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Shear strengthening of reinforced concrete beams using carbon fiber reinforced polymer laminate: A review

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Abstract: Several researches have been carried out on reinforced concrete beams strengthened with fiber reinforced polymer composite. Some of the works focused on shear strengthening compared with flexural strengthening that had the largest share. This paper reviews 10 articles on carbon fiber reinforced polymer strengthened reinforced concrete beams. Finally, this paper attempts to address an important practical issue that is encountered in 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

1. Introduction

The use of fiber reinforced polymer (FRP) materials in civil infrastructure for the repair and strengthening of reinforced concrete structures and also for new constructions has become common practice. The most efficient technique for improving the shear strength of deteriorated RC members is to externally bond fiber-reinforced polymer (FRP) plates or sheets [1]. FRP composite materials have experienced a continuous increase of use in structural strengthening and repair applications around the world, in the last decade, [2]. In addition, when the FRP was compared with steel materials, it was found that it provided unique opportunities to develop the shapes and forms to facilitate their use in construction. Although, the materials used in FRP for example, fiber and resins are relatively expensive when compared with traditional materials, noting that the crises of equipment for the installation of FRP systems are lower in cost [3]. A review of research studies on shear strengthening, however, revealed that experimental investigations are still needed [4, 5].

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 for the development of guidelines in different countries [6]. 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 [7]. Also, CFRP has made this technique even more acceptable 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 that does not reach 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 [8-10]. A more in depth explanation of these failure modes can be found in [11, 12]. Although CFRP composites are known to perform better under environmental action than glass fibre reinforced polymer laminates, no significant differences were detected, seemingly because they failed to rupture of the fibres [13]. 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 [8, 14-23].

2. Applications of FRP

There are three broad divisions into which applications of FRP in civil engineering can be classified: applications for new constructions, repairs 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. "Fig. 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

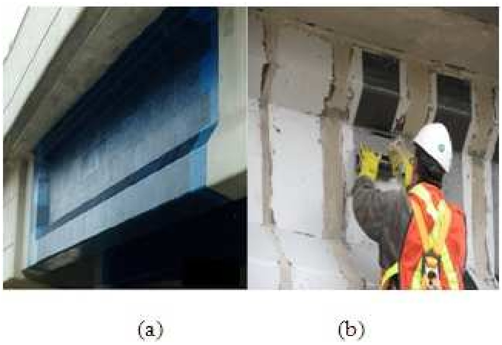

Figure 1. *Shear strengthening of Reinforced concrete using CFRP laminate*

3. 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.

Khalifa et al (1999), carried out the test of three simple supports RC T-beams to study the effectiveness of anchorage of surface mounted FRP reinforcement. The first beam was a reference beam, the second beam strengthened with CFRP without end of anchor and the last beam strengthened with CFRP with end of anchor. The anchor system, called U-anchor used GFRP bar inserted in the groove in the beam flange used as end anchor. They found that the shear capacity increased when strengthened with CFRP but, failure was governed by debonding of CFRP when CFRP was used without end anchor. However, the specimen where the anchor was used, shear capacity of the member rather increased and, ultimately no FRP debonding was observed.

Adhikary et al (2004), carried out the tests of eight simple supported RC beams strengthened for shear with CFRP sheet using two different wrapping schemas; U-wrap and two sides of the beam. He investigated the effectiveness of cross plies one over another, vertical and horizontal; the main parameter, direction of fiber alignment (90°, 0°and 90°+0°) and number of layers (1 and 2). They observed that the maximum shear strength obtained for the beam with full U-wrapped sheets having vertically aligned fibers. Horizontally aligned fibers also showed enhanced shear strengths as compared to beam with no CFRP. On the other part, they found that the lowest concrete strain was the same load range among all beams. The beam with full U-wrapping of a single layer of CFRP with vertically aligned fibers, was observed at a maximum of 119% increase in shear strength. Also, they compared with the experimental value, using models for the prediction of shear contribution of sheet to shear capacity of CFRP bonded beams.

