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GFRP Strengthening Of RCC Continuous BEAMS

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ABSTRACT

Strengthening structures through external bonding of advanced fibre reinforced polymer (FRP) composite is turning out to be exceptionally well known worldwide amid the previous decade on the grounds that it gives a more practical and in fact better option than the conventional procedures much of the time as it offers better strength, good fatigue resistance, low weight, corrosion resistance, easy and rapid installation along with minimal change in geometry of the structure. Although many in-situ RC beams are continuous in construction, there has been a limited research in the area of FRP strengthening of continuous beams. In the present study, an experimental investigation is carried out to study the behavior of continuous RC beams under static loading. The beams are strengthened with externally bonded glass fibre reinforced polymer (GFRP) sheets and also with unbonded GFRP using steel bolt system. Different scheme of strengthening have been employed. The experiment consists of six continuous (two-span) beams with overall dimensions equal to (150×250×2300) mm. All the beams will have similar longitudinal and transverse steel reinforcement. One beam was not strengthened and was considered as a control beam, whereas all other beams were strengthened in various patterns with externally bonded GFRP sheets and unbonded GFRP with end anchorage using the steel bolt system. The present study examines the responses of RC continuous beams, in terms of failure modes, enhancement of load capacity and load deflection analysis. The results indicate that the shear strength of RC beams can be significantly increased by gluing GFRP sheets to the shear face. In addition, the unbonded sheets with end anchorage also improved the cracking behaviour of the beams by delaying the formation of visible cracks and reducing crack widths at higher load levels.

INTRODUCTION

General

Concrete structures might, for a mixture of reasons, be found to perform unacceptably. This could show itself by poor execution under static loading, as cracking or excessive deflections, or there could be insufficient extreme quality or strength. A structure is designed for a specific period and depending on the nature of the structure, its design life varies. Decay in solid structures is a noteworthy test confronted by the foundation and scaffold commercial ventures around the world. The degradation could be mainly due to nature's effects, which includes gradual loss of strength with ageing, corrosion in steel, highintensity loading, freeze-thaw cycles, temperature variation, or exposure to chemicals or saline water and due to ultra-violet radiations. As complete replacement or reconstruction of the structure will be cost effective, strengthening or retrofitting is an effective way to strengthen the same.

Reinforced concrete structures regularly need to face adjustment and change of their execution amid their administration life. The primary contributing components are change in their utilization, new plan guidelines, weakening because of consumption in the steel brought about by introduction to a forceful situation and mischance occasions, for example, seismic tremors. In such circumstances there are two conceivable arrangements: substitution or retrofitting. Full structure substitution may have determinate disservices, for example, high expenses for material and work, a more grounded natural effect and drawback because of interference of the capacity of the structure, e.g. activity issues. At the point when conceivable, it is frequently better to repair or redesign the structure by retrofitting.

Strengthening of BEAMS

For flexural strengthening, there are numerous techniques, for example, steel plate holding, segment expansion, outer post tensioning system, near or close surface mounted (NSM) framework and EB or externally bonded framework. While numerous routines for fortifying structures are accessible, reinforcing structures by means of outside holding of cutting edge fiber-strengthened polymer composite (FRP) has turn out to be extremely prominent around the world. Amid the previous decade, their application in this field has been ascending because of the surely understood focal points of FRP composites over different materials. Thus, an awesome amount of exploration, both test and hypothetical, has been led on the conduct of FRP-reinforced strengthened cement (RC) structures. In such manner, the advancing innovation of utilizing carbon-fortified fiber-strengthened polymers (CFRP) for fortifying of RC pillars has pulled in much consideration as of late.

ADVANTAGES OF FRP

Some of the basic advantages of FRP are listed below:

Low weight: FRP is considerably less thick and in this manner lighter than the proportional volume of steel. The lower weight of FRP makes establishment and taking care of altogether less demanding than steel. These properties are especially imperative when establishment is done in cramped areas. Different works like deals with soffits of extensions and building floor chunks are done from man-access stages as opposed to from full framework. The utilization of fiber composites does not altogether build the heaviness of the structure or the measurements of the part. Furthermore, on account of their light weight, the vehicle of FRP materials has negligible ecological effect.

