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Performance Of Reinforced Concrete Beams Externally Prestressed With Fiber Composites

Abhijit Mukherjee*, Gopal L. Rai
Department of Civil Engineering, Indian Institute of Technology Bombay,
Mumbai 400 076, India

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abstract
This paper presents the results of an experimental study to investigate the flexural behavior of reinforced concrete (RC) beams that have reached their ultimate bearing capacities and then retrofitted with externally prestressed carbon fiber reinforced composite (CFRC) laminates. The effect of variation in prestressing force on CFRC laminates bonded to the RC beam is investigated in terms of the flexural strength, deflections, cracking behavior and failure modes. The results indicate that rehabilitation of significantly cracked beams by bonding CFRC laminates is structurally efficient.

Introduction
An increasing number of reinforced concrete structures are reaching the end of their service lives, either due to decoration of concrete and reinforcements caused by environmental factors or due increase in imposed loads, real or perceived. Renewal of these structures may not be feasible due to financial, spatial, emotional, logistic and technical constraints. Restoration of these structures is an attractive alternative; but may often lead to uncertain performance due to unproven techniques, materials, and design methods. Moreover, the restoration work can be extremely disturbing to the occupants of the structures. Recent development in the fiber reinforced composites (FRC) in rehabilitation of structures is being seriously investigated by the researchers as a sound and cost effective technique. In practice, on the other hand, FRCs are beginning to get a toehold in the construction industry, especially in the upgradation of existing structures [1–18].
The efficacy of FRCs in improving confinement of concrete and thus improving its performance

in extreme loading is well established [2]. FRCs have also been effective in augmenting the reinforcement in flexural members [3]. The seismic performance of RC frame structures can also be dramatically improved by externally bonding FRC at the beam-column joints [4]. The advantages of resistance to corrosion and higher specific strength make these materials ideal for reinforcing existing structures with minimum intrusion. The popular method adopted in such cases is adhesively bonding FRCs on concrete structures. However, the superior strength of FRCs can seldom be fully utilized due to poor capacities of the concrete and the interfaces.

Prestressing of concrete has been an effective method in exploiting its relatively higher compression capacity. Moreover, the permanent deformations in the structure can be recovered by prestressing. Although the technique is well established in new structures external prestressing of existing structures has always been difficult, especially in view of reinforcement corrosion, lateral instability, end anchorages and space restrictions. In this paper, we explore an external prestressing technology with FRCs that alleviates all these problems. The paper also addresses concerns such as substrate failure, edge peeling, stress relaxation and durability. Prior research on some aspects of prestressed FRCs is available. Triantafillou and Deskovic [5] determined the limiting prestress levels to avoid edge peeling and Triantafillou et al. [6,7] provided limited experimental verification of their analytical work. However, this limit can be exceeded if the concrete in the edge zone is reinforced in tension. It was concluded that FRC prestressed concrete members exhibit excellent strength, stiffness and ductility characteristics, provided the external reinforcement is adequately anchored at its ends. Sadaatmanesh and Ehsani [8] prestressed RC beams by cambering them with hydraulic jacks whilst the composite plate was bonded and cured. The authors reported that that this resulted in improved cracking behavior. El-Hacha et al. [9] strengthened precracked RC beams with CFRC sheets and investigated the effect of temperature on them. He concluded that beams strengthened at low temperature failed at higher loads than those at room temperature. Quantrill and Hollaway [10,11] studied flexural strengthening of reinforced concrete beams externally prestressed with CFRC laminates using a mechanical anchorage system. The key issues on this topic are – safe levels of prestress, anchorage system, application methods, durability and modeling and design methods. In this paper, we address some of these issues. Reinforced concrete beams that have been loaded to failure have been restored with CFRC laminates that are prestressed at different levels.

A method of anchorage of the laminates has been investigated. An experimental program on long term performance of the prestressed beams has been described and intermediate results have been reported.

* Corresponding author.
E-mail address: abhijit@civil.iitb.ac.in (A. Mukherjee).
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2. Material characterization

Properties of the materials used in the experimentation are enlisted in this section.

2.1. Concrete

Concrete mix was prepared using Portland cement blended with fly ash. Properties of cement and concrete are shown in Tables 1 and 2 respectively.

