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Evaluation of the Flexural Performance of the Mono and Hybrid FRP Strengthened RC Beams: Static and Cyclic Loads

JAISANKAR KARTHICK[1]*, KANNAN SUGUNA[2], PULIPAKKA NARASIMHA RAO RAGHUNATH[2]
[1]Department of Civil Engineering, PSG Institute of Technology and Applied Research, Avinashi Road, Neelambur Coimbatore, 641 062, Tamilnadu, India
[2]Department of Civil and Structural Engineering, Faculty of Engineering and Technology, Annamalai University, Annamalai Nagar, Chidambaram, 608220, Tamilnadu, India

Abstract: *The flexural response of externally strengthened RC beams with GFRP and HFRP (hybrid FRP) sheets under monotonic and cyclic loading conditions are investigated. Fourteen beams in two series (Series1and 2) were cast for this study. Each series consisted of seven beams. A total number of 14 beams were cast, out of which 2 beams considered as control specimen. The 12 beams were externally strengthened with GFRP sheets (4 beams) and HFRP sheets (8 beams). Series 1 and Series 2 beams were tested for two-point static and cyclic loads. The experimental for ultimate strength, deformation, stiffness, ductility, energy absorption and modes of failures are conversed for all the tested beams. The peak load for the RC beams tested specimens under static loads were computed using ACI 440.2R-08 guidelines. An optimum increase of 171.43 % in ultimate load carrying capacity was found for the beam strengthened with HFRP sheets than the control beam. Also, the predicted ultimate loads exhibited the good convergence with the test results.*

Keywords: *cyclic, flexure, FRP, hybrid, RC beams*

1.Introduction

Now-a-days the use of fibre reinforced polymer which is made up of polymer matrix reinforced with fibres in an engineering application is a quite natural one [1]. The fibers used either glass or carbon or aramid or basalt or any combinations of these. The polymer matrix consists either of epoxy or polyester resin or poly-vinyl ester [2]. The engineering and durability properties of FRP are influenced by the type of fibre and the type of resin used. Fibre reinforced polymer (FRP) becomes a hopeful material for retrofitting and rehabilitation of structural members over the last decades due to the higher ratio of strength to weight of FRP, excellent fatigue resistance [3,4]. Also, it implies less changes in geometry of the structure and their aesthetics and utility [5]. Hence FRP has become a value-added building material to upgrade the deteriorated RC structures due to aging, less or improper maintenance and various exposure conditions [3,4,6]. In the past decades, the researchers have used mono FRP laminates for the upgradation of concrete structural members. Mostly carbon and/or Glass FRP sheets are widely used for structural upgradation as a result of their nature and material properties [5,7-11]. The GFRP laminates have been effectively used for the upgradation of concrete members where the ductility is in demand [4]. Similarly, some researchers have been used CFRP laminates for structural strengthening where load carrying capacity is the primary objective. But in both the cases merits and demerits have been derived. Now the researchers are in the situation to address the demerits of mono FRP laminates in strengthening point of view. The latest trend involves in upgradation of structures is the utilization of hybrid materials to upgrade the performance of various RC structural elements. The HFRP is made by combination of different kinds of fibres in a polymeric matrix. This shows the better characteristics that could not be get by anyone fibre. By using hybrid FRP sheets, one can access the benefits of two or more fibres. Some researchers studied the behaviour of externally strengthened RC beams with HFRP sheets under flexure [7,12-16], CFRP and GFRP laminates under cyclic loading condition [8,9,17-20].

**email: karthickjaisankar16@gmail.com*

Hence this study has been proposed to achieve the benefits of CFRP and GFRP in an externally strengthened system for structural upgradation.

This study is aimed to assess the impact of hybrid FRP sheets in RC beams under static and cyclic loads by means of the peak load, deformation, stiffness, ductility, energy absorption, crack history and modes of failure. In order to achieve the benefits of hybrid FRP sheets for strengthening, the optimum combination of CFRP and GFRP sheets under monotonic and cyclic loading conditions have been identified. the theoretical peak load of RC beams based on ACI 440.2R-08 guidelines has also been predicted.

2. Materials and methods

2.1. Test specimens

Fourteen beams in two series were cast for this study, of which two beams considered as control specimen. The 12 beams were externally strengthened with GFRP sheets (4 beams) and HFRP sheets (8 beams). The breath, depth and length of all the beams were 150, 250 and 3000 mm. In order to achieve flexure mode of failure, all the specimens were reinforced with 2-12 Ø mm at bottom, 2-10 mm Ø diameter at top and 2-legged 8 mm Ø stirrups at 125 mm c/c distance spacing. The beams strengthened with FRP laminates only at its soffit. GFRP sheets were used to strengthen four beams and eight beams were strengthened using hybrid FRP sheets with various proportions of CFRP and GFRP. The various strengthening configurations adopted for this study are presented in Table 1. Series 1 beams (A1, A2, A3, A4, A5, A6 and A7) were subjected to monotonic loading and Series 2 beams (B1, B2, B3, B4, B5, B6 and B7) were subjected to cyclic loading condition over a simple span of 2800 mm until collapse and manual readings were noted directly [22].

Table 1. Array of beam designations

Beam designation	Description
A1/B1	Control beams
A2/ B2	3GFRP
A3/ B3	5GFRP
A4/ B4	1CFRP+2GFRP
A5/ B5	2CFRP+2GFRP
A6/ B6	3CFRP+2GFRP
A7/ B7	5CFRP+2GFRP

2.2. Constituent materials

The OPC 53 grade of cement with specific gravity of 3.14 was used [23]. The river sand (R-Sand) was used as fine aggregate with the specific gravity of 2.64 and it confirming to zone-III [24]. The specific gravity of coarse aggregate was 2.74. In this study the design mix ratio and water/cement ratio adopted for casting was 1:1.89:3.50 and 0.55 and shown in Table 2 [25]. A slump of 75 *mm* was obtained for the above mix proportion. The compressive strength achieved is 25.60 MPa [26]. The obtained yield strength of internal reinforcement was 572.29 MPa [27]. The Coupon test was carried out at the CIPET, Chennai, India. The obtained properties of FRP sheets are presented in Table 3.

