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Review on CFRP/ GFRP Composites used for Strengthening of Reinforced Concrete Beams

Mr.M.Vinodkumar[1], Dr.M.Muthukannan[2]

[1]Assistant Professor, Department of Civil Engineering, P.S.N.A College of Engineering and Technology, Dindigul, Tamilnadu, India

[2]Professor, Department of Civil Engineering, Kalasalingam University, Krishnankoil, Tamilnadu, India

Abstract

The present day world is witnessing the construction of very challenging and difficult civil engineering structures. To meet up the needs of advance infrastructure, new innovative materials and technologies are invented and used to overcome the earlier drawbacks. Efforts are being made in the field of concrete technology to prepare and develop concrete with composites. In last few decades extensive research has been carried out with the use of Fibre Reinforced Polymer (FRP) composites in the strengthening and retrofitting of reinforced concrete structures in the field of civil engineering around the world. This paper provides a brief review on flexural and shear strengthening of rectangular beams using CFRP/GFRP laminate of different thickness and scheme. Different applications of FRP laminate for external strengthening of RC beams are reviewed in this paper. Finally, a discussion on system of strengthening and conclusions are made along with prospective outlook approach of research.

Keywords: *Fibre Reinforced polymer, Strengthening, Retrofitting, Flexure, Shear.*

1. Introduction

In recent years, a number of emerging economies have begun to play a growing role in the development of infrastructure. Many infrastructures are constructed annually around the globe. Much of the concrete infrastructure in the world is aging beyond fifty years, and many of these structures are showing significant deterioration and distress. There is currently a range of techniques available for extending the useful life of structurally deficient and functionally obsolete structures. One such technique is adding fibre reinforced polymer composites (FRPCs) as external reinforcement. FRPCs have been used to strengthen / retrofit concrete members like columns, slabs beams and girders in structures such as bridges, parking decks and buildings.

Comprehensive experimental investigations conducted in the past have shown that this strengthening method has several advantages over the traditional ones, especially due to its corrosion resistance, high stiffness-to-weight ratio, improved durability and flexibility in its use over surface of the structures. Moreover, these materials are less affected by corrosive environmental conditions, known to provide longer life and require less maintenance. Apart from that FRP has more reliable bondline strength as compared to steel where corrosion at the interface is unavoidable in the presence of moisture.

The adhesives are used to bond the FRP composites to the surface of the concrete structure. Most commonly epoxy adhesive bonded FRP laminates can provide satisfactory solutions to several problems related to conventional steel plates, including the corrosion of the steel plates which brings about the bond deterioration.

In general, the flexural and shear strength of a reinforced concrete beam can be extensively increased by application of carbon (CFRP), glass (GFRP) and Aramid (AFRP) FRP laminate adhesively bonded to the soffit and side face of the beam respectively. However, for successful and cost-effective applications, engineers must improve their knowledge with respect to the actual behaviour of strengthened structures. Therefore, glass fibre reinforced polymers, because they are more ductile and cheaper than carbon fibres, can be considered as an alternative solution to repair and strengthen concrete elements.

A substantial research on CFRP/GFRP strengthening of RC beams under different thickness and scheme was briefly reviewed in this paper.

2. Previous research works on RC beams

Ramana et al., experimentally investigated the flexural strengthening of reinforced concrete beams by the external bonding of high-strength, light-weight carbon fibre reinforced polymer composite (CFRPC) laminates to the tension face of the beam. Four sets of beams, three with different amounts of CFRPC reinforcement by changing the width of CFRPC laminate, and one without CFRPC were tested in four-point bending over a span of 900 mm. The tests were carried out under displacement control. One beam in a set was extensively instrumented to monitor strains and deflections over the entire range of loading till the failure of the beam. The increase in strength and stiffness provided by the bonded laminate was assessed by varying the width of laminate. The results indicate that the flexural strength of beams was significantly increased as the width of laminate increased.

