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Behavior of RC Beams with Rectangular Opening Strengthened with CFRP

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ملخص البحث

احيانا نلجا لعمل فتحات داخل الكمرات الخرسانية لتلبية بعض المتطلبات المعمارية والميكانيكية وقد وجد ان سلوك الكمرات المحتوية علي فتحات يختلف تماما عن الكمرات الصلبة. ومن اجل ان نحصل علي فهم افضل لتلك التغيرات بتلك الكمرات المحتوية علي فتحات تم اعداد هذا البحث لدراسة سلوك الكمرات المحتوية علي فتحات مستطيله واقتراح تدعيم مناسب لها ولتحقيق تلك الاهداف تم اعداد برنامج اختبارات معملية لعدد ثمانية كمرات لها نفس الابعاد والتسليح بهدف دراسة السلوك واختبار مدي كفاءة التدعيم المقترح للكمرات المحتوية علي فتحات في منطقة القص والمدعمة باستخدام شرائح الفايبر, وايضا تحديد مدي كفاءة النظام المقترح للتدعيم علي تحسين مقاومة تلك الكمرات. وقد تبين ان التدعيم المقترح ساعدعلي تقليص الفقد الحادث في مقاومة القص للكمرات.

Abstract

Openings in Reinforced Concrete (RC) beams are required due to some architectural and mechanical reasons. The behavior of RC beams with an opening is somehow different from that of solid beams. The main objective of this research is to obtain a better understanding of the behavior of RC beams with rectangular opening and to introduce a strengthening technique with Fiber Reinforced Polymers (FRP). In order to obtain such objective, a qualitative experimental program including testing of eight RC beams of the same dimensions and steel reinforcement has been carried out. The experimental program aims to examine a proposed strengthening technique using CFRP sheets against shear to increase the load carrying capacity of RC beams with rectangular openings located at the shear zone. All the beams have been tested under four-points bending. It was found that, the purposed CFRP strengthening system has succeeded to decrease the shortage in loading capacity.

1. Introduction

Although beams are very important elements inRC building structures, they may result in contradictions with architectural, electrical and, mechanical ducts. The need to provide an opening in a RC floor beam is in many cases unavoidable due to architectural, as well as, mechanical reasons. Providing such opening usually affects the flexural behavior of the beam and its shear capacity, as well. In specific cases, RC beams are usually strengthened for the sake of enhancing loading capacity. Among diverse models of strengthening, FRP is used worldwide to increase the flexural capacity of the beams. As well, it is used to enhance shear deficient beams.

Saifullah et al, studied experimentally and analytically the flexural behavior of reinforced concrete beams(1). Jayajothi et al, conducted a finite element analysis of FRP strengthened RC beams using ANSYS (2). Ahmed Khalifa, and Antonio Nanni, studied rehabilitation of rectangular simply supported RC beams with shear deficiencies using CFRP Composites (3). Ahmed Khalifa, et al studied shear strengthening of continuous R.C beams using external bonded CFRP sheets (4).

Abdelhak Bousselham, and Omar Chaalla, studied experimentally the behavior of reinforced concrete T-beams strengthened in shear with carbon fiber reinforced polymers(5). Soliman and Osman studied the efficiency of using discrete glass fiber with concrete mixes on the shear behavior of RC beams(6). R. Santhakumar, and E. Chandrasekaran, studied analysis of retrofitted reinforced concrete shear beams using carbon fiber composites(7). A. Goda, et.al, studied size effects for reinforced concrete beams strengthened in shear with CFRP strips (8). A. Abu – Obeidah, et.al, studied finite element analysis of strengthened R.C beams in shear with aluminum plates (9).

