IJRAR.ORG E-ISSN: 2348-1269, P-ISSN: 2349-5138

INTERNATIONAL JOURNAL OF RESEARCH AND ANALYTICAL REVIEWS (IJRAR) | IJRAR.ORG

An International Open Access, Peer-reviewed, Refereed Journal

BEHAVIOUR OF RCC BEAM USING CFRP LAMINATES

[1]V.Karuppusamy, [2]Dr.M.Seethapathi,M.E.,Ph.D.,

[1]M.E Structural Engineering Student, [2]Head of Civil Department,
[1]Tamilnadu Engineering College, Coimbatore, Tamilnadu.

Abstract : This paper presents an experimental study on retro fitting of reinforced concrete beams with externally bonded CFRP with various types of resins (Epoxy, Ortho phthalic Resin(GP), IS Orexin). Externally bonded Carbon Fiber Reinforced Polymer (CFRP) RC beams were studied for flexural behavior. There are three types of beams: one number of control beam specimens, one number of CFRP singly laminated reinforced concrete beam specimens, and one number of CFRP doubly laminated reinforced concrete beam specimens. They were cast to a size of 1000mm x 100mm x100mm, respectively, and tested in a two-point bending test. After the instrumentation setup was done, beam specimens were tested to record the results. The load-deflection response at the initial crack, yield point, commencement of de bonding lamination, and at ultimate phases. The findings show that singly and doubly laminations positively affect control reinforced concrete beam specimens. Furthermore, the ultimate load carrying capacity and maximum yield The laminated beam is determined to be 59% and 49% higher than the non-laminated reinforced concrete beam and 125% and 98%higher than the control beam. On the other hand, the deflections are more significant, and their permissibility must be within the codal regulations. The laminated beams all showed slow de bonding and ductile failure, while the control beam failed in a flexural mode. The laminated beams all showed slow de-bonding and ductile failure, while the control beam failed in a flexural mode. The laminated effect might be beneficial in structural applications where both strength and ductility are needed

Keywords: CFRP, Lamination, Flexure, Deflection

I. INTRODUCTION

1.1. GENERAL

Concrete is the most widely used man-made construction material in world. It is obtained by mixing cementing materials, water and aggregates, and sometimes admixtures required proportions. Concrete has high compressive strength, low cost and abundant raw material, but its tensile strength is very low. Reinforced concrete, which is concrete with steel bars embedded in it. Concrete is an affordable material, which is extensively used throughout in the infrastructure of nation's construction, industry, transportation, defense, utility, and residential sector. The flexibility and mould ability of this material, its high compressive strength, and the discovery of there in forcing and pre stressing techniques which helped to make up for it slow tensile strength have contributed largely to its wide spread use.

Distresses in reinforced concrete structures happens due to versions causes such as development of surface cracks due to ingress of chemical agents, corrosion, lack of detailing, failure of bonding between beam-column joints, increase in service loads, improper design, poor construction and unexpected external lateral loads such as wind or seismic forecasting on a structure, environment and accident events etc. They lead to cracking, spelling, loss of strength, deflection, etc. Which are also the reasons for failure of structural members.

1.2. RETRO FITTING

Reinforced concrete structures often have to face modification and improvement of their performance during their service life. In such Circumstances there are two possible solutions. The first is replacement and the other is retro fitting. Full structure replacement might have determinate disadvantages such as high costs for material and labor, a stronger environmental impact and in convenience due to interruption of the function of the structure. So if possible, it is often better to repair or upgrade the structure by retro fitting. Retro fitting methods is shown in figure

In recent ears repair and retro fit existing structures such as buildings, bridges, etc., have been quite prevalent among the most important challenges in Civil Engineering. Structural repair describes process of reconstruction and renewal of a facility or structural elements. Structural strengthening, on the other hand, describes the process of upgrading the structural system of an existing building to improve performance under existing load or to increase the strength of structural components to carry additional load.

1.3. NEED FOR RETRO FITTING

Strengthening of existing reinforced concrete structures is necessary to obtain an expected life span and achieve specific requirements

1.4. RETRO FITTING METHODS

Structural retro fitting technologies are currently at the stage of general research, and the performance results and organization of technologies used for the different methods are not uniform.

1.5. FIBRE REINFORCED POLYMER (FRP) COMPOSITES

Fiber reinforced polymer (FRP) composites consist of high strength fiber embedded in a matrix of polymer's in, fillers, and additives as shown in Figure1.2. types of FRP composites is shown in figure1.3.