Al-Amery (2006) tested six RC beams; having various combinations of CFRP sheet and straps in addition to an un-strengthened beam, as control test. CFRP provided (CFRP sheet for flexural strengthening and CFRP straps for shear strengthening or with a couple of CFRP sheets and straps, for overall strengthening. From the experiment, two beams were tested in four-point bending over a total span of 2300 mm and a shear span of 700 mm, while the rest RR3-RR6 were tested in three points bending over a total span of 2400mm and shear span of 1200 mm. The CFRP sheets consisted of three layers, while CFRP straps consisted of one layer and extra anchorage mechanism for the CFRP sheets. They observed that the use of CFRP straps significantly reduced the interface slip between the CFRP sheets and the concrete section. CFRP straps used to anchor the CFRP sheets, increased in flexural strength of up to 95%. However, with the use of CFRP sheets alone, only an increase of 15% was achieved. Test results and observations showed that a significant improvement in the beam strength was gained due to the coupling of CFRP straps and sheets. Furthermore, a more ductile behaviour was obtained as the debonding failure was prevented.

Anil (2006) 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 $45° - 135°$ and $90°$, 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.

Bencardino et al (2007), presented an experimental and analytical investigation on the shear strengthening of reinforced concrete rectangular beams wrapped with carbon fiber reinforced polymers (CFRP) laminates. A total of four beams were specifically designed, with and without an external anchorage system. The cross sections of 140mm x 300mm with total length of 5000mm were used. The specimens were two control beams with different av/d, one beam with only CFRP and one beam with CFRP + external links. All beams had identical internal reinforcement and were tested under four point bending over an effective span of 4800 mm and nothing in the shear span but, had stirrups in the near of support. The principle variables included external anchorages, with consisted of six specimens, were classified into two categories; namely BT and BS, each category had eight different lengths in the mode of U-shaped steel stirrup. The results showed that the anchorage system enhances the strength and deformability properties of the CFRP plated beam. Also, the anchorage system modifies the failure mode of the strengthened RC beam under predominant shear force, without increasing the load capacity, to a more ductile failure with a substantial increase of load carrying capacity to almost a flexural failure.

Jayaprakash et al (2008), conducted tests to study shear capacity of pre-cracked and non- pre-cracked reinforced concrete shear beams with externally bonded bi-directional CFRP strips. The experimental program beams, four control beams, six pre-cracked/repaired beams and six initially strengthened specimens. The rectangular beam had a dimension of 2980mm length, 120mm width and 310mm depth. The variables investigated within this program included longitudinal tensile reinforcement ratio (ρ = 1.69) for 20mm and (ρ = 1.08) for 16mm, no steel stirrups, shear span to effective depth ratio (av/d=2.5 and av/d =4), spacing of CFRP strips (80 mm @ 150 mm c/c and 80 mm @ 200 mm c/c) and orientation of CFRP strips (0/90 deg and 45/135 deg) in 3 sides U- wrap schemes. From the results, they observed that the external CFRP strips act as shear reinforcement similar to the steel stirrups. They also showed that by increasing the amount of longitudinal tensile reinforcement ratio and spacing of CFRP strips, it affected the shear capacity. This study found that the orientation of CFRP strips not only affected the cracking pattern but also affectted the shear capacity.

Godat et al (2010), studied to obtain a clear understanding of size effects for Carbon Fiber-Reinforced Polymer (CFRP) shear-strengthened beams. Their experimental research presented here, investigated the shear performance of rectangular reinforced concrete beams strengthened with CFRP U-strips as well as one completely wrapped with CFRP sheet. Seven rectangular RC beams were grouped into three test series, three control beams, three beams with U-Shaped CFRP jacket and beam with completely wrapped external CFRP sheets. The cross sections were; first series 100mmx200mm with length 900mm, second series 200x400mm of length 1800mm and third series 300mmx600mm with beam length 2700mm. All beams were heavily reinforced in bending, no steel stirrups were installed in the right shear span of interest but in the left shear span. It was placed to ensure that the failure would occur in the shear span of interest. From these results, they observed that the larger beam size, CFRP sheet provided less improvement in the shear capacity. They investigated the cracking behaviour of these specimens. Their research presented a Comparison between Test Results and Predictions from Design Guidelines.

Bukhaari et al (2010), studied the shear strengthening of reinforced concrete beams with Carbone Fiber Reinforced Polymer (CFRP) sheet. Seven, two span continuous reinforced concrete (RC) rectangular beams. The cross section of rectangular was 152mmx305mm and beam length 3400mm. One beam was un-strengthened (control beam) and, the remaining six were strengthened with different arrangements of CFRP sheet. They studied orientation of fiber (0/90 and 45/135) as main variables. The tests showed that it is beneficial to orientate the fibres in the CFRP sheet at 45 so that they are approximately perpendicular to the shear cracks.

