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Shear Strengthening of Reinforced Concrete Beams Using CFRP Wraps

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Abstract

The need to retrofit existing reinforced concrete (RC) structures have increased over the decades due to corrosion of steel reinforcement inside the concrete, neglect and overuse, and increased loading. Experimental and numerical studies in this research field showed that using fiber-reinforced Polymer (FRP) materials to strengthen RC members in shear, flexure, and column confinement applications is an effective method to retrofit RC structures. This strengthening technology has numerous advantages over conventional steel plating, such as providing high strength-to-weight ratio, versatility, durability, and ease of use to strengthen RC members. The purpose of this paper is to study the effect of strengthening shear deficient RC beams with externally bonded (EB) carbon fiber-reinforced polymer (CFRP) sheets with different wrapping configurations. Two shear strengthening wrapping schemes of CFRP sheets will be investigated; U-Wrapped and completely Wrapped. Although the completely wrapped scheme is more effective, however, due to its limitations, the U-Wrapped scheme became the most commonly used method in shear strengthening of RC structures. The drawback of this strengthening scheme is the premature failure caused by debonding of the CFRP laminates, without utilizing its full strength. The main aim of this study is to compare the performance of a U-Wrapped T-beam with two completely wrapped rectangular beams. The first strengthened rectangular specimen (WBR1) has a depth equivalent to the T-beam's web height, while the second strengthened rectangular specimen (WBR2) has a depth equivalent to the T-beam's total depth. In addition, a control T-beam and two rectangular beams were cast and tested as benchmark specimens. The experimental test results showed that the beam strengthened by U-Wrapped CFRP sheets increased the control beam's shear strength by 114.82%, while the increase in shear capacity of the completely wrapped equivalent WBR1 and WBR2 beams over their control

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unstrengthened specimens was 69.28% and 201.63%, respectively. In addition, the completely wrapped scheme provided more ductility compared to that of the U-Wrapped T-beam specimen, that failed by CFRP sheets debonding in a brittle manner. Thus, it could be concluded that an ideal way to increase the shear capacity and ductility of RC beams is to completely wrap the beams using CFRP sheets. However, if the completely wrapping scheme is not possible due to geometrical obstructions, U-wrapping scheme could be effective in increasing the shear capacity of RC beams but will fail in a brittle mode by sheet debonding without utilizing its full strength. Anchoring the CFRP U-Wraps could be a viable solution to enhance the performance of strengthened RC beams that should be investigated in future research studies.

Keywords: Shear Strengthening; Reinforced Concrete; Beams; CFRP; U-Wraps; Completely Wrapped.

1. Introduction

The use of fiber-reinforced polymer (FRP) composite materials has gained its popularity in the strengthening of RC structures applications during the last three decades. This is due to its numerous advantages over the conventional retrofitting methods such as enlarging beam's sections or using steel plates. These advantages include high strength-to-weight ratio, ease of installation, corrosion resistance, versatility, and durability of the FRP composites (Mostofinejad et al. (2016); Chen et al. (2017); Nawaz et al. (2016); Chen and Teng (2003)) Numerous studies were conducted to investigate flexural strengthening and column confinement with externally bonded reinforcement (EBR) using FRP laminates (Hawileh et al. (2014); Chajes et al. (2009); Nanni et al. (2014); Hutchinson and Rahimi (2001); Ali et al. (2014); Saqaan et al. (2013); Hawileh et al. (2011); Al-Tamimi et al. (2011); Abbasnia and Ziaadiny (2015); Al-Salloum (2007)). In addition, several experimental studies were conducted to investigate shear strengthening of RC structures using FRP laminates (Bousselham and Challal (2008); Hawileh et al. (2014); Ozden et al. (2014)). Moreover, the data and analytical results in the literature are sometimes disputable. Therefore, experimental investigations are still required to cover many aspects of shear strengthening using FRP laminates.

