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RESEARCH ARTICLE - CIVIL ENGINEERING

An Investigation on Shear Behavior of Prestressed Concrete Beams Cast by Fiber Reinforced Concrete

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Abstract

Failure due to shear is brittle in nature, and inherent lesser concrete tensile strength is a main contributing factor. During loading before the shear reinforcement could start functioning, cracking in concrete starts. Use of fibers in concrete had proven improved impact on tensile strength of concrete. Active reinforcement role initiates after concrete cracking starts. This paper investigates into the shear behavior of fiber reinforced, pretensioned concrete I-section beam specimens. A total of six beam specimens were cast. Two types of fibers, steel fibers and polypropylene fibers were used in five different proportions. For comparison, one control specimen was also cast without inclusions of fibers in concrete. Concrete mix ratio, prestress force, shear span-to-depth ratio and shear and flexural reinforcement details were kept constant in all specimens. Specimens were subjected to four-point loading to ensure that all specimens fail due to excessive shear force. During tests, deflections and strains were also measured. It was concluded that shear strength of beams was improved using steel fiber reinforced concrete (SFRC) as compared to polypropylene fiber reinforced concrete (PPFRC). SFRC beam containing 0.65% fiber depicted 50.71% improvement in ultimate failure load, 67% improvement in first cracking load and 36% improvement in ultimate deflection as compared to control beam.

Keywords Shear behavior · Prestressed beams · Steel fiber reinforced beam · Polypropylene fiber reinforced beam · Hybrid fiber reinforced beam

1 Introduction

Shear strength has been under discussion from 1900, but it gained major importance as a research topic in the early 1950’s [1]. After the development of prestressed concrete, interest in the shear strength has been improved. Longer spans can be used and heavier loads can be carried, by the application of prestressing. By considering the test data and concepts of diagonal tension, it is concluded that prestressed concrete beams have more shear strength than that of reinforced concrete beams [2]. Shear strength depends on various factors such as internal friction due to the interlock of aggregates, dowel effect of flexural reinforcing bars and involvement of compressive struts formed during loading process of a beam failing in shear [3].

Antonio et al. [4] used fiber reinforced concrete (FRC) to enhance the load carrying capacity, energy dissipation performance of concrete and shear strength of the beams. The study also concluded that the quantity of fibers has influenced the first crack strength and the entire post-cracking behavior. Brittle shear failure can be suppressed in favor of more ductile behavior by addition of sufficient amount of fibers [5]. To get the best advantage of fibers in crack control and shear resistance, three-dimensional randomly distributed fibers are spread throughout the structural member. Fibers influence micro-cracks by delaying their widening [6,7]. By observing the experimental results of several researchers, it was concluded that by the use of FRC there is potential reduction or even the total replacement of steel stirrups [8,9]. Steel fibers and conventional stirrups used in combination are even more efficient [10].

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Patil and Keshav [11] added steel fibers in concrete to investigate the effect of prestressing on flexural and shear strength of concrete. They used 20% fly ash as a substitute of binder to its weight and 1.5% steel fibers by weight of concrete. It was noted that steel fiber reinforced prestressed concrete beams enhance crack resistance, shear strength and flexural strength. It was also seen that plain concrete beams showed brittle failure while steel fiber reinforced concrete beams showed ductile failure. Hwang et al. [12] investigated shear deformation of prestressed concrete beams reinforced with steel fiber by varying fiber volume dosage, compressive strength of concrete and prestressing force. It was concluded that prestressing and steel fibers were very efficient in enhancing the ultimate shear strength and shear cracking resistance of the beams. Tadepalli et al. [13] worked on shear strength of prestressed concrete I-section beams with steel fibers but without transverse steel reinforcement. From the experimental results, it was concluded that with increase in steel fiber ratio, the shear capacity of beams is also enhanced. It also reflected an influence on crack width and first crack load.

