

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.

Keywords: Ductility; Synthetic fibers; Prestressed Concrete Beam; Steel fibers.

28 **1. INTRODUCTION**

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

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44 Number of previous work have focused on the behaviour of fiber reinforced concrete under
45 flexure and shear loadings. Sahoo and Kumar [10] tested steel reinforced concrete beams and
46 observed increase in deformability (ductility) and decrease in crack widths. Few researchers
47 [11,12] have used fibers as secondary reinforcement for the concrete elements to improve the
48 shear performance. Some works in the past have [13-15] focused on the influence of fibers on
49 the fresh and hardened properties as well as on the shear capacity of prestressed beams.
50 Yazdanbakhsh et al. [16] carried out analytical studies to predict the shear capacity of synthetic
51 fiber reinforced concrete beams based on the model originally developed for steel fiber
52 reinforcement. They noted that shear capacities from RILEM 162-TDF [17] recommendations

53 were found to be more conservative than Fib-MC2010 [18] for synthetic fiber reinforced beams.
54 Alhozaimy et al. [19] investigated the mechanical properties and effects of pozzolanic materials
55 on concrete reinforced with fibrillated polypropylene fibers of low volume fractions ($< 0.3\%$).
56 They reported that fiber content variation has no significant effect on the compressive and
57 flexural strength of FRC but improved its toughness and impact resistance.

58

59 Thomas and Ramaswamy [20] noted that addition of fibers reduced the crack width of
60 prestressed concrete beams. Harajli [21] noted that the presence of fibers enhanced the bond
61 strength of rebars and reduced its bond degradation. Sahoo and Sharma [22] observed that
62 flexural capacity did not improve significantly when more than 0.5% by volume of steel fibers
63 were added to reinforced concrete beams with and without stirrups. Tiberti et al. [23] presented
64 dependency of crack propagation on the concrete strength of steel fiber reinforced concrete
65 (SFRC). They noted that steel fibers are more effective when used in high strength concrete
66 (HSC) than in normal strength concrete (NSC). Ramzi and Omer [24] studied the flexural
67 strength of under-reinforced and over-reinforced concrete T-beams with steel fiber. Their
68 results indicated that presence of steel fibers improved the ultimate strength and reduced the
69 crack width. Abbas and Khan [25] carried out pull-out tests on SFRC beams and concluded that
70 the ultimate pull-out load depends on the fiber size and its embedment length.

71

72 Yoo et al. [26] presented the effects of strength, fiber content and strain-rate on flexural response
73 of SFRC under quasi-static and impact loads. Banthia and Sappakittipakorn [27] investigated
74 the toughness enhancement of SFRC through fiber hybridization. They noted that flexural
75 toughness and deflection hardening properties were improved. To account for the post peak
76 response of different cement based materials Fantilli et al. [28] defined a unique function. Amin
77 et al. [29] reported the material characterisation of macro synthetic fiber reinforced concrete

78 through a series of tension tests. The authors concluded that the degree of variability in the
79 results is lowest in case of round panel tests compared to uniaxial tension tests. Though number
80 of previous work have focused on fiber reinforced concrete, the effect of structural macro-
81 synthetic fiber reinforcement on the behaviour of high strength prestressed concrete beams has
82 not been explored adequately.

83

84 **2.0 RESEARCH SIGNIFICANCE**

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

93

94 **3.0 EXPERIMENTAL INVESTIGATION**

95 **3.1 Test specimens**

96 The experimental program includes casting and testing of full-scale prestressed concrete beams
97 of rectangular cross section (200 mm x 300 mm) and length of 3500 mm. The beams were
98 reinforced with two prestressing strands of 12.7 mm diameter corresponding to prestressing
99 steel reinforcement ratio of 0.4%. Jacking force is applied to each of the strands to obtain an
100 initial prestressing strain of 0.004 in accordance with IS 1343 [30]. The specimens were divided
101 into three series: beams made of plain concrete (Control), beams made of steel fiber reinforced
102 concrete (SF series) and beams made of polyolefin fiber reinforced concrete (PO Series). Each

103 of the SF and PO series were further categorised based on the fiber dosage. The nomenclature
 104 details of different series used in the study are presented in Table 1.

105

106

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

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Table 2: Mix Design Details

Concrete	Quantities in kg/m ³									
	Aggregate				C	F	W	HRWR	SF	PO
	20 mm	10 mm	CSS	NRS						
Control									-	-
SF35									27.47	-
SF70									54.94	-
SF100	754.0	355.0	415.0	313.0	428.0	22.0	165.0	2.5	78.50	-
PO35									-	3.18
PO70									-	6.37
PO100									-	9.10

110 CSS - Crushed Stone Sand, NRS - Natural River Sand, C – Cement, F – Flyash, W – Water,
 111 HRWR – High Range Water Reducing admixture, SF – Steel Fiber, PO- Polyolefin Fiber

112

113

114

115 **3.2. Material Properties**

116 Concrete mix design was developed as per IS 10262-2009 [31] with a target compressive
 117 strength of 58 MPa. Table 2 presents the mix details. Coarse aggregate blended of 10 mm and
 118 20 mm aggregate, crushed stone sand, natural river sand, flyash and high range water reducing
 119 admixture (HRWR) were used to achieve workable concrete of 58 MPa strength. Addition of
 120 fibers inversely affected the workability of concrete mix. The compressive strength of concrete
 121 cubes and cylinders tested on 28th day is reported in **Error! Not a valid bookmark self-**
 122 **reference..** The prestressing strands with seven wired low relaxation steel (12.7 mm diameter,
 123 effective area of 99.7 mm²) were used as reinforcement. Prestressing strands with a constant
 124 eccentricity (e) of 100 mm was used resulting in straight profile of the strands. Tensile strength
 125 and modulus of elasticity of the strands were measured to be 1860 MPa and 196.5 GPa,
 126 respectively from the coupon tests. The hooked end steel fibers and macro- synthetic polyolefin
 127 fibers were used in developing concrete mixes of SF and PO series respectively. The shapes
 128 and various properties of the fibers used are presented in Fig. 1 and Table 4 respectively.

