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Research Article

Shear Behavior of Reinforced Concrete Beams with Different Arrangements of Externally Bonded Carbon Fiber-Reinforced Polymer

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Carbonfiber-reinforced polymer (CFRP) composites are frequently utilized in the repair and reinforcement of reinforced concrete members because they are more corrosion-resistant, durable, and flexible than commonly used materials like steel plates. Many studies have demonstrated that the use of CFRP as an internal strengthening material has a substantial impact on the shear capacity of RC beams. This research looks into the possibility of using FRP material as an externally bonded reinforcement to increase the shear strength of RC beams. Because shear improvement and mode of failure are based on the right configuration of the CFRP sheets, the experimental work consisted of eight RC beams with various types, orientations, and configurations of CFRP sheets. All beams were examined under two-point bending. The test results show that the CFRP sheet significantly improved the beam's shear strength and ductility and that it is advantageous to orient the FRP at 45 degrees to the beam's longitudinal axis.

1. Introduction

As existing structures are required to fulfill the demands of modern civilization, retrofitting and post-strengthening are becoming more common. Aside from the necessity to enhance load capacity, upgrading a structure may be required owing to structural deterioration due to a change in the structural system, corrosion or accidental damage, or to correct initial design and construction flaws. Traditional methods of strengthening structures, such as ferro-cement, steel plate bonding, and increment of the cross section, can be used, but experimental investigations have demonstrated that using fiber-reinforced polymers (FRP) provides several benefits over previous techniques. CFRP is the most commonly used type of FRP because it has numerous advantages such as ease of handling, strength, durability, corrosion resistance, lightweight, and field workability [1]. In beams with CFRP strengthening, failure may happen due to flexural, shear, FRP debonding, and FRP rupture, as conducted by Ascione and Feo [2]. Bukhari et al. compared eleven short-span RC beams with various arrangements of CFRP shear strength with four un-strengthened RC beams to investigate the impact of changing the location and area of strengthen material within the shear span of the beams. According to the results, the CFRP is more efficient when located near the supports, and even small sections of CFRP can provide good improvements in shear strength [3]. Saribiyik and Caglar studied the shear strength of RC beams wrapped with CFRP and GFRP composites. The study discussed ductility flexural strength and energy absorption capacity. The results showed that the shear and flexural strengths of RC beams with GFRP woven were less than those of RC beams with CFRP, but their energy absorption and ductility capacities were very high. Furthermore, RC beams with a CFRP fracture are more brittle than GFRP [4]. Srudhira et al. used the U-wrapping technique of CFRP for the strengthening of four RC beams with various CFRP widths. The shear behavior of strengthened RC beams through the crack pattern and load vs. deflection response shows good shear strength improvement compared to the same conventional RC beams [5]. Abdel-Jaber investigated the influence of the CFRP composites on the rehabilitation and strengthening of 19-RC T-beams. Three arrangements of CFRP were used: horizontal straight strips, 45° inclined strips, and U-shape arrangement. The test results were also compared to values computed using the ACI 440.2R17 code. The results showed that the beams with CFRP material give higher strength in comparison with the control beam. Shear capacity was improved the most by using horizontal straight CFRP strips, followed by U-shaped strips and inclined strips. Furthermore, the ACI 440.2R17 code overstated some samples' capabilities [6]. Mhanna et al. tested shear strengthening of RC T-beams using high-modulus CFRP anchors and laminates. The dowel diameter and anchor insertion angle were taken into account. The results demonstrated that the failure was mainly caused by the brittle separation of the CFRP laminates, with no ductility displayed prior to failure. It also showed that the addition of U-wraps increased the shear strength compared to the control specimen [7]. Junaid et al. investigated the shear behavior of 18 rectangular beams that had been reinforced with glass fiber-reinforced polymer (GFRP). The study examines the efficiency of externally bonded CFRP sheets for shear-enhancing such beams as well as the potential interaction with both externally and internally bonded shear reinforcement. The CFRP sheets were positioned between and above internal stirrups in two distinct arrangements. The findings show that GFRP is an effective reinforcement, whereas EB-CFRP is an effective strengthening method for these composite systems [8]. Al-Shamayleh et al. studied the flexural and shear performance of 24 RC beams with various concrete compressive strengths. The beams were strengthened using two types of external CFRP composites, including sheets and laminates. In an effort to maximize the flexural and shear load-carrying capacity of the specimens examined, CFRP composites were attached in six configurations. According to the results, the shear and flexural strengths of the beams were significantly increased by externally bonded CFRP composites [9]. Raheem and Rasheed enhanced the shear strength of rectangular RC deep beams by adding external CFRP sheets. The CFRP woven was applied to the beams in four orientations (0, 90, +45, and −45) and at different locations. The beams' behavior is described in terms of their maximum shear strength, mid-deflection, and type of failure, FRP reinforcement strain, and strut angle. The test results demonstrate varied failure modes and an improvement in ultimate shear strength compared to the reference beam based on the orientation of the CFRP woven [10]. Beramly et al. investigated the shear behavior of nine strengthened beams. The parameters used are the type of CFRP material; specimen situation (strengthened or rehabilitated); and the configuration of CFRPs. The findings showed that using various CFRP sheets in different layouts enhanced beam shear capacity in both rehabilitation and strengthening [11]. Al-abdulhady et al. experimented eight RC beams to study the effectiveness of rehabilitation and strengthening of beams by one layer of CFRP composites. The beams were constructed with different concrete compressive strengths (21.1, 36.1, 48.2, and 68.5 MPa). The results of this research showed that the efficiency of the CFRP composites was inversely related to the compressive strength of concrete repaired beams, whereas a proportion relationship was detected only in composite beam with normal to low compressive strength [12].

