Engineering Structures 152 (2017) 832–842

Contents lists available at ScienceDirect

Engineering Structures

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

Investigation of the dilatant behavior of cracks in the shear response of steel fiber reinforced concrete beams

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ARTICLE INFO

Article history:
Received 4 March 2017
Revised 9 August 2017
Accepted 24 September 2017

Keywords:
Steel fiber reinforced concrete
Ductility
Crack propagation
Shear-dilatant behaviour
Digital image correlation

ABSTRACT

Steel fiber reinforced concrete beams with fiber volume fractions equal to 0.5% and 0.75% are tested with a shear span to depth ratio equal to 1.8. The cracking in the beams is evaluated using the full-field surface displacements obtained from the digital image correlation (DIC) technique. Analysis of images shows that a full depth shear crack is established before the peak load. The displacements measured from across the shear crack indicate a continuous increase in the crack opening displacement associated with increasing slip between the two crack faces. From crack opening and sliding measurements across the shear crack, the dilatant behavior is identical in beams with and without steel fiber reinforcement. Failure in control beams is brittle and results in a large opening of the shear crack. In the SFRC beams with 0.5% volume fraction, there is a continuous decrease in the residual load carrying capacity after the peak load which is associated with an increase in the crack opening displacement. In SFRC beams with 0.75% fiber volume fraction, the increased resistance to crack opening provided by the fibers results in a significantly smaller crack opening and a large increase in the peak load. The crack opening due to dilatancy is arrested, resulting in shear failure by the formation of a secondary shear crack or by flexural failure. The crack opening displacement across the shear crack at the peak load in the load response of the control and the SFRC beams are nominally identical. Failure in shear occurs when the crack opening control provided by the flexural reinforcement and steel fibers is inadequate to sustain the aggregate interlock.

1. Introduction

Often in shear critical members, the requirement of shear reinforcement leads to very close spacing of stirrups. This problem is compounded while considering the ductile detailing requirements to meet the concerns of seismic design, which require additional stirrups. The extra stirrups often lead to heavy congestion of steel. The use of fiber reinforced concrete offers a solution for reducing steel congestion, while providing the required capacity and ductility. The shear behavior of reinforced concrete has been investigated using both only steel fibers as shear reinforcement and combination of stirrups and discrete steel fibers. A survey of literature on shear behavior of reinforced concrete indicates that there is an increase in the load carrying capacity and ductility with the addition of discrete steel fibers [1–19]. The use of discrete steel fibers reinforcement as shear reinforcement is allowed in some codes of practice [20]. Most of the data in the literature has been obtained for shear span to depth (a/d) ratios in the range 2.5–4.5. In several studies involving the use of steel fiber reinforced concrete where the a/d exceeded 2.5, failure occurred in flexure while the beams without fiber reinforcement failed in shear [1,4,5,8,17,19]. There is very limited data available from beams with low a/d ratio. The role of fibers in beams with low a/d ratio is still not clear.

Addition of fibers increases the post cracking stress transfer ability in concrete, which primarily contributes to improving the ductility [25,26]. To assess the true potential of fibers the post cracking stress transfer across crack has to be accounted for. This is accounted for by including an additional term contributed by steel fibers to the total shear resistance. The post cracking stress transfer is particularly important for shear where shear transfer by aggregate interlock provides significantly to shear capacity of RC elements [21–24,27]. The slip displacement along rough cracks also results in dilatancy under shear and torsion [28–31,43]. The crack bridging provided by fibers can potentially provide for increased mobilization of aggregate interlock, thereby providing shear load capacity. An understanding of the influence of fibers on the post-cracking shear stress transfer across rough cracks surface and its influence on the shear capacity of reinforced concrete beams needs to be understood to develop design provisions which consider the influence of fibers on shear capacity. Motivation for

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https://doi.org/10.1016/j.engstruct.2017.09.050
0141-0296/

the study comes from the need to understand the role of discrete steel fiber reinforcement in contributing to the shear behavior of reinforced concrete beams. In the experimental program, beams containing only steel fibers as shear reinforcement were tested with an a/d ratio equal to 1.80. An a/d ratio less than 2.0 was selected so that the shear behavior of concrete can be investigated without a significant influence of crack opening produced by flexure. For small a/d ratio, failure is shown to be produced by a shear crack within a small region [2,3,9], which allows for studying the behavior of the shear crack. An a/d ratio equal to 1.8 is also large enough to reduce the resistance to applied load from a potential compressive strut between the load point and support associated with strut action [43]. An approach which is based on posterior displacement analysis with the use of the digital image correlation technique is presented to study the formation of the shear crack and to obtain in-situ displacements across the shear crack during the load response. Conventional displacement measurement techniques provide displacement at the point of installation. Determining the displacements across the crack faces without precisely knowing the location of the crack is difficult. DIC technique provides full field displacement measurements and it offers the advantage of posterior evaluation of cracks; evaluation of displacements can be performed after the formation of cracks. The influence of the steel fibers on the crack opening and slip displacements across the rough shear crack is evaluated. Insights into the displacements across the shear crack and the contribution of fibers in providing shear resistance at different stages of load response of a beam are developed. The actual dilatant response measured from across the shear crack in SFRC beams is reported.