Although most research studied the behavior of solid beams strengthened with FRP composites, a few of them have paid attention to the behavior of beams having an opening. Chin et al studied strengthening of reinforced concrete beams containing large opening at flexure with CFRP laminates (10).Furthermore, strengthening of RC beams with large opening in shear by CFRP laminates has been studied by Chin et al with 2D finite element analysis (11). Tamer El-Maaddawy, and Bilal El-Ariss, studied the efficiency of using discrete Fibers on the shear behavior of R.C beam (12). A. M. Mahmud **s**tudied strengthening of concrete beams having shear zone opening using orthotropic CFRP sheets(13)**.**

In order to obtain a better understanding of the behavior of RC beams with rectangular opening, a qualitative experimental program including testing of eight RC beams of the same dimensions and steel reinforcement has been carried out. The experimental program aims to examine a proposed strengthening technique using CFRP sheets against shear to increase the load carrying capacity of RC beams with rectangular openings located at the shear zone. All the beams have been tested under four-points bending. Furthermore, an effective FRP strengthening system is suggested for enhancing their shear capacity.

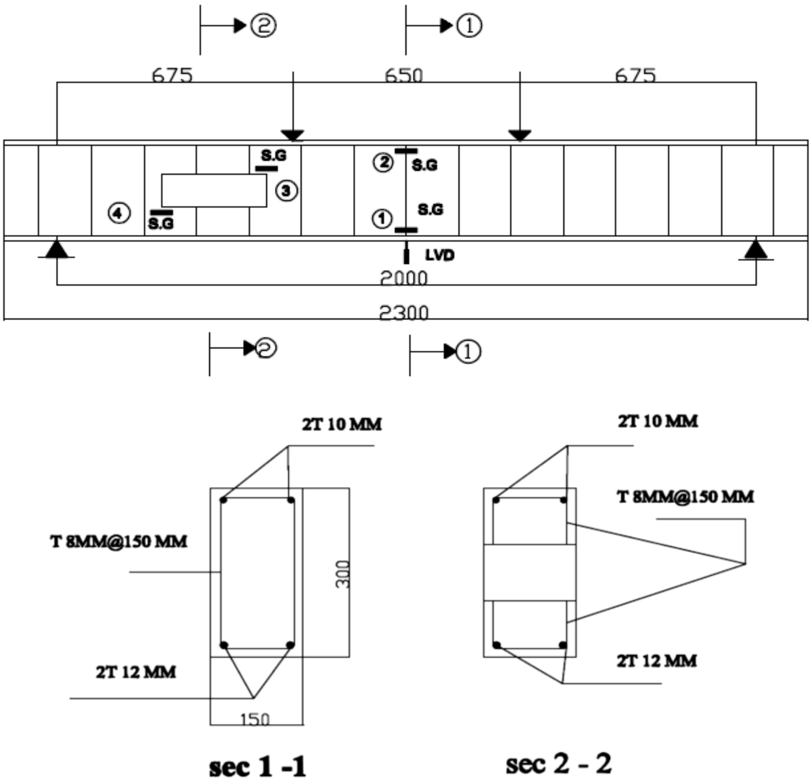
2. Experimental Work

An experimental program encompasses a number of eight rectangular RC beams of the same length and the same cross section. The beams have been tested under four points binding test to study the behavior of RC beams with a rectangular opening. All beams have a length of 2300 mm, a width of 150 mm and a height of 300 mm. The beams have been grouped in three groups. In addition, a solid beam without any openings has been used as the control beam and has been named (CB).

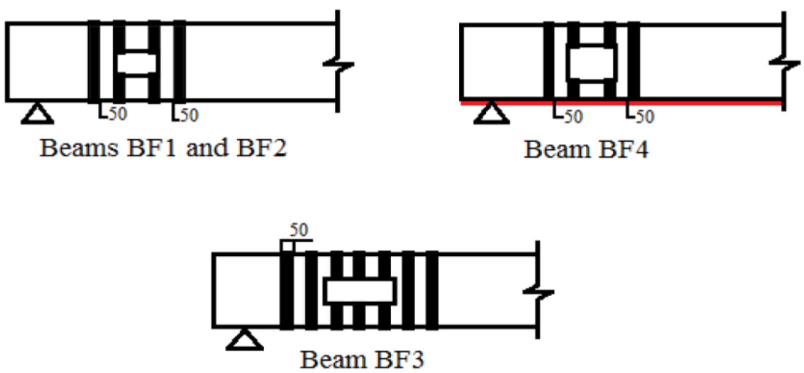
The first group includes two beams with the same opening size of 200 mm length and 100 mm height and starts at 300 mm from the left support. One of the two beams has been un-strengthened and has been named (B1).The other one has been named (BF1)and it has been strengthened with CFRP strips wrapping just before and after the opening and two other strips have been used inside the opening to examine if this strengthening will enhance the load carrying capacity of the beam or not.