Mechanical strength: FRP can give a most extreme material stiffness-density proportion of 3.5 to 5 times that of aluminum or steel. FRP is so solid and hardened for its weight, it can out-perform alternate materials.

Formability: The material can take up anomalies fit as a fiddle of the solid surface. It can be formed to any wanted shape. We can make or duplicate most shapes without hardly lifting afinger.

Chemical resistance: It is insignificantly receptive, making it perfect as a defensive covering for surfaces where there is chemical attack.

Joints: Joints and laps are not needed.

Corrosion resistance: FRP can be used to make durable structures as it does not rust away.

Low Upkeep: Once FRP is introduced, it requires insignificant support. The materials strands and tars are strong if effectively indicated, and oblige little support. In the event thatthey are harmed in administration, it is generally easy to repair them, by including an extra layer.

Long life: It has high imperviousness to weariness and has demonstrated incredibletoughness throughout many years.

Simple to apply: The utilization of FRP plate or sheet material is similar to applying wallpaper; once it has been moved on precisely to uproot entangled air and abundance cement it might be left unsupported. Fiber composite materials are accessible in long lengths while steel plate is by large restricted to 6 m.

SUITABILITY OF FRP FOR USES IN STRUCTURAL ENGINEERING

The quality properties of FRPs on the whole make up one of the essential purposes behind which structural designers select them in the configuration of structures. A material's quality is represented by its capacity to manage a heap without unnecessary twisting or disappointment. At the point when a FRP example is tried in hub strain, the connected power every unit cross-sectional zone (anxiety) is relative to the proportion of progress in an example's length to its unique length (strain). At the point when the connected burden is evacuated, FRP comes back to its unique shape or length. At the end of the day, FRP reactsstraight flexibly to pivotal anxiety. The reaction of FRP to pivotal pressure is dependent on the relative extent in volume of strands, the properties of the fiber and sap, and the interface bond quality. FRP composite pressure failure happens when the strands display great (frequently sudden and emotional) parallel or sides-way diversion called fiber clasping. FRP's reaction to transverse malleable anxiety is all that much subject to the properties of the fiberand lattice, the association between the fiber and grid, and the quality of the fiber-network interface. For the most part, in any case, elasticity in this bearing is extremely poor. Shear anxiety is affected in the plane of a range when outer burdens have a tendency to bring about two portions of a body to slide more than each other. The shear quality of FRP is hard to measure. For the most part, failure happens inside the framework material parallel to the strands. Among FRP's high quality properties, the most applicable highlights incorporate fabulous sturdiness and consumption resistance.

Applications Of Frp Composites In Construction

There are three expansive divisions into which utilizations of FRP in structural building can be characterized: applications for new development, repair and recovery applications, and design applications. FRPs have been utilized broadly by structural architects as a part of the outline of new development. Structures, for example, scaffolds and sections constructed totally out of FRP composites have exhibited uncommon strength, and powerful imperviousness to impacts of ecological presentation. Prestressing tendons, fortifying bars, network fortification and dowels are all samples of the numerous assorted uses of FRP in new structures. A standout amongst the most widely recognized uses for FRP includes the repairand restoration of harmed or crumbling structures. A few organizations over the world are starting to wrap harmed scaffold docks to avert crumple and steel-strengthened segments to enhance the auxiliary uprightness and to avoid clasping of the support. Modelers have additionally found the numerous applications for which FRP can be utilized. These incorporate structures, for example, siding/cladding, material, ground surface and parts.

Current Research On FRP

A genuine matter identifying with the utilization of FRPs in common applications is the absence of configuration codes and details. For about 10 years now, scientists from Europe,Canada and Japan have been working together their endeavors in any expectation of growing such reports to give direction to designers planning FRP structures.

REVIEW OF LITERATURE

Brief Review

This part gives a survey of writing on strengthening of RC concrete beams. This survey embodies writing on reinforced beams under two sorts of support conditions i.e. continuously supported and simply supported.

