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Effect of steel fibers on the flexural behavior of RC beams with very low reinforcement ratios

Doo-Yeol Yoo [a], Do-Young Moon [b,*]

[a] Department of Architectural Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea
[b] Department of Civil Engineering, Kyungsung University, 309 Sooyoung-ro, Nam-gu, Busan 48434, Republic of Korea

HIGHLIGHTS

- Flexural performance of RC beams with low reinforcement ratios is improved by adding steel fibers.
- Lower ductility index is obtained with lower reinforcement ratio and higher steel fiber content.
- Flexural strength margin and ductility of RC beams are deteriorated by adding steel fibers.
- Flexural strength decrease of RC beams with decreasing steel bar amount is not recovered by adding steel fibers up to 1%.
- Steel rebar cannot be replaced with discontinuous steel fibers at moderate amounts below 1%.

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ABSTRACT

This study aims to investigate the implications of hooked-end steel fibers on the flexural performance of reinforced concrete (RC) beams with very low reinforcement ratios. For this, four different fiber volume fractions, v_f, of 0.25%, 0.50%, 0.75%, and 1.00%, were incorporated into the concrete mixture and plain concrete without fibers was considered as a control specimen. Four reinforcement ratios of 0.178%, 0.267%, 0.317%, and 0.406%, which are 44%, 66%, 78%, and 100% of the minimum reinforcement ratio, ρ_{min}, were also adopted to evaluate the steel fiber effect on the flexural behavior of RC beams with various very low reinforcement ratios. The test results indicated that the overall flexural performance of RC beams, in terms of flexural strength, deflection capacity, post-cracking flexural stiffness, and cracking behavior, was improved by increasing the reinforcement ratio up to ρ_{min}. Higher initial cracking and yield loads, post-cracking stiffness, and better cracking performance of RC beams were also obtained by including steel fibers. However, the enhancement of ultimate load carrying capacity by steel fibers was relatively minor, and the ductility index and flexural strength margin, used to guarantee a ductile failure mode, deteriorated with the inclusion of steel fibers. The lower reinforcement ratios and higher fiber volume fractions clearly led to lower ductility indices. Therefore, it was concluded that longitudinal steel rebar could not be replaced with discontinuous steel fibers at moderate volume fractions, $v_f \leq 1.0\%$, in terms of ultimate load carrying capacity, ductility, and flexural strength margin. Lastly, analytical results considering material models for steel fiber-reinforced concrete (SFRC), given by the RILEM recommendation, generally overestimated the flexural capacities of reinforced SFRC beams, and the inaccuracy increased with increasing fiber contents.

1. Introduction

The strengths of steel reinforcement and concrete commonly used for civil construction have been increasing over the past few decades. In the 1990s, in situ concrete with a design compressive strength of 30 MPa or less and steel rebar with a yield strength of 300 MPa were mainly used, but in the 2000s, their strengths increased to above 30 MPa for concrete and close to 400 MPa for steel rebar in South Korea. KCI (Korea Concrete Institute) Standards [1], published in 2012, even allow the use of steel rebar with yield strengths of 500 MPa and 600 MPa as tensile reinforcement in reinforced concrete (RC) members. Using high-strength concrete and steel reinforcement can reduce the cross-sectional area of RC members and greatly decrease the amount of steel reinforcement. Thus, RC structures with amounts of steel rebar below the limit specified

* Corresponding author.
E-mail address: dymoon@ks.ac.kr (D.-Y. Moon).

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by structural design codes are emerging in practice. Since RC structures with very low reinforcement ratios can fail in a brittle manner immediately after first cracking, design codes specify a lower limit of rebar amount to prevent brittle failure and to guarantee a sufficient ductile behavior at the ultimate limit state. The lower limit of steel rebar is also required at the serviceability limit state, relevant to cracking behavior. By significantly decreasing the amount of steel rebar, a smaller number of cracks with greater widths can be obtained at service load levels, and a premature failure of steel rebar can occur. Therefore, the minimum reinforcement ratio specified in design codes is related to the lower limits of rebar amount in both the serviceability and ultimate limit states.

