

## CFRP Laminate Flexural And Shear Strengthening Technique for Reinforced Concrete Beams: A Review

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**Abstract:-** Externally bonded carbon fiber reinforced polymer (CFRP) composite laminates have been successfully applied to reinforced concrete (RC) beams and other structural elements for the purpose of increase load carrying capacity of such elements. This paper presents 10 articles reviews on the flexural and shear strengthening of reinforced concrete beams by CFRP laminates. Finally, this paper attempts to address an important practical issue that is encountered in flexural and shear strengthening of beams with carbon fibre reinforced polymer laminate. This paper also proposes a simple method of applying fibre reinforced polymer for strengthening the beam with carbon fibre reinforced polymer.

**Keywords:-** concrete beams, carbon fibre reinforced polymer, shear strengthening, flexural strengthening.

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### I. INTRODUCTION

Over the last decade there has been significant growth in the use of carbon fiber reinforced polymer (CFRP) as construction materials in the field of civil engineering. Due to its high stiffness-to-weight ratio and flexibility in its use over steel plates, CFRP has attracted researchers' interests worldwide to investigate the feasibility and effectiveness of using CFRP as reinforcements or prestressing tendons in concrete structures. Moreover, these materials are less affected by corrosive environmental conditions, several researchers pointed out that previous design provisions did not have a comprehensive understanding of the behaviour of the structures [1]. As a result, pre -1970s designs might be deficient in strength according to current codes. These materials are less affected by corrosive environmental conditions, known to provide longer life and require less maintenance. The need for rehabilitation or strengthening of bridges, building and other structural elements may arise due to one or a combination of several factors including construction or design defects, increased load carrying demands, change in use of structure, structural elements damage, seismic upgrade, or meeting new code requirements. The use of carbon fiber-reinforced polymers (CFRP) can now be considered common practice in the field of strengthening and rehabilitation of reinforced concrete structures. The effectiveness of this technique is widely documented by theoretical and experimental researches and by applications on real structures. As a consequence, the need of codes is necessary, leading to the development of guidelines in different countries [2]. The CFRP strengthening provides additional flexural or shear reinforcement, the reliability for this material application depends on how well they are bonded and can transfer stress from the concrete component to CFRP laminate [3]. Also, CFRP has made this technique even more acceptance worldwide. Commercially available FRP reinforcing materials are made of continuous aramid (AFRP), carbon (CFRP), and glass (GFRP) fibers. Possible failure modes of FRP strengthened beams are classified into two types; the first type of failure includes the common failure modes such as, concrete crushing and FRP rupture based on complete composite action, the second type of failure is a premature failure without reaching full composite action at failure. This type of failure includes: end cover separation, end interfacial delamination, flexural crack induced debonding and shear crack induced debonding. Different failure mechanisms in experimental tests were reported by ([4]-[6]). A more in depth explanation of these failure modes can be found in ([7], [8]). 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]. In addition, several studies were conducted to identify methods of preventing premature failure with the aim of improving the load capacity and ductility of RC beams. Researchers studied the use of end anchorage techniques, such as U-straps, L-shape jackets, and steel clamps for preventing premature failure of RC beams strengthened with CFRP ([4], [10]-[19]).

## II. APPLICATIONS OF FRP

There are three broad divisions into which applications of FRP in civil engineering can be classified: applications for new construction, repair and rehabilitation applications, and architectural applications. FRPs have widely been used by civil engineers in the design of new construction. Structures such as, bridges and columns built completely out of FRP composites, have demonstrated exceptional durability and effective resistance to the effects of environmental exposure. 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. It was there that the first on-site repair by externally bonded FRP took place, in 1991. Since then, strengthening by externally bonded FRP composites has been studied worldwide. This sudden increase in the use of FRP composites was attained after the 1995 Hyogoken Nanbu Earthquake in Japan. By 1997, more than 1,500 concrete structures worldwide had been reinforced with externally bonded FRP composites. Figure 1 shows the application of CFRP on site. The other application, use of FRP bars instead of steel reinforcing bars or pre-stressing strands in concrete structures.