Simply Supported BEAM

Grace et al. (1999) explored the conduct of strengthened RC beams with GFRP and CFRP sheets and covers or laminates. They considered the impact of the quantity of layers, epoxy sorts, and pattern of strengthening on response of the RC beams. They discovered that all the beams experienced brittle failure, with obvious upgrade in strength, and thus requiring a higher design factor of safety.

Trial examinations, theoretical-based calculations and a number of simulations demonstrated that fortifying the strengthened concrete beams with externally-bonded CFRP sheets in the tension zone extensively expanded the strength at flexure, diminished deflections and also crack widths (Ross et al., 1999; Sebastian, 2001; Smith & Teng, 2002; Yang et al., 2003; Aiello & Ombres, 2004). It likewise changed the conduct of these beams under load type and failure pattern. Regularly the strengthened beams fizzled in a brittle manner, for the most part because of the loss of association between the concrete or cement and the composite material. They inferred that the surface preparation alongside soundness of cement could impact a definitive bond quality. From there on, Study on de-holding issues in beams remotely reinforced with FRP composites are done by numerous analysts.

Numerous agents utilized externally bonded FRP composites to enhance the flexural quality of RC concrete. To assess the flexural execution of the reinforced individuals, it is important to study flexural firmness of FRP fortified individuals at distinctive stages, for example, pre-cracking, post-breaking and post-yielding. Notwithstanding, just few mulled over are centered around the strengthened solid individuals reinforced under preloading or pre-cracking((Arduni&Nanni, 1997).

F. Ceroni (2010) explored the experimental program on RC beams remotely bonded with carbon Fiber Reinforced Plastic (FRP) overlays and Near Surface Mounted (NSM) bars under monotonic and cyclic burdens, the last ones described by a low number of cycles in the versatile and post-flexible extent. Comparisions on theoretical and experimental failure loads are examined in point of interest.

Obaidat et al. (2010) concentrated on the Retrofitting of reinforced concrete beams composite laminates while the main variables considered were steel reinforcement, the length and position of CFRP. The trial tests were performed to research the conduct of beams composed in such a route, to the point that either shear or flexural failure will occur. The beams were loaded in four-point bending until there was cracks. The beams were then emptied and retrofitted with CFRP. At last the bars were loaded until failure. The ABAQUSsystem was utilized to create FEMs to study the conduct of beams. From the analyses the load-deflection relationships until failure, failure modes and crack patterns were obtained and compared to the experimental results. The FEM results concurred well with the analyses when utilizing the binding model in regards to failure mode and load carrying capacity

In another examination, Kim (2011) carried on test investigations of 14 strengthened RC beams retrofitted with new hybrid FRP(fiber reinforced polymer) framework comprising carbon FRP (CFRP) and glass FRP (GFRP). The target of this study was to inspect impact of hybrid FRPs on structural conduct of retrofitted RC beams and to research if different groupings of CFRP and GFRP sheets of the hybrid FRPs have impacts on strengths of reinforced RC beams. The beams are loaded with different values before retrofitting to study the factor of initial loading on the flexural behavior of the retrofitted beam. Under loaded condition, beams are retrofitted with a few layers of hybrid FRPs, then the load increases until the beams achieve failure. Test outcomes presume that impacts of hybrid FRPs on stiffness and ductility of RC beams rely on number of FRP layers.

CONTINUOUS BEAM

Grace et al. (2001) explored the test execution of CFRP strips utilized for flexural reinforcing as a part of the negative moment area of a full-scale reinforced concrete beam. They considered two classes of beams (I and II) for flexural fortifying. Class I beams were intended to fail in shear where as Class II beams were intended to come up short in flexure. A total of five full scale beams of each class were tried. It was observed that beams of Class I failed due to diagonal cracking along with local debonding at the top. Meanwhile, beams ofClass II failed by delamination at the interface of the concrete surface and the CFRP strips. The ductile failures of all the beams were observed as the strips of were not stressed to theirmaximum capacity. The greatest increment of load carrying limit because of fortifying was seen to be 29% for Class I beams, and 40% for Class II beams.