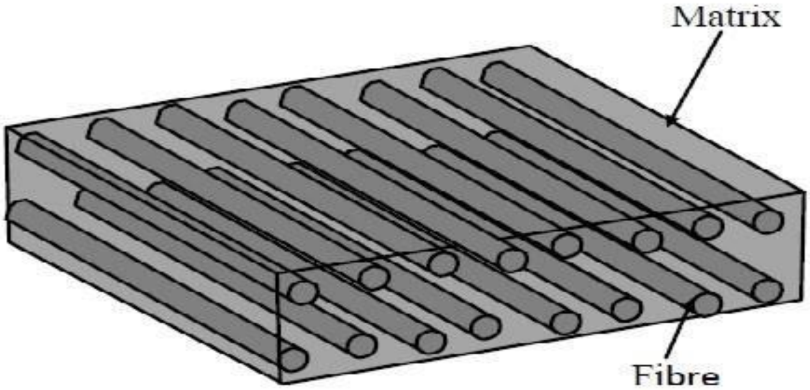


Figure1.2. A schematic diagram shows in typical unidirectional FRP plate.

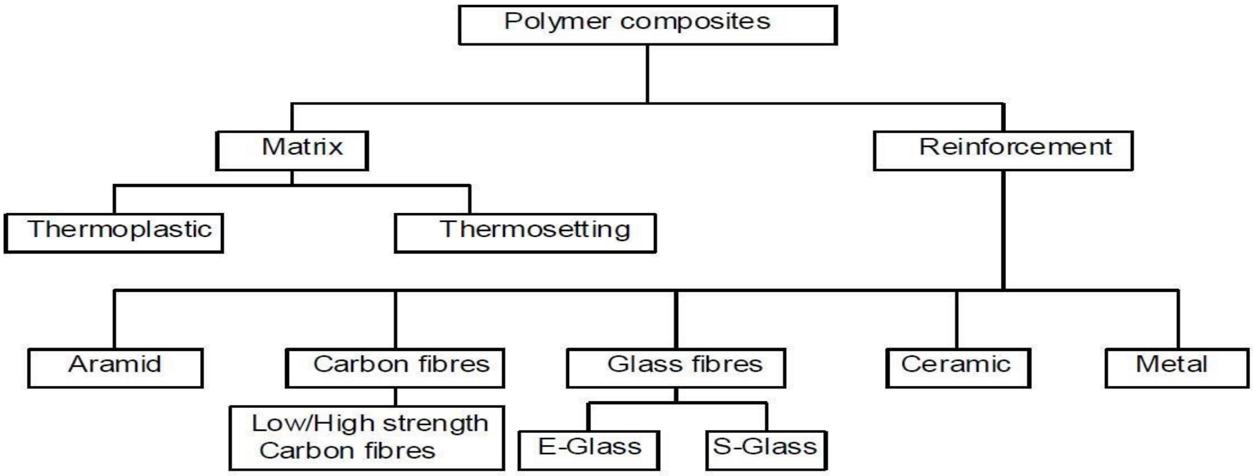


Figure:1.3 FRP Composite

1.5.1 FIBERS

The Fibers exhibit thigh tensile strength and stiffness and are the main load carrying element. The Fibers may occupy anywhere from 40 percent to 70 percent (by volume) of the material. Typical values for properties of the Fibers are given in Table1.1. These Fibers area l line are lactic up to failure, with no significant yielding compared to steel.

Fibers typically used in FRP are

i. Natural Fibre's,
ii. Synthetic Fibre's (glass, carbon and aramid).

1.5.2 RESIN

Threes in offers high compressive strength and binds the fibers into a firm matrix. The additives help to improve the mechanical and physical properties as well as the workability of composites. The primary functions of the matrix in a composite are to transfer stress between the fibers, to provide a barrier against the environment and to protect the surface of the fibers from mechanical abrasion. Typical properties for FRPC are given in Table1.1

1.5.3 ADHESIVES

Adhesives are used to attach the composites to other surfaces such as concrete. The most common adhesives are acrylics, epoxies and urethanes. Epoxies provide high bond strength with high temperature resistance, whereas acrylics provide moderate temperature resistance with good strength and rapid curing. Several considerations are involved in applying adhesives effectively. Careful surface preparation such as removing the cement paste, grinding the surface by using a disc sander, removing the dust generated by surface grinding using an air blower and carful curing are critical to bond performance.

1.6. THE MECHANICAL PROPERTIES OF COMPOSITES

The mechanical properties of composites are dependent on the fiber properties, matrix properties, fiber – matrix bond properties, and fiber amount and fiber orientation. A composite with all Fibers in one direction is designated as unidirectional. If the Fibers are woven, or oriented in many directions, the composite is bi-or multidirectional. Since it is mainly the Fibers that provide stiffness and strength composites are often anisotropic with high stiffness in the fiber direction(s). In strengthening applications, unidirectional composites are predominantly used. The approximate stiffness and strength of a unidirectional CFRP with a 65% volume fraction of carbon fiber is given inTable1.1. As a comparison the corresponding properties for steel are also given.