Patil and Mukund [14] predicted shear strength of SFRC beams without web reinforcement by taking different percentages of steel fibers. It was concluded that ultimate shear strength of matrix enhanced considerably when fibers were added to matrix. The optimum fiber content for this study was 0.75% volumetric percentage. Carnovale and Frank [15] investigated structural performance of FRC under cyclic loading. It was concluded that material response of 1.0% SFRC and 2.0% by volume of polypropylene fibers were nominally similar. Degradation of SFRC response owing to reversed cyclic loading was considerable, and crack bridging capacity was negatively affected while degradation of PPFRC was not notable. It suggested that PPF might be good for such loading conditions. Maruthachalam and Karthick [16] reviewed illustrative discussion on behavior of composite concrete beams subjected to cyclic and monotonic loading. The major concern was shear behavior of beams tested at different loading conditions. It was found that shear stress of a fiber reinforced concrete beam was enhanced because of polypropylene fibers and the mode of failure also changed towards ductile. Meda [17] also investigated SF reinforced prestressed concrete beams. It was found that SFRC beams depicted similar or even improved post-cracking behavior than the minimum transverse reinforced beams. Noghabai [18] investigated by performing series of experiments on the beams having different shear span and dimensions. Different types of fibers were also used. It was also found that as compared to beams having mono-fiber, behavior of hybrid fibers beams was much better. Narayanan and Darwish [19] investigated by performing shear test on simply supported rectangular prestressed concrete beams in which steel fibers were used for web reinforcement. It was concluded that by the addition of steel fibers to concrete, ultimate shear strength had increased up to 95 %.

This research comprised of the experimental investigation on shear behavior of pretensioned fibrous, I-sectioned concrete beams. These beams were tested up to their failure point under cyclic loading. The main variables were type of fibers (steel and polypropylene) and fiber ratios. Present research was aimed at studying the role of FRC on load deformation relationships, cracking behavior and ductility index of short beams.

2 Testing Program

2.1 Description of Test Specimens

Cross sections of all beam specimens were doubly symmetric I-shaped and with length as 3.048 m. Depth of beams was 35.56 cm of each, while flange width as 12.7 cm and thickness of web as 4.445 cm. In top flange, there were two high tensile (HT) wires each of 5 mm dia. prestressed by a force of 26.69 kN, while in bottom flange there were three strands of 9.53 mm dia. prestressed to a force of 71.17 kN. Each strand comprised of seven wires. Shear span was 38.1 cm, and shear span-to-depth ratio was 1.071. Cross section and elevation showing shear reinforcement are shown in Fig. 1.

2.2 Materials Used

Ordinary Portland cement (ASTM Type-I) was used with 28-days compressive strength of standard 50 mm cement mortar cubes cast as per ASTM C 109/C109M as 32.61 MPa. Margalla brand local crush was the source of coarse aggregates. Maximum size of coarse aggregate used was 20 mm. Lawrencepur brand local sand was used as fine aggregates. Fibers used were hooked steel fibers (SF) with rounded ends and micro-filament polypropylene fibers (PF). Details of fibers and wires used are given in Table 1. Pictorial view of fibers is provided in Fig 2.

Dosage of superplasticizer used was 1.2% by the weight of cement. This super plasticizer can enhance ultimate strength, durability and workability for longer period.

2.3 Prestressing and Casting

Prestressing of I-shaped beam specimens was carried out in casting yard of a precast unit. Longline method was adopted to get pretensioned beams as shown in Fig. 3. The complete length of the casting bed between anchorage and jacking abutment was about 95 m among which separators were installed to attain the required length of beams. Three strands and two HT wires were pretensioned for full length. They were anchored at one side, and jacking force was applied