2.2. Steel reinforcement

Longitudinal reinforcement of beams is of high yield strength deformed steel bars and shear links are of mild steel. Properties of reinforcing steel are in Table 3.

2.3. FRC materials

Composite materials used for the study is commercially available world over. Two types of CFRC sheets and laminates have been used (Fig. 1). The laminates have been prestressed and used in the longitudinal direction of the beams. The sheets have been used in the ends to protect the edges. Tables 4 and 5 detail the test results of the CFRC laminates and sheets respectively.

2.4. Adhesives

The adhesive used for the all the experiments is a compatible epoxy system recommended by the manufacturer.
It has two components, A – resin and B – hardener. Ratio of the components by weight is 100 parts of component A to 23 parts of component B.
Mixing is done thoroughly for 5 min with low speed mixer at 400 rpm until components are thoroughly dispersed.
Properties of adhesive are given in Table 6.

Table 1 : Physical properties of cement

Physical properties	Value
Fineness (m2/kg)	374
Setting time	
(a) Initial setting time	180 min
(b) Final setting time	270 min
Compressive strength (N/mm2)	
(a) 3 days	33
(b) 7 days	44
(c) 28 days	56
Percentage of fly ash in cement	24

Table 2 : Properties of concrete

Physical properties	Value
Twenty eight days compressive strength (N/mm2)	32
Modulus of elasticity (N/mm2)	21,220
Slump (mm)	56

Table 3 : Properties of steel reinforcement

Reinforcement type	Modulus of elasticity (ES)	Characteristic strength (Fy) (N/mm2)
Longitudinal tor bars	2 x 105	515
Mild steel shear links	2 x 105	250

Table 4 : Properties of CFRC laminate

Items	Test results
Width (mm)	50.8
Thickness (mm)	1.4
Ultimate tensile strength (GPa)	2.51
Percentage elongation at break	1.8
Tensile modulus (GPa)	155

Table 5 : Properties of CFRC wrap

Items	Test results
Mass per square meter (g/m2)	644
Ultimate tensile strength (MPa)	876
Tensile modulus (GPa)	72.46
Percentage elongation at break	1.2

Table 6 : Properties of epoxy

Items	Test results
Tensile strength (MPa)	21.4
Tensile strain failure (%)	5
Flexural modulus (MPa)	1690
Flexural strength (MPa)	40.7
Glass transition temperature (C)	80

3. Specimen preparation

Beam of length 1.8 m and cross section 90 180 mm is used. Detailed dimensions and reinforcements are shown in given Fig. 2.

3.1. Test method

The test method consists of four phases – Fresh beam failure test, rehabilitation, design load test and ultimate load test. We describe each phase sequentially.

(a) Laminate (b) Wrap

Fig. 1. CFRC materials used in the experiment

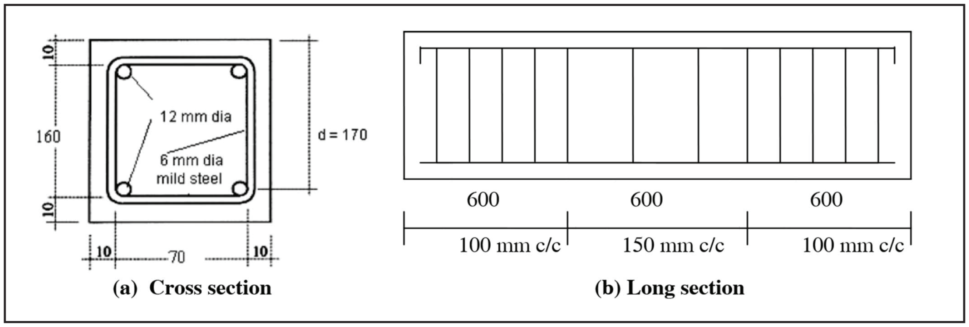


Fig. 2. Details of Beam Specimens.

