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CYCLIC RESPONSE OF PRESTRESSED CONCRETE BEAMS RETROFITTED WITH PRECURED FIBRE REINFORCED POLYMER COMPOSITES

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ABSTRACT

The study herein presents the investigation on the cyclic response of post-tensioned prestressed concrete beam retrofitted with precured fibre reinforced polymer plates with different orientations and thicknesses. The load carrying capacity and deformation capacity of the precured glass fibre reinforced polymer plates were evaluated. The experimental results revealed that the prestressed concrete beams retrofitted with unidirectional glass fibre reinforced polymer plates attained a maximum increase in ultimate load. The stiffness has greatly reduced in post-tensioned prestressed concrete beam as the load progresses till the failure of beams. The retrofitted prestressed concrete beam sustained more number of cycles than the control prestressed concrete beam. The prestressed concrete beams retrofitted with fibre reinforced polymer showed a delamination and rupture of glass fibres.

Keywords: Cyclic response; fibre reinforced polymer; orientation; prestressed concrete beam; post-tensioned; precured.

1. INTRODUCTION

Post-tensioning system is found to be an advanced technology that provides the structure more efficient, economic and elegant structural solutions for a wide range of applications. Due to vehicular repeated loading on bridges, overloading on structural members etc., are subjected to varying loadings which causes damages to structural members. This tends to decrease the load carrying capacity and stiffness of the structural members. Hence it is required to strengthen and restore to meet these load demands. The traditional strengthening such as plate bonding [1] and repair techniques could eventually lead to a very serious consequence in terms of increase in maintenance cost and difficulties with handling and installation. Hence, there is a growing need for more economical and efficient retrofitting techniques. Fibre reinforced polymer (FRP) has recently come into play due to its

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remarkable advantages include high strength-weight ratio, high stiffness-weight ratio and good corrosion resistance. It successfully adopted for flexural strengthening of beams [2,3] and axial strengthening of columns [4,5,6] and corrosion damaged beams and columns [9]. Several researchers have been carried out in the past to observe the flexural and cyclic behaviour of beams. Suraj parkash et al. [8] investigated on prestressed concrete beams under fatigue loading, the author is focused on simulation of traffic live load on beam element and were subjected to cyclic loading. Du et al. [9] conducted a study on ductility analysis of prestressed concrete beams with unbonded tendons. The results showed that the curvature ductility factor of prestressed concrete members with unbonded tendons decreased with the increase of combined reinforcement index (CRI). The curvature ductility factors for members with bonded and unbonded tendons for given values of CRI were also analyzed and compared. Cha [10] carried out an experimental and analytical study of prestressed concrete beams strengthened with carbon fibre composites. The results indicated that prestressed concrete beams could be effectively strengthened using carbon fibre composites. CFRP strengthened prestressed beams increased the load carrying capacity of 79% and 86% respectively for normal and high strength concrete beams. Reed et al. [11] investigated on the evaluation of prestressed concrete girders strengthened with carbon fibre reinforced polymer sheets. The test results showed that two layers of longitudinal CFRP sheets increased the flexural capacity of the strengthened specimens by 20% compared to an unstrengthened control specimen. Meski et al. [12] investigated on the flexural behavior of unbonded post tensioned concrete members strengthened using external FRP composites. It was found that the use of FRP laminates increased the load capacity and post-cracking stiffness of unbonded members. The increase in load capacity varied between a minimum of 24% and a maximum of 105%. It has been observed from an extensive literature survey that not much work has been done on the cyclic behavior of prestressed concrete beams retrofitted with precured glass fibre reinforced polymer plates with different orientations and thicknesses.

2. EXPERIMENTAL STUDY

In this research study, totally seven post-tensioned prestressed concrete beam were investigated under compression cyclic loading. This section presents the materials and its properties, preparation of beam specimen and testing of PSC beam specimen under cyclic load.