Table 2. Design mix of concrete matrix

Ingredients	Quantity per m^3
OPC-53 grade	349 kg
Aggregate (Fine)	662.43 kg
Aggregate (coarse) 20 mm size 12mm size	 733.35 kg 488.9 kg
Water	192 l

Table 3. Mechanical properties of FRP sheets

Coupon test	Sample thick (mm)	Yield strength (MPa)	Elastic modulus (GPa)	Elongation (%)
3GFRP	3.00	446.90	13.90	3.10
5GFRP	5.00	451.50	17.40	2.60
1CFRP+2GFRP	3.52	382.89	26.80	8.70
2CFRP+2GFRP	3.96	401.81	28.20	9.30
3CFRP+2GFRP	4.39	440.32	30.80	10.50
5CFRP+2GFRP	5.26	463.05	32.40	9.10

2.3. Test beams preparation

A rotary type mixer machine was used to prepare concrete mix. The constituent materials were placed inside the cylinder for making dry mix. This has been converted as a wet concrete by adding water gradually and systematically. The beams were fabricated in moulds. The needle vibrator was used for compaction. The control specimens such as cube, cylinder and prism were also fabricated using the same concrete in the standard size moulds. The water curing is adopted after 24 h of de-shuttering the fabricated beams [28].

2.4 Strengthening of test beams

In this study, the externally bonded GFRP and HFRP laminates were used to strengthen RC beams. The HFRP comprised of glass and carbon fibres with epoxy resin. The epoxy resin and curing agent are mixed for both GFRP and HFRP laminates at a mass ratio of 5:1 and then placed into mould [45]. The fibres in the FRP laminates were concerned with parallel to the beam axis. The beams prepared for strengthening process after curing [29]. The slack material present in the beam surface was removed using grinder and it was removed by a jet of compressed air [29]. Then, all the surface imperfections were repaired using mortar putty to make an even surface and to attain good bonding of FRP wraps with the surface of concrete beams. Beams were wrapped with FRP laminates by applying measured quantities of resin on the soffit of the specimen. The wrapped exterior surfaces were smoothly pressed using a roller to guarantee proper distribution of resin and adhesion between FRP and concrete surface [29].

2.5. Test set-up

Fourteen numbers of RC beams were cast, strengthened and tested under monotonic and cyclic loading conditions for this study. Series 1 beams tested for static loading condition using loading frame of 500 kN capacity [30] and Series 2 beams were tested for cyclic loading condition using a push-pull jack of 250 kN capacity. All beams were tested under simply supported with four-point bending through a distribution girder. The deflections at mid-span and under the loading point were observe using dial gauges with a least count of 0.01 mm. On the compression face of the beam, two dial gauges were mounted near to the supports to monitor the slope at the supports under static loading condition [31]. The mid-span deformation was observed during cyclic load test using dial gauges with 0.02 mm as least count [32]. The formation and distribution of cracks was observed all over the process of testing through a magnifying glass using crack identifying microscope with 0.02 mm least count.

3. Results and discussions

3.1 Monotonic load response

3.1.1 Strength

The static load response of all tested beams in the context of first cracking load, yield load and peak load are presented in Table 4. The beams strengthened using hybrid FRP sheets show an enhancement in peak load than A1. The beam A7 exhibits the maximum load carrying capacity which is 2.7 times higher than the A1 beam. Normally, CFRP sheets are stronger than the GFRP sheets, due to its higher degree of confinement. The CFRP sheets are more significant in the hybrid FRP sheets in consequence of bridging effect produced by it. The maximum increase in first crack load was found as 12.5-40 kN. The A3 beam exhibits the maximum yield load, because of GFRP is more ductile than CFRP.

Table 4. Static loading test results for tested beams

Beam Designation	First crack load (kN)	Deflection at FCL (mm)	Yield load (kN)	Deflection at YL (mm)	Ultimate load (kN)	Deflection at UL (mm)
A1	12.50	0.95	32.00	5.00	70.00	15.80
A2	27.50	1.16	70.00	4.02	112.50	16.50
A3	37.50	1.28	82.50	4.33	117.50	18.60
A4	20.00	2.90	56.00	7.50	145.00	29.30
A5	27.50	2.50	62.00	7.00	162.50	26.20
A6	30.00	1.60	70.00	6.50	170.00	25.30
A7	40.00	1.10	80.00	5.80	190.00	23.60

3.1.2. Deformation

The strength-deformation behaviour of all the tested beams under static loading condition is shown in Figure 1. The deformations of the beams are mainly be governed by the type of loading condition, span, second moment of area and modulus of elasticity of concrete. Attaching of FRP sheets at the bottom of a beam leads to an increased stiffness and cross-sectional dimension. An enhancement of rigidity impacts their deformation behavior in strengthened beams at all stages of loading. The beams strengthened with GFRP and HFRP sheets exhibit a reduction in deformation than the unstrengthened beam. The beam A7 shows a maximum reduction of 60% at ultimate stage. The beam A3 exhibits a deformation of 18.6 mm at an ultimate load of 117.5 kN whereas the A7 beam exhibits a deformation of 11.8 mm at the same ultimate load [34]. Even though the beams A3 and A7 was strengthened with the same thickness of FRP sheets, the beam A7 shows a reduction of 36.24% in deformation than A3. The increase of CFRP layers in the HFRP sheets reduces the deformation significantly. This may be because of the higher strength imparted by the CFRP sheets [12,14].

