concrete composition (crimped or hooked fibers) for a concrete strength lower than 40 MPa and beam depth lower than 60 cm.

The prediction models to calculate the shear resistance (all of

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them empirical) are unavoidably affected by the complexity of the problem. As stated above, the shear resistance is a function of several parameters such as shear span to effective depth ratio, longitudinal reinforcement ratio, fiber volume, fiber aspect ratio, and concrete tensile and compressive strengths.

As observed in Ref. [7], a first group of prediction models considers concrete and fibers with a separate contribution to shear resistance, whereas a second group suggests improved concrete shear resistance directly. A more coherent method, with a strain-based approach, has been suggested by Choi et al. [20].

This paper takes an experimental approach to study the shear-flexure response of steel fiber reinforced concrete beams. Thirty-six reinforced concrete beams, with and without conventional shear reinforcement (stirrups), were tested under a four-point bending configuration to investigate the effectiveness of steel fibers on shear and flexural strengths, failure mechanisms, crack control, and ductility.

Both normal vibrated concrete and high strength concrete beams (up to 100 MPa) were considered. Three different groups categorized by their shear span-effective depth ratio ($a/d = 1.5$, 2.5, 3.5) were tested. The response of reinforced concrete (RC) beams was assessed based on the results of crack patterns, load at first cracking, ultimate shear capacity, and failure modes. The experimental evidence confirmed that the addition of steel fibers improved the mechanical response, both in terms of flexural and shear strengths and the ductility of the flexural members. The most recent code-based shear resistance formulas for RC beams are considered; additionally, the crack pattern predictions are reviewed based on the major factors that affect the results.

2. Experimental research

The experimental program considered three types of concrete designed for a compressive strength f_{ck}, at 28 days, of approximately 40, 75 and 90 MPa. The mix-design and the main mechanical properties at the time of the test are reported in Table 1.

The compressive strength was evaluated on the 150 mm standard cube (at least three), the tensile strength on plain concrete was evaluated by splitting tests (diameter 100 mm length 200 mm), and the bending strength was evaluated on prisms (side $150 \times 150 \times 600$ mm) on a three-point test configuration according to EN 14651 [21]. For fiber reinforced concretes, the associated stress at a Crack Mouth Opening Displacement (CMOD) of 0.5 mm (f_{R1}) and of 2.5 mm (f_{R3}) are also reported (Fig. 1).

The high strength concretes were made with the addition of different mineral admixtures: fly ash was added to the concrete with the characteristic strength of 75 MPa, while microsilica was added to the mix with the strength of 90 MPa. For each type of concrete, two mixes were considered, plain and with steel hooked fibers of low (40) and high tenor (75 and 90) carbon content, and length of 30 mm. The first type of fibers had an aspect ratio equal to 48 and a tensile strength of 1250 MPa, while the second type had an aspect ratio equal to 79 and a tensile strength of 2300 MPa. The powder addition (microsilica and fly ash) led to a different compressive strength at the time of the test with respect to the designed one.

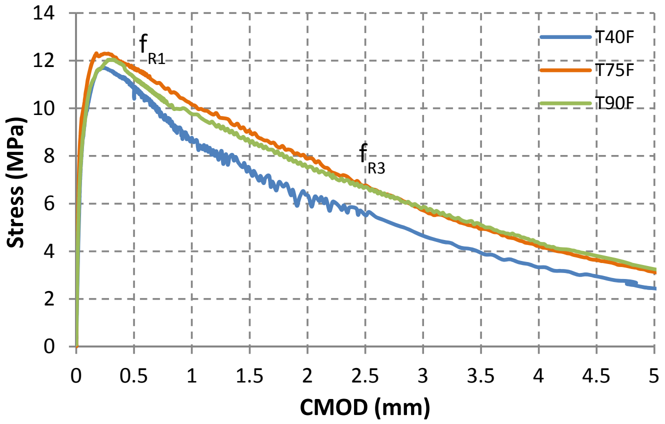

Fig. 1. Bending test on concrete T75F: CMOD vs stress.

Beams of three different span/depth ratios were cast (Fig. 2):

- S: $15 \times 30 \times 240$ cm^3 tested with shear span $a/d = 1.5$;
- M: $15 \times 30 \times 290$ cm^3 tested with shear span $a/d = 2.5$;
- L:$15 \times 30 \times 340$ cm^3 tested with shear span $a/d = 3.5$.

For each size and mix, beams with and without stirrups (diameter ϕ 6/15 cm) were examined, a total of 36 beams. All specimens had the same longitudinal reinforcement B450C (2 ϕ 16), while in the beams with shear reinforcement, 2 ϕ 8 were used as compression steel. The average yielding strength of the longitudinal reinforcement was 522 MPa and that of transversal reinforcement was 533 MPa. The effective depth of the cross section, d, was 26 cm.

Each beam was given a proper code in order to identify all the features: T-$f_{ck,cube}$ (compressive strength)- size (S, M or L) -shear reinforcement (N = none, S = stirrups)- fibers (N = none, F = fibers).

Table 1
Mix-design and mechanical characteristics.

	T40	T40F	T75	T75F	T90	T90F
Cement CEM II-AL 42,5 R (kg/m^3)	300	300	//	//	//	//
Cement CEM I 52,5 R (kg/m^3)	//	//	380	380	405	405
Fly ash (kg/m^3)	80	80	60	60	//	//
Microsilica in slurry al 50% (kg/m^3)	//	//	//	//	90	90
Sand + aggregates (kg/m^3)	1870	1870	1905	1905	1920	1920
Naphthalene sulfonate superplasticizer (l/m^3)	4.5	6	//	//	//	//
Acrylic superplasticizer (l/m^3)	//	//	5,5	7	10	12
Water (l/m^3)	175	175	150	150	80	80
Steel fiber low tenor C (kg/m^3)	//	50	//	//	//	//
Steel fiber high tenor C (kg/m^3)	//	//	//	50	//	70
f_{cm} (MPa)	64.5	62.5	86.7	104.8	94.9	91.8
Standard Deviation (MPa)	4.7	4.4	9.8	0.6	7.7	7.3
f_{ctm} (MPa)	4.6		5.1		5.3	
f_{cfm} (MPa)	6.85	11.70	8.03	12.30	7.41	12.04
f_{R1} (MPa)		10.40		11.70		11.26
f_{R3} (MPa)		5.50		6.76		6.7