129

130

Table 3: Compressive strength of concrete

Specimen	Average Compressive strength (MPa) [SD]		Specimen	Average Compressive strength (MPa) [SD]	
	Cube	Cylinder		Cube	Cylinder
Control	65[2.42]	43[1.85]	Control	65[2.42]	43[1.85]
SF35	62 [0.75]	47[2.40]	PO35	67[2.82]	48[2.44]
SF70	61[0.15]	47[4.21]	PO70	74[1.33]	50[4.72]
SF100	63 [0.30]	50[3.98]	PO100	72[2.05]	46[4.30]

131 [SD] – Standard Deviation

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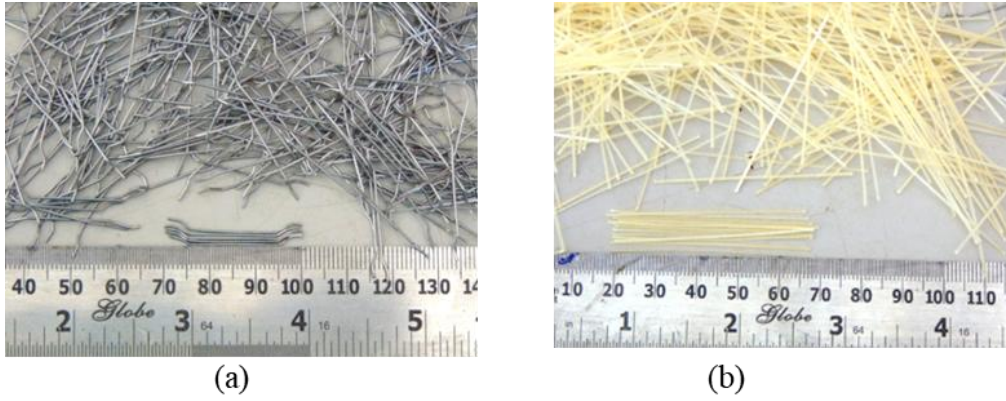


Fig. 1: Fibers (a) Steel Fiber and (b) Structural Synthetic Fibers

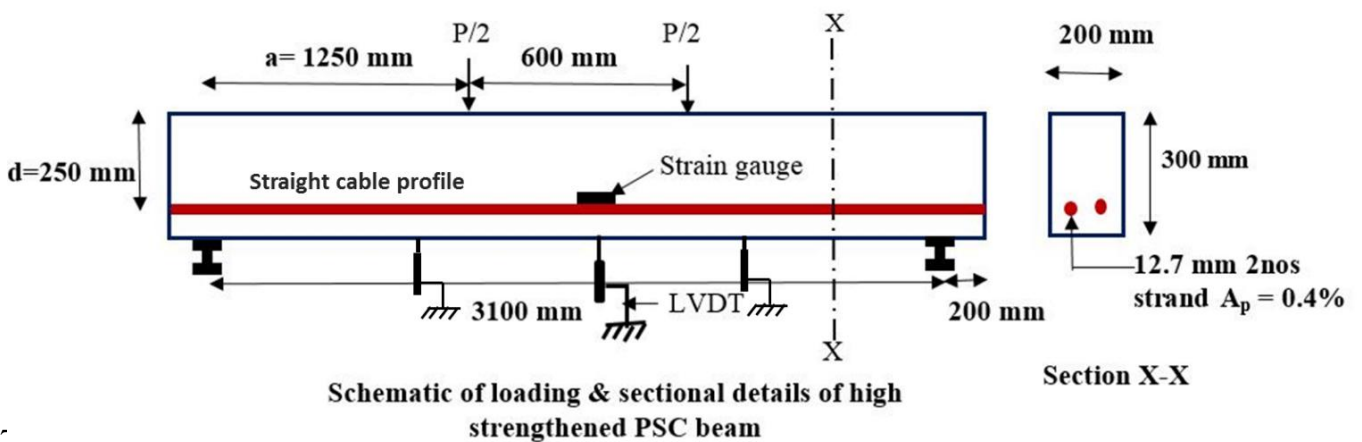
Table 4: Properties of Steel and Polyolefin Fibers

Properties	Fiber Type	
	Steel	Polyolefin
Specific gravity	7.85	0.91
Length (mm)	30	50
Tensile strength (MPa)	1000	618
Modulus of elasticity (GPa)	200	10
Diameter (mm)	0.6	0.5
Aspect ratio	50	100

3.3 Test Setup and Instrumentation

The shear span to depth ratio (a/d) of five is considered to simulate the flexure-shear behavior. 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

150 not restrained as they are simply supported and the same is portrayed in the Figure 2. Support
 151 width is expected to have minimal influence on the behaviour as the specimens are tested at
 152 higher a/d ratio of 5. The effect of different a/d ratio, support conditions, cross section details
 153 and size effect on the behaviour of fiber reinforced prestressed concrete beams would be
 154 interesting and is scope for further work. Eleven beams were cast with different fiber dosages
 155 of 0.00%, 0.35%, 0.70% and 1.00% and were water-cured for a period of 28 days at room
 156 temperature. The beam schematic and loading configuration is presented in the Fig. 2.