Then again, Grace et al. (2005) performed another exploration work where three continuous beams were tried. And one of them was considered as a control beam and a ductile flexural failure happened. They strengthened the other two bars along their negativeand positive moment areas around the top and base faces on both sides as a U-wrap. It was reasoned that the fortified beams with the tri-axial fabric demonstrated more noteworthy ductility than the beams strengthened with CFRP sheets.

In another exploration, El-Refaie et al., (2003) inspected 11 RC beams (two-span) fortified in flexure with outer reinforced CFRP sheets. The beams were classified into two groups according to the arrangement of their internal steel reinforcement. Each group had one control beam. It was noted that, all strengthened beams showed less ductility compared withthat of control beams. A limit to the number of CFRP layers was found after which there was no further increase in the capacity of the beam. It was also seen that increasing the CFRP sheet length to cover the entire hogging or sagging zones did not prevent the failure of the CFRP sheets, which was the dominant mode of failure.

Ashour et al., (2004) tried 16 strengthened cement (RC) continuous beams with various reinforcements of inner steel bars and outside CFRP covers. Every single test example had the same geometrical measurements and were ordered into three gatherings asper the measure of interior steel support. Every gathering incorporated one non-reinforced control beam intended to fizzle in flexure. Three types of failure modes were watched, to be peeling failure of the concrete cover, laminate rupture and cover detachment. The ductility of every single reinforced beam was diminished in examination with their particular reference beam. Moreover, rearranged routines for assessing the flexural load capacity and the interface shear stresses between the concrete and the adhesive material were displayed. As in past studies, they watched that expanding the CFRP sheet length did not counteract peeling failure of the CFRP laminates.

Aiello et al., (2007) thought about the conduct between continuous RC beams reinforced with CFRP sheets at negative or positive moment areas and RC beams fortified atboth negative and positive moments. All the bars were fortified with one CFRP sheet layer and with the comment that the beams were not loaded at the mid-span. The control beams experienced a typical bending and failure of the reinforced beams happened by debonding of the CFRP sheets, along with crushing of the concrete. It was figured out that when the reinforcing was connected to both sagging and hogging areas the ultimate capacity was greatest.

As of late, Maghsoudi et al., (2009) inspected the flexural conduct and moment redistribution of RHSC (Reinforced High-Strength Concrete) continuous beams reinforced with carbon fiber. They watched that by expanding the quantity of CFRP layers, a ultimate capacity expands, and in the mean time ductility, moment redistribution, and ultimate strain of CFRP sheet diminish. Test outcomes likewise demonstrated that by expanding the quantity of CFRP sheet layers, there was an adjustment in the failure mode from ductile break to IC debonding.

OBJECTIVE AND SCOPE OF THE PRESENT WORK

The objective of the present work is to study the behavior of continuous beams strengthened with bonded and unbonded GFRP sheets under static loading condition. In the present work, behavior of RC continuous rectangular beams strengthened with externally bonded or unbonded GFRP is experimentally studied. The beams have same longitudinal and transverse steel reinforcement ratios. All beams have the same geometrical dimensions. These beams are tested up to failure by applying two points loading to evaluate the enhancement of its strength due to strengthening.

EXPERIMENTAL STUDY

The experimental part comprises of casting six two-span continuous rectangular reinforced concrete beams. All the beams had same longitudinal and transverse steel reinforcement ratios and were cast and tested to failure. The beams were strong in flexure and shear reinforcement was not strong. Beams geometry as well as the loading and support arrangements are illustratedin the figure below. All beams had the same geometrical dimensions: 150 mm wide × 250 mm deep × 2300 mm long.

One of the six beams was not strengthened by GFRP and was considered as a control or reference beam, whereas other five beams were strengthened with unbonded or externally bonded GFRP sheets. Experimental data on load, deflection and failure modes of each of the six beams were obtained. The change in the load carrying capacity and the failure modes of the beams are investigated for different types of strengthening pattern.