The aforementioned review shows that there are not many studies on RC beams with shear strengthening. Researchers have mostly concentrated on increasing shear capacity by external bonding CFRP materials to the surface of the beams, employing patterns including entire wrapping, U-shaped wrapping, and complete side wrapping of the FRP. The issue of shear improvement by the external use of CFRP in varied patterns and anchor lengths along various regions of the shear span is not addressed by these CFRP setups. An experimental program was created in order to determine how the CFRP arrangement and wrapping technique affect the shear strength of short-span RC beams with shear deficiencies. The CFRP-strengthened beams at various orientation angles were studied to gain a better understanding of their behavior and to enhance our understanding of the impact of the orientation and type of CFRP materials on ultimate load and deflection. The main drawback of the research is that a single experiment has been run for each strengthening pattern, making it challenging to find certain unexpected results. It is advised to expand the database by carrying out more tests in the future because this limitation has been noted in the literature that has previously been published on the issue.

2. Experimental Program

The CFRP strengthening approach is being used in this work to improve the shear resistance of RC beams. The approach is based on bonding CFRP to the lateral surfaces of beams. An experimental program was conducted on reinforced concrete beams designed to fail under shear to evaluate the efficacy of this method. One beam was un-strengthened beam which represents the reference. The beam specimens enhanced using the strengthening approach were divided into three series. The first series, A, comprises two strengthened beam specimens reinforced with CFRP woven in a U-shape (webs and tension side) at an angle of 0 and 90°. The second series involves only applying CFRP to the webs at angles of 0, 90°, 63° and 45°. The last series consisted of one specimen strengthened with a CFRP plate at the webs only, and all beams were designed following the ACI 440.2R17 code [13], as shown in Table 1 and Figure 1.

The specimens were all constructed with the same concrete mix (1 : 1.8 : 2.7 by weight) for cement, fine aggregate, and coarse aggregate, with a water content of 0.47 percent of cement. The aggregate utilized had a largest size of 20 mm, and a superplasticizer material was employed as a percentage of the cement weight to enhance the

Table 1: The distribution of tested RC beams.

