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Structural Response of FRP Strengthened Post-Tensioned Concrete Beams

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Abstract

The paper presents the experimental results on the flexural behaviour of prestressed concrete (PSC) beams strengthened with externally bonded Fibre Reinforced Polymer (FRP) plates. The beam specimens used for this study were unbonded post-tensioned. The PSC beams were strengthened with Glass Fibre Reinforced Polymer (GFRP) plates with different configurations and thicknesses of 3 mm and 5 mm. The beams were tested under a static gradual loading up to failure to examine its flexural behaviour. The study parameters were ultimate load, ultimate deflection, ductility, failure mode and cracking pattern of the beams. The study showed that the UDCGFRP plates were found to be very effective in ultimate load carrying capacity, deflection and ductility when compared to other beams. The test results showed that the GFRP strengthened PSC beam increased its load carrying capacity by 89 % over the control beam. GFRP strengthened PSC beam showed an increase in ductility by 90% than the control beam. The PSC beam specimens failed either by crushing of concrete and by rupturing of FRP.

Keywords: Deflection, Ductility, GFRP, Strengthening, unbonded, post-tensioned beam.

Introduction

In the world scenario, rehabilitation and strengthening of aging structures are major challenges facing by structural engineers. These structures that have been built more than several decades may need to be strengthened and upgraded to meet the current service load demands. Several methods of strengthening structures using various materials have been studied and applied in the rehabilitation field. Fibre Reinforced Polymer (FRP), a non-metallic material with immense potential, which is suitable material to upgrade and extend the life span of civil engineering structures. FRP sheets are light-weight with a high tensile strength and are not subject to electrochemical corrosion. In addition, FRP has high fatigue strength under repeated loads. 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. When compared to conventional repair and strengthening methods, externally bonded FRP sheets provide excellent solutions in civil engineering structures that are both cost effective and durable.

FRP technology has been successfully used for retrofitting and rehabilitation of concrete slabs[1], beams[2-6] and columns[7,8]. 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. Suraj Parkash et al. investigated on the prestressed concrete beams subjected to cyclic loading. The study revealed that the flexural cracks were developed along the depth and near to mid-span portion of the beam[9]. El-Hacha et al. evaluated the flexural behaviour of prestressed concrete beams strengthened with prestressed CFRP sheets in various temperature conditions. The study showed that that the contribution of cold temperature to the short term performance of the strengthened beams was not significant[10]. Reed et al. 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[11].

Kyle Larson et al. 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 test results showed that the application of FRP increased the live load of concrete beams prestressed with straight strands[12]. Meski et al. has evaluated the performance of flexural behaviour of unbonded post-tensioned concrete members strengthened using external FRP composites. It was found from the test results that the use of FRP laminates increased the load capacity and post-cracking stiffness of unbonded members which has accompanied with reduction in deformation capacity. It was also observed that the failure of the specimens occurred either by concrete crushing or by FRP debonding[13]. Murphy et al. conducted an experimental study on 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[14].

Very little information was available on the effect of FRP laminates on strengthening of prestressed concrete beams. This paper is primarily intended to investigate the effectiveness of externally bonded suitable FRP in improving the structural performance of prestressed concrete beams. The ultimate load carrying capacity, deflection and ductility of FRP plated prestressed concrete beams under static loading have to be systematically evaluated. The major parameters of the proposed investigation are the configurations of FRP and its thicknesses.

Methodology

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. In this study, river sand was used as fine aggregate, 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[15]. The coarse aggregate was crushed granite of 20 mm size and specific gravity of 2.77 was in the study. Potable water conforming to IS 456-2000 was used for concreting and curing the specimens. A trial mix of concrete has been done with an assumed water-cement ratio of 0.45. 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 150mm c/c. The yield strength of steel for 12mm diameter and 8mm diameter was found to be 436N/mm^2 and 287N/mm^2 respectively. In this study, prestressing steel wires of 7mm diameter were used. The ultimate stress of the prestressing wire was 1532 MPa.

The glass fibre reinforced polymer (GFRP) plates of different configurations viz., chopped strand mat glass fibre reinforced polymer (CSMGFRP) and Uni-directional Cloth glass fibre reinforced polymer (UDCGFRP) with different thicknesses of 3 mm and 5 mm were used for strengthening the unbonded post-tensioned concrete beams. The Chopped Strand Mat (CSM) has randomly oriented E-glass fibres whereas Uni-directional Cloth (UDC) fibres were aligned in one direction. The properties of GFRP (table-1) were tested as per ASTM D 638.