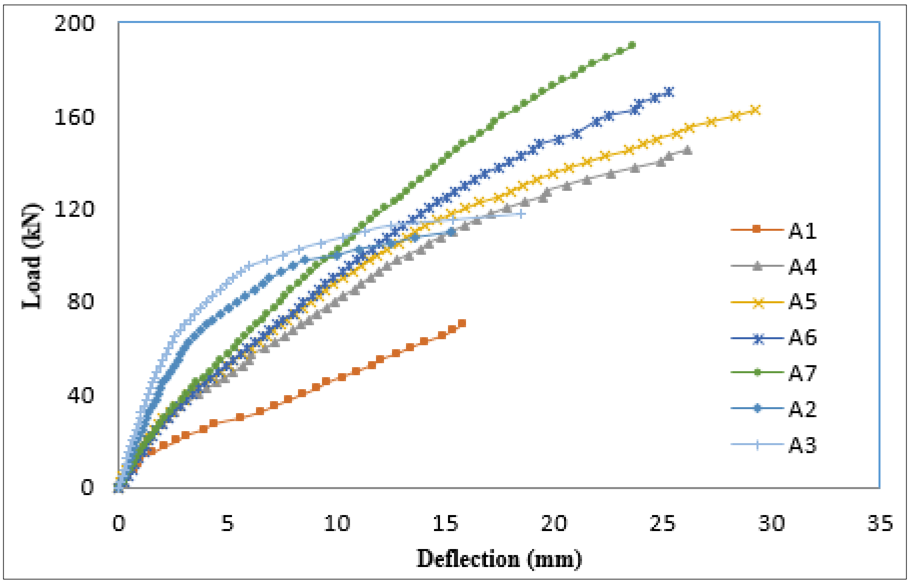


Figure 1. Load versus deflection under static loading condition

3.1.3. Crack history and failure mode

The Crack history of all the tested beams is shown in Figure 2. The beams strengthened using hybrid FRP sheets exhibit a reduction in crack width than A1 and the beams laminated using GFRP sheets. Among the tested beams, the beam A6 exhibits a maximum reduction of 90 % when compared to control beam. Reduction in deformation triggered by the resistance offered by the HFRP sheet. It was noted that the beams exhibit substantial flexural cracking with scattered and closely spaced [22]. The beam A5 shows an increase of 62.5% in number of cracks than the A1. All the tested strengthened RC beams exhibited a decrease in average spacing of cracks than A1 [35]. But the HFRP strengthened beams evolved with an additional flexural crack around the primary cracks that resulted in reduction between the crack spacing. Cracks remained hairline until failure. The beam A4 shows a maximum reduction of 87.59% in average spacing of cracks when compared to A1.

The failure mode of all the beams is shown through Figure 3a to g. The mode of failure of flexure (i.e.) yielding of steel followed by compression concrete crushing was observed for all the beams. The beam A1 failed by flexure mode of failure as shown in Figure 3a [36]. The beams strengthened using GFRP laminates (A2 and A3) failed through the steel reaches its yield value followed by crack in external bonded GFRP sheets which is shown in Figure b and c [37]. The beams strengthened using HFRP laminates (A4, A5, A6 and A7) failed by steel yielding. After reaching the ultimate stage, tearing of concrete cover occurred along with partial delamination of FRP sheets as shown in Figure 3d to g [15].

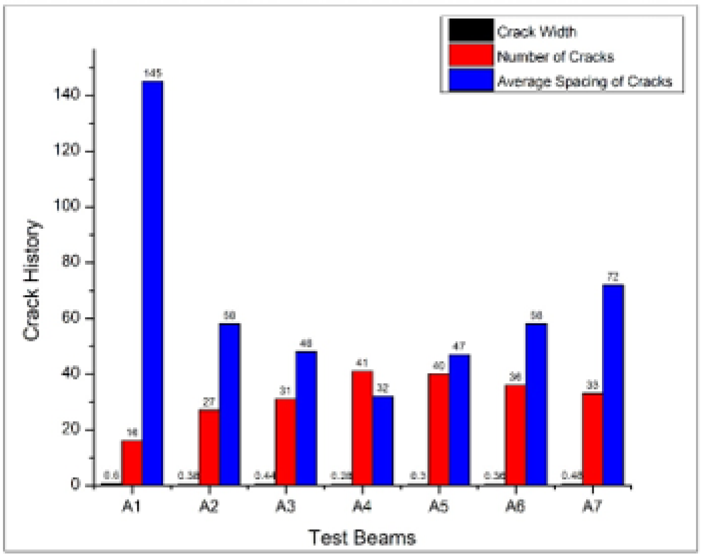
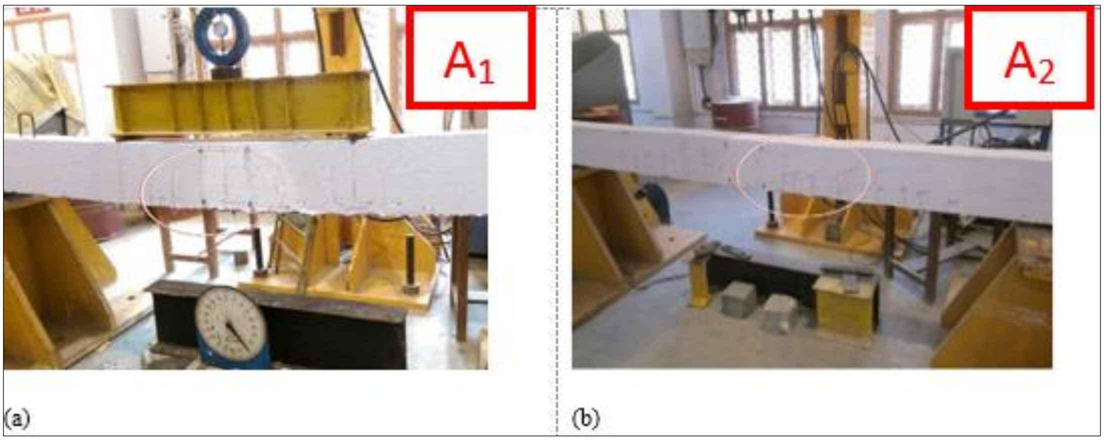