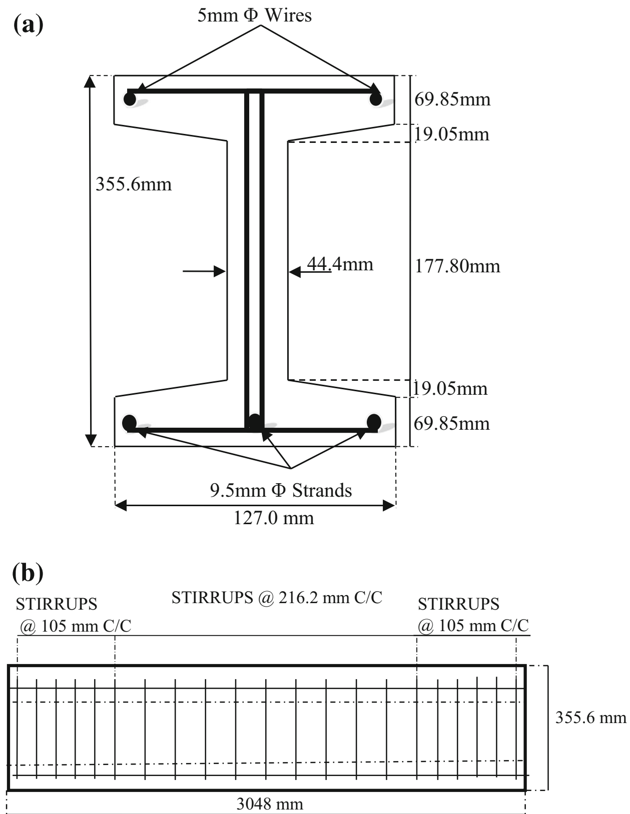

Fig. 1 Section and elevation (**a** & **b**, respectively) of prestressed I-shaped beam

Table 1 Characteristics of fibers and strands used in prestressed beam specimens

Fiber type	Length (mm)	Dia. (mm)	Tensile strength (Mpa)	Young's Modulus (kN/mm^2)
Steel	26	0.5	1100	20
Polypropylene	14	0.2	1400	0.45
Strands	–	8.407	1906	
HT wires	–	5	1772	

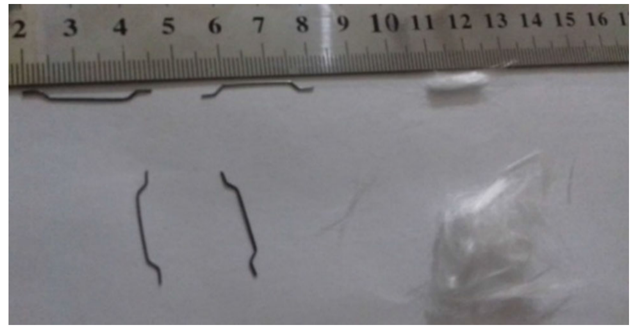

Fig. 2 Fibers used in the research

Fig. 3 Pretensioning by longline method

on another side. Initial prestressing force applied on each HT wire was 26.69 kN, while on each strand was 71.17 kN. After that, stirrups were placed and later on shuttering plates were fixed for full length of bed. In all six specimens, concrete mix ratio was kept uniform, i.e., 1:1:2, as achieved in the laboratory for a target cylindrical strength of 35 MPa. Fiber content was varied in each beam specimen, and full details of casting schedule are given in Table 2.

2.4 Experimental Setup

In order to find shear strength of prestressed concrete beam specimens, four-point loading was used as per ASTM D6272. Four-point loading arrangement is shown schematically in Fig. 4a. A spreader beam was used to transfer the applied load to rollers so that a four-point loading arrangement could be established. Mid-span deflections were observed by deflection gauges, and strain was recorded by strain indicator and recorder box. Experimental setup is shown in Fig. 4c, and detail of location of gauges is shown in Fig 4a.

The loading protocol applied to the beam specimens is shown in Fig. 4b. Loading rate was 0.2 mm/s. The first loading cycle was applied up to 2 mm deflection due to discharge load and after that load was applied for every 1 mm deflection.

Table 2 Fiber contents in all prestressed beam specimens

Sr #	Name of specimen	Fiber contents (by percentage of volume of concrete)	
		Steel fibers	Polypropylene fibers
P1	Control beam	--	--
P2	Hybrid fiber reinforced concrete beam	0.75	0.5
P3	Steel fiber reinforced concrete beam-1	0.65	--
P4	Steel fiber reinforced concrete beam-2	0.85	--
P5	PPFRC beam-1	--	0.4
P6	PPFRC beam-2	--	0.6