Material	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Density (kg/m^3)	Modulus of Elasticity to density ratio (mm^2/s^2)
Carbon	2200-5600	240-830	1800-2200	130-380
Aramid	2400-3600	130-160	1400-1500	90-110
Glass	3400-4800	70-90	2200-2500	31-33
Epoxy	60	2.5	1100-1400	1.8-2.3
CFRP	1500-3700	160-540	1400-1700	110-320
Steel	280-1900	190-210	7900	24-27

Table 1.1. Typical strength and stiffness values for materials used in retrofitting.

1.7. BASIC CHARACTERISTICS AND ADVANTAGES OF FRP COMPOSITES

- High corrosion resistance,
- High strength,
- Light Weight
- High stiffness,
- Excellent fatigue performance
- Good damping resistance
- Good resistance to chemical attack
- High strength to weight ratio
- Design Flexibility
- Electromagnetic transparency

1.8. APPLICATION IN RETRO FITTING

For structural applications, FRP is mainly used in two areas. The first area involves the use of FRP bars instead of steel reinforcing bars or pre stressing strands in concrete structures. The other application, which is the focus of this is to strengthen structurally deficient structural members with external application of FRP.

Retro fitting with adhesive bonded FRP has been established around the world as an effective method applicable to many types of concrete structural elements such as columns, beams, slabs and walls.

FRP sheets/plates can be bonded to reinforced concrete structural elements using various techniques such as external bonding, wrapping and near surface mounting. Retro fitting with externally bonded FRP has been shown to be applicable to many types of RC structural elements. FRP plates or sheets may be glued to the tension side of a structural member to provide flexural strength or glued to the web side of a beam to provide shear strength. FRP sheets can also be wrapped around a beam to provide shear strength and be wrapped around a column to provide confinement and thus increase the strength and ductility. Near surface mounting consists of sawing a longitudinal groove in a concrete member, applying a bonding material in the groove and inserting an FRP bar or strip.

The laminate can act as a protective cover at the joint by reducing the exposed concrete surface area where moisture or salts can penetrate into the joint and cause corrosion of rein forcing bars

1.9. OBJECTIVES AND SCOPE OF PROJECT

This paper presents an experimental study on retro fitting of reinforced concrete beams with externally bonded CFRP with various types of resins (Epoxy, Orthophthalic Resin(GP), IS Oresin).

The objective of this study is to investigate the flexural behavior of beams after retrofitting over an effective span of 1000 mm. The beams are designed as under-reinforced concrete beams used as control specimen. The beams are strengthened with externally bonded CFRP fabricinsing le layer which are parallel to beam axis at the bottom and sides (U shape) after initial load (60%) and are tested until failure.

The field of FRPC strengthening of RC beams show that the researchers have tried CFRP, CFRP or hybrid laminates with different thicknesses and number of layers. Most of the authors have used epoxy resins for attaching FRP laminates with concrete surface. Most of their search works have compared the experimental values with the oretical values. Hence there is a need for further experimental investigation to know the ability of CFRP retro fitting of RC beam with various resin.

1.10. PROBLEMS OF STRENGTHENING RC BEAMS

The study indicates that researchers have used FRP plane laminates at different number of layers. The failure of FRPC strengthened beams occurred due to deboning of laminates from concrete surface, deboning between FRP laminates, concrete crushing, and cover separation as shown in figure2.1. In those cases, the beams failed by premature failure which means, beams failed under the initial load. Also it has been noticed that, failure due to deboning of laminates occurs for beams retro fitted only at the bottom.

PROPOSED METHOD OF STRENGTHENING THE RC BEAM

To overcome the problem discussed in above, in the proposed work, FRP laminates will be provided with full length of the beam to take into account shear and bending. To avoid premature failure, FRP sheet is provided at bottom.

