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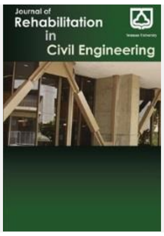

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Flexural Performance of RC Continuous Beams Strengthening by CFRP with Grooves

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ABSTRACT

Externally Bonded Reinforcement (EBR) is the most common technique used to strengthen the RC members with carbon fiber reinforced polymer (CFRP) sheets. Recently, a new proposed technique was named Externally Bonded Reinforcement on Grooves (EBROG) has been presented as an alternative method to avoid or eliminate the undesirable de-bonging failure mode that is accompanying to EBR method. This paper is devoted to investigating the effect of the strengthening techniques on the flexural behavior of RC continuous beams externally strengthened with CFRP sheets in both hogging and sagging zones, by testing twelve beam specimens. All beams have the same cross-section (200×130) mm and 2300 mm length. The parameters of this study include strengthening methods, length and layers number of CFRP sheet and number, length and direction of grooves, in addition to the effect of presence of steel fiber in the hogging zone. The results are introduced in terms of ultimate load, ultimate deflection, ductility index and mode of failure. The test results showed that the EBROG strengthening method has highly effective in improving the ultimate load of strengthened beams. The specimens strengthened by one and two layers of CFRP using EBROG with three longitudinal grooves have a rising in the ultimate load by about (24.4 and 52.6) % respectively, in comparison with the same beams but strengthened by EBR. Also, the mode of failure was changed from CFRP debonding in case of EBR beams to CFRP rupture, or to concrete cover separation in EBROG beams. Finally, the strengthened beams with CFRP sheets presented a more brittle behavior at failure than the unstrengthening specimen.

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1. Introduction

Some of RC structures required strengthening and rehabilitation or repair during their service life. In the last few years, strengthening using externally bonded reinforcement (EBR) is considered as one of the available strengthening techniques. The FRP composites are available in many types; Carbon (CFRP), Glass (GFRP), and Aramid (AFRP). The most common one is CFRP sheet, which can significantly improve the flexure and shear capacities of RC members. The CFRP sheet have important features represented by its light weight and flexibility, which let to improve the bonding of CFRP sheet to RC elements in different configurations as well as resistance to corrosion, large tensile and fatigue strength, and large stiffness/ weight ratio. The externally bonded reinforcement method is assumed to be the most common technique that is used in the strengthening of concrete members, however, the strengthened members by this technique mostly suffer from de-bonding failure which is considered an undesirable failure mechanism. When the earlier de-bonding of the CFRP from concrete cover occurs, the reinforced member shows a brittle failure mode before the CFRP reaches to the ultimate tensile strength. Many analytical and experimental studies have been presented to investigate the structural response of different RC members strengthening with CFRP sheet. In most of these studies, it was found that the flexural capacity, stiffness and durability of tested concrete members enhanced with using CFRP sheet as externally bonded reinforcement, but brittle failure seems to be the prevalent failure due to de-bonding of CFRP sheet from the concrete face [1–8]. Recently, a new technique has been introduced to overcome/ postponed the de-bonding of CFRP sheet-named externally bonded reinforcement on grooves (EBROG) method which is developed by Mostofinejad and Mahmoudabadi (2010) [9]. In (EBROG) technique, numbers of grooves should conduct into the concrete surface of strengthened beams, then the grooves are filled with well epoxy resin, finally the CFRP sheets are bonded on the concrete cover across the filled grooves. EBROG seems unsimilar to near surface mounted method (NSM), in which grooves are formed on the concrete surface, then the circular or rectangular FRP rods are embedded using adhesive materials [10,11]. Different configurations of cutting grooves can be prepared such as; transverse, diagonal and longitudinal grooves. Experimental studies observed that EBROG technique may delay or sometime eliminate the CFRP de-bonding. CFRP rupture, or concrete cover separation are the most occurred failure mode in the tested strengthening beams by EBROG technique [12–19].

Also, the ductility is very important in continuous RC beams, it allows for moment redistribution, which permits to reach of the full capacity of most beam segments. It was noted that there was an improvement in the flexural resistance of tested RC continuous beams strengthening with CFRP sheets using EBR, but with reducing the ductility values [20–24]. So, some previous studies investigated the flexural moment resistance and ductility index of strengthened RC continuous beams by CFRP using near surface mounted (NSM) or EBR techniques [25–28]. However, the previous studies and most of the design codes focused on the structural behavior of simply supported beams strengthening with CFRP sheets [29,30]. So that, more researches are still necessary to fully understand the structural response of continuous beams strengthening externally by CFRP, especially with the new EBROG technique, which is considered the main objective of this study.

In this paper, the flexural behavior of two spans continuous beams strengthening with CFRP sheets using EBROG technique was studied. The parameters of the study include; the method of strengthening (traditional EBR and EBROG), number of grooves, grooves direction, length and layers number of CFRP. The mid-span deflections, failure modes, ultimate load, and ductility index of the tested strengthened specimens will be discussed.

2. Experimental Program

To investigate the effect of EBROG strengthening technique on the flexural behavior of continuous RC beams, twelve beam specimens strengthening with CFRP sheet using EBROG and EBR techniques were cast and tested. The grooves were constructed in different directions (longitudinal, transverse, and inclined with a 30^{o} angle), varied in length and located in both sagging and hogging zones. additionally, the length and the number of the layers of CFRP sheet were studied. Finally, the effect of steel fiber (SF) in the hogging zone of the continuous beam was studies in two beam specimens.

More details of specimens, testing procedure, materials properties and strengthening techniques were presented in the following sections.

