https://erjm.journals.ekb.eg
ISSN: 1110-1180

DOI: 10.21608/ERJM.2020.112799

ERJ
Engineering Research Journal
Faculty of Engineering
Menoufia University

Flexural and Shear Strengthening of RC Beams with Large Openings by Steel or CFRP Plates

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ABSTRACT

Existence of transverse openings in the web of reinforced concrete beams is usually used to provide paths for required ducts and pipes which are necessary to accommodate essential services like water supply, sewage, air-conditioning, telephone and electricity. However providing an opening in the beam reduces its stiffness, which decreases the overall strength. The provision of openings through the beam depth, changes its simple mode of behavior to a more complex one depending on the size, shape and location of openings. Repair and strengthening of an existing structure may be essential in many cases such as increasing the stiffness of the beams due to making transverse openings in the web of beams after construction. An experimental test program of fourteen RC beams with large openings were strengthened by using additional layers of externally bonded steel plates or CFRP Plates with different techniques then tested by four-point bending test. The behaviors of the tested specimens were investigated with and without strengthening and compared to identify the effectiveness of each method and material of strengthening to increase the flexural and shear strength of beam with different opening location. The research shows that strengthening using CFRP Plates were more effective than using steel plates.

Keywords: *RC Beams, Large Openings, Strengthening, Steel plates, CFRP Plates.*

1. Introduction

Creating an opening in the web of the RC beam may be required to provide a track for ducts or pipes. However, making an opening in the web of the beam reduces the stiffness subsequently decreases the resistance for shear, flexure and torsion [1,2]. Therefore, providing a transverse opening in a beam, changes its simple mode of behavior to complex mode depending on the location and the dimensions of the opening [3]. In case of large openings when the depth of the opening > 30% the total depth of the beam [4] , the design of these beams requires special treatment, which falls beyond the range of the major building codes [5,6,7].

Retrofitting or strengthening of beams with openings may be required when loads are expected to be amplified than the design loads due to the usage change of the RC building. Openings may be required also to be created on the web of the beams after finishing the construction. In this case, it is important to compensate for the reduction of the stiffness by a suitable method to retrofit the beam with its full capacity [8,9]. Many researches concentrate on the shear, bending or torsional stresses of beams without openings [10,11,12]. Upgrading the stiffness of RC beams of rectangular, L or T sections using FRP due to different stresses is investigated by many researches [13,14].

In this research, an experimental test program is arranged to study the behavior of RC beams with central or side web openings subjected to four-point bending test to investigate and compare some different techniques of strengthening to increase the overall stiffness of the beams.

Carbon and glass fiber reinforced polymers (FRP) in the form of rods, plates and wraps woven in one or multi-directions are commonly used for repair and strengthening RC slabs, shells, beams or columns [15,16,17]. This may be attributed to the simple installation and the attractive characteristic such that lightweight, high tensile strength, and resistance to corrosion. These advantages have made FRP an attractive choice instead of traditional repair or strengthening techniques. In this research, the strengthening of RC beams with openings was executed by using both steel plates as traditional material or CFRP as an advanced material for comparison.

2. Research Objectives

It is necessary sometimes to make a hole as a transverse opening in the web of the reinforced concrete beam. Providing an opening in the beam decreases the stiffness, which reduces the overall strength of the beam. Limited researches investigate the behavior of beams with openings subjected to shear and flexural stresses. Only very limited literatures are available regarding retrofitting beams with web openings to increase their flexural and shear stiffness. The main object of this research is to determine the efficiency of using different methods and materials as external bonded steel plates and CFRP Plates to increase the strength of rectangular reinforced concrete beams with different large opening locations.

3. Experimental Program

Fourteen typical dimensions and reinforcement of the tested RC specimens were cast. The cross-section of the tested beams is 100 × 300 mm. The span length is 1900 mm. No reinforcement around the openings is considered in this research to simulate making an opening after construction. Three specimens were considered as control beams without any strengthening and classified in Group 1. One of them has no opening; CB, and the other two reference specimens CBSO and CBMO have an opening dimension; 300×100mm near one support and at the midspan of the beam respectively. Figures 1, 2 and 3 show the concrete dimensions and reinforcement details of control specimens in Group 1; CB, CBSO and CBMO.

