VOL. 6, NO. 11, NOVEMBER 2011 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

FLEXURAL STRENGTHENING OF REINFORCED CONCRETE BEAMS USING FIBRE REINFORCED POLYMER LAMINATE: A REVIEW

Murali G. and Pannirselvam N.
School of Mechanical and Building Sciences, VIT University, Vellore, Tamil Nadu, India
E-Mail: murali_220984@yahoo.co.in

ABSTRACT

Several researches have been carried out on reinforced concrete beams strengthened with fibre reinforced polymer composites. A few works has been focused on strengthening of rectangular beams with different type and different thicknesses of fibre reinforced polymer. This paper reviews 12 articles on fibre reinforced polymer strengthened reinforced concrete beams. Finally, this paper attempts to address an important practical issue that is encountered in strengthening of beams with different type and different thicknesses of fibre reinforced polymer laminate. This paper also proposes a simple method of applying fibre reinforced polymer for strengthening the beam with different fibre reinforced polymer types with different thicknesses.

Keywords: concrete beams, carbon fibre reinforced polymer, glass fibre reinforced polymer, strengthening.

INTRODUCTION

Reinforced concrete (RC) structure using externally bonded fibre reinforced polymer (FRP) components has become a very universal practice, extensively accepted by recent design codes [1, 2]. In particular, the flexural strength of a reinforced concrete beam can be extensively increased by application of carbon (CFRP), glass (GFRP) and Aramid (AFRP) FRP plates/sheets adhesively bonded to the tension face of the beam. Glass fibre reinforced polymers sheets are being increasingly used in rehabilitation and retrofitting of concrete structures, since low cost comparison with other types of FRP fibres are generally high strength-to-weight ratio, corrosion resistance and fatigue resistance. A low weight of the fibre make it easy to handle without lifting equipment at site, negligible change of cross section, self weight and free height of a structure. Based on the chemical composition, properties and their usage glass fibres are classified as chopped strand mat, woven roving, continuous rovings, E-glass, S- glass, satin weave cloth and laminate. Glass fibres have temperature resistance and high strength but it is the low cost that makes GFRP the most fashionable FRP reinforcement in civil engineering applications. In the Asian region GFRPs have been found very attractive due to their cost competitiveness over carbon fibre composites [14]. Over past few years, external strengthening using FRP composites gained popularity over steel because of several reasons including material cost, lightweight feature, corrosion free and ease of application. At the same time, widespread experimental, numerical and analytical research has been carried out to understand and model the structural behaviour of FRP strengthened reinforced concrete beams. For literature reviews on different aspects of FRP strengthening of reinforced concrete structures, the interested reader is referred to [3-20]. Particular awareness has been given to recognizing and understanding the failure modes that reinforced concrete beams retrofitted with FRP. The experimentally identified that the failure modes can be grouped as follows: (1) flexural failure by concrete crushing (2) FRP rupture failure mode (3) Debonding failure mode and (4) shear failure. A more in depth explanation of these failure modes can be found in [17, 18]. Although CFRP composites are known to perform better under environmental action than glass fibre reinforced polymer laminates, no significant differences were detected, seemingly because failure was not due to rupture of the fibres [9].

APPLICATIONS OF FRP

For structural applications, FRP is mainly used in two areas. The first area involves the use of FRP sheets/plates which is to strengthen structurally deficient structural members with external application of FRP. Retrofitting 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. As an example, a highway reinforced concrete bridge slab in China was retrofitted using CFRP as shown in Figure-1 and a column in India was retrofitted using glass FRP wrapping as shown in Figure-2. The other application, use of FRP bars instead of steel reinforcing bars or pre-stressing strands in concrete structures.

PREVIOUS RESEARCH WORKS ON BEAMS

Investigation on the behaviour of FRP retrofitted reinforced concrete structures has in the last decade become a very important research field. In terms of experimental application several studies were performed to study the behaviour of retrofitted beams and analyzed the various parameters influencing their behaviour.

On the field of strengthening structure Michael *et al*., 1994 experimentally investigated fourteen reinforced concrete beams. The author examined three control beams having same steel reinforcement. They evaluated the strength behaviour by casting beams strengthened with aramid fabric (1 layer), E-glass fabric (3 layers) and graphite fibre fabric (2 layers) and their thickness of 1.04, 1.42 and 1.22 mm, respectively. They found that use of external composite fabric reinforcement increased the flexural capacity by 36 to 57% and 45 to 53% increase in flexural stiffness.