2.1 Material properties

The concrete made with a mixture of cement, fine and coarse aggregate. In the present study, ordinary Portland cement of 53 grade was used. As per IS 4031 (Part 11): 1980[13], the specific gravity of cement found to be 3.15. As per IS 4031 (Part 1): 1996[14], the fineness of the cement found to be 8%. The standard consistency of cement was determined by Vicat's apparatus as per IS 4031 (Part 4): 1988 [15] and found to be 28%. As per IS 4031 (Part 5): 1988 [16], the initial and final setting time was found to be 45 minutes and 540 minutes. As per IS 4031 (Part 6): 1988 [17], average of the compressive strength of cement mortar at the age of 28 days was found as 52.38 MPa. Locally available natural river sand was used as fine aggregate. The specific gravity of 2.65 was obtained as per IS 2386 (Part 3):1963 [18]. As per IS 383:1970 [19], the particle size below 4.75 mm conforming to zone II was found. The water absorption was found to be 8%. As per IS 2386 - 1963 (Part 3) [18], crushed granite stone was used as coarse aggregate. The maximum size of coarse aggregate adopted in the study was 12 mm and 10 mm, with a specific gravity of 2.68 and water absorption was found to be 1.2%. Potable water was used for the concrete mix recommended as per IS 456:2000 [20]. In accordance with IS 10262: 2009 [21], a trial mix was designed for M 35 grade of concrete with water to cement ratio of 0.40. The mix proportion of concrete was 1: 1.6: 2.64. To measure the workability of concrete, slump test [22] was performed and found to be 58 mm. The average cubic compressive strength of concrete [23] at the age of 28 days was 42 N/mm^2.

The high yield strength deformed (HYSD) steel reinforcement bars of 10 mm and 12 mm diameter were used in the study. The yield strength of HYSD was tested as per IS 1786 (2008) [24] and it was found to be 435 N/mm^2. High tensile steel (HTS) wire of 7 mm diameter was used in the study. As per IS 1785 (part 1) 1983 [25], the ultimate tensile strength of the wire was found to be 1532 N/mm^2, percentage of elongation after fracture was 4.0 and the breaking load was 59.1 kN.

PSC beams were retrofitted with precured glass fibre reinforced polymer (GFRP) plates of 3 mm and 5 mm thickness with different types of orientations of glass fibres. Randomy distributed chopped glass fibres (chopped strand mat - CSM), unidirectional (UD) glass fibres where the 95% of fibres arranged in single direction, bidirectional glass fibres where glass fibres are aligned in two perpendicular directions (woven roving – WR). As per ASTM D 638 [26], the properties of GFRP were tested and shown in Table 1. Iso-phthalic polyester resin formed the part of the GFRP system.

Table 1: Properties of FRP

Orientation of FRP	Thickness (mm)	Elasticity Modulus (MPa)	Ultimate Elongation (%)	Tensile Strength (MPa)
Random orientation - CSM	3	7467.46	1.60	126.20
	5	11386.86	1.37	156.00
Bidirectional -WR	3	6855.81	2.15	147.40
	5	8994.44	1.98	178.09
Unidirectional -UD	3	13965.63	3.02	446.9
	5	17365.38	2.60	451.5

2.2 Details of PSC beam specimens

A rectangular beam of 150 mm wide and 250 mm deep with an overall span length of 2500 mm was used. Two numbers of 12 mm and 10 mm diameter HYSD steel reinforcements were provided respectively at the tension and compression face of the PSC beam. Two numbers of 7 mm diameter HTS wire were provided as a straight profile with an eccentricity of 50 mm below the centroidal axis of the beam. The schematic view of cross - sectional details of PSC beam specimens are shown in Fig. 1. Two legged stirrups of 8 mm diameter at a spacing of 150 mm c/c were provided as shear reinforcement in PSC beam specimens. In the study, totally seven post-tensioned prestressed concrete beam were investigated. One PSC beam was considered as control beam. Remaining six beams were retrofitted with precured FRP plates of 3 mm and 5 mm thicknesses with different orientations and presented in Table 2.

Table 2: Description of PSC beam

Beam ID	Orientation of FRP	Thickness of FRP (mm)	Description of PSC beam
CB	--	-	Control beam
CBC1	CSM	3	PSC beam strengthened with CSM FRP of 3 mm thickness
CBC2		5	PSC beam strengthened with CSM FRP of 5 mm thickness
CBW1	WR	3	PSC beam strengthened with WR FRP of 3 mm thickness
CBW2		5	PSC beam strengthened with WR FRP of 5 mm thickness
CBU1	UDC	3	PSC beam strengthened with UD FRP of 3 mm thickness
CBU2		5	PSC beam strengthened with UD FRP of 5 mm thickness