Group	Specimen code	Type of CFRP	CFRP location	Angle
Control	Reference	—	—	—
A	U-W-0	Woven	Three sides	0
	U-W-90	Woven	Three sides	90
B	W-W-0	Woven	Webs	0
	W-W-90	Woven	Webs	90
	W-W-45	Woven	Webs	45
	W-W-63	Woven	Webs	63
C	W-P-0	Plate	Webs	0

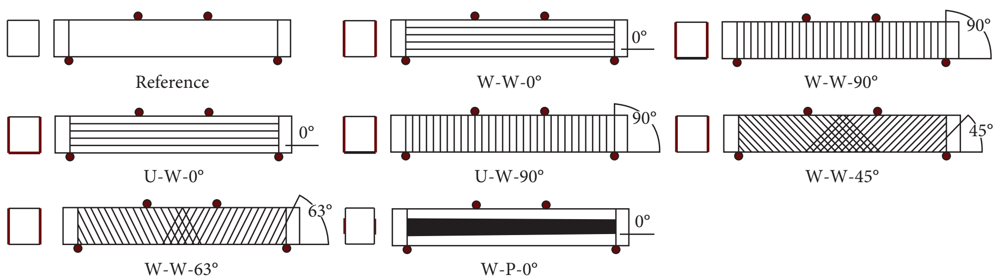


Figure 1: Details of tested beams.

workability of the concrete mixture; the concrete mix design is illustrated in Table2. To determine the tensile properties of steel reinforcement, three coupon specimens that were examined in accordance with ASTM A370 were averaged [14]. Table 3 shows the properties of concrete and the reinforcement steel bars N16 and N10 for flexural and shear reinforcement, respectively.

The experimental investigation used eight simply supported RC beams under four-point loads to assess the efficacy of CFRP as a strengthening material. Plywood sheets were created and produced for the beams to ensure the precision of the specifications and a high-quality finish for the concrete surface. The depth of the tested beams was 250 mm, the breadth was 200 mm, and the length was 1700 mm. Steel reinforcement was added to all beams in the form of two N16 bars at the compression surface and three N16 bars at the tension surface. Two bars of shear-reinforced N10 stirrups were meant to be 80 mm apart at the beam ends, which were designed to fail in shear only. To obtain the requisite cover, steel reinforcement was incorporated into the molds and supported by concrete cover spacers at the three sides of the beams. The beam size and strengthening features are depicted in Figure 2. The parameters investigated include the CFRP type, the CFRP orientation, and the CFRP position, as illustrated in Figure 3.

As can be seen in Figure 3, there are two types of CFRP used for strengthening. The CFRP sheets used in the strengthening application were SikaWrap®-300 unidirectionally woven. The structural adhesive paste used for bonding the SikaWrap®-300 to the concrete substrate was Sikadur®-330 LP, which has a high modulus and is a high-quality product. The other included CFRP plates (Sika CarboDur) attached to the structure using epoxy resin (Sikadur 30 LP) as the adhesive. Both types of CFRP were employed in a single layer for strengthening. The use of the CFRP material was a simple and quick process. First, the desired surface was cleaned with high air pressure. Second, a light coating of epoxy was applied to the surface. Finally, the carbon fiber material was put on the wet epoxy. The tested beams were cured for 7 days under laboratory conditions after bonding operations were completed. Tables 4 and 5 show the recommended properties by the manufacturer of CFRP materials and epoxy.

3. Results and Discussion

Ductility is a major requirement for any structural element, particularly in seismic zones. Ductile components deform significantly before failure. The displacement ductility index (maximum displacement/yield displacement) can be used to calculate ductility, and the maximum displacement can be measured as the displacement where the load reduced to 0.8 of the ultimate load after reaching the peak. Furthermore, the yield displacement was calculated by dividing the displacement at 0.75 of the ultimate load by 0.75 [12]. Table 6 indicates the ductility index of all studied beams with various CFRP arrangements.

