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Flexural behaviour of arch-type steel fibre reinforced cementitious composites

Jong-Pil Won *, Jae-Ho Lee, Su-Jin Lee

Department of Civil & Environmental System Engineering, Konkuk University, Seoul 143-701, Republic of Korea

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ABSTRACT

We investigated the flexural performance of arch-type steel fibre reinforced cementitious composites. We used arch-type steel fibres with a bend length of 1.5 mm and a radius of curvature of either 25 mm or 35 mm. The flexural performance of the two arch-type steel fibres with different radii of curvature was characterised in accordance with ASTM C1609, where the tensile strength of the steel fibre (i.e., 1100 or 1300 MPa) was also varied. With the 1100-MPa steel fibre reinforced cementitious composites, the composite with a radius of curvature of 35 mm exhibited higher flexural performance compared with the composite formed using the hooked-end-type fibres. The flexural tests of the 1300-MPa steel fibre reinforced cementitious composites formed using arch-type steel fibres with both radii of curvature revealed higher flexural performance compared with the composites formed using hooked-end type fibres. The flexural performance was characterised depending on volume fraction of fibres in accordance with EN 14652:2005 using the 1300-MPa arch-type steel fibres with a radius of curvature of 35 mm. The arch-type steel fibre reinforced cementitious composites exhibited higher flexural strength and higher residual flexural tensile strength than those formed using the hooked-end-type steel fibre reinforcements at all volume fractions.

1. Introduction

The energy absorption capacity of brittle cementitious composites can be improved via the use of steel fibres, leading to ductile behaviour. The energy absorption capacity is increased due to the bridging effect of the reinforcing fibres across the cracks in the cementitious composite, which improves the mechanical properties [1–4].

The bond performance of steel fibres and cementitious composites is an important factor, and is closely correlated with the mechanical properties of steel fibre reinforced cementitious composites. Bond performance is influenced by the geometry of the steel fibre, the surface properties, and the tensile strength of the fibre. Of these factors, geometry affects bond strength most significantly, and so the shape of steel fibre is especially important [5–9].

Holschenmacher investigated how mechanical performance is affected by the geometry of steel reinforcements using flexural performance tests with hooked-end, straight, crimped, and crimped-flat-end steel fibre reinforcements, where the fibres had a tensile strength of 1100 MPa [10]. The results revealed that the hooked-end-type steel fibre exhibited the best flexural performance, and that the crimped and crimped-flat-end types exhibited an abrupt decrease in the load as the steel fibre began to be pulled out, and subsequently failed when the peak load was reached [10].

Hooked-end-type steel fibres exhibit constant energy absorption capacity and stable ductile behaviour in the post-crack behaviour of steel fibre reinforced cementitious composites [11]. These are the most widely used type of reinforcement, and are commonly used with both ends bent. However, with these fibres, the bond performance is substantially lowered and pull out resistance abruptly reduces at the time of pull out following the occurrence of cracks in the matrix. This occurs in the straight part of the fibres, rather than the hooked part, and limits the mechanical properties of the composite. To overcome this limitation, arch-type steel fibres have been developed. These have superior maximum bond strength and energy absorption capacity compared to hooked-end-type steel fibres, due to their smaller radius of curvature. However, they also exhibit fracturing due to excessive anchoring in the cement matrix.

Here we investigate the flexural performance of two arch-type steel fibres with a bend length of 1.5 mm and radii of curvature of either 25 or 35 mm. These reinforcements have previously been shown to exhibit stable pull out and good bond performance. We compared the mechanical properties of composites formed using

* Corresponding author. Tel.: +82 2 450 3750; fax: +82 2 2201 0907.
E-mail address: jpwon@konkuk.ac.kr (J.-P. Won).

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arch-type and hooked-end-type steel fibres. Notched-beam flexural tests were also carried out for reinforcements with different radii of curvature and volume fractions.

2. Materials and mix proportions

2.1. Arch-type steel fibres

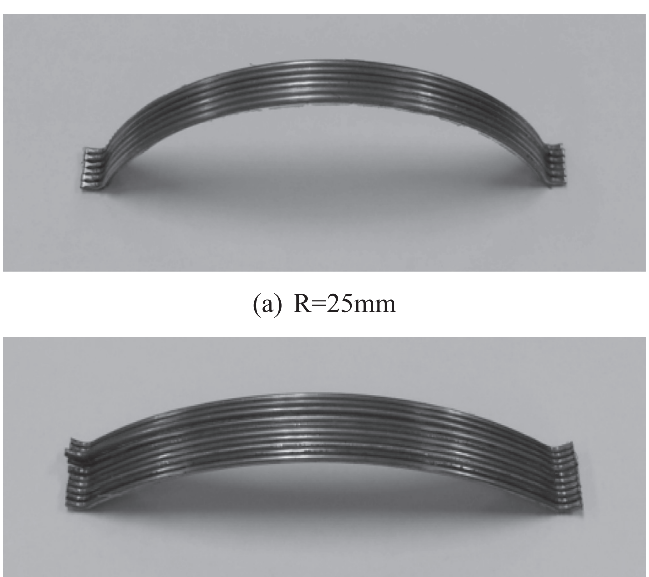
The flexural tests were carried out in accordance with the ASTM C1609 [14]. We used arch-type steel fibres with a bend length of 1.5 mm and radii of curvature of either 25 or 35 mm. These structures have been shown to pull out stably, and to exhibit good bond performance. Two fibres were investigated with tensile strengths of 1100 or 1300 MPa, and the results were compared with flexural tests on composites formed with hooked-end-type steel fibre reinforcements of the same tensile strength. Fig. 1 shows photographs of the arch-type steel fibre reinforcements.