Many studies that have been conducted to investigate strengthening of RC structures by the EBR technique proved that bonding FRP sheets to concrete substrate improved the flexural and shear capacity of the structural elements. However, the main drawback of this method is debonding of the FRP laminates from the concrete substrate before utilizing the FRP tensile strength. To increase the effectiveness of the utilization of FRP tensile strength, complete and partial wrapping were introduced. Ideally, completely wrapped RC beams have proven to be effective in terms of delaying FRP debonding failure. In addition, it utilizes the effective strain in the CFRP sheets. However, this wrapping scheme cannot always be implemented due to the presence of geometrical obstructions, since in most of the cases RC beams are connected to the slabs. Accordingly, U-Wrapped scheme is the most commonly used in the shear strengthening of RC structures.

Shear failures are usually sudden and brittle, since the internal forces do not get redistributed (Belarbi et al. 2012). Therefore, it is vital that RC beams have sufficient shear capacity to prevent such sudden failures. In general, the three ways in which the FRP laminates can be bonded to RC beams to strengthen them in shear includes side-bonded, where the laminates are bonded to the vertical sides of the beam; U-wrapped, where the laminates are bonded to the sides of the beam as well as the tension face in a U-shaped manner; and completely wrapped, where the laminates are bonded around the beam (Belarbi and Acun (2013); Chen et al. (2012)). Studies proved that completely wrapped beams perform the best in terms of enhancing the shear capacity and ductility of RC beams. This is due to the higher attained effective strain along the fibers' vertical direction than that with side-bonded and U-wrap strengthening schemes. However, practically it cannot be implemented in many cases, where the beams are connected to the slabs. Hence, U-wrapped scheme is the most commonly used method to strengthen RC beams in shear.

In general, most of the studies concluded that FRP-EBR is an effective method for strengthening RC beams.

However, there are many factors that affect the enhancement in shear capacity. These factors have been reported in many experimental investigations (Khalifa and Nanni (2000); Hawileh et al. (2015); Lee et al. (2017)). The efficiency of FRP system to strengthen shear deficient RC beams depends on all those parameters reported in the literature. These factors include beam geometry, strengthening material, strengthening scheme, shear span to depth ratio (a/d), concrete compressive strength, flexural reinforcement ratio, loading type, and layout method (wet or dry). In this study two parameters will be investigated – mainly the beam geometry and the CFRP strengthening scheme.

2. Research Objective and Significance

Numerous studies were carried out to investigate using FRP sheets in shear strengthening of RC structural members. Most of the experiments in the literature have proven that the scheme of complete wrapping is the best and ideal method for shear strengthening of the RC members. While it can be easily implemented in columns, it is very difficult to implement in beams, in most cases, due to the presence of slabs above the beams. Therefore, the aim of this study is to compare the most commonly used U-Wrap scheme to the completely wrap scheme of rectangular beams (R-beam) with two different depths. One R-beam's depth is equivalent to the T-beam's web length, and the other R-beam's depth is equivalent to the T-beam's total depth. Furthermore, there is still controversy in the literature about shear strengthening of RC members using FRP-EBR, and more research needs to be done to cover all aspects of this topic.

3. Experimental Program

3.1. Test Matrix

The experimental program consisted of two RC T-beams and four RC R-beams. All beams have a total length of 2 m and were designed to fail in shear from one side, between the location of the applied load at beam's midspan and right support (shear span). This was accomplished by reinforcing the other (left) side with 8 mm stirrups spaced at 80 mm, as shown in Fig. 1. Each T-beam had a span to depth ratio (a/d) of 2.75 and was reinforced with 4ϕ16 mm and 4Φ12 mm steel bars in the tension and compression zones, respectively as shown in Fig. 2. One of the T-beams was not strengthened and considered as control, and the remaining one was strengthened with CFRP U-wraps as shown in Fig. 2. In addition, rectangular beams were reinforced and cast with similar detailing and materials of the T-beam specimens, with two different depths equivalent to the T-beam web's and section's heights of 250 and 350 mm, respectively. The R-beam with depth 350 mm had a/d ratio of 2.75, and the other R-beam with depth of 250 mm had a/d ratio of 4.07. Two beams of different depths were not strengthened and considered as control beams, and the other two beams were strengthened with completely wrapped CFRP sheets as shown in Fig. 2. A total of six CFRP wraps having width of 100 mm with 150 mm center to center spacing, were wrapped in form of U-Wraps for the T-beams and completely wrapped for the R-beams. Beam designations and detailing are provided in Table 1.