Figure 2. Crack history for tested beams



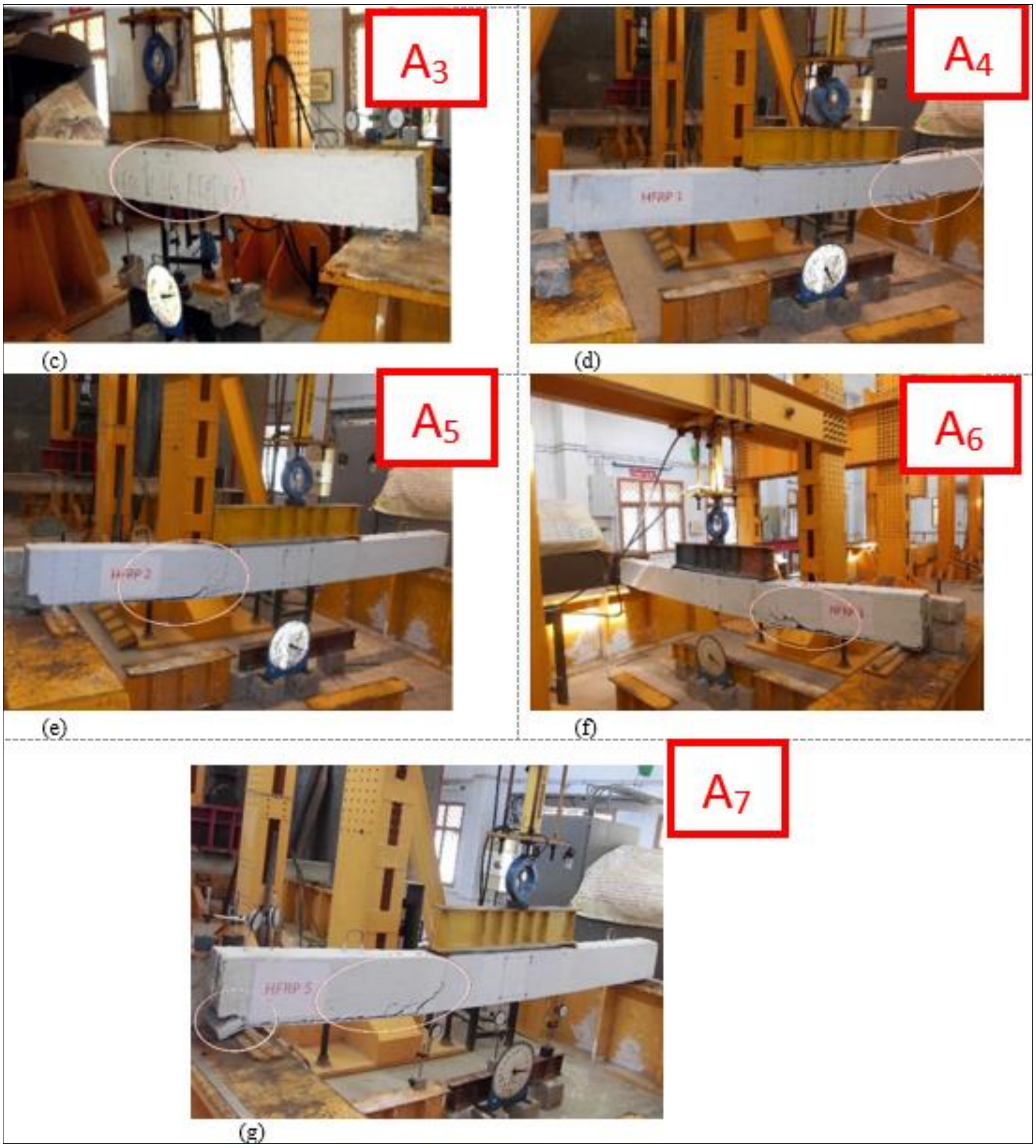


Figure 3. Mode of failure of all tested beam for monotonic loading condition

3.1.4. Ductility

The ductility indices of the beams are presented in Table 5. The strengthened RC beams using GFRP sheets exhibit a substantial increase in ductility in than the A1 and the beams strengthened with HFRP sheets. The beam A3 exhibits a maximum deflection and energy ductility value of 4.3 and 13.45 than all other beams. A small deviation was observed between the beams A2 and A3 in both deflection and energy ductility. This reveals the impact of increase in number of GFRP layers in respect of ductility [15,16,38]. The strengthened RC beams with hybrid FRP sheets exhibit enhanced ductility in comparison with the A1 beam but it was relatively less than the GFRP sheet strengthened RC beams. Since CFRP is having lesser ductility as compared to GFRP, the A5 beam exhibits the better ductility performance than other CFRP beams. The increase in CFRP layers resulted in reduced ductility. The GFRP sheets are preferable for structural strengthening when ductility is in demand.

Table 5. Summary of ductility indices pertaining to ultimate stage

Beam Designation	Deflection ductility	Deflection ductility ratio	Energy ductility	Energy ductility ratio
A1	3.16	1.00	6.57	1.00
A2	4.10	1.47	12.72	2.25
A3	4.30	1.54	13.45	2.65
A4	3.91	1.24	9.39	1.43
A5	3.74	1.18	10.54	1.61
A6	3.89	1.23	7.83	1.19
A7	4.07	1.29	6.98	1.06

3.1.5. Computation of ultimate load carrying capacity of beams

The equation 10-26 of ACI 440.2R-08 guidelines was used to compute the ultimate load of all tested beams. Good convergence was observed between the experimental and predicted results as shown in Figure 4.