Table–1
Properties of GFRP

GFRP Configurations	Thickness (mm)	Elasticity Modulus (MPa)	Ultimate Elongation (%)	Tensile Strength (MPa)
CSM	3	7467.46	1.69	126.20
	5	11386.86	1.37	156.00
UDC	3	13965.63	3.02	446.90
	5	17365.38	2.60	451.50

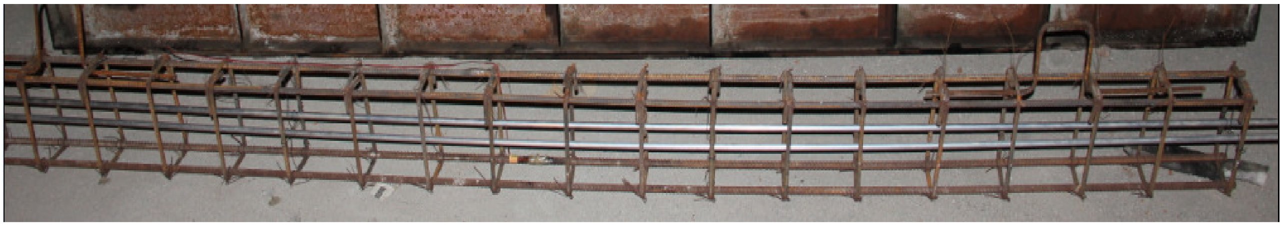

Figure-1
Duct with non-prestressed steel reinforcement

Figure-2
Stressing the prestressing wire and application of FRP on beams

Beam Preparation: The test program consists of five prestressed concrete beams of dimensions of 150 mm x 250 mm having a length of 3000 mm. 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 as depicted in Figure-1. 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 one end of the beam and at the other end, prestressing force was applied up to 2298 MPa stress level (75% of the ultimate stress of prestressing steel). During prestressing, the elongation of each wire was measured as shown in figure-2. After the completion of prestressing operation, one unstrengthened beam was used as a reference beam (UBPTR) and the other four beams (UBPTC3, UBPTC5, UBPTU3, UBPT5) were externally bonded on the tension side with glass fibre reinforced polymer plates of different thicknesses as shown in figure-2.

Instrumentation and Test Procedure: The PSC beams were tested under four point bending (figure–3) and the load was applied statically at a rate of approximately 2 kN/min. Electrically bonded resistance (EBR) strain gauge was attached to the FRP sheet at mid-span and three EBR 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. Loading, deflection and strain measurements were recorded through a data acquisition system. At each load stage, the crack patterns were also observed.

Results and Discussion

The summary of load carrying capacity at various stages and deflection at ultimate load for the beam specimens are presented (table–2). It was observed that the UBPTC3 and UBPTC5 beam specimens exhibit an increase in ultimate load by 16% and 35% respectively compared to the reference beam. When compared to the reference beam, UBPTU3 and UBPTU5 plated unbonded post-tensioned concrete beam showed an increase in ultimate load carrying capacity respectively by 65% and 89%. The test results also indicate that the UDCGFRP strengthened unbonded post-tensioned concrete beam specimen resulted in higher ultimate load carrying capacity when compared with CSMGFRP of same thickness. A noteworthy behaviour was found in UDCGFRP material over other material. This was because fibres in UDCGFRP where so oriented as to effectively strengthened the beam specimens.