3.1.1. Fresh beam tests

All the reinforced concrete (RC) beam specimens have been loaded in a four point bend test setup (Fig. 3). This test has been carried out on the RC beams prior to the application of any FRC. The set up ensures pure bending in the central third portion of the beam. The beams have been loaded with equal force on the two load points until the beams deformed did not take any further load. A deflection controlled experiment was carried out and the load rate was kept slow at 0.5 mm/s. The deflection of the beam was monitored with linear variable diode transducers (LVDT). It may be noted that the beam sections were under-reinforced. Therefore, steel had yielded in all the specimens. The damage in the beams started with bending cracks in the central region of the beam. At higher load levels the shear and shear-bending cracks at the end sections had initiated. At still higher levels of deformation the cracks coalesced with a rapid loss of stiffness. The loading was discontinued when the load deflection curve was flat and no increase load was observed due to the increase in deflection. After unloading the permanent deformations in al the specimens have been recorded. (Fig. 4) shows a typical load–deflection curve for the specimens. The curves were similar for all the samples.

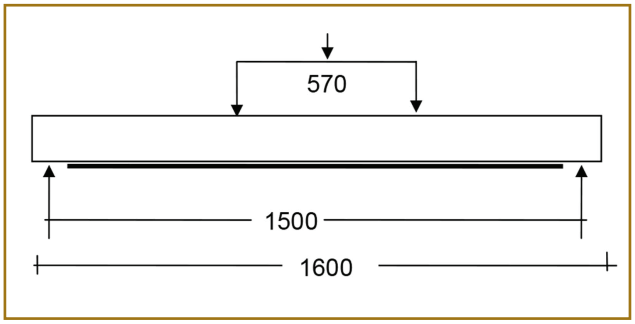


Fig. 3. Four point bend setup.

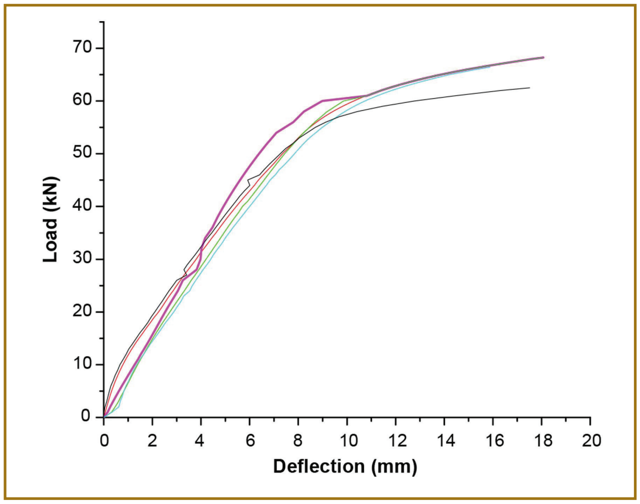


Fig. 4. Load deflection curves for fresh specimens.

3.1.2. Rehabilitation

The RC beams that were damaged in the previous phase were taken up for repairs using the prestressed FRC. It may be noted that the fresh beams had failed due to the yielding of tension steel. The aim of the rehabilitation is to augment the tension reinforcement to a level so that the tension failure of the reinforcement is avoided. CFRC laminates have been applied on the tension face of the beam. As a result, the failure would shift to the compression region. The resulting increase in the load capacity of the beam would also enhance the shear forces. The rehabilitation aims at augmenting the shear capacity of the beam by applying a CFRC wrap in the shear critical zone. The wrap would also anchor the laminates to prevent their delamination to augmentation of strength. In addition the permanent deformation in the beams after the first test was reverted by applying prestress on the laminates. The main parameter in this experiment is the level of prestress. The level of prestress was decided based on the capacities of the prestressing facilities and the strength of the beams. Prestressing force is calibrated in terms of the percentage of axial capacity of laminate (Table 7). The force is also calibrated against the tensile force generated in the steel reinforcements when the fresh RC beam reaches its ultimate bending moment. It may be noted that a substantial ratio of the force that the steel reinforcements had reached during the initial loading has been applied by prestressing. Therefore, we expect a substantial recovery of the permanent deformation in the beams. The details have been discussed later in the paper.

3.1.3. Method of rehabilitation

After the first phase of the test the concrete beams have been rehabilitated with prestressed CFRC. The following procedure has been adopted.

3.1.3.1. Surface preparation.

The concrete surface is prepared for bonding with composite material. The bottom surface of beam is ground with a paper grinder to remove laitance. The aggregates are exposed for better adhesion. The corners of beam are rounded with a radius of 15 mm, to avoid stress concentration in the wrap. The surface dust has been removed by means of an air blower is. Finally, surface is cleaned with acetone.