Houssam *et al*., 1997 investigated the long-term durability of concrete beams externally bonded with FRP sheets and studied the effect of harsh environmental conditions such as wet/dry cycling using salt water on the performance of FRP bonded concrete beams and on the interfacial bond between the fibre and the concrete. Four different types of FRP composite material were used: two carbons and two glasses with a thickness of 1.165, 0.118 and 1.3 mm, respectively. Three different two-part epoxy systems were used: epoxy I modified amine/epoxy resin blend, epoxy II polyoxypropylenediamine hardener/epoxy resin and epoxy III Amine saturant solvent-free epoxy. They studied that the specimens subjected to wet/dry conditions showed less improvement than those kept at room temperature. The reduction in strength improvement may be attributed to the degradation of the epoxy, which led to the weakening of the bond between the concrete specimens and the FRP sheets. Beams bonded with any of the four different FRP sheets using epoxy II exhibited the highest load capacity, under either condition, room temperature or wet/dry, compared with those bonded using epoxies I or III.

Figure-1. Flexural strengthening of a highway RC bridge slab, China.

Figure-2. Seismic retrofit of supporting columns for a cryogenic tank in Gujarat, India

Kachlakeva *et al*., 2000 examined four full-scale reinforced concrete beams were replicated from an existing bridge. The original beams were significantly deficient in shear strength, particularly for projected increase of traffic loads. Of the four replicate beams, one served as a control beam and the remaining three beams were implemented with varying configurations of CFRP and GFRP composites to simulate the retrofit of the existing structure. CFRP unidirectional sheets were placed at the tension side of the beam to increase flexural capacity and GFRP unidirectional sheets were utilized to mitigate shear failure results from this study show that the use of FRP composites for structural strengthening provides significant static capacity increases approximately 150% when compared to unstrengthened sections. Load at first crack and post cracking stiffness of all the beams was increased mainly due to flexural CFRP. Test results recommend that beams retrofit with both GFRP and CFRP should well exceed the static demand of 658 kNm sustaining up to 868 kNm applied moment. The addition of GFRP to the side face of the beam alone for shear was sufficient to offset the lack of steel stirrups and allow conventional reinforced concrete beam failure by yielding of the tension steel. This allowed ultimate deflections to be 200% higher than the pre-existing shear deficient beam.

Almusallam *et al*., 2001 examined a straightforward and efficient computational analysis to predict the nominal moment carrying capacity of RC beams strengthened with external FRP laminate. They investigated the determination of the limits on the laminate thickness in order to guarantee tensile failure due to steel yielding and to avoid tensile failure due to FRP laminate rupture. They cast eighteen specimens and were divided into three series. The first series consisting of three groups was employed as a control group without any strengthening. The second series consisting of three groups, first group were strengthened with one layer of GFRP laminate, second group were strengthened with two layer of GFRP laminate and third group were strengthened with four layer of GFRP laminate. The third series consisting of two groups, first group were strengthened with one layer of CFRP laminate and second group were strengthened with two layer of CFRP laminate. The thickness of GFRP and CFRP is 1.3 and 1 mm. They found that beam strengthened with CFRP laminate require less number of layers than those strengthened with glass FRP laminate for the same load capacity. The computational analysis to determine the nominal capacity of RC beams strengthened with external FRP laminate proved to be good and efficient in the prediction of experimental values and indicates that a significant gain in flexural strength can be achieved by bonding FRP laminate to the tension face of RC beams.

Grace *et al*., 2002 investigated thirteen rectangular beams. Two strengthening configuration were used such as strengthening material only on the bottom face beam and strengthening material on the bottom face and extending upto 150mm on both side face of beams.

Out of nine beams one beam were used as a control beam and four beams were strengthened with three carbon fibre strengthening material such as an uniaxial carbon fibre sheet, carbon fibre fabric and pultred carbon fibre plate. Remaining eight beams were strengthened with two different thickness of hybrid fabric. The thickness of hybrid fabric was 1.0 mm and 1.5 mm. The author investigated that the beam strengthened using carbon fibre strengthening system showed lower in yield load than those strengthened with hybrid fabric. The beam strengthened with hybrid fabric system showed no significant loss in beam ductility.