157
 158 **Fig. 2: Schematic Details of the Test specimen**

159

160 The beams were tested using a servo controlled hydraulic MTS actuator of 250 kN capacity.
 161 Load from the actuator was transferred to the specimen through spreader beam and then to the
 162 two I-beams (to obtain four-point bending). The test setup is presented in Fig. 3. Loading was
 163 applied monotonically in displacement control mode at a rate of 0.05 mm/sec. Loading was
 164 paused at every 10 kN intervals to mark the crack propagation and study the failure progression.
 165 All the specimen displacements were recorded using Linear Variable Displacement Transducers
 166 (LVDTs). LVDTs were positioned at specific locations (at mid span and at a distance of one
 167 third of the span from support) along the length of the beam to capture the entire curvature
 168 profile during testing. Strain gauges of 5 mm gauge length were instrumented on the

169 prestressing strands at mid-span location to capture the strain variation during testing. Data
170 acquisition system (DAQ) was used to acquire and store the data from external instrumentation.

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173 1. 250 kN MTS Actuator; 2.HBM DAQ system; 3.Camera; 4. DAQ Controller; 5. MTS
174 Controls system; 6. Light source; 7. Test Specimen

175

Fig. 3: Test setup and Instrumentations

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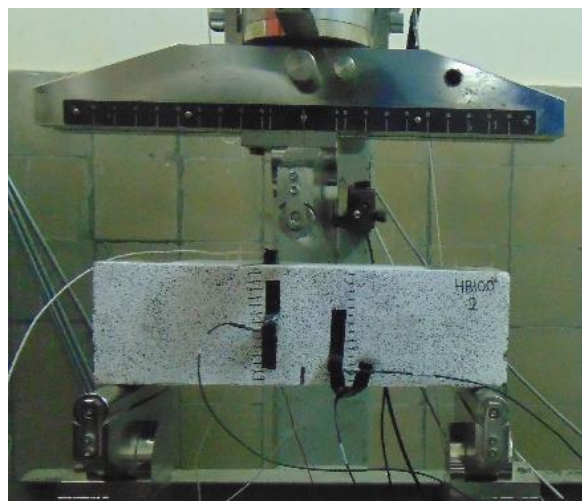


Fig. 4: Fracture test setup

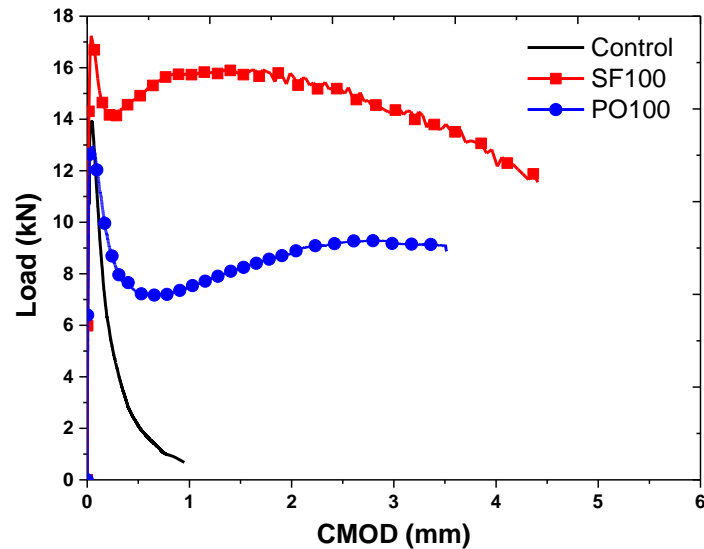


Fig. 5: Load-CMOD response of fiber reinforced specimen

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178 **4.0 TEST RESULTS AND DISCUSSION**

179 **4.1 Fracture behaviour of fiber reinforced concrete (FRC)**

180 As part of a companion study, fracture tests were conducted on steel and polyolefin reinforced
 181 beam samples under flexure to understand the efficiency of steel and synthetic fibers with 1%
 182 volume fraction of fibers. The test setup and results are presented in Fig. 4, 5. Load vs crack
 183 mouth opening displacement (CMOD) response of fiber-reinforced specimens with steel (SF
 184 100) and synthetic fibers (PO 100) is shown in Fig. 5. The load vs CMOD curves indicate that
 185 steel fiber restrict the crack opening more efficiently than that of macro-synthetic fiber at same
 186 fiber dosages. The load drop after the peak load is minimum in case of steel fiber reinforced
 187 specimen due higher elastic modulus and tensile strength of steel fiber.

