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Efficiency of steel and macro-synthetic structural fibers on the flexure-shear behaviour of prestressed concrete beams

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ABSTRACT

The efficiency of steel and structural synthetic fibers on the performance improvement of prestressed concrete (PSC) beams under combined flexure-shear is studied. Results of eleven PSC beams tested at a shear span (a) to depth (d) ratio of five are presented. Discrete steel and macro synthetic structural polyolefin fibers of varying dosages of 0.35%, 0.7% and 1.0% by volume of concrete were used. The effect of fiber addition on overall load – displacement, load- strain, and strain energy absorption capacity of PSC beams is analysed. Other parameters such as shear span to depth ratio (a/d), compressive strength of concrete, prestressing reinforcement ratio were kept constant. The test results portray that the addition of steel fibers stiffens the post cracking response, increases the strain energy absorption capacity more efficiently when compared to macro synthetic fibers (Polyolefin). The failure mode changed from less ductile flexure-shear to more ductile flexure dominant mode at 0.35% and 0.70% volumetric dosage of steel and synthetic fibers, respectively. The strain energy absorption capacity increased by more than 100% at 1.0% fiber addition for both steel and macro-synthetic fibers.

1. Introduction

Fiber Reinforced Concrete (FRC) is tailored by addition of randomly oriented fibers to plain concrete. FRC has gained popularity in the recent years due to advantages like (i) ease of availability of fibers; (ii) better performance in serviceability regime; and (iii) improved mechanical properties in compression, tension, flexure, and shear when compared to the conventional concrete [1–5]. Apart from crack resistance, steel fibers can also be used to replace the conventional transverse reinforcement in the concrete [6,7]. Though steel fibers have superior mechanical properties compared to that of synthetic fibers, they decrease the workability and creates balling effect at higher dosage. On the other hand, structural synthetic fibers, being non-corrosive and malleable, have gained attention in the recent years. They are also used for reinforcing cementitious materials to control the crack propagation and improve the overall structural performance [8,9]. Polyolefin fibers comes under the category of synthetic fibers. Polyolefin fibers are categorized as micro-synthetic and macro-synthetic (structural) fibers. Micro-synthetic fibers are typically 12 mm long and 0.018 mm in diameter, whereas the macro ones are significantly larger with 40–50 mm in length and 0.3–1.5 mm in diameter.

Number of previous work have focused on the behaviour of fiber reinforced concrete under flexure and shear loadings. Sahoo and Kumar [10] tested steel reinforced concrete beams and observed increase in deformability (ductility) and decrease in crack widths. Few researchers [11,12] have used fibers as secondary reinforcement for the concrete elements to improve the shear performance. Some works in the past have [13–15] focused on the influence of fibers on the fresh and hardened properties as well as on the shear capacity of prestressed beams. Yazdanbakhsh et al. [16] carried out analytical studies to predict the shear capacity of synthetic fiber reinforced concrete beams based on the model originally developed for steel fiber reinforcement. They noted that shear capacities from RILEM 162-TDF [17] recommendations were found to be more conservative than Fib-MC2010 [18] for synthetic fiber reinforced beams. Alhozaimy et al. [19] investigated the mechanical properties and effects of pozzolanic materials on concrete reinforced with fibrillated polypropylene fibers of low volume fractions ($< 0.3\%$). They reported that fiber content variation has no significant effect on the compressive and flexural strength of FRC but improved its toughness and impact resistance.

Thomas and Ramaswamy [20] noted that addition of fibers reduced the crack width of prestressed concrete beams. Harajli [21] noted that the presence of fibers enhanced the bond strength of rebars and reduced its bond degradation. Sahoo and Sharma [22] observed that flexural capacity did not improve significantly when more than 0.5% by volume of steel fibers were added to reinforced concrete beams with and without stirrups. Tiberti et al. [23] presented dependency of crack propagation on the concrete strength of steel fiber reinforced concrete

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(SFRC). They noted that steel fibers are more effective when used in high strength concrete (HSC) than in normal strength concrete (NSC). Ramzi and Omer [24] studied the flexural strength of under-reinforced and over-reinforced concrete T-beams with steel fiber. Their results indicated that presence of steel fibers improved the ultimate strength and reduced the crack width. Abbas and Khan [25] carried out pull-out tests on SFRC beams and concluded that the ultimate pull-out load depends on the fiber size and its embedment length.

Yoo et al. [26] presented the effects of strength, fiber content and strain-rate on flexural response of SFRC under quasi-static and impact loads. Banthia and Sappakittipakorn [27] investigated the toughness enhancement of SFRC through fiber hybridization. They noted that flexural toughness and deflection hardening properties were improved. To account for the post peak response of different cement based materials Fantilli et al. [28] defined a unique function. Amin et al. [29] reported the material characterisation of macro synthetic fiber reinforced concrete through a series of tension tests. The authors concluded that the degree of variability in the results is lowest in case of round panel tests compared to uniaxial tension tests. Though number of previous work have focused on fiber reinforced concrete, the effect of structural macro-synthetic fiber reinforcement on the behaviour of high strength prestressed concrete beams has not been explored adequately.

