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Influence of Fibre Geometry on the Fracture of Steel Fibre Reinforced Concrete

Komathi Murugan[1*], Stefie J Stephen[2] and Ravindra Gettu[3]

[1] Senior Project Officer (Postdoc), Department of Civil Engineering, IIT Madras, India

[2] Junior Research Fellow (Postdoc), Department of Civil Engineering, IIT Madras, India

[3] VS Raju Chair Professor, Department of Civil Engineering, IIT Madras, India

[*]komathimurugan@gmail.com

Abstract. Steel fibre reinforced concrete (SFRC) is used in various structural applications such as slabs, pavements, hydraulic structures, tunnel linings etc., due to their ability to limit the initiation and propagation of cracks, thereby improving the tensile load-carrying capacity and toughness. Two important parameters affecting the mechanical performance of a given SFRC are the type and dosage of fibres. The study presented in this paper examines the influence of fibre geometry on the fracture properties, considering two different types of cold-drawn hooked-ended steel fibres. Details of the pertaining experimental investigations conducted on SFRC with two different hooked-end geometries (denoted as 3D and 5D) at equivalent dosages are included; the tests conformed to EN 14651:2005+A1:2007. With the change in geometry, from the more conventional (3D) hooked-end with one kink, to that with three kinks at the ends (5D), even with a reduction of dosage from 45 to 35 kg/m^3, 5D fibres were found to exhibit a slight superior performance than 3D fibres.

1. Introduction

Steel fibre reinforced concrete (SFRC) has the toughness and crack bridging ability to encourage its use in a wide range of applications, such as shotcrete, bridge decks, tunnel linings, slabs, pavements, hydraulic structures and precast elements. The geometry of the fibre plays an important role in the SFRC response, as it affects the pull-out characteristics and crack-bridging response during crack propagation. An appropriate geometry should ensure both resistance to crack opening and dissipation of energy in controlled manner, without brittle failure. Also, the geometry should be such that entanglement and balling during fabrication are prevented.

The present study investigates the flexural properties of SFRC with cold-drawn wire fibres, with two configurations having the hooked-ends with one kink (denoted as 3D) and with two kinks (denoted as 5D); see figure 1.

(a) (b)

Figure 1. Selected types of fibres (a) 3D (b) 5D (Courtesy: www.bekaert.com).

2. Research background and motivation

The fibre parameters such as aspect ratio, tensile strength, volume fraction, dosage etc., along with concrete parameters, have been investigated previously for hooked-ended steel fibres (Johnston, 1974 [1]; Naaman, 1985 [2]; Michels *et al.*, 2013 [3]; Tiberti *et al.*, 2015 [4]; Jose *et al.*, 2018 [5]; Stephen *et al.*, 2019 [6]). Recently, the conventional hooked-end steel fibres have been modified with more kinks at the ends to increase the performance. Fibres with multiple kinks have been found to exhibit higher efficiency due to better anchorage, more stress distribution, multiple cracking and increased ductility (Abdallah *et al.*, 2016 [7]; Lee *et al.*, 2019 [8]). The study reported in this paper probes the mechanical performance of SFRC under flexure to assess the parameters used normally in design criteria for structural applications.

3. Experimental investigation

3.1. Details of specimens

SFRC specimens with nominal dimensions of 150 mm × 150 mm × 550 mm (width × depth × length) were examined; see table 1 for details of the fibres used (as available in the product specifications given by manufacturer). Note that both the types of fibres had lengths of 60 mm and diameter of 0.9 mm, and made with cold-drawn wires with modulus of elasticity equal to 210 GPa. The grade of concrete is M50, with a cement content of 340 kg/m^3.

Table 1. Details of fibres

Type of fibre	Dosage (kg/m^3)	Tensile strength (MPa)	Specimen designation
3D	45	1.16	3D - S1 to S8 (8 beam specimens)
5D	35	2.30	5D - S1 to S8 (8 beam specimens)

3.2. Tests for flexural toughness characterisation

The flexural performance of the SFRC beams was evaluated in terms of the limit of proportionality (LOP) or flexural strength, and the residual flexural strengths, using the experimentally-determined load versus crack mouth opening displacement (CMOD) curves. The tests were conducted using a closed-loop servo-hydraulic testing system of 300 kN capacity; see figure 2 for test set-up. Eight specimens were tested for each type of fibre concrete.

Figure 2. Test setup to determine flexural strength.

The test procedure, broadly conforming to EN 14651:2005+A1:2007 [9], is as follows.

- First, a 25 mm deep notch was cut at the bottom surface of a specimen at mid-span, perpendicular to the direction of casting.
- Next, the specimen was simply-supported with a centre-to-centre span of 500 mm. A clip gauge was mounted on knife-edges across the notch mouth to record the change in CMOD (horizontal displacement), with increase in load.
- The load is vertically applied at the mid-span, perpendicular to the longitudinal axis of the beam (along the notch plane). It was initially controlled based on load, with application at a constant rate of 100 N/s, up to a value corresponding to about 40% of the peak load (peak load for trial specimens with 3D and 5D fibres were found to be about 30 kN). Beyond this level, it was controlled based on displacement, by increasing the CMOD at a constant rate of 0.018 mm/min up to 0.1 mm, and then further by 0.09 mm/min. Each test was performed up to a CMOD of not less than 3.5 mm. The load and CMOD readings were recorded during the entire duration of a test.

