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Rehabilitation of Shear damaged Reinforced Concrete Beams with U-Wrapped Carbon Fiber Reinforced Polymer Sheets: Experimental Study

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ABSTRACT

This paper presented an experimental study of external rehabilitation of damaged Reinforced Concrete (RC) Beams with Carbon Fibre Reinforced Polymer (CFRP) sheets. The primary objective is to study the shear behavior of four simply supported beam specimens with an total length of 1700mm, a width of 150 mm, and a depth of 250 mm was tested under a monotonic two-point load. The variable used in this study was the specimen damage ratio (50%, 60%, and 70%), while the layout of CFRP sheets and shear-span to effective depth ratio (a/d = 2.5) were kept constant. The design of the examined beams was according to ACI 318M-19 to ensure shear failure. From this study, it was concluded that external rehabilitation with U-shape CFRP sheets offered a very adequate and efficient rehabilitation method for damaged RC beams. Each beam's behavior was examined concerning the crack pattern, first crack load, load-deflection and ultimate load. The CFRP rehabilitation has improved the ultimate load capacity of damaged beams by about 10.91% to 15.96% compared with the expected remaining ultimate load capacity of control specimens without rehabilitation, as well as an increment in the deflection of mid-span from -6.81%, 24.11% at an ultimate load.

1. Introduction

As a result of loading and extreme environmental effects, old Reinforced Concrete (RC) structures go through deterioration of strength. To enable structural members to retrieve structural capacities cost-effectively, efficient retrofitting techniques can be used. Up to now, several techniques of rehabilitation of RC structures have been used, such as steel plate bonding, external pre-stressing, section enlargement, and materials like fiber-reinforced polymers (FRP) bonded externally. For such applications, carbon FRP (CFRP) materials have been used widely for the last few decades, because of their high strength compared to the weight, flexible usability, cost-effectiveness, low thermal conductivity, high corrosion resistance, and enhanced structural performance under critical loading conditions. Particularly, for upgrading the shear capacity of the members, CFRP is an effective technique for rehabilitation the shear deficiency [1]. Experimental literature on the RC beams shear behavior strengthened with CFRP had many parameters to focus on, like the inclination angle of CFRP strips, layouts and schemes of wrapping, the effective number of CFRP layers, and the quantity of CFRP material anchorage. For example, Norris et al. [2], Thanasis [3], Islam, et al. [4], and Zhang [5], studied the effect of the orientation of CFRP strip and approved

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that as the direction of the strip becomes almost perpendicular to the direction of the shear crack, the CFRP effectiveness increases.

Moreover, the effectiveness of CFRP bonded materials in restricting the diagonal cracks' width was dependent on the bond characteristics, orientation and amount of reinforcement. Adhikary and Mutsuyoshi [6] said that the shear strength increased as the depth of carbon fiber sheets and the number of layers increased, and the most efficient rehabilitation between the different wrapping layouts was provided by the vertical U-wrap of the sheet. Likewise, the shear behavior of RC beams strengthened with CFRP was investigated by several studies [1, 7, 8, 9, 10], reporting that the CFRP rehabilitation effectiveness on shear resistance was affected by the used shear reinforcement quantity. Taljsten [11] agreed that when CFRP layers are placed perpendicular to the direction of the crack, the RC beams rehabilitation in shear becomes more effective. The structural members could easily be over strengthened; however, the shear rehabilitation is limited by the compressive strength of concrete. In an experimental study on the debonding failure state, Cao et al. [12] studied the distribution of strain in CFRP strips which intersect with the critical shear crack and the shear capacity at debonding. Shear-strengthened rectangular RC beams were tested by Pellegrino and Modena [13] reporting that the effectiveness of the shear rehabilitation is strongly influenced by the interaction mechanism between the internal shear reinforcement and the externally bonded CFRP, which is neglected in the current design codes. Sarah et al. [14] concluded that it is possible to produce fracture failure in CFRP sheet by providing a large number of small anchors with an overall cross-sectional area at minimum two times larger than that of the longitudinal sheet. Kim et al. [15] recommended to consider the design of rehabilitation layouts of CFRP because the shear strengthened members failure mode was affected by the variable shear span-depth ratios (a/d); Chalioris et al. [16] examined five RC beams critical in shear and retrofitted by U-shaped jackets made of cementitious mortar and reinforced with mild steel bars with small diameter and U-shaped open stirrups. The results of the test showed that the retrofitted beams' shear strength was basically increased from 38% to 48%.