The second group includes three beams with an opening having a length of 200 mm and a height of 150 mm height and starts at 300 mm from the left support. The first one of them has been un-strengthened and named (B2).The second beam has been named (BF2) and has been strengthened with CFRP wrapping strips before, after and, inside the opening with the same number of the strips which has been applied in the first group. The third beam in this group, BF4,has been strengthened with the same wrapping strips as the beam BF2 but with applying an additional longitudinal CFRPsheet to enhance its flexural capacity.

Finally, the third group consists of two beams have an opening of length 300 mm and width 100 mm height and starts at 300 mm from the left support.The first beam in this group has been kept without strengthening and has been named (B3). The other beam has been named (BF3) and it has been strengthened with two FRP wrapping strips before the opening, other two strips after the opening and, three through the opening's length. The loading scheme, the geometric configuration, the reinforcement details and, the FRP strengthening configurations of the tested beams are shown in Figure (1). Furthermore, Table (1) summarizes the opening size and the reinforcement configuration for each group.



(a) Geometric configuration, reinforcement details and, loading scheme of the tested beams



(b) FRP strips configuration

Figure 1. Geometric configuration, reinforcement details, and schematic representation of CFRP strengthening schemes.

Table 1. Openings' sizes and reinforcement details of the beams.

Group	Specimens	Opening Size		Bottom RFT	Top RFT	Stirrups
		X (mm)	Y (mm)			
-	CB	-	-	2 T 12	2 T 10	R 8 @150 mm
First Group	B1 -BF1	200	100	2 T 12	2 T 10	R 8 @150 mm
Second Group	B2 - BF2 - BF4	200	150	2 T 12	2 T 10	R 8 @150 mm
Third Group	B3 - BF3	300	100	2 T 12	2 T 10	R 8 @150 mm

2.1 Materials

Concrete mixture has been designed according to themethod and the recommendations of the ACI standards to achievethe required compressive strength, the mixture quantities with the concrete properties have been presented in Table (2). It is worth to mention that six concrete blocks were taken during casting the concrete beams to be examined at seven and twenty eight days to obtain the characteristic strength of the concrete. Furthermore, three test specimens have been taken from the used reinforcing steel, one for each diameter, to be tested to obtain the mechanical properties of the used steel. The mechanical properties of the reinforcing steel are listed in Table (3).Furthermore, for those beams in which the FRP strengthening will be applied, the properties of the CFRP strips and its constituents, carbon fiber C230 and the resign Sikadur330 (A+B), are listed in Table (4).

Table 2. Mixture details and concrete properties.

Mixture quantities		Concrete properties	
Material	Weight (kg/m^3)	property	value
Basalt	1220	Compressive Strength	39 MPa
Sand	555	Water / Cement Ratio	0.4
Cement	450	Slump	8 mm
Water	180	Max. aggregate size	25 mm

Table 3. Reinforcing steel properties.

Diameter (mm)	Yield stress (MPa)	Tinsel stress (MPa)	Elongation (%)
12	419	619	12 %
10	458	662	12 %
8	285	450	10 %

Table 4. Properties of CFRP strips.