The test results show that the CFRP sheets' orientation has a large influence on the beam's ductility. The impact of CFRP composites was noticeable on improving the shear strength, peak deflection, and beam's ductility. These results were discussed in terms of load-deflection, failure pattern, and performance improvements. As shown in Figure 4, all beams were tested with two concentrated loads by a measurement device with a maximum load of 500 kN. The force was increased in 5 kN per minute until the beam failed, during which point the ultimate load was evaluated. The ultimate deflections were also determined using a least count positioned at the center of the beams. The load-deflection curve for all RC beams is plotted in Figure 5, and the data are summarized in Table 7.

Table 2: Concrete mix design of one cubic meter.

Material (kg/m^3)	Cement type I	Fine aggregate	Coarse aggregate	Superplasticizer	Water
	402.0	723.5	1085.5	2.15	189.0

Table 3: Mechanical properties of steel and concrete.

Concrete			
Slump		170 mm	
Compressive strength		36 MPa	
Average splitting tensile strength		2.6 MPa	
Average concrete modulus of rupture		4.1 MPa	
Steel reinforcement			
Bar diameter (mm)	16		10
Modulus of elasticity (GPa)	200		199.7
Ultimate strength (MPa)	680		635
Yield strength (MPa)	510		490

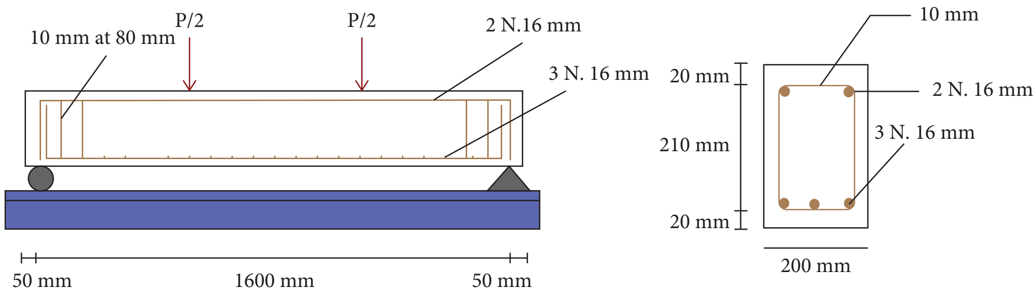


Figure 2: Specimen details and concrete beam preparation.

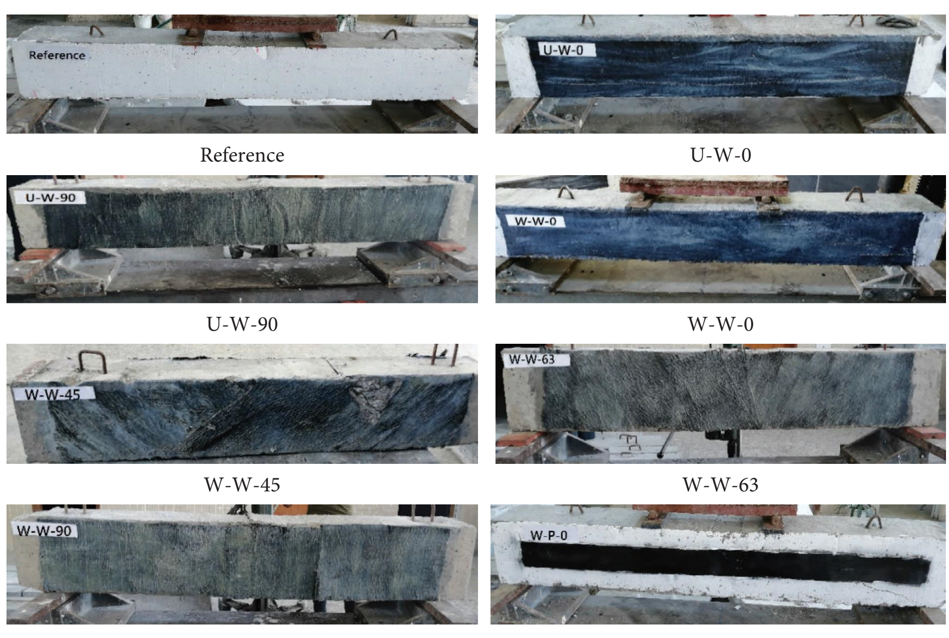


Figure 3: Layout and application of CFRP warps and anchors.