2.1. Test specimens

In this study, twelve RC beams continuous were designed based on the ACI318-19 code [31] and tested to examine the effect of external strengthening on structural behavior. All beams have an overall length of 2300 mm over two spans, each span has 1050 mm clear length and a rectangular cross-section of (130×200) mm. The tested specimens were subjected to a single point load applied at the mid of each span. The longitudinal reinforcement of 2Ǿ8 mm at the tension and compression zones. To ensure that the flexural failure will occur before shear, the beams were reinforced with stirrups of (φ8 @ 60 mm c/c) over the whole beam length. The beams geometric and distribution of the reinforcement bars are shown in Figure 1. The first beam specimen (CB), is assumed as a control specimen which has no external strengthening. All other specimens were strengthened by CFRP sheet. Two of the beams named, (E1L and E2L), are strengthened in both hogging and sagging zones using EBR method with single and double layers of CFRP sheet, respectively. The other nine beams were strengthened with CFRP sheet using EBROG technique. Table 1 and Figure 2 illustrate in detail all beam specimens.

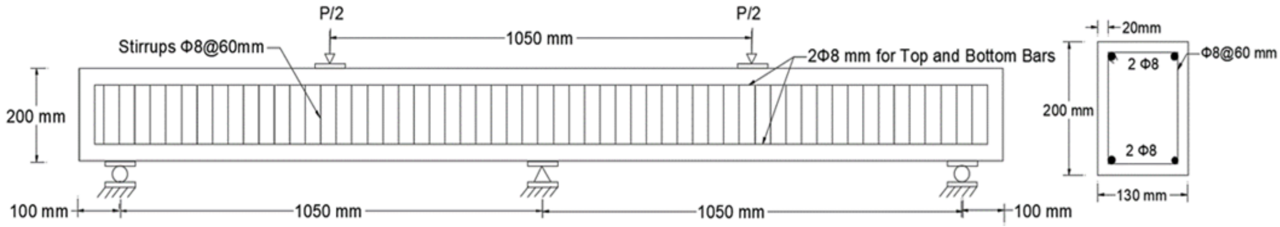
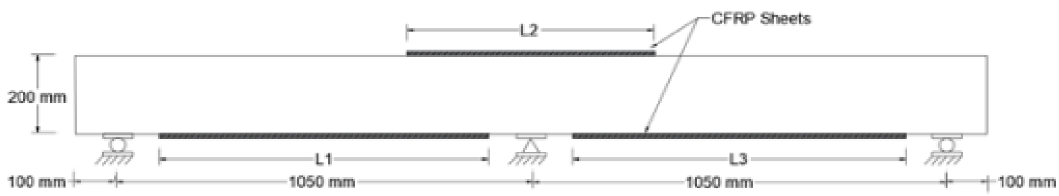


Fig. 1. The beams geometric and distributed of the reinforcement.

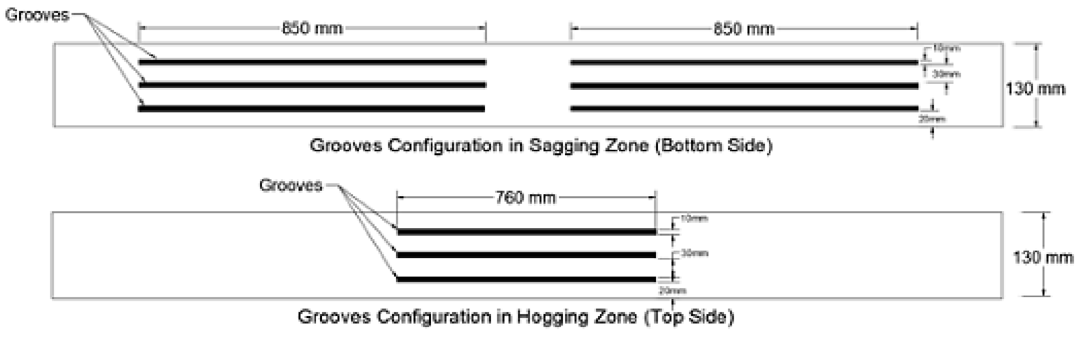
Table 1. Details of Tested Beams.

Specimen	Steel fiber V_f (%)	Groove Properties		CFRP sheet Configuration					Strengthening Technique
				Sagging Zones			Hogging Zone		
		Direction	Number	No. of layers	Length (L1) cm	Length (L3) cm	No. of layers	Length (L2) cm	
CB	-	-	-	-	-	-	-	-	-
E1L	-	-	-	1	85	85	1	76	EBR
E2L	-	-	-	2	85	85	2	76	EBR
O1L3G	-	Long.	3	1	85	85	1	76	EBROG
O2L3G	-	Long.	3	2	85	85	2	76	EBROG
O1LVD	-	Long.	3	1	85	85	1	76	EBROG
		transverse (90°)	5						
O1LDL	-	Long.	3	1	45*	85	1	76	EBROG
O1LDG	-	Long. **	3	1	85	85	1	76	EBROG
O1L2D	-	Long.	3	1	85	85	1	76	EBROG
		Inclined (30°)	5						
O1L2G	-	Long	2	1	85	85	1	76	EBROG
SF-OB	1.6	Long	3	1	85	85	-	-	EBROG
SF-O	1.6	Long	3	1	85	85	1	76	EBROG

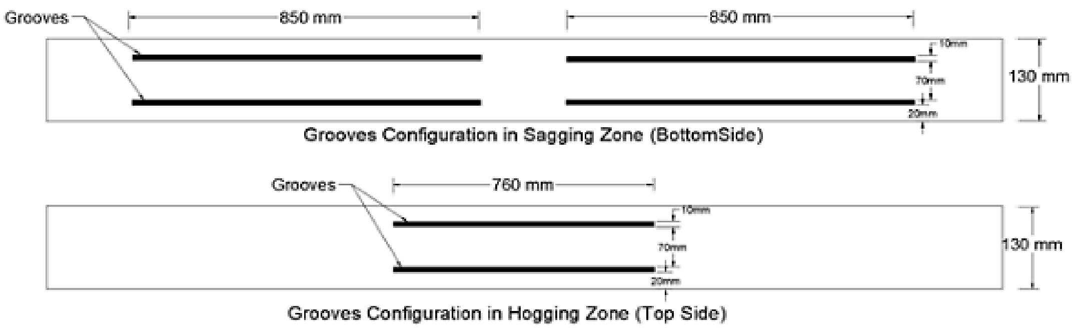
* Length of grooves and CFRP sheets is 45 cm in one side (one sagging zone) of O1LDL beam.
** Length of grooves in O1LDG is 45 cm in the sagging and hogging zones, while the length of CFRP sheet is 85 cm.