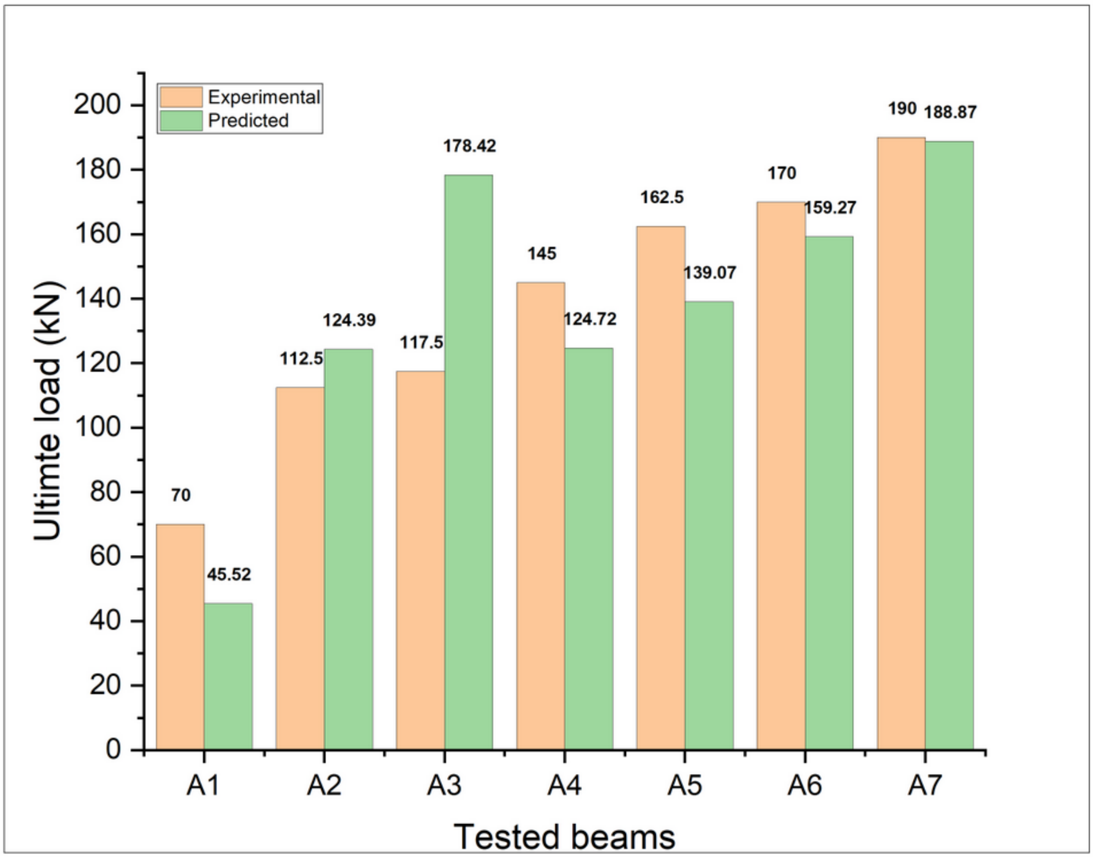


Figure 4. Experimental versus predicted ultimate load for tested beams

3.2. Cyclic response of tested beams

3.2.1. Number of cycles

The obtained experimental results for all the tested beams under cyclic loading condition are presented in Table 6. The control beam (B1) sustained 5 cycles with a cyclic force of 37.13 kN. The beam B2 sustained 11 cycles with a cyclic force of 119.08 kN. The beam B2 exhibits an increase of 120% in number of cycles and 120.84% in cyclic force at 5 cycles than the control beam. The beam B3 sustained 12 cycles which is 140 and 9.09 % higher than the B1 and B2. The beam B3 exhibits an increase of 128.25 and 3% in cyclic force at 5 and 11 cycles than the B1 and B2. The beams B4 and B5 sustained the same number of cycles (10 cycles). But a slight difference in cyclic force was observed. The beam B5 shows an increase of 5.25% in cyclic force compared to B4. The beams B6 and B7 also sustained the same number of cycles (9 cycles). Here also a slight difference in cyclic force was observed. The beam B7 shows an increase of 13.03% in cyclic force compared to B6. In the hybrid FRP laminated beam, there was no significant change in number of cycles observed. But there was a notable increase in the cyclic force as shown in Figure 5. The beam B7 exhibits a maximum cyclic force in comparison with B4, B5 and B6. CFRP sheet exhibits higher strength than GFRP sheet. The increase of CFRP layers resulted in an increase in the cyclic force. But the beam B7 sustained lesser number of cycles and cyclic force in comparison with B3. The increase of CFRP layers in HFRP sheets reduces the total energy absorption of the beams resulting in a reduction of cyclic performance and also introduces a brittle mode of failure. It has also been observed that external bonding of FRP sheets is a viable method to enhance the behaviour of RC beams under repeated loading condition [14, 39]. But care must be taken in the selection of FRP material for strengthening.

Table 6. Cyclic load test response for tested beams

Test beam	No. of cycles	Max. cyclic force (kN)	Deflection at max. load (mm)	Stiffness (kN/mm)	Crack width (mm)	Total energy absorption (kN-mm)
B1	5	37.13	15.00	2.48	0.26	174.588
B2	11	119.08	27.50	4.33	0.26	1242.54
B3	12	133.50	30.00	4.50	0.26	1715.68
B4	10	78.38	25.00	3.10	0.16	1622.49
B5	10	82.50	25.00	3.30	0.20	1478.85
B6	9	94.88	22.50	4.20	0.20	1085.27
B7	9	107.25	22.50	4.80	0.22	1045.49