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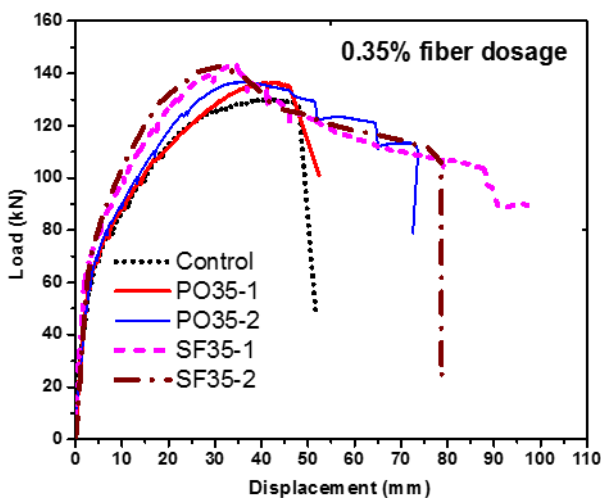
189 **4.2 Load-deflection behaviour**

190 The load vs mid-span displacement of beams are compared in Fig. to understand the
 191 contribution of steel and polyolefin fiber towards the load resistance. The load displacement
 192 curves presented in Fig. depicts the behaviour of the specimens with particular dosage/type of
 193 fibers to that of the control specimen (without fibers). Details such as overall behaviour of

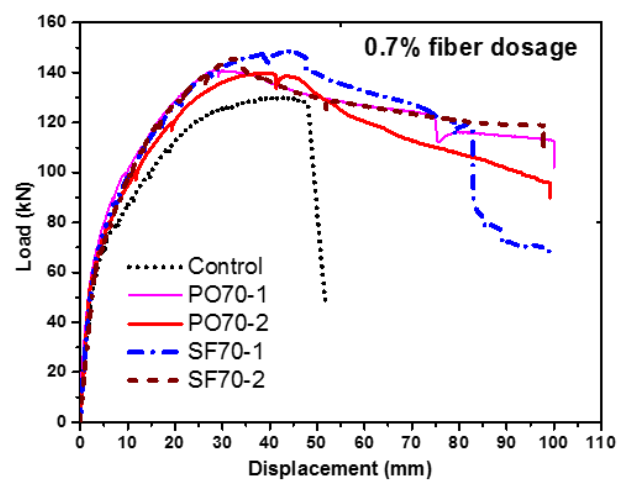
194 beams in terms of cracking load, post cracking stiffness, peak load, displacement at failure and
195 failure mode are summarized in Table 5. Though two specimens of SF100 series were cast, one
196 of the specimens had honeycombing due to improper compaction and is discarded for further
197 comparisons. In addition, one of the PO100 specimens had an instrumentation error and hence
198 is not used for comparison of load-displacement curves. For the control specimens, the first
199 crack appeared on the tension fibers near the loading point at a load of 60 kN (Table 6). After
200 cracking, stiffness degradation was observed due to formation of multiple cracks. Finally, the
201 specimen failed in flexure-shear mode at a peak load of 130 kN corresponding to a displacement
202 of 52 mm. The strands just yielded before reaching peak load due to low reinforcement ratio
203 used in the beams.

204
205 Fig. 6a shows the load displacement behaviour of beams with 0.35% fiber dosage. Both the
206 beams with steel and polyolefin exhibited similar behaviour before cracking. Post-cracking
207 stiffness increased in fiber-reinforced beams as compared to post cracking stiffness of control
208 specimen. This increase in stiffness is mainly due to contribution of fibers in crack bridging.
209 However, the steel fiber specimen exhibited stiffer post-cracking response than the specimen
210 with synthetic (polyolefin) fibers. Both the control and synthetic fiber reinforced specimens
211 (PO-35) cracked at 60 kN while the steel fiber reinforced specimen (SF35) cracked at 69 kN.
212 The addition of steel fiber (0.35%) improved the cracking load and post-cracking stiffness by
213 15% and 36% respectively when compared to synthetic fibers (0.35%) (Fig. 6a). A peak load
214 increment of 4.8% was observed in SF35 when compared to PO35. Post-peak behaviour was
215 almost similar for both steel and synthetic fibers at 0.35% dosage. Steel fiber reinforced
216 specimens (SF35) failed in flexure mode while the specimens reinforced with synthetic fibers
217 (PO35) failed in flexure-shear mode. In this study, if the final failure of beam is due to shear
218 tension cracking after the yielding of prestressing strand, it is defined as the flexure-shear mode.
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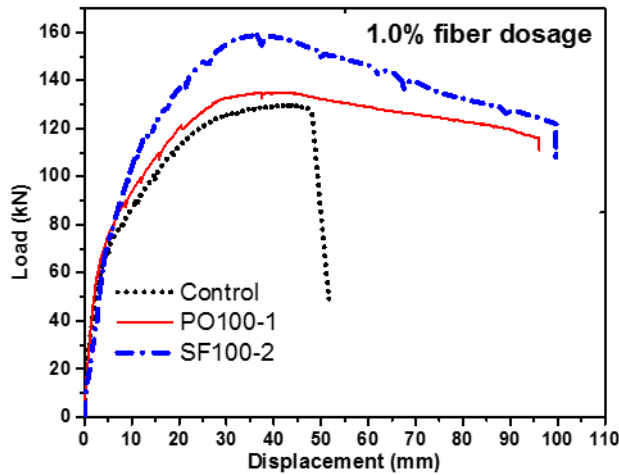
220 The comparison of behaviour at 0.7% fiber dosage exhibited by SF70 and PO70 is depicted in
 221 Fig. 6b. In comparison to control specimen, due to the higher modulus of steel fibers, SF
 222 specimens exhibited a higher cracking load when compared to the PO specimens (Table 5).
 223 Average post-cracking stiffness of the SF70 was found to be 12% more than that of PO70 (Fig.
 224 6b). Though diagonal shear cracks formed in both the SF and PO specimens (0.70%), the fibers
 225 were effective in arresting the propagation of shear cracks, which resulted in the formation of
 226 flexural cracks. Due to limitation in stroke capacity of the actuator, the test was terminated when
 227 the actuator displacement reached vicinity of 100 mm (for specimens SF70 and PO70). The
 228 average peak load for SF70 and PO70 was observed to be 147 kN and 140 kN, respectively. In
 229 case of beams with 1.0% fiber dosage, the cracking load of steel fiber specimen (SF100) was
 230 70 kN (Fig. 6c). Soon-after cracking, in comparison to synthetic fibers, steel fibers contributed
 231 more efficiently to crack arresting. This is mainly due to higher modulus of elasticity of the
 232 steel fibers. The synthetic fiber specimen (PO100) reached a peak load of 135 kN. Presence of
 233 steel fibers of same volume improved the peak load by 17% and post-cracking stiffness by 46%
 234 when compared to the synthetic fiber reinforced specimen. The testing was terminated for
 235 SF100-2 and PO100-1 when the mid-span deflection reached 100 mm due to limitation in the
 236 stroke capacity of the actuator.