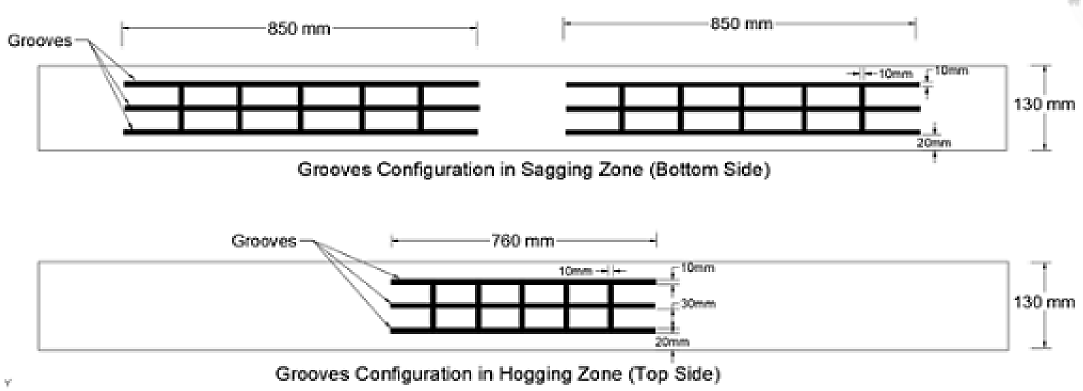
(a) Externally Strengthening Using CFRP Sheets



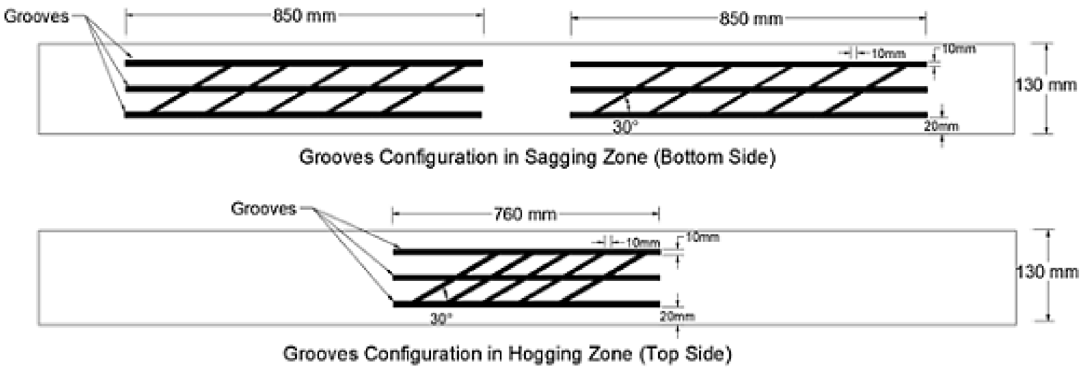
(b) Three Longitudinal Grooves in Sagging and Hogging Zones



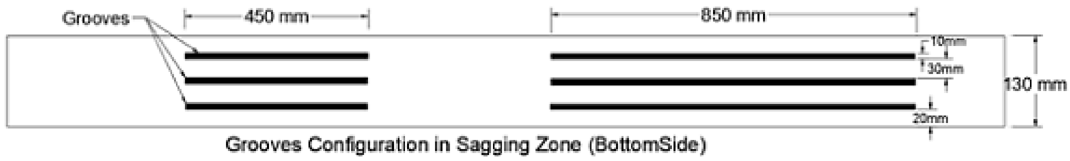
(c) Two Longitudinal Grooves in Sagging and Hogging Zones



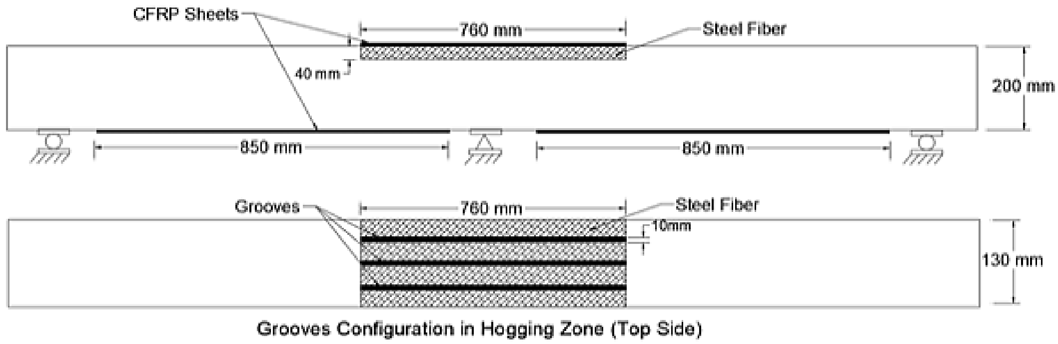
(d) Longitudinal and Transverse Grooves in Sagging and Hogging Zones



(e) Longitudinal and Inclined Grooves in Sagging and Hogging Zones



(f) Different Length Grooves in Sagging Zones as in Beam O1LDL



(g) Three Longitudinal Grooves with Steel Fiber in Hogging Zone

Fig. 2. Grooves Configuration in the Tested Beams.