H.K. Lee, S.H. Cheong, S.K. Ha and C.G. Lee (2011), investigated the behaviour and performance of reinforced concrete (RC) T-section deep beams strengthened in shear with CFRP sheets. A total of fourteen reinforced concrete T-section deep beams were designed to be deficient in shear. The cross section of 180mmx460mm with flange thickness of 100 mm and the beam's length of 1800mm, were used. The specimens were reinforced with longitudinal steel and stirrups near the mid-span. They also studied variables such as; strengthening length, fiber direction combination of CFRP sheets, and an anchorage using U-wrapped CFRP sheets, these variables have significant influence on the shear performance of strengthened deep beams. Their tested Experimental results T-section beams were regarded as deep beams, since the shear span-to-effective depth ratio (a/d) was 1.22. On the other hand, Crack patterns and behaviour of the tested deep beams were observed during four-point loading tests.

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

Author/ size of beam (mm)	Beam ID	Material	No of layer	Fcu MPa	Anchorage (mm)	Adhesive	Ultimate load (kN)	Failure mode
24/150x405x3050mm, flange thickness=100mm	BT1	-	-	35	-	Epoxy paste.	180	Diagonal shear crack
	BT2	CFRP sheet	1	35	No		310	Shear compression
	BT3	CFRP sheet	1	35	yes		442	Flexural failure
25/150 x200 x2600 mm	B-1	-	-	30.5	-	Primer and epoxy	39.2	Diagonal shear
	B-2	CFRP sheet	1	34.4	No		50.5	Diagonal shear+ CFS rupture (horizontal).
	B-3	CFRP sheet	2	33.5	No		63.6	Shear crashing + CFS rupture (horizontal).
	B-4	CFRP sheet	1	31.5	No		58.6	Shear crashing + CFS debonding
	B-5	CFRP sheet	2	31.0	No		60.3	Shear crashing + CFS debonding
	B-6	CFRP sheet	2	33.7	No		80.8	Shear crashing + horizontal cracks at top face
	B-7	CFRP sheet	1	34.4	No		68.5	Shear crashing + CFS debonding + tearing
	B-8	CFRP sheet	1	35.4	No		85.8	Shear crashing + horizontal cracks at top face
26/140x260x2700mm	RR1	-	-	37.8	No	Undercoat and Over-coat Resin	106.2	Shear
	RR2	CFRP straps	1	39.5	Yes		121.4	Flexure
	RR3	CFRP sheet	3	39.1	No		100.3	Shear
	RR4	CFRP straps+ sheet	3+1	39.4	No		112.1	Flexure (CFRP break)
	RR5	CFRP straps + sheet	3+1	39.0	Yes		126.3	Flexure (CFRP break)
	RR6	CFRP straps +sheet	3+1	41.0	Yes		123.2	Flexure (CFRP break)
27/120x360x1750mm,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
	Beam-4	CFRP strips	1	35.8	Yes		89.9	Flexure-shear
	Beam-5	CFRP strips	1	35.2	Yes		90.0	Flexure
	Beam-6	CFRP strips	1	35.0	Yes		91.9	Flexure
28/140 mm x 300 mm5000 mm	B2	-	-	37.3	-	Epoxy resin	57.5	Concrete crushing
	B2.1	-	-	35.1	-		82.5	Shear crack
	B2.2	CFRP laminates	1	38.2	No		82.1	Shear crack
	B2.3	CFRP laminates	1	42.7	Yes		206.3	Slice end concrete section
29/340x200x2980mm thickness flange=100mm.	TT1a	-	-	27.4	-	Epoxy resin (sikadur 330)	174.65	Shear
	TT1-1	CFRP strips	1	27.4	No		241.16	Flexural
	TT1-1I	CFRP strips	1	27.4	No		281.08	Flexural
	TS1a	-	-	16.7	-		134.74	Shear
	TS1-1	CFRP strips	1	16.7	No		187.98	Flexural
	TS1-1I	CFRP strips	1	16.7	No		121.44	Flexural
	TT2a	-	-	27.4	-		148.04	Shear
	TT2-2	CFRP strips	1	27.4	No		201.26	Flexural
	TT2-2I	CFRP strips	1	27.4	No		214.56	Flexural

