SHEAR BEHAVIOR OF STEEL FIBER REINFORCED PRECAST PRESTRESSED CONCRETE BEAMS

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ABSTRACT

Precast industries constantly look for better alternative solutions to reduce the secondary reinforcement to speed up the production process. Addition of fibers in concrete helps in reducing the use of secondary reinforcement. Presence of fiber reinforcement has proven to enhance the ductility and energy dissipation capacity of the concrete under flexure and shear. Shear behavior of concrete members mainly depends on the compressive strength of concrete, shear span to depth ratio (a/d), amount of stirrups, aggregate interlock and dowel action of longitudinal reinforcement. The present study focuses on the shear behavior of steel fiber reinforced PSC beams with different volume fractions i.e., 0.50% and 1.00%. Fiber reinforced prestressed concrete (FRPC) beams were cast using long line method and tested with a shear span to depth ratio of 2.4 to simulate shear dominant behavior. Strain gauges were attached to the strands at loading point and at the center of shear span (a/2) to measure strain variation at different stages such as prestressing, de-tensioning and testing. During experimentation, load-deflection and strand strain was recorded. Test results indicate that the addition of steel fibers improved the shear resistance and ductility of the prestressed concrete beams.

1 INTRODUCTION

Prestressed concrete members without transverse reinforcement can fail in fail in brittle shear mode by forming diagonal crack leading to rapid decrement in load carrying capacity [1]. Shear behavior mainly depends on the compressive strength of concrete, shear span to depth ratio (a/d), amount of stirrups, dowel action of longitudinal reinforcement, type and dosage of fibers used, prestressing force [2]. Shear failure of concrete can be witnessed when the shear span (a) to depth (d) ratio of the member is found to be less than 2.5 [3], the ratio of the moment to shear force (M/V) at critical section subjected to maximum load (V) works out exactly to distance 'a' called shear span, between the support and load.

$$f_x = \frac{M\,Y}{I} \therefore f_x \,\alpha\, \frac{M}{b\,d^2} \quad \text{[Here M= V X a]} \tag{1}$$

$$\tau_X = \frac{V\,Q}{Ib} \therefore \tau_X \,\alpha\, \frac{V}{b\,d} \tag{2}$$

$$\frac{f_x}{\tau_X}\alpha\,\frac{a}{d}$$

This dimensionless ratio (a/d) provides a measure of relative magnitudes of flexural stress and shear stress, and hence it enables to predict the failure modes under combined flexure and shear loading [4]. With the increase in load level, the reinforced concrete beam transforms into a comb-like structure. For small a/d ratios, the capacity of the concrete teeth (cracks in tension zone with offset) is lower than the capacity of the arch. Therefore, under gradually increasing loads, the transformation of the beam into an arch occurs gradually and the structure fails when the capacity of the arch is exceeded. In the medium region of a/d ratio of 2.4 to 6, the capacity of the arch is lower than the capacity of the concrete teeth, but, failure does not occur until the capacity of the concrete teeth is exceeded at which stage the transformation begins. When the a/d ratio is more than five, flexural behaviour typically governs the type of failure [3].

In ductile detailing of reinforced concrete elements (girder, slabs), a minimum aount of transverse reinforcement is closely spaced to satisfy the ductility criteria [5]. This causes congestion of steel. In such cases, steel fibers can be effectively used to replace the extra secondary reinforcement to meet the ductility demands of structural elements. Addition of discrete randomly oriented steel fiber not only improves the engineering properties such as ultimate strength, post cracking tensile strength, and ductility but also helps in reducing the shrinkage and thermal cracks [6,7]. Previous studies [1-3,6,8] on the shear performance of steel fiber reinforced concrete beams indicated that volume fraction (V_f) of 0.75% can effectively perform the role of secondary reinforcement. Shear behavior of prestressed concrete members are of much importance due to the availability of their limited experimental study [9]. Shear cracking of prestressed concrete element is brittle and sudden in [9] and leads to rapid strength and stiffness degradation. The shear span to effective depth ratio and fiber volume fraction affects the failure modes. 0.75% of steel fiber is sufficient to change failure mode from diagonal tension to shear compression [6,7]. Further increase in fiber dosage (0.8-1.2%) causes the beam to fail in flexure [6]. In the present study, steel fiber reinforced prestressed beams were cast with different dosage (0.5% and1%) of steel fibers and tested at a/d ratio of 2.4.