Table 4: Properties of strengthen material.

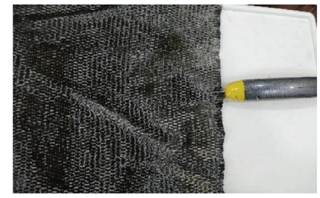
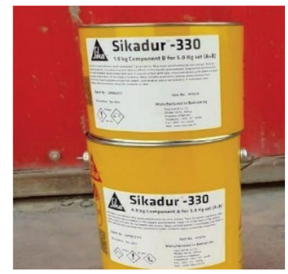
SikaWrap®-300		
Density (g/cm^3)	1.82	
Thickness (mm)	0.167	
Width (mm)	500 mm	
Elongation at break (%)	1.7	
Modulus of elasticity (MPa)	230,000	
Tensile strength (MPa)	4,000	
Fiber orientation	0° (unidirectional)	
Properties of epoxy resin (Sikadur®-330LP)		
Density (kg/l)	1.3	
Elongation at break (%)	0.9	
Modulus of elasticity (MPa)	3800	
Tensile strength (MPa)	30	

Table 5: Properties of strengthen material.

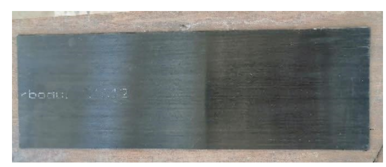
Sika CarboDur, Type S 1012		
Density (g/cm^3)	1.60	
Thickness (mm)	1.2	
Width (mm)	100	
Elongation at break (%)	1.69	
Modulus of elasticity (MPa)	160,000	
Tensile strength (MPa)	2800	
Properties of epoxy resin (Sikadur®-30LP)		
Density (kg/l)	1.65	
Modulus of elasticity (MPa)	10000	
Tensile strength in flexure (MPa)	25	

Table 6: Ductility index of the studied beams.

Beam code	Maximum displacement (mm)	Yield displacement (mm)	Ductility index	Increase of ductility index (%)
Reference	7.10	3.867	1.836	—
U-W-0	9.35	3.893	2.581	41
U-W-90	11.91	4.667	2.609	42
W-W-0	9	3.88	2.319	26
W-W-90	9.8	3.893	2.517	37
W-W-45	13	3.387	3.838	109
W-W-63	14.1	5.97	2.362	28
W-P-0	8.8	4.533	1.941	6

Figure 4: Testing machine of simply supported beam.