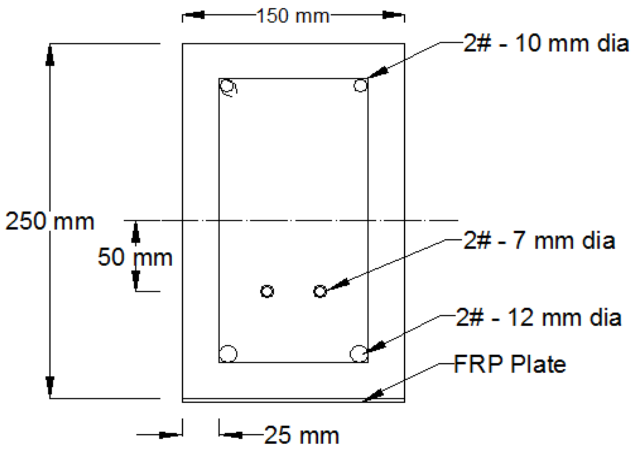

Figure 1. Cross-sectional details of beam

2.3 Prestressing and retrofitting of PSC beam specimens

The reinforcement cage was placed inside the wooden mould with sufficient effective cover. Concrete mix was poured inside the mould in layers and good compaction was attained by using electric internal vibrators as shown in Fig. 2. After sufficient hardening of concrete, the beam specimens were demoulded and curing was provided with jute bags for a period of 28 days.

Figure 2. Casting of PSC beam

Figure 3. Stressing of wire in beam specimen

After adequate curing and hardening of concrete over a period of 28 days, the beam specimens were set for stressing operation (Fig. 3). Steel plates of required dimension were act as bearing plates and fixed at both ends of beam. After fixing of steel bearing plates, wedges were inserted into HTS wire and anchored at one end of the beam. At the other end of the beam, the force was applied using wire jack to HTS of about 75% of the ultimate stress of HTS wire. During stressing of HTS wire, elongation of wire was measured and is shown in Table 3.

Table 3: Extension of strand with the increase of jack pressure

Gauge pressure of jack (kgf/cm^2)	Jack reading		Extension of HTS wires (mm) by increase of pressure		Total extension of strand (mm)	
	HTS Wire 1 (W1)	HTS Wire 2 (W2)	HTS Wire 1 (W1)	HTS Wire 2 (W2)	HTS Wire 1 (W1)	HTS Wire 2 (W2)
0	13	17	0	0	0	0
30	15	21	2	4	2	4
60	16	22	1	1	3	5
90	19	24	3	2	6	7
120	22	26	3	2	9	9
150	23	29	1	3	10	12
180	24	31	1	2	11	14
210	27	33	3	2	14	16
240	32	37	5	4	19	20

The gauge pressure of jack for HTS wires 1 and 2 were 32 mm and 37 mm. The jack reading after unloading the pressure for wires 1 and 2 were 29mm and 32 mm. Hence slip can be computed as gauge pressure jack for HTS wire 1 minus jack reading after unloading the pressure for HTS wire 1. The elongation of wire can be calculated as total extension of the HTS wire minus slip of the respective HTS wire. Therefore, slip for wire 1 and 2 were 3 mm and 5 mm respectively. The elongation of wires W1 and W2 was found to be 16 mm and 15 mm.

The precured FRP plates were used to retrofit the prestressed concrete beams. Prior to bonding of the FRP plates, the soffit of beams was cleaned well with a wire brush to remove the lose materials on the surface and well-grounded with a surface grinder for roughness. The surface was then blown free of dust using compressed air. After surface preparation, the adhesive components were mixed thoroughly and applied to the surfaces. The adhesive applied was profiled so that excess would be extruded from the centre onwards, thereby dispelling air. The thickness of the adhesive was maintained at 0.2 mm on the concrete surface prior to bonding. The FRP plate was placed over the beam which was arranged with its soffit facing upwards and then held in position by dead weights kept over the laminate. The process of retrofitting on PSC beams is depicted through Figs. 4 to 6. Complete curing took a period of 7-days at room temperature. The coin tap test was conducted to identify areas of debond, if any. The retrofitted beams were tested after an interval of 14-days.

Figure 4. Grinding the surface of PSC beam

Figure 5. Application of adhesives on PSC beam

Figure 6. Bonding precured FRP plate over the PSC beam

2.4 PSC beam test setup

The PSC beams were tested in a loading frame of 100 tonne capacity. The beam was simply supported over an effective span of 2000 mm. The PSC beams were tested under four - point bending system. The PSC beams were applied by the compression cyclic loading. The mid - span deflection of the beam was measured using linear variable displacement transducer (LVDT), placed at the bottom face of PSC beam. The load cell and LVDT were connected through a 20-channel data acquisition system where it acquired load and deflection. A visual inspection was made to observe cracks on PSC beams. The crack pattern and the crack growth at different stages of loading were marked on the beams. Fig. 7 shows the experimental test setup of PSC beam specimen.