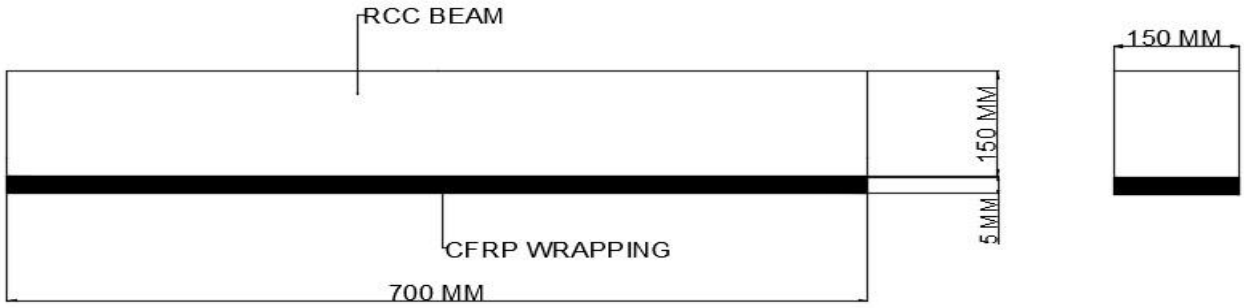
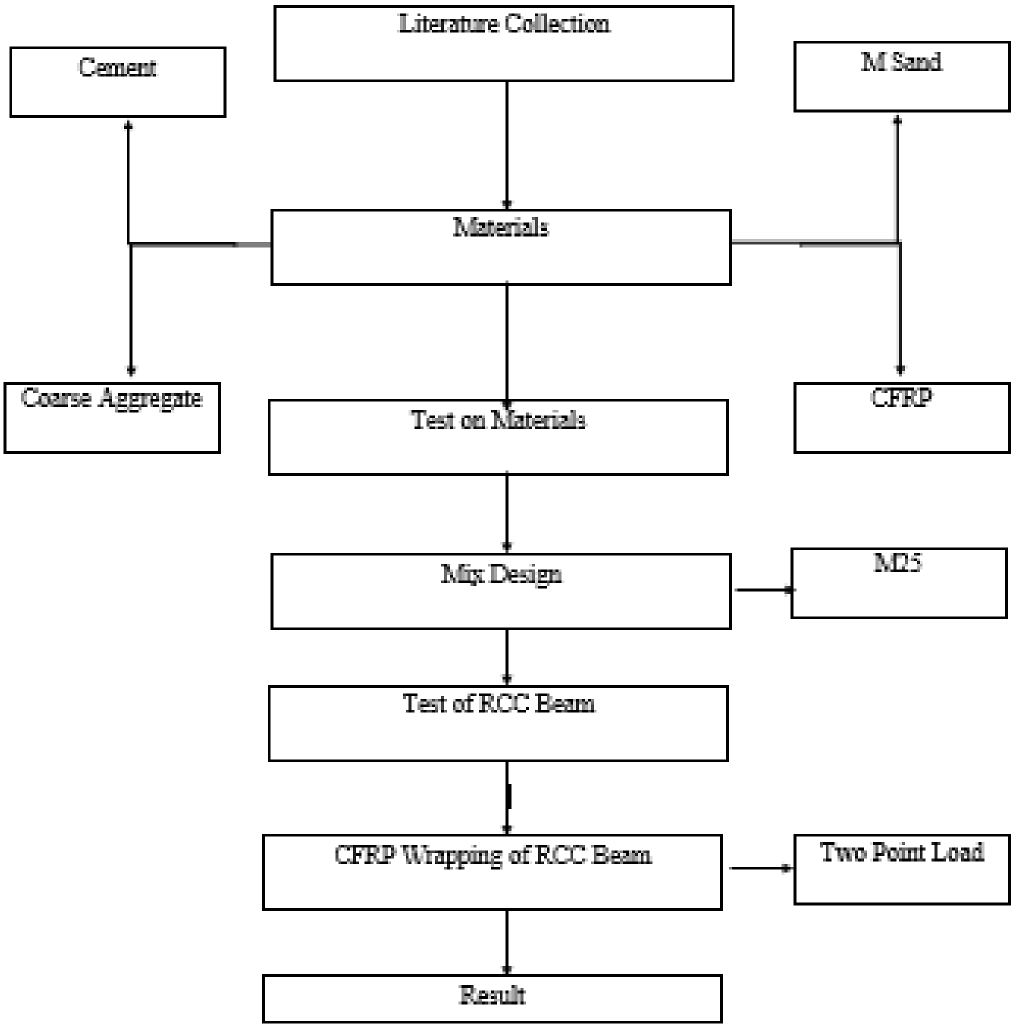


Figure1.5 A schematic diagram showing a typical beam retro fitting.

II. METHODOLOGY



III. MATERIALS

The following material are used in the Study, those materials are Concrete, Cement, Fine Aggregate, Coarse Aggregate, Water, Reinforcement, Fiber Reinforced Polymer (FRP), Carbon Fiber, Epoxy Resin and Adhesive.

IV. EXPERIMENTAL STUDY

4.1 GENERAL

Before testing the member was checked dimensionally, and a detailed visual inspection made with all information carefully recorded. After setting and reading all gauges, the load was increased incrementally up to the calculated working load, with loads and deflections recorded at each stage. Loads will then normally be increased again in similar increments up to failure, with deflection gauges replaced by a suitably mounted scale as failure approaches. This is necessary to avoid damage to gauges, and although accuracy is reduced, the deflections at this stage will usually be large and easily measured from a distance. Similarly, cracking and manual strain observations must be suspended as failure approaches unless special safety precautions are taken. If it is essential that precise deflection readings are taken up to collapse. Cracking and failure mode was checked visually, and a load/deflection plot was prepared.