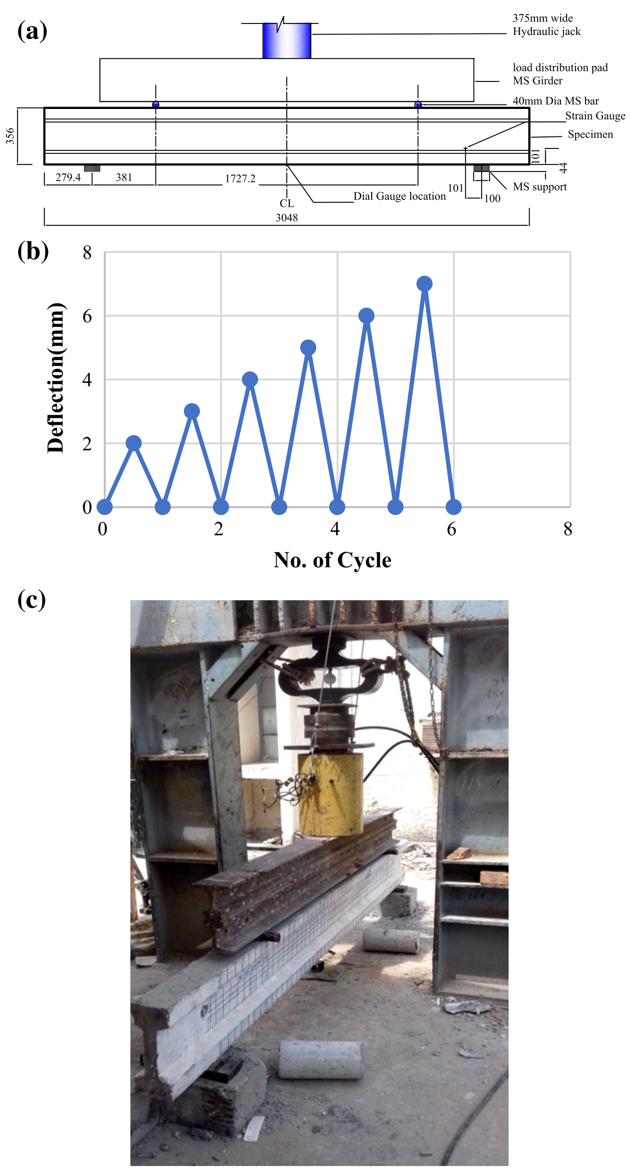

Fig. 4 **a** Schematic view of four-point loading arrangement. **b** Loading Protocol. **c** Test setup using four-point loading arrangement

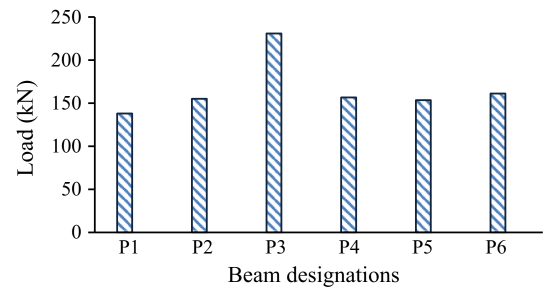

Fig. 5 Cracking load (kN) for the specimens

3 Results and Discussion

3.1 First Crack Load

During the testing of each specimen, first crack load was noted and results are graphically presented in Fig. 5. Highest first crack load was achieved by P3 specimen that was 67% higher than that of control beam. On the other hand, the first crack loads of P2, P4, P5 and P6 were found to be 12.35, 13.47, 11.23 and 16.84%, respectively, higher than that of control beam P1. It can be seen that by the use of fibers, first crack appeared at higher load. The reason is that in case of steel fibers, fibers are randomly distributed throughout the cross section. So, a good bond is formed between concrete and fibers which help in resisting the crack. But results would be not so appreciable if we use excessive steel fibers. Polypropylene fibers also act as the crack arrestors. These short discrete fibers like secondary reinforcement offer increased resistance to the propagation of crack. As we increased the polypropylene fiber ratio, crack resistance increased, and crack appeared at higher load.