2.2. Material properties

All examined beams are constructed using the same materials; cement, sand, gravel, steel bars, SF, CFRP, and Epoxy. All materials are tested at the laboratories of University of Thi-Qar, and compared the tests results with the ASTM specifications. The beam specimens are casted using normal strength concrete with a 37 MPa as compressive strength at 28 days. The average concrete compressive strength is predicted based on the standard test of (150×150×150) mm cubic samples. The average compressive strength of tested cubic samples for concrete with steel fiber (SFC) is 40 MPa. Also, a splitting tensile test was carried out using the cylinder specimens to estimate the tensile strength of normal concrete (NC)and concrete with steel fiber volume fraction of (V_f =1.6%). The concrete beams and cubes are cured for 28 days after casting. A summary of materials characteristics is shown in Table 2.

Table 2. The properties of the used Materials in Tested Beams.

Material	Property	Value
Concrete	Compressive strength of normal concrete, (MPa)	37
	Compressive strength of concrete with SF, (MPa)	40
	Tensile strength of normal concrete, (MPa)	2.7
	Tensile strength of concrete with SF, (MPa)	4.6
Steel bar	Bar diameter, (mm)	8
	Yield stress, (MPa)	455
	Ultimate stress, (MPa)	665
	Elongation, (%)	15.5
Steel fiber	Diameter	0.62
	Lengths	40
	Aspect ratios	64.5
	Tensile strength, (MPa)	1150
CFRP	Thickness, (mm/ply)	0.167
	Tensile strength, (MPa)	3500
	Modulus of elasticity, (GPa)	220
Epoxy Resin	Tensile strength, (MPa)	30
	Tensile modulus, (MPa)	4500
	Flexural modulus, (MPa)	3800

2.3. Testing Layout and Strengthening Techniques

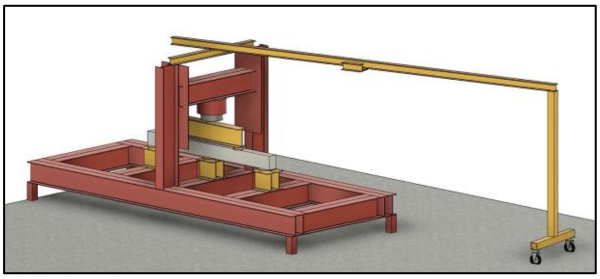
To study the effect of the strengthening of continuous beams by CFRP sheets using EBR and EBROG techniques on the flexural strength, deflection and mode of failure, nine beam specimens are strengthened using EBROG and two beams strengthened by conventional method (EBR), in addition to the control specimen without strengthening. For beam specimens strengthening by EBR technique, the concrete surface at tension faces were roughed by a grinder machine and well cleaned with an electric air blower and washed with water to remove dust. The CFRP sheet with selected sizes of length of 850 mm and 100 mm in width, then the Sikadur330 epoxy resin was mixed and overlaid along the concrete face. Finally, the CFRP sheet were bonded to concrete surface in a wet layup procedure. Generally, in case of EBROG technique the grooves with width of 10 mm and depth of 8mm with different lengths and directions were formed in specified location at the concrete face using a grinding machine. The grooves were cleaned with an electric air blower and then fully filled with epoxy resin in addition to the specified surface of the concrete. Immediately, CFRP sheets were adhered to the concrete surface along the grooves. Figure 3 shows the steps of the strengthening procedure.

(a) Grooves Configuration | (b)Grooves Cutting Sheets | (c) Final Form of the Concrete Surface | (d) Adhesion of CFRP | (e) CFRP Sheets Overlay

Fig. 3. The steps of Strengthening Method of Tested Beams.

2.4. Test Setup

All strengthened beams were subjected to one point load at the mid of each span until the failure. The specimen was placed on three supports; roller support at both edges with one hinge support at the middle of the beam. Then the load cell with a capacity of (500 kN) was located on a steel beam to distribute the pressure force on the tested beam as in two points loads, as shown in Figure 4.



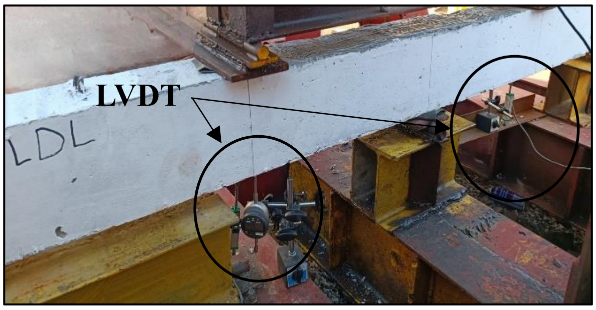


Fig. 4. The step up of Test.

The deflection of examined beams was determined using Linear Variable Differential Transformer (LVDT) sensors fixed at the middle of each span and attached to the tension face as shown in Figure 4.

3. Presentation and Discussion of Results

The experimental results were presented and discussed in terms of ultimate load, ultimate deflection, ductility index, and failure mode of tested beams. Table 3 summarizes the results of load carrying capacity, increasing ratio in the load and mode of failure of tested beams.

3.1. Load Carrying Capacity

3.1.1. Influence of strengthening techniques

Four specimens were designed to study the effect of the strengthening technique on the load carrying capacity of RC continuous beams strengthening with CFRP sheet. Two beams (E1L and O1L3G) strengthened by single layer of CFRP in each hogging and sagging zone. E1L beam was strengthened by using EBR method, while O1L3G was strengthened by EBROG, with three longitudinal grooves. It is observed that there is an increase in the load carrying capacities of E1L and O1L3G beams were 14.2% and 42.0%, respectively in comparison with the control specimen as presented in Table 3.

Table 3. The Ultimate Load and Mode of Failure of Tested Beams.