Most of the previous authors studied rehabilitation of RC members with unidirectional CFRP strips to in shear, some [9, 17, 18, 19] studied the rehabilitation of the RC members with bidirectional CFRP strips. These studies demonstrated that it is more efficient to use bidirectional CFRP than to use unidirectional CFRP. J. Garcia et al. [9] tested four I-girders strengthened for shear and made a comparison between the performances of unidirectional and bidirectional CFRP with reference specimens. It was concluded from the results that the shear capacity was significantly increased (up to 40%) in members with bidirectional CFRP strips, and when anchored unidirectional CFRP was used, the shear capacity was slightly increased (2%). Although the performance of the application of bidirectional CFRP was indicated in these results that it was remarkable, but the mechanism that resulted in the improved performance kept unclear.

In this experimental study, the shear behavior of rectangular RC beams strengthened with unidirectional CFRPs is investigated. An experimental program was executed on rectangular RC beams to evaluate the effectiveness of bidirectional CFRP strips for rehabilitation under shear. The test was implemented on 4 rectangular RC beams to evaluate the effect of CFRP on the shear capacity of beams under different ratios of damage.

2. Methodology

The experimental program consists of testing four simply supported RC beams with two applied points load. Longitudinal reinforcement, transverse reinforcement, compressive strength, load location, and configuration of CFRP sheets were kept constant throughout this study, while damage ratio was considered.

2.1 Beam specimens' details

The specimens were tested under shear. The primary variable studied was the pre-cracking effect on repair and rehabilitation.

Since the subject includes an investigation of the shear behavior of RC beams, its flexural strength should be high enough so that no flexural failure occurs before shear failure. The tested beams have been designed according to ACI 318-19 with a total length of 1700 mm, a width of 150 mm, and a depth of 250 mm. Table 1 and Figure 1 show the details of the beams.

Table 1. Description of work program

Specimen symbol	Damage ratio	CFRP Rehabilitation details
BG1/0 – 1/100	100%	None
BG1/0 – 2/70	70%	U-wrapped
BG1/0 – 3/60	60%	U-wrapped
BG1/0 – 4/50	50%	U-wrapped

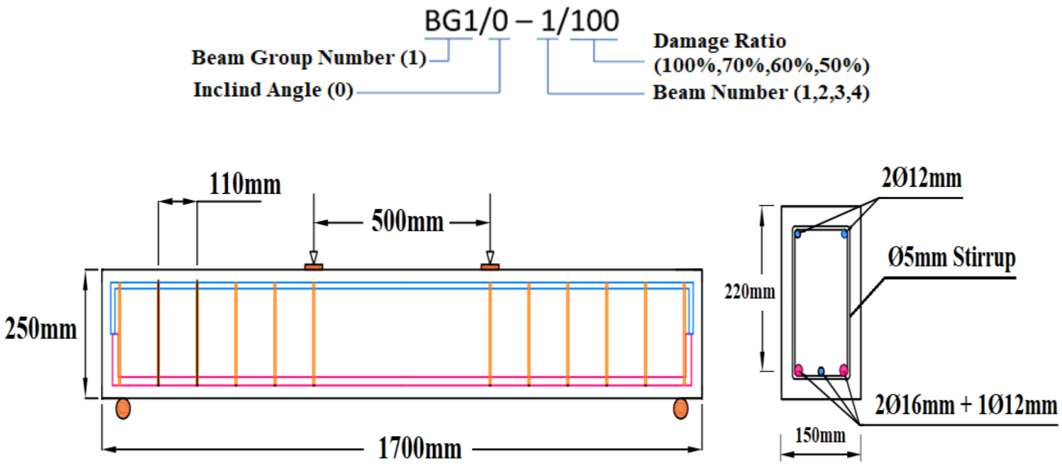


Figure 1. Details of beam specimen

2.2 Pre-Cracking test

A monotonic loading was applied to all beams using the 2000 kN maximum capacity hydraulic testing machine as shown in Figure 2. Firstly, beams were put at the machine of testing and the supports, center-line and load arms were fixed at their locations. The applying test loading was applied on the midpoint of the loading bridge and then load equally divided into two points load transferred to the RC beams as shown in Figure 2.

