Construction and Building Materials 189 (2018) 205–217

Contents lists available at ScienceDirect

Construction and Building Materials

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

Improvements in fracture behavior and shear capacity of fiber reinforced normal and self consolidating concrete: A comparative study

Sahith Gali, Kolluru V.L. Subramaniam *

Department of Civil Engineering, Indian Institute of Technology Hyderabad, India

HIGHLIGHTS

- Fracture and shear behaviors of SCC and NC with the addition of steel fibers are compared.
- Significant tensile post cracking resistance and higher crack closing cohesive stresses are produced in steel fiber reinforced SCC when compared with normal concrete.
- Displacements measured across the shear crack indicate a continuous dilatant crack opening displacement produced by slip between the crack faces.
- There is a larger increase in shear capacity of SCC with the addition of fibers than the corresponding increase in normal concrete.
- The relative increases in the shear capacity of NC and SCC with the addition of steel fibers are consistent with the relative increases in the tensile fracture energies.

ARTICLE INFO

Article history:
Received 16 April 2018
Received in revised form 23 August 2018
Accepted 28 August 2018

Keywords:
Shear
Reinforced concrete
SCC
Fiber reinforced
Dilatancy
Fracture

ABSTRACT

Flexural fracture and shear behaviors of self-consolidating concrete (SCC) and normal concrete (NC) with 0.75% volume fraction of hooked-end steel fibers are evaluated and compared. The cohesive stress-crack separation behavior obtained from the fracture test indicates that the steel fibers are significantly more effective in providing crack control in SCC than in NC. A significantly larger crack closing stress is generated in steel fiber reinforced SCC (SFSCC) even at small crack opening when compared with steel fiber reinforced normal concrete (SFNC). The fracture energy of SFSCC obtained from flexure tests is higher than the fracture energy of SFNC. In the shear response of reinforced concrete, there is a significantly larger increase in the shear capacity of SCC with the addition of fibers when compared with relative increase in NC with the addition of fibers. Full-field displacements obtained from Digital Image Correlation (DIC) is used to establish the in-situ dilatant behavior of the shear crack. The displacements measured across the primary shear crack indicates a continuous increase in the relative slip accompanied by an increase in the crack opening. The dilatant response measured in SCC indicates a smaller crack opening displacement resulting from slip across the primary shear crack when compared with normal concrete. In both NC and SCC, the shear capacity is determined by the failure of stress transfer across the shear crack. Shear failure in SCC occurs at a small crack opening, less than 0.1 mm whereas in NC it occurs at an opening of around 1.0 mm. With the addition of fibers, there is an increase in the load carrying capacity and the load transfer across the primary shear crack is sustained for a larger crack opening in both NC and SCC. The shear stress transfer across the primary shear crack in SFSCC is sustained for a crack opening up to 1 mm. The increase in the crack closing stress provided by steel fibers in SCC matrix contributes to an increase in the shear capacity through better crack control, which results in better shear stress transfer characteristics. The relative increases in the shear capacity of NC and SCC with the addition of steel fibers are consistent with the relative increases in the fracture energies.

1. Introduction

Aggregate interlock contributes significantly to the post-cracking shear stress transfer and thus the shear capacity of reinforced concrete elements [1,2]. The shear capacity of concrete is derived from the frictional contact across the rough crack interface

* Corresponding author.
E-mail address: kvls@iith.ac.in (K.V.L. Subramaniam).

https://doi.org/10.1016/j.conbuildmat.2018.08.194
0950-0618/

of a shear crack. Crack control provided by the reinforcement results in contact stresses on the crack faces, which determine the frictional capacity of the interface. In the conventional strength-based approach, compositional differences in concrete are not considered in deriving the shear capacity. Self-consolidating concrete (SCC) typically contains smaller sized aggregate and larger paste content when compared with conventional concrete of comparable strength. The fundamental characteristics of the shear crack and the frictional characteristics in SCC would be different contributing to differences in the shear capacity when compared with normal concrete [3–5]. An understanding of the shear resistance in reinforced SCC structures and its difference with normal concrete is required.

Steel fibers have been shown to increase the shear capacity and enhance the ductility of reinforced concrete in shear [6–21]. Addition of fibers results in an increased residual strength and toughness of concrete [22–26]. The post-cracking behavior is improved by the resistance to crack opening provided by fibers. The crack bridging stresses provided by fibers ensure stress transfer across the cracked sections. The contribution of fibers in providing resistance to crack opening has been quantified by combining a fracture mechanics-based formulation with high resolution surface displacement measurements [22–25]. The contribution of post cracking stress transfer across a crack produces an immediate benefit in the tensile response with an overall increase in the residual strength and a decrease in the crack width [27–29].