Specimen	Ultimate Load (kN)	Increasing Ratio in Ultimate Load (%)	Mode of Failure
CB	125.4	_	Flexure
E1L	143.2	14.2	De-bonding
E2L	153.9	22.7	De-bonding
O1L3G	178.1	42.0	Rupture of CFRP
O2L3G	234.8	87.2	Concrete cover separation
O1L2G	162.6	29.7	Rupture of CFRP
O1LVD	190.3	51.8	Rupture of CFRP
O1L2D	189.7	51.3	Rupture of CFRP
O1LDG	164.1	30.9	Concrete cover separation
O1LDL	145.4	16.0	Concrete cover separation
SF-OB	152.4	21.5	Rupture of CFRP
SF-O	178.9	42.7	Rupture of CFRP

The EBROG technique resulted in a higher increasing ratio in flexural strength of the beam, this can be related to the large contact surface between CFRP and concrete, which means better bonding and then higher benefit can be achieved from used CFRP sheets. However, E2L and O2L3G beams strengthened by double layers of CFRP sheet in each hogging and sagging zones. The results showed that the ultimate load of beams E2L and O2L3G larger by (22.7 and 87.2) % respectively, than that of the control beam. Figure 5 shows the influence of the strengthening technique on the ultimate load.

3.1.2. Influence of the number of CFRP sheets layers

From Figure 5, it is found that an increase of (7.5 and 32) % in the load carrying capacities of E2L and O2L3G beams respectively, in comparison with identical beams but with one layer of CFRP sheet. It can be also concluded that the effectiveness of using double layers of CFRP sheets in hogging and sagging zones is more significant in beam strengthening with CFRP sheet, using EBROG technique. Again, this can be attributed to the higher bond between the CFRP sheets and concrete surface in case of EBROG method, which resulted in elimination the de-bonding mode of failure and then higher effective of using double CFRP layers can be achieved as a compression with EBR beams.

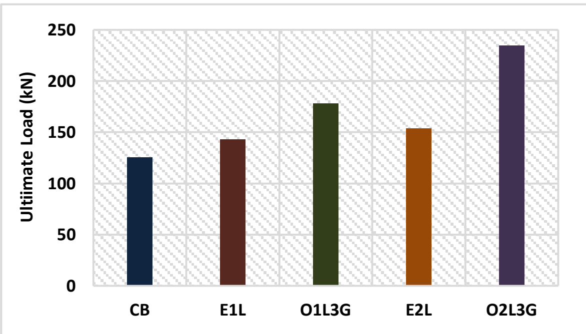


Fig. 5. Effect of Strengthening Technique on Ultimate Load.

3.1.3. Influence of the number, length and direction of Grooves

Beams E1L, O1L2G and O1L3G were designed with similar geometric and material properties except the number of grooves. No grooves in beam E1l and two longitudinal grooves have been created in beam O1L2G, while three longitudinal grooves were created in beam O1L3G. Due to increasing contact area between CFRP sheets and concrete with increasing the numbers of formed grooves, It is found that the strengthened beam by EBR (without grooves) and increase of number grooves from two to three grooves in strengthened beams by EBROG resulted in an increasing the load carrying capacity by about (14.2, 29.7 and 42.0) % for beams E1L, O1L2G and O1L3G, respectively as in comparison with the control beam (CB) as illustrated in Figure 6.

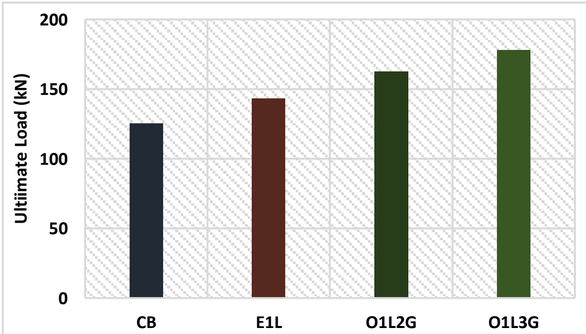


Fig. 6. Effect the Number of Grooves on Ultimate Load.

However, five transverse grooves in addition to three longitudinal grooves were created in O1LVD beam, while five inclined grooves make an angle of 30° with a longitudinal axis in the presence of three longitudinal grooves were presented in O1L2D beam to study the influence of grooves direction/configuration on the load carrying capacity. It is clear from Figure 7 that the groove configurations have an effect on the behavior of strengthened beams. An increase of (42.0, 51.8 and 51.3) % in the load capacity of beams O1L3G (with only three longitudinal grooves only), O1LVD and O1L2D respectively, in comparison with the control beam (CB). It can be concluded from the results that using grooves in two directions resulted in higher ultimate load. But there is unsignificant effect on the load carrying capacity with using either transverse or inclined grooves.

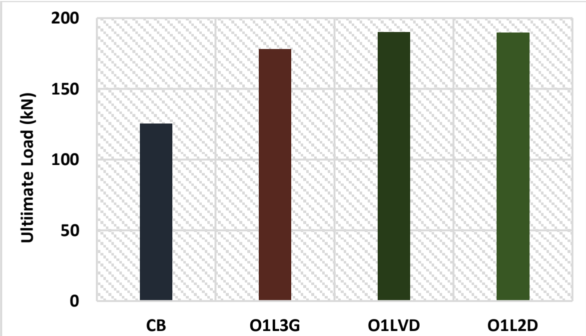


Fig. 7. Effect of Grooves Direction on Ultimate Load.

Finally, changing the length of CFRP sheet and grooves has affected the load capacity as presented in Table 3 and Figure 8. It obvious from the results of beams O1LDL and O1LDG that the reducing length of CFRP in the sagging zone from 85 cm as in O1L3G to 45 cm as in beam O1LDL resulted in decreasing the load capacity of O1LDL by 18.4%. In the same manner, reducing groove length in the sagging zone from (85 to 45) cm led to a decrease in the load capacity by 8 % as in O1LDG in comparison with O1L3G beam.

