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Behavior and FRP Strengthening of RC Beams Having Rectangular Openings near the Shear Zone

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Abstract: *Due todifferentarchitectural and mechanical reasons, openings in Reinforced Concrete (RC) beams are needed. The behavior of an RC beam with an opening is; in somehow, different from that of solid beams whether these openings are located at mid-span or near the maximum shear zone. In well-coordinated projects, the openings' locations and sizes are determined during the design phase of the project. Accordingly, the beam's dimensions and reinforcement are determined considering the existence of the openings. However, in many cases, the decision of making an opening in an existing RC beam may come a while after the construction due to different reasons such as changing the function of the building which needs architectural or mechanical modifications. This, in turn, results in the need for strengthening the beam at the opening area to overcome the expected loss of the load carrying capacity of the beam in flexure or in shear. This research aims to obtain a better understanding of the behavior of RC beams with rectangular openingsnear the shear zone and to introduce a strengthening technique with Fiber Reinforced Polymers (FRP) strips. Both experimental and numerical studies have been carried out to investigate the behavior of such beams under four points bending. For the experimental study, a qualitative experimental program including testing of five RC beams of the same dimensions and steel reinforcement has been carried out. One of them has no openings; the control beam, and the others have openings. A strengthening wrapping technique using CFRP strips has been applied in two beams. It was found that, the purposed CFRP strengthening system has succeeded to decrease the loss of the load carrying capacity but failed in provide a significant enhancement to its load-deflection behavior. On the other hand, a step-by-step nonlinear Finite Element (FE) analysis has been carried out including conducting a parametric study in order to obtain a comprehensive understanding about the behavior of such beams with or without strengthening.*

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I. Introduction

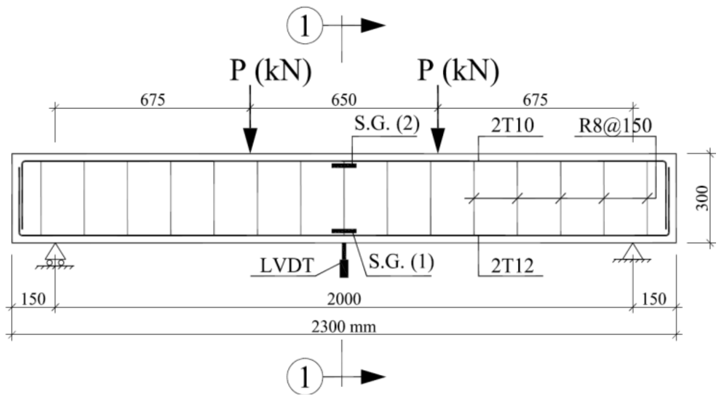
Reinforced Concrete (RC) beams are very important structural elements that transfer the loads from the slabs to the columns through flexure and shear. The behavior of RC beams is one of the subjects which were deeply investigated during the last sixty years. Due to the need for repair or rehabilitation of existing RC structures and because of the continuous updates in the design standards to accommodate the updates in normal as well as abnormal loads, the different strengthening techniques were developed over decadesto enhance the load carrying capacity of these beams[1,2,3,4]. This resulted in several research waves all over the world to investigate the behavior of the conventional un-strengthened RC beams and the strengthened ones, as well[1,5,6,7,8,9].

Due to the unavoidable need for making openings in RC beams to fulfill mechanical as well as architectural requirements, the necessity of investigating the behavior of such beams with openings became of increasing importance through the last decade. The existence ofan opening may significantly affect the flexural behavior of the beam and its shear capacity, as well.Locating the opening at the flexure zone or at the shear zone will have a great influence on the beams behavior. Definitely, it is preferable not to locate the opening at the zone of high shear or bending stresses to avoid the expected great drop in the load carrying capacity and in its ductility. However, to overcome the expected loss in their flexural and shear capacities due to the occurrence of openings, several strengthening techniques were introduced[10,11,12,13]. Among diverse techniques of strengthening, Fiber Reinforced Polymers (FRP)was used worldwide to increase the flexural and shear capacities of RC beams.Although most researchers studied the behavior of solid beams that are strengthened with FRP composites, a few of them have paid attention to the behavior of those beams having an opening[3,4,5,7,10,11,12,13].

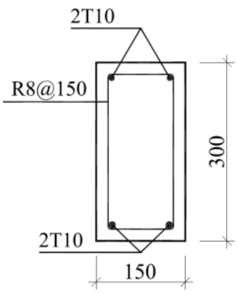
As an extension to those efforts that aim to reveal the answer of the raised question of how the opening affects the beam's load carrying capacity when located near the maximum shear zone and in order to obtain a better understanding of the behavior of RC beams with rectangular opening, a qualitative experimental program including testing of five 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 near 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. Furthermore, a numerical study including a comprehensive parametric study to reveal the key factors that affect the beam's behavior when an opening exists near the shear zone has been conducted. Moreover, the parametric study has been used to assess the effectiveness of the proposed strengthening technique.

II. Experimental Program

The experimental study has been conducted to investigate the effect of the rectangular opening near the shear zone on the behavior of the beam. This experimental program has included a number of five rectangular RC beams of the same length and the same cross sectional dimensions. The beams have been tested under four points bending. All of them have a length of 2300 mm, a width of 150 mm and a height of 300 mm. The first beam of the tested beams has been used as the reference one, the control beam, which is a solid beam without any openings and has been referenced by (CB). Furthermore, no strengthening has been applied for this beam. The four remaining beams have been grouped intotwo groups. The firstgroup includes two beams with the same opening size of 200 mm length representing 10% of the beam's clear spanand 100 mm height representing one third of the beam's total depth and located at a distance of 300 mm from the left support. One of the two beams has been kept un-strengthened and has been referred to by (B1). The other one has been referred to by (BF1) and has been strengthened with CFRP wrapping strips 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.Finally, the second group consists of two beams with opening of 300 mm length representing 15% of the beam’s clear span with the same opening height of100 mm and starts at the same distance from the left support, 300 mm, as for the first group. The first beam in this group has been kept without strengthening and has been referred to by (B2). The other beam has been named (BF2) and it has been strengthened with two FRP wrapping strips before the opening, other two strips after the opening and, three strips through the opening's length. The geometric configuration, the loading scheme and, the reinforcement details of the tested beams are shown in Figure (1) and Figure (2) while, Figure (3) shows the FRP strengthening configurations of the tested beams. Furthermore, Table (1) summarizes the opening size and the reinforcement configuration for each group.