The lack of ductility and fewer cracks with greater widths in RC beams with very low reinforcement ratios (below the minimum reinforcement ratio) can be expected to be compensated and improved by including steel fibers. This is supported by several previous studies on the steel fiber-reinforced concrete (SFRC) beams with conventional steel rebar [2–7]. Even though increase in ultimate strength was insignificant, cracking behavior was improved significantly by the randomly oriented steel fibers in concrete [4]. No crack localization was observed in the test results under service load, while the number of cracks increased and the average crack spacing and maximum crack width decreased. This is caused by the enhancement of bond performance between the concrete and steel rebar and the better post-cracking tensile performance by the added steel fibers. Chaia et al. [2,3] have reported that the minimum reinforcement ratio can decrease, and a ductile failure mode is ensured in RC members subjected to compression and bending actions when conventional steel rebar and steel fibers are used simultaneously. They observed the more obvious effect of steel fibers obtained in lightly reinforced concrete beams because the steel fibers can guarantee resistance to tensile stress and inhibit the widening of cracks. However, Dancygier et al. [8,9] proposed increase in the amount of steel rebar to secure a ductile behavior of reinforced SFRC beams. Dancygier and Savir [9] conducted flexural beam tests of high strength SFRC with a minimum reinforcement ratio and suggested to increase the minimum reinforcement ratio since the steel fibers included in high-strength concrete (HSC) led to the beams being more brittle under flexure. Even in the flexural tests of normal-strength SFRC beams with low reinforcement ratios, Dancygier and Berkover [8] noted crack localization phenomenon and reduced ductility.

A literature review reveals that the effect of steel fibers on the flexural behavior of RC members is still controversial and unclear. In particular, although some previous studies have published regarding the effect of steel fibers on the flexural response of RC beams [6,8,9–11], most of them have adopted RC beams with reinforcement ratios higher than or at least equal to the minimum reinforcement ratio. There is a lack of experimental research on SFRC beams with very low reinforcement ratios, below the minimum reinforcement ratio, as specified in the ACI 318 code [12]. Accordingly, this study focuses on the implication of steel fibers on the flexural behavior of RC beams with reinforcement ratios below the minimum reinforcement ratio and first evaluates feasibility of replacing some of conventional steel rebars to discontinuous steel fibers. In the experimental program, to comprehensively investigate their effects, four reinforcement ratios below the minimum ratio and four volume fractions of steel fibers below 1% were considered along with ordinary concrete without fibers. The test results are presented in terms of flexural strength, deflection capacity, post-cracking stiffness, ductility, and cracking behavior, and sectional analysis is conducted to simulate the flexural behaviors of tested beams.

2. Experimental program

2.1. Mix proportion and steel fiber

Table 1 summarizes the mixture proportions of ordinary concrete and SFRC with various fiber volume fractions used. Type I Portland cement with a density of 3.15 g/cm^3 and specific surface area of 3,413 cm^2/g was used to fabricate both the concretes. Major chemical composites of the cement were calcium oxide (CaO, 61.33%) and silicon dioxide (SiO_2, 21.01%), and the detailed information can be found elsewhere [13]. A water-to-cement (W/C) ratio of 0.37 was adopted, and the unit weights of cement and water were 460 and 170 kg/m^3, respectively. Crushed sand and gravel with maximum grain size of about 25 mm were used for fine and coarse aggregates, respectively. The sand-to-total aggregate (s/a) ratio of 0.45 was adopted, and an air entraining (AE) admixture, with amounts ranging from 4.4 to 6.6 kg/m^3, was also incorporated to enhance the workability of SFRC mixtures. To examine the effect of the volume fraction of hooked-end steel fibers on the flexural behavior of RC beams with various reinforcement ratios smaller than the minimum reinforcement ratio, four different volume fractions (i.e., 0.25%, 0.50%, 0.75%, and 1.00%) were adopted along with ordinary concrete without fibers. The geometrical and physical properties of the hooked-end steel fibers are given in Table 2. The diameter and length of the fibers were 0.55 and 35 mm, respectively, leading to an aspect ratio of 65, and their ultimate tensile strength was approximately 1100 MPa.

Table 1
Mixture proportions.

W/C [%]	s/a [%]	G_{max} [mm]	Unite weight [kg/m^3]						Measured strength[†] [MPa]
			Water	Cement	Sand	Gravel	AE agent	Steel fiber[*]	
37	45	25	170	460	777	949	4.4–6.6	0	43.4
								20	46.2
								40	48.9
								60	36.6
								80	40.9

[Note] W/C = water-to-cement ratio, s/a = ratio of amount of fine aggregate and total amount of aggregate, G_{max} = maximum gravel size, and AE agent = air-entraining agent.
[*] Steel fiber contents of 0, 20, 40, 60, and 80 kg/m^3 equal to 0, 0.25, 0.5, 0.75, and 1.0% in volume fractions, respectively.
[†] Compressive strength is measured as per ASTM C39 at 28 days.

Table 2
Geometrical and physical properties of hooked steel fiber.

Diameter, d_f [mm]	Length, l_f [mm]	Aspect ratio [l_f/d_f]	Density [g/cm^3]	Tensile strength [MPa]	Elastic modulus [GPa]
0.55	35	65	7.9	1100	200