**Fig. 1:** Flexural and Shear strengthening of Reinforced concrete using CFRP laminate.

## III. PREVIOUS RESEARCH WORKS ON BEAMS

Investigation on the behaviour of CFRP 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.

Reference [20] tested T-beams strengthened using different configurations of CFRP to improving shear capacity. They used two sides and U-wrap as strengthening scheme for all of their test beams. Additionally, end anchorage was existed; they used U-wrap without end anchor and U-wrap with end anchor. The application of CFRP sheet was found to increase shear capacity and increase in shear strength of 35-145% was achieved. Also from the results they found that the most effective observed on U-wrap with end anchorage compared with U-wrap without end of anchorage. From the other part, the two sides gave less shear contribution compared with U-wrap. Results showed that the proposed design approach is conservative and acceptable.

Reference [21] tested RC beams strengthened with CFRP sheets for. He conducted a seven rectangular RC beams, as control, four beams warped as 45 degree by CFRP with different weight of the fabric, one warped as 0 degree and one as 90 degree. From the results, showed the beams with 90 degree ply higher than 0 degree ply an ultimate load but less than 45degree ply, which is the 45 degree ply was highest with weight of the fabric (300 g/m<sup>2</sup>). He found the beams tested an increase in ultimate shear capacity of 60-150%.

Reference [22] improved the shear capacity of RC T-beams using unidirectional CFRP composites and compared between the experimental and analytical used ACI Committee report. He tested six beams of sizes; 120mm width 360mm depth 1750mm length and 75mm flange thickness. Of these, two beams were control specimen and four beams were strengthened with different configurations of CFRP strips, all these beams were tested under cyclic loading. These beams had longitudinal reinforcement and no stirrups for beams except one of the control beam. The parameters of this case were; 1) CFRP orientation of CFRP and , 2) spacing of CFRP was 285 and 143mm, 3) CFRP strengthened scheme was both sides and U-wrap, 4) different compressing strengths were used and 5) anchorage was used as steel plates on both sides and ( L-shaped). From the results, he observed that the stiffness of the beams were very close. He also observed that the strength and stiffness of the specimens improved by using CFRP unidirectional. On the other side, the analytical shear load capacity showed 20% less than the experimental shear load capacity, due to using the successful performance of anchorage.

Reference [23] has studied the shear resistance of concrete beams strengthened in shear with externally bonded CFRP. A total of seventeen performed on full size T-beams divided by two groups ED1 and ED2. Each group have two control beams, other beams wrapped with CFRP as U-wrap. The cross for group ED1 was 152mmx 406mm and group ED2 was 95mmx220mm. The flange thickness for group ED1 were 102mm and group ED2 were 55mm. the length for each groups (ED1 and ED2) were 4520mm and 3000mm respectively. The variables in this case were: 1) all beams had identical longitudinal reinforcement, 2) group ED1 had stirrups except the first three, group ED2 also had stirrups had except the first four, 3) number of CFRP layer and 4) thickness of CFRP. They observed that the yielding of stirrups occurs under relatively high shear force, between 85 and 95%

for the ultimate shear force. Also showed increased applied load because of the reissuance mechanism evolution of the behavior of the strengthened beams

Reference [24] presented an experimental and analytical investigation on the shear strengthening of Reinforced Concrete T-beams wrapped with Carbon Fiber Reinforced Polymer (CFRP) strips. A total twenty-six simply-supported T-beams of length 3600mm and cross section of 475mmx953mm with flange thickness 178mm were used. All test beams except for the control beams were strengthened with one-ply CFRP strips in the form of a U-wrap with 90° fiber orientation to the horizontal axis. The main variables included the mechanical anchorage system. From the results, showed an increased in shear strength for beams strengthened with CFRP from about 23% to 26% when mechanical anchorage not used. They also observed than the CFRP-strengthened beams with mechanical anchorage showed 7-48% higher shear strength than the beams without mechanical anchorage.