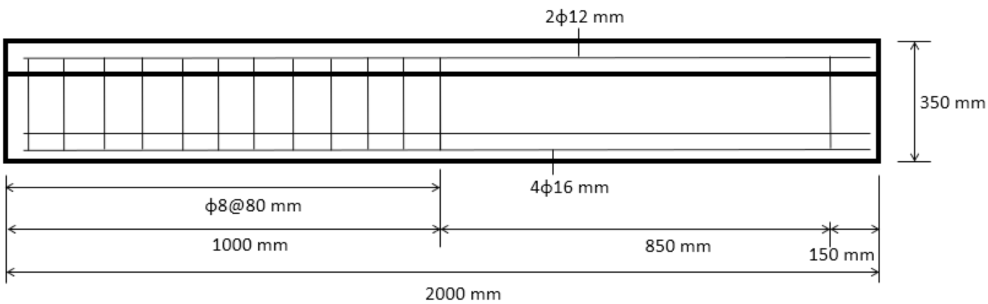

Fig. 1. Beams reinforcement detailing

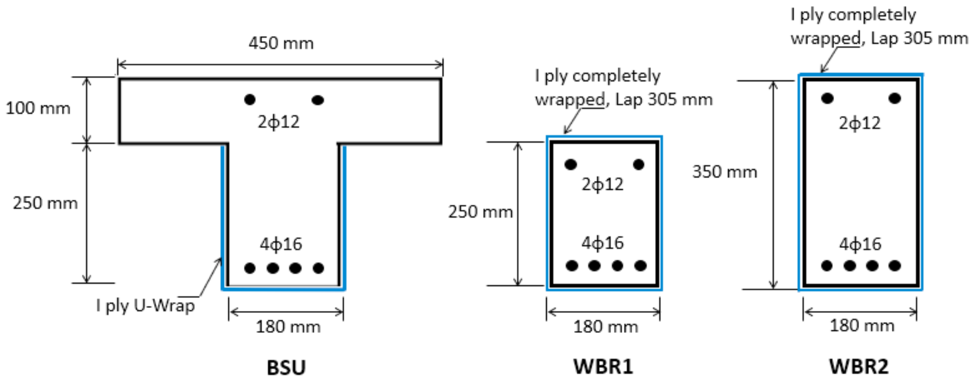

Fig. 2. Cross-section detailing of strengthened specimens in the strengthened shear span.

Table 1. Beams Details

Beam Designation	Beam Type	Wrap Scheme
CB	T-Beam	-
BSU	T-Beam	U-Wrapped
CBR1	Rectangular Beam (Depth 250 mm)	-
WBR1`	Rectangular Beam (Depth 250 mm)	Completely Wrapped
CBR2	Rectangular Beam (Depth 350 mm)	-
WBR2	Rectangular Beam (Depth 350 mm)	Completely Wrapped

3.2. Material Properties

The concrete compressive strength for the beam specimens was measured by crushing 3 cubes in a compression-testing machine after 28 days of casting the beam specimens. The average cylindrical concrete compressive strength (*f'c*) value was calculated to be 45.9 MPa. It should be noted that the cylindrical compressive strength was estimated as 80% of the cube compressive strength values. The yield strength of steel reinforcement was 460 MPa with an elastic modulus of 200 GPa. The CFRP sheets were composed of high strength carbon fiber fabric (V-Wrap™ C200H) that will be bonded to concrete surfaces using epoxy adhesives (V-Wrap™770). Table 2 presents the mechanical properties of the CFRP sheets, laminates, and epoxy adhesive, as provided in the materials' specifications of the manufacturer.

Table 2. Properties of CFRP Sheets, Laminates (sheets with epoxy), and epoxy adhesive.