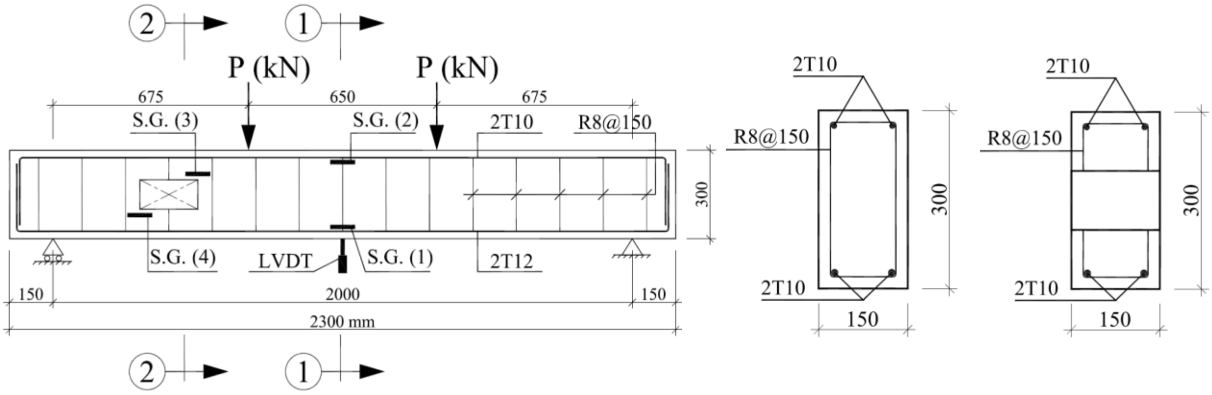


(a) Solid beam



(b) Section (1-1)

Figure (1): Geometric configuration, reinforcement details and, loading scheme of theControl Beam, CB.



(a) Beam with opening (b) Section (1-1) (c) Section (2-2)

Figure (2): Geometric configuration, reinforcement details and, loading scheme of the beams with openings.

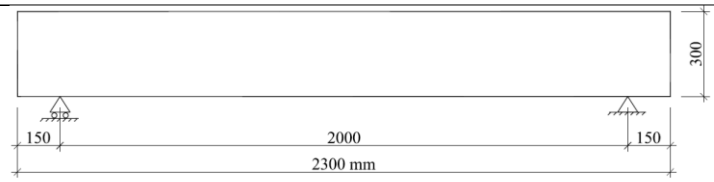
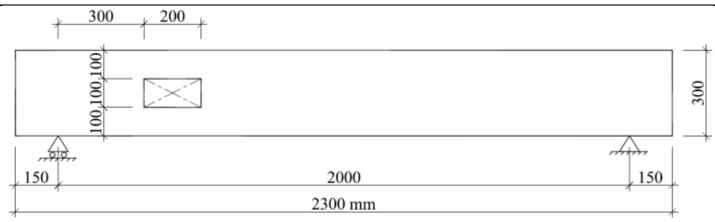
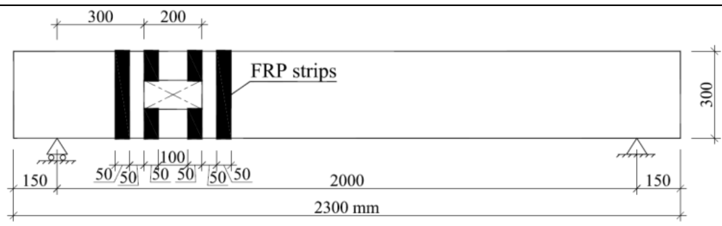
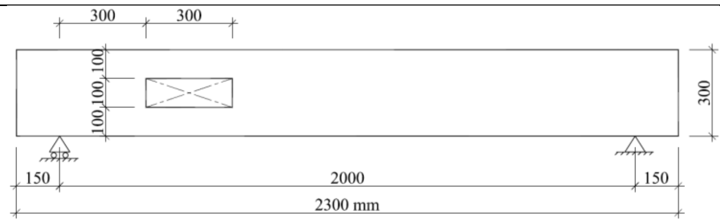
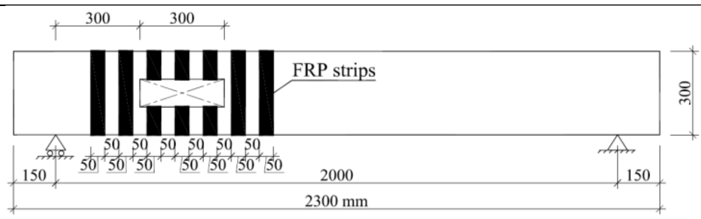
Control beam, beam (CB)	
First group, beam (B1)	
First group, beam (BF1)	
Second group, beam (B2)	
Second group, beam (BF2)	

Figure (3): Schematic representation of the opening dimensions and the proposed FRP strengthening for each beam.

Table no 1: Opening's dimensions and the used reinforcement of the tested beams.

Group	Specimens	Opening size		Bottom RFT	Top RFT	Stirrups
		Length (mm)	Height (mm)			
Control beam	CB	-	-	2T12	2T10	R8-150
First group	B1 – BF1	200	100	2T12	2T10	R8-150
Second group	B2 – BF2	300	100	2T12	2T10	R8-150

Concrete mix and material properties:

The ACI standards have been used in the design of the used concrete mix and in determining the required quantities of the different materials to get the required compressive strength. Table (2) shows the mixture details along with the resulting concrete properties. In order to obtain the concrete characteristic strength, six cubes of the poured concrete have been taken during casting the concrete mix into the wooden forms. Moreover, the reinforcing steel properties have been determined by testing three specimens taken from the used reinforcement. These properties are listed in table (3). Finally, the properties of the used Carbon FRP laminates are listed in table (4)

Table no 2: Quantities of the concrete mix's materials and the resulting concrete properties.

Quantities of the concrete mix		Resulting concrete properties	
item	amount	property	Value
Coarse aggregate (Basalt)	1220 kg	Compressive strength (MPa)	38
Fine aggregate (Sand)	555 kg	Water/Cement ratio	0.4
Cement (OP)	450 kg	Slump (mm)	8
Water	180 Liter	Max. aggregate size (mm)	25

Table no 3: Reinforcing steel properties.

Diameter (mm)	Usage	Yield stress (MPa)	Tensile stress (MPa)	Elongation at failure (%)
8	stirrups	280	450	10 %
10	Top reinforcement	460	660	12 %
12	Bottom reinforcement	420	620	12 %

Table no 4: Properties of FRP strips.