Table 7 : Test matrix

Notation	Percentage of axial capacity of laminates	Percentage of flexural capacity of beams
RB-0	0	0
RB-5	5	15
RB-10	10	30
RB-15	15	45
RB-20	20	60

3.1.3.2. Prestressing.

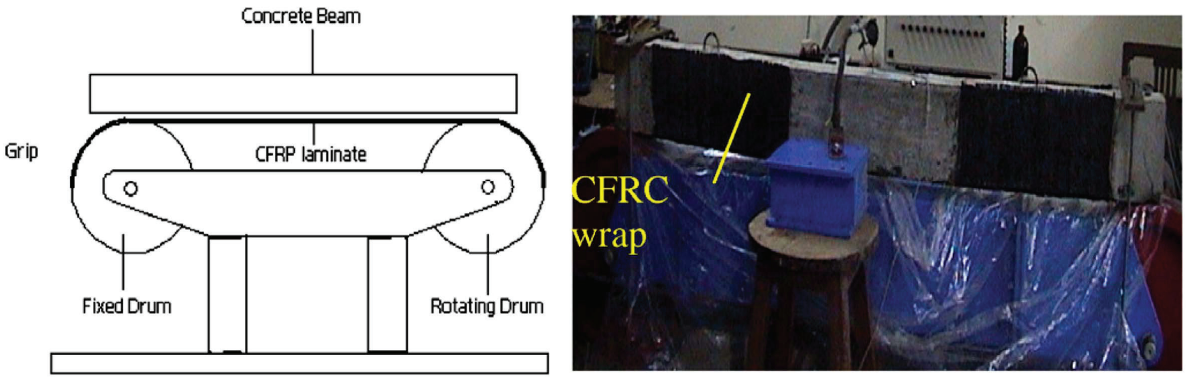
Prestressing of the CFRC laminate is done by using a machine specially designed for this purpose (Fig. 5). A strain gauge was attached at the center of the CFRC laminate to measure the longitudinal strain. The laminate was mounted on the two drums of the prestressing machine and secured at the ends to prevent slippage of the laminate. The surface of the laminate is cleaned and the adhesive is uniformly spread on the top surface of the laminate and the bottom surface of the beam. The beam is then kept over the laminate. The ends of the beam are held down by steel bracket before applying force to the laminate. This is necessary since the beam bottom is not straight due to permanent deformations. The laminate is pulled to the desired tensile force by operating the machine. The strain in the laminate is monitored by the strain gauge. The force is measured by correlating load v/s strain curve for the CFRC as well by the load cell mounted under the screw jack.

To avoid peeling off of CFRC laminates, the ends of the laminates are secured by means of a wrap of CFRC sheet (Fig. 5b). 350 mm wide unidirectional CFRC wraps are used at both ends of the beams. The fibers of the wraps are aligned 90 degrees to the longitudinal axis of the beam. The bottom corners of the beams at the portion of the wrap were rounded to a radius of 15 mm to avoid large concentration of stress.

The set up is left for 6 days for curing of epoxy. On the sixth day, the laminate is slowly released by operating the screw jack to transfer the load in laminate to the RCC beam. The upward deflection of the beam during tensioning of the laminate as well as during transfer of prestress is monitored.

3.1.4. Design load and ultimate load tests

The rehabilitated beams are tested in the same manner as described in Fig. 3. A 1 MN capacity UTM was used for the tests. The laminates and the wraps terminated about 50 mm away from the support to ensure that no artificial anchorage of the laminate takes place due the support reactions. The test had two phases. They are first subjected to a load level that is in the vicinity of their numerically predicted as the ultimate loads (100 kN). The beams were unloaded from that level to observe their permanent deformation. The beams were then reloaded up to failure. They were instrumented with a strain gauge and a LVDT at the center.



(a) Schematic diagram (b) Prestressing in progress

Fig. 5. Prestressing machine.

3.1.5. Failure modes

All the rehabilitated beams sustained up to 100 kN load without any sign of damage. Therefore, in the first phase of the tests there was no visible cracking at this stage. Cracks started appearing in the second phase of the test when the load levels exceeded 100 kN.