Material	Density/weight	Thickness (mm)	Elastic Modulus (GPa)	Tensile strength (MPa)	Elongation at failure (%)
CFRP sheets	600 g/m^2	0.17	227.500	4,830	2.1
CFRP laminates	600 g/m^2	1.02	73.770	1034	1.4
Epoxy Adhesive	1.11 Kg/L	-	2.760	60.7	4.4

3.3. Strengthening Procedure

All beams surfaces were grinded to create a rough surface for better bonding with CFRP wraps, and then cleaned. Following that, markings were made on the places where the CFRP wraps were attached. Next, the two parts of the epoxy adhesive V-Wrap™770 were mixed in the ratio of 2:1 to form the primer and fumed silica was then added to the primer to form the epoxy paste. After cutting the CFRP sheets into the required lengths, they were impregnated with the primer using grooved rollers. The surfaces of the beams were also brushed with a primer layer followed by an epoxy layer before attaching the CFRP sheets on top. Finally, grooved rollers were used on the attached CFRP laminates to remove the air voids. Figure 3 shows specimen preparation and adopted strengthening procedure.

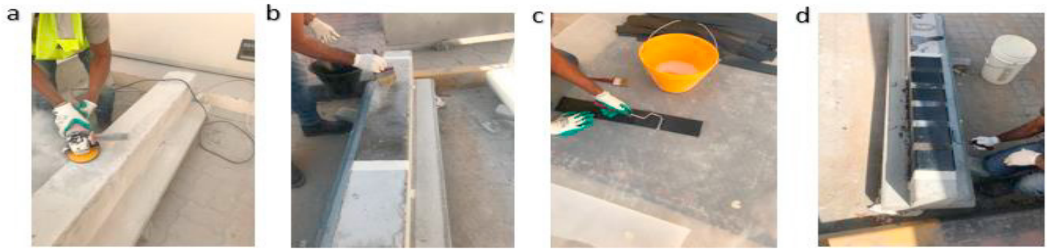

Fig. 3. Strengthening procedure. (a) surface preparation; (b) applying epoxy on beam's surface; (c) impregnating carbon sheets with primer; (d) removing air voids using grooved rollers

3.4. Test Setup

All beams were loaded under one-point loading (three-point bending) using an Instron Universal Testing Machine (UTM) that has a capacity of 2000 kN, under a displacement rate of 2 mm per minute. Figure 4 shows a schematic of the loading test setup. In addition, six strain gauges were attached to each CFRP laminates as shown in Fig. 5 to monitor the axial strain in the laminates during loading. Moreover, the mid-span vertical displacement was monitored using an external Linear Variable Differential Transformer (LVDT) as shown in Fig. 5.

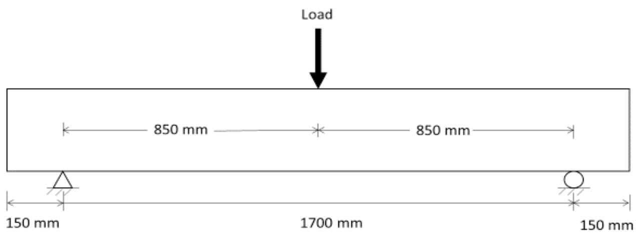

Fig. 4. Test setup

Fig. 5. Strain gauges on beam BSU

4. Results and Discussion

A total of six beams were tested under three-point bending. Beams CB, CBR1 and CBR2 were considered as control beams and used as benchmarks for beams BSU, WBR1, and WBR2, respectively. The failure modes of all the beams are presented in Fig. 6, and the load versus mid span deflection responses are shown in Fig. 7. In addition, the results in terms of ultimate load (P_u), mid-span deflection at ultimate load (δ_u), mid-span deflection at failure load (δ_f), ultimate strain in the CFRP wraps (ε_{frp}), percent increase of ultimate load (P_u) over the control specimen of each beam, percent increase in mid-span deflection at ultimate load compared to the control specimens (δ_u), and percent increase in mid-span deflection at failure load (δ_f) compared to the control specimens are presented in Table 3.