Sherif H. Al-Tersawy et al., examined the performance of reinforced concrete (RC) beams strengthened in shear. Experimental investigation was carried out on nine RC beams of three different sets, as-built beams (unstrengthened), beams strengthened with vertical carbon fiber-reinforced polymer (CFRP) wraps, and beams strengthened with inclined CFRP wraps. The main parameters investigated were concrete strength, CFRP thickness and wraps orientations (90^o,45^o). The results of the experimental work indicated that externally bonded CFRP wraps enhanced the shear strength of beams significantly and that inclined CFRP configuration is more effective than vertical ones.

Nadeem A. Siddiqui et al., studied the efficiency and effectiveness of different FRP schemes for flexure and shear strengthening of RC beams. For this purpose, 6 RC beams were cast in two groups, each group containing 3 beams. 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. 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 Carbon FRP (CFRP) strengthening schemes. All the beams of two groups were tested under similar loading. The response of control and strengthened beams were compared and efficiency and effectiveness of different schemes were evaluated. It was observed 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.

Zhichao Zhang et al., examined the shear behavior of RC beams with externally bonded CFRP shear reinforcement. In this study, 11 RC beams without steel shear reinforcement were casted. After the beams were kept in the curing room for 28 days, carbon-fiber strips and fabrics were applied on both sides of the beams at various orientations with respect to the axis of the beam. Results of the test demonstrate the feasibility of using an externally applied, epoxy-bonded CFRP system to restore or increase the shear capacity of RC beams. The CFRP system can significantly increase the serviceability, ductility, and ultimate shear strength of a concrete beam; thus, restoring beam shear strength by using CFRP is a highly effective technique.

Habibur Rahman Sobuz et al., experimentally investigated the flexural behavior of reinforced concrete beams strengthened with CFRP laminates attached to the bottom of the beams by epoxy adhesive subjected to transverse loading. A total of five beams having different CFRP laminates configurations were tested to failure in four-point bending over a clear span 1900mm. Four beams were strengthened by changing the levels of CFRP laminates whereas the last one was not strengthened with FRP and considered as a control beam. Test results showed that the addition of CFRP sheets to the tension surface of the beams demonstrated significantly improvement in stiffness and ultimate capacity of beams. The response of control and strengthened beams were compared and efficiency and effectiveness of different CFRP configurations were evaluated. It was observed that tension side bonding of CFRP sheets with U-shaped end anchorages is very efficient in flexural strengthening.

Ayman S. Mosallam et al., presented the results of an experimental investigation on shear strength enhancement of reinforced concrete beams externally reinforced with fiber-reinforced polymer (FRP) composites. A total of nine full-scale beam specimens of three different classes, as-built (unstrengthened), repaired and retrofitted were tested in the experimental evaluation program. Three composite systems namely carbon/epoxy wet layup, E-glass/epoxy wet layup and carbon/epoxy procured strips were used for retrofit and repair evaluation. Experimental results indicated that the composite systems provided substantial increase in ultimate strength of repaired and strengthened beams as compared to the pre-cracked and as-built beam specimens.

Akhrawat Lenwari et al., investigated the effects of the two types of fiber sheets, namely, carbon and glass fiber sheets, on the flexural behaviors of reinforced concrete (RC) beams when they are bonded to the tension zones of the beams. A total of eight full-scale beams were tested in the experiments. The flexural strength and stiffness of RC beams were found to increase significantly after the installation of fiber sheets. Finally the characteristics of de-bonding problem which limits the effective use of fiber materials are highlighted.

Attari et al., conducted a study to examine the efficiency of external strengthening systems for reinforced concrete beams using FRP fabric (Glass–Carbon). In order to address this problem, different strengthening configurations are considered (use of separate unidirectional glass and carbon fibres with some U-anchorages or of bidirectional glass–carbon fibre hybrid fabric). A total of seven flexural strengthened reinforced concrete beams are instrumented and tested under repeated loading sequences using a 4-point bending device to complete a failure analysis. The results for strength, stiffness, ductility and failure modes are discussed for the various strengthening solutions considered.