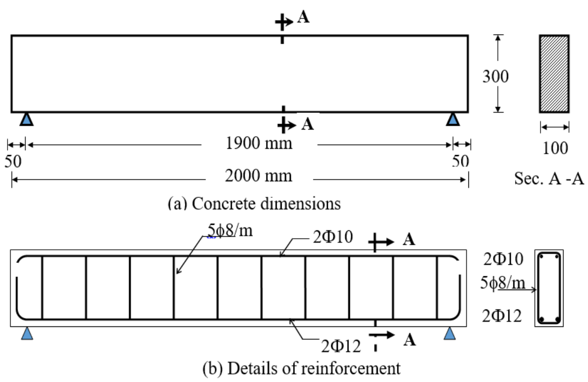

Fig. 1: Dimensions and reinforcment details of control specimen CB

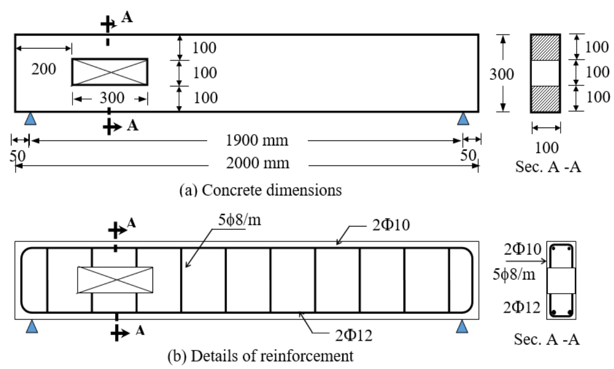

Fig. 2: Dimensions and reinforcment details of control specimen CBSO

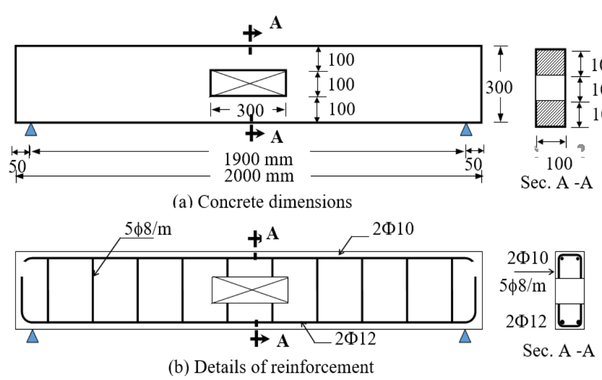

Fig. 3: Dimensions and reinforcment details of control specimen CBMO

Five specimens were cast similar to reference beam CBSO with side opening. Three of them were strengthened using steel plates, 2 mm thick and 100 mm width and fixed by epoxy Sikadur®-31CF and also with steel dowels (5 mm diameter and 30 mm long) with different techniques. The other two specimens were strengthened using carbon fiber reinforced polymer CFRP Plates of 1.2 mm thickness and 100 mm width, Sika Carbodur®S1012, fixed by epoxy Sikadur®-30LP. Figure 4 shows the dimensions of the strengthening for specimens in Group 2; BSOST1, BSOST2, BSOST3, BSOC1 and BSOC2.

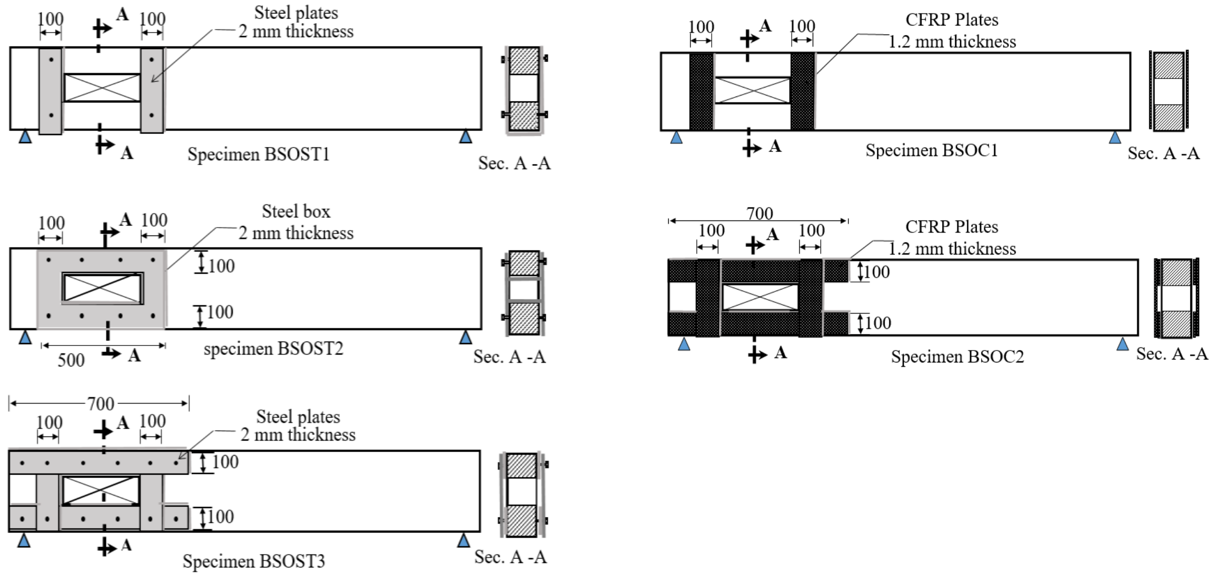

Fig. 4: Strengthening details of specimens in Group 2
(Diminsions in mm)

Six specimens were cast similar to reference beam CBMO with midspan opening. Three of them were strengthened using steel plates, 2 mm thick and 100 mm width and fixed by epoxy Sikadur®_31CF [18] and also with steel dowels (5 mm diameter and 30 mm long) with different techniques. The other three specimens were strengthened using carbon fiber reinforced polymer CFRP Plates of 1.2 mm thickness and 100 mm width, Sika Carbodur®S1012 [18], fixed by epoxy Sikadur®-30LP. Figure 5 shows the dimensions of strengthening for specimens in Group 3; BMOST1, BMOST2, BMOST3, BMOC1, BSOC2 and BSOC3.