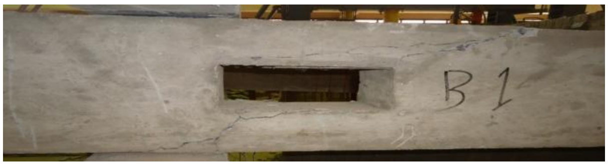
Material	Property	Value
Carbon fiber	Tension modulus	234 GPa
	Tensilestrength	4300 MPa
	Elongation at failure	1.8%
FRP Laminate	Laminate thickness	1 mm
	Characteristic tension modulus	26 GPa
	Characteristic tensilestrength	365 MPa

Preparation of the Specimens:

The position of the tested specimens on the steel supports has been adjustedto provide a clear span of2000 mm. the hydraulic jack has been aligned with the centerline of the tested beams to produce two equal loads on the tested beam. At the tested beam's mid-span, the Linear Variable Displacement Transducer (LVDT) has been located and connected to the control unit in order to monitor the mid-span deflection during the experiment. The loading frame, the steel support and one of the tested beams are shown in Figure (3).In addition, the crack patterns of the control beam (CB), the un-strengthened beams;B1 and B2, and, the strengthened beams; BF1 and BF2, are shown in Figure (4). According to the shown crack patterns in this figure, it can be noticed that the failure mode has been changed from a flexural one in the control beam (CB) to a shear failure when an opening exists in the beams B1 and B2 with the shear cracks are located at the opening's corners. However, significant change in the inclination angle of the failure surface has been occurred due to applying the FRP strengthening system as shown in the case of BF1 and BF2. Furthermore, in the strengthened beam BF2 the crack pattern indicates a flexural failure due to applying more wrapping strips which in turn has affected the beam's mode of failure.

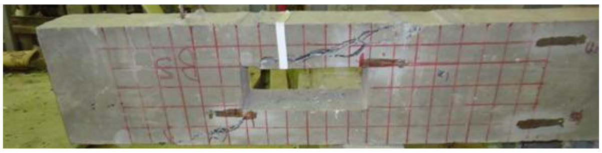
Figure (3): The loading frame and setting out of the tested beams.

(a) Crack pattern of the control beam (CB).



(b) Crack pattern of the beam (B1).

(c) Crack pattern of the beam (BF1).



(d) Crack pattern of the beam (B2).

(e) Crack pattern of the beam (BF2).

Figure (4): Crack patterns of the tested beams.

III. Results of the Experimental Program

The load-mid span deflection relations for the tested beams have been obtained and plotted together to compare their behaviors. Figure (5) shows a comparison between the load-deflection behavior of the beams with respect to each other and to the control beam. Besides, Table (5) lists 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 this figureand as listed in Table (5),the behavior of the beam has been severely altered when the opening exists near the maximum shear zone. The ductility of all beams having openings has severely reduced resulting in a brittle mode of failure. However, the proposed strengthening technique resulted in a relatively enhanced ductility comparing to the un-strengthened beams.

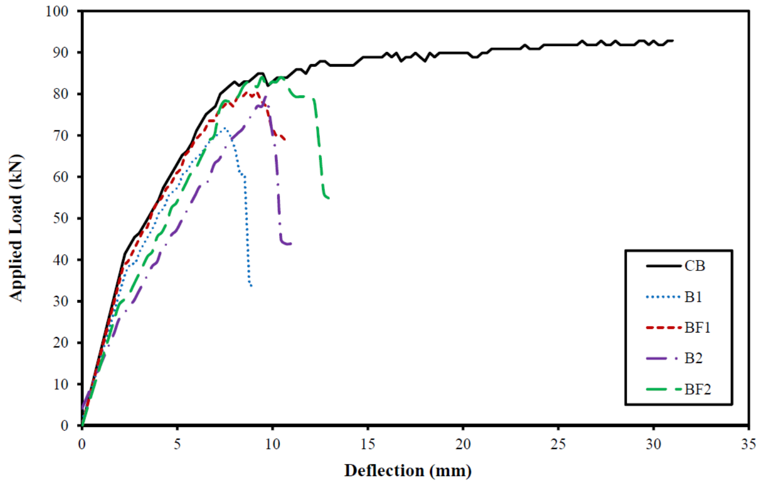


Figure (5): Comparison between the Load-Deflection relations of the experimentally tested beams.

Table no 5: List of the results of the experimentally tested beams.

Beam	Maximum Load (kN)	Maximum Deflection (mm)	% Loss in capacity w.r.t.(CB) (%)	% Increase in capacity w.r.t.similar un-strengthened beam in the same group (%)	Notes
CB	92.83	31.00	-	-	
B1	74.89	9.03	19.33	-	
BF1	80.53	10.67	13.25	7.53	Increase w.r.t. (B1)
B2	79.17	10.94	14.72	-	
BF2	84.03	12.94	9.48	6.14	Increase w.r.t. (B2)

For the first group it can be noticed 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 comparing to the case in which 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 FRP strengthening system with wrapping strips before, after and, inside the opening 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 significantly enhanced.

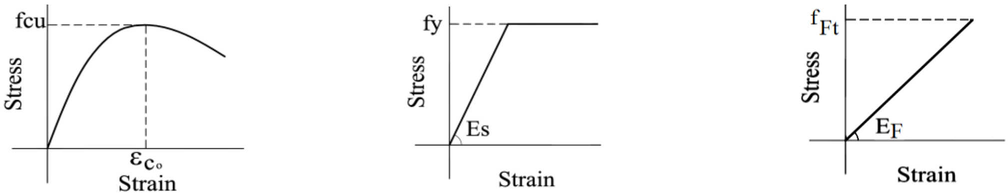
In the case of the second group, the opening height has been adjusted to one third of the beam's depth as for the first group. However, the opening length has been adjusted to 300 mm (i.e. the opening length has been increased by 50% comparing to that of the first group representing 15% of the beam’s clear span) 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 (5) shows a comparison between the load-deflection relation of the beams B3 and BF3 along with the first group’s beams and 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 (5). As shown in Figure (5) and as listed in Table (5), the load carrying capacity of the un-strengthened beam has been reduced by 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 B2 and B1 are close to each other.Furthermore, applying the CFRP wrapping strengthening system in case of 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.

IV. Numerical Modeling

Finite Element Model and Analysis Type:

In order to carry out a comprehensive experimental parametric study, it will be a very expensive study. On the contrary, the Finite Element (FE) analysis provides a powerful tool to perform such studies and get reliable results and conclusions without consuming much time and cost. However, before starting the proposed parametric study, a verification phase should be passed first. Accordingly, five finite element (FE) models have been constructed using the well-known FE software; ANSYS, to simulate the behavior of the tested beams that have an opening located near the maximum shear zone with or without FRP strengthening strips, as well as, the control beam. The 3-D 8-nodes structural solid element; Solid65, which has three degrees of freedom at each node has been used to model the concrete. The 3-D spar 2-nodes Link8 element has been used to simulate the reinforcing bars as discrete reinforcement. For modeling the FRP strips, the multilayered 4-nodes structural shell element; Shell181, has been used. It is worth to mention that the Solid65 element has the ability of cracking in tension and crushing in compression which is important to accurately model the concrete behavior at cracking and ultimate stages. The most important aspect of this element is the treatment of the nonlinear material properties, as well as, the induced plastic deformation. Furthermore, the Link8 element has three translational degrees of freedom at each node with plasticity, creep, rotation, large deflection, and large strain capabilities are included.