The failure modes are illustrated in Fig. 6. Shear cracks at 45 angle with the beam axis appeared first in the region between the ends of the wraps and the loading point (Fig. 6a). Therefore, due to rehabilitation the bending capacity of the beams was fully utilized. At later stages of loading some of the cracks in this region had steeper angles manifesting shear-bending interaction. These cracks met at about mid-height of the beam and formed triangular wedges. The cracks continued towards the top of the beam; they gradually bent and became nearly horizontal towards the top of the beam (Fig. 6b). It manifests tension failure of concrete at the load point due to Poisson's effect. However, this failure did not lead to a sudden loss of stiffness, as commonly expected due to the compression failure of concrete.

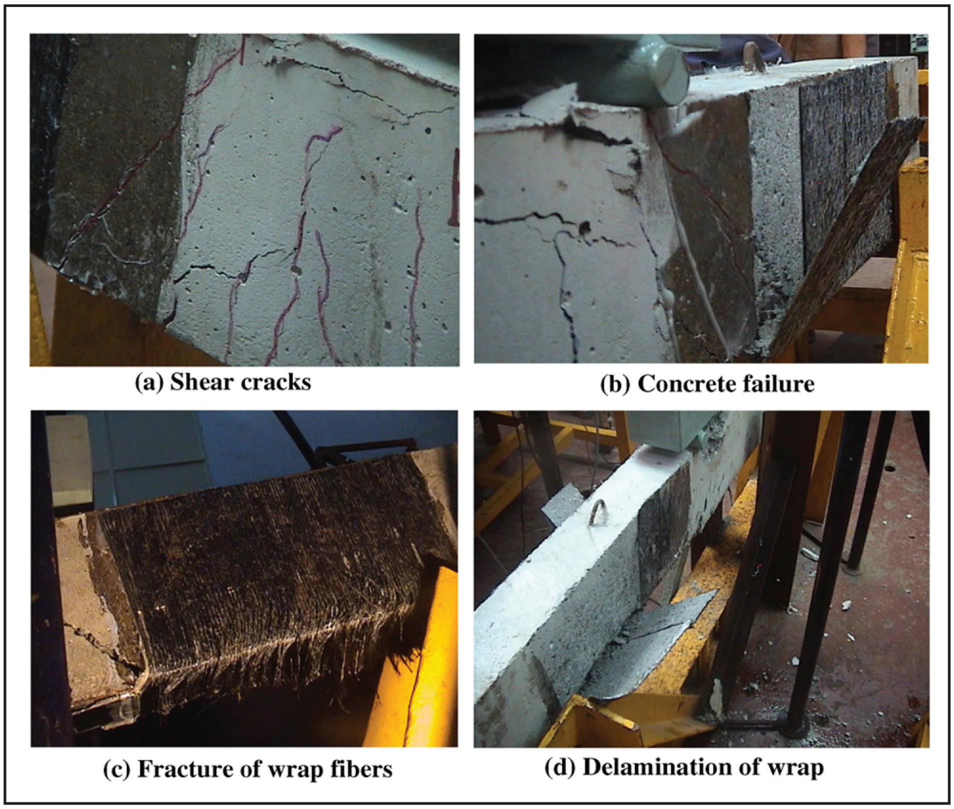
At higher deformations the failure reached the rehabilitated region. The failure in this region initiated in two ways – (i) wrap fracture at the beam bottom (Fig. 6c), (ii) delamination at the beam sides (Fig. 6d). In type (i) failure clearly the tension in the prestressed laminate is causing deformation in the CFRC sheet at the perpendicular direction of the fiber. It also indicates debonding between the laminate and concrete. The prestressing is also released when the bond length was insufficient to transfer the prestressing force to concrete. The bond slip also causes tension between the CFRC sheet and concrete at the side faces (type (ii)). The peeling of the sheet from concrete of this region takes place when the tensile force exceeds the capacity of concrete. There was a thin layer of concrete on the sheets bearing the testimony of tension failure of concrete rather than that of the adhesive. Finally, the beam did not bear any additional load and at this point the experiment was terminated. Fig. 7 shows the shape of the beam at failure. It is clear that the beam had undergone substantial deformation before failure. We shall analyze the performance of the rehabilitated beams in the next section.

4. Result and discussion

The load–central deflection curves of the beam at all the different phases of test have been plotted in Fig. 8. The fresh beam has been loaded until failure; the beam is unloaded. The permanent deformation is measured. The beam is rehabilitated. The rehabilitation includes prestressing. The rehabilitated beam has been loaded up to the design load and unloaded. The permanent deformation in the beam is measured once again. The beam has been loaded once again to take it to the ultimate load.