4. Test results and discussions

The typical failure pattern of a specimen under load applied at mid-span is shown in figure 3, with a single macro-crack emanating from the notch tip, as expected. The load versus CMOD curves of all the tested specimens are given in figures 4.1, 4.2, 5.1 and 5.2. The first crack for each specimen was observed in a load range of 6 kN to 8 kN. For Specimens 3D - S7, 3D - S8, 5D - S3, 5D -S4, 5D - S6 and 5D-S8, there is a gradual reduction in load with increase in CMOD, on the widening of crack. This is attributed to the absence of fibres at immediate vicinity to effect the bridging action. With respect to the ultimate load, a wide variation is obtained between the specimens of each type (3D and 5D). This is because of the inherent variability in the specimens due to the casting and action of fibres.

Figure 3. Typical failure pattern (shown for Specimen 5D - S1).

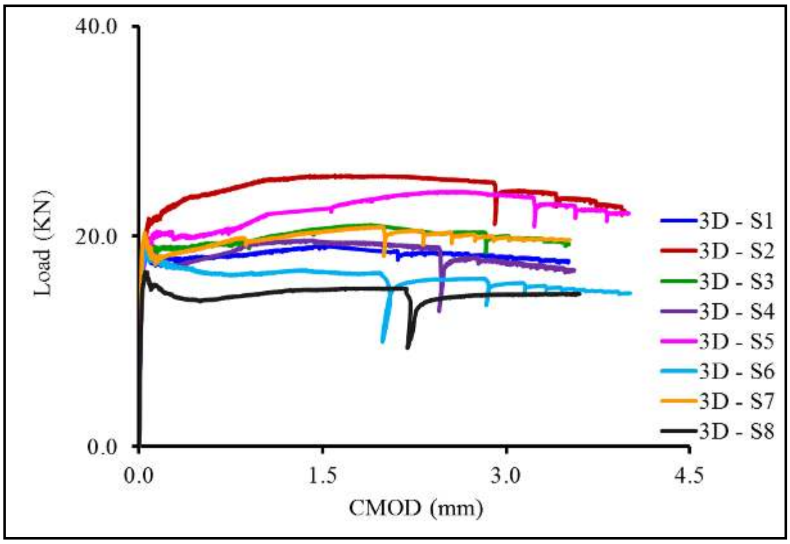

Figure 4.1. Load versus CMOD curves for specimens with 3D fibres (complete behaviour).

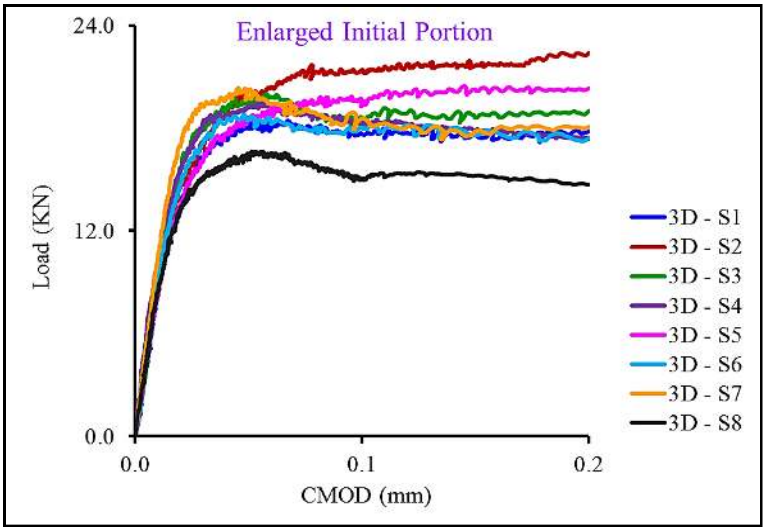

Figure 4.2. Load versus CMOD curves for specimens with 3D fibres (enlarged initial portion).

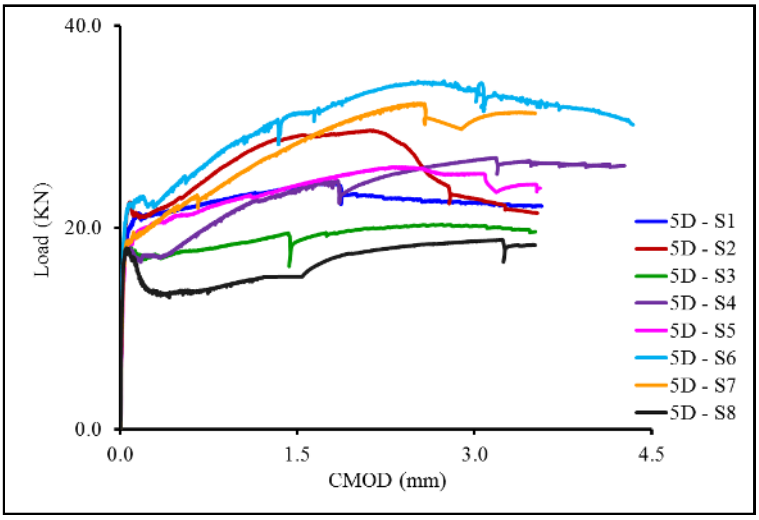

Figure 5.1. Load versus CMOD curves for specimens with 5D fibres (complete behaviour).

