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Behaviour of prestressed concrete beams strengthened with externally bonded fibre reinforced polymer laminates

Revathy Jayaseelan, Saranya S, Illakkiya B

Abstract —The paper explores the results of an experimental study concerning the flexural strengthening of prestressed concrete beams using fibre reinforced polymer (FRP) laminates. Five unbonded post-tensioned concrete beams were tested in the laboratory to evaluate the strength enhancement provided by the FRP plates. Four beams were strengthened with different orientations and thicknesses of FRP laminates. Structural behaviour of the prestressed concrete beams were evaluated in terms of strength, stiffness, composite action between FRP laminate and concrete and the associated failure modes were tested under a static gradual loading up to failure. The test results indicate that the FRP plated unbonded post-tensioned concrete beams considerably increase the strength, stiffness and composite action until failure. The failure of the specimen occurred either by crushing of concrete and/or by FRP rupture.

Keywords—deflection, ductility, FRP, strengthening, unbonded, prestressed concrete, post-tensioned beam

I. Introduction *(Heading 1)*

In the past few decades, repair and retrofitting of structures has become a primary problem for civil engineers. These structures that have been built more than several decades are necessary to be strengthened and upgraded to meet the current service load demands. Different methods of strengthening the structures using various materials have been studied and applied in the rehabilitation field. When compared to conventional repair and strengthening methods, externally bonded Fibre Reinforced Polymer (FRP) provide excellent solutions in civil engineering structures that are both cost effective and durable. FRP, a non-metallic material with immense potential, which is suitable to upgrade and extend the life span of civil engineering structures. These advanced composite materials consist of high strength fibres embedded in a polymer matrix; have unique properties which make them extremely attractive for structural applications. It has been recognized for high strength to weight ratio, good fatigue life, ease of transportation and handling, low maintenance cost and good corrosion resistance. Since the high-strength FRP sheets are extremely thin, they are easy to install, can be applied to complex shapes and cross sections and facilitate a significant reduction in construction time.

Revathy Jayaseelan, Saranya S, Illakkiya B

B.S.Abdur Rahman University, Vandalur, Chennai
India

FRP becoming an increasingly common practice as more research investigations are favourably qualifying this technique. Retrofitting and rehabilitation of concrete slabs [9, 10] beams [3, 4, 5, 6,] girders [12] and columns [7,15]. The focus has consistently been on investigating reinforced concrete members rather than prestressed concrete members due to their ease of construction and the similarity in their behaviour. Russell et al.[1] recommend that prestressed concrete flexural members be designed such that cracking does not occur in the transfer region of the prestressing tendons under factored ultimate loads. Peterman [11] repaired and strengthened 30-year-old prestressed concrete T girders with carbon FRP sheets. The girders were removed from an existing bridge that may have been overloaded during its life span. They reported that the girders were strengthened with a strand stress range of 255 MPa in its harped strands.

Kyle Larson et al.[12] conducted an experimental study on pretensioned prestressed concrete T beams. The beams were designed for specific prestressing strand stress ranges under live-load conditions. FRP rupture was observed for all the strengthened beams. The results favourably qualify the application of FRP strengthening to increase the live load of concrete beams prestressed with straight strands. Murphy et al.[16] investigated an experimental study on the behaviour of prestressed concrete I-girders strengthened in shear with externally bonded fiber-reinforced-polymer sheets. The test results showed that the failure modes are complex and could vary considerably with respect to the test parameters. The test results also showed that the application of externally bonded CFRP shear reinforcement might not increase the load-carrying capacity of a prestressed concrete girder.

El-Hacha et al.[10] evaluated the flexural behaviour of prestressed concrete beams strengthened with prestressed CFRP sheets in various temperature conditions. They found that the contribution of cold temperature to the short term performance of the strengthened beams was not significant. Suraj Parkash et al. [14] investigated on the prestressed concrete beams subjected to cyclic loading. The study was addressed on the development of cracking, ultimate moment carrying capacity and load-deflection response of post-tensioned bonded & unbonded beams in flexure

Limited research was available on the effectiveness of FRP laminates on strengthening of prestressed concrete beams. The present study has been primarily intended for evaluating the effects of FRP laminates on prestressed concrete beams. The strength, deflection and ductility of FRP plated prestressed concrete beams under static loading have to be systematically assessed.