2 RESEARCH SIGNIFICANCE

Previous work on steel fiber reinforced concrete indicates that steel fiber addition helps in improving the post-crack behavior through fiber bridging action. Moreover, it improves ductility and toughness characteristics of concrete. However, only a handful of studies are available on the shear behavior of steel fiber reinforced prestressed concrete beams. The broad objective of this study is to illustrate the efficiency of steel fiber in replacing the secondary reinforcement. Moreover, this work also highlights the effect of various dosage of steel fibers on shear strength, ductility, failure modes and crack propagation.

3 EXPERIMENTAL PROGRAM

3.1 Materials

3.1 (A) Concrete

The prestressed concrete beams were cast at a local precast industry using ready-mix concrete designed as per the guidelines of IS: 10262-2009[10]. The specimens are designed to have a target cubic compressive strength of 68 MPa, concrete-mix was design as shown in Table1. The concretes were made with different volume fractions of steel fibers (0%, 0.5%, 1%). The hooked ended short steel fibers (Figure 1) of length 30mm, the nominal diameter of 0.6mm, aspect ratio of 50 was used in this experimental study. The mechanical properties such as tensile strength, Elasticity modulus of the fibers were 1000 MPa and 200 GPa respectively.

Concrete compressive strength (Table 2) was measured by testing five cube specimens of size 150 mm. In addition to that, cylinder specimens (Figure 2) of 150 mm diameter and 300 mm height were tested at a rate of 1mm/min [11] to determine the effect of fibers on the compressive stress-strain behavior of concrete (Figure 2a). (Figure 2b) shows the typical failure modes observed in the cylinders. With the increase in fiber dosage from 0% to 1%, the steel fiber is found to arrest the crack and result in a gradual decline in post cracking stiffness (Figure 2 c), increase the compressive toughness index (CTI). The positive effect of the addition of fibers is quantified by measurement of the toughness indices of all the series of the concrete cast. The toughness indices (Table 3) are calculated from the area of stress-strain curve of fiber reinforced cylinders to control specimen[12-15] as shown in Figure 2 d.

3.1 (B) Prestressing Strands

The seven-wire low relaxation steel strand of 12.7mm diameter was used as a prestressing reinforcement in beams. Three specimens of strands were tested for tensile properties which includes the tensile strength, elastic modulus according to ASTM A1061/A1061M-16 [16] with the help of servo-controlled fatigue testing machine (FTM). The average tensile strength, modulus of elasticity of strand was 1860MPa and 196.5GPa respectively.

4 SPECIMEN PREPARATION

In this study, six prestressed concrete beams were cast and tested under three-point bending configuration at a shear span to depth (a/d) ratio of 2.4. Two specimens were tested for each series to ensure the consistency of test results (Table4). All the specimens were 1800 mm long with a rectangular cross-section of 150 mm x 300 mm. Cross-sectional dimensions and schematic view of test specimens are depicted in Figure 3. All the specimens are singly reinforced, with two prestressing strands provision in the tensile zone. To ensure the test region to be shear critical, the non-test region is sufficiently provided with shear stirrups of 8mm diameter bars of Fe500MPa as shown in (Figure 3). The overall test matrix with study parameters is detailed in Table 4.

The specimens were cast at a precast site on a prestressing bed. Various stages of casting are presented in Figure 4. Once the strands are anchored to the dead end, they are instrumented with TML make strain gauges of gauge length 5mm at a distance of 350 mm and 750 mm distance from the near end of testing region as shown in Figure 3. Prestressing force of 100kN (after anchorage loss load is 786 kN i.e. 0.004 μm/m strain) was applied at the live end of each strand using a hydraulic jack. The strain induced in the strands were measured using strain gauges attached, before and after anchoring the live end. Later, concrete was placed in the moulds and sufficiently vibrated. The strands were cut once the concrete gains a minimum required strength.