Reference [25] examined ten full-scale simply support concrete beams were divided in two categories such as category I and II. The specimens of first category I were designed to fail in shear as (Beam (control beam), Beam2, Beam3 and Beam2/2), while category II beams were designed to fail in flexural as (Beam (control beam), Beam2, Beam3, Beam3 and Beam SikaWarp). The Carbon Fiber Reinforced Polymer (CFRP) strips used for flexural strengthening in the negative moment region of a full-scale reinforced concrete beams. All rectangular beams had same cross section of 250x457x8230 mm. The response of the beams in terms of deflection, strains, and mode of failure were examined. He found that the category I beams failed by diagonal cracking with local debonding at the top of the beams, while the Category II beams failed by the onset of delamination at the interface of the CFRP strips and the concrete surface, both with and without concrete-cover failure (shear / tension delamination). It was also noted that the CFRP strips were not stressed to their maximum capacity when the beams failed, which led to ductile failures of all the beams. The maximum stress experienced by the CFRP strips was 28.5% of their ultimate strength in the case of Category I beams, and 52% for Category II beams. The maximum increase in load-carrying capacity of the beam due to strengthening was observed to be 29% for Category I beams, and 40% for Category II beams with respect to corresponding control beams.

Reference [26] they conducted a sixteen RC continuous beams divided three groups with different arrangement of internal steel bars and CFEP laminates. Group H, contains six beams with 2T8 at top and 2T20 at bottom for this group used CFRP sheet. Group S contains five beams with 2T20 at top and 8T20 at bottom, also this group used CFRP sheet. Group E contains five beams with 2T16 at top and 8T20 at bottom. In group E used CFRP plate for four beams and CFRP sheet for one beam. Each group included one unstrengthened control designed to fail in flexure. The main parameters in this case were, number of layer, length of CFRP and different concrete compressive. The observed three failure modes namely laminate rupture, laminate separation and peeling failure of the concrete cover attached to the composite laminate, also from the results showed higher beam load capacity for all strengthened beams but ductility was reduced in comparison with their respective reference beam. On the other hand, they observed that increasing the CFRP sheet length was found no prevent peeling failure and ineffective on CFRP sheet when the tensile rupture was failure mode. Additionally, they presented simplified methods for estimating the flexural load capacity and the interface shear stresses between the adhesive and the concrete material.

Reference [27] tested an experimental program conducted to study the behaviour of RC two-span beams strengthened with hybrid carbon and glass reinforced polymer sheet (HCG). The program consists of a total of six continuous beams with overall geometrical dimensions. The main parameters, different concrete cylinder compressive strength, number of layers, width of FRP and thickness layer CFRP and GFRP. Test results showed that using the HCG for strengthening the continuous RC beams lead to significantly increase of bearing capacity, ductility and moment redistribution ratio compared to strengthened beams with CFRP or GFRP. In addition, they observed that used of the HCG was needed for ensuring of minimum moment redistribution in continuous beams.

Reference [28] has studied the experimental on concrete T-beams strengthened with Carbon Fiber Reinforced Polymer CFRP sheet on three sides. The test was used three simply- supported T-beams, one as control beam which does not be pasted with CFRP, the other two pasted with CFRP. Used the distribution beams to load on the point which was at the one third of the beam. All T-beams had same cross section of 120 mm wide, flange wide 300 mm, 50 mm thick and the flange's whole height was 250 mm. the beam was 2500 mm long. The variables included three sides of CFRP, the failure modes, ultimate flexural limit states, measured deflection beams at the midspan under the loads, the strain concrete and anchorage all used U-shaped for beams pasted with CFRP. The results showed that the yield load's increased rate was ranged on 15% to 20% and ultimate load increased by 30% to 50%. Also they showed the beams were at ultimate destroyed the deflection was decreased slightly than the control beam but it still have quite deflections.