The load has been applied as a downward displacement of 40 mm. Both geometric and material nonlinearities have been considered in the analysis. The analysis type has been set to be step-by-step nonlinear static analysis. The automatic time stepping feature has been turned on with a minimum number of sub-steps of 100. The cylindrical compressive strength of the concrete f'_chas been set to 31MPa at a strain (ε_{co}) of 0.0025, while the yield stress of the reinforcing steel bars has been set to 400 MPa. Figure (6) shows a schematic representation for the constitutive material models for the concrete, the reinforcing steel and, the FRP strips.



(a) Concrete (b) Reinforcing steel (c) FRP

Figure (6): Schematic representation for the constitutive material models for (a) concrete, (b) reinforcing steel and, (c) FRP.

Verification of the FE Model:

In order to verify the accuracy of the numerical model and to assess its reliability to be used in subsequent parametric study, a comparison of its results to those of the experimental program is needed. Accordingly, the non-linear static analysis has been triggered and the resulting load-deflection behavior of the five models have been obtained and compared to that of the tested specimens. Figure (7) shows a comparison between the obtained FE results with those of the experimental tests. The FE model that corresponds to each beam of the tested ones has been labeled with the same reference name of the corresponding tested beam with adding "-FE". Accordingly, the FE models for the beams CB, B1, BF1, B2 and, BF2 are referred to by CB-FE, B1-FE, BF1-FE, B2-FE and BF2-FE; respectively.

From Figure (7), it can be noticed that the numerical models show good agreement with the experimental results. The difference in the ultimate load is about 1% and the obtained behavior is almost identical to the experimental one for the case of the solid beam, CB. When the beam has an opening, although the FE models show close ultimate loads to those of the tested beams, these models;however, show a more ductile behavior than that of some of the experimentally tested specimens. This can be clearly noticed in the obtained maximum deflection and the behavior of the models near the ultimate stage. This can be due to the fact that the stiffness of the concrete after reaching its ultimate stress has been set to zero to avoid convergence problems. At early loading stages, the behaviors of the FE models are identical to the corresponding behaviors of the tested beams. After cracking, the FE models show a stiffer behavior than that of the experimental ones till the yield of the reinforcing steel. The models can predict the ultimate loads of the corresponding specimens. The maximum percentage of difference between the obtained ultimate loads from the FE models and the corresponding ones of the tested beams is less than 7%. Accordingly, the FE models can predict the behavior and the load carrying capacity of the tested beams.

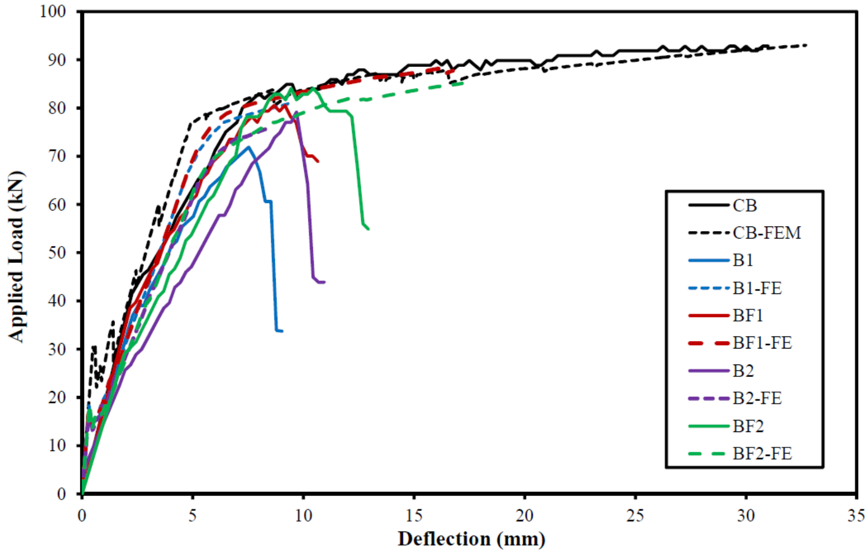


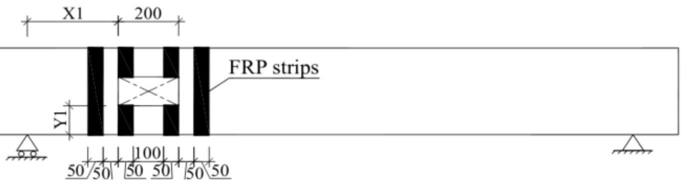
Figure (7): Comparison between the Load-Deflection relations of the FE models and the tested beams.

V. Parametric study

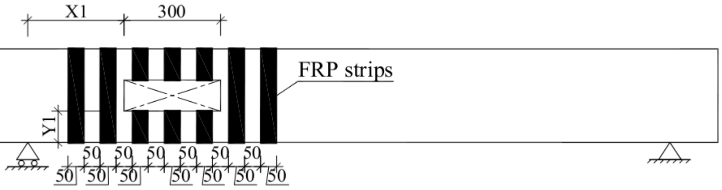
Configuration of the models

Based on the results of the FE models' verification, this researchwork has been extended to include a parametric study aiming to investigate the effect of changing the opening size and its location from the support on the beam's behavior and on its load carrying capacity. Furthermore, the study aims to assess the effectiveness of the proposed strengthening technique in increasing the beam's load carrying capacity and its ductility. Accordingly, a comprehensive parametric study has been conducted with aFE model for a beam with geometric configuration similar to that has been used in the control beam. The same reinforcement, FRP wrapping properties and,the same material properties have been applied, as well. The parametric study includes thirty-six models for beams with different opening sizes and locations. These models have been grouped into six groups each group of them includes six beams. Three of the six beams have been kept un-strengthened and for the other three beams, the proposed FRP wrapping system has been applied.Regarding the opening size for all the six studied groups, the opening length has been varied between 10% and 15% of the beam's clear span while its height has been set tobe one third, one half and two thirds of the beam's depth. Furthermore, for the opening location, the opening left edge has been located at a distance set to be 10%, 15% and, 20% of the beam's clear span.