Author/ size of beam (mm)	Beam ID	Material	No of layer	Fcu MPa	Anchorage (mm)	Adhesive	Ultimate load (kN)	Failure mode
30/120x310x2980mm	TS2a	-	-	16.7	-	Epoxy resin (sikadur 330)	108.14	Flexural
	TS2-1	CFRP strips	1	16.7	No		148.04	Flexural
	TS2-1I	CFRP strips	1	16.7	No		121.44	Flexural
	BT1aa	-	-	27.38	No		98.14	Shear
	BT1-I	CFRP strips	1	27.38	No		134.73	Shear-CRP fracture
	BT1-1I	CFRP strips	1	27.38	No		174.64	Shear-CFRP fracture
	BT1-2I	CFRP strips	1	27.38	No		134.73	Shear-CFRP fracture
	BS1a	-	-	27.38	No		74.86	Shear
	BS1-1	CFRP strips	1	27.38	No		121.42	Shear-CFRP fracture
	BS1-2	CFRP strips	1	27.38	No		101.46	Shear-CFRP fracture
	BT2a	-	-	16.73	No		64.88	Shear
	BT2-1	CFRP strips	1	16.73	No		134.73	Shear-CFRP fracture
	BT2-2	CFRP strips	1	16.73	No		121.42	Shear-CFRP fracture
	BT2-2I	CFRP strips	1	16.73	No		154.68	Shear-CFRP fracture
	BS2a	-	-	16.73	No		61.56	Flexural
	BS2-1	CFRP strips	1	16.73	No		108.19	Flexural
	BS2-2	CFRP strips	1	16.73	No		81.51	Flexural
	BS2-2I	CFRP strips	1	16.73	No		88.16	Flexural
	BS2-1I	CFRP strips	1	16.73	No		68.21	Flexural
31/a)100x200x900 mm b)200x400x1800mm c) 300x600x2700mm	RC1	-	-	51.2	No	Epoxy resin	160	Concrete crushing
	U4	CFRP jacket	1	51.2	No		203	Debonding
	RC2	-	-	49.7	No		709	Concrete crushing
	U5	CFRP jacket	1	51.2	No		809	Debonding
	RC3	-	-	50.5	No		1626	Concrete crushing
	U6	CFRP jacket	1	51.0	No		2018	Debonding
	W7	CFRP sheet	1	50.7	No		2221	CFRP rupture
32/152x305x3400mm	C1	-	-	60	-	Epoxy	250	Shear
	C2	CFRP sheet	1	60	No		384.7	Sheet delamination
	C3	CFRP sheet	1	60	No		423.2	Sheet delamination
	C4	CFRP sheet	1	60	No		383.2	Sheet delamination
	C5	CFRP sheet	1	60	No		452.0	Sheet rupture
	C6	CFRP sheet	1	60	No		480.9	Sheet delamination
	D6	CFRP sheet	1	44	No		461.7	Sheet delamination
33/180x460x1800mm, flange thickness = 100mm.	CT	-	-	22.45	-	primer and saturant resin	458.2	shear-compression
	CS-QL-HP	CFRP sheet	1	22.45	No		528.6	shear-compression due to partial delamination
	CS-QL-VP	CFRP sheet	1	22.45	No		505.9	shear-compression due to partial delamination
	CS-QL-CP	CFRP sheet	1	22.45	No		512.9	shear-compression due to partial delamination
	CS-QL-AP	CFRP sheet	1	22.45	No		525.3	shear-compression due to partial delamination
	CS-HL-HP	CFRP sheet	1	22.45	No		599.4	shear-compression due to partial delamination
	CS-HL-VP	CFRP sheet	1	22.45	No		528.6	shear-compression due to partial delamination
	CS-HL-CP	CFRP sheet	1	22.45	No		562.7	shear-compression due to partial delamination
	CS-HL-AP	CFRP sheet	1	22.45	No		547.2	shear-compression due to partial delamination
	CS-FL-HP	CFRP sheet	1	22.45	No		760.5	shear-compression due to rupture of CFRP sheets

Author/ size of beam (mm)	Beam ID	Material	No of layer	Fcu MPa	Anchorage (mm)	Adhesive	Ultimate load (kN)	Failure mode
	CS-FL-VP	CFRP sheet	1	22.45	No		542.1	shear-compression due to partial delamination
	CS-FL-CP	CFRP sheet	1	22.45	No		660.5	shear-compression due to partial delamination
	CS-FL-AP	CFRP sheet	1	22.45	No		646.5	shear-compression due to partial delamination
	CS-FL-CP	CFRP sheet	1	22.45	Yes		699.5	shear-compression due to partial delamination

4. 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 was young as compared with strengthened beams in flexural. There is no design guideline for optimizing and choosing the thickness of CFRP sheet/laminate for strengthening RC beams. From the researches conducted on RC rectangular and T-Beams sections which, were strengthened in shear with CFRP and which were strengthened with 1, 2 and 3 layers of CFRP laminate.

5. 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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