**Table I:** Experimental results and numerical simulation of load-carrying capacity of reference RC beams

Author/ size of beam	Se rie s	Beam ID	Materi al	No of laye	Fcu MP a	Anch orage (mm)	Adhe sive	Ulti mat e	Failure mode
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(mm)				r				load (kN)	
20/150x405x3050mm, flange thickness=100mm and flange width=380mm	BT1	-	-	-	35	-	Epoxy paste	110	Shear compression CFRP debonding
	BT2	CFRP sheet	1	35	No	310			
	BT3	CFRP sheet	1	35	No	315		CFRP debonding	
	BT4	CFRP sheet	1	35	No	140			
	BT5	CFRP sheet	1	35	No	243		CFRP debonding	
	BT6	CFRP sheet	1	35	Yes	442		CFRP debonding	
21/180x500x4000mm	R1	-	-	-	67.4	-	Epoxy primer	248.1	Brittle/failure in concrete
	RC1	CFRP sheet	1	67.4	No	612.1		Brittle/failure in concrete	
	C1	CFRP sheet	1	67.4	No	493.3			Brittle/ fibre failure
	C2	CFRP sheet	1	71.4	No	514.2		Brittle/failure in concrete	
	C3	CFRP sheet	1	58.7	No	521.2			Brittle/failure in concrete
	C4	CFRP sheet	1	58.7	No	308.1		Brittle/failure in concrete	
	C5	CFRP sheet	1	71.4	No	668.6			Brittle/failure in concrete
22/120x360x1750mm, flange thickness=75mm	Beam-1	-	-	-	33.0	-	Epoxy resin	104.8	Flexure
	Beam-2	-	-	-	30.0	-		41.4	Shear
	Beam-3	CFRP strips	1	35.6	Yes	74.3		Shear	
		CFRP	1	35.6	Yes			Flexure-	

		Beam-4	CFRP strips	1	35.8	Yes		89.9	shear	
		Beam-5	CFRP strips	1	35.2	Yes		90.0	Flexure	
		Beam-6			35.0			91.9	Flexure	
23/a)152x406x4520mm, flange thickness=102mm and flange width =508mm b)92x220x3000mm, flange thickness=55mm and flange width =270mm	E	ED1-S0-0L	-	-	25	-	Adhesive	81	Flexure	
	D1	ED1-S0-0.5L	CFRP continuous	0.5	25	No		102	Diagonal crack	
	S0	ED1-S0-1L	CFRP continuous	1	25	No		120	Diagonal crack	
			ED1-S0-2L	CFRP continuous	2	25	No	122	Diagonal crack	
					-	25	-	263	Flexure (CFRP break)	
					0.5	25	No	282	Diagonal crack	
	E	ED1-S1-0L	-	0.5	25	No			Diagonal crack	
	D1	ED1-S1-0.5L	CFRP continuous	1	25	No		255	Diagonal crack	
	-	ED1-S1-1L	CFRP continuous	2	25	No		267	Diagonal crack	
	S1	ED1-S1-2L	CFRP continuous	-	25	-		295	Diagonal crack	
			ED1-S2-0L	CFRP continuous	1	25	No		309	Diagonal crack
	E	ED1-S2-1L		2	25	No		297		
	D1	ED1-S2-2L		-	25	-		36	Flexure	
	-		ED2-S0-0L	CFRP continuous	1	25	No		59	Flexure
	S2	ED2-S0-1L	CFRP continuous	2	25	No		68	Flexure	
			ED2-S0-2L	CFRP continuous	-	25	-		93	Flexure
	E	ED2-S1-0L	-	1	25	No		96	Flexure	
	D2	ED2-S1-1L	CFRP continuous	2	25	No		105	Flexure	
-	ED2-S1-2L	CFRP continuous						Flexure		
S0								Flexure		
E								Diagonal		
D2										
-										
S1										

