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Feasibility of replacing minimum shear reinforcement with steel fibers for sustainable high-strength concrete beams

Doo-Yeol Yoo [a], Tianfeng Yuan [b], Jun-Mo Yang [c], Young-Soo Yoon [b],*

[a] Department of Architectural Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea
[b] School of Civil, Environmental and Architectural Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea
[c] Steel Structure Research Group, POSCO, 100, Songdogwahak-ro, Yeonsu-gu, Incheon 21985, Republic of Korea

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ABSTRACT

This study aims to investigate the feasibility of eliminating the minimum shear reinforcement in reinforced sustainable high-strength concrete (HSC) beams by incorporating 0.75% (by volume) of hooked steel fibers. To do this, five large reinforced HSC beams, with and without stirrups and steel fibers, were fabricated and tested. In order to have minimum shear reinforcement, the reinforced HSC beams were designed with longitudinal steel bar ratios of 0.64–0.72%. Test results indicate that the use of 0.75 vol% of steel fibers (instead of stirrups) leads to higher flexural strength but lower ultimate deflection and ductility. The failure mode of lightly-reinforced HSC beams was transformed from concrete crushing to longitudinal steel bar rupture by including the steel fibers. However, both the reinforced HSC and steel-fiber-reinforced concrete (SFRC) beams exhibited flexural failure modes; as a result, it was concluded that the minimum shear reinforcement for reinforced HSC beams can be efficiently eliminated by including 0.75 vol% of hooked steel fibers. In addition, the flexural behavior of reinforced SFRC beams was successfully simulated based on sectional analysis by considering fiber orientation factor.

1. Introduction

For more than three decades, a number of researchers [1–6] have tried to use discontinuous, randomly-oriented steel fibers to improve the performance of reinforced concrete (RC) beams. Due to the inhibition of crack propagation and widening through fiber-bridging mechanisms, it is well-known that the shear strength of RC beams can be improved by including steel fibers [1]. The flexural strength of lightly-RC beams was also improved by adding steel fibers [4,5]. In addition to the improved shear and flexural strengths, a high volume of deformed steel fibers (typically greater than or equal to 0.5% by volume) can result in multiple diagonal cracks [7]; these can be used as a minimum shear reinforcement when the ultimate shear force, V_u, is smaller than or equal to the shear resistance of plain concrete ($V_c = 0.17 f_c'^{0.5} b_w d$, where f_c' is the compressive strength, b_w is the beam width, and d is the effective beam depth) [6]. Therefore, the application of steel-fiber-reinforced concrete (SFRC) can overcome the congestion-related problems of steel reinforcement by reducing the amount of stirrups or eliminating the stirrups.

From the database for the shear strength of RC beams that include various amounts of deformed steel fibers, ACI 318-14 Code [8] reported that SFRC can be used to provide the shear resistance of RC beams if it satisfies the following three requirements: (i) it contains at least 100 lb of deformed steel fibers per cubic yard of concrete (v_f of approximately 0.75%), (ii) its residual strength at a deflection point of $L/300$ is higher than 90% of the first-peak flexural strength, and (iii) its residual strength at a deflection point of $L/150$ is higher than 75% of the first-peak flexural strength, where v_f is the volume fraction of fibers and L is the clear span length. This recommendation is only appropriate when the ultimate shear force does not exceed the factored shear resistance of plain concrete. Even though ACI 318-14 Code [8] mentions that SFRC can be used to provide shear resistance, it is still beneficial to determine whether we can eliminate the minimum shear reinforcement of any size RC beams by simply including 0.75 vol% deformed steel fibers.

Most previous studies [1,7,9–11] have examined the effect of steel fibers on improving the shear strength of RC beams without stirrups, but only a few studies [6,12] have investigated the feasibility of replacing the minimum shear reinforcement with discontinuous steel fibers. Aoude et al. [1] and Tan et al. [11] reported that the addition of a moderate amount of steel fibers improves the shear strength of shear-deficient reinforced normal-strength

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* Corresponding author.
E-mail addresses: dyyoo@hanyang.ac.kr (D.-Y. Yoo), yuantianfeng@korea.ac.kr (T. Yuan), jm.yang@posco.com (J.-M. Yang), ysyoon@korea.ac.kr (Y.-S. Yoon).

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Table 1
Mixture proportions.

W/B (%)	GGBFS/B (%)	s/a (%)	Unite weight (kg/m^3)					
			Water	Cement	GGBFS	Fine aggregate	Coarse aggregate	AEWR agent
27.5	60	42.4	163	237	356	671	916	0.70

Note: W/B = water-to-binder ratio, GGBFS/B = ratio of granulated blast furnace slag and total binder, s/a = ratio of amount of fine aggregate and total amount of aggregate, GGBFS = ground granulated blast furnace slag, and AEWR agent = air-entraining and water-reducing agent.

Table 2
Chemical compositions and physical properties of cement.

Surface area (cm^2/g)	Density (g/cm^3)	Ig. loss (%)	Chemical composition (%)					
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
3413	3.15	1.40	21.25	5.28	3.02	61.00	3.71	1.24

Table 3
Chemical compositions and physical properties of GGBFS.