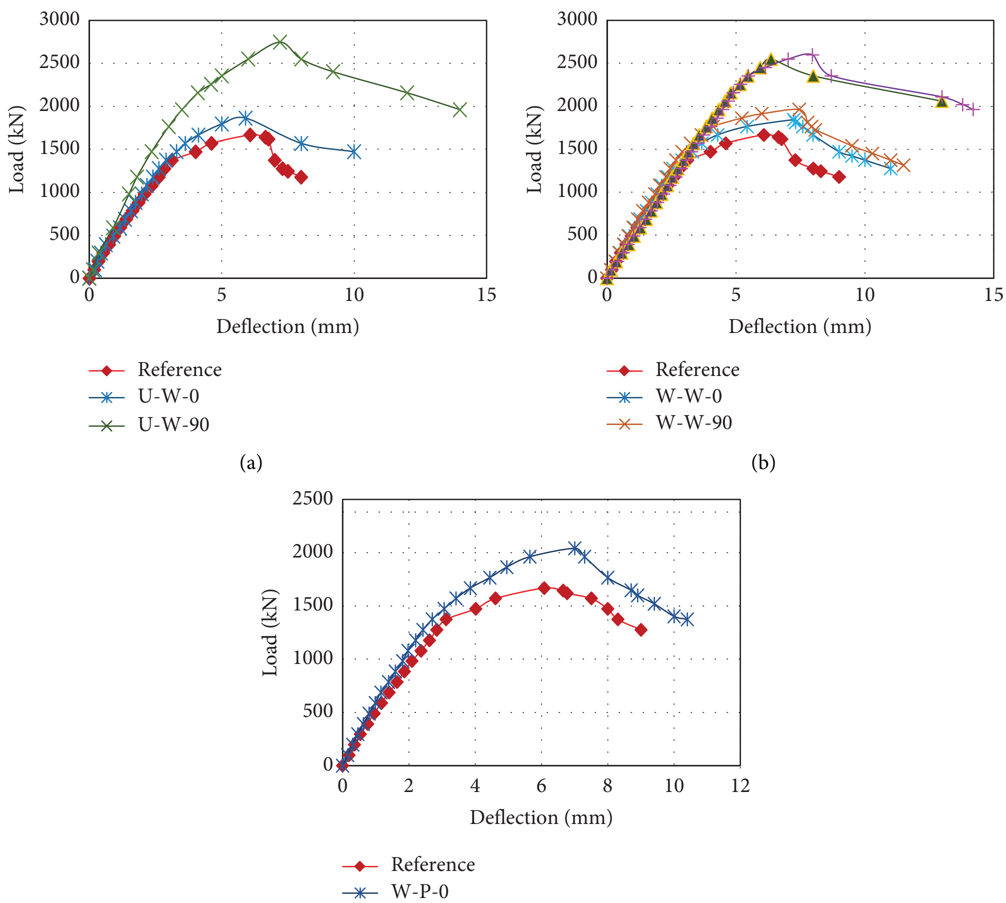


Figure 5: Load-deflection curves of the tested beams.

Table 7: Summary of the results of the tested beams.

Beam code	Peak load (kN)	Increase of peak load (Ti-T0)/T0 (%)	Peak def. (mm)	Increase of peak def. (Ti-T0)/T0 (%)
Reference	170	—	6.08	—
U-W-0	190	11.7	6.9	13.4
U-W-90	280	64.7	7	15.1
W-W-0	188	10.6	7.25	19.2
W-W-90	200	17.6	7.46	23.0
W-W-45	260	52.9	6.36	4.6
W-W-63	265	55.9	7.97	31.1
W-P-0	208	22.4	6.9	13.5