For the first three groups, the opening length has been set to be 10% of the beam's clear span; i.e. 200 mm, while its height has been set to be one third of the beam's depth; 100 mm, for the first group, one half of the beam's depth; 150 mm, for the second group and, two thirds of the beam's depth; 200 mm for the third group. In addition, for the other three groups, the opening length has been increased to be 15% of the beam's clear span; 300 mm, and its height has been set to be one third, one half and, two thirds of the beam's depth for the fourth group, the fifth group and, the sixth group; respectively. For each group, the opening has been located at 10% of the clear span; i.e. 200 mm, from the left support in the first two beams while this distance has been increased to be 15% and 20% of the clear span; i.e. 300 mm and 400 mm, in the second two beams and in the third two beams; respectively. For the FRP strengthening system, two techniques have been applied. The first one is to provide wrapping a single strip before the opening and another one after the opening and two strips have been applied through the opening. This technique has been applied when the opening length equals 10% of the clear span; 100 mm. While the second technique has been applied when the opening length reaches 15% of the clear span; i.e. 300 mm. in this technique, two strips have been provided before the opening, two other strips have been used after the opening and, three strips through the opening. A schematic representation of the two techniques is shown in Figure (8). Furthermore, asummary of the configurations of the thirty-six studied cases islisted in Table (6).



(a) First strengthening technique for opening length equals 200mm, Type (1).



(b) Second strengthening techniquefor opening length equals 300mm, Type (2).

Figure (8): The two FRP strengthening techniques: (a) Type (1) and, (b) Type (2).

Table no 6: Configurations of the studied cases in the parametric study.

Group No.	Beam's No. in the group	Model ID	Opening Length (mm)	Opening Height (mm)	Distance from the left support (X1) (mm)	Distance from the bottom of the beam (Y1) (mm)	FRP strengthening type	Distance to the first FRP strip from the left support
1	1	B2010-20100	200	100	200	100	Type (1)	100
	2	BF2010-	200	100	200	100		100
	3	B2010-30100	200	100	300	100		200
	4	BF2010-	200	100	300	100		200
	5	B2010-40100	200	100	400	100		300
	6	BF2010-	200	100	400	100		300
2	1	B2015-2075	200	150	200	75	Type (1)	100
	2	BF2015-2075	200	150	200	75		100
	3	B2015-3075	200	150	300	75		200
	4	BF2015-3075	200	150	300	75		200
	5	B2015-4075	200	150	400	75		300
	6	BF2015-4075	200	150	400	75		300
3	1	B2020-2050	200	200	200	50	Type (1)	100
	2	BF2020-2050	200	200	200	50		100
	3	B2020-3050	200	200	300	50		200
	4	BF2020-3050	200	200	300	50		200
	5	B2020-4050	200	200	400	50		300
	6	BF2020-4050	200	200	400	50		300
4	1	B3010-20100	300	100	200	100	Type (2)	25
	2	BF3010-	300	100	200	100		25
	3	B3010-30100	300	100	300	100		125
	4	BF3010-	300	100	300	100		125
	5	B3010-40100	300	100	400	100		225
	6	BF3010-	300	100	400	100		225
5	1	B3015-2075	300	150	200	75	Type (2)	25
	2	BF3015-2075	300	150	200	75		25
	3	B3015-3075	300	150	300	75		125
	4	BF3015-3075	300	150	300	75		125
	5	B3015-4075	300	150	400	75		225
	6	BF3015-4075	300	150	400	75		225
6	1	B3020-2050	300	200	200	50	Type (2)	25
	2	BF3020-2050	300	200	200	50		25
	3	B3020-3050	300	200	300	50		125
	4	BF3020-3050	300	200	300	50		125
	5	B3020-4050	300	200	400	50		225
	6	BF3020-4050	300	200	400	50		225

VI. Results and Discussion of the Parametric Study

The step-by-step nonlinear static analysis has been triggered and the load-mid-span deflection relations have been obtained and plotted for each group in order to investigate the effect of changing the opening size and its location on the beam’s behavior and its ultimate capacity. Furthermore, the ultimate capacities and the maximum deflections of the studied beams have been compared to those of the solid beam as will be shown later on.

First group

For the first group in which the opening length has been set to 10% of the span; 200 mm, and its height has been set to one third of the beam's depth; 100 mm, the load-mid span deflection relations of the six beams of this group are shown in Figure (9). It can be noticed that the behavior of the six beams are almost identical at the early loading stages till the yield of the reinforcement takes place. The three un-strengthened beams show almost the same load carrying capacity. The loss in the beams' capacities ranges between 13% and 16% comparing to the solid beam in which no openings exist. Slight decrease of about 2.5% in the beam's capacity can be noticed when the opening has been located at the largest distance from the support (i.e. 20% of the beam's clear span). Besides, these beams have failed at almost the same small deflection regardless the location of the opening from the support. This, in turn, result in a severe loss in their ductility because of the existence of the opening in the shear zone regardless its location. The decrease in the maximum deflection at failure reaches 72% approximately comparing to the solid beam.

When the FRP wrapping, Type (1), has been applied, the load carrying capacity of the three beams has been relatively increased by about 10% with respect to the corresponding un-strengthened beams andthe loss of these beams' capacities has been decreased by 5% to 7.5% comparing to the solid beam.On the other hand, significant increase in the beams' deflections at failure can be noticed comparing to the un-strengthened beams when the FRP wrapping has been applied. When the opening has been located at the smallest distance from the support; 10% of the span, the deflection at failure has been significantly increased by about 220% comparing to the un-strengthened case. This can be due to the small size of the opening and its position which has been located before the expected critical section of shear which is usually located at a distance equals to the beam's depth; 280 mm in this case. Furthermore, when the strengthening has been applied to the beams in which the opening has been located at 15% and 20% of the span from the support, significant enhancements in the deflection at failure can be noticed reaching 79% and 98% comparing to the corresponding un-strengthened cases. This has resulted in a relative enhancement in the strengthened beam's ductility comparing to the un-strengthened one. In general, the strengthened beams show lower deflection at failure by about 8.5% to 48.5% comparing to the solid beam.