			- CFRP contin uous CFRP contin uous						crack
24/457x 940x366 00mm, flange thicknes s=178m m and flange width =1067m m		RC-8- Contr ol	-	-	27. 6	-	Epox y resin	153	diagonal cracks
		RC- 12- Contr ol	-	-	27. 6	No		123. 8	diagonal cracks
		RC- 8- S90- NA	CFRP sheet	1	27. 6	Yes		188. 5	FRP debonding
		RC-8- S90- DMA	CFRP sheet	1	27. 6	No		200. 3	FRP debonding
		RC-12- S90- NA	CFRP sheet	1	27. 6	Yes		156. 4	FRP debonding
		RC- 12- S90- DMA	CFRP sheet	1	27. 6	Yes		183. 4	FRP debonding
		RC- 12- S90- SDA MA- PC	CFRP sheet	1	27. 6	No		216. 1	prevented the debonding of FRP sheets almost until the failure
		RC- 12- S90- RC- 12- S90- HS- PC	CFRP sheet	1	27. 6	Yes		191. 2	
		Contr ol Beam	-	-	27. 58	-	Epox y resin	155. 75	Shear at the inner support.
25/ 250 x 457 x 8230 mm	Beam 1	CFRP Strips	1	27. 58	No		163. 31	Shear at the inner support.	
	Beam 2	CFRP strips	1	27. 58	No		155. 75	Shear at the inner support.	
		CFRP	1	27. 58	No				

		Beam 3	CFRP strips	1	27.58	No		200.7	Shear at the inner support.	
		Beam 2/2	CFRP strips	1	27.58	No		194.5	Shear at the inner support.	
		Control Beam	CFRP strips	1	27.58	No		142	Flexural mode	
		Beam 2	CFRP strips	1	27.58	No		163.32	Flexural mode	
		Beam 3	CFRP (strips and sheet)	2	27.58	No		177.6	Shear tension failure	
		Beam 3/2			27.58			188.23	failed by the onset of delamination	
		Beam 3/Sika Wrap (the beam with Sika Wrap fabric)			27.58			199	failed by the onset of delamination	
26/150 mm wide · 250 mm deep · 8500 mm long	H	H1	-	-	24.0	-	adhesive/concrete interface	138.0	flexural failure	
		H2	CFRP Sheet	2	43.5	No		152.3	tensile rupture of the CFRP sheets	
		H3	CFRP sheet	6	33.0	No		172.9	Peeling failure	
		H4	CFRP sheet	10	33.2	No		162.6	Peeling failure	
		H5	CFRP sheet	2	46.0	No		162.6	Peeling failure	
		H6	CFRP sheet	2	44.0	No		172.9	tensile rupture of the CFRP sheet	
	S	S1	-	-	-	-	-		172.9	tensile rupture of the CFRP sheet
		S2	CFRP sheet	2	26.0	No		83.6		
		S3	CFRP sheet	6	26.0	No				

		S4	CFRP sheet	6	42.9	No		121.8	flexural failure
		S5	CFRP sheet	10	33.3	No		121.8	CFRP sheet separation
	E	E1	-	-	42.8	-		170.5	Peeling failure
		E2	CFRP plate	1	24.4	No		111.7	CFRP sheet separation
		E3	CFRP plate	1		No			
		E4	CFRP plate	1		No			
		E5	CFRP sheet	6	24.0	No		149.7	flexural failure
					43.8			178.6	Peeling failure
					47.8			207.0	Peeling failure
					46.1			231.4	Peeling failure
					44.7			174.6	Peeling failure
27/250x150x600 mm		CB	-	0	74.2	-	Epox y resin	162	Flexural failure
		SC1	CFRP	1	74.6	Yes		183.3	Rupture of FRP sheet
		SC3	Sheet CFRP	3	74.4	Yes		238	Debonding
		SG3	Sheet CFRP Sheet	3	79.7	Yes		180.6	debonding
		SC1G1	CFRP Sheet + GFRP	1+1	79.46	Yes		209.3	debonding