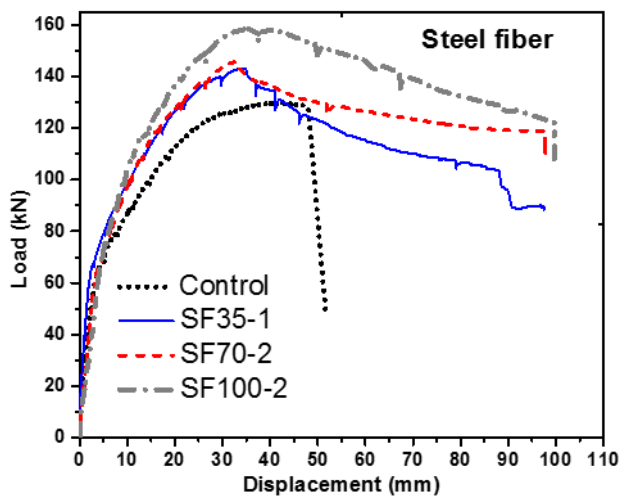
(a) Beams with 0.35% dosage of fibers



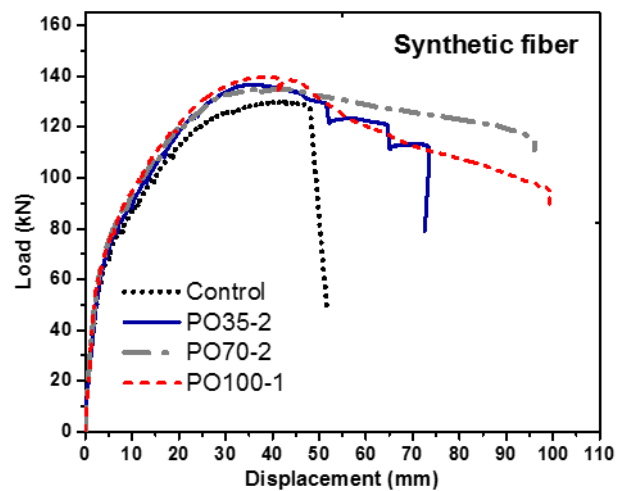
(b) Beams with 0.7% dosage of fibers



(c) Beams with 1.0% dosage of fibers



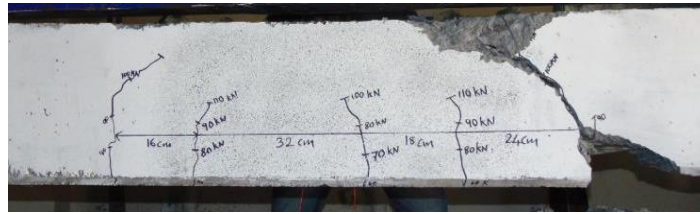
(d) Beams with Steel fibers



(e) Beams with synthetic fibers

Fig. 6: Comparison of Load-Deflection behaviour

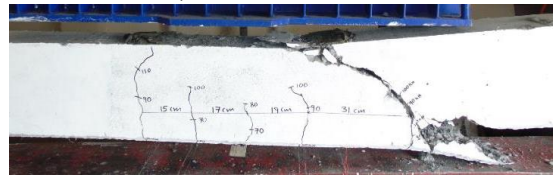
The difference in the behaviour with steel and synthetic fibers can be clearly noticed at high fiber dosage of 1.0% (Fig. 6c). Steel fibers were more efficient in improving the serviceability performance. Fig. 6 (d, e) indicates the behaviour of PSC beams with steel and synthetic fibers separately. The experimentally observed cracking and peak moment was verified by RILEM 162-TDF[17] recommendations as shown in Table 5. RILEM 162-TDF[17] approach was used for both steel and synthetic fiber specimens by suitably modifying the tensile stress strain curves from literature [29,33]. More details on the RILEM calculations of fiber reinforced prestressed concrete beams can be found elsewhere [29, 33,34].