4.2 EXPERIMENT STUDY

The experimental study consists of casting of two sets of reinforced concrete (RC) beams. In SET I three beams weak in flexure were casted, out of which one is controlled beam and other two beams were strengthened using continuous glass fiber reinforced polymer (CFRP) sheets in flexure. In SET II three beams weak in shear were casted, out of which one is the controlled beam and other two beams were strengthened by using continuous glass fiber reinforced polymer (CFRP) sheets in shear. The strengthening of the beams is done with varying configuration and layers of CFRP sheets. Experimental data on load, deflection and failure modes of each of the beams were obtained. The change in load carrying capacity and failure mode of the beams are investigated as the amount and configuration of CFRP sheets are altered. The following chapter describes in detail the experimental study**.**

4.3 STRENGTHING OF BEAM

Before bonding the composite fabric onto the concrete surface, the required region of concrete surface was made rough using a coarse sand paper texture and cleaned with an air blower to remove all dirt and debris. Once the surface was prepared to the required standard, the epoxy resin was mixed in accordance with manufacturer's instructions. Mixing was carried out in a plastic container (Araldite LY 556 – 100 parts by weight and Hardener HY 951 – 8 parts by weight) and was continued until the mixture was in uniform colour. When this was completed and the fabrics had been cut to size, the epoxy resin was applied to the concrete surface. The composite fabric was then placed on top of epoxy resin coating and the resin was squeezed through the roving of the fabric with the roller. Air bubbles entrapped at the epoxy/concrete or epoxy/fabric interface were to be eliminated. Then the second layer of the epoxy resin was applied and CFRP sheet was then placed on top of epoxy resin coating and the resin was squeezed through the roving of the fabric with the roller and the above process was repeated. During hardening of the epoxy, a constant uniform pressure was applied on the composite fabric surface in order to extrude the excess epoxy resin and to ensure good contact between the epoxy, the concrete and the fabric. This operation was carried out at room temperature. Concrete beams strengthened with glass fiber fabric were cured for 24 hours at room temperature before testing.

4.4 EXPERIMENTAL SETUP

All the specimens were tested in the loading frame of the "Structural Engineering" Laboratory of National Institute of Technology, Rourkela. The testing procedure for the entire specimen was same. After the curing period of 28 days was over, the beam as washed and its surface was cleaned for clear visibility of cracks. The most commonly used load arrangement for testing of beams will consist of two-point loading. This has the advantage of a substantial region of nearly uniform moment coupled with very small shears, enabling the bending capacity of the central portion to be assessed. If the shear capacity of the member is to be assessed, the load will normally be concentrated at a suitable shorter distance from a support.

Two-point loading can be conveniently provided by the arrangement shown in. The load is transmitted through a load cell and spherical seating on to a spreader beam. This beam bears on rollers seated on steel plates bedded on the test member with mortar, high-strength plaster or some similar material. The test member is supported on roller bearings acting on similar spreader plates.

The loading frame must be capable of carrying the expected test loads without significant distortion. Ease of access to the middle third for crack observations, deflection readings and possibly strain measurements is an important consideration, as is safety when failure occurs.

The specimen was placed over the two steel rollers bearing leaving 150 mm from the ends of the beam. The remaining 2000 mm was divided into three equal parts of 667 mm as shown in the figure. Two points loading arrangement was done as shown in the figure. Loading was done by hydraulic jack of capacity 100 KN. Three number of dial gauges were used for recording the deflection of the beams. One dial gauge was placed just below the center of the beam and the remaining two dial gauges were placed just below the point loads to measure deflections.

4.5 FABRICATION OF CFRP LAMINATES

To meet the wide range of needs which may be required in fabricating composites, the industry has evolved over a dozen separate manufacturing processes as well as a number of hybrid processes. Each of these processes offers advantages and specific benefits which may apply to the fabricating of composites. Hand lay-up and spray-up are two basic molding processes. The hand lay-up process is the oldest, simplest, and most labour intense fabrication method. The process is most common in FRP marine construction. In hand lay-up method liquid resin is placed along with reinforcement (woven glass fiber) against finished surface of an open mould. Chemical reactions in the resin harden the material to a strong, light weight product. The resin serves as the matrix for the reinforcing glass fibers, much as concrete acts as the matrix for steel reinforcing rods. The percentage of fiber and matrix was 50:50 in weight.

