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RETROFITTING OF REINFORCED CONCRETE BEAMS USING FIBRE REINFORCED POLYMER (FRP) COMPOSITES – A REVIEW

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Abstract: Rehabilitation and strengthening of old structures using advanced materials is a contemporary research in the field of Structural Engineering. During past two decades, much research has been carried out on shear and flexural strengthening of reinforced concrete beams using different types of fibre reinforced polymers and adhesives. Strengthening of old structures is necessary to obtain an expected life span. Life span of Reinforced Concrete (RC) structures may be reduced due to many reasons, such as deterioration of concrete and development of surface cracks due to ingress of chemical agents, improper design and unexpected external lateral loads such as wind or seismic forces acting on a structure, which are also the reasons for failure of structural members. The superior properties of polymer composite materials like high corrosion resistance, high strength, high stiffness, excellent fatigue performance and good resistance to chemical attack etc., has motivated the researchers and practicing engineers to use the polymer composites in the field of rehabilitation of structures. This paper reviews fourteen articles on rehabilitation of reinforced concrete (RC) beams. The paper reviews the different properties of Glass Fibre Reinforced Polymer (GFRP) and Carbon Fibre Reinforced Polymer (CFRP) composites and adhesives, influence of dimensions of beams and loading rate causing failure. The paper proposes an enhanced retrofitting technique for flexural members and to develop a new mathematical model.

Keywords: Flexural Strengthening; CFRP; GFRP; Epoxy Resins

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INTRODUCTION

Externally bonded FRP composites may be laid on RC structures using FRP and epoxy adhesives. FRP can be retrofitted for any RC structural member like slab, beam, masonry wall or column. This paper deals with an extensive review of literature on earlier work done in the light of different types of FRP composites, its dimensions, type of adhesives used, experimental methodology conducted by various investigators so far.

FRPC Properties and applications

A polymer composite is a material which is composed of a polymer matrix or reinforcement and manufactured in the form of chopped strand or woven mat (Budinski, 1998). Types of polymer composites are shown in **Fig. 1**.

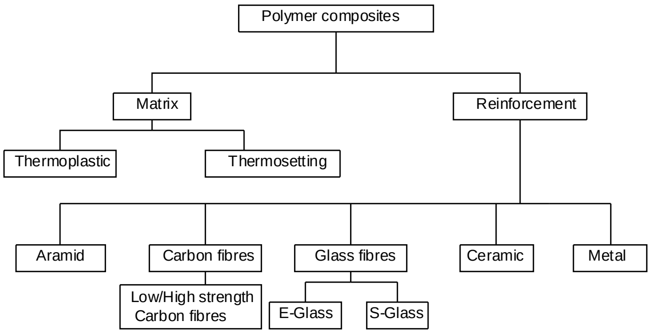

Fig. 1 Types of composites.

During the year 1994, about 60% of the total polymer composites consumption was used in the field of aerospace constructions. Later on composite materials were used for boat constructions and renovation works for buildings (Budinski, 1998).

At present, FRP composites are universally accepted for repairs and rehabilitation of buildings due to the availability of the same with superior mechanical properties. Also the Glass Fibre Reinforced Polymer (GFRP) composites are easily available in the market with less cost than Carbon Fibre Reinforced Polymer (CFRP) composites.

Although traditionally steel plates are used for retrofitting works despite its high density, corrosiveness, requirement of mechanical fasteners to get attached with concrete, FRP composites are popularly used.

Failure modes of a strengthened beam

The failures modes of FRP strengthened RC beams are classified into four types such as, concrete crushing, cover separation, debonding between FRP laminates and laminates separation (Au & Buyukozturk, 2013). Also to achieve expected load carrying capacity of FRP strengthened RC beam, premature failure, which occurs in a strengthened beam before reaching full composite action, has to be avoided (Nadeem, 2009).

PREVIOUS RESEARCH WORK ON RC BEAMS STRENGTHENED WITH FRP

Several investigations on strengthening of RC beams using different FRP composites and adhesives have been studied and discussed in this paper. **Table 1** shows the summary of test results, types and dimensions of FRP and beams, types of loading and types of adhesives used for RC beams modeling done by different investigators.

Hamid & Mohammad, (1991) have studied experimentally the characteristics of five rectangular beams, ‘A to E’ of cross section of size 205×455mm and one Tee beam ‘F’ of web size 205×455mm and flange of size 610×75mm. All beams were retrofitted using GFRP plates of dimensions 150×6mm cross section and a length of 4.26m at tension zone with epoxy resins. Beams were provided with different types of tension and shear reinforcements. Beam ‘A’ designed as shear deficient beam according to American Concrete Institute (ACI) code, to study the effect of shear crack. Two point load system at 610mm spacing was applied for all beams, to study the relationship between load and deflection, load and strain in concrete, steel reinforcement and GFRP plates for each beam. The FRP plate strengthened beams resist more loads and reduces crack width. An analytical model was developed based on equilibrium of forces and compatibility of deformations to predict the strength of beam to compare with the experimental values. It was suggested that the comparison study between analytical and theoretical values provide reasonable accuracy, however additional analytical study will be required to predict the strength of upgraded beams.

Grace *et al.* (1999) has tested fourteen pre-cracked beams including one control beam. GFRP and CFRP plates and three types of epoxy resins with different tensile strengths were used for strengthening the beams. Strength and ductility of FRP strengthened beams were studied, both vertical and horizontal layers of FRP plates were placed on bottom and sides of beams at different orientations for experiments. Concentrated load was acting at mid span of the beam. Based on experiments, the load carrying capacity has increased and deflection has reduced for strengthened beam over control beam. For example, the load carrying capacity of strengthened beam, ‘UG2-III’ with both horizontal and vertical layers of GFRP plates is almost two times that of the control beam. Also it was mentioned that, high value of factor of safety is to be taken in design, since all the FRP strengthened beams were subjected to brittle failure. Also the beam was strengthened with vertical layers over entire span of the beam to resist diagonal cracks.