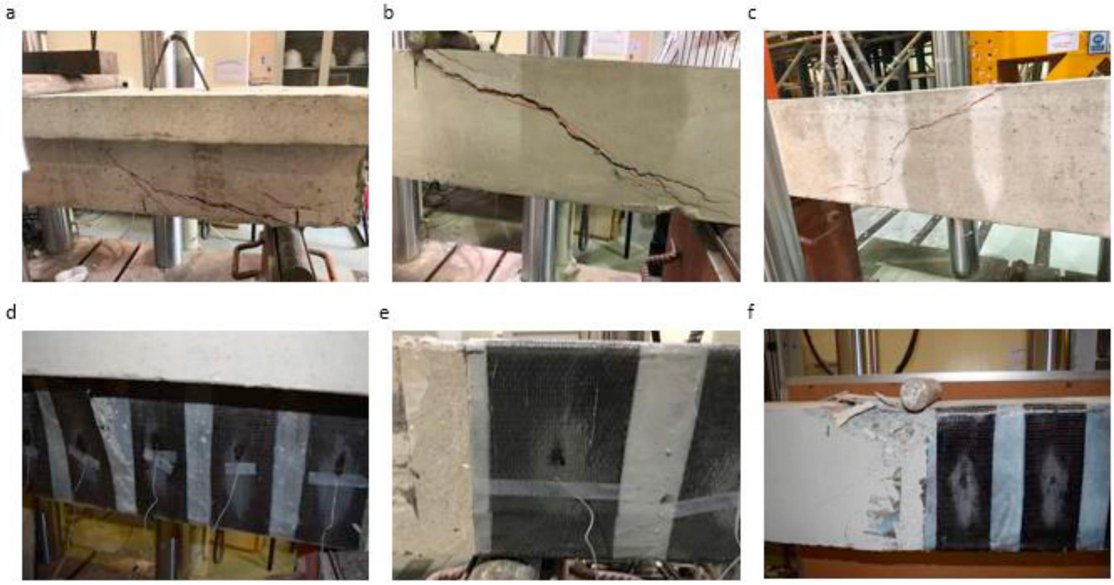

Fig. 6. Failure of Tested Specimens. (a) CB; (b) CBR1; (c) CBR2; (d) BSU; (e) WBR1; (f) WBR2

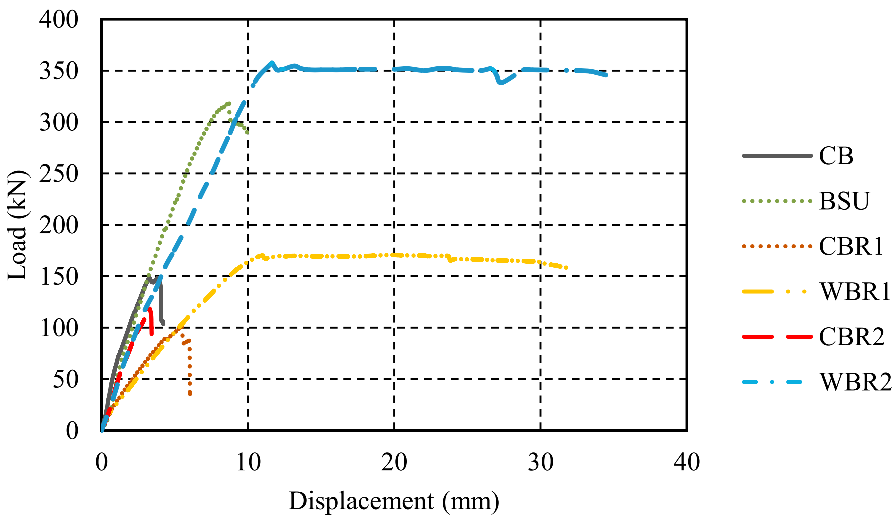

Fig.7. Mid-span Load-Displacement Curves

Table 3. Results Summary

Beam	P_u (kN)	δ_u (mm)	δ_f (mm)	ε_{frp} ($\mu\varepsilon$)	% increase in P_u	% increase in δ_u	% increase in δ_f
CB	148.30	3.85	4.22	-	-	-	-
BSU	318.58	8.70	10.07	2847.33	114.82	125.75	138.80
CBR1	101.00	5.43	6.08	-	-	-	-