Contact molding in an open mould by hand lay-up was used to combine plies of woven roving in the prescribed sequence. A flat plywood rigid platform was selected. A plastic sheet was kept on the plywood platform and a thin film of polyvinyl alcohol was applied as a releasing agent by use of spray gun. Laminating starts with the application of a gel coat (epoxy and hardener) deposited on the mould by brush, whose main purpose was to provide a smooth external surface and to protect the fibers from direct exposure to the environment. Ply was cut from roll of woven roving. Layers of reinforcement were placed on the mould at top of the gel coat and gel coat was applied again by brush. Any air which may be entrapped was removed using serrated steel rollers. The process of hand lay-up was the continuation of the above process before the gel coat had fully hardened. Again, a plastic sheet was covered the top of plate by applying polyvinyl alcohol inside the sheet as releasing agent. Then, a heavy flat metal rigid platform was kept top of the plate for compressing purpose. The plates were left for a minimum of 48 hours before being transported and cut to exact shape for testing.

4.6 DETERMINATION OF ULTIMATE STRESS, ULTIMATE LOAD AND YOUNG'S MODULUS

The ultimate stress, ultimate load and Young's modulus are determined experimentally by performing unidirectional tensile tests on specimens cut in longitudinal and transverse directions, and at 45° to the longitudinal direction, as described in ASTM standard: D 638-08 and D 3039/D 3039M - 2006. A thin flat strip of specimen having a constant rectangular cross section was prepared in all cases. The dimension of the specimen was taken as below:

LENGTH (mm)	WIDTH (mm)	THICK (mm)
1000	100	100

Table 4.1 size of the specimen for tensile stress

The specimens were cut from the plates themselves by diamond cutter or by hex saw. After cutting in the hex saw, it was polished in the polishing machine. At least three replicate sample specimens were tested and mean values adopted.

Coupons were machined carefully to minimize any residual stresses after they were cut from the plate and the minor variations in dimensions of different specimens are carefully measured. For measuring the Young's modulus, the specimen is loaded in INSTRON 1195 universal testing machine monotonically to failure with a recommended rate of extension (rate of loading) of 5 mm/minute. Specimens were fixed in the upper jaw first and then gripped in the movable jaw (lower jaw). Gripping of the specimen should be as much as possible to prevent the slippage. Here, it was taken as 50mm in each side. Initially strain was kept at zero. The load, as well as the extension, was recorded digitally with the help of a load cell and an extensometer respectively. From these data, engineering stress vs. strain curve was plotted; the initial slope of which gives the Young's modulus. The ultimate stress and ultimate load were obtained at the failure of the specimen.

Figure 5.2 Curing of Beam

V. RESULT

Principle test results of beams are summarized in Table 5 and comparison of loads of all the tested beams are shown in Fig. 5. It can be inferred from the results that the load carrying capacity of laminated RC beam (RBC S 5), at first crack, yield and ultimate stages have increased by about 31%, 41% and 33% respectively, when compared to the control beam. This shows the influence of CFRP lamination on the load carrying capacity of the strengthened beam, which is along expected lines. It should be noted that the increase in the load is highest, among the above three stages, at yield point. However, the above (highest) level of increase could not be sustained beyond the yield point, may be due to sudden debonding of the laminate. Nonetheless, the very high increase in the load carrying capacity due to CFRP lamination can be advantageously used in actual structural engineering applications. have reported that the use of CFRP laminates for strengthening of RC beams increases the ultimate load-carrying capacity significantly.

SI. NO.	BEAM DESIGNATION	ADHSIEVE	NO OF LAYER	CFRP LAMINATE THICKNESS (MM)
1	RBC 0	**-**	**-**	**-**
2	RBC S 5	Epoxy	Single	**5**
3	RBC D 5	Epoxy	Double	**5**

Table 6.1 Specimen details

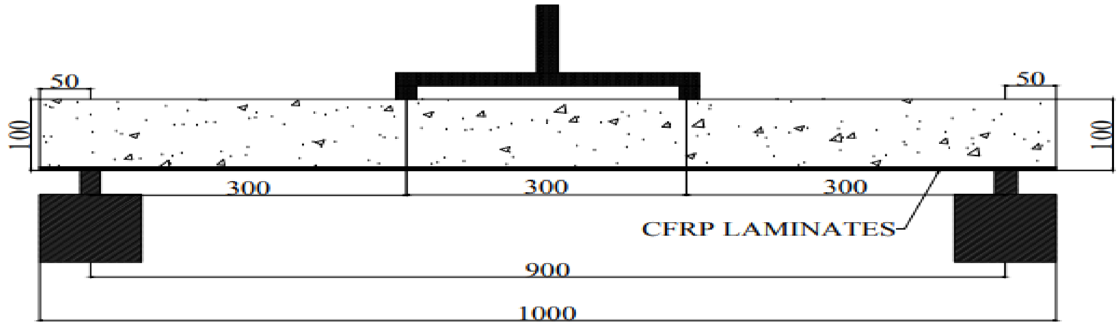


Fig. 6.1 Schematic diagram of experimental test setup

S.NO	BEAM DESIGNATION	FIRST CRACK LOAD (KN)	FIRST CRACK DEFECTION (MM)	YIELD LOAD (KN)	YIELD LOAD DEFECTION (MM)
1	RBC 0	17.54	1.25	34.00	3.61
2	RBC S 5	23.00	1.30	48.00	3.76
3	RBC D 5	28.16	1.90	57.82	4.05