Figure 2. Test setup for beam specimens

Firstly, the control beam was tested until the full damage is reached. Then, the other beams were tested before strengthening with various ratios of damage from the ultimate load for reference beams, in reality, this damage ratio represents the service load. After these tests, beam specimens were prepared to apply to the CFRP sheets. The surface of the beams must be ground; the corners must not be sharp to prevent any loose and weak materials. The surface must be clear of any oil, dust or other substances that may damage the bonding.

2.3 CFRP application

After the pre-cracking tests, Figure 3 shows the preparation of CFRP sheets was done by cutting them into strips with appropriate dimensions. Then, the components of epoxy resin (A and B) were mixed following the specification of the manufacturer. Mixed epoxy was added to the concrete surface with a thin layer. Finally, CFRP sheets were placed using a metallic roller to impregnation the epoxy and left to dry. The beams were tested after seven days according to the product datasheet. Figure 4 shows the application of CFRP and Figure 5 shows the beams after rehabilitation.

a) Remove the paint

b) Grinding the edges of the beams

c) Blowing the dusts

d) cleaning the surface of the beam

e) Mixing epoxy components

f) epoxy after mixing

g) applying CFRP sheets

Figure 3. Application of CFRP sheets

Figure 4. Beam after rehabilitation

2.4 Post-Cracking test

After rehabilitation the beam specimens with CFRP sheets, the second series of tests, the post-cracking teat, was done. Beams were placed at the testing machine again. Then, at regular increments, loading was applied as the load increased regularly. Load-deflection behavior was recorded for each beam. The applied loading was increased until the beams failed.

3. Results and discussion

3.1 Pre-Cracking test results

The observed mode of failure of the test specimens was shear failure as planned in the design. Cracking patterns for the tested specimens for pre-cracking test are shown in Figure 5. For the control beam, the initial cracks were under tension in the bottom fibre, but they soon turned into inclined shear cracks propagating from the support to the loading point.

As the load was further increased, a single major crack appeared with increasing width until reaching the maximum load.

A clear shear-compression failure was shown by the observation of cracking and failure patterns of the control beam. In the other beams, a similar cracking mechanism was observed.

a) BG1/0 – 1/100

b) BG1/0 – 2/70

c) BG1/0 – 3/60

d) BG1/0 – 4/50

Figure 5. Damage ratios of the beams

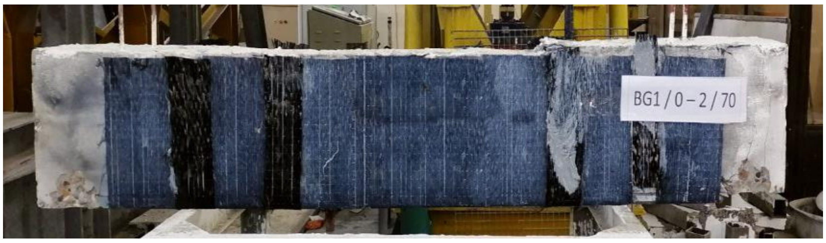
3.2 Post-Cracking test results

In the beams strengthened using CFRP sheets, a similar cracking mechanism was observed. The failure was delayed by the CFRP strips and both maximum deflection and load increased, despite being shear-dominated. The CFRP materials' full strength all beams was utilized successfully. CFRP delamination and debonding was not observed because additional support to the vertical CFRP strips in beams was provided by the U-wrapped configuration. The test results and failure modes observed for the tested beams in the experimental program are shown in Table 2. It was very difficult to remove the CFRP strips and only overlapped strips were removed to see the shear failure as shown in Figures 6 to 8.