Shanmugam et al., carried an experimental investigation to study the influence of hybrid laminates (such as, carbon (C) and Glass (G) fibre) wrapped over the reinforced concrete beams in flexure. The cross sections of the beams are 100 mm wide and 200 mm depth with the varying length of 900, 1200 and 1500 mm. A set of beams were tested for ultimate load carrying capacity under four point bending and measured the strain and deformation for the corresponding loads. Hybrid laminates wrapping was done over the tested and non-tested beam specimens for comparison. Finally the details of beam specimens, testing method and discussion of test results on strength, deformation characteristics and observations are described.

Pannirselvam et al., evaluated the structural behaviour of reinforced concrete beams with externally bonded FRP reinforcement. Beams bonded with four different types of Glass Fibre Reinforced Polymer (GFRP) having 3.50 mm thickness were used. Totally five rectangular beams of 3 m length were cast. One beam was used as reference beam and the remaining beams were provided with GFRP laminates on their soffit. The variable considered for the study is type of GFRP laminate. The performance of FRP plated beams was compared with that of unplated beam. The test results showed that the beams strengthened with GFRP laminates exhibited better performance.

Table 1: Experimental data's of CFRP/GFRP strengthened RC beams

Author	**Size of beam used lxbxd (mm)**	**Beam ID**	**Strength scheme / Width / length & spacing (mm)**	**Composite material used / Angle**	**f_{ck} (Mpa)**	**Thickness (mm)**	**Layers**	**Mode of failure**
[1]	100* 100* 1000	0.2B 0.52B 0.89B 1.42B	Soffit	CFRP	30	10, 20 & 40	1	shear
[2]	100* 200* 1800	B1	Full Side / 100mm @ 75mm c/c on shear zone	-	21	-	-	shear
		B2		-	35	-	-	
		B3		CFRP (90^0)	21	0.13	1	
		B4		CFRP (90^0)	21	0.26	1	
		B5		CFRP (45^0)	21	0.13	1	
		B6		CFRP (45^0)	21	0.26	1	
		B7		CFRP (45^0)	35	0.13	1	
		B8		CFRP (45^0)	35	0.26	1	
		B9		CFRP (45^0)	35	0.39	1	
[3]	200* 300* 2000	BCF	-	-	35	-	-	Shear
		BFS1	Soffit	CFRP	35	1	1	
		BFS2	Soffit & U wrapping at ends	CFRP	35	1	1	

		BCS	-	-		-	-	Flexure
		BSS1	Side faces only / 50mm @150mmc/c	CFRP(90º)	35	1	1	
		BSS2	-	CFRP(30º)	35	1	1	
[4]	152.4* 228.6* 1220	ZC4	-	-	45	-	-	Shear diagonal cracking
		Z445	Side face only 50mm @127mm c/c	CFRP(90º)	45	1	1	Strip delamination
		Z490		CFRP(45⁰)	45	1	1	
		ZMID	Mid wrapping on side face	CFRP	45	1	1	
		ZFAB	Full wrapping	CFRP	45	1	1	Fibre rupture
[5]	150* 200* 1900	CB	-	-	36	-	-	Concrete crushing Debonding
		FB1L	soffit (1500mm length)	CFRP	36	1.2	1	
		FB2L	soffit (1500mm + 1300mm length 2nd layer)	CFRP	36	1.2	2	
		FB3L	soffit (1500mm + 1100mm length 2nd layer)	CFRP	36	1.2	3	
		FB1LU	soffit (1500mm + U wrapping at ends)	CFRP	36	1.2	1	
[6]	150* 250* 3620	B20	-	-	27.54	-	-	Shear
		B21	-	-	27.54	-	-	
		B22	-	-	27.54	-	-	
		B3	U wrapping 150mm	GFRP	27.54	2.1	2	Flexure
		B5	length & 410mm width @ 50mm near the supports	CFRP	27.54	1.6	1	
		B19	U wrapping (5 strips 51mm@ 152mm c/c) 250mm near the supports	Procured CFRP	27.54	1.19	1	
[7]	150* 200* 2000	CB1	-	-	55	CFRP 0.165 & GFRP 0.353 for one layer	-	Concrete crushing
		CB2	-	-	55		-	
		CF1	soffit	CFRP	55		1	Debonding & rupture
		GF1	soffit	GFRP	55		1	
		CF2	soffit	CFRP	55		2	Delamination
		GF2	soffit	GFRP	55		2	Debonding
		CF-GF1	soffit	CFRP+ GFRP	55		2	Debonding
		CF-GF2	soffit	CFRP+ GFRP	55		2	Debonding
[8]	100* 160* 1500	PC	-	-	39	CFRP 0.13 & GFRP 0.17 for one layer	-	Concrete crushing
		PA1	U Wrapping	CFRP	39		1	Flexure
		PA2	U Wrapping	GFRP	39		2	Flexure
		PA3	U Wrapping	CFRP + GFRP	39		2	Debonding & rupture
		PB1	U Wrapping	HFRP	39		3	Shear
		PB2	U Wrapping	HFRP	39		2	Shear