Tarek & Al-Salloum (2001) have strengthened and tested the three beams with GFRP and two with CFRP composites using epoxy resins and test results were compared with a control beam. 1, 2 and 4 numbers of layer of 1.3mm GFRP and 1 and 2 layers of 1mm CFRP were used for externally strengthening beams. All beams were reinforced with 3-10mm diameter bars at tension zone, 1-6mm diameter bar at compression zone and 2 legged 8mm diameter stirrups at 100mm c/c. The developed equations based on ACI code for moment capacity of strengthened beams, thickness of FRP are theoretically verified with experimental values. Two point loads with spacing 200mm were applied for experiments. All beams were failed by concrete crushing at compression zone. It was concluded that the flexural strength of strengthened beams using FRP laminates at tension zone, more than that of control beam. Outcome results based on computational model which has been presented by the author were performed well in the prediction of experimental results.

Abdelhady *et al. (*2006) has studied on the influence of hybrid FRP wrapping techniques on the reinforced concrete Tee beams. Seven beams were tested including one control specimen. CFRP, GFRP and both laminates were provided at different locations, directions and connected with a beam by epoxy adhesives. The corners of the beams are rounded at radius of 15mm to fix 'U' wrap of thickness 0.117 and 0.135mm for CFRP & GFRP respectively. The beams were tested with two point cyclic loads acting at a distance of 750mm. The ultimate loads for strengthened beams are between 16.5 and 69.7 percent than controlled beam. Strain compatibility approach was used for ultimate load predictions and integration of the curvature along the span for deflection calculations. Theoretical values were compared with experimental values and it shows good correlation. The characteristics of beams can be determined by strain compatibility approach accurately.

Chiew *et al. (*2007) focused on the experimental work on two unstrengthened and ten flexurally strengthened beams using GFRP laminates. Total beams grouped into two, such as 'A' and 'B' based on points of application of loads. Spacing between two point loads are 1000mm and 400mm for group A and B respectively. Number of layers and length of GFRP laminates were varied for strengthened beams. Epoxy resin adhesive was used for attaching GFRP with beam. This experimental study shows that, two unstrengthened beams were failed by flexure and strengthened beams were failed by laminates debonding. The strength and stiffness were increased significantly for flexurally strengthened beams. The progress of debonding started from the point of loading towards the supports. Analysis of interface relationship between concrete and laminates was done by finite element method. Moment-deflection relationships for strengthened beams calculated by FE analysis were moderately well, since during the analysis, the interfacial debonding of FRP from the beam is negligible.

Pannirselvam *et al.* (2008) tested nine beams out of which six beams were strengthened with GFRP and three were controlled beams. A model was developed with the data available from seven beams by General Regression Neural Network (GRNN) technique using MATLAB and two beam results were used for testing the model. Also a varied tension reinforcement for beams 1, 2 and 3 such as 0.419, 0.603 and 0.905 percent respectively was studied. Two concentrated loads were applied on the beam at a spacing of 933mm. Load and deflections at first crack, yield and ultimate levels are measured for all beams. 3 and 5mm GFRP plates and epoxy adhesives were used for strengthening RC beams. First crack load was increased for beams by increasing thickness of plates. Yield strengths for strengthened beams were increased by a maximum of 76.49 and 111.79 percent for 3 and 5mm thick plates.

Jumaat & Alam, (2008) also worked on three beams of dimensions 125×250×2000mm such as A1, B1 & C1. A1 was kept as control beam; B1 and C1 were strengthened by steel plate of dimensions 2.76×73×1900mm and CFRP laminates of dimensions 1.2×80×1900mm respectively. Compression and shear reinforcements were provided only on ends of a beam. Those dimensions were designed based on simplified stress block method of BS 8110. Steel plate and CFRP laminate (SikaCarboDur S812) were provided full length off the beams to maximize the strengthening effects. From the experiments, it was found that the controlled beam A1 failed by flexure, while B1 failed by debonding followed by concrete cover separation and the beam C1 failed by debonding. Experimental results were compared with the values obtained by finite element analysis. From the comparison study it was found that those two results were almost equal for control beam, but failure loads for strengthened beams by finite element analysis were more than experimental results. The reason was, the FE analysis was done based on assumption of bond between strengthening materials and concrete surface was perfect.

In another research Sundarraja *et al. (*2008) tested thirteen beams including five control beams. All beams were divided into three sets based on wrapping such as five control beam 'C' without wrapping, four beams with vertical strips 'V' and four 'U' wrap strip beams. For 'V' group beams, strips were provided at a width of 15mm and c/c spacing of 45mm. The widths of these GFRP strips were designed based on ACI recommendations. GFRP composites were connected with beams using epoxy resins and hardener. The wrapped beams resist more load than controlled beams and the vertical GFRP strips prevent diagonal cracks significantly. It was concluded that the recommendations provided by ACI code can be used for design of strips for retrofitted works.

Amer & Mohammed (2009) analyzed theoretically by finite elements methods by ANSYS package on FRP retrofitted beams. Experiment investigated six shear deficient rectangular beams of cross section 150×250mm including two control beams B1 and B2. Epoxy resins were used to retrofit Carbon or Glass fiber reinforced polymers with RC beams. For B1C-90 type, one layer of 1.6mm CFRP laminates was provided perpendicular to the longitudinal axis of a beam. B1G-90 beam was similar to previous type but two layers of 2.1mm GFRP were used. For B2C-90 type, one layer of 0.18mm CFRP composites was wrapped perpendicular to the longitudinal axis of a beam. For B2C-90-0 type, two layers of 0.18mm CFRP composites were wrapped on two directions such as 90° and 0° to the longitudinal axis of a beam. Effect of directions of FRP composites on RC beams were studied, since it is an orthotropic material. The ultimate shear strength values of retrofitted beams by experimental values were good agreement with shear strength analyzed by finite element model, concluding that the carbon fibres were resisting more load than glass fibres retrofitted with beams.