CASTING OF SPECIMEN

A proportion of **1: 1.6: 3.2** is taken for cement, fine aggregate and course aggregate for casting of beams. The mixing of these materials is done by using concrete mixture. The beams are cured for 28 days. Six concrete cube specimens of dimensions 150mm cube were made at the time of casting of every beam and were kept for curing. The uni-axial compressive tests on the concrete produced were performed and the average compressive strength (fcu) of the beams after 28 days for each beam was recorded.

MATERIALS FOR CASTINGCEMENT

Portland Slag Cement (PSC) of Konark brand is used for the experiment. It is tested for Its physical properties in accordance with Indian Standard specifications.

Tests were conducted on Cement and the results are as below:

1. Normal Consistency : 33%
2. Setting Times: Initial Setting Time: 85 minutes Final Setting Time: 485 minutes
3. 28-day Compressive Strength : 47.33 MPa
4. Fineness: 1 gm retained in 90 micron sieve

FINE AGGREGATE

The fine aggregate passing through 4.75 mm sieve is used. The grading zone of fine aggregateis zone III as per Indian Standard specifications.

WATER

Ordinary tap water is used for concrete mixing in all the mix.

COARSE AGGREGATE

Two grades of coarse aggregates are used one retained on 10 mm size sieve and the other grade contained aggregates retained on 20 mm sieve. Both the grades of coarse aggregates had equal weight age.

REINFORCING STEEL

All the beams had same longitudinal and transverse steel reinforcement ratios and were casted and tested to failure. The beams were reinforced with two 12 mm diameter at the bottom, two 10 mm diameter bars as top reinforcement throughout the length to strengthen the beam in flexure. Stirrups of 8 mm diameter high-yield Strength Deformed (HYSD) bars were provided throughout the beam at 150 mm center-to-center distance to make the beam weak in shear. And,finally 6 mm bars are used as hanger bars for lifting of the beam.

MIXING OF CONCRETE

Machine mixer is used for mixing of concrete thoroughly to produce uniform quality of concrete.

COMPACTION

Needle vibrator was used for proper Compaction and proper care was taken so as to prevent the displacement of the internal steel reinforcement cage. And then with the help of a wooden float and metal trowel, the concrete surface was leveled.

CURING OF CONCRETE

The loss of water due to evaporation can be prevented by curing which is important for the cement hydration and hardening of concrete. Here curing is done by pouring water on the jute bags spread over the concrete surface for 28 days.

STRENGTHENING OF BEAMS

At the time of bonding of glass fiber, the concrete surface was made rough using a coarse sand paper texture and then the surface was cleaned with an air blower to remove all dirt and debris.The fabrics were cut according to the size and then the epoxy resin was mixed according to the instructions of the manufacturer. The mixing was carried out in a plastic mug with 10 parts by weight of Hardener HY 951 to 100 parts by weight of Araldite LY 556. After mixing it uniformly, the epoxy resin was applied to the surface where the GFRP is to be applied. Then theGFRP sheet was placed on top of the coating and the resin was squeezed with the help of the roller. The entrapped air bubbles in the inter-phase were eliminated. The above process took place at room temperature. Concrete beams strengthened with GFRP were cured for at least 7 days before testing each of them.

Two beams were strengthened with unbonded glass fibre-reinforced polymer sheets with end anchorage using steel bolt system. The holes were made during casting and glass FRP sheets were applied externally on the surface without applying epoxy resin. And, steel bolts were inserted into the holes and using steel plates at both the ends the glass FRP sheets were applied.Finally, the beams were tested under two point loading.

EXPERIMENTAL SETUP

The beams were tested in the loading frame of the “Structural Engineering” Laboratory of National Institute of Technology, Rourkela. The procedure of testing was same for the all the beams. The two-point loading arrangement was used for the testing of the beams. Two-point loading was easily provided by the arrangement shown in the figure Fig 3.3

The load was transmitted to the beams through the load cell and a spherical seating. Thebeam was installed on rollers seated on steel plates bedded on the test member and cement wasput on the surface to provide a smooth surface. The roller bearings acting on the spreader platesprovided the support to the test member. The specimen was placed over the two steel rollers bearing and 150 mm from the length of the beam was left from both the ends of the beam. The 1000 mm remaining was bisected into 500 mm each. Two dial gauges are placed just below the center of the mid span of the beam i.e. just below the load point for recording the deflection of the beams.