WBR1	170.98	19.88	31.97	1530.92	69.28	266.07	425.84
CBR2	118.57	3.29	3.43	-	-	-	-
WBR2	357.63	11.64	34.46	4929.82	201.63	253.74	904.06

It is clear from Fig. 7 and Table 3 that the ultimate load-carrying capacity (P_u) of the control specimens CB and CBR2, which had the same depth, is higher than that of beam CBR1 that had a lower depth. Comparing the two T-beams CB and BSU, strengthened U-wrapped beam BSU had higher load-carrying capacity than CB by 114.82%. In addition, the mid-span displacement at failure of BSU specimen was 138.80% more than that of the control T-beam specimen.

Comparing the two R-beams with depth 250 mm, which is equivalent to the T-beam's web depth, the ultimate load-carrying capacity (P_u) for the completely wrapped beam WBR1 exhibited a 69.28% increase over CBR1. In addition, the mid-span deflection at ultimate load (δ_u) and the mid-span deflection at failure load (δ_f) in beam WBR1 was significantly higher than CBR1. Similarly, strengthened beam specimen WBR2 exhibited significant ductile behaviour before failure, compared to unstrengthened beam CBR2. In addition, the ultimate load-carrying capacity (P_u) attained in WBR2 was 201.63% more than CBR2.

The experimental results show that the U-wrapped T-beam BSU had a higher ultimate load-carrying capacity than beam WBR1, although the latter was completely wrapped. This is due to the increased depth which increases the shear capacity of the concrete. However, comparing the results of the U-wrapped T-beam with the completely wrapped R-beam of the same depth shows that completely wrapping scheme increased the ultimate load-carrying capacity of the RC beam by two times more than the U-wrapped scheme. In addition, it utilized more of the FRP strain, and prevented the debonding phenomena of the FRP. Furthermore, it is clear from Fig. 7 that completely wrapped R-Beams WBR1 and WBR2 exhibited a significant enhancement in ductility before failure over beam BSU which failed in a sudden brittle manner by debonding of the CFRP laminates. The failure of WBR1 and WBR2 was dominated by flexural failure of crushing of concrete. Hence, this shows that completely wrapping scheme changes the mode of failure from brittle shear failure to the ductile flexural failure mode.

The values of ultimate strain attained in the CFRP wraps (ε_{frp}) provided in Table 3 show that beam WBR2 utilized the CFRP strain the most (ε_{frp} = 0.0049). Beam WBR2 thus utilized 35% of the CFRP laminates ultimate strain, while beams BSU and WBR1 utilized 20 and 10% of the CFRP laminates ultimate strain, respectively. This indicates that an ideal way to increase the shear capacity and ductility of shear deficient RC beams is to completely wrap the beams using CFRP laminates. However, in most practical cases, completely wrapping the beam is not possible due to geometrical obstructions. Accordingly, the U-wrapping strengthening scheme is an effective scheme in increasing the shear capacity of RC beams, but the beam will fail in a brittle mode by FRP debonding at a much lower effective strain.

5. Summary & Conclusion

This paper investigated shear strengthening of RC beams using U-Wrapped and completely wrapped CFRP laminates. Three-point bending tests were performed on all beam specimens, and the mid-span load displacement response curves were plotted. Based on the experimental results the following conclusions were drawn:

- Complete-wrapping scheme provides the best performance in terms of increasing the shear strength and significantly increasing the ductility of the strengthened RC beams, compared to U-Wrapped beams with the same depth.
- Completely wrapping the beams with CFRP laminates utilizes more of its strain capacity than that with the U-wrapped scheme.
- The failure mode of completely wrapped beams is FRP rupture, which is more favorable compared to the sudden debonding of the FRP laminates of the U-Wrapped beams.
- In the case where beams cannot be completely wrapped, the U-wrapping scheme is a feasible option. However, for the U-Wrapped beams to reach the same performance of the completely wrapped beams, CFRP laminates should be properly anchored to avoid the brittle debonding. This will be the subject of a future work to be conducted by the authors.

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