Table 1. Concrete mix designs

	SF00	SF50	SF100
Cement (kg/m^3)	450	450	450
Robo sand (kg/m^3)	415	415	415
Natural river sand (kg/m3)	312	312	312
Coarse aggregate 20mm (kg/m^3)	755	755	755
Coarse aggregate 10mm (kg/m^3)	355	355	355
Superplasticizer (kg/m^3)	2.6	2.6	2.6
Water (kg/m^3)	152	152	152
Fiber dosage (kg/m^3)	0	39.3	78.5

Table 2. Concrete cube strengths

Series	Avg. strength(MPa)	Standard deviation (MPa)	Coefficient of variation
SF00	69.37	1.25	1.81
SF50	69.40	2.97	4.28
SF100	70.73	1.49	2.11

Table 3. Test Results of Concrete Cylinders under compression

Series	Cylinder strength (MPa)	% increase in strength	Toughness index	Toughness ratio
SF00	51.90	-	1.00	0.11
SF50	53.06	2.20	5.15	0.55
SF100	55.35	6.25	6.15	0.63

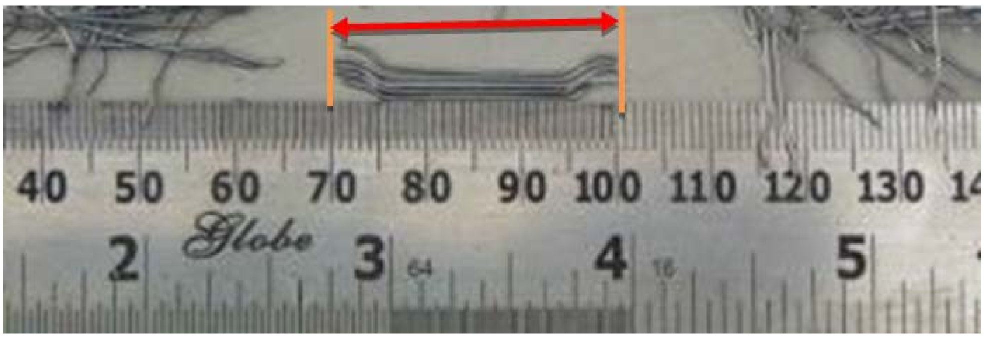


Figure1. Hooked end steel fiber

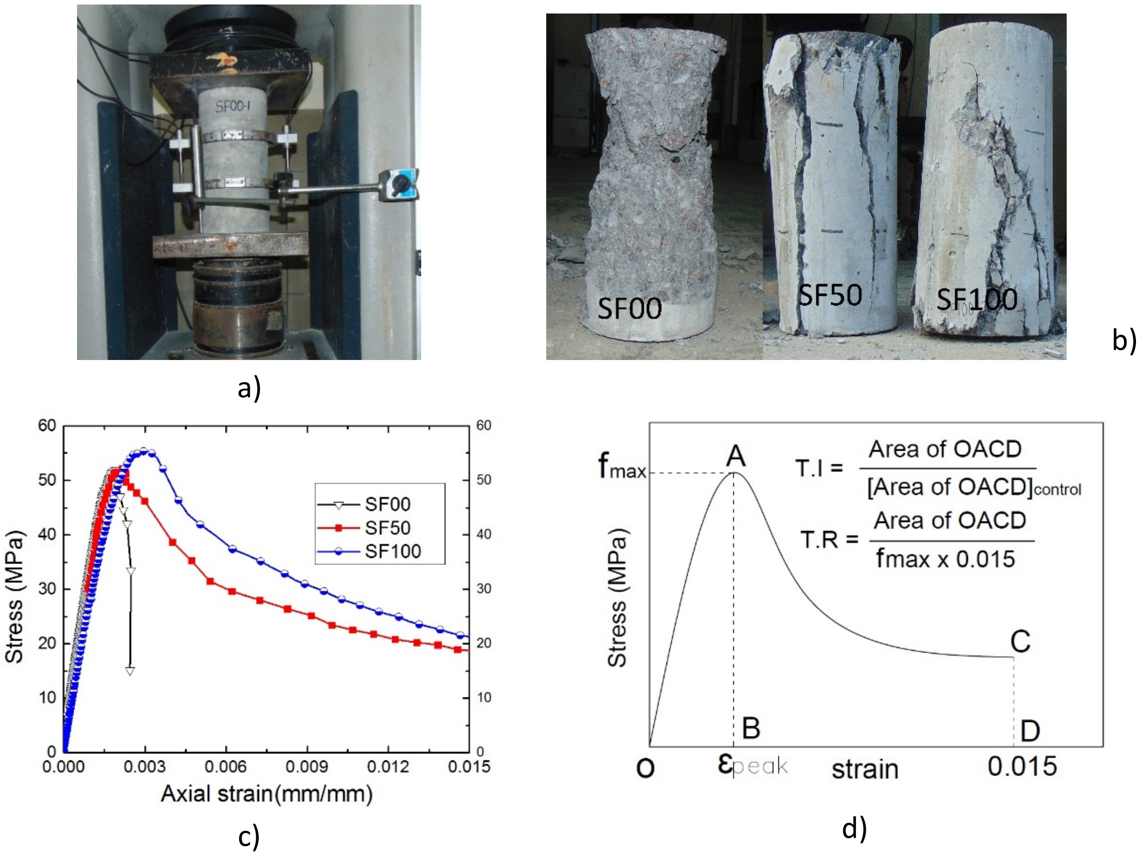


Figure 2. Testing of concrete cylinders

a) Instrumentation; b) Failure mode of cylinders; c) Stress-strain behavior of concrete;

d) Typical stress-strain curve of toughness index & Toughness ratio from σ-ε curve.

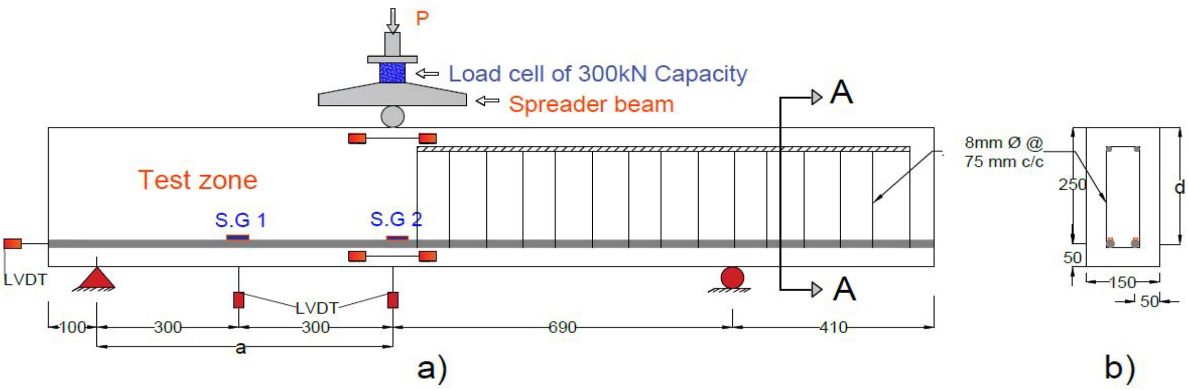
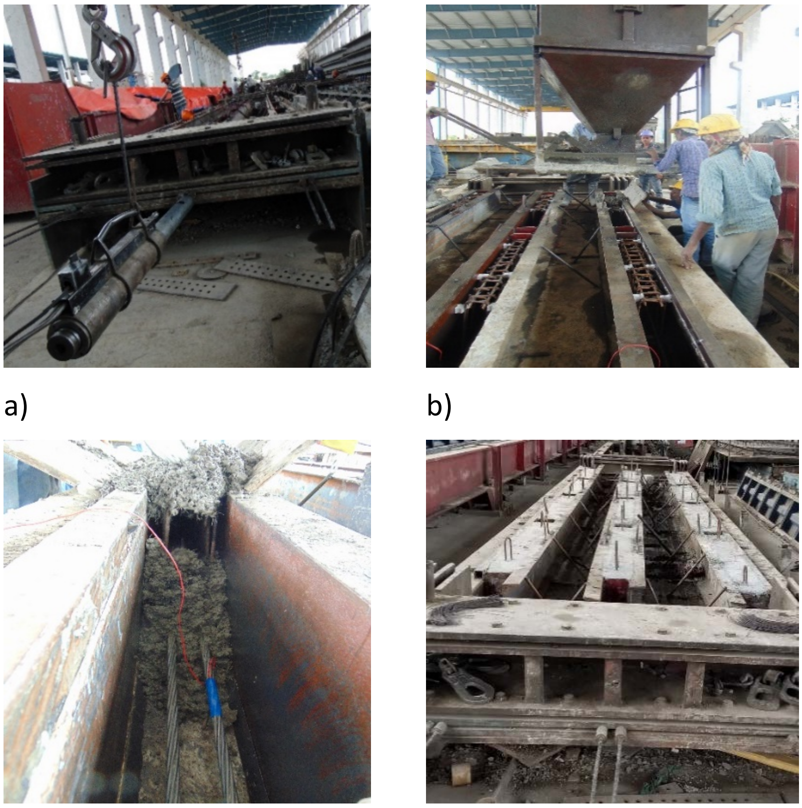