Figure 7. PSC Beam Test Setup

3. RESULTS AND DISCUSSION

Table 4 presents the summary of test results of PSC beams under cyclic loading.

Table 4: Results of PSC beams under cyclic loading

Beam ID	Total no. of cycles	Ultimate Load (kN)	Ultimate Deflection (mm)	Stiffness kN/mm	Total Energy Absorption (kNmm)
CB	5	55	46	1.20	1452.50
CBC1	8	62.5	51	1.23	1986.38
CBC2	12	73.4	57	1.29	2517.45
CBW1	10	74.2	58	1.28	2704.60
CBW2	14	85.4	65	1.31	3484.00
CBU1	12	90.2	68	1.33	4048.20
CBU2	16	106.3	77.5	1.37	5375.33

3.1 Load - deflection response

The load - deflection response of control PSC beam specimen and FRP retrofitted PSC beam specimens under compression cyclic loading is presented through Figs. 8 to 14. In control beam the ultimate load of 55 kN was reached within 5 cycles of loading. In 3 mm and 5 mm thick GFRP plate strengthened beams, the ultimate load reached at 8 cycles for CBC1, 10 cycles for CBW1, 12 cycles for CBU1, 12 cycles for CBC2, 14 cycles for CBW2 and 16 cycles for CBU2. The stiffness of the beam gets reduced as the load progresses till the failure of beams.