II. Experimental Programme

A. Material Properties

Concrete mix was prepared using ordinary Portland cement of 53 grade conforming to IS 4031–1988 having a specific gravity of 3.15. The fine aggregate used for the investigation was river sand, passing through 4.75 mm sieve with a specific gravity of 2.63. The grading zone of fine aggregate was Zone II in accordance with IS 383-1970. The crushed granite coarse aggregate of 20 mm maximum size and specific gravity of 2.77 was used. Potable water conforming to IS 456-2000 was used for concreting and curing the specimens. For an assumed water-cement ratio of 0.45, trial mix of concrete has developed. The average cubic compressive strength of concrete at the age of 28 days was 42 N/mm^2.

The longitudinal reinforcement used was high-yield strength deformed bars of 12 mm diameter at tension face. The stirrups were made of 8 mm diameter at 150 mm c/c. The yield strength of steel for 12 mm diameter and 8mm diameter was found to be 436 N/mm^2 and 287 N/mm^2 respectively. In this study, prestressing steel wires of 7 mm diameter were used. The ultimate stress of the prestressing wire was 1532 MPa. The details of the section are shown in fig.1.

In this study, two types of orientations of glass fabrics viz., 0°- unidirectional (UD) and 0°/90° - woven roving (WR) were used for the preparation of FRP plates. UD glass fibre placed in the 0° direction has approximately 90% of fibres with sparsely glass fibres in the 90° direction to hold the main fibres. WR glass fibre consisted of bi-directional weaved fibres with equal fibre in the two perpendicular directions. UD and WR glass fibre reinforced polymer laminates having 3 mm and 5 mm thicknesses were used for strengthened the unbonded post-tensioned concrete beams. Table I shows the mechanical properties of FRP composites and they were tested according to ASTM D 638.

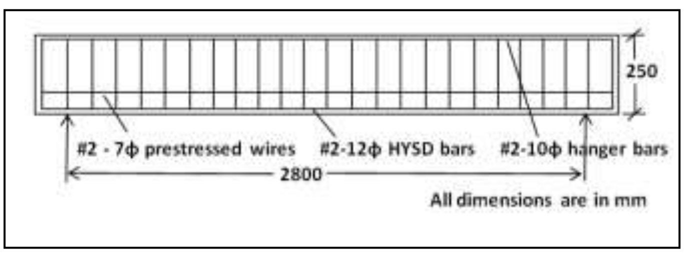

Figure 1. *Longitudinal section of beam specimen*

TABLE I. MECHANICAL PROPERTIES OF FRP COMPOSITES

Type of FRP	Thickness	Tensile strength (MPa)	Ultimate Elongation	Modulus of Elasticity (MPa)
WR	3	6855.81	2.15	147.40
	5	8994.44	1.98	178.09
UDC	3	13965.63	3.02	446.90
	5	17365.38	2.60	451.50

B. Specimen Preparation

A total of five beam specimens, 150 mm x 250 mm in cross-section and 3000 mm in length were used. Of the above five beams, one beam was served as a reference beam (UBPTR) and the other four beams (UBPTW3, UBPTW5, UBPTU3, UBPT5) were externally bonded on the tension side with glass fibre reinforced polymer plates of 3 mm and 5 mm thicknesses. The variables considered in the study included the orientations and thicknesses of FRP. The non-prestressed reinforcements were insulated with strain gauges and adequate water proofing was provided before concreting. The prestressing wires were placed in the galvanised flexible tubes. The reinforcement cage was placed in the steel moulds for concrete casting. After curing, beams were made ready for prestressing operation. The prestressing steel was anchored at the far end and then prestressing force was applied at the other end up to 2298 MPa stress level (75% of the ultimate stress of prestressing steel). During prestressing, the elongation of each wire was measured. After the completion of prestressing operation, four beams were strengthened with GFRP plates.