Figure 1. Schematic of SF00 beam with instrumentation



a) b) c) d)

Figure4. Casting of beam specimens; a) Prestressing by mono-strand jack; b, c) Placing of concrete in moulds; d) Beams after 7 days of curing

Table 4. Study matrix

Specimen No	Specimen Label	Fiber dosage (volume fraction) V_f (%)	Span to depth ratio (a/d)
1	SF00-1	0	2.4
2	SF00-2	0	
3	SF50-1	0.5	
4	SF50-2	0.5	
5	SF100-1	1.0	
6	SF100-2	1.0	

5 LOADING AND INSTRUMENTATION DETAILS

The prestressing beams were tested under three-point bending configuration (Figure 3). The effective span and the shear span of the beams were 1290 mm and 600 mm, respectively. The testing was performed using a servo-controlled flexure testing machine of 300 kN capacity. The beams were tested under displacement control mode at the rate of 25 µm/sec until failure. The strain gauges attached to the strands were used to measure applied tensile strain during the testing. Additionally, a total of seven LVDTs were mounted on the test specimen as shown in Figure 3. Four LVDTs were placed horizontally at the top and bottom layers to obtain the surface strain for curvature measurements. Two LVDTs were placed vertically at the center of the shear span and under the loading point to measure deflections. One LVDT was mounted horizontally at the location of strand, to measure the slip of prestressing strand. All data including load, mid-span deflection and strain were recorded using a high-speed data acquisition system (DAQ).

6 TEST RESULTS AND DISCUSSION

6.1 Load-Deflection Behaviour

Figure 5 represents the experimental load-deflection curves for all series of beams. Additionally, Table 5 summarizes the loads -deflections behaviour at different instances. All the test specimens were observed to exhibit similar behavior before cracking. The fiber reinforced specimens showed higher first cracking load, peak load and ultimate displacement. This increase can be attributed to the efficiency of fibers in delaying the crack propagation. Though SF100 specimens exhibited a better performance compared to control specimens, the ulitmate sttrength was lower than the peak load carrying capacity of SF50. Moreover, similar results were previously observed by [2]. In control (SF00-1) specimen, a first shear crack formed at a load and deflection of 220kN and 3.7mm, respectively. On further loading up to 240kN, the cracks widened up and the shear crack propagated along the prestressing strand. The crack propagation along the strand led to splitting of concrete around the strand which caused the failure of the beam. Even though SF00-2 specimen exhibited similar behavior as SF00-1 upto the peak load, the failure was found to be sudden [3]. With the increase in fiber content from 0% to 1% there is no much increment in first crack load. The increase from first shear crack load to peak load was 9.11% in case of control beams. In case of 0.5% steel fibers, the increment from first shear crack load to peak load was 32%. However, in case of 1.0% volume fraction, the increment from first shear crack load to peak load was 25%.

6.2 Post-Cracking Ductility (μ)

The post cracking ductility (μ) of the specimen is calculated as the ratio of the area under load-deflection curve up to ultimate load to the area of the load-deflection curve of the first crack [9,13]. The calculated values are summarized in Table 5a. The increase in fiber content from 0% to 0.5% resulted in an average twofold increase in the post cracking ductility of the beam specimens. Even though the specimens with 1% exhibited an increase in post-cracking ductility, it is same as that of 0.5% volume of steel fibers. This increase can be attributed to the crack arresting mechanisms provided by fibers resulting in improved post cracking stiffness and less brittle failure of beams.