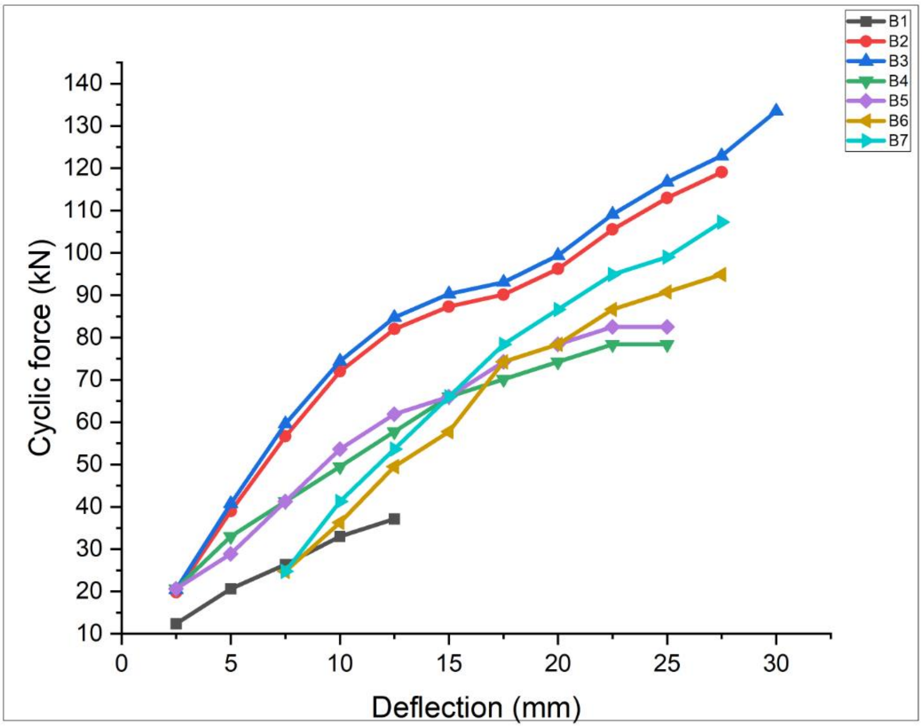
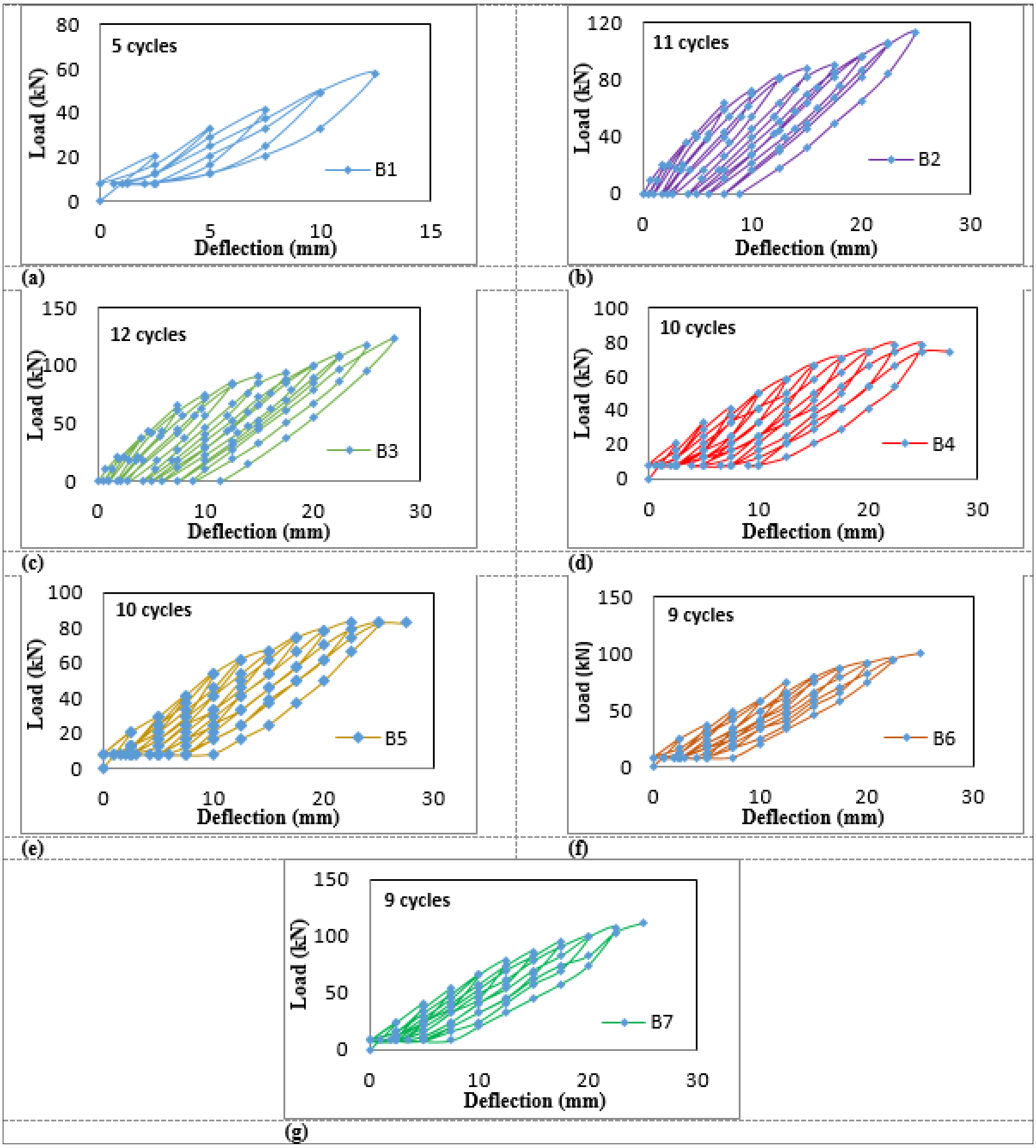


Figure 5. Cyclic force versus deflection under cyclic loading

3.2.2. Deformations

The cyclic force-mid-span deformation response of all beams is indicated in Figure 6. It was identified that all the test beams exhibit slow and steady as well as similar trend until failure. The beams strengthened using FRP sheets sustained larger deformation than the beam B1 [18]. The beams strengthened using GFRP sheets sustained much higher deformation than the hybrid FRP laminated beams. The beam B3 sustained a maximum deformation of 30 mm at the maximum load of 133.50 kN.