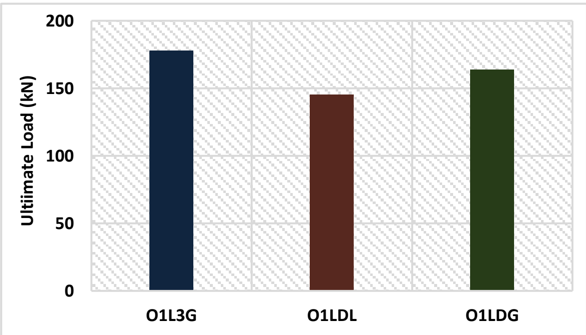


Fig. 8. Effect of CFRP Sheets and Grooves Length on Ultimate Load.

3.1.4 Influence of steel fiber

The effect of steel fiber on the flexural resistance of RC continuous beam strengthening with CFRP sheets is examined by testing of two specimens; SF-O and SF-OB. Table 3 and Figure 9 show a slight effect on ultimate load by using steel fiber in the hogging zone as in SF-O beam, the ultimate load of this beam reached to 178.9 kN with increasing in the load capacity by about 42.7% over the control specimen (CB). The absence of CFRP sheet in the hogging zone of (SF-OB) beam resulted in an increase in the ultimate load by 21.5% compared with the control beam.

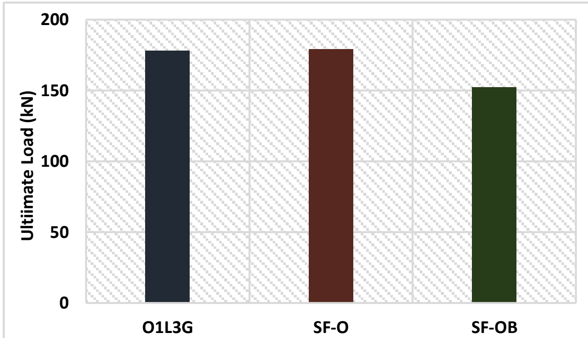


Fig. 9. Effect of Steel Fiber on Ultimate Load.

3.2. Failure Mode

In this study, four modes of failure are observed included; flexure, CFRP rupture, CFRP de-bonding, and concrete cover separation as presented in Table 3. The control specimen (CB) showed a traditional flexural failure as a result of yielding of the main reinforcement bars at the beam tension zone, and then the concrete at both the middle support and the middle of each span was crashed as shown in Figure 10.

Figure 11 illustrates the failure modes of beams E1L and E2L (strengthened with single and double CFRP layers at hogging and sagging zones using EBR technique). It can be noted that both tested beams failed by CFRP de-bonding. After the initiation and propagation of the flexural cracks in the concrete, de-bonding of the CFRP sheet from the concrete surface occurred close to the formed cracks, this is may be due to high local strain concentration at the cracks region. With increasing the applied loading, the interfacial stresses increase and de-bonding propagates toward the ends of CFRP sheet.

Fig. 10. Flexural Failure Mode, (CB).

The de-bonding of the CFRP sheets was followed by the crashing of the concrete in the tensile zone in the mid-span of the beam. The failure was accompanied a little noise indicating imminent failure of the adhesive. The beams strengthening with CFRP sheets using EBROG technique showed different modes of failure, CFRP rupture or concrete cover separation. So, it can be indicated that EBROG technique is more effective in the bond of CFRP sheets along the concrete surface, and it can completely transfer the occurred shear and bending interfacial stresses to the deeper concrete layers.

(a) E1L

(b) E2L

Fig. 11. CFRP Sheets De-bonding Failure of beams E1L and E2L.

Beams O2L3G and O1LDL exhibited a concrete cover separation in both hogging and sagging zones as illustrated in Figure 12, crack propagation along the level of the main reinforcement bars has been observed. In spite of this failure associated with stress concentration at the edge of CFRP sheet, it cannot be considered the type of failure as a de-bonding mode because it creates away from the bond-line.

(a) O2L3G

(b) O1LDL

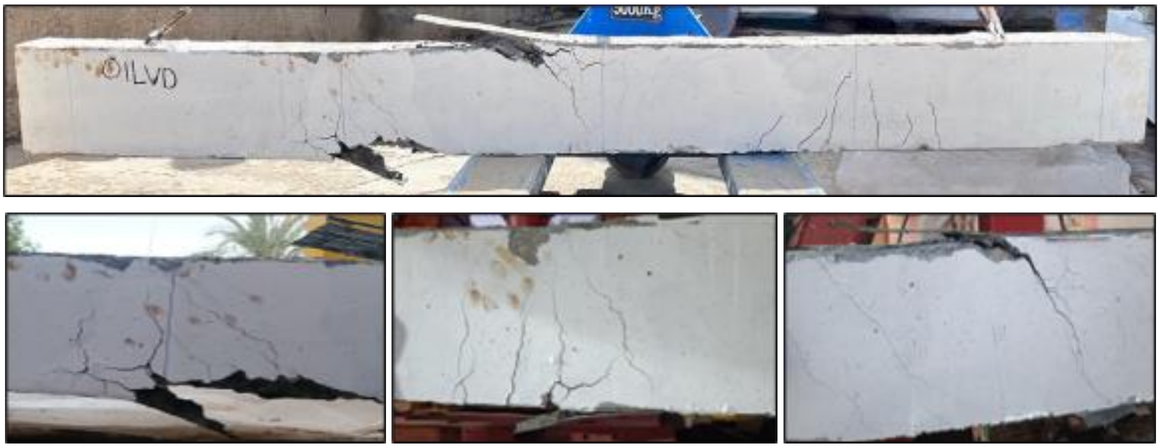
(c) O1LDG

Fig. 12. Concrete Cover Separation Failure of beams O2L3G, O1LDL and O1LDG.