The U-wrapped rehabilitation is an efficient technique to increase the ultimate load capacity and shows an important role in the RC beams repairing.

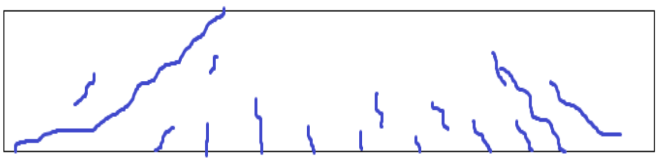
Table 2. Test results

		Control beam					
Specimen symbols	**Damage ratio**	**Load at first rack Pcr (KN)**	**Deflection at first crack (mm)**	**Ultimate load Pu (KN)**	**Ultimate deflection (mm)**	**Pcr / Pu (%)**	**failure mode**
BG1/0-1/100	100%	63.44	5.47	213.31	16.59	29.74	diagonal shear failure
		Before rehabilitation		**After rehabilitation**			
Specimen symbols	**Damage ratio**	**Load at first rack Pcr (KN)**	**Deflection at first crack (mm)**	**Ultimate load Pu (KN)**	**Ultimate deflection (mm)**	**Pcr / Pu (%)**	**failure mode**
BG1/0-2/70	70%	66.27	5.82	236.59	15.46	28.01	diagonal shear failure
BG1/0-3/60	60%	63.44	6.51	238.29	20.59	26.62	diagonal shear failure
BG1/0-4/50	50%	68.55	5.56	247.37	18.76	27.71	diagonal shear failure



a) beam specimen immediately after test

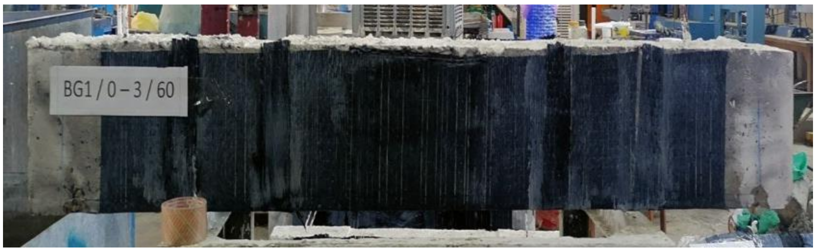
b) beam specimen after removing some CFRP sheets



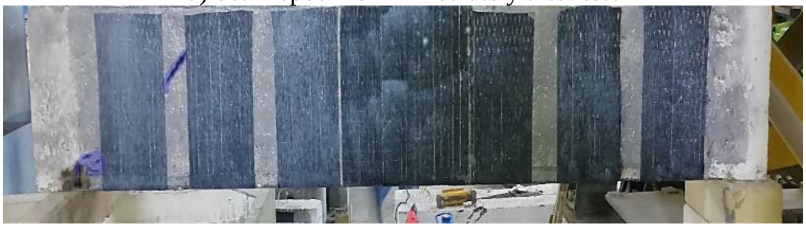
c) beam specimen drawing showing the cracks

d) failure crack from the top

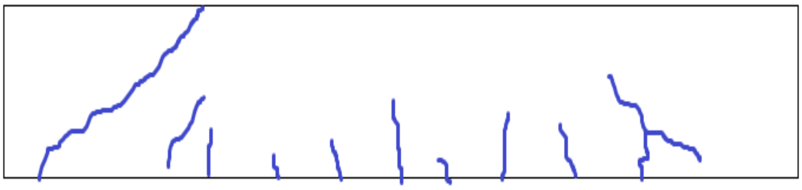
Figure 6. Cracks pattern for beam specimen BG1/0-2/70