2. Research significance

Most of the previous studies focused on behaviour of concrete elements reinforced with steel fibers and fibrillated or micro-synthetic fibers. Inadequate information is available on the performance of structural synthetic fibers (polyolefin) on flexure, shear and flexure-shear behaviour of prestressed concrete beams and is the focus of this investigation. Thus, this study aims at the following: (i) study the effect of different dosages of steel and synthetic fibers on flexure-shear behaviour of prestressed concrete beams, and (ii) study the crack propagation, strain reduction of prestressing strand and assess the change in failure modes at different fiber additions.

3. Experimental investigation

3.1. Test specimens

The experimental program includes casting and testing of full-scale prestressed concrete beams of rectangular cross section (200 mm × 300 mm) and length of 3500 mm. The beams were reinforced with two prestressing strands of 12.7 mm diameter corresponding to prestressing steel reinforcement ratio of 0.4%. Jacking force is applied to each of the strands to obtain an initial prestressing strain of 0.004 in accordance with IS 1343 [30]. The specimens were divided into three series: beams made of plain concrete (Control), beams made of steel fiber reinforced concrete (SF series) and beams made of polyolefin fiber reinforced concrete (PO Series). Each of the SF and PO series were further categorized based on the fiber dosage. The nomenclature details of different series used in the study are presented in Table 1.

Table 1
Details of concrete series.

	Type of fiber		Dosage of fiber (%)
	Steel	Polyolefin	
Series	Control	Control	0.00
	SF35	PO35	0.35
	SF70	PO70	0.70
	SF100	PO100	1.00

3.2. Material properties

Concrete mix design was developed as per IS 10262-2009 [31] with a target compressive strength of 58 MPa. Table 2 presents the mix details. Coarse aggregate blended of 10 mm and 20 mm aggregate, crushed stone sand, natural river sand, flyash and high range water reducing admixture (HRWR) were used to achieve workable concrete of 58 MPa strength. Addition of fibers inversely affected the workability of concrete mix. The compressive strength of concrete cubes and cylinders tested on 28th day is reported in Table 3. The prestressing strands with seven wired low relaxation steel (12.7 mm diameter, effective area of 99.7 mm^2) were used as reinforcement. Prestressing strands with a constant eccentricity (e) of 100 mm was used resulting in straight profile of the strands. Tensile strength and modulus of elasticity of the strands were measured to be 1860 MPa and 196.5 GPa, respectively from the coupon tests. The hooked end steel fibers and macro- synthetic polyolefin fibers were used in developing concrete mixes of SF and PO series respectively. The shapes and various properties of the fibers used are presented in Fig. 1 and Table 4 respectively.

3.3. Test setup and instrumentation

The shear span to depth ratio (a/d) of five is considered to simulate the flexure-shear behaviour. Kani [32] investigated the effect of different a/d ratios on the behaviour of RC beams. The author found that the beams had flexure dominant behaviour above a/d ratio of 6. The author also observed that the a/d ratio of 2.5 is a transition point below which the beams are shear critical and the corresponding bending moment at failure was found to be minimum. Below the a/d ratio of 2.5, the beam is shown to develop an arch action with a considerable reserve strength beyond the first cracking point. Similarly, for a/d ratio between 2.5 and 6, the failure was due to sudden diagonal shear tension and flexure-shear mode. Therefore, a higher a/d ratio of five is considered to study the influence of steel and synthetic fibers on the flexure-shear behaviour. All the beams were tested in a four-point bending configuration. The beams were simply supported on I-beams. The horizontal movement of the support is restrained. The specimens are not restrained as they are simply supported and the same is portrayed in the Fig. 2. Support width is expected to have minimal influence on the behaviour as the specimens are tested at higher a/d ratio of 5. The effect of different a/d ratio, support conditions, cross section details and size effect on the behaviour of fiber reinforced prestressed concrete beams would be interesting and is scope for further work. Eleven beams were cast with different fiber dosages of 0.00%, 0.35%, 0.70% and 1.00% and were water-cured for a period of 28 days at room temperature. The beam schematic and loading configuration is presented in Fig. 2.

The beams were tested using a servo controlled hydraulic MTS actuator of 250 kN capacity. Load from the actuator was transferred to the specimen through spreader beam and then to the two I-beams (to obtain four-point bending). The test setup is presented in Fig. 3. Loading was applied monotonically in displacement control mode at a rate of 0.05 mm/s. Loading was paused at every 10 kN intervals to mark the crack propagation and study the failure progression. All the specimen displacements were recorded using Linear Variable Displacement Transducers (LVDTs). LVDTs were positioned at specific locations (at mid span and at a distance of one third of the span from support) along the length of the beam to capture the entire curvature profile during testing. Strain gauges of 5 mm gauge length were instrumented on the prestressing strands at mid-span location to capture the strain variation during testing. Data acquisition system (DAQ) was used to acquire and store the data from external instrumentation.