Brena *et al*., 2003 experimentally carried out tests on twenty rectangular beams. Two beams were used as reference beams and eighteen beams were strengthening using carbon fibre reinforced polymer. Four composite material systems used such as two unidirection carbon fibres, woven fabric and pultruded plates were applied to the surface of the beams with four different layouts. In the first layout the CFRP composites were attached to the soffit of beams. Second layout straps were wrapped around the bottom of the cross section and extended vertically to within 75 mm of the compression face. Third layout the longitudinal composites were positioned on the sides of the beams rather than on the bottom surface. Fourth layout the longitudinal composites were positioned on the sides of the beams rather than on the bottom surface in addition with that transverse straps were used with the side application of the composites. The author concluded that the debonding is prevented by adding transverse straps alone the shear span and debonding of the longitudinal composites was delayed. The flexural capacity of reinforced concrete beams can be increased by attaching CFRP laminate than control beams.

Adhikary *et al*., 2004 investigated the behaviour of aramid and carbon fibre reinforced polymer with nine rectangular reinforced concrete beams. One beam as a control and four beams were strengthened with AFRP sheet and the remaining was strengthened with CFRP sheet. The authors investigated four different layouts with CFRP sheets were attached to the U wrap of the beam. In the second and third layout CFRP sheets wrapped around the bottom and side face of the beam and anchored at the top of the beam at a distance of 80 and 110 mm from top longitudinal edge of the beam. The fourth layout compromises CFRP sheet with full wrapping of beam. The author found that the shear strengthening on reinforced concrete beams with externally bonded CFRP and AFRP was increased the maximum shear capacity 0f 123 and 118%. The FRP sheet with bonded anchorage that extends to the top face of the beam is much more effective for shear strengthening of reinforced concrete beams than the U-wrap scheme.

Sing *et al*., 2007 experimentally investigated twelve 2.8 m long reinforced concrete beams and tested till failure. The beams were divided into two groups based on loading location and two point loads are applied at 500 mm from the midspan of the beams in group A. In group B, this distance is 200 mm. There are six beams in each group: one beam was used as a control beam without external GFRP laminates, three beams bonded with one layer, two layers and three layers of 2.5 m long GFRP laminates. The other two beams were strengthened with one layer of GFRP laminates at length of 2.2 and 1.9 m. The nominal thickness of the laminate is 1.3 mm and the authors revealed that the bonding of the GFRP laminates; the ultimate strengths of the beams are enhanced to an extent of 18-46%. The increases of the stiffness of the beams are noticeable up to 24% of the control beam. By bonding GFRP laminates to the tension face of flexural RC beams, both strength and stiffness of the beams can be increased.

Pannirselvam, *et al*., 2008 analyzed fifteen rectangular beams experimentally of 3 m length. Three rectangular beams were used as control beam and the remaining were strengthened with GFRP laminates on the soffit of the rectangular beam. Three different steel ratios with two different GFRP types such as chopped strand mat and woven roving and two different thicknesses in each type of GFRP were used. The authors carried out the flexural test with two-point loading to study the performance of FRP plated beams interms flexural strength, deflection, ductility and compared with the unplated beams. The test results show that the beams strengthened with GFRP laminates exhibit better performance. The increase in first crack loads were 88.89% and 100% for 3 mm and 5 mm of woven rovings GFRP plated. The increase in ductility interms of energy and deflection was found to be 56.01% and 64.69% for 3 mm and 5 mm thick.