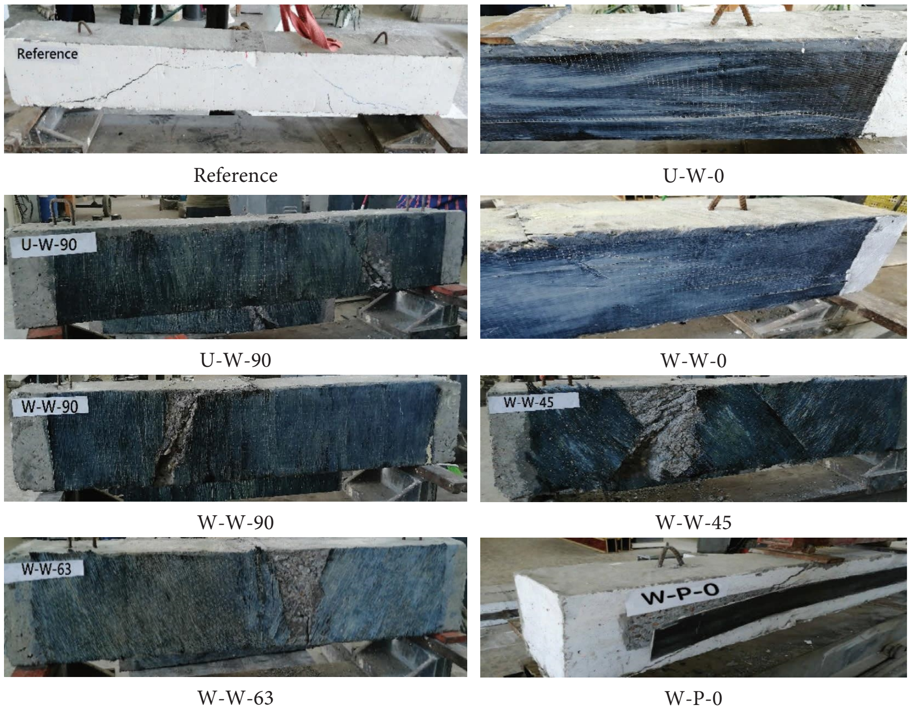


Figure 6: Failure mode of experimented beams.

The results of the eight beams experimented are as follows:

(i) "Reference" was un-strengthened beam which worked as a control beam. Beam "Reference" failed at a load of 170 kN and at 6.08 mm deflection due to the shear failure as shown in Figure 5. The use of CFRP strengthen with various angles improved the peak load and ductility compared to the reference beam. The failure pattern of beams is depicted in Figure 6.

(ii) Beam U-W-0 was reinforced on three sides with CFRP woven wrapped parallel to the beam's longitudinal axis. As illustrated in Figure 5, the shear failure of beam occurs at a peak load of 190 kN and ultimate deflection of 5.9 mm, both of which exceed those observed in the reference beam. The strengthened beam was 41% more ductile than the control beam. Figure 6 depicts that the diagonal shear crack occurs for the RC beam, without debonding of the CFRP woven.

(iii) Beam U-W-90 was wrapped on three sides with CFRP woven orthogonal to the beam longitudinal axis. As illustrated in Figure 5, the ultimate load that the beam could withstand before failure was 280 kN, and the ultimate deflection was 7 mm. Shear failure was demonstrated as a result of a major diagonal shear crack, as indicated in Figure 6. The effect of CFRP woven on improving beam ductility was remarkable, with a ductility index of 42% higher than that of the reference beam.

When comparing the two beams, U-W-0 and U-W-90, it was noticed that the beam strengthened at an angle of 90° fails at a greater load, but the failure is accompanied by CFRP woven rupture in the crack area.

(i) Beam W-W-0 was strengthened horizontally with CFRP woven on the beam webs only. In Figure 5, the addition of CFRP woven had a considerable impact on improving the strength and deflection of the beam by 10.6% and 19.2%, respectively, with a 26% increase in ductility compared to the reference beam. The ductility of beam W-W-0 was lesser compared to that of the U-W-0 beam, which was strengthened with CFRP woven into three sides.

(ii) For beam W-W-90, the CFRP sheets are positioned perpendicular to the beam's longitudinal axis. Shear cracks propagated in addition to the CFRP rupture as loading increased. As shown in Figures 5 and 6, shear failure and rupture of CFRP woven appeared at a maximum load of 200 kN and a deflection of 7.46 mm. In comparison to the control beam, the addition of CFRP increased beam strength by 17.6%, while increasing deflection and ductility by 23% and 37%, respectively. The increase in strength, ductility, and deflection caused by CFRP sheets in beam W-W-90 was greater than that observed in beam W-W-0. Also, the result showed that the beam W-W-90 can withstand less load than the beam U-W-90.

(iii) In beam W-W-45,, CFRP woven was oriented on the webs at 45° to the beam axis. The influence of the inclined CFRP increased the beam ductility and shear strength, as shown in Figure 5, where the shear failure of the beam happened at 260 kN load and an maximum deflection of 6.36 mm. The beams' ductility was significantly enhanced due to the 45-

degree oriented CFRP, which has a ductility that is 109% higher than the control beam. After the spreading of the diagonal shear crack, rupture of the CFRP woven was observed on the beam webs, as shown in Figure 6. The presence of the 45-degree inclined CFRP woven delayed the creation and spreading of the diagonal shear crack, which improved the response of the beam by postponing load degradation.