TESTING OF BEAMS

All the six beams were tested one by one. All of them were tested in the same arrangement.The deformation readings in the dial gauge for each 10KN of load were recorded throughoutthe test. The load at which the first visible crack is developed is recorded as cracking load.Then the load is applied till the ultimate failure of the beam. The dial gauges placed at mid-spans measured the deflections at different loads (multiples of 10KN) for all beams with andwithout GFRP. The data furnished in this chapter have been interpreted and discussed in the next chapter to obtain a conclusion.

BEAM -1 CONTROL BEAM (CB1)

The control beam, CB1, failed in the RC shear failure mode. The wide diagonal shear cracks were observed. The cracks were well extended from mid support to the left centre span. The first crack of CB1 was obtained at 80KN load and the ultimate failure of the beam occurred at 240KN load.

BEAM-2

STRENGTHENED BEAM 1 (SB1)

Single layer of glass FRP was applied at the surfaces as shown in the above figure to prevent shear failure. And it was observed that the beam failed due to debonding of FRP sheet, and flexural as well as diagonal cracks were also observed. Ultimate load was found to be 288 KN.

BEAM-3
STRENGTHENED BEAM 2 (SB2)

Double layer of glass FRP was applied at the same surfaces as shown above in the figure to prevent shear failure. And it was observed that the beam failed due to debonding of FRP sheet.This beam showed higher strength compared to CB1 and SB1 and ultimate load was found to be 310KN.

BEAM-4
STRENGTHENED BEAM 3 (SB3)

Four layers of FRP were applied on the similar surfaces like in SB1 and SB2 to make it strong in shear. And the result was that this beam also failed due to debonding of FRP sheets and flexural cracks were found at the central support due to negative bending moment (hogging) at the central support. The ultimate load of this beam was 340 KN.

BEAM-5
STRENGTHENED BEAM 4 (SB4)

In SB4 beam, steel bolt system with unbonded FRP sheet was used to avoid debonding of FRP.

BEAM 6
STRENGTHENED BEAM 5

In SB4 beam, steel bolt system with unbonded FRP sheet was used to avoid debonding of FRP.FRP sheet was wrapped and steel bolts were used at the portion where there was shear failure in Beam number 5. And expectedly, the beam showed much resistance to shear failure. Interestingly, the beam developed cracks due to shear from the right mid-span to the end support and also cracks were found at the central support.

TEST RESULTS AND DISCUSSIONS

The loadings on the beams were a concentrated load at each mid-span and the experimental results thus obtained are discussed in terms of the failure mode observed and the load vs deflection curve. The crack patterns and the mode of failure of each beam are also described in this chapter. All the beams are tested for their ultimate strengths and it is observed that the control beam had less load carrying capacity than the strengthened beam. One beam from the series was tested as un-strengthened control beam and rest beams were strengthened with various patterns of FRP sheets. The different failure modes of the beams were observed for different beams.

EXPERIMENTAL RESULTSFAILURE MODES CONTROL BEAM

The control beam failed completely in shear. The failure started first at the center span areas and then propagated towards the central support and finally failed in shear.

STRENGTHENED BEAM

Generally, the rupture of FRP sheet was very quick and sudden, and a loud noise was audible indicating a sudden energy release and thus loss in load-carrying capacity. For all the strengthened beams, the failure modes are described as below.