Nadeem *et al*., 2009 examined six reinforced beams which were divided in two groups such as group 1 and 2. The specimens of first group were designed to be weak in flexure and strong in shear, whereas specimens of second group were designed just in an opposite manner i.e., they were made weak in shear and strong in flexure. In each group, out of the three beams, one beam was taken as a control specimen and the remaining two beams were strengthened using two different CFRP strengthening schemes. For Group-1 specimens, in the first scheme, CFRP sheets were attached at the tension (i.e., bottom) face of the beam whereas in the second scheme, after externally bonding a single layer of CFRP sheets at the bottom tension face, U-strip anchorages were also provided at the ends of the beam. For Group-2 specimens, in the first scheme, CFRP strips were attached at 90º with respect to longitudinal axis of the beam, whereas in the second scheme strips were attached at an angle of 30º from the same axis of the beam. All the beams of two groups were tested under similar loading. They found that tension side bonding of CFRP sheets with U-shaped end anchorages is very efficient in flexural strengthening; whereas bonding the inclined CFRP strips to the side faces of reinforced concrete beams are very effective in improving the shear capacity of beams.

Amer Ibrahim, M. *et al*., 2009 investigated the six reinforced concrete beams externally reinforced with fiber reinforced polymer laminates using finite elements method adopted by ANSYS and the dimension of the beam was 3.2 x 1.5 x 2.5 m. The results from the analysis were compared with the experimental results. Two beams were used as reference beam and the one beam Strengthened by one layer of unidirectional transverse carbon/epoxy laminates CFRP inclined at an angle of 90º to the longitudinal axis with the thickness of 1.6mm. Another beam strengthened by two layers of unidirectional transverse E-glass/epoxy laminates GFRP inclined at an angle of 90º to the longitudinal axis with the thickness of 2.1mm. Another beam strengthened by warping with one layer of CFRP inclined at an angle of 90º to the longitudinal axis with the thickness of 0.18mm and final beam strengthened by warping with one layer of CFRP inclined at an angle of 90º with an additional layer of CFRP on both sides of the web inclined at an angle of 0^o to the longitudinal axis with the thickness of 0.18 mm. Author found that the load-deflection curves from the finite element analysis agree well with the experimental results in the linear range, but the finite elements results are slightly stiffer than that from the experimental results. The maximum difference in ultimate loads for all cases is 7.8% and the results obtained demonstrate that carbon fiber polymer is efficient more than glass fiber polymer in strengthening the reinforced concrete beams for shear.

Sundarraja *et al.*, 2009 investigated the thirteen rectangular beams; from the thirteen beams five control beams were taken (C1, C2, C3, C4 and C5). The beam C1 is the fully strengthened beam and used as a reference beam whereas the other beams have been made shear deficient by changing either the internal shear reinforcement or by changing the longitudinal reinforcement. The beam deficient in shear were externally bonded with GFRP strips on sides as well as in U-wrap fashion and were tested to check whether the beams have achieved the strength of that of the fully

Table-1. Experimental results and numerical simulation of load-carrying capacity of reference RC beams.

Author/ size of beam lxbxd (mm)	**Beam ID**	**Material**	**No of layer**	**fck MPa**	**Thickness** (mm)	**Adhesive**	**Ultimate load** (kN)	**Failure mode**
[3]/ 4880x 230x380	CB4-2S	CFRP	2	31	1.4	Epoxy resin	260	Concrete crushing
	CB6-3S	CFRP	3		1.4		275	Concrete crushing
	CB7-1S	CFRP	1		4.78		256	Concrete crushing
[4]/ 3620x 150x250	B1C-90	CFRP	1	27.54	1.6	Epoxy resin	119	Flexure
	B1G-90	GFRP	2	31	2.1		107	Flexure
	B2C90	CFRP	1		0.18		414	Flexure
	B2C-90-0	CFRP	1		0.18		420	Flexure
[5]/ 3500x 300x300	C1	CFRP	1	37.2	0.167	Epoxy resin	330	Diagonal shear+debonding
	C2	CFRP	1	41.0	0.167		457	Diagonal shear+ spalling
	C3	CFRP	1	41.1	0.167		475	Diagonal shear+ spalling
	C4	CFRP	1	42.4	0.167		500	Flexure
	A1	AFRP	1	39.6	0.286		310	Diagonal Shear+debonding
	A2	AFRP	1	41.8	0.286		400	Diagonal shear+ spalling
	A3	AFRP	1	43.9	0.286		490	Diagonal shear+ spalling
	A4	AFRP	1	43.5	0.286		488	Flexure
[6]/ 356x 51x51	C1I	CFRP	1	30	0.165	I-Modified amine/epoxy resin blend II-Polyoxypropylenediamin hardener/epoxy resin III-Amine saturantkolvent-free epoxy	8.00	Fabric debonding
	C1II	CFRP	1		0.165		8.70	Fabric debonding
	C1III	CFRP	1		0.165		6.80	Fabric debonding
	C2I	CFRP	1		0.165		9.80	Fabric debonding
	C2II	CFRP	1		0.165		11.30	Fabric debonding
	C2III	CFRP	1		0.165		7.90	Fabric debonding
	G1I	GFRP	1		0.118		6.30	Fabric debonding
	G1II	GFRP	1		0.118		6.50	Fabric debonding
	G1III	GFRP	1		0.118		4.80	Fabric debonding
	G2I	GFRP	1		1.30		7.70	Fabric debonding
	G2II	GFRP	1		1.30		8.90	Fabric debonding
	G2III	GFRP	1		1.30		8.00	Fabric debonding
[7]/ 2300x125x250	C1	CFRP	1	30	1.2	Sikadur	123.90	Debonding
[10]/ 1120x 127x76	A_1	Aramid	1	37.8	1.04		16.26	Fabric debonding
	A_2	Aramid	1		1.04		14.75	Concrete crushing
	A_3	Aramid	1		1.04		16.88	Concrete crushing
	E_1	E-glass	3		1.42		15.28	Fabric tensile failure
	E_2	E-glass	3		1.42	Sikadur 32	15.28	Fabric tensile failure