3.2 Ultimate Load

Ultimate loads for all specimens are shown in Fig. 6. The highest load was attained by specimen P3 having steel fiber contents of 0.65% by volume of concrete. Its load was 50.71% higher than that of control beam (P1), while those of P2, P4 and P6 were 25.72, 25.72 and 8.08%, respectively, higher than that of control beam. The specimen P5 having

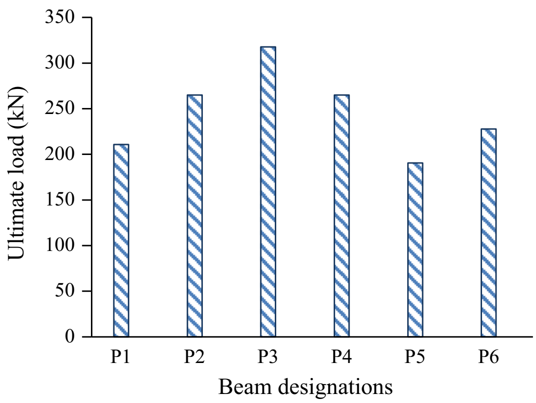

Fig. 6 Ultimate load for all specimens

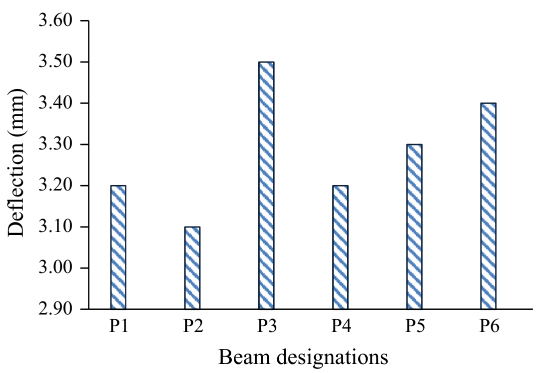

Fig. 7 Deflection at initial crack (mm)

polypropylene fiber content of 0.4% showed premature failure as compared to that of control beam due to the reason that polypropylene fibers decreased the density of concrete due to which ductility decreases. As steel fibers provide structural strength, its ultimate loads are higher as compared to other specimens whereas behavior of polypropylene fibers was not so appreciable in this concern.

3.3 Deflections

3.3.1 Deflection at Initial Crack

Deflections at initial crack for all beams are shown in Fig. 7. The deflection during initial stages of loading was identical in all specimens. Maximum deflection at initial crack was recorded in P3 as 9.4% greater than that in control beam. It is due to ductile nature of steel fibers and compatibility of steel fiber with concrete matrix. But when excessive steel fibers were used, beams become a bit stiff.

3.3.2 Deflection at Failure

Deflections at ultimate failure in all beams are shown in Fig. 8. Maximum deflection was observed for P3 which was

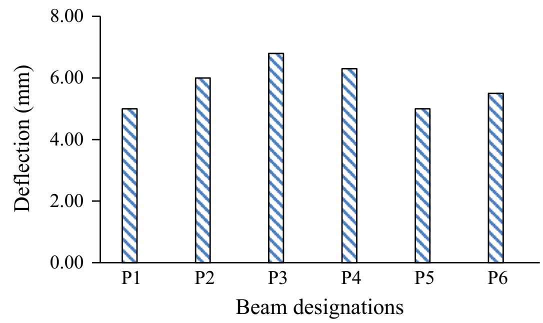

Fig. 8 Deflection at ultimate failure

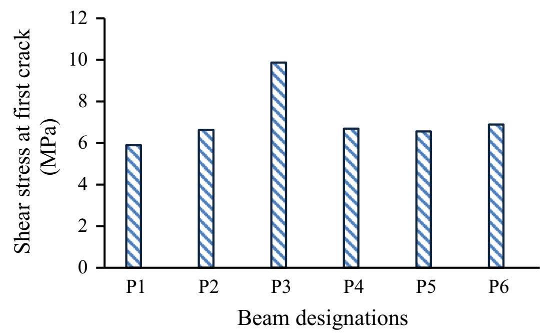

Fig. 9 Shear stress at first crack

36% higher than that of control beam. Deflections of P2, P4 and P6 were 20, 26 and 10%, respectively, higher than that of control beam. It shows that beam P3 gave enough indication before failure as it deflected more. As steel fibers help to bind the concrete matrix together at higher loads while exhibiting ductile behavior.

3.4 Shear Stress

3.4.1 Shear Stress at First Crack

Shear stress value was calculated for each beam specimen by the formula $\tau = \frac{QV}{It}$, where

τ = shear stress in MPa,
Q = first moment of area in m^3,
V = total shear force at the point of location in N m,
I = moment of inertia of entire cross section area in m^4,
t = material thickness perpendicular to shear in m.