The following observations are made:

- The fresh beam exhibited permanent deformation.
- Prestressing resulted in recovery of the permanent deformation.
- The rehabilitated beam exceeded the capacity of the fresh beam by a large margin.
- There was little permanent deformation in the rehabilitated beam even at estimated capacity load.
- The stiffness of the rehabilitated beam was close to that of the fresh beam.
- The stiffness did not degrade due to the loading up to the design load.
- The maximum load was reached at a deflection beyond the maximum deflection of the fresh beam.
- The rehabilitated beam had a deflection at failure that was much higher than that in the fresh beam.
- The area under the curve is a measure of the energy dissipation capacity of the beam. It was observed that the rehabilitated beam had much higher area than the fresh beam.



(a) Shear cracks (b) Concrete failure

(c) Fracture of wrap fibers (d) Delamination of wrap

Fig. 6. ***Failure sequence.***

Fig. 7. ***Beam at failure.***

4.1. Level of prestress

The load–central deflection graph of the beams with different levels of prestress has been plotted in Fig. 9. It can be seen that:

- The recovery at prestressing is proportional to the level of prestress.
- For higher prestressing forces the recovery has been more than the permanent deformation resulting in bending in the opposite direction.
- The maximum load has gone up marginally with the increase in prestressing force.
- The deflection at failure is nearly the same for all the beam samples.
- Level of prestress had no significant effect on the stiffness of the rehabilitated beams.
- The higher recovery of permanent deformation due to prestressing has increased the area under the curve with the increase in the level of prestress.
- In P15 and P20 we observe a roughness at the time of unloading after the design load was reached. This may be due to the local bond slip between concrete and FRC and the resulting friction between the two surfaces. This did not have any significant effect on the ultimate load behavior of the specimens.