The concrete substrate was prepared well. Prior to bonding of the laminates, the soffit of beams was cleaned well with a wire brush to remove the loose materials. By means of a grinding wheel, the irregularities, unevenness, and sharp protrusions on the surface were grinded away and an air blower was used to blow off dust and dirt, if any. After surface preparation, a two-part epoxy adhesive with a paste-like consistency was used to bond laminates to the prestressed concrete beam soffits. To ensure a proper bonding, the strengthened beams were cured for a minimum of 10 days.

C. Instrumentation and Test Procedure

Four point bending tests were performed as shown in Fig. 2. The beams were statically tested at a load rate of approximately 2 kN/min. The beams were instrumented to record load, deflection and strain measurements. Electrical resistance strain gauges were attached to the FRP sheet at mid-span and three strain gauges were attached directly to the concrete on the top and sides of the beam at mid-span. Linear variable displacement transducers (LVDTs) were used to measure deflection of all beam specimens. All instruments were connected to a data acquisition system that made it possible to monitor the test specimen throughout the investigation. At each load stage, the crack development and propagation were observed. The crack widths were measured using a crack detection microscope.

Figure 2. *Test set-up and Instrumentation*

III. Results and Discussions

The strength and deformation properties of unstrengthened and strengthened unbonded post-tensioned concrete beams are presented and discussed herein.

A. *Load- Deflection Behaviour*

TABLE II. SUMMARY OF TEST RESULTS

Beam Specimens	Yield Load (kN)	Ultimate Load (kN)	Deflection at Ultimate Load (mm)	Ductility Index
UBPTR	18.6	51.5	65.2	21
UBPTW3	25.6	70.2	55.2	14
UBPTW5	30.4	79.4	64.5	16
UBPTU3	33.7	85.2	68.0	14
UBPTU5	36.1	97.5	75.5	19

Table II presents summary of load carrying capacity at various stages and deflection at ultimate load for the beam specimens. It was observed that the UBPTW3 and UBPTW5 beam specimens exhibit an increase in load carrying capacity by 36% and 54% respectively compared to the reference beam. Unidirectional oriented fibre reinforced polymer of 3 mm and 5 mm thickness plated unbonded post-tensioned concrete beam showed an increase in ultimate load carrying capacity by 65% and 89% respectively compared to that of the control beam. This is due to the fact that fibres were aligned in a single direction. The FRP strengthened beams exhibit a maximum decrease by 15% in deflection at the ultimate load stage.

Fig. 3 presents the load-deflection behaviour of all the tested beam specimens. It can be seen that FRP strengthened beams significantly improved both load carrying capacity and deflection when compared to the reference beam. It can also be observed that the FRP strengthened prestressed concrete beams showed a considerable flexural stiffness than the reference beam. A tri-linear behaviour can be seen in the tested beams which represent the uncracked, cracked pre-yielding and cracked post-yielding stages. It was examined that the cracked post-yielding stiffness has increased in the FRP strengthened unbonded post-tensioned beams when compared to the reference beam.