Shear stress at first crack is shown in Fig. 9. Highest shear stress was achieved by P3 that was 67% higher than in control beam. Shear stress values for P2, P4, P5 and P6 were 12.39, 13.58, 11.37 and 16.97%, respectively, higher than that of control beam (P1). There was not enough increase in shear strength in beams having only polypropylene fibers due to poor tensile properties of polypropylene fibers in comparison with steel fibers, and specimen with higher percentage of steel

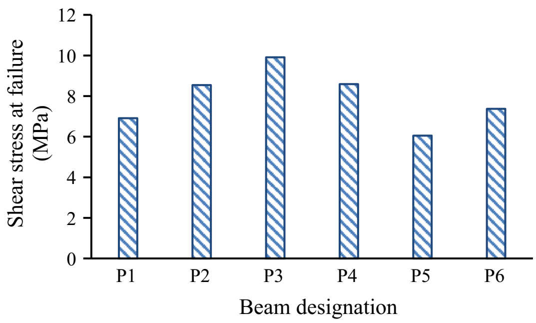

Fig. 10 Shear stress at failure

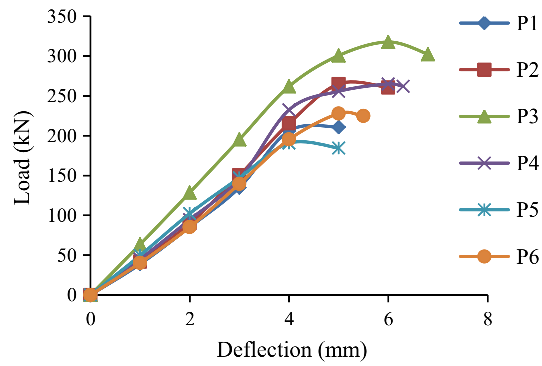

Fig. 11 Load-deflection backbone curves of all hysteresis loops for all specimens

fibers causes non-uniformity of concrete matrix and increase in shear stress was also limited.

3.4.2 Average Shear Stress

Average shear stresses for all the specimens have been graphically presented in Fig. 10. Average shear stress was calculated by dividing the shear force at failure by the web width and the effective depth. The highest shear stress value was attained by specimen P3 having steel fiber content of 0.65% by volume of concrete. This implies that resistance to shear failure has been increased by incorporating steel fibers within concrete matrix. The improvement in resistance to cracking may be attributed to improvement in microstructure of concrete and resulting boosted tensile properties. The failure stress value for this specimen was 43.4% higher than that of control beam “P1” that was cast without any fibers. Failure stress values also improved in other specimens containing fibers in varying ratios. Failure shear stress values of specimens P2, P4 and P6 were 23.59, 24.3 and 6.66%, respectively, higher than for control beam. This behavior also verifies that concrete with fiber content in various proportions has also improved cracking resistance capability. As in this study, loading arrangement were selected in such a manner that failure of specimens should occur due to shear only. The test results confirm that failure in specimens containing fibers was delayed due to fiber action. The specimen P5 depicted lesser shear stress values than other owing to less fiber percentage.

3.5 Load-Deflection Curves

Static cyclic loading was applied in order to observe the behavior of beam in detail, and load was noted after every 1 mm deflection. In first cycle, load was applied up to 2 mm deflection and then released. This process of loading and unloading by increase of 1 mm deflection at every cycle continued until the beam failed. Residual deflection was noted after release of load in every cycle. Control beam P1 failed in its fourth loading cycle. Maximum loading cycles were carried by the beam specimens P3 and P4, which failed in sixth loading cycle. P2 and P6 beams failed in fifth loading cycle, while P5 beam failed in fourth loading cycle. Load-deflection backbone curve of each beam is plotted by joining the peaks of hysteresis loops and is shown in Fig. 11.