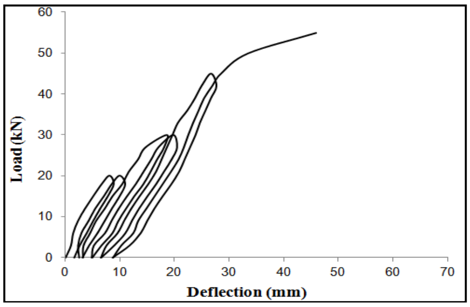

Figure 8. Load-Deflection for beam, CB

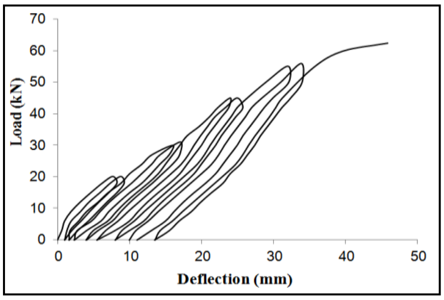

Figure 9. Load-Deflection for beam, CBC1

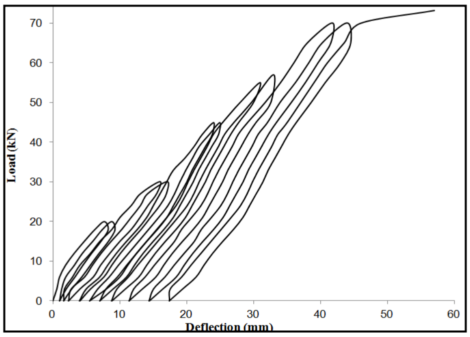

Figure 10. Load-Deflection for beam, CBW1

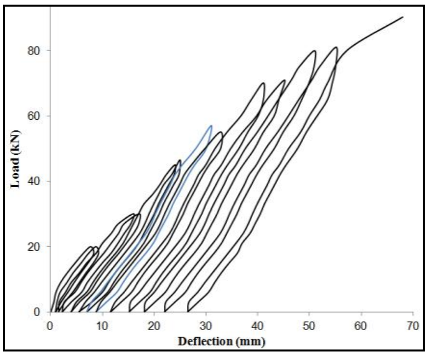

Figure 11. Load-Deflection for beam, CBU1

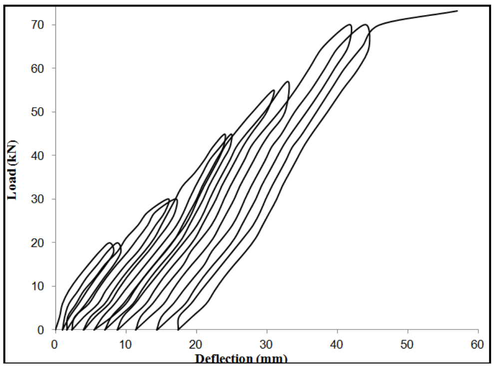

Figure 12. Load-Deflection for beam, CBC2

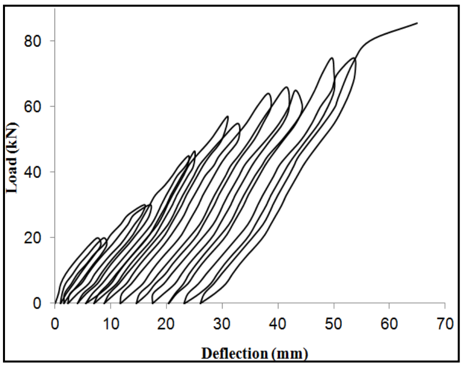

Figure 13. Load-Deflection for beam, CBW2

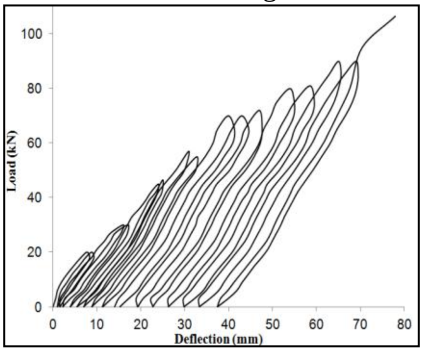

Figure 14. Load-Deflection for beam, CBU2

The load vs deflection behaviour of beams in loading-unloading-reloading stages pertaining to each load cycles was obtained in the form of loop curves as shown through Figs. 8 to 14. For each cycle of loading-unloading-reloading, the deflection increased while loading, then dropped to zero or minimum residual value while unloading and then attained a maximum value while reloading. All these individual load-deflection cycles are assembled from initial to ultimate stages of loading till failure to form the envelope curve of deflection under cyclic loading. It was observed that the deflection gradually increased at higher load levels till it reached the ultimate load at failure. The stiffness was greatly enhanced in PSC beams retrofitted with precured FRP plates. Also it was noticed that maximum of 16 number of cycles sustained for PSC retrofitted with unidirectional FRP precured plates than the other type of PSC beams.

3.2 Behaviour of PSC beams

In all the PSC beam specimens, the initial cracks were observed within the constant moment region. As the load increased, the cracks were formed in the flexure zone along with the propagation of existing initial cracks in PSC beam specimens. It was observed that the yielding of tension longitudinal steel reinforcement followed by crushing of concrete at the compression side of control PSC beam specimen, CB and is shown in Fig. 15. It was observed that the crack widths were smaller for externally bonded post-tensioned concrete beam specimens. The average crack width of 0.18 mm was observed in control PSC beam specimen. Average crack widths of 0.07 mm to 0.12 mm were noticed in PSC beam retrofitted with FRP plates. The failure of retrofitted PSC beam specimens occurred by rupture of FRP and delamination of FRP material and is presented through Figs. 16 to 20. The delamination and rupture of FRP laminates has observed after the load reached the ultimate stage.

Figure 15. Concrete crushing in control beam, CB

Figure 16. Delamination of FRP in CBC1

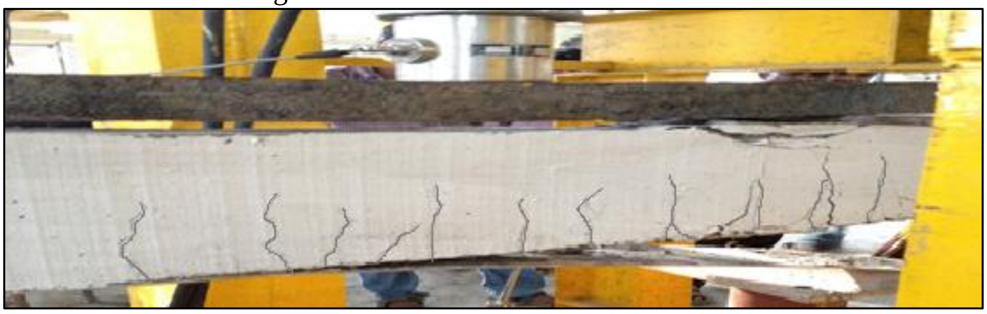

Figure 17. FRP rupture in CBW1

Figure 18. Flexural Cracking in CBU1

Figure 19. Rupturing of FRP in CBC2

Figure 20. Flexural cracking and Debonding of FRP from concrete substrate, CBW2

3.3 Effect of GFRP plates on ultimate load

Fig. 21 shows the effect of GFRP plates on ultimate load when compared to control specimens. It was observed that the CBC1 and CBC2 beam specimen exhibit increase in load carrying capacity by 13.6 and 33.45%. CBW1 and CBW2 beam specimens showed an increase in load carrying capacity by 34.9 and 54.27%. CBU1 and CBU2 specimens exhibit an increase in load carrying capacity by 64 and 93.27% respectively when compared with the control beam.