In beam O2L3G, the two layers of 85 cm CFRP sheets seem strong enough to take off the concrete cover before reaching to CFRP yield point. However, the de-bonding of CFRP sheet was noted firstly in (O1LDG) beam. Then, the debonding propagated and the concrete cover separation took place at the grooves zone, Figure 12.

Rupture of CFRP sheet was noted in the sagging zone of beams (O1L3G, O1LVD and O1L2G), which was followed by the peeling of concrete cover in the hogging zone at the central support and the final failure occurred, as illustrated in Figure 13.

(a) O1L3G



(b) O1LVD

(c) O1L2G

Fig. 13. Concrete Cover Separation Failure Prior by CFRP Rupture.

Using diagonal grooved in the (O1L2D) resulted in the failure with the rupture of CFRP sheets in both sagging and hogging zones, Figure 14.

In the (SF-OB and SF-O) beams, CFRP rupture was predominant mode of failure as illustrated in Figure 15.

Fig. 14. Rupture of CFRP Failure Mode.

(a) SF-OB

(b) SF-O

Fig. 15. CFRP Rupture of Beams with Steel Fiber.

3.3. Load-Deflection Curves and Ductility Index

The load-deflection relationships for all tested beams are illustrated in Figures (16 to 18), also, Table 4. presented the ultimate deflection and the ductility index (μ) which was calculated based on Eq. 1 [32];

$$\mu = \Delta u/\Delta y \quad (1)$$

where; Δu is ultimate deflection, and Δy is the yield deflection (deflection at 0.75 ultimate load).

It can be noted from Figure 16 that the strengthened RC beams by CFRP sheet resulted in reduction in the deflection and the ductility index, this is may be due to the linear behavior of CFRP sheets. Beams E1L and O1L3G have a reduction of (63 and 72.3) %, respectively, in the ultimate deflection in comparison with the control specimen. Also, the ductility index values of these beams are smaller than the control beam. However, the beams strengthened by EBR method demonstrated more brittle failure than the beams strengthened by using EBROG technique. For example, the ductility index of beams O1L3G and E1L are 1.9 and 1.3 respectively, as presented in Table 4. In both strengthening techniques a reduction in deflection accumulated with a decrease in ductility index is observed with using double layers of CFRP sheets instead of one layer.

Table 4. The Ultimate Deflection and Ductility Index of Tested Beams.

Specimen	Ultimate Deflection (mm)	Decreasing Ratio in Ultimate Def. (%)	Ductility Index
CB	31.1	-	3.2
E1L	11.5	63.0	1.3
E2L	7.6	75.6	1.2
O1L3G	8.6	72.3	1.9
O2L3G	7.7	75.2	1.6
O1L2G	10.0	67.8	1.5
O1LVD	8.6	72.3	1.8
O1L2D	8.6	72.3	1.9
O1LDG	8.6	72.3	1.6
O1LDL	14.1	54.7	3.3
SF-OB	8.1	74.0	1.7
SF-O	9.9	68.2	1.7

The reduction ratio in ultimate deflection is more significant in beam strengthening using EBR, E2L beam shows a 34% decreasing ratio with respect to E1L beam while O2L3G has a decrease by about 10.5% with respect to O1L3G beam.

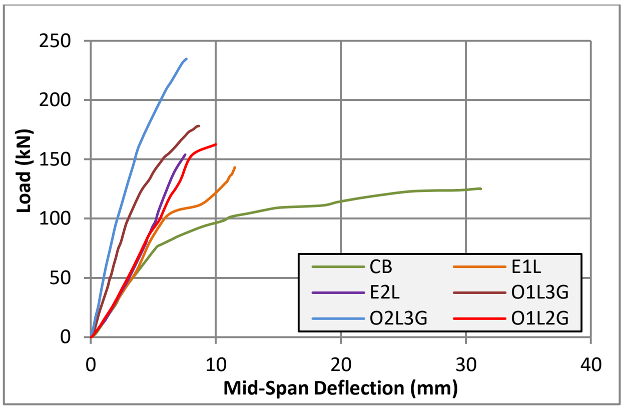


Fig. 16. Effect of Strengthening Technique, Layers of CFRP Sheets and Number of Grooves on Load-Deflection Relationship.

Also, increasing grooves numbers led to an increase in the ductility index. It is clear from Table 4 that the ductility index of beams O1L2G (with two grooves) and O1L3G (with three grooves) are 1.5 and 1.9, respectively.

Also, Figure 17 shows that the direction of the grooves resulted in a slight difference in the load-deflection relationship and ductility index, this is clear from the results of beams O1LVD, O1L2D and O1L3G. The higher ultimate deflection value for strengthened beams is achieved in beam(O1LDL) with EBROG, which is (14.1) mm. Also, this beam has a ductility index of 3.3 (i.e. more ductile behavior at failure).

Finally, the presence of steel fiber in the hogging zone of continuous beam as in SF-O beam resulted in slightly increase in the ultimate deflection. The increasing in the deflection is 15.1% as compared with beam O1L3G (same beam, but without steel fiber). Figure 18 shows the load-deflection relationships for beams with steel fibers as well as the control beam.

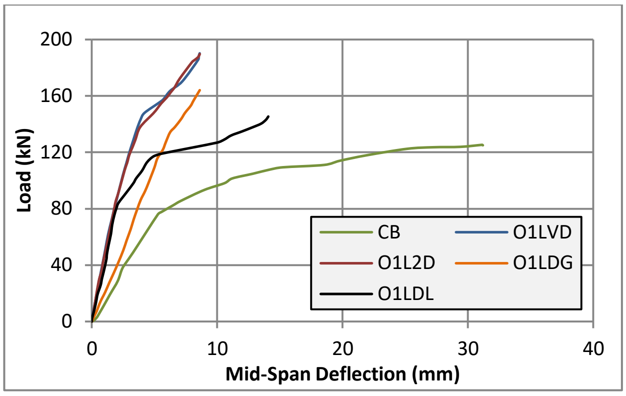


Fig. 17. Effect of CFRP Sheets Length, Direction and Length of Grooves on Load-Deflection Relationship.