The load-deflection curves of P1 and P2 beams were similar in start but after elastic range, P2 beam showed enhanced behavior in terms of load and deflection. Fiber reinforced concrete enhanced post-elastic properties of structural members. From initial loading to the ultimate load, P3 beam showed enhanced behavior throughout in terms of load as compared to control beam and its ultimate deflection was also higher than that of control beam. Load-deflection curves of P4 beam specimen and control beam were similar in start but at the end, it has more deflection at failure and higher ultimate load due to fiber content. Load-deflection curves of P1 and P5 were almost similar but P5 showed abrupt failure and its ultimate load was less than that of control specimen due to the presence of low polypropylene fiber content. Curves of P6 and P1 were quite similar but P6 has slightly more ultimate load and deflection than that of the control specimen. The backbone curve of P3 specimen showed the improved behavior of steel fibers in terms of both deflection and load as well due to enhanced post-elastic behavior of steel fibers having higher tensile properties in comparison with polypropylene fibers. This is because there was not considerable difference in beams having polypropylene fibers and control beam.

3.6 Stress–Strain Curves

Shear stress–strain curves for all beams are shown in Fig. 12. As compared to the control specimen (P1), hybrid fiber reinforced beam (P2) has shown much enhanced performance in terms of shear stress and shear strain. Shear strain values of hybrid beam were greater than that of control beam. A steel fiber reinforced beam containing 0.65 % of steel fibers by volume of concrete (P3) has much improved shear stress-strain values than those of control beam (P1). Shear strain

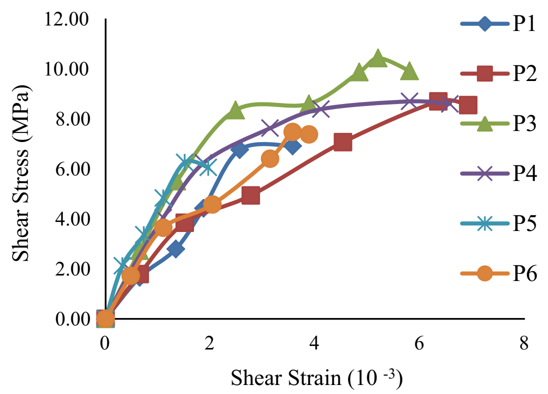

Fig. 12 Shear stress–strain curves for all beams

values of steel fiber reinforced beam containing 0.85 % of steel fibers by volume of concrete (P4) are much higher than that of control beam (P1). As compared to control beam (P1), shear strain values are quite lesser in PPFRC beam containing 0.4% polypropylene fibers by volume of concrete (P5). Shear stress is lesser in P6 at the start but at the failure, its shear stress-strain values were greater as compared to those in P1.

3.7 Ductility

Azizinamini et al. [20] proposed displacement ductility index (DI) as the ratio of max. mid-span displacement (Δ_{max}) to first yield displacement(Δy) of beam. The first yield displacement comes out by intersection of tangents to load displacement curve at origin and maximum displacement as shown in Fig. 13a. Ductility index is shown in Table 3 and plotted in Fig. 13b. P4 beam has maximum ductility index which shows that this beam failed after giving enough indication as compared to other specimens. P1 and P5 have shown similar behavior. Yield displacement of P3 and P2 specimen was on higher side as compared to others favoring the use of hybrid fibers and steel fibers. The values of P3 and P4 are although higher than other specimens but these do not differ to much when compared with each other. This shows that increasing SF percentage above 0.65% has not noticeable effect on yield load or yield displacements.

3.8 Crack Patterns

During testing, crack patterns of all beam specimens were observed carefully. These are shown in Figs. 14, 15, 16, 17, 18 and 19. For beam P1, shear crack appeared at 3.2 mm deflection which initiated from web and propagated toward flange when deflection reached to 4.5 mm level. This beam showed brittle failure at 5 mm deflection and huge crack of 14 mm appeared at failure. For beam P2, crack initiated from web and propagated toward flange. Initial crack appeared at 3.1