Nadeem (2009) experimentally investigated six beams on strengthening of RC beams in flexure and shear using 1mm thick CFRP sheet and epoxy resins. The beams were categorized into two groups such as 1 and 2. Group 1 beams were weak in flexure and strong in shear and group 2 beams were weak in shear and strong in flexure. BCF and BCS were control beams from each group. For BFS-1&2 beams, one layer of CFRP was fixed at bottom and for BFS-2, additional 'U' wrap attached at ends of a beam. For BSS-1&2 beams, vertical and inclined CFRP strips were attached on the sides of a beam. Concentrated loads at a distance of 500mm were applied on all beams. It was found that, BCF, BCS and BFS-2 were failed by flexure, shear and concrete crushing at compression zone respectively. Remaining three beams were failed by debonding of laminates. Also it was observed that beam with CFRP sheets at bottom & 'U' shaped anchorages resisted more flexural load than BFS-1, and beam with inclined strips resisted more shear than vertical strips.

Pan *et al.* (2010) examined eight beams to study the effect of flexural and shear cracks on FRP debonding. The beams were grouped into two, on first group, opening in the shape of notches developed at tension zone along the length of the beam to avoid the secondary cracks in the shear or flexural portion (B1-B4). Single notch for beams B1, B2 and double notches for beams B3, B4 were provided at bottom and GFRP plates were connected at sides and bottom of the beams. Multiple cracks were developed for group two beams by preloaded technique (B5-B8). For beam B5 two shallow notches were provided at bottom. B6 and B8 were un-notched and GFRP plates were provided at bottom of the beams. B7 was un-notched but flexural or shear cracks were developed. All beams were anchored with 'U' shaped FRP plates. A mathematical model has been developed for determination of stress strain distribution along the FRP corresponding to number of secondary cracks and major cracks. Beams were strengthened using 0.22mm thick GFRP composites with epoxy resins. Two point loading system is applied at a loading span of 300mm. All beams were failed by FRP debonding. The average load carrying capacity of second group beams are much more than that of beams from first group. Developed mathematical model has been validated by the data which are available from experimental results, and it revealed that calculated stress and strain values using mathematical model were matched well with the experimental values.

Yasmeen *et al.* (2011) investigated twelve beams which were divided into two groups such as RF and RS. In RF group beams, reinforcements were deficient in flexure and shear and the beams were flexurally strengthened by 50mm CFRP plates at soffit of the beam by varying its lengths after preloading. In RS group, the beams were shear strengthened by 50mm CFRP strips at sides of the beam at a spacing of 100mm c/c and it is not provided at middle third 520mm portion. Out of which four beams were tested as control beams, two from RF and two from RS group. Thickness of CFRP used is 1.2mm and number of layer is 1 for both beam groups and epoxy resin is used to fix the beam. Two point loads were applied at a distance of 520mm. After loading, it has been noted that crack width of the strengthened beam has been decreased by comparing control specimen. All the strengthened beams were failed by brittle and followed by sudden CFRP debonding from the concrete. Control beams RF and RS were failed by flexure and shear. Two equal beams were casted in each set and the mean value has been considered as maximum load. Also it was found that load carrying capacity of strengthened beams was increased from 7 upto 33 percent in flexure and about 23 percent in shear.

Recently, Heshmi & Al-Mahaidi (2012) have presented an experimental work on RC beams retrofitted with CFRP textile and fabrics using cement based adhesives at high temperature. Testing of seven beams at cross sectional area of 120×180mm was done. The cement based adhesives consists of OPC, micro cement at ratio of 1:4, super plasticizer and silica fume. The beams were tested at two types such as beams subjected to high temperature at constant service load and failure load at constant temperature. The reinforced concrete beams retrofitted using epoxy adhesives were failed by CFRP delamination at a temperature of 462°C and performed similar to normal beam. On the other hand, beam retrofitted using cement based adhesives has resisted 844°C and this value is almost equal to the failure temperature of RC beams. The performances of beams such as crack pattern and strain distribution were theoretically determined by finite element analysis and values were compared with the test results, reveals that the two results are closely correlated.

Most recently Dong *et al.* *(*2013) has conducted test on fourteen beams divided into two groups such as flexural (CR) and flexural shear strengthening (SR) using FRP sheets. A study on the effect of beam size and concrete cover to the reinforcements on the flexural strength of strengthened beam was conducted. Concrete grades are not specified for CR group beams and it is common for that group, since beams were tested with varying cover thickness and reinforcement percentage. 28 days compressive strength for five beams of SR group was 22.8MPa and two beams of same group was 31.3MPa. One layer of GFRP sheet with size 1500×50×0.273mm and two layers of CFRP sheets of same length and width and 0.111mm thickness were applied on bottom and sides of the beams. Two point load system were applied on beams at a spacing of 500mm. While loading, three numbers of LVDT were fixed at bottom of beams at different locations to measure deflections. Experimental results show that, ultimate loads for flexural strengthened beams increased between 41 and 125 percent over control beam and shear capacity of strengthened beams increased by 31 and 74 percent. Based on existing data from previous studies, theoretical values were calculated and correlated with experimental values.

COMMENTS ON THE PRESENT STATE OF ART.

The above review of literatures on the field of strengthening of RC beams show that the researchers have tried GFRP, CFRP or hybrid laminates with different thicknesses and number of layers. Most of the research works have compared the experimental values with theoretical values. Out of fourteen papers, for theoretical analysis, Pannirselvam *et al.* (2008) have used General Regression Neural Network (GRNN) technique using MATLAB neural network, (Amer & Mohammed, 2009; Hashemi & Al-Mahaidi, 2012; Jumaat & Alam, 2008) and Sing *et al.* (2007) have used finite element analysis, in which (Hamid & Mohammad, 1991) has developed analytical model based on equilibrium of forces and compatibility of deformations, equations for moment capacity of strengthened beams. Also Sundarraja *et al.* (2008) has designed thickness of FRP laminate based on ACI code, while Abdelhady *et al.* (2006) has used strain compatibility approach for ultimate load predictions and deflection calculations.