Material	Property	Value
Carbon fiber C230	Arial Weight	230±10 g/m^2
	Fabric Design Thickness	0.128 mm
	Fiber Density	1.8 g/cm^3
	Tension Modulus	234000 MPa
	Tension Strength	4300 MPa
	Elongation at Break	1.8%
Laminate Properties using resin Sikadur 330	Laminate Thickness (nominal)	1 mm
	Design Cross section / 1000 mm width	1000 mm^2
	Average Tension Modulus	28.2 GPa
	Characteristic Tension Modulus	26 GPa
	Average Tension Strength	415 MPa
	Characteristic Tension Strength	365 MPa

2.2 Installation of the CFRP strips

The specimens, for which the CFRP strengthening will be applied, have been freshly exposed and free of loose or unsounded materials. The corners have been rounded to prevent stress concentration. The surface preparation has been accomplished using abrasive, all liaisons, dusts, dirties, oil, curing compounds, existing coating and, any other matter that could interface with the bond of CFRP have been removed. Mixing of the resins has been carried out in accordance with the CFRP manufacturer's instructions using electrical powered mixing balance, epoxy resin and amino hardened mixed together with a ratio (4:1), the reaction between the two component give a thermosetting polymer which have reacted to produce a material make the carbon fiber bonded with concrete surface. Figure (2) shows the process of the applying the CFRP strips including surface preparation, mixing the resign and, installation of the CFRP strips.

(a) Surface preparation

(b) Mixing the resign

(c) Installation of the CFRP strips

Figure 2. Applying the CFRP strengthening.

2.3Preparation of the Specimens

All specimens have been placed on the supports such that the clear span of the beam 2000 mm. all the beams have been centered w.r.t the centerline of the jack. The Linear Variable Displacement Transducer (LVDT)has been placed at the middle of the bottom face of the tested beams and has been linked to the control unit. Figure (3) shows the loading frame, the setting out of a tested beam and, placing of the LVDT.

Figure 3.Setting out the tested beam.

3. Results and Discussion

The test has been carried out and the load-mid span deflection relations for the tested beams have been obtained. Figure (4) shows a comparison between the load-deflection behavior of the beams of the first group; in which the opening size was 200 mm length and 100 mm height, with respect to each other and to the control beam. Besides, Table (5) presents the maximum load, the maximum deflection and, the percentage of loss in the load carrying capacity for the tested beams of this group.

As shown in Figure (4) and as listed in Table (6), the effect of the opening on the beam's behavior and its load carrying capacity is very clear. It can be seen that, making an opening with a height of one third of the beam's height and a length of about 10% of the beam's clear span reduces the load carrying capacity of the beam by about 20% of its capacity when no opening exists. Besides, the maximum deflection of the beam with such opening has been reduced to about one third of that of the control beam where no opening exists. This will in turn lead to a considerable reduction in the beam's ductility comparing to the solid beam, the control beam.

Furthermore, applying the CFRP strengthening system with wrapping strips before, after and, inside the opening as shown before in Fig. 1 resulted in enhancing the beam's load carrying capacity by about 7.5%. On the other hand and despite the small enhancement in the maximum deflection, the overall ductility of the beam has not greatly enhanced.