(a) (b) (c) (d) (e) (f) (g)

Figure 6. Under cyclic loading condition – Load vs Deflection response of tested beams

3.2.3. Stiffness degradation

The ratio of load to deflection is referred to as stiffness. The reduction in stiffness at the time of loading is called as stiffness degradation. In this study, both the strengthened and control beams exhibited a gradual degradation of stiffness at all cycles as shown in Figure 7. This shows that confinement has been provided by externally bonded FRP sheets for the strengthened beams [40]. After each cycle of loading the stiffness was predicted at the ultimate load and the same is presented in Table 6. The stiffness degradation was observed as 40% for B1, 45.32% for B2, 46% for B3, 63% for B4, 60% for B5, 58% for B6 and 52% for B7 respectively. The beam B7 exhibits a maximum stiffness of 4.8 kN/mm at 9 cycles than the all-other beams. This may be due to the higher CFRP layers in the hybrid FRP laminates [41]. This fundamental mechanical property may improve the stiffness of the beam section significantly which results in a reduction of stiffness degradation. Also, the stiffness degradation could be controlled by increasing the FRP contact area to the concrete surface to avoid concentration of stresses in the FRP sheets.

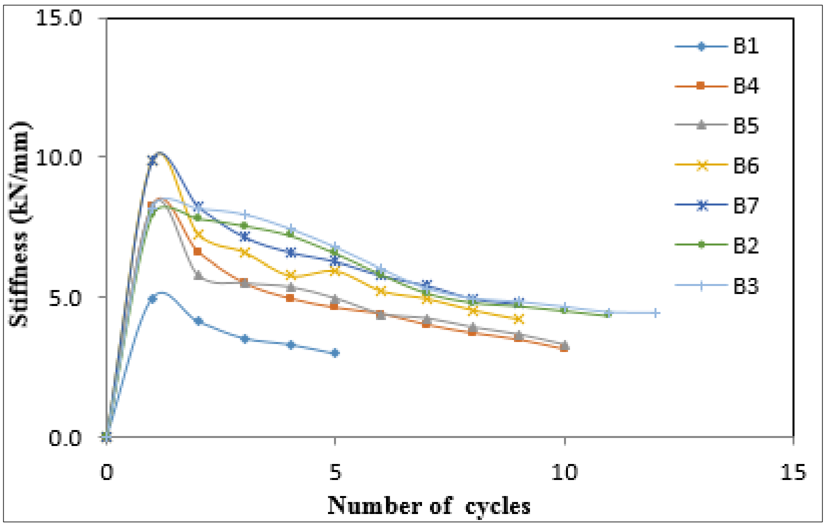


Figure 7. Number of cycles versus stiffness for tested beams

3.2.4. Energy absorption

The cyclic load response for tested beams in terms of deflection, stiffness crack width and the total energy absorption is presented in Table 6. All the beams exhibit an increase in energy absorption at every cycle of loading as shown in Figure 8 [42]. The beam strengthened using GFRP sheets exhibits higher energy absorption than all other beams. Particularly, the beam B3 exhibits a maximum energy absorption of 1715.68 kN-mm at 12 cycles. The ductile nature of GFRP laminates improves the tested beams energy absorption capacity. Among the strengthened RC beams using hybrid FRP sheets, the beam B4 shows a maximum energy absorption of 1622.49 kN-mm at 10 cycles. The increase of CFRP layers in the HFRP sheets reduced the ductility and also induced a brittle mode of failure resulting in reduction in the energy absorption capacity [3, 12, 13].

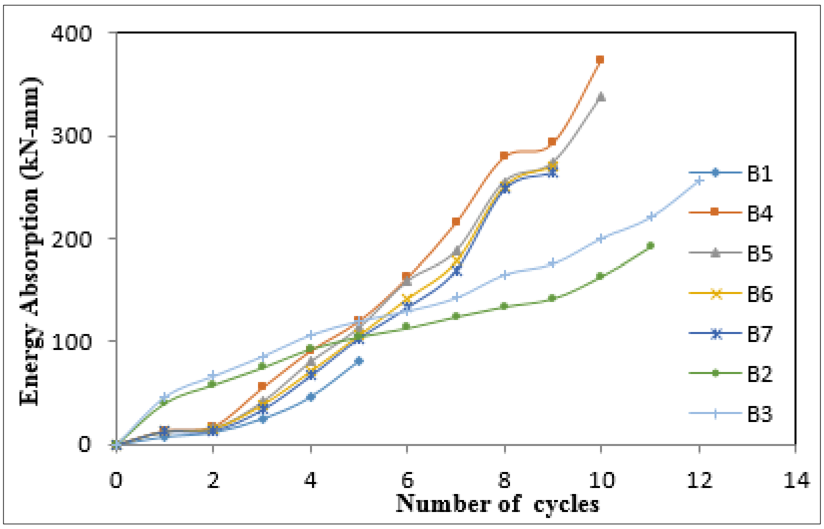


Figure 8. Number of cycles versus energy absorption for tested beams

3.2.5. Crack pattern and mode of failure

The beams strengthened using FRP sheets show a lesser crack width than the control beam B1 at all cycles [14, 42]. The crack width primarily depends on the tensile stress in steel reinforcement and the number of cracks formed. The principal flexural crack started at the first cycle of loading and further cracks opened and distributed as the number of cycles increased [40]. The beam B3 shows a reduction of 18.18% in crack width compared to B2. This reduction in crack width shows the effect of number of layers of GFRP sheets on the behaviour of strengthened beams [43]. The beam B4 showed a reduced crack width than the other HFRP strengthened beams, the maximum being 57.14%. In specific, the beams B3 and B4 exhibit the same crack width at 9 cycles. The extent of reduction primarily depends on the amount of external FRP reinforcement applied [8].