PROBLEMS OF STRENGTHENING RC BEAMS

The study indicates that researchers have used FRP plane laminates at different number of layers. Authors (Hamid & Mohammad, 1991; Pannirselvam et al., 2008; Jumaat & Alam, 2008; Sundarraja, 2008; Yasmeen *et al.*, 2011; Heshmi & Al-Mahaidi, 2012) have used one layer of laminates, authors (Amer & Mohammed, 2009; Jinlong *et al.*, 2010; Jiangfeng *et al.*, 2013) have tried up to two layers of laminates, while authors Abdelhady *et al*, (2006) and Sing *et al.* (2007) has attached three layers and authors Grace *et al*, (1999) and Tarek & Al-Salloum (2001) used upto four layers.

According to ACI code assumptions, the bond between laminates and concrete surface is perfect (ACI 440.2R-08). But most of the cases discussed in failure modes of a strengthened beam, the failure of beams occurred due to debonding of laminates from concrete surface. 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 debonding of laminates occurs for beams retrofitted only at the bottom.

From theoretical analysis, the researchers have used only one tool for model development such as either finite element analysis or neural network.

PROPOSED METHOD OF STRENGTHENING THE RC BEAM

To overcome the problem discussed in this paper, in the proposed work, FRP composites are used to develop a new profile and investigations for its physical dimensions and structural behaviors, in flexural members. FRP laminates will be provided with full length of the beam to take into account shear and bending. To avoid premature failure, FRP laminates are provided at bottom and are extended to the sides also. Most of the authors have used epoxy resins for attaching FRP laminates with concrete surface due to its superior property by comparing other adhesives. The same resins will be used for proposed work. Thirteen authors out of the reviewed literatures have used two point load system for their experimental setup.

Table 1. Summary of test results, types & dimensions of FRP and beams, type of loading and type of adhesive used for RC beams

Author (year) / numbers & size of beam nos. x clear span x b x D *(mm)*	Load type / load spacing *(mm)*	Beam ID	Type of Fibers	No. of layers /type or location	FRP thickness t_f *(mm)*	Concrete grade *(MPa)*	Reinforcement details Zone-Nos.× *mm* ø and stirrups *mm* ø @ *mm* c/c or Nos.	Adhesive type	Failure load (*kN*) Type of failure/Remarks
Hamid & Mohammad, (1991) / 5(Rect.)×4570×205×455 & 1(Tee-beam) ×4570×(205×455 overall web) ×(610×75 flange)	Two point load/ 610	A (R)	GFRP	1/T	6	35	T–3×25&C–2×13	Epoxy	300/Concrete crushing
		B (R)	GFRP	1/T			T–2×25&C–2×13		250/Debonding
		C (R)	GFRP	1/T			T–2×13&C–2×13		182/Concrete failure
		D (R)	GFRP	1/T			T–2×25&C–2×13		270/Cover separation
		E (R)	GFRP	1/T			T - 0&C–2×13		64 /Premature failure
		F (Tee)	GFRP	1/T			T–2×25&C–3×13		300/Debonding
Grace *et al*, (1999) / 14 × 2743 × 152 × 292	One point load at mid span	CF-I	CFRP	1/H	5	48.26	T–2×16, C–2×16 & stirrups 8mm ø at 152 *mm* c/c for all beams	Epoxy Type I, II, III, IV with different tensile strength	104.5/FRP Rupture
		CFS-I	CFRP	2/H&V	5				110.3/FRP Rupture
		CFS-II	CFRP	2/H&V	13				108.9/FRP Rupture
		UG1-III	GFRP	4/2H&2V	10				164.5/FRP Rupture
		UG2-III	GFRP	4/2H&2V	10				177.9/Concrete crushing
		BG1-IV	GFRP	1/T & sides	13				80.0 / FRP Rupture
		BG2-IV	GFRP	2/T & sides	13				94.7 / Bond failure
		BG3-IV	GFRP	3/T & sides	13				92.5 / Bond failure
		BG2-IV-E4	GFRP	2/T & sides	13				142.2 / FRP Rupture
		BG2-IV-E1	GFRP	2/T & sides	13				129.0 / FRP Rupture
		CP1-V	CFRP	1/T	13				110.3 / Shear failure
		CP2-V	CFRP	1/T+(1/4) sides	13				120.1 / Shear failure
		CP3-V	CFRP	1/T+(1/2) sides	13				131.2 / Shear failure
Tarek & Al-Salloum (2001) / 6 × 2050 × 150 × 200	Two point load/ 200	F0 Control	-	0	-	37.5	T–3×10, C–1×6 & stirrups 8*mm* ø at 100*mm* c/c for all beams	Epoxy	35.31 All beams failed by concrete crushing at top
		FG1	GFRP	1/'U' wrap	1.3				70.4
		FG2	GFRP	2/'U' wrap	1.3				82.4
		FG4	GFRP	4/'U' wrap	1.3				105.9
		FC1	CFRP	1/'U' wrap	1.0				81.9
		FC2	CFRP	2/'U' wrap	1.0				103.1
Abdelhady *et al*, (2006) / 7 × 3000 × (Tee-beam) ×4570×(160×300 overall web) × (460×60 flange)	Two point cyclic load / 750	F00	Control	-	CFRP/0.117	25	T–2×16&C–2×10	Epoxy	100 /Ductile failure
		F01	CFRP	2/at bottom	GFRP/0.135		6@150 for flanges 10@150 for web		116.5/CFRP rupture
		F02	CFRP+GFRP	on sides + 3/at bottom					127.2/GFRP debonding
		F03	CFRP+GFRP	on sides +3/at bottom					117.3/Rupture of CFRP + GFRP
		F04	GFRP	3/at bottom					125.25/CFRP rupture
		F05	GFRP	2/different orientations					169.7/GFRP debonding
		F06	CFRP+GFRP	at bottom + on sides					110.25/Rupture of CFRP + GFRP