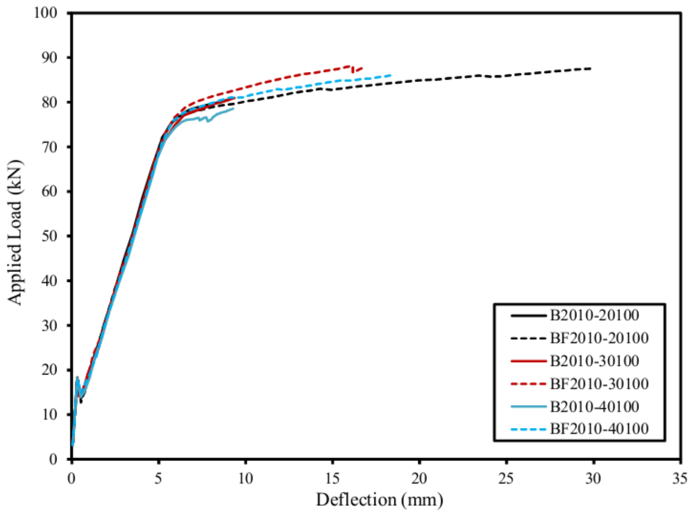


Figure (9): Load-Deflection relation of the beams in the first group.

Secondgroup

For the second group in which the opening length has been set to 10% of the span; 200 mm, as in the first group and its height has been set to one half of the beam's depth; 150 mm, the load-mid span deflection relations of the six beams of this group are shown in Figure (10). It can be seen that the behavior of the six beams are almost identical at the early loading stages till the yield of the reinforcement. The un-strengthened beam with in which the opening has been located at 10% of the beam's clear span show a loss of about 16% of its load carrying capacity comparing to the solid one. This loss has increased to reach about 24% for the other un-strengthened two beams in which the opening has been located at 15% and at 20% of the clear span. It is worth to mention that the loss in the load carrying capacities of the un-strengthened beams of this group ranges between 9% and 12% comparing to the similar beams in the first group with the same opening locations. Furthermore, these beams show lower value of the maximum deflection at failure comparing to the first group. The reduction in their deflections ranges between 77% and 83.5%; approximately, comparing to the solid beam which led to more reduction in their ductility.

When the FRP strengthening, Type (1), has been applied, the load carrying capacity of the three beams has been relatively increased byabout 2% to 22% with respect to the corresponding un-strengthened beams and the loss of these beams' capacities has been ranged between8.3% to 14.75% comparing to the solid beam. Furthermore, when the opening has been located at the farthest distance from the support; i.e. 20% of the span, the proposed wrapping system has led to significant increase in the beam's ductility comparing to the un-strengthened one. This can be noticed from the significant enhancement in the beam's maximum deflection. However, this enhancement could not recover more than 40% of the solid beam's maximum deflection; i.e. the reduction in the deflection reaches about 60% of that of the solid beam. Accordingly, increasing the opening height to one half of the beam's height has resulted in significant drop in the beam's load carrying capacity and its ductility, as well. In addition, the proposed FRP wrapping has enhanced the beam's capacity and its maximum deflection and it has led to a partial recovery of their ductility.

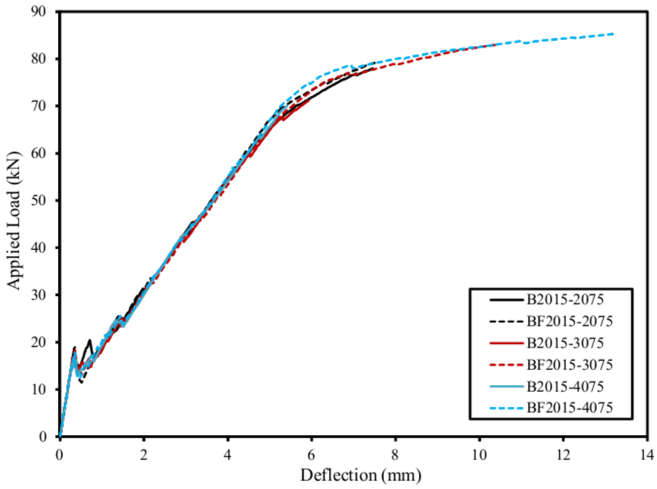


Figure (10): Load-Deflection relation of the beams in the second group.

Thirdgroup

For the third group in which the opening length has been set to 10% of the span; 200 mm, as in the first and the second groups and its height has reached two thirds of the beam's depth; 200 mm, the load-mid span deflection relations of the six beams of this group are shown in Figure (11). From this figure, it can be concluded that the un-strengthened beams have suffer from sever drop in the beams' capacities and their ductility, as well. The failure is brittle and has occurred before the yield of the tension reinforcement. The beams have lost about 29% to 49% of their load carrying capacities and their maximum deflection has examined a very severe drop ranges between 76.4% and 87.2% comparing to the solid case. All these beams show almost no ductility at failure.

When the same FRP strengthening, Type (1), has been applied as has been done in the previous two groups, the load carrying capacity of the three beams has been relatively increased by about 2.5% to 50% with respect to the corresponding un-strengthened beams and the loss of these beams' capacities has been ranged between 22% to 26.7% comparing to the solid beam. It can be also noticed that the FRP wrapping technique has not succeeded in enhancing the beams' ductilitysignificantly. This may be due to the large opening height; two thirds of the beam's depth, that has made the beam to act as a two small top and bottom chords at the opening zone resulting in increasing the stresses concentrations at the opening's corners specially the shear stresses. The existence of the FRP wrapping could not replace the lost concrete and shear reinforcement in this case.

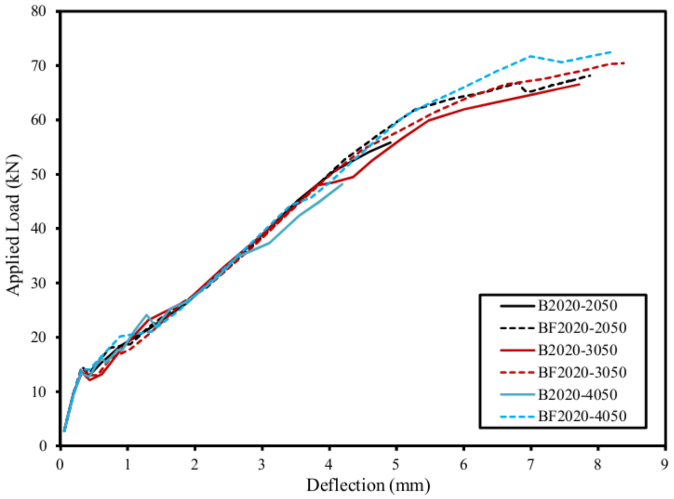


Figure (11): Load-Deflection relation of the beams in the third group.

Fourthgroup

For the fourth group in which the opening length has been increased to be 15% of the span; 200 mm, and its height have been set to be one third of the beam's depth; 100 mm, the load-mid span deflection relations of the six beams of this group are shown in Figure (12). It can be noticed that the behavior of the six beams are almost identical at the early loading stages till the yield of the reinforcement takes place. The three un-strengthened beams show close values for their ultimate capacities. The loss in the beams' capacities ranges between 18.4% and 28.9% comparing to the solid beam. Besides, these beams have failed at lower values of deflection. The reduction in their maximum deflection ranges between 73.9% and 84.2% comparing to the solid one. This, in turn, result in a significant loss in their ductility.