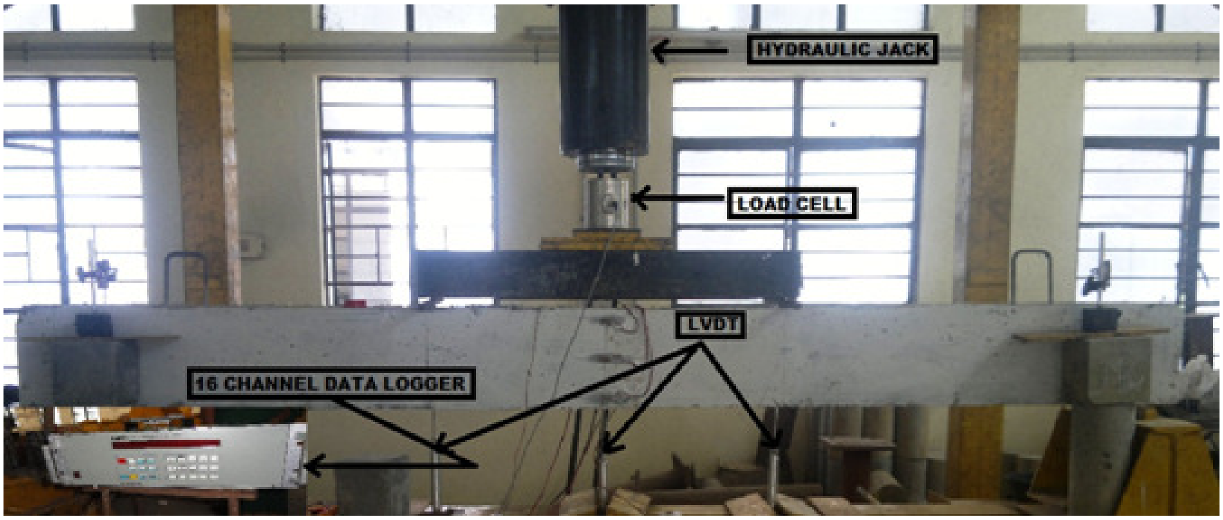

Figure-3
Test Set up

Table-2
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
UBPTC3	20.4	59.5	42.0	14
UBPTC5	23.2	69.4	50.0	16
UBPTU3	33.7	85.2	68.0	14
UBPTU5	36.1	97.5	75.5	19

Load-Deflection Behaviour: The load-deflection behaviour of all the tested beam specimens are presented (figure–3). Figure 3 indicates that FRP strengthened beams significantly improved both ultimate load and deflection. The behaviour of load-deflection curve for the reference beam replicates the behaviour of reinforced concrete flexural members. 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.

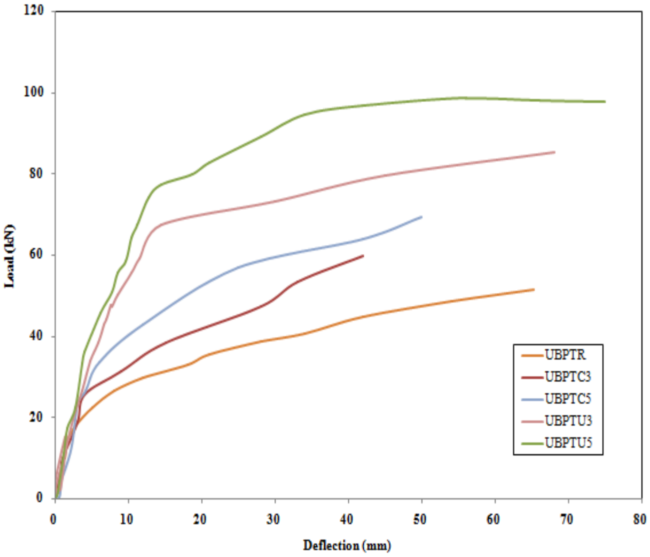

Figure-3
Load-deflection for post-tensioned beam specimens

Ductility Response: An important parameter is to be considered in a structure is the ductility and it can be defined as its ability to sustain inelastic deformation without loss in load carrying capacity, prior to failure[16]. The deflection ductility can be obtained as the ratio of mid-span deflection at ultimate load to the mid-span deflection at yield load[17]. The ductility index was calculated for the tested beams and is summarized (table–2). FRP plated unbonded prestressed concrete beams exhibit a maximum increase of 90% in ductility.

Failure Modes and Crack pattern: In all the beam specimens, the first cracks were observed within the constant moment region. In the unstrengthened beam specimen, it was observed that on increasing the load, new cracks were formed in the flexure region and the existing cracks were also propagated towards the middle of the beam. It was also 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 crushing of concrete at the compression face are presented (figure 4). 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 strengthened PSC beam specimens failed by FRP debonding (figure 5) and rupture of CSMGFRP laminates were observed in UBPTC3 and UBPTU3.

Figure-4
Failure of UBPTR Specimen

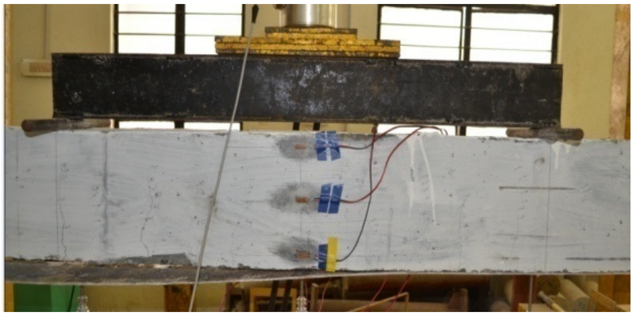

Figure-5
Failure of UBPTU5 Specimen

Conclusion

The experimental results revealed that the 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 beam UBPTU5 showed an increase in ultimate load by 89% when compared to the control specimen. FRP strengthened post-tensioned beam specimens provided a maximum increase in ductility to a level of about 90%. It was observed from the study, on utilizing the externally bonded FRP plates on tension face increased the cracked post-yielding stiffness of the unbonded post-tensioned beams. The unbonded post-tensioned concrete beam specimen was failed by yielding of tension steel reinforcement followed by crushing of concrete. The failure of strengthened PSC beam specimens occurred by rupturing of FRP and by FRP debonding.

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