		SC2G 2	CFRP Sheet + GFRP	2+2		Yes		216	debonding
					79. 34				
28/120x 250x250 0mm, flange thicknes s=50mm and flange width =300m m		TL1	-	-	27. 3	-	paste	84.3 2	break
		TL2	CFRP Sheet	1	27. 3	Yes		110	break in CFRP
		TL3	CFRP Sheet	2	27. 3	Yes		120. 8	break in CFRP
29/300x 120x200 0mm		B1	-	1	39. 5	-	Epoxy resin adhesive	155	Flexure (steel yielding)
		B1F	CFRP (sheet + strips)	1	39. 5	Yes		170	Flexure (CFRP rupture)
		B2	-	-				170	
		B2S	-	1	39. 5	No		225	Shear- tension Shear- compression
		B3	-	-	39. 5	-		125	
		B3S	CFRP strips	1		No		150	
		B3FS	CFRP (sheet + strips)	1	39. 5 39. 5	Yes		155	Shear- tension Combined flexure- shear Combined flexure- shear
					39. 5				

Reference [29] studied the experimental and analytical investigation of CFRP flexural and shear strengthening efficiencies of RC beams. A total of seven half-scale RC rectangular beams with cross section 120x 300x 2000mm. All beams were tested in three –point bending and divided into three groups. Group 1 consisted of two flexure-critical beams (B1 and B1F) where B1 was control beam and B1F was strengthened in flexure one soffit sheet (100 mm wide x 0.176 mm thick) also used two ends U-wraps to prevent the flexural sheet’s peeling, group 2 consisted of two shear-critical beams (B2 and B2S) where B2 was control beam and B2S was shear

strengthened by similar U-wraps (50 mm wide x 0.176 mm thick) spaced at 187.5 mm within the constant shear zones. The U-wraps vertically extended to 40 mm below the top fibers (simulating slabs' existence) and group 3 consisted of three flexure-shear-critical beams (B3 , B2S and B 3FS) where B3 was control beam, B3S was similar scheme to B2S and B3FS was strengthened in flexure and shear by similar schemes to B1F and B2S. The results showed that At high flexural damage, 38.3% reduction in shear strengthening efficiency was noted at higher ductility, while the flexural strengthening efficiency reduced by 65.7% at high shear damage, both from capacity perspectives. The U-wraps were 22% activated, while full sheet activation occurred and reduced by dowel rupture by 30.8% at high shear damage. While single failures were accurately predicted by ACI 318M-05 and ACI 440.2R-08, combined ones were not.

#### **IV. COMMENTS ON THE ACTUAL STATE OF ART**

From the above review of literature (Table-1), illustrates that although substantial research has been conducted on CFRP strengthening of reinforced concrete beams still, the behaviour of CFRP strengthened beams in shear and flexural were young need more research . There is no design guideline for optimizing and choosing the thickness of CFRP sheet/laminate for strengthening RC beams. From the researchers conducted on RC rectangular and T-Beams sections which, were strengthened in shear with CFRP and which were strengthened with (1, 2, 3... etc.) layers of CFRP laminate.

#### **V. PROPOSED METHOD OF STRENGTHENING**

To overcome the problems stated above, the future new technique for strengthening the beam with CFRP uses different Options (Bonded Surface Configurations, End Anchor, Spacing and Fiber Orientation), to understand the behaviour of strengthened beam with CFRP laminates. The study parameters including end of anchorage, failure mode, orientation, number of layer, spacing, strength scheme and shear capacity must be investigated in shear strengthening with CFRP laminate. Finally, the proposed study is to improve the understanding of reinforced concrete beams retrofitted with CFRP 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.

#### **VI. CONCLUSIONS**

This paper reviewed the existing research works on reinforced concrete beams strengthened by CFRP. The beam strengthened with more than one layer of CFRP laminate unnecessarily increased the strengthening time as well as cost by providing more than one layer of CFRP laminate. The importance of the study in the strengthening of the beam using CFRP laminate 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 is favoured in strengthening and also the end of anchorage was used to eliminate the debonding failure. Future research is needed for a complete awareness for strengthening reinforced concrete beams with FRP, with the aim to efficiently contribute in the concrete structures repair tasks as well as, to decrease the dimensional stability of the structure. A working knowledge of how material properties change as a function of climate, time and loading will also be of great value to the engineering and design communities. Moreover, FRP in concrete allows engineers to increase or decrease margins of safety depending on environmental and stress conditions, generic FRP type and required design life.

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