a) beam specimen immediately after test



b) beam specimen after removing some CFRP sheets

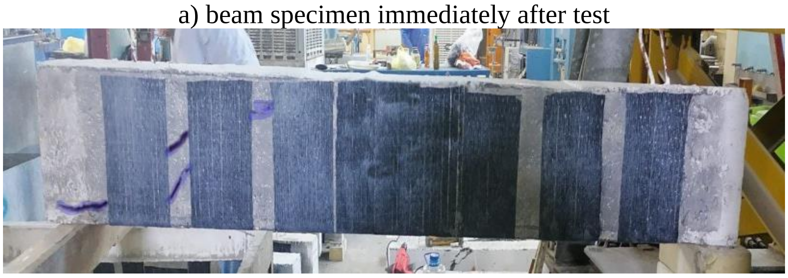


c) beam specimen drawing showing the cracks

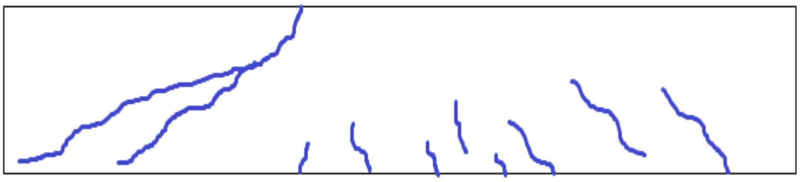
d) failure crack from the top

Figure 7. Cracks pattern for beam specimen BG1/0-3/60

a) beam specimen immediately after test



b) beam specimen after removing some CFRP sheets



c) beam specimen drawing showing the cracks

d) failure crack from the top

Figure 8. Cracks pattern for beam specimen BG1/0-4/50

3.3 Ultimate load capacity

From the results, we can see that the ultimate load capacity of damaged beams (BG1/0 – 1/70, BG1/0-3/60, and BG1/0-4/50) is improved the about 10.91%, 11.72%, and 15.96% respectively compared with the expected remaining ultimate load capacity of reference specimens without rehabilitation, also, an increment in the deflection of mid-span about -6.81%, 24.11% and 13.1% at an ultimate load.

Figure 9 shows the difference in the ultimate load failure of the tested specimens. The results show that the change in the damage ratio leads to a difference in the ultimate load. Also, the results show that the beam with 50% damage after rehabilitation is the most effective to increase the ultimate load capacity by over 4.7% on average compared to other damage ratios.

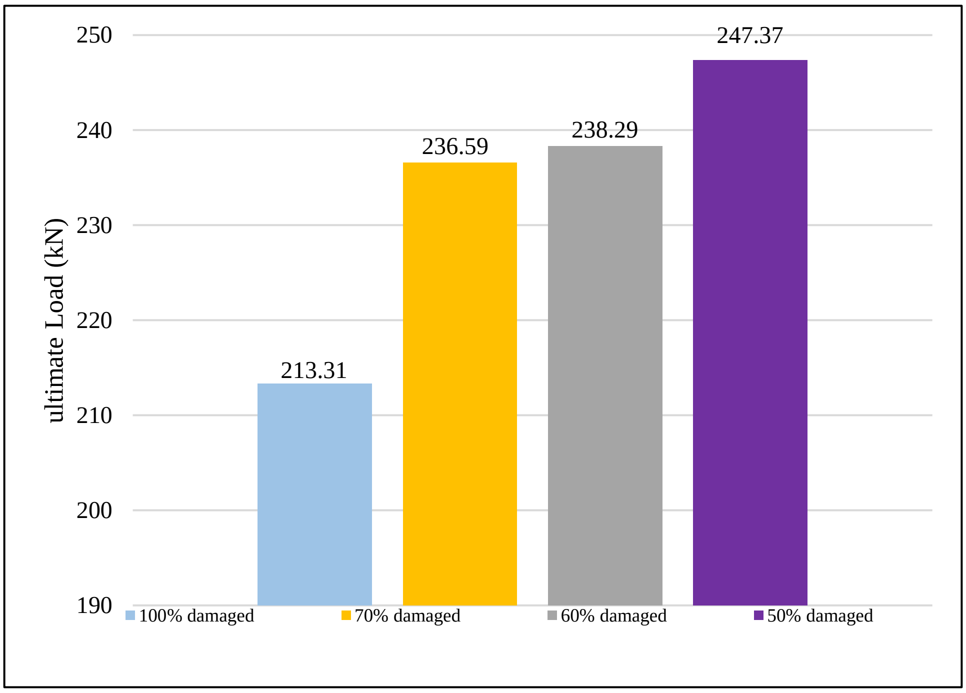


Figure 9. Ultimate load for all beams

3.4 Load-Deflection behavior

The load-deflection relationship can clearly explain the behavior of structural elements. Tests were stopped when the failure occurred. Because it was hard to observe the damage on the beams because of the full coverage of CFRP sheets from three sides, the failure was known when the load could no longer be increased or begins to decrease with the continuous increase in deflection. The load-displacement curves for all beams are shown in Figure 10.