Flexural tests were carried out in accordance with the EN 14651:2005 test method for metallic fibred concrete, where the fibre volume fraction was varied [15]. The specimens were named according to the specification, the steel fibre volume fraction and the tensile strength; for example, the name A25_30_1100 corresponds to arch-type fibres with a radius of curvature of 25 mm, a volume fraction of 30 kg/m^3, and a tensile strength of 1100 MPa, and H_30_1100 corresponds to the hooked-end type fibres, with a volume fraction of 30 kg/m^3 and a tensile strength of 1100 MPa.

2.2. Mix proportions

Table 1 lists the composition of the cementitious composite used for the flexural tests. It consisted of type-I ordinary Portland cement with a specific gravity 3.15, fine aggregates with a specific gravity of 2.58, and coarse aggregates with a specific gravity of 2.69 and a maximum size of 25 mm. The mix was designed to have a compressive strength of 30 MPa. The target slump was 150 ± 25 mm, the air content was 2 ± 1.5%, and the steel fibre volume fraction was 30 kg/m^3.

The cementitious composites used for the notched beam flexural tests employed the same materials as above, and Table 2 lists the mix proportions. The mix was designed to have a compressive strength of 42 MPa. The target slump was 50 ± 15, the air content was 2 ± 1.0%, and the volume fraction of steel fibre was varied through 20, 30, and 40 kg/m^3.



(a) R=25mm

(b) R=35mm

Fig. 1. Photographs of arch-type steel fibres.

3. Experimental

3.1. Flexural tests

The flexural tests were carried out in accordance with ASTM C1609. Two 150 × 150 × 550 mm prismatic specimens that had been aged for 28 days were used for each test. Following curing in water at a constant temperature of 23 ± 2 °C, the specimens were set up as shown in Fig. 2. A 250-kN displacement-controlled universal testing machine (UTM) (SH-250, Shimadzu, Japan) was used for tests, which were carried out with the rate of increase of the net deflection as specified by ASTM C1609; i.e., 0.1 mm/min until a deflection of L/900, and 0.3 mm/min thereafter. The flexural strength was calculated as follows [14]:

$$\boldsymbol{f_P} = \frac{\boldsymbol{P_P} \cdot \boldsymbol{L}}{\boldsymbol{b} \cdot \boldsymbol{d}^2}, \tag{1}$$

where $\boldsymbol{P_P}$ is the peak load, $\boldsymbol{L}$ = 450 mm is the span length, $\boldsymbol{b}$ = 150 mm is the average width of the specimen at fracture, and $\boldsymbol{d}$ = 150 mm is the average depth of the specimen at fracture. The equivalent flexural strength ratio is given by:

$$\boldsymbol{R}^{\boldsymbol{D}}_{\boldsymbol{T},150} = \frac{150 \cdot \boldsymbol{T}^{\boldsymbol{D}}_{150}}{\boldsymbol{f_P} \cdot \boldsymbol{b} \cdot \boldsymbol{d}^2} \cdot 100\% \tag{2}$$

where $\boldsymbol{T}^{\boldsymbol{D}}_{150}$ is the equivalent flexural strength (i.e., the area under the load *vs.* net deflection curve form 0 to L/150).

3.2. Notched-beam flexural tests

The notched-beam flexural tests were carried out in accordance with EN 14651:2005. Two 150 × 150 × 550 mm prismatic specimens were used, and the test was repeated. Twenty-four hours before the flexural performance evaluation, a notch (25 mm deep) was cut from the lower central part of the specimen, and a jig was attached to fix a gauge. The crack mouth opening displacement (CMOD) was measured using a clip gauge (UB-5, Tokyosokki, Japan) installed at the notch. After curing for 28 days in water at 23 ± 2 °C, the specimens were set up as shown in Fig. 3. The tests were carried out using a UTM (SH-250, Shimadzu, Japan). In accordance with EN 14651:2005, the loading rate was 0.05 until a CMOD of 0.1 mm, and was 0.2 until a CMOD of 4 mm. The limit of proportionality (LOP) was calculated as follows:

$$\boldsymbol{f}^{\boldsymbol{f}}_{\boldsymbol{ct},\boldsymbol{L}} = \frac{3 \cdot \boldsymbol{F_L} \cdot \boldsymbol{L}}{2 \cdot \boldsymbol{b} \cdot \boldsymbol{h}^2_{\boldsymbol{sp}}} \tag{3}$$

where $\boldsymbol{F_L}$ is the load corresponding to the LOP, $\boldsymbol{L}$ = 500 mm is the span length, $\boldsymbol{b}$ = 150 mm is the width of the specimen, and $\boldsymbol{h}^2_{\boldsymbol{sp}}$ = 125 mm is the distance between the tip of the notch and the top of the specimen. The residual flexural tensile strength is given by:

$$\boldsymbol{f_{Rj}} = \frac{3 \cdot \boldsymbol{F_j} \cdot \boldsymbol{L}}{2 \cdot \boldsymbol{b} \cdot \boldsymbol{h}^2_{\boldsymbol{sp}}} \tag{4}$$

so that $\boldsymbol{f_{Rj}}$ is the residual flexural tensile strength corresponding to CMOD = CMODj or $\delta = \delta_j$ ($\boldsymbol{j}$ = 1, 2, 3, 4), and $\boldsymbol{F_j}$ is the load corresponding with CMOD = CMODj or $\delta = \delta_j$ ($\boldsymbol{j}$ = 1, 2, 3, 4).