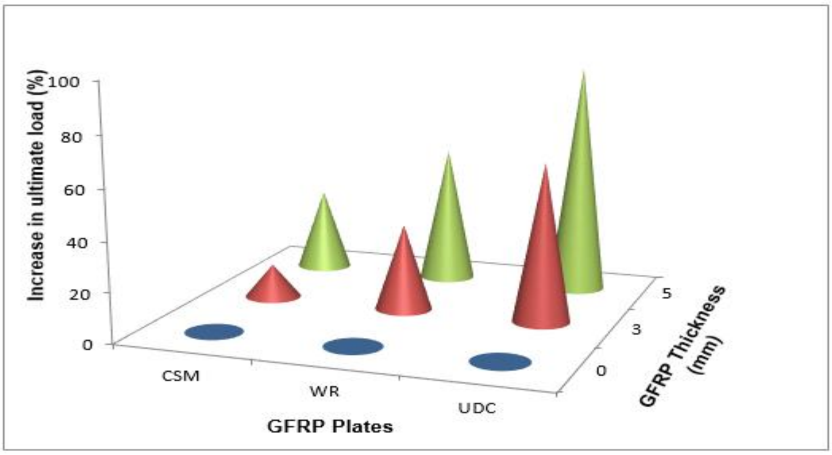

Figure 21. Effect of GFRP Plates on Ultimate Load

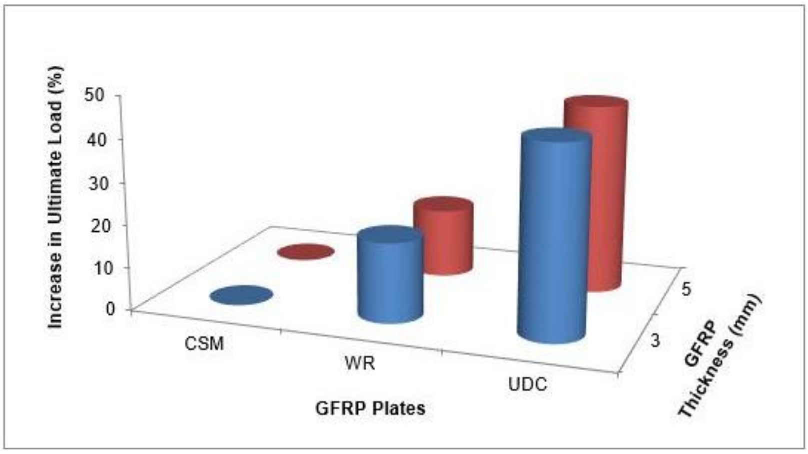

Figure 22. Effect of GFRP Orientation on Ultimate Load

Fig. 22 shows the effect of GFRP material on ultimate load, when compared with the CSM type of strengthened beams, CBW1 and CBW2 shows a significant increase of ultimate load by 18.72 % and 16.35 %. CBU1 and CBU2 exhibits an increase of 44.32 % and 44.82 % in ultimate load carrying capacity.

3.4 Effect of GFRP plates on deflection

Fig. 23 shows the effect of GFRP plates on ultimate deflection when compared to control specimens.

The 3mm and 5mm thick GFRP laminate strengthened PSC beams exhibited a higher resistance to deflection when it was examined for the ultimate load of the control beam. The variation of deflection for 3mm and 5mm thick GFRP laminate strengthened beams were observed and it shows that CBC1 and CBC2 beam exhibits an increase of 10.87% and 23.91% in ultimate deflection. Specimen CBW1 and CBW2 depict an increase in ultimate deflection by 26.09% and 41.3%. It was observed an increase of 47.83% and 68.48% in ultimate deflection for CBU1 and CBU2 beam specimens.