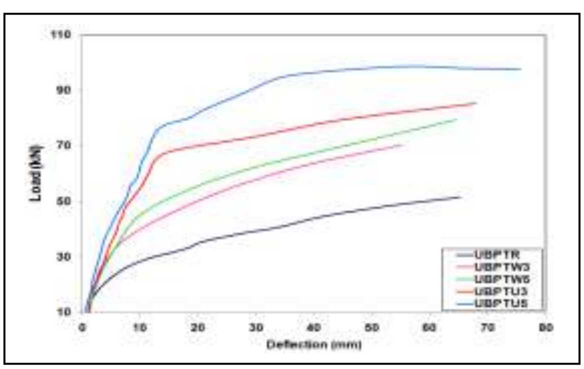

Figure 3. *Load – Deflection behaviour of prestressed concrete beams*

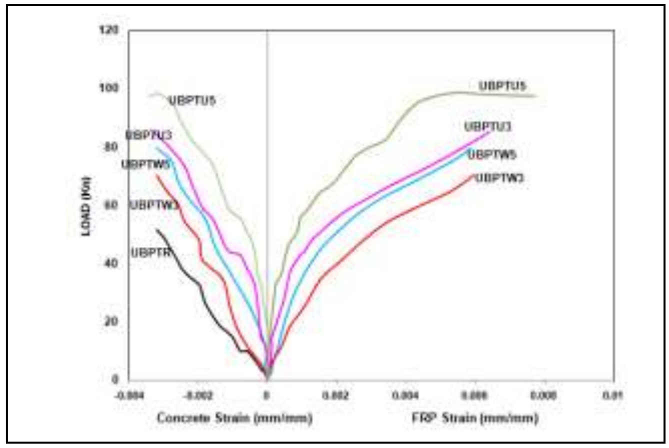

Figure 4. *Load – Strain at mid-span for all beams*

B. *Load – Strain Response*

Fig.4 shows the load – strain response at mid-span for all the prestressed concrete beams. UBPTU5 has a maximum composite strain of 0.0077mm/mm where the rupture of fibre occurred. The concrete compressive strain also has three distict regions represents pre-cracking, pre-yielding and post-yielding stage. The maximum failure strains were about 0.003 mm/mm for all the tested beam specimens.

C. *Ductility Response*

Ductility can be defined as its ability to sustain inelastic deformation without loss in load carrying capacity, prior to failure. The method presented by Park and Paulay [17] for deflection ductility is obtained as the mid-span deflection at ultimate load divided by the mid-span deflection at the point where the steel starts yielding. Generally, the ductility index can be obtained based on based on deflection and energy absorption capacity. The ductility index was calculated based on the above method for the tested beams are summarized in Table 2. The unidirectional and WR FRP strengthened prestressed concrete beams enhanced the maximum deflection ductility by 90% and 100% respectively.

D. *Failure Modes & Crack Pattern*

In all the beam specimens, the first cracks were observed within the constant moment region. As the load increased, the new cracks were formed in the flexure zone along with the propagation of existing cracks in the unstrengthened beam specimen. It was noticed that on increasing the load; cracks were also started in the shear span region. The unbonded post-tensioned concrete beam specimen was failed by yielding of tension steel reinforcement followed by the crushing of concrete at the compression face as presented in Fig.5. It was observed that the crack widths were smaller for externally bonded post-tensioned concrete beam specimens. Flexural cracks were appeared at the mid-span followed by yielding of tensile steel reinforcement. The failure of strengthened PSC beam specimens occurred by rupture and debonding of GFRP laminates and is presented through fig.6 and fig.7

Figure 5. *Crushing of concrete in UBPTR specimen*

Figure 6. *Failure of UBPTU5 beam specimen*

Figure 7. *Debonding failure of UBPTW5*

IV. Conclusions

This study was mainly focussed on evaluating the effect of fibre reinforced polymer laminates on the flexural behaviour of post-tensioned concrete beams. Based on the experimental results, the following conclusions are drawn:

- FRP strengthened post-tensioned concrete beams was found to be very effective in the load carrying capacity, deflection and ductility when compared to the reference beam specimen.
- The unidirectional FRP strengthened beam UBPTU5 showed an increase in ultimate load carrying capacity by 89% when compared to the reference specimen.
- FRP strengthened post-tensioned beam specimens provided a maximum increase in ductility by 90%.
- On utilizing the externally bonded FRP laminates on tension face increased the cracked post-yielding stiffness of the unbonded post-tensioned beams.
- A maximum composite strain of 0.0077 mm/mm was occurred in the strengthened prestressed concrete beam.
- The unbonded post-tensioned concrete beam specimen was failed by yielding of non-prestressed steel reinforcement followed by the crushing of concrete.
- Failure of strengthened PSC beam specimens occurred by rupturing of FRP and by FRP debonding.

Acknowledgment

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About Author (s):

[Revathy Jayaseelan - Fibre Reinforced Polymer (FRP) provide excellent solutions for repair and retrofitting of structures]

[Saranya S - FRP strengthened post-tensioned concrete beams significantly improved the load carrying capacity and deflection]

[Illakkiya B - Failure of strengthened PSC beam specimens occurred by rupturing of FRP]