The following failure modes were examined for all the tested beams:

- Shear failure
- Debonding failure (with or without concrete cover)
- Debonding along with shear cracks at the span

LOAD DEFLECTION AND LOAD CARRYING CAPACITY

The GFRP strengthened beams and the control beams are tested to find out their ultimate load carrying capacity. The deflection of each beam under the load point i.e. at the midpoint of each span position is analyzed. Mid-span deflections of each strengthened beam are compared with the control beam. It is noted that the behavior of the beams when unbonded or bonded with GFRP sheets are better than the control beams. The mid-span deflections of the beams are lower when bonded externally with GFRP sheets. The strengthened beams were found to have higher stiffness than the control beams. Increasing the numbers of GFRP layers generally reduced the deflection at mid span and increased the beam stiffness for the same value of load.

LOAD-DEFLECTION CURVES FOR ALL BEAMS

The deflections at the mid-spans were recorded at various loads for control as well as the strengthened beams and the load-deflection curves of the strengthened beams were contrasted with the control beams and the conclusions were drawn for each beam.

STRENGTHENED BEAMS

Load-displacement curve for SB 1 vs CB

To strengthen SB1, single layer of glass FRP was applied at the surfaces to prevent shear failure. And it was observed that the deflection values were less than that of the control beam for the same load value. At lower load value, debonding of FRP without concrete cover occurred and SB1 finally failed in shear. At the load of 110 KN initial cracks appeared. Later on increasing the load values, the cracks propagated further and the beam failed with an ultimate load of 288 KN.

Load-displacement curve for SB 2 vs CB

SB2 was strengthened with two layers of glass FRP applied at the surfaces similar to SB1 to prevent shear failure. And from Fig 4.2, it is clear that the deflection values of SB2 are less thanthat of the control beam for the same load value. At the load of 130 KN initial hairline cracks appeared. Later on increasing the load values, the cracks propagated further and the beam failedwith an ultimate load of 310 KN.

Load-displacement curve for SB 3 vs CB

Similarly, SB3 was strengthened with four layers of glass FRP. And, from the graphs in Fig 4.3 it is clear that the deflection values are much less compared to the control beam for the same load value. Moreover, the beam failed due to debonding of glass FRP sheets from the concrete cover and flexural cracks were found at the central support due to negative bending moment (hogging) at the central support. The ultimate load of SB3 was found out to be as high as 340 KN.

Load-displacement curve for SB 4 vs CB

The technique of strengthening the beams with unbonded glass FRP was used. End anchorage was provided using steel bolts and plates. In SB4, one layer of glass FRP was U-wrapped just under the loading points. The ultimate failure of the beam was in shear at 270 KN. And it was observed that the displacement values were nearer to that of the control beam.

Load-displacement curve for SB 5 vs CB

SB5 was also strengthened with unbonded glass FRP provided with end anchorages using steel bolts and plates. In SB5, one layer of glass FRP each was U-wrapped from loading point to central support .And expectedly, the beam showed much resistance to shear failure. Interestingly, the beam developed cracks due to shear from the right mid-span to the end support and also cracks were found at the central support. The ultimate failure occurred at 318 KN.

Thus, the load carrying-capacity of all the strengthened beams are discussed here, and it is found that beam SB3 has the maximum load capacity of 340 KN and maximum percentage increase of load carrying capacity, i.e., 41.67%. Moreover, the ultimate shear capacities of all the strengthened beams are higher than that of the control beam.

CONCLUSIONS

The present experimental study is carried out on the behavior of reinforced concrete rectangular beams strengthened by GFRP sheets. Six reinforced concrete (RC) beams weak in shear are casted and tested. All the beams had same longitudinal and transverse steel reinforcement ratios. The conclusions drawn from the experimental results are as follows:

1. The strengthened beams had higher load-carrying capacity as compared to the control beam.
2. The initial cracks in the strengthened beams appeared at higher loads compared to the control beam.
3. The test results show that on strengthening the beams using FRP technique, the shear capacity can be increased.
4. Strengthened beam SB3, which was strengthened by four layers of FRP showed the highest ultimate load value of 340 KN and the percentage increase in the load capacity of SB3 was 41.67 %.
5. On increasing the number of layers of glass FRP, the load carrying capacity of the beams also increases.
6. Unbonded FRP system with end anchorage using steel bolts and plates is a very new, time and cost-effective technique.