When the FRP wrapping, Type (2), has been applied, the load carrying capacity of the three beams has been relatively increased with respect to the corresponding un-strengthened beams and the loss of these beams' capacities has ranged between 8.5% and 14% comparing to the solid beam. On the other hand, moderate increase in their deflections can be noticed comparing to the un-strengthened beams. The reduction of their maximum deflection has been reduced to be ranged between 47.5% and 73.3% comparing to that of the solid beam instead of 73.9% to 84.2% for the un-strengthened ones. This slight enhancement, however, has not resulted in a significant increase in the beam's ductility although more strips of FRP wrapping system have been applied.

Fifthgroup

For the fifth group in which the opening length has been set to be 15% of the span; 200 mm, and its height have been increased to be one half of the beam's depth; 150 mm, the load-mid span deflection relations of the six beams of this group are shown in Figure (13). It can be seen that the behavior of the six beams are almost identical at the early loading stages. The three un-strengthened beams show close values for their ultimate capacities. The loss in the beams' capacities ranges between 26.36% and 37.36% comparing to the solid beam. Besides, these beams have failed at very low values of deflection comparing to the solid one. The reduction in their maximum deflection ranges between 76.23% and 83.53% comparing to the solid one. This, in turn, result in a large reduction in their ductility.

When the FRP wrapping, Type (2), has been applied with its larger number of strips before, after and, through the opening, the load carrying capacity of the three beams has been relatively increased with respect to the corresponding un-strengthened beams and the loss of these beams' capacities has ranged between 23% and 25.95% of that of the solid beam. On the other hand, slight increase in their deflections can be noticed comparing to the un-strengthened beams with a reduction of their maximum deflection has ranged between 71.78% and 77.5% of that of the solid beam. Accordingly, the beams ductility has not significantly enhanced.

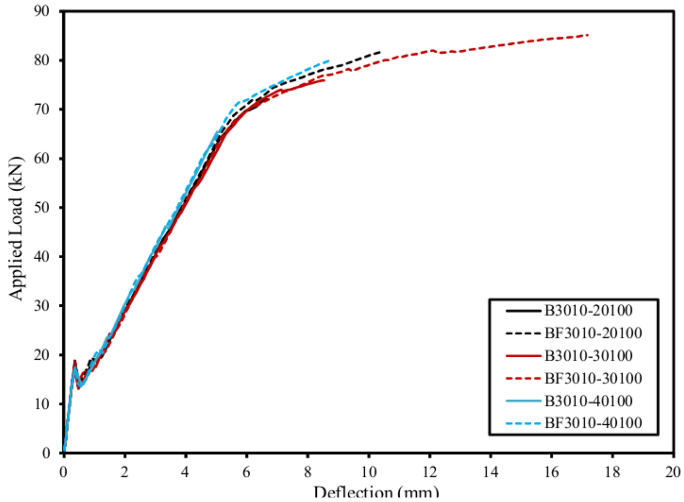


Figure (12): Load-Deflection relation of the beams in the fourth group.

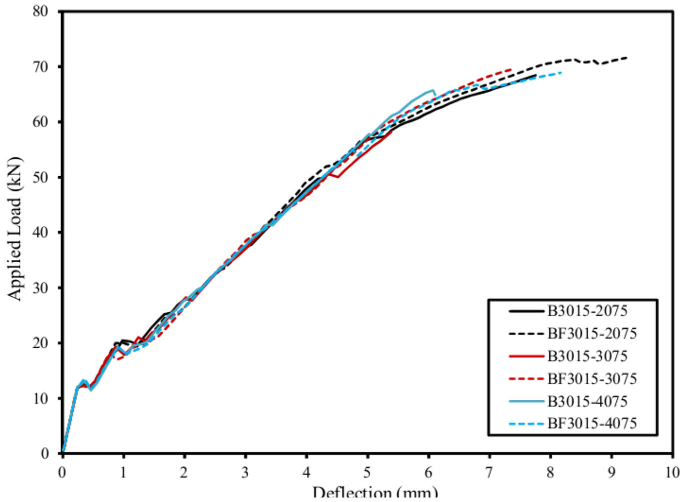


Figure (13): Load-Deflection relation of the beams in the fifth group.

Sixthgroup

For the sixth group in which the opening length has been set to be 15% of the span; 200 mm, and its height have been increased to be two thirds of the beam's depth; 200 mm, the load-mid span deflection relations of the six beams of this group are shown in Figure (14). It can be seen that this increase in the opening size has resulted in a very sever loss in the beam's capacity and ductility. The loss in the beam's capacity has ranged between 65.66% and 78.61% of that of the solid beam and the reduction in the maximum deflection has ranged between 86% and 94.45% of the maximum deflection of the solid beam. In this case, applying the wrapping system is almost insignificant. This is due to the fact that the wrapping system could not succeed in changing the failure mode of the beam from the brittle one to a more or even a relatively ductile one despite of the increase of the beams' capacity and their maximum deflection comparing to the corresponding un-strengthened ones. The loss of these beams' capacities has ranged between 36.6% and 69.31% of that of the solid beam. On the other hand, the reduction of their maximum deflection has ranged between 73.52% and 91.03% of that of the solid beam. Accordingly, the beams ductility has not significantly enhanced.

A summary of all the obtained results for all the studied cases are listed in Table (7) along with the results of the FE model of the control beam (CB-FE). These results include the ultimate loads, the maximum deflection at failure, the percentage of loss in the beam's load carrying capacity with respect to the solid beam and, the percentage of the reduction in the beam's deflection at failure with respect to the solid beam.

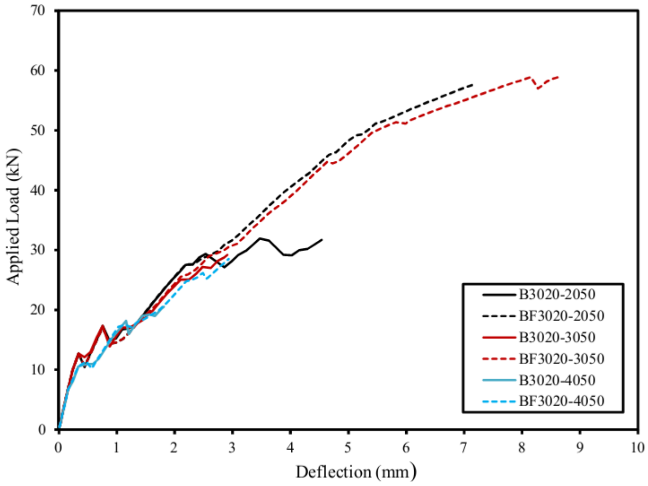


Figure (14): Load-Deflection relation of the beams in the sixth group.