Author (year) /numbers & size of beam nos. x clear span x b x D *(mm)*	Load type / load spacing *(mm)*	Beam ID	Type of Fibers	No. of layers /type or location	FRP thickness t_f *(mm)*	Concrete grade *(MPa)*	Reinforcement details Zone-Nos.× *mm* ø and stirrups *mm* ø @ *mm c/c or Nos.*	Adhesive type	Failure load (*kN*)/Type of failure/Remarks
Sing-Ping Chiew *et al*, (2007) / 12 × 2600 × 200 × 350	Two point load/ A-1000 & B – 400	A1	GFRP	0	-	41.4	T–2×16 C–2×10 and stirrups 10*mm* ø mild steel at 150 *mm* c/c	Epoxy	163 /Flexure
		A2	GFRP	1/T, L – 2.5*m*	1.7				203.5 /Debonding
		A3	GFRP	2/T, L – 2.5*m*	3.4				219.25/Debonding
		A4	GFRP	3/T, L – 2.5*m*	5.1				238.5 /Debonding
		A5	GFRP	1/T, L – 2.2*m*	1.7				196 /Debonding
		A6	GFRP	1/T, L – 1.9*m*	1.7				204.75 /Debonding
		B1	GFRP	0	-				167.75 / Flexure
		B2	GFRP	1/T, L – 2.5*m*	1.7				201 /Debonding
		B3	GFRP	2/T, L – 2.5*m*	3.4				209 /Debonding
		B4	GFRP	3/T, L – 2.5*m*	5.1				243.25 /Debonding
		B5	GFRP	1/T, L – 2.2*m*	1.7				198 /Debonding
		B6	GFRP	1/T, L – 1.9*m*	1.7				200.25/Debonding
Pannirselvam *et al*, (2008) / 9 × 2800 × 150 × 250	Two point load/ 933	B1	GFRP	0	-	23.54	T-0.419%	Epoxy	34.34 Deflection at first crack, yield, ultimate deflections are noticed
		B2		0	-		T-0.603%		41.69
		B3		0	-		T-0.905%		63.77
		B1F3		1/T	3		T-0.419%		58.86
		B2F3		1/T	3		T-0.603%		73.58
		B3F3		1/T	3		T-0.905%		78.48
		B1F5		1/T	5		T-0.419%		63.77
		B2F5		1/T	5		T-0.603%		88.29
		B3F5		1/T	5		T-0.905%		105.46
Jumaat & Alam (2008) / 3 × 2000 × 125 × 250	Two point load/ 700	A1 Control	-	0	-	30	T–2×12, C–2×10 & stirrups 6*mm* ø at 75*mm* c/c for all beams	Sika-dur	80.59 / Flexure
		B1	Steel plate	1/T	2.76				104.3/ Debonding + cover separation
		C1	CFRP	1/T	1.2				123.9/Cover separation
Sundarraja *et al*, (2008) / 13 × 1000 × 100 × 150	Two point load/ 300	C1	-	0	1	20	T–2×10, C–2×8&6@75	Epoxy	49 / Shear
		C2	GFRP	0			T–2×10&6@75		47.5/ Shear
		V2	GFRP	1/Wf-15/Sf-45			T–2×10&6@75		48.1/ Concrete crushing
		U2	-	1/Wf-15/Sf-45			T–2×10&6@75		50.2/ Concrete crushing
		C3	GFRP	0			T–2×10, C–2×8&6@150		42 / Shear
		V3	GFRP	1/Wf-20/Sf-45			T–2×10, C–2×8&6@150		49 / GFRP tearing
		U3	-	1/Wf-20/Sf-45			T–2×10, C–2×8&6@150		50.5/ Concrete crushing + flexure
		C4	GFRP	0			T–2×10&–2×8		32 / Shear
		V4	GFRP	1/Wf-40/Sf-45			T–2×10&C–2×8		59 / GFRP tearing
		U4	-	1/Wf-40/Sf-45			T–2×10&C–2×8		52.3/ GFRP rupture + concrete crushing
		C5	GFRP	0			T–2×10, C–2×8&6@75		37 / Shear
		V5	GFRP	1/Wf-20/Sf-45			T–2×10, C–2×8&6@75		51 / Flexure
		U5	GFRP	1/Wf-20/Sf-45			T–2×10, C–2×8&6@75		50.1/ Concrete crushing