LOAD AT DEBONDING INITIATION (KN)	DEFECTION AT DEBONDING INITIATION (MM)	ULTIMATE LOAD (KN)	ULTIMATE LOAD DEFECTION (MM)
-	-	42.34	8.60
51.29	4.24	56.5	6.30
62.43	5.84	68.5	10.6

Table 6.2 Results of tested beams

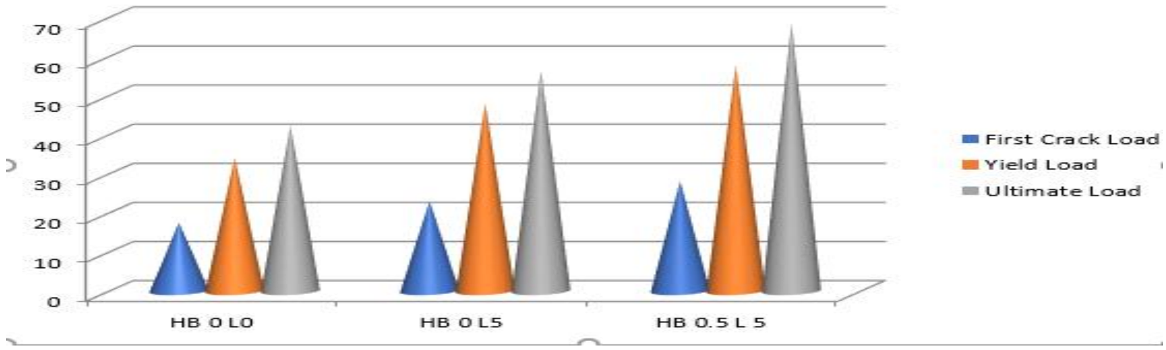


Fig no 6.2 Load comparison at various stages of tested beams

S.NO	BEAM DESIGNATION	DUCTILITY	DUCTILITY RATIO	MODE OF FAILURE
1	RBC 0	2.38	1	Flexural failure
2	RBC S 5	1.67	0.70	Sudden debonding of CFRP laminates
3	RBC D 5	2.30	0.96	Gradual debonding of CFRP laminates

Table 6.3 Ductility and failure mode of tested beams

Load-carrying capacity and defection of the above beam. However, mere lamination of beam (RBC S 5) has reduced the ductility by about 30% than the 'control beam (RBC 0)', which is clearly due to the 'stoppering effect' of lamination, on the tension face of the beam, even though the actual material used for lamination is a lightweight and flexible material. Similar behavior (as stated above) has been reported by Spadea et al. [34] and Hawish et al. [35] due to CFRP and CFRP lamination on tension face of a beam. Thus, there will be stiffening effect of lamination, irrespective of the type of lamination, whereas, the 'degree of stiffening' may vary. This 'stiffening effect' contributes to the increased load-carrying capacity up to the 'debonding' of laminate. Ductility and ductility ratios are maximum for the strengthened HFRC beam with Vf=1.5%, which incidentally also carries the maximum load. Thus, there is combined effect of lamination and hybrid-fiber reinforcement, which is highly advantageous for structural applications. It is to be noted that the increase in ductility of laminated RC beam (RBC D 5) is 62% than the mere laminated RC beam, which is very very high, and may be attributed slowly to the addition of this kind of hybrid -Fibers used in this study.

