Construction and Building Materials 121 (2016) 676–685

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Size effect in normal- and high-strength amorphous metallic and steel fiber reinforced concrete beams

Doo-Yeol Yoo [a], Nemkumar Banthia [b], Jun-Mo Yang [c], Young-Soo Yoon [d,*]

[a] *Department of Architectural Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, South Korea*
[b] *Department of Civil Engineering, The University of British Columbia, 6250 Applied Science Lane, Vancouver, BC V6T 1Z4, Canada*
[c] *Steel Structure Research Group, POSCO, 100, Songdogwahak-ro, Yeonsu-gu, Incheon 21985, South Korea*
[d] *School of Civil, Environmental and Architectural Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, South Korea*

HIGHLIGHTS

- Increase of specimen size results in a decrease of flexural performance.
- HSC is more sensitive to size effect than NSC.
- The use of amorphous metallic and steel fibers mitigates the size effect of concrete.
- Effectiveness of using steel fibers in decreasing the size effect is greater for HSC.
- Size effect of AM-FRC and SFRC beams is well simulated using Bažant's USEL.

ARTICLE INFO

Article history:
Received 3 April 2016
Received in revised form 11 June 2016
Accepted 13 June 2016
Available online 20 June 2016

Keywords:
Size effect
Amorphous metallic fiber
Steel fiber
Flexure
Strength

ABSTRACT

In this study, the size effect on the flexural behavior of amorphous metallic fiber reinforced concrete (AM-FRC) was investigated. For this, several AM-FRC beams having three different sizes were fabricated with different values of water-to-cementitious material (w/cm) ratio and fiber volume fraction. In order to estimate the implication of fiber type on the size effect, steel fiber reinforced concrete (SFRC) having the same mixture proportion as that of the AM-FRC and 0.75% by volume of hooked-end steel fibers were also fabricated and tested. The experimental results showed that lower flexural performance including flexural strength, normalized deflection capacity, and normalized toughness was obtained with an increase in the specimen size, regardless of w/cm ratio and volume content and type of fibers. High-strength concrete was more sensitive to the size effect on flexural strength than normal-strength concrete, whereas less sensitivity to the size effect was observed with an increase in the fiber volume content. The effectiveness of using hooked-end steel fibers in reducing the size effect was greater for high-strength concrete compared to normal-strength concrete, due to the better fiber bond performance.

1. Introduction

Concrete has been widely used in the construction industry for the past several decades because of its excellent mechanical strength, durability, and economic benefits. However, due to several inherent drawbacks of concrete such as a high brittleness, a low strength-to-weight ratio, and a low tensile strength, its use for special applications for tension-dominant and thin structures was limited. Furthermore, the relatively low tensile strength and high brittleness can lead to the deterioration of durability of concrete structures due to corrosion of internal steel reinforcing bars. In order to solve such drawbacks, numerous studies [1–6] have been conducted to increase the tensile strength and ductility of concrete by using discontinuous fibers.

Several types of discontinuous fibers such as metallic, polymeric, and carbon fibers are currently available. Among others, deformed steel fibers have distinct advantages due to their high elastic modulus and superb bonding performance with the surrounding cementitious matrix [7]. In particular, due to their anchorage mechanism, they substantially improve the crack growth resistance and energy absorption capacity of concrete. For these reasons, ACI 318-14 code [8] recommends that concrete with deformed steel fibers can be used to improve the shear resistance when the residual strength obtained from a bending test as

---

* Corresponding author.
E-mail addresses: dyyoo@hanyang.ac.kr (D.-Y. Yoo), banthia@civil.ubc.ca (N. Banthia), jm.yang@posco.com (J.-M. Yang), ysyoon@korea.ac.kr (Y.-S. Yoon).

http://dx.doi.org/10.1016/j.conbuildmat.2016.06.040
0950-0618/

per ASTM C 1609 [9], at mid-span deflections of $L/300$ and $L/150$ are greater than 90% and 75% of the first-peak strength or $7.5 \times (f_c')^{0.5}$, where L is the clear span length and f_c' is the compressive strength. However, although deformed steel fibers have the noted advantages, their application to structures under marine environmental conditions has been limited due to corrosion of the steel fibers, leading to poor bond performance and a decrease in toughness [10].

Amorphous metallic fibers, whose production is characterized by low energy consumption and CO_2-emissions, have been recently developed and are advantageous from an environmental perspective. Approximately 20% CO_2 is omitted from the production of amorphous metallic fibers, compared to that of conventional deformed steel fibers [11]. In addition, owing to their special production process, in which molten metal is rapidly cooled down at a rate of more than 10^5 K/s, irregular arrays of atoms are formed during solidification, and thus, very thin and flexible metallic fibers, having a low specific gravity, an excellent strength, a low friction coefficient, and a high corrosion resistance, can be produced [11]. According to Redon and Chermant [12], no corrosion was observed in amorphous metallic fibers when they were immersed in HCl (0.1 N) and $FeCl_3$ (0.4 N) for 24 h, because they consisted of 80% (Fe, Cr) and 20% (P, C, Si) by mass. Therefore, amorphous metallic fibers hold promise as a solution for the severe drawback (corrosion) of conventional steel fibers under marine environmental conditions.