Table no 7: Summary of the results of the parametric study.

Group No.	Beam's No. in the group	Model ID	Opening dimensions		Opening location		Results			
			Length (mm)	Height (mm)	X1 (mm)	Y1 (mm)	Ultimate Load (kN)	Maximum deflection (mm)	% Loss in capacity	% reduction in deflection at failure
-	-	CB-FEM	-	-	-	-	92.99	32.70	-	-
1	1	B2010-20100	200	100	200	100	80.63	9.08	13.29	72.24
	2	BF2010-20100	200	100	200	100	87.56	29.95	5.83	8.40
	3	B2010-30100	200	100	300	100	80.92	9.36	12.98	71.36
	4	BF2010-30100	200	100	300	100	88.15	16.76	5.20	48.76
	5	B2010-40100	200	100	400	100	78.53	9.26	15.55	71.67
	6	BF2010-40100	200	100	400	100	86.04	18.41	7.47	43.69
2	1	B2015-2075	200	150	200	75	77.98	7.45	16.14	77.22
	2	BF2015-2075	200	150	200	75	79.28	7.57	14.75	76.86
	3	B2015-3075	200	150	300	75	71.19	5.92	23.44	81.88
	4	BF2015-3075	200	150	300	75	83.02	10.43	10.73	68.09
	5	B2015-4075	200	150	400	75	70.05	5.42	24.67	83.44
	6	BF2015-4075	200	150	400	75	85.25	13.19	8.33	59.66
3	1	B2020-2050	200	200	200	50	55.81	4.91	39.98	84.99
	2	BF2020-2050	200	200	200	50	68.15	7.87	26.71	75.92
	3	B2020-3050	200	200	300	50	66.54	7.72	28.44	76.40
	4	BF2020-3050	200	200	300	50	70.43	8.38	24.26	74.38
	5	B2020-4050	200	200	400	50	48.20	4.19	48.17	87.19
	6	BF2020-4050	200	200	400	50	72.53	8.21	22.00	74.89
4	1	B3010-20100	300	100	200	100	72.16	6.69	22.41	79.53
	2	BF3010-20100	300	100	200	100	81.82	10.47	12.01	67.97
	3	B3010-30100	300	100	300	100	75.88	8.53	18.40	73.92
	4	BF3010-30100	300	100	300	100	85.10	17.17	8.49	47.49
	5	B3010-40100	300	100	400	100	66.12	5.16	28.90	84.22
	6	BF3010-40100	300	100	400	100	79.93	8.71	14.04	73.37
5	1	B3015-2075	300	150	200	75	68.48	7.75	26.36	76.29
	2	BF3015-2075	300	150	200	75	71.61	9.23	22.99	71.78
	3	B3015-3075	300	150	300	75	58.25	5.38	37.36	83.53
	4	BF3015-3075	300	150	300	75	69.48	7.36	25.29	77.50
	5	B3015-4075	300	150	400	75	65.70	6.11	29.35	81.32
	6	BF3015-4075	300	150	400	75	68.89	8.17	25.91	75.03
6	1	B3020-2050	300	200	200	50	31.93	4.54	65.66	86.13
	2	BF3020-2050	300	200	200	50	57.62	7.15	38.03	78.14
	3	B3020-3050	300	200	300	50	29.22	2.91	68.58	91.10
	4	BF3020-3050	300	200	300	50	58.95	8.66	36.60	73.52
	5	B3020-4050	300	200	400	50	20.54	1.81	77.91	94.45
	6	BF3020-4050	300	200	400	50	28.54	2.93	69.31	91.03

VII. Summary and Conclusions

This research work aimed to assess the effect of locating rectangular openings near the maximum shear zone of rectangular RC beams on the behavior of these beams. The effectiveness of a proposed FRP strengthening system was investigated too. The proposed strengthening system includes as FRP wrapping technique before, after and, through the opening. A qualitative experimental program including testing of five RC beams of the same dimensions and steel reinforcement was carried out. The experimental program aimed to examine a proposed strengthening technique using CFRP sheets against shear to increase the load carrying capacity of RC beams with rectangular openings located near the shear zone. All the beams have been tested under four-points bending. Furthermore, the work was extended to conduct a numerical simulation including a comprehensive parametric study to reveal the key factors that affect the beam's behavior when an opening exists near the shear zone. Moreover, the parametric study was used to assess the effectiveness of the proposed strengthening technique.

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

1- The ductility of all beams having openings has severely reduced resulting in a brittle mode of failure.

2- Making an opening with a height ranges between one third to one half 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 15% to 20% of its capacity comparing to the case in which no opening exists. Besides, the maximum deflection of the beam with such opening was reduced to about one third of that of the control beam where no opening exists.

3- Although the proposed FRP strengthening technique; the wrapping technique, has succeeded in increasing the beam's capacity comparing to the corresponding un-strengthened beam, the enhancement in the beam's overall ductility was not greatly affected.

Based on the findings of the numerical study, the following conclusions can be drawn:

1- When the opening height reaches one third of the depth, the beam's load carrying capacity was decreases by about 13% to 15% comparing to the solid beam. While their maximum deflection at failure was decreased by about 72% of that of the solid beam resulting in a sever loss in the beam's ductility.

2- When the proposed wrapping technique has been applied, the loss in the capacity was decreased to range between 5.5% and 7.5% of that of the solid beam and the decrease in the maximum deflection was reduced to be about 8.5% to 48.5% of that of the solid beam resulting in a moderate enhancement in the beam's ductility.

3- Increasing the opening height to one half of the beam's height has resulted in sever drop in the beam's load carrying capacity by about 16% to 25% and its ductility comparing to the solid beam. In addition, the proposed FRP wrapping has enhanced the beam's capacity and its maximum deflection and it has led to a partial recovery of their ductility.

4- When the opening height reaches two thirds of the beam's depth, the beam loses its load carrying capacity and its ductility. Furthermore, the proposed wrapping technique could not help in overcoming this sever loss in ductility.

5- It is not recommended to make any opening near the shear zone with a height more than one third of the beam's depth and the opening's length is not recommended to exceed 10% of the beam's clear span.

6- The proposed FRP wrapping technique has succeeded in increasing the beam's load carrying capacity. However, it did not significantly enhance its ductility when the opening length exceeds 10% of the clear span and its height exceeds one third of the beam's depth.

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