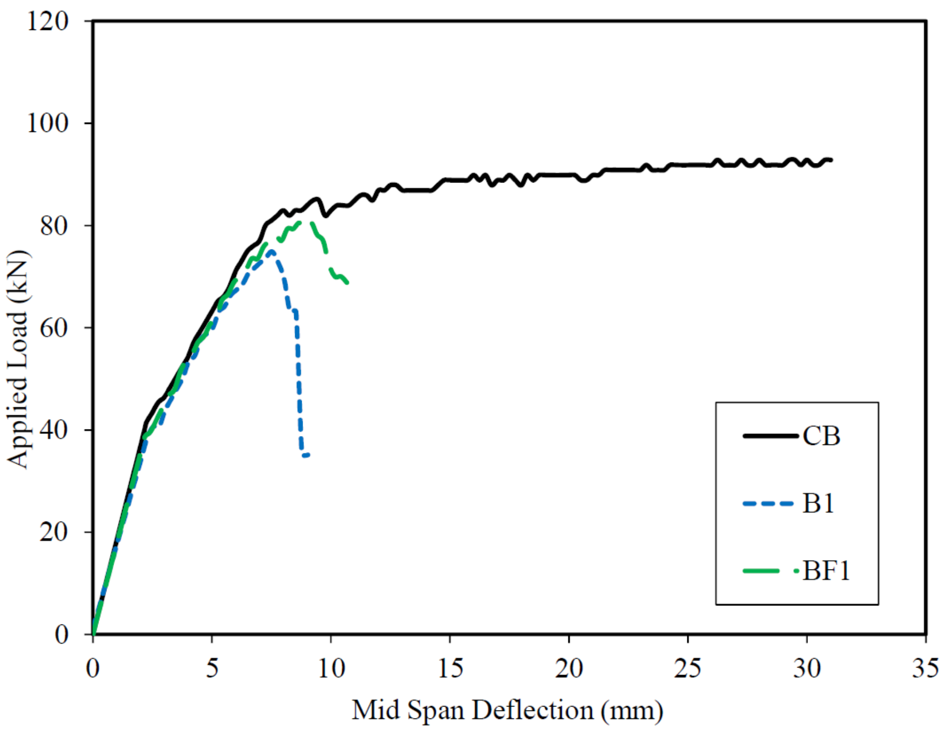


Figure 4. Comparison between the behaviors of the beams of the first group with the control beam.

Table 5. List of results of the first group.

Beam	Maximum Load	Maximum Deflection	% Loss in capacity w.r.t CB	% Increase in capacity w.r.t B1
	(kN)	(mm)	%	%
CB	92.83	31.00	-	-
B1	74.89	9.03	19.33	-
BF1	80.53	10.67	13.25	7.53

In addition, the crack patterns of the control beam (CB), the un-strengthened beam (B1) and, the strengthened beam (BF1) are shown in figures 5 through 7. According to the shown crack patterns in these figures, it can be seen that the failure mode has been changed from a flexural one in the control beam (CB) to a shear failure in the beams B1 and BF1 with the shear cracks are located at the opening's corners.. Also it can be noticed that significant change in the inclination angle of the failure surface has been occurred due to applying the CFRP strengthening system.

Figure 5. Crack pattern of the control beam (CB).

Figure 6. Crack pattern of the beam (B1).

Figure 7. Crack pattern of the beam (BF1).

For the second group where the opening size was 200 mm length and 150 mm height which represents one half of the beam's depth, Figure (8) shows a comparison between the load-deflection relation of the beams B2, BF2 and, BF4 along with the control beam (CB). Besides, the maximum load, the maximum deflection and, the percentage of loss in the load carrying capacity of the beams of this group are listed in Table (6).As shown in Figure (8) and as listed in Table (6), increasing the opening height to reach one half of the beam's height has reduced the load carrying capacity by about 45% of that of the solid beam (CB). Besides, the maximum deflection of the beam with such opening has been reduced to about 20% of that of the control beam where no opening exists making a significant loss in the beam's ductility.

Furthermore, applying the CFRP wrapping strengthening system, Beam BF2, resulted in enhancing the beam's load carrying capacity by about 17.5%. In addition, applying the wrapping system along with the bottom longitudinal strengthening in case of beam BF4 has resulted in significant increase in the load carrying capacity by 87%; approximately, comparing to the un-strengthened beam B2. Furthermore, the load carrying capacity of the beam BF4 has exceeded that of the control beam itself due to the presence of the longitudinal strengthening. Moreover, the enhancement in the maximum deflection and in the beam's ductility is much bigger when applying the longitudinal strengthening with the wrapping one than when applying the wrapping only.

Comparing the crack pattern of the un-strengthened beam B2 which is shown in Figure 9 with that of the control beam CB, Figure 5, shows that the mode of failure has been changed from flexural to shear one with the shear cracks are located at the opening's corners. On the other hand in the strengthened beams BF2 and BF4, Figures 10 and 11, although the crack patterns still indicate a shear failure, the inclination angles of the failure surfaces have been significantly reduced in BF2 and BF4 comparing to that of the beam B2.