(iv) In beam W-W-63, CFRP woven was oriented on the webs at 63° to the beam axis. This inclination angle was used in particular because it is perpendicular to the cracking pattern. The 63° CFRP woven had a considerable impact on the beams' strength and stiffness. Beam W-W-63 outperformed the other beams in terms of shear failure at a peak load 265 kN and max deflection of 7.67 mm, as shown in Figure 5, although its ductility was less than that of beam W-W-45. The ductility of the RC beam was increased by adding 63° inclined CFRP woven, with the ductility index of 28% higher than that of the reference beam. Rupture of the CFRP woven was noted at the location of the beam's applied load.

(v) Beam W-P-0 with CFRP plates on the webs failed due to debonding of CFRP plates (Figure 6). The shear failure of the beam is shown at a peak load of 208 kN and at a max deflection of 6.9 mm. Also, the ductility was increased by 6% than the reference beam.

The results demonstrate that the 45-degree inclined CFRP woven is orthogonal to the diagonal shear cracks, which can encourage aggregate interlock, decrease the crack width, enhance the beams' ductility, and delay the propagation of cracks. Moreover, because of the CFRP characteristics that improve the tensile stresses and strains of the beams, they are typically utilized in the strengthening of the beams. In comparison, the un-strengthened beam's diagonal shear cracks continue to expand and grow in width without any improvement. As can be seen in Figure 5, the 45-degree inclined CFRP had the greatest impact on improving the beams' ductility, followed by the 63-degree inclined CFRP.

4. Conclusion

To increase shear capacity, strips of CFRP are frequently put in various configurations on the webs of RC elements. The primary uses for shear strengthening involve U-wrapping and complete wrapping of the member if the beam is a component of a monolithic floor. To get a better knowledge of the behavior of shear-strengthened beams, this research examined the mode of failure and shear behavior of RC beams with CFRP sheets of various types (woven and plate), different configurations (U-shape strengthening and web strengthening), and different orientations (0, 45, 63, and 90). Under a four-point load, one un-strengthened (reference beam) and seven beams bonded with CFRP sheets were examined, and the failure results were discussed.

The following are the main findings of this study:

(i) Experimental results showed that the improvement in ductility and strength of the beams can be achieved by convenient CFRP application to shear deficiency concrete beams. The existence of CFRP composite increased the resistance of propagation of crack and shifted the mode of failure from brittle to ductile.

(ii) The direction angle of CFRP woven has a considerable influence on the ductility and strength of RC beams.

(iii) Because of the CFRP properties, the ultimate deflection of the beams can be significantly increased regardless of orientation angle.

(iv) CFRP sheets can improve the beams' ductility, but this improvement depends on the inclination angle. The 45-degree orientation of CFRP woven had the greatest impact on rising ductility of the beam, followed by the beams with 63-degree orientation.

(v) The 45-degree inclined CFRP sheet is orthogonal to the shear cracks, which promotes interlock, reduces the width of cracks, and thus enhances beam ductility and delays crack propagation.

(vi) When compared to all other specimens, the 63-degree inclined CFRP had the greatest impact on increasing the shear strength and ultimate deflection of the specimen. The ductility of the W-W-63 beam was lower than that of the W-W-45 beam but higher than that of the other beams.

(vii) Both types of CFRP sheets (woven and plates) raised the load capacity compared to the control beams, but the use of CFRP woven is more effective in increasing the shear capacity than the CFRP plates.

(viii) The results clearly indicate that the beam strengthened at U-shape fails at a greater load than the beams with web strengthing.

Data Availability

All data are available in the manuscript, and any other data that the reader may need can be obtained from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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