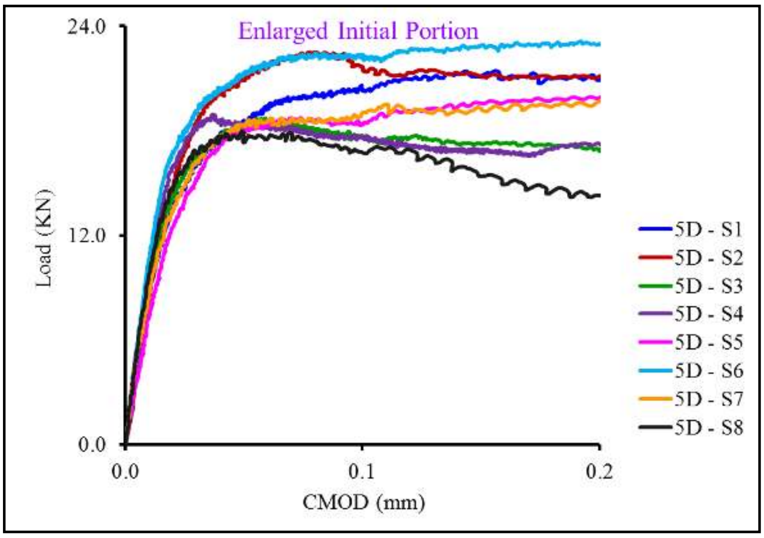

Figure 5.2. Load versus CMOD curves for specimens with 5D fibres (enlarged initial portion).

The flexural toughness parameters were computed as explained below:

- The LOP is given by the following expression (equation (1)):

$$f_{ct,L}^{f} = \frac{3F_L l}{2bh_{sp}^2} \quad (1)$$

Here,

$f_{ct,L}^{f}$ = LOP (MPa)
F_L = load corresponding to the LOP (N)
l = supported length of the specimen (= 500 mm)
b = width of the specimen (= 150 mm)
h_{sp} = distance between the tip of the notch and the extreme compression fibre at top of the specimen (= 125 mm)

The LOP for each specimen was calculated. It is expressed in terms of mean, standard deviation (s) and characteristic strength (f_{Lk} = mean – ks, where k = 2.00 for 8 samples, as per RILEM TC 162-TDF, 2003 [10]), for each type of fibre in table 2. The values of limit of proportionality indicate that there is no significant change in flexural strength or its variability due to the addition of different types of fibres.

- The residual flexural tensile strength ($f_{R,j}$) is given by the following expression (equation (2)):

$$f_{R,j} = \frac{3F_j l}{2bh_{sp}^2} \quad (2)$$

Here, F_j is the load (N) with j = 1, 2, 3, 4 corresponding to CMOD of 0.5, 1.5, 2.5 and 3.5 mm, respectively. The values of $f_{R,j}$ pertaining to each type of fibre are reported in table 2. The mean values of residual flexural tensile strength are found to be highest for the specimens with 5D fibres. However, the characteristic values are similar due to the larger scatter in the concretes with 5D fibres.

Table 2. Estimated flexural toughness parameters.

Type of fibre	LOP (mean ± standard deviation), $f_{ct,L}^{f}$ (MPa)	Characteristic flexural strength, f_{Lk} (MPa)	$f_{R,j}$ (mean ± standard deviation) (MPa)				Characteristic strength, $f_{R,jk}$ (MPa)			
			$f_{R,1}$	$f_{R,2}$	$f_{R,3}$	$f_{R,4}$	$f_{R,1k}$	$f_{R,2k}$	$f_{R,3k}$	$f_{R,4k}$
3D	6.02 ± 0.38	5.26	5.92 ± 0.92	6.36 ± 1.05	6.23 ± 1.25	5.98 ± 1.07	4.08	4.25	3.73	3.83
5D	6.03 ± 0.45	5.13	6.47 ± 1.13	7.78 ± 1.74	8.25 ± 1.76	7.82 ± 1.67	4.20	4.30	4.73	4.49

5. Summary and conclusions

The experimental investigation on SFRC with two different types of end-hook fibre geometry shows that the fibres with one kink (3D) at 45 kg/m^3 and the fibres with two kinks (5D) at 35 kg/m^3 gave similar characteristic flexural strength parameters and fracture toughness. However, in terms of the mean performance, the 5D fibres were slightly superior, even though they were used at a lower dosage.

6. References

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