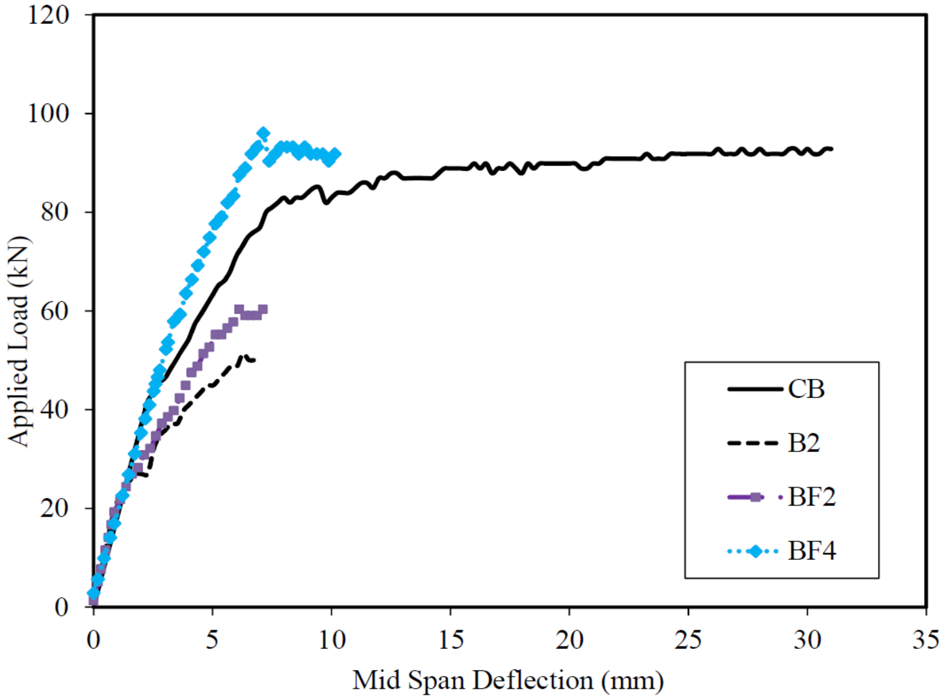


Figure 8. Comparison between the behaviors of the beams of the second group with the control beam.

Table 6. List of results of the second group.

Beam	Maximum Load	Maximum Deflection	% Loss in capacity w.r.t CB	% Increase in capacity w.r.t B2
	(kN)	(mm)	%	%
CB	92.83	31.00	-	-
B2	51.35	6.78	44.68	-
BF2	60.34	7.12	35.00	17.50
BF4	96.02	10.13	-3.44	87.00

Figure 9. Crack pattern of the beam (B2).

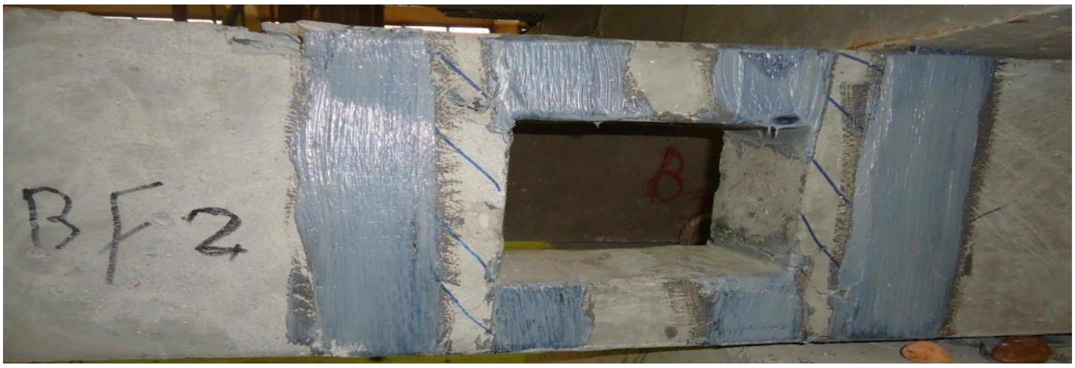


Figure 10. Crack pattern of the beam (BF2).