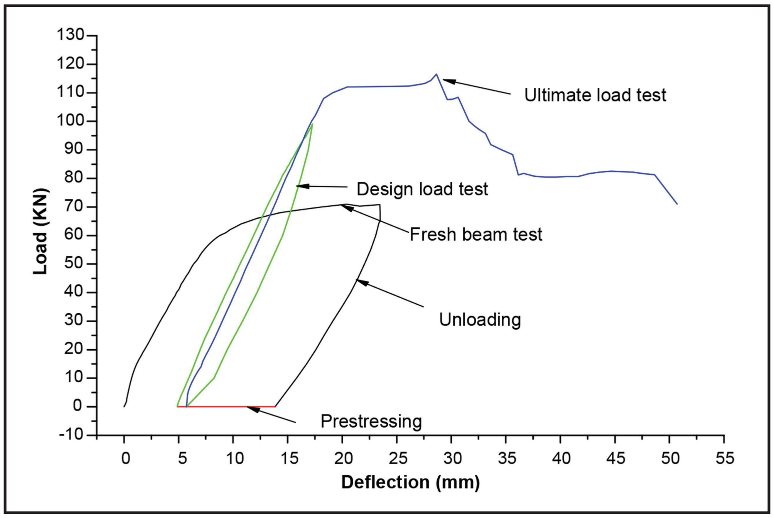


Fig. 8. ***Load–deflection curve for different phases of test.***

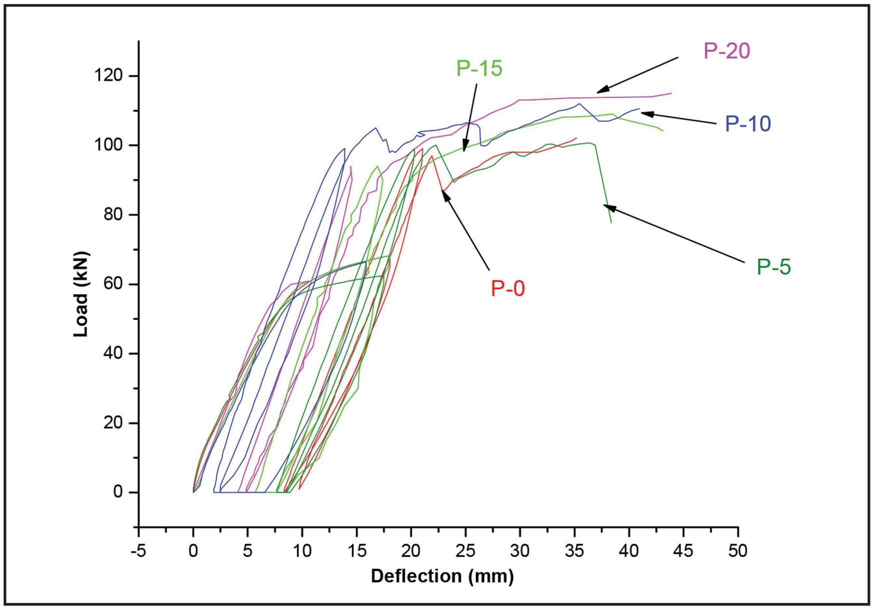


Fig. 9. ***Beams at different levels of prestress.***

Table 8 presents the relative performance of different samples. It may be noted that the fresh beams had very consistent behavior. The highest variation in the maximum load was within 5% and the final deflection in the beams varied within 10%. The residual deflection after the removal of load is also within 10%. Thus, it can be concluded that the samples were within the permissible levels of variation and the performance of the rehabilitated samples can now be compared.

The performance of the rehabilitated samples is presented in Table 9. In the design load tests all the samples have been loaded to a predetermined level. It is seen that the maximum displacement has reduced with the increase in the level of prestressing. The residual displacement after the removal of the design load has also reduced with the increase in the prestressing force. In the next phase, the specimens were loaded up to failure. It is observed that there was no significant effect of the level of prestress on the maximum load sustained by the beams. Maximum deflection generally increased with the level of prestress. However, the trend was not very consistent. The deflection at failure is heavily dependent on the failure pattern. Therefore, it can be concluded that prestressing has no significant effect on the failure loads and displacements. However, it improves the prefailure behavior of the beam significantly. The deflection at the design load was significantly lower when the prestressing forces are high. The higher prestressing force also leads to better recovery from deformation at unloading.

Finally, we compare the areas under the load–deflection curves for all the samples. It is a measure of the capability of the beam to absorb energy before collapse. It is clear that the area under the curve increased with corresponding increase in the prestressing force. This is a very significant advantage of prestressing.

Table 8 : Performance of the samples				
Beam	Fresh beam		Residual deflection (mm)	% Recovery
	Max load (kN)	Max deflection (mm)		
RB-0	68.25 1	8.07	8.345	0
RB-5	62.50	17.51	8.885	13.33
RB-10	66.45	15.875	7.52	40.10
RB-15	68.25	18.075	8.5	37.10
RB-20	68.25	18.00	8.35	51.5

Table 9
Samples in design load and ultimate load tests

Beam	Design load			Ultimate load		
	Max load (kN)	Deflection (mm)		Max load (kN)	Max deflection (mm)	Area under curve (kN m)
		Maximum	Residual			
RB-0	90.00	21.045	9.705	102.13	35.177	270.3
RB-5	99.00	20.285	8.49	100.07	40.38	306
RB-10	99.50	13.913	2.47	105.08	46.97	376
RB-15	94.00	12.021	7.6205	108.11	33.94	382.88
RB-20	94.00	9.756	4.802	115.03	43.881	424.058

5. Performance of rehabilitated beams

The main objectives of the rehabilitation were (i) to increase capacity of the beams (ii) avoid tensile and shear failure; (iii) to recover permanent deformations after the first test. All these objectives were achieved in the present rehabilitation. Both the design and ultimate loads increased by more than 100%. The cracking was distributed all over the beam resulting in considerable postyield deformation of the beam. An oft found argument against FRC repairs is the apprehension of loss of ductility. This experiment demonstrates the ability of prestressed FRC beams' to deform plastically.

6. Field applications

Prestressed FRC rehabilitation is a very attractive proposition for RC buildings and bridges alike. The methodology of prestressing described here is suitable for laboratory experiments. The present facility can prestress beams of up to 3 m span both in the lab and at site. Large girders and beams can be rehabilitated using the same methodology. However, they would require a different setup for prestressing. Although the setup is available with the authors its description is beyond the scope of the present paper.