		PB3	Soffit	HFRP	39		3	Debonding
[9]	100* 200* 900	B1,B2, B3	-	-	38	Not Specified	-	Shear
		B1VCG	Soffit	CFRP + GFRP	38		2	Shear
		B1VGC	Soffit	GFRP + CFRP	38		2	Shear
[10]	150* 200* 3000	SR	-	-	33.50	-	-	Concrete crushing
		SRCSM	Soffit	GFRP	33.50	3.50	1	Shear
		SRWR	Soffit	GFRP	33.50	3.50	1	Shear
		SRUD	Soffit	GFRP	33.50	3.50	1	Shear
		SRCSM + WR	Soffit	GFRP	33.50	3.50	1	Shear

3. Observations on the actual state of art

A concise review of existing research on the behaviour and strength of CFRP/GFRP strengthened RC beams in flexure and shear has been conducted and clearly illustrated in Table 1. It is seen that the sizes of CFRP/GFRP laminate used in above studies were chosen arbitrarily. There is no standard design guidelines are offered for selecting the thickness of FRP laminate for flexural and shear strengthening of RC beams. Most of the researches were conducted on RC rectangular beams which are strengthened in flexure and shear with CFRP/GFRP laminate with various thickness. Although substantial research has been conducted on FRP strengthening of RC beams, but still the behavior of FRP strengthened beams under different schemes of strengthening is not well established.

4. Expected system of strengthening

From the above review of literature, there is a need to understand the parameters such as effective length, width, thickness and suitable anchorage system of CFRP/GFRP laminate for strengthening reinforced concrete beams. Future research is necessary to prepare a design guideline for selecting the thickness and different schemes for strengthening of RC beams.

5. General concluding remarks

In this paper, previous research programs conducted by other researchers in the areas of the flexural and shear strengthening of reinforced concrete beams using CFRP/GFRP laminate has been reviewed. Following general concluding remarks are made:

- Externally bonded FRP laminate reinforcement is a viable solution towards enhancing strength, stiffness and energy dissipation characteristics of reinforced concrete beams subjected to various loading.
- It is clear that existing research has established the effectiveness of various methods of strengthening and identified many possible failure modes.
- Use of FRP laminate improves load carrying capacity; delays crack formation and energy absorption capability of beams reinforced with FRP laminates.
- Studies have demonstrated improvement in ultimate capacity and stiffness leading to reduction in the overall maximum deflection and strains.
- It also enhances flexural and shear capacity and improves overall damage control.
- Extent of benefit, however, depends upon many factors such as type, amount, and direction of confining material, size, shape and loading condition of the beam.
- To utilize the full capacity of the FRP laminate, the bond strength between FRP laminate and concrete as it is the key factor affecting the overall integrity of beams.
- CFRP laminates carries more loads as compared to GFRP laminates with same thickness/scheme, but in practice GFRP laminates are recommended in terms of economy.

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