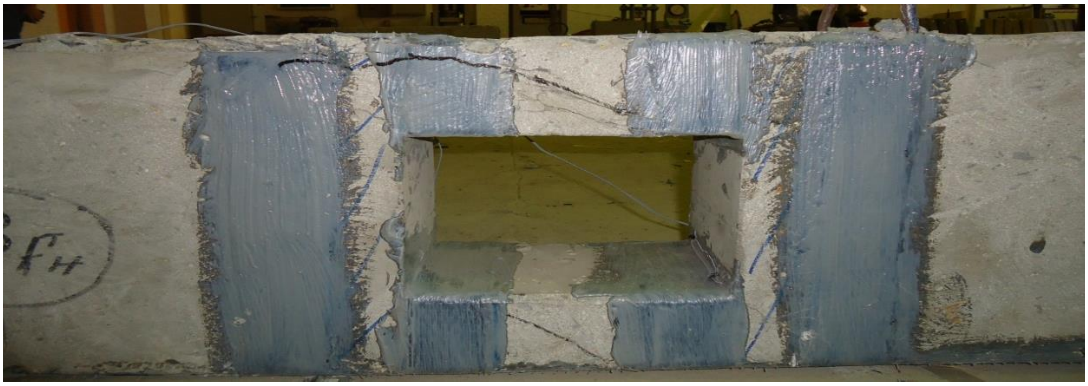


Figure 11. Crack pattern of the beam (BF4).

In the case of the third group, the opening height has been adjusted to one third of the beam's depth as for the first group. However, the opening length has been adjusted to 300 mm (i.e. the opening length has been increased by 50% comparing to that of the other two groups) to study the effect of increasing the opening length on the load carrying capacity of the beam. Also, the wrapping system has been used such that the number of the used strips before, after and, along the opening zone has been increased. Figure (12) shows a comparison between the load-deflection relation of the beams B3 and BF3 along with the control beam (CB). Besides, the maximum load, the maximum deflection and, the percentage of loss in the load carrying capacity of the beams of this group are listed in Table (7). As shown in Figure (12) and as listed in Table (7), the load carrying capacity of the un-strengthened beam has been reducedby about 15% of that of the solid beam (CB). Besides, the maximum deflection of the beam with such opening has been reduced to about one third of that of the control beam making a significant loss in the beam's ductility. It is worth to mention that the maximum load values for the beams B3 and B1 are close to each other.

Furthermore, applying the CFRP wrapping strengthening system, Beam BF3, resulted in enhancing the beam's load carrying capacity by about 6.10%. On the other hand and despite the small enhancement in the maximum deflection, the overall ductility of the beam has not greatly enhanced.

Comparing the crack pattern of the un-strengthened beam B2 which is shown in Figure 13 with that of the control beam CB, Figure 5, shows that the mode of failure has been changed also from a flexural to a shear one with the shear cracks are located at the opening's corners as occurred in the first group too. On the other hand in the strengthened beam BF3, Figure 14, the crack pattern indicates a flexural failure due to applying more wrapping strips which in turn affected the beam's mode of failure.

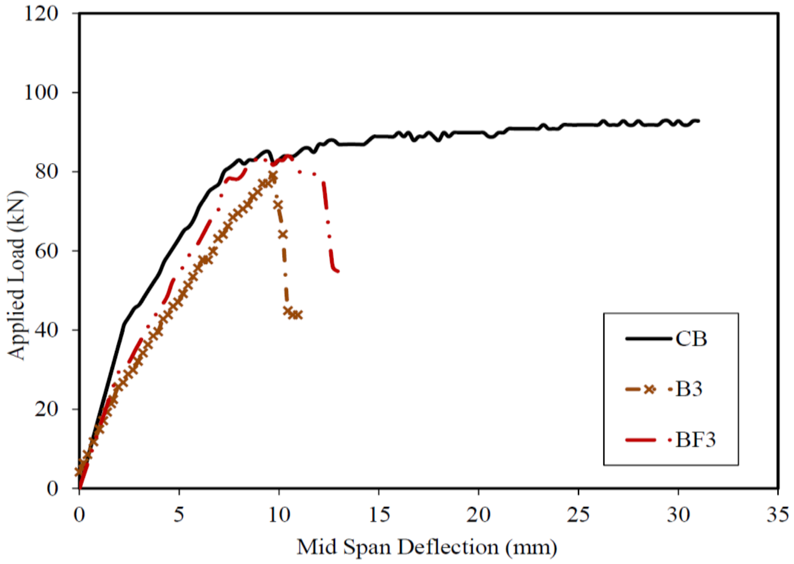


Figure 12. Comparison between the behaviors of the beams of the third group with the control beam.