SCOPE OF THE FUTURE WORK

It promises a great scope for future studies. Following areas are considered for futureresearch:

a. Experimental study of continuous beams with opening

b. Non-linear analysis of RC continuous beam

c. FEM modeling of unanchored U-wrap

d. FEM modeling of anchored U-wrap

REFERENCES

[1]. Aiello MA, Valente L, and Rizzo A, "Moment redistribution in continuous reinforced concrete beams strengthened with carbon fiber-reinforced polymer laminates",*Mechanicsof Composite Materials*, vol. 43, pp. 453-466, 2007.
[2]. Aiello MA, and Ombres L, "Cracking and deformability analysis of reinforced concrete beams strengthened with externally bonded carbon fiber reinforced polymer sheet", *ASCEJournal of Materials in Civil Engineering*, vol. 16, No. 5, pp.292-399,2004.
[3]. Arduini M, and Nanni A, "Behaviour of pre-cracked R. C. beams strengthened with carbon FRP sheets", *ASCE Journal of Composites for Construction*, vol. 1, No. 2, pp. 63- 70, 1997.
[4]. Ashour AF, El-Refaie SA, and Garrity SW, "Flexural strengthening of RC continuous beams using CFRP laminates", *Cement and Concrete Composites*, vol. 26, pp. 765-775, 2003.
[5]. Ceroni F, "Experimental performances of RC beams strengthened with FRP materials",
[6]. *Construction and Building Materials*, vol. 24, pp. 1547-1559, 2010.
[7]. Grace NF, "Strengthening of negative moment region of reinforced concrete beams using carbon fiber- reinforced polymer strips", *ACI Structural Journal*, vol. 98, No. 3, pp. 347- 358, 2001.
[8]. Grace NF, Sayed GA, and Saleh KR, "Strengthening of continuous beams using fibre reinforced polymer laminates", *American Concrete Institute*, Farmington Hills, Mich, pp. 647-657, 1999.
[9]. Grace NF, Wael R, and Sayed AA, "Innovative triaxailly braided ductile FRP fabric forstrengthening structures", *7th International Symposium on Fiber Reinforce Polymer*
[10]. *for Reinforced Concrete Structures*, ACI, Kansas City, MO, 2005.
[11]. Grace NF, Abdel-Sayed G, Soliman AK, and Saleh KR, Strengthening of reinforced concrete beams using fibre reinforced polymer (FRP) laminates", *ACI Structural Journal*, vol. 96, No. 5, pp. 865-874, 1999.
[12]. Maghsoudi AA, and Bengar H, "Moment redistribution and ductility of RHSC continuous beams strengthened with CFRP", *Turkish Journal of Engineering and EnvironmentalSciences*, vol. 33, pp. 45-59, 2009.
[13]. Obaidat YT, Susanne H, Ola D, Ghazi A, Yahia A, "Retrofitting of reinforced concrete beams using composite laminates", *Construction and Building Materials*, vol. 25, pp. 591-597, 2010.
[14]. Smith ST, and Teng JG, "Debonding failures in FRP-plated RC Beams with or without U strip end anchorage" *FRP Composites in Civil Engineering*, vol. 1, pp. 607–615, 2001.
[15]. Ross CA, Jerome DM, Tedesco JW, and Hughes ML, "Strengthening of reinforced concrete beams with externally bonded composite laminates", *ACI Structural Journal*, vol. 96. No. 2, pp. 65-71, 1999.
[16]. Sebastian WM, "Significance of mid-span de-bonding failure in FRP-plated concrete beams", *ASCE Journal of Structural Engineering*, vol. 127, No. 7, pp.792-798, 2001.
[17]. Smith ST, and Teng JG, "FRP-strengthened RC beams I: Review of debonding strength models", *Engineering Structures*, vol. 24, No. 4, pp. 385-395, 2002.
[18]. Teng JG, Smith ST, Yao J, and Chen JF, "Intermediate crack-induced debonding in RC beams and slabs", *Construcion and Building Materials*, vol. 17(6–7), pp. 447–462, 2003.