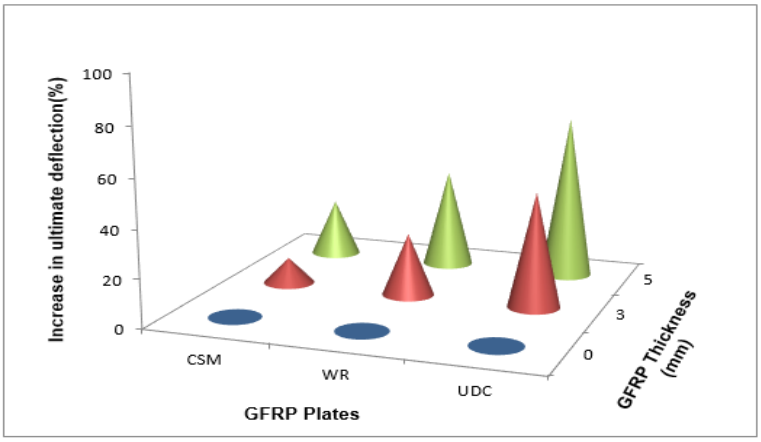

Figure 23. Effect of GFRP plates on deflection

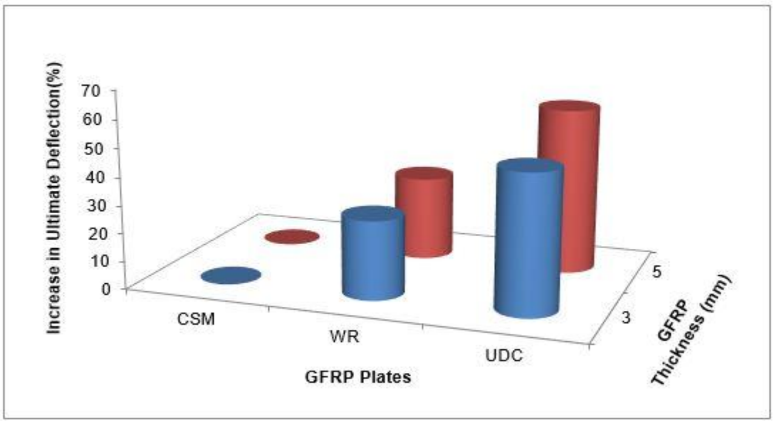

Figure 24. Effect of GFRP Orientation on Ultimate Deflection

Fig. 24 shows the effect of GFRP material on ultimate deflection, when compared within the different configuration of FRP with reference to CSM, CBW1 and CBU1 showed an increase of 13.73% and 14.04%. CBW2 and CBU2 exhibit an increase in ultimate deflection by 33.33% and 35.96% when compared with the CSM type of FRP configuration.

3.5 Energy absorption under cyclic loading

The energy absorption capacities for all the specimens under cyclic loading are presented in Table 4. The energy absorbed by the PSC beams when subjected to cyclic loading was computed from the area under the loop curve obtained as a result of load-deflection behaviour. The area under the individual loop curve pertaining to each cycle of loading were added cumulatively to arrive at the total energy absorbed by a beam in withstanding the effect of cyclic loading. From Table 4, it is clear that the PSC beams retrofitted with FRP enhanced the energy absorption capacity under cyclic loading. It is also observed that PSC beams retrofitted with unidirectional FRP of 3 mm and 5 mm thickness respectively showed a greater energy absorption capacity of about 170% and 270% than the other PSC beam specimen.

4. CONCLUSIONS

1. Prestressed concrete beams retrofitted with precured glass fibre reinforced polymer plates showed an increase in load carrying capacity, stiffness and energy absorption capacity under compression cyclic loading.
2. Prestressed concrete beams retrofitted with unidirectional type of orientation enhanced a maximum increase in ultimate load of 93.27% when compared with control beam.
3. The stiffness has greatly reduced in post-tensioned prestressed concrete beam as the load progresses till the failure of beams.
4. The maximum deflection for the retrofitted PSC beam specimens attributed in the range of 10% to 68.48% when compared to control beam under cyclic loading.

5. Prestressed concrete beams retrofitted with precured glass fibre reinforced polymer sustained more number of cycles when compared to control beam.
6. The strengthened PSC beams showed a considerable increase in energy absorption capacity when compared to control specimen under compression cyclic loading.
7. Flexural mode of failures exhibited in all PSC beam specimens.
8. The failure of control beam occurred by crushing of concrete.
9. The failure of PSC beam specimens retrofitted with FRP occurred due to rupture and delamination of glass fibres in GFRP system at ultimate stage.