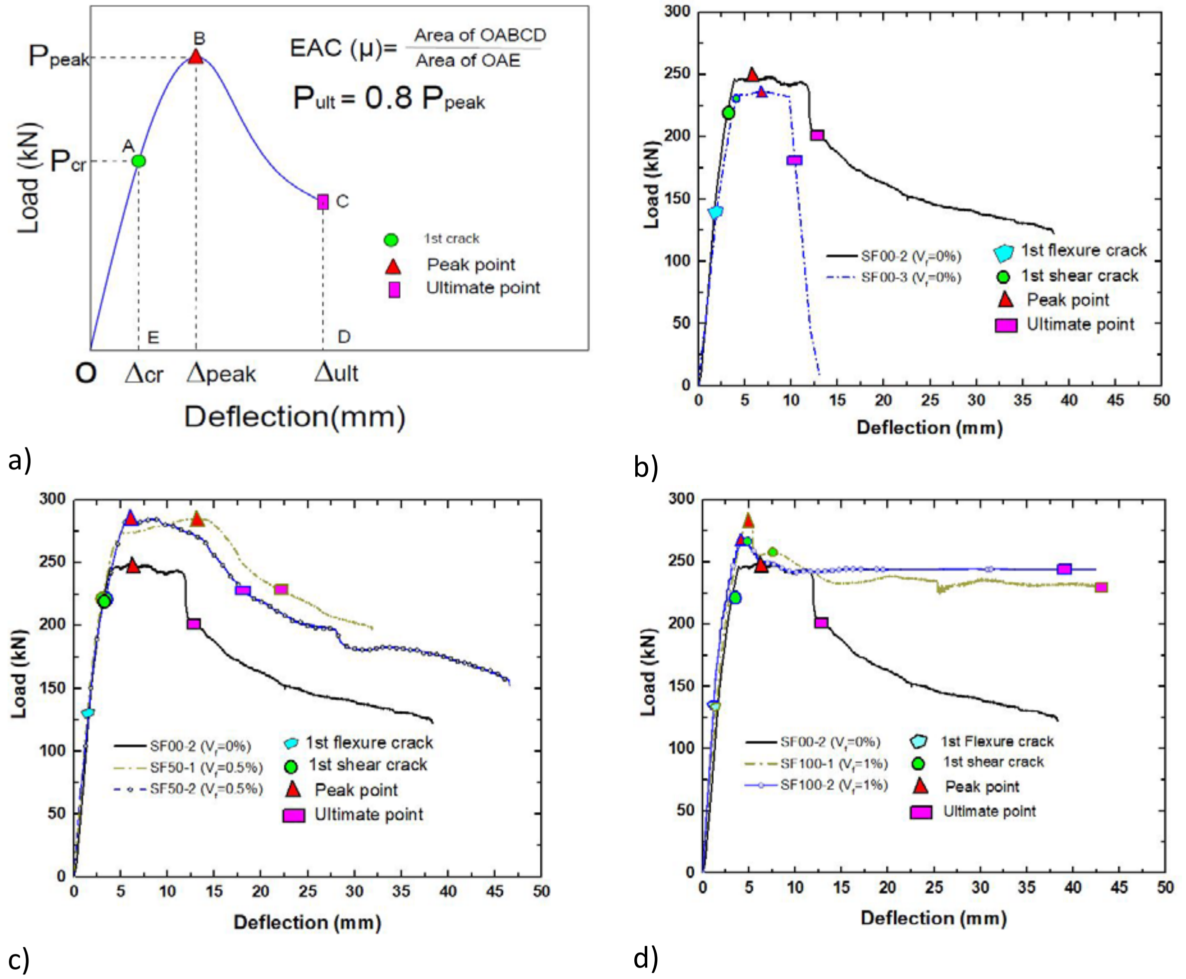


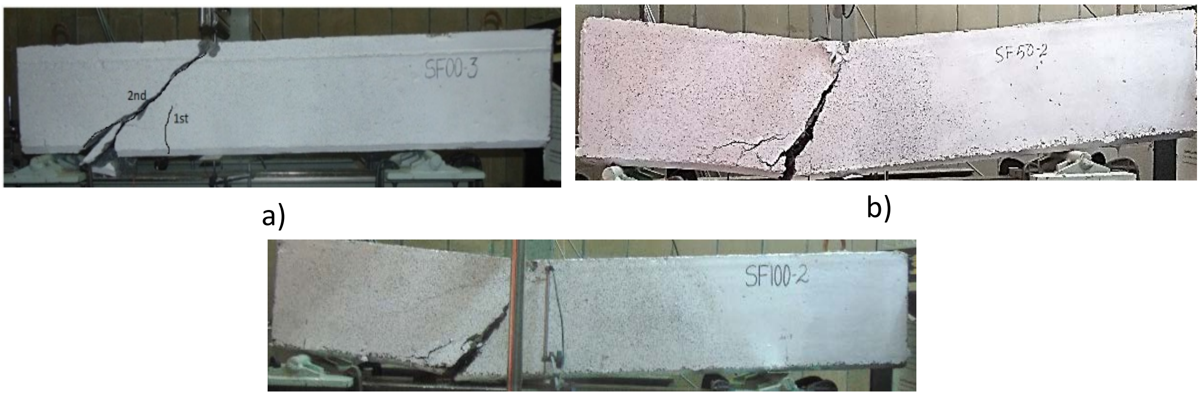
Figure 5. a) Salient points in Load-deflection Graph, b) Load-deflection behavior of prestressed beams(b,c,d)