Surface area	Density	Ig.loss (%)	Chemical composition (%)		
(cm^2/g)	(g/cm^3)		SiO_2	MgO	Cl^-
4250	2.90	0.32	21.01	6.40	0.005

concrete beams. In addition, a sufficient amount of steel fibers (equal to or greater than 1 vol%) led to a transformation from brittle shear failure to ductile flexural failure [5], which is identical to the test results reported by Kwak et al. [9]. From a database based on 147 RC beams that included deformed steel fibers, Parra-Montesinos [6] noticed that deformed steel fibers could be used as an alternative to the minimum shear reinforcement in RC beams when the factored shear forces were between $0.5V_c$ and V_c. Minelli and Plizzari [12] also reported that steel fibers can effectively replace the minimum amount of stirrups. Furthermore, slender SFRC beams including $v_f \geq 0.75\%$ exhibited a failure shear strength that was greater than the conservative lower bound of $0.3f_c'^{0.5}$, which is approximately 1.76 times higher than the factored shear strength of plain concrete [6].

Although significant efforts have been made to evaluate the effectiveness of using deformed steel fibers to provide shear resistance of RC beams, to the best of the author's knowledge there have been no published studies that have investigated the feasibility of replacing the minimum shear reinforcement of reinforced high-strength concrete (HSC) beams of various sizes. Furthermore, if it is verified that the brittle shear failure of RC beams is transformed into ductile failure by including steel fibers, a numerical method to predict the flexural behavior of various-sized reinforced SFRC beams (without stirrups) must be suggested for practical applications.

Accordingly, in this study, the feasibility of eliminating the minimum shear reinforcement in reinforced HSC beams with a compressive strength of 67 MPa by adding 0.75 vol% of hooked steel fibers was investigated. For this, reinforced HSC beams were designed to have a minimum shear reinforcement (ρ of 0.64–0.72%), where ρ is the reinforcement ratio. In order to evaluate the size effect in beams, three reinforced SFRC beams with different sizes were fabricated and tested. Lastly, the flexural behavior of reinforced SFRC beams without stirrups was predicted based on sectional analysis, and an equation that considers the fiber orientation effect was suggested by comparing the experimental and numerical results.

2. Test program

2.1. Materials, mixture proportions, and mechanical tests

The detailed mixture proportions used for fabricating HSC are summarized in Table 1. Type 1 Portland cement and Type III ground granulated blast furnace slag (GGBFS) were used as cementitious materials. The chemical and physical properties of these cementitious materials are given in Tables 2 and 3. In order to develop a low-carbon and sustainable HSC, 60% of the cement was replaced with GGBFS. A water-to-binder ratio (W/B) of 0.275 was adopted. Also, to obtain adequate fluidity and freezing and thawing resistance, a polycarboxylic acid–based, air-entraining and water-reducing (AEWR) agent was incorporated. A ratio of fine aggregate and total aggregate (s/a) of 42.4% was used, and a unit water content of 163 kg/m^3 was adopted. Crushed aggregate was used for the sand (fine aggregate), and coarse aggregate with a maximum size of 20 mm was included. The amount of cementitious materials was determined to be 593 kg/m^3. For the concrete including a high volume fraction of steel fiber, the amount of cementitious materials is quite high for improving workability [13]. However, as the amount of cement is increased, the volume stability of concrete will be reduced substantially due to the effects of temperature variation, creep, and shrinkage. In order to minimize such drawbacks, the amount of cement paste was controlled to be similar to HSC without fibers [14,15], and the workability was achieved by using AEWR agent. In addition, based on a previous study performed by Li and Yao [15], the creep and drying shrinkage of HSC were significantly reduced by including GGBFS. Since high volume of GGBFS was included in this study, the creep and drying shrinkage might be reduced as compared to the plain HSC without GGBFS.

The slump flow of HSC was found to be 520 mm, as shown in Fig. 1a, which is a type of self-consolidating concrete. For fabrication of SFRC, hooked steel fibers with a diameter of 0.55 mm and a length of 35 mm were included at 0.75% by volume. The volume fraction (0.75%) of steel fiber adopted in the present study was determined based on the recommendations by ACI 318 Code [8]. The physical and geometrical properties of the fiber are summarized in Table 4. The slump flow of HSC mixture without fibers decreased by including a high volume fraction of steel fibers and found to be about 450 mm, as shown in Fig. 1b. Although the workability of HSC decreased with the addition of steel fibers, its fluidity is much higher than ordinary concrete mixture. Insufficient workability of SFRC may need substantial in-situ compaction, which increases the cost of casting, limits construction time since poker vibration is not generally allowed at night – particularly is a metropolitan, and is environmentally unfriendly – increases carbon footprint of construction. Therefore, some drawbacks of using steel fibers in construction site regarding in-situ compaction, caused by insufficient workability, could be overcome. In addition, due to the addition of AEWR agent, air content of SFRC was obtained as 6%, according to ASTM C231 [16].

The mixing sequence of SFRC was as follows. First, fine and coarse aggregates were included in the pan type mixer and premixed for 60 s. After that, other dry components such as cement and GGBFS were incorporated and mixed for 120 s. Then, 75% water premixed with AEWR agent was included in the dry components and mixed for 60 s, and the steel fibers were slowly