7. Concluding remarks

An experimental investigation on the rehabilitation of RC beams with prestressed carbon FRC sheets is reported. RC beams were loaded until failure and then rehabilitated with externally bonded CFRC laminates. The ends were protected from peeling by a layer of CFRC sheet wrap. It is noticed that the flexure performance of the rehabilitated beams were far superior to that of the fresh RC beams. The beams had higher failure loads and lower deflections. They remained in the elastic zone for a much higher applied load. The recovery from the deformation increased with the increase in the prestressing force. As a result, the area under the load–deflection curve was much higher for the highly prestressed beams. However, the ultimate load and the maximum deflection did not go up significantly with higher levels prestress. To design a rehabilitation one must decide the amount of CFRC based on the requirement of the ultimate capacities. By prestressing one would be able to achieve a linear load–deflection curve for higher levels of loading. Thus, the operating levels of the beam can be extended by prestressing. Our present research focuses on a numerical model that captures the phenomenon.

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References

[1] Mukherjee A, Joshi MV. Seismic retrofitting using fiber composites. Indian Concrete J 2002;76(8): 496–502.

[2] Mukherjee A, Bakis CE, Boothby TE, Maitra SR, Joshi MV. Mechanical behavior of FRP wrapped concrete – complicating effects. ASCE J Compos Constr 2004;8(2):97–103.

[3] Ramana VPV, Kant T, Morton SE, Dutta PK, Mukherjee A, Desai YM. Behavior of CFRPC strengthened reinforced concrete beams with varying degrees of strengthening. Compos Part B 2000;31:461–70.

[4] Mukherjee A, Joshi M. FRPC reinforced concrete beam–column joints under cyclic excitation. Compos Struct 2005;70(2):185–99.

[5] Triantafillou TC, Deskovic N. Innovative prestressing with FRP sheets: mechanics of short-term deflection. J Eng Mech 1991;117(7):1653–73.

[6] Triantafillou TC, Deskovic N, Deuring M. Strengthening of concrete structures with prestressed fiber reinforced plastic sheets. ACI Struct J 1992;89(3):235–44.

[7] Triantafillou T, Pelvis N. Flexural behavior of structures strengthened with epoxy-bonded FRPs. In: International seminar on structural repairs/ strengthening of the plate bonding technique. England: University of Sheffield; 1990. p. 411–9.

[8] Sadaatmanesh H, Ehsani MR. RC beams strengthened with GFRP plates. I – experimental study. J Struct Eng ASCE 1991;117(11):3417–33.

[9] El-Hacha R, Wight RG, Green MF. Prestressed carbon fiber reinforced polymer sheets for strengthening concrete beams at room and low temperatures. J Compos Constr 2004;8(1):3–13.

[10] Quantrill RJ, Hollaway LC. The flexural rehabilitation of reinforced concrete beams by the use of prestressed advanced composite plates. Compos Sci Technol 1998;58:1259–75.

[11] Garden HN, Hollaway LC. An experimental study of the failure modes of reinforced concrete beams strengthened with prestressed carbon composite plates. Compos Part B 1998;29B:411–24.

[12] Joshi M. Fiber reinforced composites for rehabilitation of concrete structures, Ph.D thesis, IIT Bombay; 2004.

References

[13] Lees JM, Winistorfer AU, Meier U. External prestressed CFRC straps for shear enhancement of concrete. J Compos Constr 2002;6(4):249–56.

[14] Pelvis N, Triantafillou TC, Veneziano D. Reliability of RC structures strengthened with CFRP laminates. J Struct Eng ASCE 1995;12(7):1037–44.

[15] Shahawy MA, Beitelman T. Experimental investigation on structural repair and strengthening of damaged prestressed concrete slabs utilizing externally bonded carbon laminates. Compos Part B 1996;27B:217–24.

[16] Shahrooz BM, Boy S, Baseheart TM. Flexural strengthening of four 76 years old T-beams with various fiber reinforced polymer systems: testing and analysis. ACI Struct J 2002;99(5):681–91.

[17] Sheikh SA, De Rose D, Mardukhi J. Retrofitting of concrete structures for shear and flexure with FRP. ACI Struct J 2002;99(4):451–9.

[18] Stoll F, Saliba JE, Casper LE. Experimental study of CFRP-prestressed high strength concrete bridge beams. Compos Struct 2000;49:191–200.