Table 7. List of results of the third group.

Beam	Maximum Load	Maximum Deflection	% Loss in capacity w.r.t CB	% Increase in capacity w.r.t B3
	(kN)	(mm)	%	%
CB	92.83	31.00	-	-
B3	79.17	10.94	14.72	-
BF3	84.03	12.94	9.48	6.14

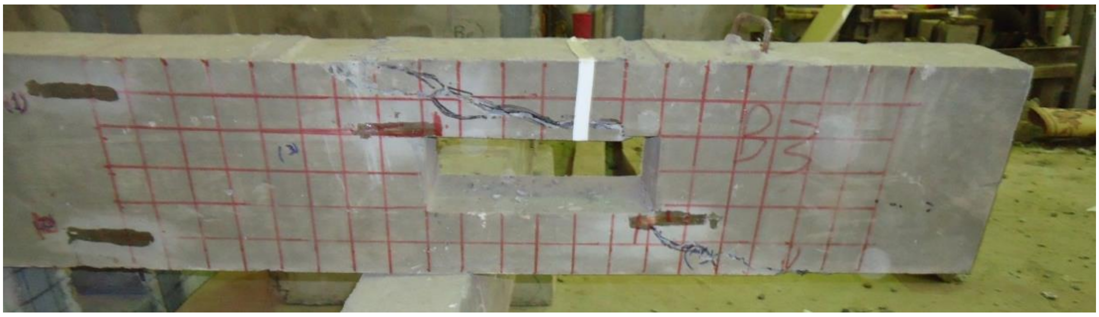


Figure 13. Crack pattern of the beam (B3).

Figure 14. Crack pattern of the beam (BF3).

5. Conclusions

In this research work, a qualitative experimental program has been carried out aiming to obtain a better understanding of the behavior of RC beams with rectangular opening. This program has included testing of eight RC beams of the same dimensions and steel reinforcement with rectangular openings with different sizes. Furthermore, the experimental program aims to examine a proposed strengthening technique using CFRP sheets against shear to increase the load carrying capacity of RC beams with rectangular openings located at the shear zone. All the beams have been tested under four-points bending.

Based on the findings of the experimental program, the following conclusions can be drawn:

1. Making openings in RC beams significantly affect their load carrying capacities and their maximum deflection at failure depending on the opening size with respect to the beam's dimensions.
2. Making openings with a height of one third of the beam's height resulted in a decrease in the beam's load carrying capacity in a range of 15% to 20% if the opening length does not exceed 15% of the beam's clear span. While if the opening height reaches one half of the beam's height, the decrease in the load capacity reaches 45% comparing to the solid beams where no openings are provided.
3. Locating the opening in the shear zone changed the mode of failure of the beam from a flexural mode of failure to a shear one with the shear cracks are located at the opening's corners.
4. The proposed CFRP strengthening system has succeeded to decrease the shortage in load carrying capacity for all beams which have been strengthened in shear only.
5. Applying the proposed CFRP wrapping system to provide strengthening at the opening zone enhances the load carrying capacity by about 6% to 7.5% comparing to the un-strengthened beam when the opening height does not exceed one third of the beam height.
6. When the CFRP wrapping system was used without any flexural strengthening, the enhancement in the load carrying capacity of the strengthened beam ranged between 6% and 17% depending on the opening sizes and the number of the used CFRP strips at the opening zone.
7. When the CFRP wrapping system was used along with flexural strengthening, the enhancement in the load carrying capacity of the strengthened beam reached 87%. For the beam BF4 that has been strengthened in shear and flexure with CFRP composites, the strengthening system has succeeded in restoring the loading capacity of the beam and great enhancements have been noticed for the beam's behavior and its ductility.

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