Because most laboratory tests are performed at a reduced scale, generalizations are required for real structures with much larger sizes. Therefore, understanding the size effect in concrete is imperative to translate the laboratory test data to real structures [13]. Since the fracture front of concrete is blunted by a fracture process zone with micro-cracks, its size effect exhibits a gradual transition from the yield criterion to the linear elastic fracture mechanics (LEFM) criterion (Bažant size effect law [13]): this phenomenon has been well investigated in numerous previous studies [13–15]. The fibers included in the cementitious matrix generally inhibit crack growth and thus provide a more ductile response. Since the brittleness of concrete is the major factor of the size effect, the mitigation of the brittleness by including fibers can result in a different magnitude of size effect compared to that of conventional concrete without fibers. However, only very limited studies [16–18] are available with regard to the size effect of concrete with fibers. Particularly, to the best of the authors' knowledge, no published study exists on the size effect of amorphous metallic fiber reinforced concrete (AM-FRC). Thus, investigation of the size effect in AM-FRC remains a pressing need.

Accordingly, in this study, the size effect of flexural performance of AM-FRC with two water-to-cementitious material (*w*/*cm*) ratios and three fiber volume fractions was mainly investigated by using three different specimen sizes. In order to evaluate the influence of the fiber type on the size effect, steel fiber reinforced concrete (SFRC) containing 0.75% by volume of hooked-end steel fibers was also fabricated with mixture proportions identical to those of AM-FRC and tested according to ASTM C 1609 [9]. Lastly, the size effect in the AM-FRC and SFRC beams was quantitatively analyzed based on two different size effect laws proposed by Weibull [19] and Hoover and Bažant [14].

2. Experimental program

2.1. Materials and specimen preparation

The mixture proportions used in this research are given in Table 1. Two *w*/*cm* ratios of 0.6 and 0.45 were adopted to obtain two different compressive strengths. Type 1 Portland cement, washed sea sand as the fine aggregate, and crushed gravel having a maximum size of 19 mm as coarse aggregates were included. The weight ratio between sand and gravel (*s*/*a*) of 0.42 was applied for all mixtures. In order to investigate the effect of volumetric fiber content on the mechanical properties (compressive, flexural and tensile properties) and size effect on the flexural performance of AM-FRC, three different volume fractions of 0%, 0.5%, and 0.75% were adopted, using amorphous metallic fibers with a length of 30 mm and a thickness of 0.029 mm. By increasing the length of amorphous metallic fibers, better flexural performance was obtained based on preliminary test results. However, the use of fibers longer than 30 mm obviously decreased the workability due to its higher ratio of length and thickness, so the 30-mm-long amorphous metallic fibers were determined. Because research with regard to the size effect in AM-FRC beams has been very limited, it is difficult to quantitatively determine the magnitude of the size effect for AM-FRC. Therefore, the size effect of SFRC, which is a relatively well-known material, was also investigated. For the SFRC, two different *w*/*cm* ratios, identical to those of AM-FRC, were applied, and one volume fraction of 0.75% for hooked-end steel fibers was adopted based on the previous ACI 318-08 [20] code that the use of deformed steel fibers with a volume fraction of 0.75% or more is acceptable to obtain a significant improvement of shear resistance. The geometrical and mechanical properties of the used fibers are summarized in Table 2. The workability of concrete was reduced at a higher fiber content with a lower *w*/*cm* ratio. Therefore, various amounts of liquid-type polycarboxylate superplasticizer were included to obtain suitable slump values in the range of 60–80 mm. Since the amorphous metallic fibers are very flexible as shown in Fig. 1, no fractured fibers were observed after completion of mixing.

Table 1
Mix proportions.

w/*cm* (%)	*s*/*a* (%)	Unit weight (kg/m^3)				
		Water	Cement	Fine agg.	Coarse agg.	Superplasticizer (%)
60	42	210	350	746	1030	0.0–0.7%
45	42	210	467	705	973	0.3–1.0%

[Note] *w*/*cm* = water-to-cementitious material ratio, *s*/*a* = weight ratio of fine aggregate to total aggregate.

Table 2
Properties of amorphous metallic and hooked-end steel fibers.

Properties	Amorphous metallic fiber	Hooked-end steel fiber
Elastic modulus (GPa)	140	200
Specific gravity (g/cm^3)	7.2	7.85
Fiber length (mm)	30	30
Fiber diameter (mm)	–	0.5
Fiber width (mm)	1.6	–
Fiber depth (μm)	29	–
Tensile strength (MPa)	1400	1195.5
Acid/alkali resistance	High	Low
Electrical conductivity	High	High
Composition	Amorphous metal $(Fe, Cr)_{80}$ $(P, C, Si)_{20}$	Alloy

The test specimens were marked with the letter 'W', denoting *w*/*cm*, and the volume fraction of fiber. For example, W0.45-0.5% indicates a specimen with a *w*/*cm* ratio of 0.45 and 0.5% by volume of amorphous metallic fibers. In the case of SFRC, the letter 'S', denoting the steel fiber, was added in front of the fiber volume fraction.

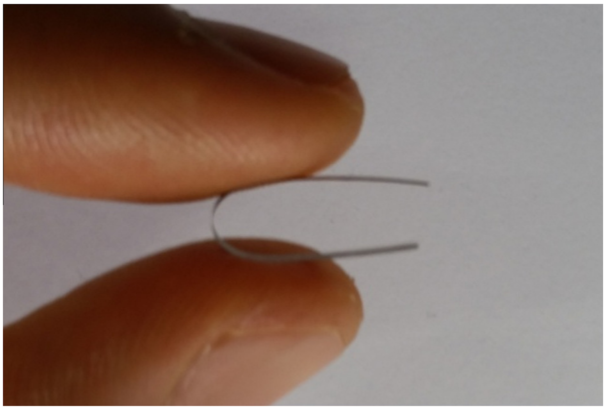

Fig. 1. Flexibility of amorphous metallic fiber.