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REFERENCES

1. Al-Hassani HM, Al-Taan SA, Mohammed AA. Behavior of damaged reinforced concrete beams strengthened with externally bonded steel plate, *Tikrit Journal of Engineering Sciences*, **20**(2013) 48-59.
2. Ki-Nam Hong, Chang-Geun Cho, Swoo-Heon Lee, Yeonho Park. Flexural behavior of RC members using externally bonded aluminum glass fiber composite beams, *Polymers*, **6**(2014) 667-85.
3. Pam HJ, Kwan AKH, Islam MS. Flexural strength and ductility of reinforced normal and high strength concrete beams, *Structures and Buildings*, No. 4, **46**(2001) 381-9.
4. Almusallam TH. Behaviour of normal and high-strength concrete cylinders confined with e-glass/epoxy composite laminates, *Composites, Part B-Engg*, **38**(2007) 629-39.
5. Hadi MNS, Li J. External reinforcement of high strength concrete columns, *Composite Structures*, Elsevier, **65**(2004) 279-87.
6. Challal O, Shahawy M, Hassan M. Performance of axially loaded short rectangular columns strengthened with fiber reinforced polymer wrapping, *ASCE JL of Composites for Construction*, No. 3, **7**(2003) 200-8.
7. Revathy J, Suguna K, Raghunath PN. Strength and ductility of GFRP wrapped corrosion-damaged concrete columns, *International Journal of Applied Engineering and Research*, No. 6, **4**(2009) 989-98.
8. Prakash S, Kumnar R, Sharma BB. Prestressed concrete beams under fatigue loading, *Journal of Advances in Bridge Engineering*, (2006), 433-43.
9. Du JS, Francis TK Au, Cheung YK, Albert KH. Kwan. Ductility analysis of prestressed concrete beams with unbonded tendons, *Engineering Structures*, **30**(2008) 13-21.
10. Jun Y. Cha, Balaguru P, Chung L. Experimental and Analytical Investigation of Partially Prestressed Concrete Beams Strengthened with Carbon Reinforcement, SP 188-55.
11. Reed CE, Peterman RJ. Evaluation of prestressed concrete girders strengthened with carbon fiber reinforced sheets, *ASCE Journal of Bridge Engineering*, No. 2, **9**(2004) 185-92.
12. EI Meski F, Harajli M, Flexural behaviour of Unbonded Post Tensioned Concrete

Members Strengthened using External FRP Composites, *Journal of Composites for Construction*, **17**(2013) 197-207.
13. IS 4031(Part-11)-1988, Methods of physical tests for hydraulic cement, Determination of density, Bureau of Indian Standards.
14. IS 4031(Part-1) -1996, Methods of physical tests for hydraulic cement, Determination of fineness by dry sieving, Bureau of Indian Standards.
15. IS 4031(Part-4) -1988, Methods of physical tests for hydraulic cement, Determination of consistency of standard cement paste.
16. IS 4031(Part-5)-1988, Methods of physical tests for hydraulic cement, Determination of initial and final setting times, Bureau of Indian Standards.
17. IS 4031(Part 6)-1988, Methods of physical Tests for hydraulic cement, Determination of compressive strength of hydraulic cement other than masonry cement, Bureau of Indian Standards.
18. IS 2386(Part-3)-1963, Methods of Test for Aggregates for Concrete Specific Gravity, Density, Voids, Absorption and Bulking, Bureau of Indian Standards.
19. IS 383-1970, Specification for Coarse and Fine Aggregates from Natural Sources for Concrete, Bureau of Indian Standards.
20. IS 456-2000, Plain and Reinforced Concrete-Code of Practice, Bureau of Indian Standards.
21. IS 10262-2009, Recommended guidelines for Concrete Mix Design, Bureau of Indian Standards.
22. IS 1199-1959 Methods of Sampling and Analysis of Concrete, Bureau of Indian Standards.
23. IS 516-1959, Methods of Tests for Strength of Concrete, Bureau of Indian Standards.
24. IS 1786-2008, High strength deformed steel bars and wires for concrete reinforcement, Bureau of Indian Standards.
25. IS 1785(Part -1)-1983, Plain Hard- drawn steel wire for prestressed concrete-cold drawn stress – relieved wire, Bureau of Indian Standards.
26. ASTM D 638-14, Standard test method for tensile properties of plastics.