DEBONDING BEHAVIOUR AND FAILURE MODES

Load at initiation of debonding of laminate and the corresponding defection at that stage for all beams tested are summarized in Table 5. The load at initiation of debonding and the corresponding deflection for all strengthened HFRC beams (HB0.5L5 to HB1.5L5) increase with the increase in Vf up to Vf=1.5% and thereafter decrease for Vf= 2.0% (HB2.0L5). The above trend is similar to the behavior of load-carrying capacity and deflection at first crack, yield point and at ultimate stage of the above beams. However, the actual load at initiation of debonding and defection at debonding lies between the yield point and ultimate stage, more specifically, slightly higher than the value of yield point. In other words, debonding (sudden/gradual) of the laminate occur immediately after the yield point for laminated and/or laminated HFRC beams. Any further increase in the load carrying capacity of the above beams is primarily due to the incorporation of hybrid Fibers. On the other hand, the defection of laminated HFRC beams at ultimate stage increases by more than two times than at the stage of initiation of debonding. This shows the ductility effect of hybrid Fibers used and plays a very significant role, especially, after 'debonding of animate'. The above phenomenon correlates well with the actual values of ductility/ductility ratios (Table 6). The failure modes of all tested beams are shown in Fig. 8a–f. As expected, the 'control beam' exhibits 'flexural mode' of failure, whereas laminated HFRC beams exhibit gradual debonding of laminate and ductile failure. The RC beam with lamination only exhibit sudden deboning of laminate. Further, thin and short vertical cracks appear at mid-span in tension zone in the laminated RC beam. However, in laminated HFRC beams more number of fine and uniform cracks appear closely, when compared to laminated RC beam.

VI. CONCLUSION

- CFRP lamination has contributed to the increase in the load-carrying capacity at first crack, yield and ultimate stages of a RC beam than the 'control beam' (that is un-laminated RC beam).
- The maximum yield and ultimate load- carrying capacity of laminated HFRC beam with Vf = 1.5% and 5 mm thick CFRP lamination (HB1.5L5), is 59% and 49% higher than laminated RC beam (RBC S 5) and 125% and 98% higher than the control beam (RBC 0).
- However, the defection of the above beam 5.5 mm and 15.0 mm respectively at yield and ultimate stages and the above maximum defections are 46.8% and 138.1% higher than the laminated RC beam. The permissibility of the above defection values has to be ascertained with respect to relevant codal provisions for a particular structural application
- Laminated HFRC beam (HB1.5L5) has the highest ductility and is 62% higher than laminated RC beam (RBC S 5), which is very highly advantageous from an application point of view.
- All the laminated beams have failed by 'debonding' just after the 'yield point' and ductile failure thereafter, until ultimate stage.

VI. REFERENCES

[1] Ghafoori E, Motavalli M, Botsis J, Herwig A, Galli M. Fatigue strengthening of damaged metallic beams using prestressed unbonded and bonded CFRP plates. Int J Fatigue 2012;44:303–15.

[2] Faber MH, Val DV, Stewart MG. Proof load testing for bridge assessment and upgrading. Eng Struct 2000;22(12):1677–89.

[3] US-FHWA U. Department of Transportation Federal Highway Administration. 2011. Available from: h http://www fhwa dot gov/bridge (accessed 2018).

[4] Stratford T, Cadei J, Hollaway L. CIRIA C595–Strengthening metallic structures using externally-bonded frp. Advanced Polymer Composites for Structural Applications in Construction. Elsevier 2004:693–700.

[5] Zhao X-L, Zhang L. State-of-the-art review on FRP strengthened steel structures. Eng Struct 2007;29(8):1808–23.

[6] Ghafoori E, Schumacher A, Motavalli M. Fatigue behavior of notched steel beams reinforced with bonded CFRP plates: Determination of prestressing level for crack arrest. Eng Struct 2012;45:270–83.

[7] Teng JG, Yu T, Fernando D. Strengthening of steel structures with fiber-reinforced polymer composites. J Constr Steel Res 2012;78:131–43.

[8] Miller TC, Chajes MJ, Mertz DR, Hastings JN. Strengthening of a steel bridge girder using CFRP plates. J Bridge Eng 2001;6(6):514–22.

[9] Schnerch D, Dawood M, Rizkalla S, Sumner E. Proposed design guidelines for strengthening of steel bridges with FRP materials. Constr Build Mater 2007;21 (5):1001–10.

[10] Hollaway LC, Teng JG. Strengthening and rehabilitation of civil infrastructures using fibre-reinforced polymer (FRP) composites. Elsevier 2008.

[11] Schnerch D, Rizkalla S. Flexural strengthening of steel bridges with high modulus CFRP strips. J Bridge Eng 2008;13(2):192–201.

[12] Shaat A, Fam A. Repair of cracked steel girders connected to concrete slabs using carbon-fiber-reinforced polymer sheets. J Compos Constr 2008;12(6):650–9.

[13] Teng JG, Fernando D, Yu T, Zhao X, editors. Debonding failures in CFRP strengthened steel structures. Proceedings of the Third Asia-Pacific Conference on FRP in Structures; 2012.

[14] Tavakkolizadeh M, Saadatmanesh H. Strengthening of steel-concrete composite girders using carbon fiber reinforced polymers sheets. J Struct Eng 2003;129 (1):30–40.

[15] Al-Saidy AH, Klaiber FW, Wipf TJ. Repair of steel composite beams with carbon fiber-reinforced polymer plates. J Compos Constr 2004;8(2):163–72.