(a) Control Beam (Flexure-Shear Mode)



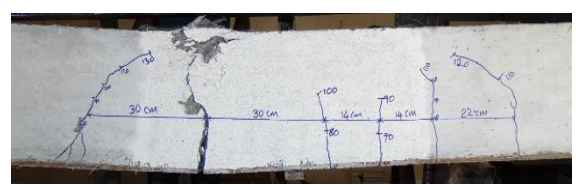
(b) SF35 (Flexure Mode)



(c) PO35 (Flexure Shear Mode)



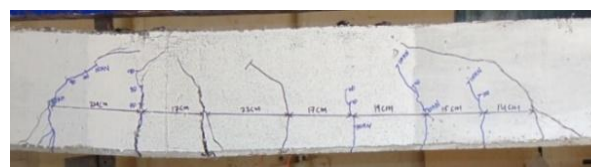
(d) SF70 (Flexure Mode)



(e) PO70 (Flexure Mode)



(f) SF100 (Flexure Mode)



(g) PO100 (Flexure Mode)

Fig. 7: Failure modes of PSC beam with steel and synthetic fiber

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238

239 4.3 Crack Distribution and Failure Modes

240 The crack distribution and failure modes of the tested specimens is detailed below. Crack

241 propagation of different specimens at three levels of loading is presented in Table 6. Control

242 beam had few flexural cracks between the loading points. At higher loads, the prestressing

243 strands reached their yielding strain, on further increase in loads, flexural crack converted to

244 shear and propagated through aggregates leading to sudden energy release at failure. The

245 flexure-shear failure mode of control specimen is presented in Fig. 7a and Table 6. Beams with

246 low dosage (0.35%) of fibers exhibited multiple flexure cracks and better crack distribution.

247 Steel fibers arrested the propagation of shear crack and changed the failure of specimens (SF35)
248 to flexure dominant mode (Fig. 7b, Table 6). However, PO35 specimens still failed in flexure-
249 shear mode (Fig. 7c) due to lesser efficiency of synthetic fibers in arresting the shear cracks.

250
251 In the specimens with moderate dosage (0.7%) of fibers, crack bridging effect of fibers was
252 evident in steel specimens (SF70). Steel fiber reinforced specimens exhibited flexure dominant
253 behaviour (Fig. 7d). In synthetic fiber reinforced specimen (PO70), the propagation of shear
254 cracks was arrested and led to flexure dominant behaviour (Fig. 7e, Table 6). Both PO100 and
255 SF100 specimen had numerous flexural cracks and experienced good amount of inelastic
256 deformation. Addition of steel at high fiber dosage resulted in better distribution of flexural
257 cracks and exhibited significant crack bridging (Fig. 7f,g). Addition of fibers improved the
258 ductility as the fibers in the matrix formed a closed network, which hindered the formation of
259 crack and its propagation. Even during the crack growth, the fibers in the matrix bridged the
260 crack and prevented its further propagation. Thus, the presence of the fibers bridges the cracked
261 surfaces and provides a restricting effect to the crack path. This increases the possibility of
262 redistribution of stresses in the fracture process and improves the ductility of the specimen.

Table 5: Summary of test results

Parameters for Comparison	Control	SF35-1	SF35-2	PO35-1	PO35-2	SF70-1	SF70-2	PO70-1	PO70-2	SF100-2	PO100-1
	0.00%	0.35%				0.70%				1.00%	
Cracking load, P_{cr} (kN)	60	68	70	60	60	70	67	60	60	70	60
Deflection at Cracking load, Δ_{cr} (mm)	4.76	3.02	3.28	3.02	3.22	4.03	4.02	2.45	2.813	4.66	2.81
Peak load, P_{pl} (kN)	130.0	143.0	143.5	136.6	136.8	148.6	146	141.1	139.7	159	135.1
Increase in P_{pl} (%)	-	10.0	10.4	5.1	5.2	14.3	12.3	8.5	7.5	22.3	3.9
Deflection at peak load, Δ_{pl} (mm)	42.7	34.4	29.6	43.3	36.5	45.0	32.4	29.0	38.5	36.6	39.1
Mid-span deflection at failure (Δ_f) (mm)	51.7	97.5	78.8	52	73.5	99.0*	97.8*	99.9*	99.2*	99.7*	96.1*
Post cracking stiffness (kN/mm)	2.06	2.903	3.457	1.962	2.710	3.076	3.335	3.133	2.572	3.871	2.656
Increase in post cracking stiffness (%)	-	41.0	68.0	-	31.6	49.4	62.0	52.1	25.0	88.0	29.0
Strain Energy (Joule)	5481	9309	10989	5758	8464	11534	11774	12000	11291	13239	11453
% increase in strain energy	-	69.8	100.5	5.1	54.4	110.4	114.8	118.9	106.0	141.5	109.0
Peak load Ratio $\left(\frac{SF}{PO}\right)$		1.05				1.05				1.17	
Post cracking stiffness ratio $\left(\frac{SF}{PO}\right)$		1.36				1.12				1.46	
Cracking Moment(kN-m) (Experimental)	37.50	43.12		37.50		42.81		37.5		43.75	37.5
Peak Moment(kN-m) (Experimental)	81.25	89.53		85.43		92.06		87.75		99.37	84.43
Cracking Moment(kN-m) (RILEM 162-TDF)	32.00	34.60		38.92		37.00		37.75		39.50	36.68
Peak Moment(kN-m) (RILEM 162-TDF)	81.00	86.00		82.96		90.00		85.62		95.00	88.16