Author (year) /numbers & size of beam nos. x clear span x b x D *(mm)*	Load type / load spacing *(mm)*	Beam ID	Type of Fibers	No. of layers /type or location	FRP thickness t_f *(mm)*	Concrete grade *(MPa)*	Reinforcement details Zone-Nos.× *mm* ø and stirrups *mm* ø @ *mm c/c or Nos.*	Adhesive type	Failure load (*kN*) / Type of failure/Remarks	
Amer & Mohammed, (2009) / 6 × 2440 × 150 × 250	Two point load/1700	B1		0	-	27.54	T–2×13&C–2×10	Epoxy	69	Experimental ultimate loads have been compare with numerical loads and mode of failure not discussed. Stirrups 10mm ø at 600mm c/c used for B1 type beams &9mm ø at 300mm c/c used for B2 type beams
		B1C-90	CFRP	1/Uni directional	1.6	27.54	T–2×13&C–2×10		125	
		BIG-90	GFRP	2/Uni directional	2.1	27.54	T–2×13&C–2×10		116	
		B2	-	0	-	31	T–2×25&C–2×9		416	
		B2C-90	CFRP	1/90° to LA	0.18	31	T–2×25&C–2×9		435	
		B2C-90-0	CFRP	2/1 layer at 90° & 1 layer on both sides of web 0° to the LA	0.18	31	T–2×25&C–2×9		445	
Nadeem (2009) / 6 × 2000 × 200 × 300	Two point load/ 500	BCF Control	-	0	-	35	T–3×14&C–1×6	Epoxy	197.2 / Flexure	
		BFS-1	CFRP	1/T	1		T–3×14&C–1×6		241.5 / Debonding	
		BFS-2	CFRP	1/T+1/U wrap	1		T–3×14&C–1×6		255.2 / Concrete crushing at top	
		BCS Control	-	0	-		T–3×20&C–1×6		81.98 / Shear	
		BSS-1	CFRP	1/Vertical strips on sides	1		T–3×20&C–1×6		95.97 / Debonding	
		BSS-2	CFRP	1/Inclined strips on sides	1		T–3×20&C–1×6 and stirrups 10*mm* ø at 100 *mm* c/c for first 3 beams & 6*mm* ø at 150 *mm* c/c for remaining 3 beams		111.01 / Debonding	
Jinlong *et al*, (2010) / 8×1800×150 × 200	Two point load/ 300	B1	GFRP	2/T L-1.7*m* For all beams	0.22	42.9	T–2×10 8@14Nos.	Epoxy	28.43	All beams are failed by FRP debonding
		B2	GFRP						27.69	
		B3	GFRP						27.71	
		B4	GFRP						27.52	
		B5	GFRP						79.61	
		B6	GFRP						77.00	
		B7	GFRP						76.34	
		B8	GFRP						75.31	
Yasmeen *et al*, (2011) / 12×1560× 150 × 300	Two point load/ 520	2×RF	Control	0	-	29	**RF** T–2×12, C–2×10 & 6@100	Epoxy	118 / flexure	
		2×RF1	CFRP	1/L-1.56*m*, b-50	1.2				166 / debonding	
		2×RF2	CFRP	1/L-1.04*m*, b-50	1.2		**RS** T–2×18, C–2×10 & 6@400		142 / debonding	
		2×RF3	CFRP	1/L-0.52*m*, b-50	1.2				128 / debonding	
		2×RS	Control	0	-				220 / shear	
		2×RS1	CFRP	1/Wf-50/Sf-100	1.2				270 / debonding	

Author (year) /numbers & size of beam nos. x clear span x b x D *(mm)*	Load type / load spacing *(mm)*	Beam ID	Type of Fibers	No. of layers /type or location	FRP thickness t_f *(mm)*	Concrete grade *(MPa)*	Reinforcement details Zone-Nos.× *mm ø* and stirrups *mm ø @ mm c/c or Nos.*	Adhesive type	Failure load (*kN*) / Type of Failure / Remarks
Heshmi & Al-Mahaidi, (2012) / 7 × 1300 × 120 × 180	Two point load/ 200	Control-27 -HT	-	1/T & L-1.16*m* For all beams	Not Specified	57	T–2×10 C–2×8 & 10 @ 125	-	65.7/Steel yielding at 876° C
		ESF-38-HT	CFRP Fabric					Epoxy	90.7/Concrete crushing at 428° C
		ESF-38-HT	CFRP Fabric					Epoxy	90.7/Concrete crushing at 496° C
		MTF-38-HT	CFRP Textile					Mortar	90.8 / FRP debonding & rupture at 846° C
		MTF-38-HT	CFRP Textile					Mortar	90.8 / FRP debonding & rupture at 855° C
		MTR-39-HT	CFRP Textile					Mortar	94.9 / FRP debonding & rupture at 841° C
		MTR-39-HT	CFRP Textile					Mortar	94.9 / FRP debonding & rupture at 832° C
Jiangfeng *et al*, (2013)/ / 14×1500× 150×250	Two point load/ 500	CR1	Control	0	-	Cc-25	T–0.49%	N	54.30 / Flexure
150×250		CR2	CFRP	1/T&U anchor at supports	0.111	Cc-25	T–0.49%		76.93 / FRP rupture + flexure
150×250		CR3	CFRP	2/T&U anchor at supports	0.111	Cc-25	T–0.49%		93.66 / CFRP rupture + flexure
150×250		CR4	CFRP	2/T&U anchor at supports	0.111	Cc-25	T–0.49%		84.39 / CFRP debonding +shear
150×250		CR5	CFRP	2/ T&U anchor at supports	0.111	Cc-25	T–0.95%		121.7 / CFRP debonding +flexure
150×300		CR6	CFRP	2/ T&U anchor at supports	0.111	Cc-25	T–0.40%		95.89 / CFRP rupture + flexure
150×250		CR7	CFRP	2/T&U anchor at supports	0.111	Cc-35	T–0.51%		80.45/ CFRP debonding +flexure
150×300		SR1	Control	0	-	22.8	S–0.25%		111.49/ Shear
150×300		SR2	GFRP	1/'U' shape configuration	0.273	22.8	S–0.25%		146.20/ Flexure
150×300		SR3	CFRP	2/ diagonal 'L' shape configuration	0.111	22.8	S–0.25%		187.12/ CFRP rupture + flexure
150×300		SR4	CFRP	2/ diagonal 'L' shape configuration	0.111	22.8	S–0.38%		187.74/ CFRP rupture + flexure
150×250		SR5	CFRP	2/ diagonal 'L' shape configuration	0.111	22.8	S–0.25%		158.49/ CFRP debonding +shear
150×300		SR6	Control	0	-	31.3	S–0.25%		115.81/ Flexure
150×300		SR7	CFRP	2/ diagonal 'L' shape configuration	0.111	31.3	S–0.25%		193.35/ CFRP rupture + flexure

D: Overall depth; *b*: Width or breadth; *R*: Rectangular in cross section; *T*: Tension reinforcement; *C*: Compression reinforcement / Hanger bars; *N*: Not mentioned; *H*: Horizontal; *V*: Vertical; *F* is Flexure; *S* is Shear; *L* is Length of FRP; W_f : Width of strip; S_f : Spacing between strips; *ESF*: Epoxy+ Fabric; *MTF*: Mortar + Textile; *MTR*: Mortar + Textile; *HT*: High temperature; *Cc*: Concrete cover in mm; *LA*: Longitudinal axis; *E*: Epoxy.