	E_3	E-glass	3		1.42		15.37	Fabric tensile failure
	G_1	Graphite	2		1.22		15.05	Fabric tensile failure
	G_2	Graphite	2		1.22		17.03	Fabric tensile failure
	G_3	Graphite	2		1.22		14.48	Fabric tensile failure
[11]/ 2744x 152x254	C1	CFRP	1	55.2	0.13	Epoxy resin	28.4	Steel yield followed by FRP rupture
	CS	CFRP	1		0.13		29.0	steel yield followed by concrete failure
[12]/2000x 200x300	BBFS-1	CFRP	1	35	1.0		241.50	Crushing of concrete
	BFS-2	CFRP	1		1.0	Epoxy resin	255.20	Crushing of concrete
[13]/3000	SR1CSM3	CSM	1	23.54	3	Epoxy resin and silica filler	22.07	Flexural failure
	SR1CSM5	CSM	1		5		39.24	Flexural failure
	SR1WR3	WR	1		3		44.15	Flexural failure
	SR1WR5	WR	1		5		51.50	Flexural failure
	SR2CSM3	CSM	1		3		41.69	Flexural failure
	SR2CSM5	CSM	1		5		44.15	Flexural failure
	SR2WR3	WR	1		3		49.05	Flexural failure
	SR2WR5	WR	1		5		56.40	Flexural failure
	SR3CSM3	CSM	1		3		51.50	Flexural failure
	SR3CSM5	CSM	1		5		58.86	Flexural failure
	SR3WR3	WR	1		3		74.80	Flexural failure
	SR3WR5	WR	1		5		55.86	Flexural failure
[15]/ 3000x 203x356	A1	CFRP Unidirectional fibre	2	35.1	0.165	Epoxy resin	119.7	Debonding
	A2		2	35.1	0.165		125.9	Debonding
	A3		2	35.1	0.165		138.3	Debonding
	A4		1	37.2	0.165		129.0	Debonding
	B1		2	37.2	0.168		132.6	Debonding
	B2	CFRP Unidirectional fibre	2	37.2	0.168		141.9	Rupture
	B3		2	37.2	0.168		137.0	Rupture
	B4		2	34.3	0.168		132.6	Rupture
	B5		2	34.3	0.168		129.9	Debonding
	C1		2	35.1	1.04		143.7	Debonding
	C2		2	35.1	1.04		125.9	Debonding
	C3	CFRP Woven fabric	2	35.1	1.04		149.0	Rupture
	C4		2	37.2	1.04		132.6	Debonding
	D1		1	37.2	1.19		128.1	Debonding
	D2		1	37.2	1.19		133.9	Debonding
	D3	CFRP Pultrtuded plate	2	37.2	1.19		158.8	Debonding
	D4		2	34.3	1.19		188.2	Debonding
	D5		2	34.3	1.19		180.6	Debonding
[19]/ 150x100	RF2	GFRP	1	29.11	0.363	Araldite GY 257 and Hardener HY 840,	53	Flexure failure
	RFU2	GFRP	1		0.363		55	Flexure failure + crushing of concrete
	RF3	GFRP	1		0.363		50	Flexure failure
	RFU3	GFRP	1		0.363		52	Flexure failure
	RF4	GFRP	1		0.363		48	Flexure failure
	RFU4	GFRP	1		0.363		55	Flexure failure + rupture of FRP
	RF5	GFRP	1		0.363		49	Concrete crushing
	RFU5	GFRP	1		0.363		50	Flexure failure + crushing of concrete
[20]/ 2050X 150X200	FG1	GFRP	1	37.5	1.3	Epoxy resin	70.40	Concrete crushing
	FG2	GFRP	2		1.3		82.40	Concrete crushing
	FG4	GFRP	4		1.3		105.90	Concrete crushing
	FC1	CFRP	1		1.0		81.90	Concrete crushing
	FC2	CFRP	2		1.0		103.10	Concrete crushing