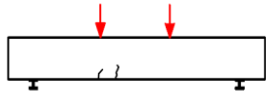
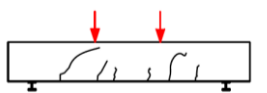
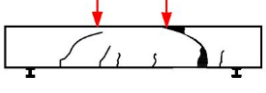
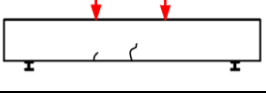
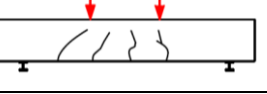
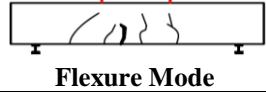
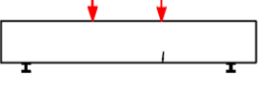
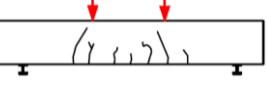

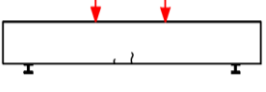
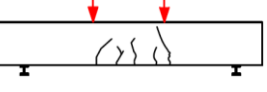
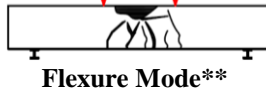
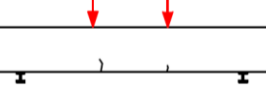
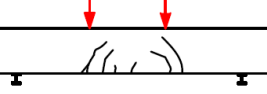
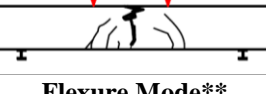
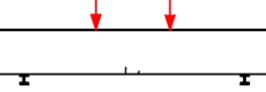
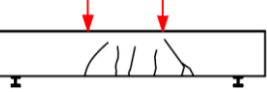

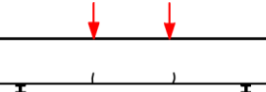
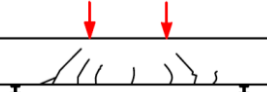
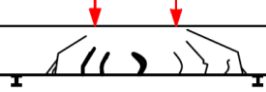
264 **Note:**

- 265 • SF and PO are specimens containing steel and polyolefin fibers, respectively
- 266 • * Test was terminated at 100 mm due to limitation in stroke capacity of the actuator.

267

268

Table 6: Crack Propagation at Different Load Levels

	Fiber dosage	at cracking	at 120kN	Final stage
Control Specimen	-			 Flexure Shear Mode
SF35	0.35%			 Flexure Mode
PO35				 Flexure-Shear Mode
SF70	0.7%			 Flexure Mode**
PO70				 Flexure Mode**
SF100	1.0%			 Flexure Mode**
PO100				 Flexure Mode**

270 ** Test was terminated due to limitation on actuator stroke capacity, but the specimens exhibited more of flexure dominant behaviour
 271 .

272 **4.4 Load vs. Prestressing Strand Strain Behaviour**

273 The strain in the prestressing strands was measured using strain gauges installed during the pre-
274 tensioning process. Initial prestressing strain was measured to be 4000 $\mu\text{m/m}$. The applied
275 prestressing force was released once the concrete attained a minimum compressive strength of
276 40 MPa. The initial loss in applied prestressing force was measured to be about 400 micro strain.
277 The variation of strain with respect to the applied load was measured and presented in Fig. 8.
278 As the prestressing strands do not possess a well-defined yield point, a value of 10,000 $\mu\text{m/m}$
279 is considered as yield strain (ϵ_{py}) [35].

280

281 From the Fig.8, with the increase in steel fiber dosage, the reduction of strain in strands at same
282 load level is noticeable. This reduction in strand strain can be attributed to the increase in
283 effective contribution of fibers in arresting the propagation of cracks with the increase in steel
284 fiber dosage. The same phenomenon was illustrated by synthetic PO fibers at lower dosage of
285 fibers (0.35%, 0.7%). Additionally, it can also be observed from Fig. that at 0.35% and 0.70%,
286 both SF and PO specimens exhibited similar strain variations in prestressing strand.

287

288 At higher steel fiber dosage of 1.0%, the strain in strand reduced significantly at same load level
289 when compared to the control specimen. In all the specimens, the strands reached their yield
290 strain because of low reinforcement ratio of the specimens. Due to malfunctioning of the strain
291 gauges, the complete load strain curves could not be presented in the graphs. The yielding strain
292 of the steel strand (10,000 micro strain) was reached in all the specimens before final failure
293 (Fig. 8).