When the RC beams strengthened with CFRP, deflection increased linearly with the load. This indicates that deflection remains within the elastic range. The shear cracks were formed and increased with the load increment, resulting in a reduction in the stiffness of the beam specimens. It was observed that the behavior of strengthened beams is affected by CFRP sheets compared with the control beams by reducing the mid-span deflection and increasing the ultimate strength. Finally, the study shows that U-wrapped rehabilitation is an efficient technique to increase the ultimate load capacity of strengthened beams by over 12.86% on average compared to un-strengthened beams. Thus, CFRP plays a vital role in the RC beams repairing.

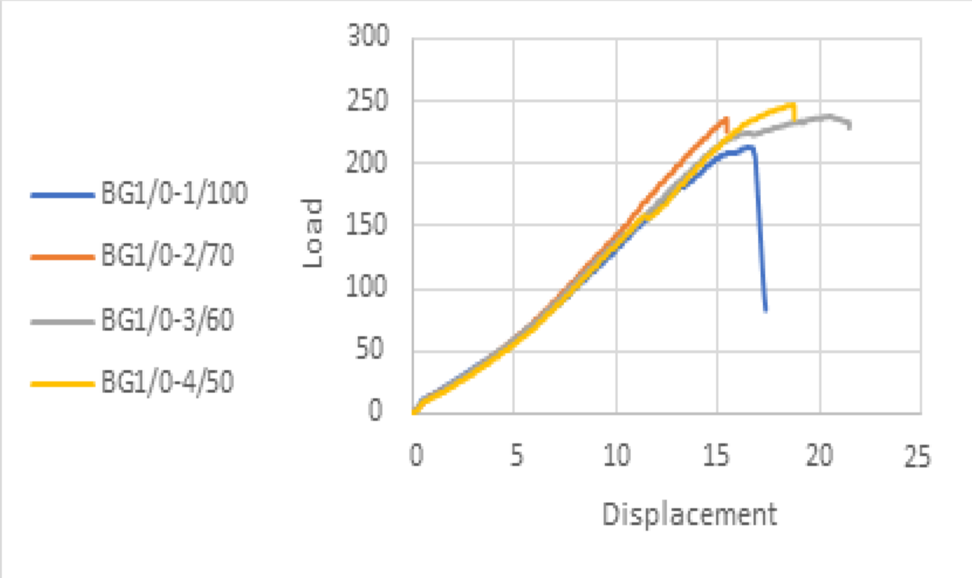


Figure 10. Load-deflection curve

4. Conclusions

This study investigates the unidirectional CFRP rehabilitation effectiveness of rectangular RC beams. The studied parameter was the damage ratio. The following conclusions can be drawn from the results:

1. The first crack is flexural and was observed at the bottom of the beam. This crack is formed at around 30% of the ultimate load for the beams.
2. Initial cracks were in the bottom fiber under tension, but they turned into shear cracks and a single major crack appeared until the maximum load was reached.
3. The ultimate load capacity of 50% damaged beam is improved by about 15.96% compared with the expected remaining ultimate load capacity of control beam specimens without rehabilitation, as well as an increment in the mid-span deflection of about 4.7 % at an ultimate load.
4. The beam with 50% damage after rehabilitation is the most effective to increase the ultimate load capacity by over 4.4% on average compared to other damage ratios.
5. The behavior of strengthened beams is affected by CFRP sheets compared with the control beam specimens by reducing the mid-span deflection and increasing the ultimate strength.
6. U-wrapped rehabilitation is an efficient technique to increase the ultimate load capacity and shows a vital role in the RC beams repairing.

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