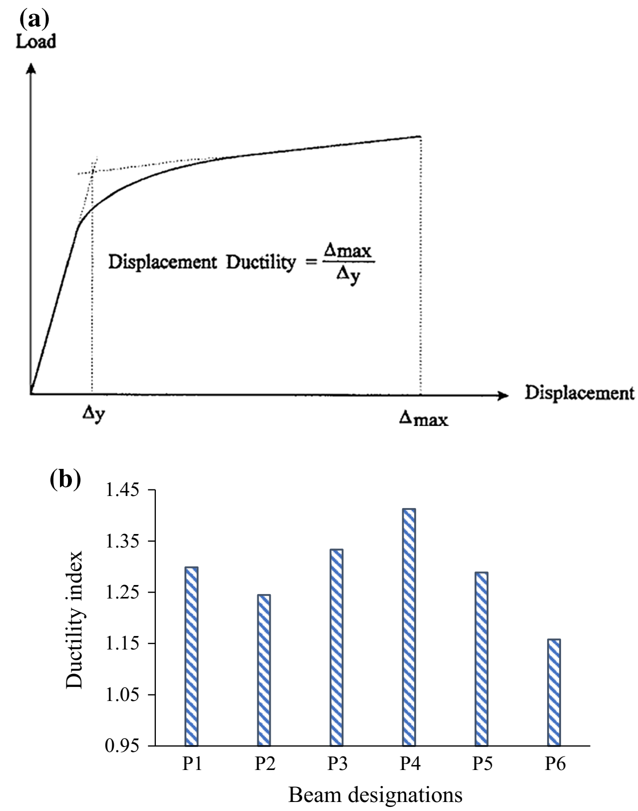

Fig. 13 **a** Displacement of ductility ratio [20]. **b** Ductility index of all beams

Table 3 Ductility index of all beams

Specimen	Maximum deflection Δ_{max}	First yield displacement Δy	Ductility index ($\Delta_{max}/\Delta y$)
P1	5	3.85	1.30
P2	6	4.82	1.24
P3	6.8	5.1	1.33
P4	6.3	4.46	1.41
P5	5	3.88	1.29
P6	5.5	4.75	1.16

mm deflection, transferred to flange at 4 mm deflection and beam failed due to shear at 6 mm deflection when crack width was 8 mm. For P3 beam, deflection at initial crack was 3.5 mm, crack transferred to flange at 4.2 mm deflection while it was 6.8 mm at failure. Crack width of this beam is 7 mm. For P4, deflection at initial crack was 3.2 mm, crack transferred to flange at 4.5 mm deflection while it was 6.3 mm at failure. Crack width of this beam was 6.5 mm. For P5, deflection at initial crack was 3.3 mm while it was 5 mm at failure. Crack width of this beam was 7.5 mm. For P6, deflection at initial crack was 3.4 mm while it was 5.5 mm at failure. Crack width of this beam was 9.5 mm. Crack width was much reduced by

Fig. 14 Crack patterns of P1 beam

Fig. 15 Crack patterns of P2 beam

Fig. 16 Crack patterns of P3 beam

Fig. 17 Crack patterns of P4 beam

Fig. 18 Crack patterns of beam P5

Fig. 19 Crack patterns of P6 beam

the usage of fibers, and the best reduction was observed by P4 specimen. Angle of crack failure for all beams was within the range of 45°.

4 Conclusions

Following conclusions were drawn based on experimental results of normal prestressed and fiber reinforced prestressed concrete beam specimens subjected to four-point loading:

1. First crack load can be increased more using SF as compared to hybrid or PF. However, first crack load would reduce if excessive amount of SF is used.
2. Using SF, ultimate load of beams can be improved appreciably. Hybrid fibers also give good results but PF do not give appreciable results in this concern.
3. Steel fibers and hybrid fibers would improve deflection, i.e., give enough indication before failure as compared to polypropylene fiber.
4. Use of fibers improves ductility index. However, this improvement is more pronounced in SF and hybrid fibers as compared to PF.
5. Due to usage of fibers, crack width is much reduced. SF, hybrid fibers and PF all show good reduction, but SF would give best results.
6. SFRC prestressed beam with optimum fiber percentage is recommended in overall, as it performed better in terms of load, deflection, crack width compared to other beams

investigated in the research. However, by increasing SF percentage above optimum value, adverse results may be obtained. In this investigation, when SF percentage was increased to 0.85%, the behavior was not improved.
7. Increasing SF percentage above 0.65% as 0.85% in P4 has not shown noticeable improvement in yield load or yield displacements.

In this research, conclusions have been drawn based on the test results of relatively smaller beam sections on few specimens due to limited laboratory facilities and casting yard capabilities. The authors believe that further research is needed in this area with greater number of specimens considering other variable like shape and size of beam sections, tendon properties, quantity and types of fibers to draw more interesting outcomes.

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