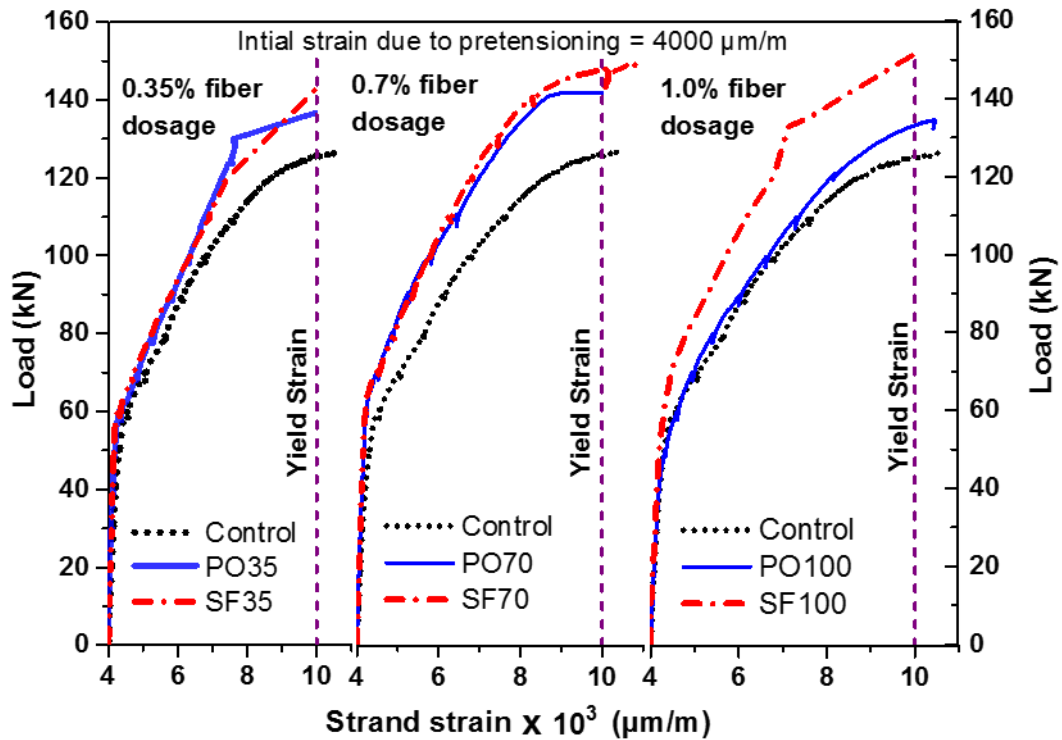


Fig. 8: Effect of Steel Fibers on Strain Variation of Strands in PSC Beams

294
295
296

297 4.5 Strain Energy Absorption capacity

298 Strain energy absorption capacity is one of the key factors in deciding the effectiveness of
 299 different fibers and its dosage for specific application. Strain energy absorption of the test
 300 specimens is calculated from the area under load-displacement curve until maximum
 301 displacement upto failure. Addition of fibers delays the crack propagation by bridging the
 302 cracked surfaces. Therefore, the specimen with higher fiber dosage had high energy absorption
 303 before failure. The energy absorption is closely related to the size of fracture process zone
 304 (FPZ). In FRC, FPZ covers a region of crack band and only the region along the crack path is
 305 affected by the cracking. Due to well-distributed cracks in flexure, the energy absorption
 306 increased significantly due to fiber addition. The energy absorption of steel and synthetic fibers
 307 is compared in Fig. 9. In general, the steel fiber specimens absorbed more strain energy when
 308 compared to macro synthetic fiber reinforced beams.

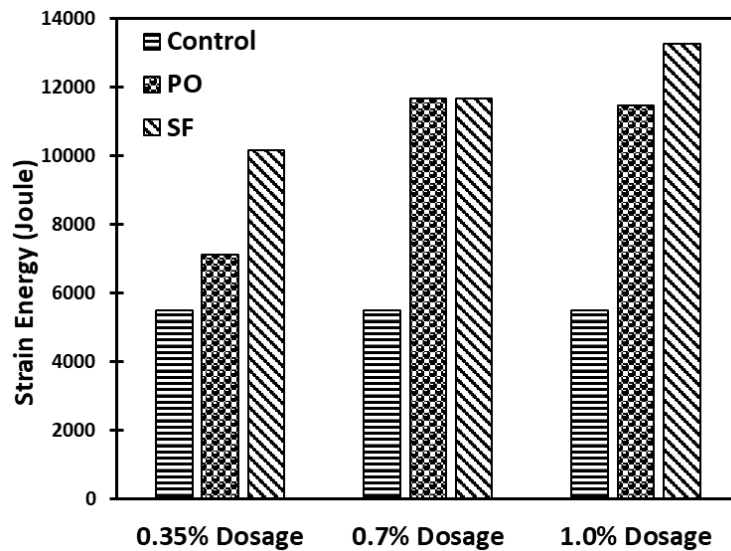


Fig. 9: Variation in strain energy absorption due to fiber addition

5 SUMMARY AND CONCLUSIONS

Prestressed concrete beams reinforced with steel and synthetic fibers were tested at a shear span to depth ratio of five to understand the efficiency of fibers in performance improvement. Based on the test results presented in this study, the following major conclusions can be drawn:

- i) Both the steel and synthetic fibers improved the post-cracking behaviour and ductility of the prestressed concrete beams under flexure-shear.
- ii) Steel fibers were more efficient in improving the post-cracking and ductility of the prestressed concrete beams at all fiber dosages.
- iii) Addition of fibers helped in converting the less ductile flexure-shear mode to more ductile flexure mode. At low dosage (0.35%), only steel fibers were effective in arresting the shear cracks and ensured flexure dominant behaviour. However, the beams with high fiber dosage (0.70% and 1.0%) of steel as well as structural synthetic fibers ensured ductile flexural failure mode.
- iv) Macro-synthetic fibers marginally increased the peak strength. However, steel fibers increased the peak strength significantly when compared to macro-synthetic fibers. The

327 ultimate strength increased by 17% due to steel fibers when compared to synthetic fibers at
328 1.0% addition.

329 v) Energy absorption capacity of prestressed concrete beams increased with increase in both
330 steel and macro synthetic fiber dosage. At all fiber dosages, steel fibers had higher energy
331 absorption when compared to macro synthetic fibers.

332

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