strengthened beam. The beams strengthened by bonding GFRP strips in the side face of the beam are designated as RF2, RF3, RF4 and RF5, whereas those strengthened by providing U-wraps of GFRP strips are designated as RFU2, RFU3, RFU4 and RFU5. The reinforcement details of RF2 and RFU2 are same as that of C2. Similarly the reinforcement details of RF3 and RFU3, RF4 and RFU4, and RF5 and RFU5 are same as that of C3, C4 and C5, respectively. The author found that since the use of GFRP strips in the shear deficient beams, the initial cracks are formed at higher loads than their respective control beams. This shows that use of GFRP strips are more efficient in the case of shear strengthening of structures and the ultimate strength of beams can be increased by the use of

GFRP inclined strips. The ultimate loads of beams strengthened with U-wrapping were greater than the beams retrofitted by bonding the GFRP strips on the sides alone.

COMMENTS ON THE ACTUAL STATE OF ART

From the above review of literature (Table-1) illustrates that although substantial research has been conducted on FRP strengthening of reinforced concrete beams but still the behavior of FRP strengthened beams under different thickness of GFRP and CFRP schemes of strengthening is not well established. In all the above cases, it is seen that the thickness of GFRP and CFRP laminates were chosen arbitrarily. There is no design guideline for optimizing and choosing the thickness of FRP sheet/laminate for strengthening RC beams. Most of the researches were conducted on RC rectangular sections which are strengthened in flexure with different type of FRP with constant thickness of GFRP and which are strengthened with 1, 2 and 3 layer of FRP.

PROPOSED METHOD OF STRENGTHENING

To overcome the problems stated above, the future new technique for strengthening the beam with the different type of GFRP (chopped strand mat, woven roving and uni-directional) and CFRP with the different thickness to understand the behaviour of strengthened beam for varying thickness of FRP. The study parameters included first crack load, yield load, ultimate load, first crack deflection, yield deflection, ultimate deflection, crack width, deflection ductility and energy ductility has to be investigated with different thickness of FRP.

At the end, the proposed study is to improve the understanding of reinforced concrete beams retrofitted with different thickness of FRP and this proposal brings new challenges for professionals and who are working in the field of structural repair and strengthening of reinforced concrete structures and due to the latest technologies in binding the delamination concept can be totally eradicated

CONCLUSIONS

This paper reviewed the existing research works on reinforced concrete beams strengthening by FRP. The beam strengthened with more than one layer of FRP laminate unnecessarily increase the strengthening time as well as cost by providing more than one layer of FRP laminate. The importance to study the strengthening of the beam with different thickness of FRP to optimize the thickness of FRP in the strengthening system provides an economical and versatile solution for extending the service life of reinforced concrete structures. From the literature, it is evident that epoxy resin favoured in strengthening and eliminates the debonding failure. Most of the researchers adopted the grade of concrete such as M30 and M35. The research can be extended for higher strength. Future research is needed for a complete awareness for strengthening reinforced concrete beams with different thickness of FRP, with the aim to contribute in the concrete structures repair tasks efficiently as well as to decrease the dimensional stability of the structure.