But practically most of the beams are subjected to uniformly distributed load (UDL). It has been noticed that, UDL test on beam is difficult, since once the beam started to yield, the inner load application points will detach from the beam. Hence the same two point load setup will be maintained for experimental work.

It is proposed to develop and test a mathematical model for flexural strength in relation with the thickness of the FRP laminates. It is proposed to use Artificial Neural Network (ANN) and Response Surface Methodology (RSM) to develop the mathematical model for flexural strength of beams with composite laminates. Also the developed mathematical model will be used for determining optimal thickness of FRP material for various loads and beam dimensions.

The following parameters are to be modified to get better experimental results. The parameters are profile of FRP composites, number of layers with different thicknesses and preloading techniques.

Effect of number of layers

The study describes that researchers have used FRP plane laminates at different number of layers such as 1, 2, 3 and 4. Due to composite action between concrete and FRP composites, the strengthened beams have taken more loads by comparing normal beams.

Jumaat & Alam (2008 have used one layer of CFRP for flexural strengthening of RC beams and found that ultimate load for strengthened beam was 53.7% increased over control beam.

Jiangfeng *et al.* (2013) have taken one and two layers of CFRP laminates, for flexural strengthening of RC beam and 'U' anchors were provided at the supports for beams CR2 and CR3respectively. Based on the experimental results, ultimate load for the beam was based on the number of CFRP layers. Comparing the control beam, the beam strengthened with one and two layers were increased to 41.7% and 72.5% respectively. Therefore, second layer of CFRP laminates over the existing one was effective in improving the stiffness.

Abdelhady *et al.* (2006) has attached three layers of GFRP laminates at tension zone of 'T' beam F04. Ultimate load capacity of RC beam with three layers was 25.25% more than that of control beam and the strengthened beam failed due to CFRP laminate rupture. Also author has mentioned that U-shape FRP laminates helps to prevent the rupture failure of longitudinal CFRP laminates.

Tarek & Al-Salloum (2001) have used four layers of 1.3 mm GFRP for FG4 group RC beams. Among all of them, two layers were attached at bottom of the beam and the remaining two layers were wrapped over the first two layers and subsequently extended to the sides upto 50% of overall depth. The test results show that the failure load for a RC beam with four layers of GFRP was 200% more than control beam.

All the beams, FRP laminates were retrofitted at tension zone of the beams, but beam dimensions and thickness of FRP laminates were different.

The experimental results given by (Jumaat & Alam, 2008), Jiangfeng *et al.* (2013), Abdelhady *et al*, (2006) and Tarek & Al-Salloum (2001) revealed that the failure load for RC beams strengthened with 1, 2, 3 and 4 layers of FRP composites were 53.7, 72.5, 25.25 and 200% increased over control beam respectively. The calculation shows that the load carrying capacity of strengthened beam will be proportional to the number of layers used for retrofitting works. But additional care should be taken to avoid beam failure due to delamination or rupture of FRP laminates, since failure load RC beam with three layers was very less due to premature failure.

For the proposed work, one layer of corrugated profile will be used for strengthening the RC beam instead of many plain number of FRP layers. The dimension of the corrugated profile was chosen with a view to improve the sectional properties and subsequently flexural strength of RC beams. To avoid premature failure, another plain layer of GFRP laminate will be used for covering the corrugated profile and extended to the sides upto 75% of overall depth.

Effect of laminates thickness

Pannirselvam *et al.* (2008), has used one layer with 3 and 5 mm thickness GFRP laminates retrofitted at tension zone of RC beam. Ultimate load for control beam and beam retrofitted with two different thicknesses were studied. Three beams in each group were tested and varied by tension reinforcements. Test result shows that the average increase in ultimate load for RC beam retrofitted with 3 and 5 mm thickness were 56.98% and 87.62% respectively by comparing control beam.

Effect of preloaded beams

Pan *et al. (*2010) investigated eight beams strengthened with GFRP plates including pre-cracked beam (B7) and the results were compared with that of normal beams. Preloaded technique was used to develop multiple cracks for beam type B7. The beams B6 and B8 were normal beams without any cracks or notches. Based on the test results, average ultimate load for beams B6 and B8 was 76.16% and this value was almost equal to that of B7. Also ultimate load for B7 was in between that of B6 and B8. This result shows that an effect of FRP on existing structures with multiple cracks is similar to a new structure.

Advantage of corrugated profile over plain layer

Before the commencement of experimental work, Finite Element Analysis using ANSYS software was carried out to observe the extent to which the rectangular profile helps to strengthen the RC beams over plain layer. For theoretical analysis, singly reinforced RC beam of dimensions 100 × 150 × 1200 mm was used. Two bars of 10 mm diameter have been used as main reinforcements. Twisted bars with grade of steel Fe 415 (TOR steel) was used as tension reinforcement for all beam types. Clear cover for main reinforcements was 20 mm on sides and bottom. Point loads were to be applied on midpoint of mild steel plate to avoid concentration at single point. Two steel plates were provided at top of the beams for external application of loads at a distance of 333 mm c/c and same size steel plates were provided at bottom of beam for supports at c/c spacing of 1 m. Bearing strength of steel plates was considered as 300 MPa. Thickness and length of laminates were 1 mm and 900 mm respectively were used for the strengthening of RC beam. Failure loads were determined using ANSYS software and based on the results, failure loads for control beam, the beam with plain and corrugated layer were 39.20, 45.25 and 54.95 kN. ANSYS results show that increase in load carrying capacity of RC beam with rectangular corrugated profile was 21.43% by comparing the beam with plain layer.