The control beam displayed the primary failure mode which is fracture of internal reinforcementas shown in Figure 9a [44]. The beams strengthened with GFRP sheets (B2 and B3) failed through the fracture of internal reinforcement followed by the rupture of GFRP materialas shown in Figure 9b and c. In this case, GFRP material present in the strengthened beams ensures ductile mode of failure [40]. The beams strengthened using hybrid FRP sheets (B4, B5, B6 and B7) also failed through the fracture of internal reinforcement. At the maximum cycles, debonding of FRP sheets occurred along with the ripping of cover concrete as shown in Figure 9d and 9e. In hybrid FRP strengthened beams, the CFRP existing in the HFRP sheets initiated a brittle failure mode.

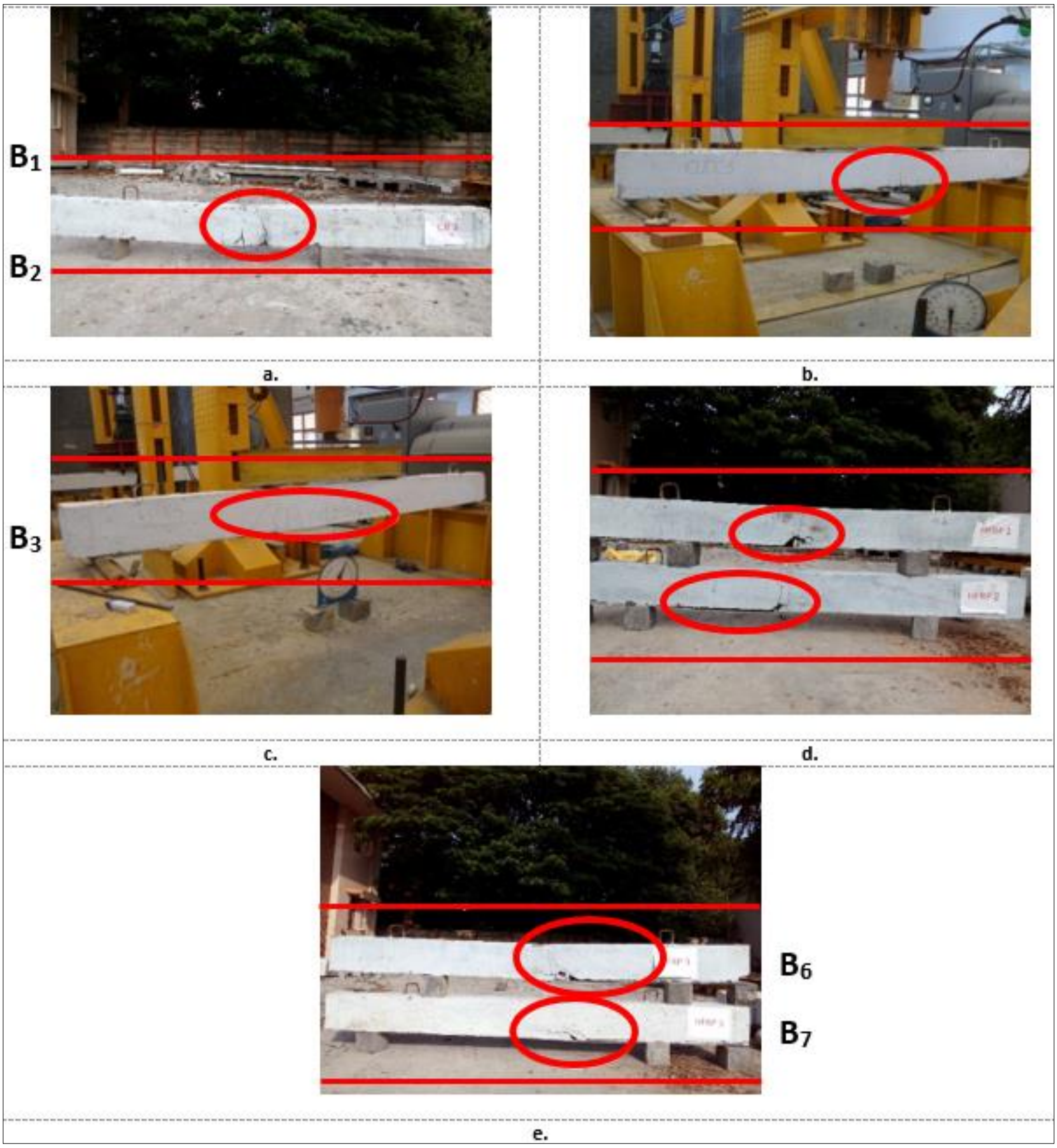


Figure 9. Mode of failure of beams tested under cyclic loading condition

4. Conclusions

The proposed work is aimed to assess the static and cyclic response of GFRP and HFRP laminated beams under flexure. The achieved results from this study are,

The beams strengthened with HFRP sheets exhibit an increased load carrying capacity and a reduction in deformation at all stages of loading than control beam A1. The beam A7 exhibited a maximum load carrying capacity enhancement of 171.43 % at ultimate stage than A1.

The strengthened RC beams with HFRP sheets exhibited an appreciable drop in crack width and average spacing of cracks and increase in number of cracks at ultimate stage than the beam A1.

The beams strengthened with GFRP sheets show a considerable enhancement in energy absorption and ductility than all-other beams under monotonic and cyclic loading conditions. The beam A3 exhibits a maximum increase of 104.71 % in energy ductility than the beam A1. The ductile nature of GFRP laminates improves the performance of the beams significantly.

Flexural failure mode was noticed under static loading condition. GFRP present in HFRP sheets induced a ductile failure mode. The A1 beam failed by rupture of steel followed by concrete crushing in the compression zone and the strengthened RC beams failed through the rupture of steel reinforcement followed by partial delamination of FRP sheets and some ripping of cover concrete under cyclic loading condition.

Good convergence was obtained between the experimental ultimate load of all tested beams and those computed using ACI 440.2R-08 guidelines under static load.

The use of externally strengthened RC beam using FRP system is well suited for the structural upgradation of concrete beams under monotonic and cyclic loading conditions.

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