REFERENCES

[1] 2003. ACI Committee 440. Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-02). American Concrete Institute, Farmington Hills, Michigan, USA.

[2] 2008. ACI Committee 440. Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-08). American Concrete Institute, Farmington Hills, Michigan, USA.

[3] Alagusundaramoorthy. P, Harik. I. E, M. ASCE and Choo. C. C. 2003. Flexural Behavior of RC Beams Strengthened with Carbon Fiber Reinforced Polymer Sheets or Fabric. Journal of composites for construction. pp. 292-301.

[4] Amer M. Ibrahim, Mohammed and Sh. Mahmood. 2009. Finite Element Modeling of Reinforced Concrete Beams Strengthened with FRP Laminates. European Journal of Scientific Research. 30: 526-541.

[5] Bimal Babu Adhikary, Hiroshi Mutsuyashi and Muhammed Ashraf. 2004. Shear Strengthening of Reinforced Concrete Beams Using Fiber-Reinorced Polymer Sheets with Bonded Anchorage. ACI Structural journal. pp. 660-668.

[6] Houssam A. Toutanji and William Gomez. 1997. Durability Characteristics of Concrete Beams Externally Bonded with FRP Composite Sheets. Cement and Concrete Composites. 19: 351-358.

[7] Jumatt. M.Z and Alam. A. 2008. Experimental and Analytical Investigation on the Structural Behaviour of Steel Plate and CFRP Laminate Flexurally Strengthened Concrete Beams. Journal of applied sciences. 8(23): 4383-4389.

[8] Kachlakeva. D and Mc Curry. D.D. 2000. Behavior of Full-Scale Reinforced Concrete Beams Retrofitted for Shear and Flexural with FRP Laminates. Composites: Part B. 31: 445-452.

[9] Manuel A.G. Silva and Hugo Biscaia. 2008. Degradation of Bond between FRP and RC Beams. Composite Structures. 85: 164-174.

[10] Michael J. Chajes, Theodore A. Thomson JR, Ted F. Januszka and William W. Finch JR. 1994. Flexural strengthening of Concrete Beams using Externally Bonded Composite Materials. Construction and Building Materials. 8: 191-201.

[11]Nabil F. Grace, George Abdel-Sayed and Wael F. Ragheb. 2002. Strengthening of Concrete Beams Using Innovative Ductile Fiber-Reinforced Polymer Fabric. ACI Structural journal. pp. 692-700.

[12]Nadeem A. and Siddiqui. 2009. Experimental Investigation of RC Beams Strengthened with Externally Bonded FRP Composites. Latin American journal of solid and structures. 6: 343-362.

[13]Pannirselvam. N, Raghunath P.N. and Suguna. K. 2008. Strength Modeling of Reinforced Concrete Beam with Externally Bonded Fibre Reinforcement Polymer Reinforcement. American J. of Engineering and Applied Sciences. 1(3): 192-199.

[14]Saadatmanesh H. 1994. Fiber composites for New and Existing Structure. ACI Structutral Journal. 91(3): 346-54.

[15]Serigo F. Brena, Regan M. Bramblett, Sharon L. Wood and Michael E. Kreger. 2003. Increasing Flexural Capacity of Reinforced Concrete Beams Using Carbon Fiber-Reinforced Polymer Composites. ACI Structural journal. pp. 36-46.

[16]Sing-Ping Chiew, M. ASCE, Qin Sun and Yi Yu. 2007. Flexural Strength of RC Beams with GFRP Laminates. Journal of composites for construction. ASCE. pp. 497-506.

[17]Smith S.T., Teng J.G. 2002. FRP-strengthened RC beams I: Review of Debonding Strength. Eng Struct. 24: 385-95.

[18]Smith S.T and Teng J.G. 2002. FRP-strengthened RC beams. II: Assessment of Debonding Strength Models. Engineering Structures. 24: 397-417.

[19]Sundarraja M.C. and Rajamohan S. 2009. Strengthening of RC beams in Shear Using GFRP Inclined Strips - An Experimental Study. Construction and Building Materials. 23: 856-864.

[20]Tarek H. Almusallam and Yousef A. Al-Salloum. 2001. Ultimate Strength Prediction for RC Beams Externally Strengthened by Composite Material. Composites part B. 32: 609-619.