Figure 2 shows the failure loads of control beam, strengthened with plain and rectangular corrugated GFRP laminates. Also to get accurate theoretical results, ANN and RSM will be used.

CONCLUSIONS

The critical review of literature revealed; strengthening of RC beams using FRP composites, which are mainly focused on type, dimensions, orientation, number of layers of FRP composites and modeling techniques. There are no mention in IS code for design of FRP strengthened RC beam, as available in ACI guidelines.

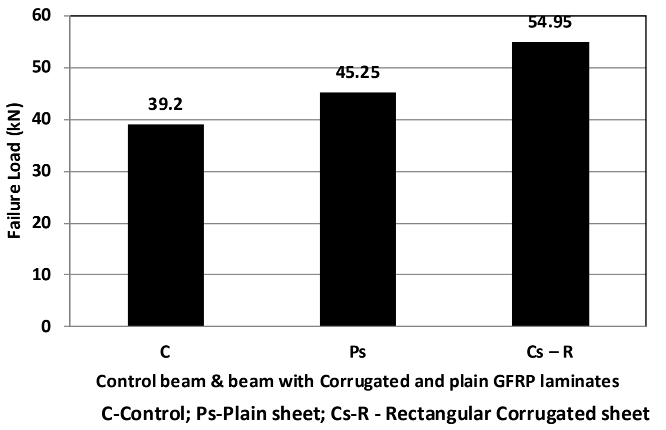

Fig. 2 Failure loads of RC beams with and without GFRP profiles.

An extensive study is chosen to apply modeling tools and use of standard code of practice for designs. Finally a need for research in use of different GFRP profile can further enhance the strengthening of RC beams. The Artificial Neural Network and Response Surface Methodology can be applied to develop a mathematical model to optimize the flexural member.

REFERENCES

Saadatmanesh, H., Mohammad, R.E. (1991). RC Beams Strengthened with GFRP Plates. I: Experimental Study, *J. Struct. Engin.*, **117**(11), 3417-3433.

Grace, N.F., Sayed, G.A., Soliman, A.K., Saleh, K.R. (1999). Strengthening Reinforced Concrete Beams Using Fiber Reinforced Polymer (FRP) Laminates. *ACI Structural J.* **96**(5), 865-871.

Tarek, H.A., Al-Salloum, Y.A. (2001) Ultimate Strength prediction for RC beams externally strengthened by composite materials. *Composites: Part B*, **32**(7), 609-619. doi: 10.1016/S1359-8368(01)00008-7

Abdelhady Hosny, Hamdy Shaheen, Amr Abdelrahman & Tamer Elafandy, (2006) Performance of reinforced concrete beams strengthened by hybrid FRP laminates. *Cement & Concrete Composites*, **28**(9), 906-913.

Chiew, S.-P., Sun, Q., Yi, Y. (2007) Flexural strength of RC Beams with GFRP Laminates. *J. Compos. Construc.* **11**(5), 497-506. doi: 10.1061/(ASCE)1090-0268(2007)11:5(497)

Pannirselvam, N., Raghunath, P.N., Suguna, K. (2008). Neural Network for Performance of Fibre Reinforced Polymer Plated RC Beams. *American J. Engin. Applied Sci.* **1**(1), 82-88.

Jumaat, M.Z., Alam, A. (2008). Experimental and Analytical Investigation on the Structural Behavior of Steel Plate and CFRP laminate Flexurally strengthened Reinforced Concrete beams. *J. Applied Sci.* **23**(8), 4383-4389.

Sundarraja, M.C., Rajamohan, S., Bhaskar, D. (2008). Shear Strengthening of RC beams using GFRP Vertical Strips – An Experimental Study. *J. Reinforced Plastics Comp.*, **27**(14), 1477-1495. doi: 10.1177/0731684407081772

Amer, M.I., Mohammed, S.M. (2009). Finite Element Modeling of Reinforced Concrete Beams Strengthened with FRP Laminates. *European Journal of Scientific Research*, 30(4), 526-541.

Nadeem, A. Siddiqui, K. (2009). Experimental investigation of RC beams strengthened with externally bonded FRP composites. *Latin Amer. J. Solids Struc.* **6**(4), 343-362.

Pan, J., Christopher, K.Y.L., Luo, M. (2010). Effect of multiple secondary cracks on FRP debonding from the substrate of reinforced concrete beams. *Construc. Build Mater.* **24**(6), 2507-2516. doi:10.1016/j.conbuildmat.2010.06.006

Yasmeen, T.O., Heyden, S., Dahlblom, O., Abu-Farsakh, G., Yahia, A.-J. (2011). Retrofitting of reinforced concrete beams using composite laminates. *Construction and Building Materials*, 25(2), 591-597. doi.10.1016/j.conbuildmat.2010.06.082

Heshmi, S., Al-Mahaidi, R. (2012). Flexural performance of CFRP textile-retrofitted RC beams using cement-based adhesives at high temperature. *Construction and Building Materials*, 28, 791-797.

Dong, J., Wang, Q., Guan, Z. (2013). Structural behavior of RC beams with external flexural and flexural-shear strengthened by FRP sheets. *Composites: Part B* **44**(1), 604-612.

Budinski, K.G. (1998). Principles of Polymeric Materials. In: *Engineering Materials,* (ed. by Prentice-Hall) 55-78. Prentice-Hall of India Private Limited, Delhi

Au, C. & Buyukozturk, O. (2013). Debonding of FRP plated concrete: A tri-layer fracture treatment. *Engin. Frac. Mech.* **73**(4), 348-365.

ACI Committee 440 (2008). 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.