Comparisons between the tensile fracture and the shear responses of normal (NC) and self-consolidating concrete (SCC) of similar strength are reported in this paper. The fracture response of concrete with and without fibers is experimentally investigated. The crack closing stresses generated as a function of crack separation in tension are obtained from the fracture response in flexure. The crack propagation and the post-cracking response in the concrete are studied using Digital Image Correlation (DIC). In shear tests, the crack formation and the displacements across the shear crack at different stages of load response of a reinforced concrete beam are measured. The actual dilatant response measured across the shear crack in reinforced concrete beams is reported. The improvements in the shear capacity in both NC and SCC with the addition of fibers are correlated with improvements in the respective fracture responses from flexure tests.

2. Research significance

With the use of discrete steel fiber reinforcement being allowed for structural applications [30,31], an understanding of the contribution of cohesive crack closing stresses to the shear resistance of steel fiber reinforced concrete is required to develop rational design procedures using steel fibers. In conventional approaches, empirical equations, which include the fiber volume fraction and the dimensions of the fiber have been proposed for predicting shear capacity of steel fiber reinforced concrete [7,8,12,32,33]. Proposed shear capacity prediction equations do not account for the performance of fibers in different matrices. Typically, the influence of the matrix is included using the compressive strength. The compressive strength of concrete does not reflect the improvements in the tensile response, which is primarily related to its fracture behavior.

The effectiveness of steel fibers for use as structural reinforcement depends on the crack closing stress mobilized across a crack. The use of fibers in SCC results in a large improvement in the fracture behavior through improvements in the fiber-matrix bond and the fiber dispersion [34–43]. In shear, the contribution of fibers is to provide crack control and increase the frictional shear capacity by mobilizing additional contact forces between the crack faces. The increased efficiency of steel fibers in an SCC matrix in providing crack closing stresses would produce improvements in the frictional capacity of the shear cracks. Increase in the shear capacity with the use of steel fibers should therefore be linked to the fracture response to include the influence of the concrete matrix. This study provides essential data in linking fracture and shear behaviors of SCC and NC with addition of fibers.

3. Experimental program

3.1. Materials

In the experimental program, hooked end steel fibers at 0.75% volume fraction which corresponds to the minimum reinforcement at 59.3 kg/m^3 (100 lb/yd^3) allowed in codes of practice [30] were used. In the test program, NC and SCC mixtures were prepared with and without fibers. The cementitious material used in the concrete mixtures consisted of a combination of ordinary Portland cement (Grade 53 of the Indian standard, [44]) and siliceous Class F fly ash [45,46]. Cement with a Blaine fineness of 325 m^2/kg and a specific gravity of 3.1 was used. The specific gravity and the Blaine fineness of Class F fly ash were equal to 2.5 and 320 m^2/kg, respectively. Fine aggregate with a specific gravity of 2.67 and fineness modulus of 2.83 was used. The coarse aggregate consisted of crushed granite with a specific gravity of 2.63. The coarse aggregate used in the concrete was a blend of 10 and 20 mm sized aggregate in equal mass proportions. The 20 mm coarse aggregate represent aggregate passing through 20 mm sieve and retained on the 10 mm sieve [47]. The 10 mm coarse aggregate represent aggregate passing through 10 mm IS sieve and retained on 4.75 mm IS sieve [47].

Concrete mixture proportions of NC and SCC were developed to achieve a characteristic strength of 30 MPa. Concrete mixture proportions for the SCC were developed using the hybrid method of EFNARC 2005 [48]. The proportions by mass of the ingredients for the NC and the SCC are listed in Table 1. The water and the powder contents in the SCC mixture were 205 L/m^3 and 500 kg/m^3, respectively whereas, these were 160 L/m^3 and 340 kg/m^3 for NC, respectively. A superplasticizer (BASF Glenium sky 8233) and a viscosity modifying agent (BASF Glenium stream 2) were used for SCC mix. Dramix^{RM} 3D hooked- end steel fibers manufactured by Bekaert industries with a modulus of elasticity of 210 GPa and a tensile strength of 1225 MPa were used. The length and aspect ratio of the steel fibers were equal to 60 mm and 80, respectively.

The concrete was prepared using a drum mixer. One mixture each of NC and SCC without fibers and one mixture each of NC and SCC with hooked end steel fibers were prepared. After mixing, the slump flow test, the L-box test and the V-funnel test were performed to check for workability, segregation resistance and viscosity requirements of SCC and the values are reported in Table 2. A needle vibrator was used for internal compaction of NC in specimen molds. The molds for the SCC specimens were filled by dumping the concrete at one end and allowing the concrete to flow under its own weight. No vibration was applied to the SCC speci-

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

Materials	Mass (kg/m^3)	
	NC	SCC
cement	200	300
Fly ash	140	200
20 mm aggregate	508	–
10 mm aggregate	508	790
Fine aggregate	823	827
Water	163	205.6