Table 5. Summary of test results (P= Load, Δ= Deflection)

		1st flexure crack	1st shear crack	Peak (P_{peak})	Ultimate ($P_{ult} = 0.8\,P_{peak}$)	% increment in peak capacity	Post-Cracking Ductility (μ)	Failure mode
SF00-3	P (kN)	136.39	217.2	237.0	45.0	--	7.45	Shear
	Δ (mm)	1.86	4.1	6.8	12.1	--		
SF50-1	P (kN)	135.76	225.9	285.4	228.3	20.39	13.48	Shear
	Δ (mm)	1.52	3.1	13.2	22.1			
SF50-2	P(kN)	138.10	208.3	287.0	229.6	21.10	11.10	Shear
	Δ (mm)	1.87	3.1	6.0	18.2			
SF100-1	P (kN)	127.96	256.6	282.6	226.1	19.20	16.54	Shear
	Δ (mm)	1.59	7.6	5.2	43.6			
SF100-2	P (kN)	130.00	268.5	269.2	215.4	13.60	15.80	Shear
	Δ (mm)	1.30	5.3	5.1	39.0			

7. CRACK DISTRIBUTION AND FAILURE MODES

Depending on the fiber content, the specimens showed different behavior in terms of cracking patterns and failure modes. The crack patterns observed at the time of failure are represented in Figure 6 . For all the specimens, the cracks developed and propagated only in the test zone. In control beams, the first flexure crack developed at a load of 136.4 kN. On further increase in load to 230 kN load, a shear crack formed altering the behavior of the specimen to fail in diagonal shear mode. Beams of SF50 series had a first flexure crack developed in the tension zone at a load of 137 kN. Moreover, the failure was characterized by the conversion of flexure crack into shear crack at higher loads leading to sudden failure of specimens. The SF100 specimens displayed same response as that of SF00-3, with slight increase in cracking load and peak load. From Figure 6, it is evident that with the increase of fiber content, the crack angle has increased. This indicates the evolution of failure from brittle shear mode to less brittle-shear mode.



a) b)

c)

Figure 6. Failure modes of prestressed fiber reinforced concrete beam with different fiber ratios

8 LOAD-STRAIN AND MOMENT-CURVATURE DISCUSSION

Strain gauges were installed on the strand at the loading point of the specimen to measure the strain variation during pre-tensioning and testing. During pretensioning, strain gauges recorded an average value of 4000μm/m strain. To measure the curvature during experimentation, LVDTs were attached at the top and bottom as shown in Figure 7a**.** For all beams, the strain value increased linearly up to first crack. The first change in slope Figure 7a, b indicates the formation of first crack at the location of the maximum bending moment (at loading point). After cracking, the synergic effect of strand and steel fiber (0.5%,1.0%) is shown in terms of strand strain and curvature variation. Due to malfunctioning of the LVDTs/strain gauges, the complete response was not captured by sensors. Soon after the initiation of cracking, fibers help in reducing the curvature compared to the control specimen. A similar trend was observed in load vs strain in strand at loading point. Steel fibers helped in resisting the tensile stress in concrete, resulting increase in the shear resistance occurred.