2. Experimental program

Reinforced concrete beams of dimensions 125 mm (width), 250 mm (height) and 1500 mm (length) were used in the test program. SFRC beams with different fiber volumes as a percentage of volume of concrete equal to 0.5% and 0.75% were cast. The proportions by mass of the concrete mixture are given in Table 1**.** Crushed granite coarse aggregate of two sizes, 20 mm and 10 mm, were blended in equal proportions. Dramix^{RM} 3D hooked end, glued non-balling steel fibers with an aspect ratio 80 (length 60 mm and diameter 0.75 mm) manufactured by Bekaert industries were used in this study. The fibers have a modulus of elasticity of 210 GPa and tensile strength equal to 1225 MPa.

From each mixture of concrete three numbers of 150 mm cubes and three numbers of reinforced concrete beams were casted. The 28-day compressive strengths obtained from the concrete cubes of the different mixtures evaluated in this study are given in Table 2. All beams were reinforced with two reinforcing bars of 16 mm diameter, placed with a clear cover of 20 mm as shown in Fig. 1. The reinforcing bars conformed to the requirements of IS 1786 (2008) [32] and had a prescribed yield stress defined at 0.2% offset strain equal to 500 MPa. The elastic modulus of the reinforcing bars was equal to 200 GPa and the ultimate strain was equal to 0.16. One half of the beam was reinforced with 8 mm closed shear stirrups, at a spacing of 150 mm. The stirrups were provided in one half of the beam to limit the cracking and shear failure to one side of the beam. Stirrups were provided at a spacing equal to 100 mm at the supports of beam to avoid possible anchorage failure. The flexural reinforcement bars were instrumented with strain gauges.

Table 2
Compressive Strengths of Concrete Mixtures.

Specimen	Mean Compressive Strength (MPa)	Std. Deviation (MPa)
Control	38.7	0.97
SFRC50	40.4	1.82
SFRC75	44.1	1.04

Strain gauges were attached on the flexural reinforcement at two locations, at the mid span location and at 150 mm from the support (shown in Fig. 1).

All the beams were tested in a third-point loading configuration with an a/d ratio equal to 1.80. The testing was performed in displacement control using a servo-hydraulic test machine. The net deflection of the center of the beam was measured using a linear variable differential transformer (LVDT) attached to a reference beam. The reference beam was supported on inserts placed in the concrete beam at the mid-height location directly over the supports. A specially designed loading setup, which conformed to the requirements of ASTM 1609-2006 [33] was used in this study. The load was applied to the beam using a load applying block with hardened steel rollers, which ensured perfect line loading at precisely marked locations of the beam. All forces were applied perpendicular to the face of the specimen. Supporting rollers were capable of rotating on their axis. The load applying block was attached to the actuator through a swivel head which allowed for reducing the influence of torsion in the loading arrangement. The loading arrangement also allowed for in-plane rotation of the loading fixture relative to the actuator, which keeps the applied loads constant even for the small differences in the deflections resulting from unsymmetric crack patterns.

For use in DIC measurement, a sprayed-on speckle pattern was created on the surface of the beam. The speckle pattern was created on the side of the beam without the shear reinforcement (the side where stirrups were not provided). In preparation for DIC, a uniform coat of acrylic-based white paint was applied over the surface of the beam. After the white paint dried, the speckle pattern was created by spraying a mist of black paint. During a test, digital images of the specimen were captured using a high resolution camera (5 mega pixel), which was connected to a computer. Uniform light intensity was ensured across the surface of the beam using normal white light. The camera was fitted with a 50 mm lens and was placed at a distance of 1 m from the specimen surface. The physical calibration for the pixel size was established to be in the range of 7–10 pixels per mm. A reference image of the beam was captured in the undeformed state, before initiating the load. Images of the specimen were captured at regular intervals during the test. A photograph of the test setup is shown in Fig. 2(a) and a schematic sketch of the DIC test setup is shown in Fig. 2(b).

Full-field, surface displacements were obtained from the analysis of digital images captured during the test. At a given load point, a 2-dimensional displacement field was generated from the correlation of the random pattern of speckles between images of the specimen in the deformed state and the specimen in the reference configuration (unloaded state). Spatial correlation and pattern identification was performed within small neighborhoods called subsets of size equal to 35 pixels $\times$ 35 pixels. Spatial domain cross-correlation analysis was performed to establish correspondence between matching subsets in images of the reference and

Table 1
Summary of mass proportions for 1.0 m^3 of the concrete mixture.

Fine aggregate	20 mm coarse aggregate	10 mm coarse aggregate	Water	Cement	Fly ash
823	508	508	163	200	140