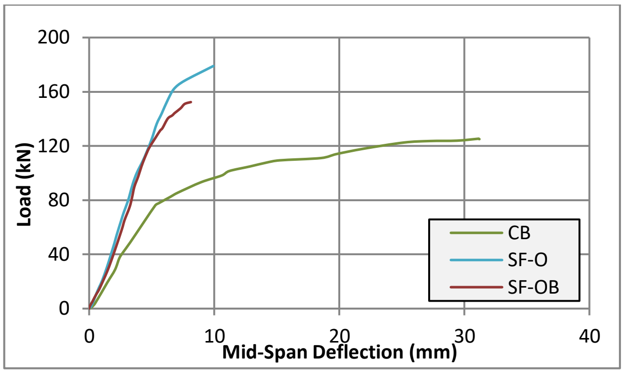


Fig. 18. Effect of Steel Fiber on Load-Deflection Relationship.

4. Analytical results

According to ACI 440.2R-17[30], the ultimate moment (M_u) can be predicted using Eq. (2), based on FRP debonding failure mode.

$$M_u = A_s f_s \left(d - \frac{\beta_1 c}{2}\right) + \psi_f A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2}\right) \quad (2)$$

Where, A_s, A_s' and A_f are the cross-sectional areas of tensile reinforcement, compression reinforcement and FRP sheet/laminate, respectively. f_s is the stress in steel reinforcement, c is the depth of the neutral axis, and d, d', and d_f are the effective depth of tensile steel reinforcement, compression bars, and FRP reinforcement. ψ_f is the reduction factor that is created by FRP, which is taken to equal to 0.85. β_1 is the ratio of rectangular stress block depth to the that to the neutral axis. The effective FRP stress (f_{fe}) given by;

$$f_{fe} = E_f \varepsilon_{fe} \quad (3)$$

In which; the effective strain (ε_{fe}) can be calculated from;

$$\varepsilon_{fe} = \varepsilon_{cu} \left(\frac{d_f - c}{c}\right) - \varepsilon_{bi} \leq \varepsilon_{fd} \quad (4)$$

ε_{cu} is the ultimate concrete strain which taken to equal to 0.003, ε_{bi} is the initial strain which can be calculated from an elastic analysis of the existing member, due to the effect of the loads applied on the member during the installation of the FRP system. ε_{fd} is the FRP de-bonding strain that may obtain from Eq. (5)

$$\varepsilon_{fd} = 0.41 \sqrt{\frac{f_c'}{n E_f t_f}} \leq 0.9 \varepsilon_{fu} \quad (5)$$

Where; ε_{fu} is ultimate strain of FRP sheet.

Table 5 shows the ratio between the predicted load according to ACI 440-2R-17 to experimental ultimate load for tested specimens. It was found the ACI formula correctly estimated the load carrying capacity of beams strengthening with one/ double layers of CFRP sheets using EBR method, with difference ratio less than (8%). Again, ACI model seems highly underestimated the ultimate load of EBROG beams, with ratio reaches to (29%). Excepted specimen strengthening with least CFRP length, O1LDL, in which (3%) is the difference ratio.

Table 5. The Predicted to Experimental load Ratio of Tested Beams.

Specimen	P_{ACI}/ P_{exp}
E1L	0.98
E2L	1.08
O1L3G	0.79
O2L3G	0.71
O1L2G	0.86
O1LVD	0.74
O1L2D	0.74
O1LDG	0.86
O1LDL	0.97

5. Conclusions

The structural behavior of RC continuous beams with CFRP sheets using (EBR and EBROG) methods, was investigated in this study by testing twelve specimens. The final conclusions can be summarized in the following:

1. Strengthening the continuous RC beam strengthening with CFRP sheets, results in enhancing the ultimate load. The EBROG method is more effective than EBR, the increase in the ultimate load of two beams strengthened by one layer of CFRP using EBR and EBROG are (14.2 and 42.0) % respectively, in comparison with control beam.

2. More benefit of using double layers of CFRP sheets can achieved in case of EBROG than EBR. The improvement ratio reaches 87.2% for beam with EBROG and 22.7% for beam with EBR in comparison with a beam without strengthening.

3. According to the testing results, the number of grooves can be considered an important parameter, increasing the number of grooves from zero, two to three in a longitudinal direction resulted in an increase in ultimate load by about 13.6% and 24.5%, respectively for beams strengthening by oner layer of CFRP.

4. The mode of failure changed from CFRP debonding mode in beams strengthening using EBR to CFRP rupture or concrete cover separation modes in the case of using EBROG, this means that EBROG method is more effective in achieving most of benefits of using CFRP sheets.

5. More brittle behavior was achieved in strengthened beams with CFRP sheets.

6. Slightly effect on the values of load carrying capacity, mid-span deflection and ductility index was noted with changing the direction of transverse grooves.

7. Providing steel fiber in the hogging zone of continuous beam in addition to CFRP sheets resulted in CFRP rupture failure mode, with slightly effect on the ultimate load and deflection values.

6. Recommendation for future study

1. Studying the structural behavior of continues beams strengthening with CFRP sheets using EBROG techniques using finite element method.

2. Studying the flexural behavior of RC continues beams enhancing with different ratio of steel fiber volume.

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Conflicts of interest

The authors declare no conflict of interest.

Authors contribution statement

Hanan J. Qassim: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Roles/Writing – original draft; Resources; Software.

Mohammed A. Mashrei: Supervision; Project administration; Validation; Visualization; Writing – review & editing.

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