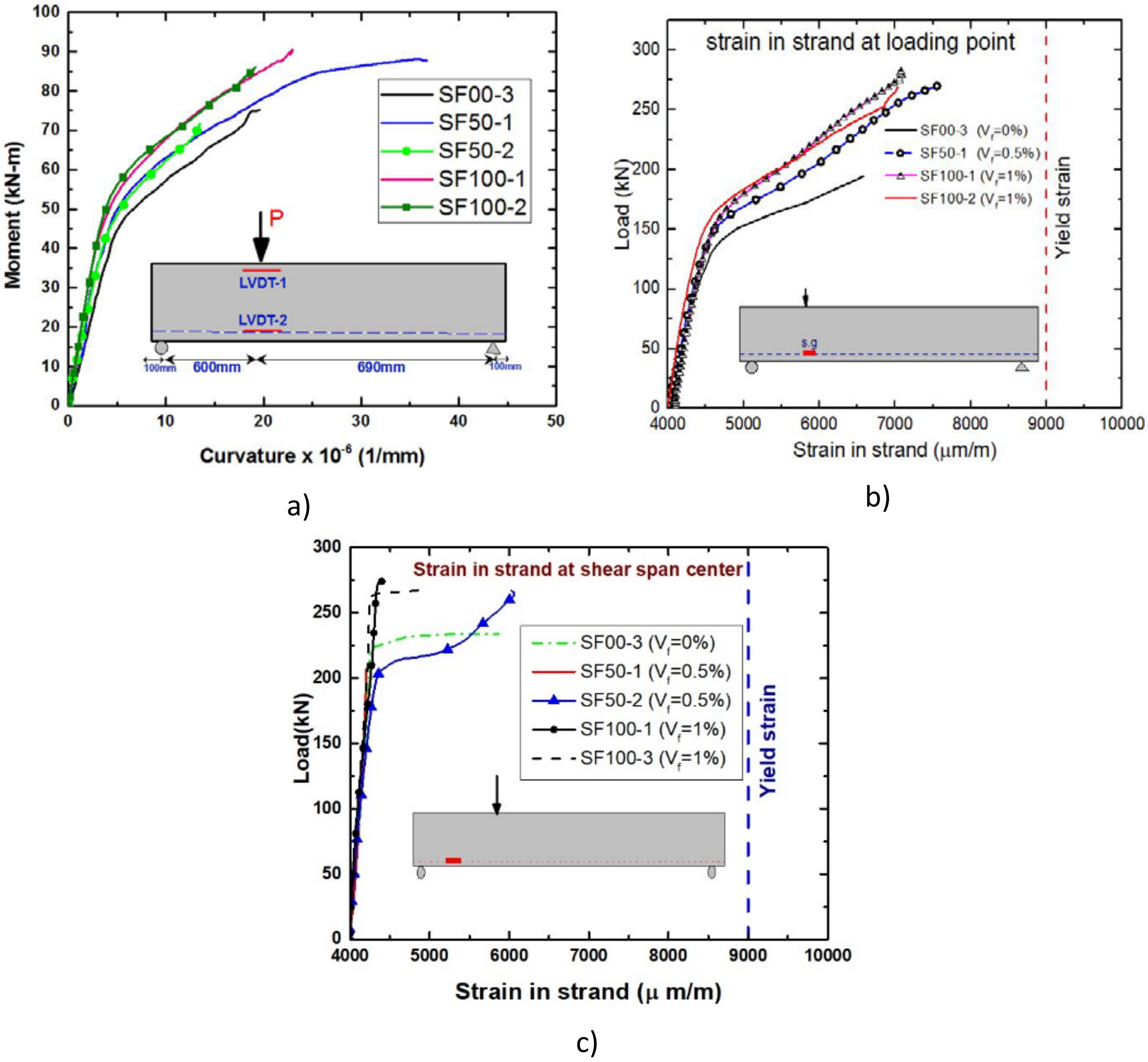


Figure 7: a) Moment curvature comparison, b) Load-strain in strand at loading point, c) Load-strain in strand at shear span enter point

9 SUMMARY AND CONCLUSIONS

Six Prestressed precast beams were cast and tested at a shear span to depth ratio of 2.4 for evaluating the shear performance of prestressed concrete beams. Based on the experimental observations, the following major conclusions can be made:

1. Marginal improvement in the shear capacity of the prestressed concrete beams was observed due to the addition of steel fibers. The increase in peak load capacity was 20% and 16%, respectively for 0.5% and 1.0% of volume fractions of steel fibers.
2. As the fibers effectively arrested the crack propagation, the energy absorption capacity increased by om 73% and 113% for 0.5% and 1.0% fibers respectively when compared to control beams.
3. Concrete cylinder tests under compression indicates that the strain corresponding to the peak stress increased with increase in fiber dosages. Moreover, compressive toughness index is enhanced by 5-6 times due to the addition of steel fibers.

4. Presence of steel fibers converted the brittle shear failure to less brittle flexure-shear mode. The angle of major crack changed from 30° to 65° corresponding to 0% to 1.0% steel fiber dosage indicating the change in behaviour from shear dominant to more flexure dominant mode.

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