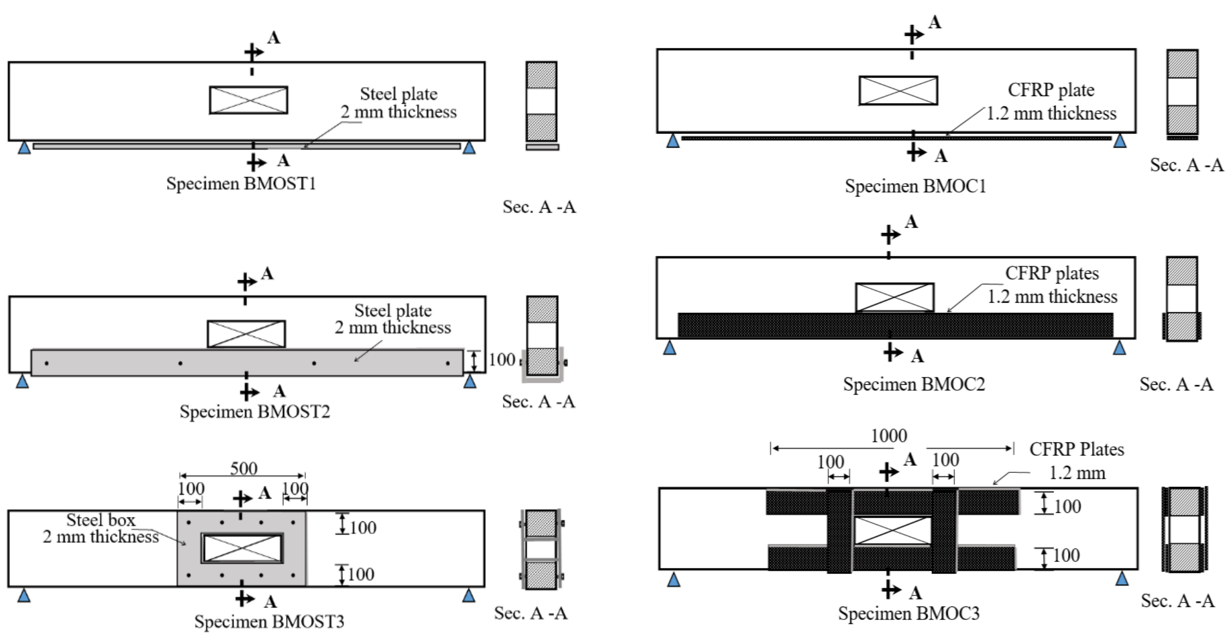

Fig. 5: Strengthening details of specimens in Group 3
(Diminsions in mm)

Table 1: Experimental test program

Group	Specimen Code	Location of opening	Method of strengthening
1	**CB**	Without opening	without strengthening
	CBSO	Side opening	
	CBMO	Midspan opening	
2	**BSOST1**	Side opening	Strengthened by vertical steel plates 2mm thick in the form of U shape at the vertical edges of the opening.
	BSOST2	Side opening	Strengthened by steel box formed from steel plates 2mm thick as U shape around the opening.
	BSOST3	Side opening	Strengthened by vertical and horizontal steel plates 2mm thick around the opening at both faces of the beam.
	BSOC1	Side opening	Strengthened by vertical CFRP Plates 1.2mm thick at the edges of the opening at both faces of the beam.
	BSOC2	Side opening	Vertical and horizontal CFRP Plates 1.2mm thick around the opening at both faces of the beam.
3	**BMOST1**	Midspan opening	Strengthened by a steel plate 2mm thick at the bottom surface of the beam.
	BMOST2	Midspan opening	Strengthened by U steel plate 2mm thick formed as U shape at the bottom side of the beam.
	BMOST3	Midspan opening	Strengthened by steel box formed from steel plates 2mm thick around the interior and exterior edges of the opening.
	BMOC1	Midspan opening	Strengthened by CFRP Plates 1.2mm thick as horizontal strips at the bottom side of the beam at both faces.
	BMOC2	Midspan opening	Strengthened by CFRP Plates 1.2mm thick at the bottom side of the beam at both faces of the beam.
	BMOC3	Midspan opening	Strengthened by vertical and horizontal CFRP Plates 1.2mm thick around the opening.

4. Test Set-up and Instrumentation

Specimens, 1900 mm span, were tested under four-point bending test by applying two equal concentrated loads at the two-thirds of the span. The loading system is shown in Fig. 6. Loads were applied in increments using a hydraulic jack of 50 ton maximum capacity. Deflections under the concentrated loads and at the midspan, first cracking loads and ultimate failure loads were recorded. Propagation of cracks was marked after each load increment up to failure. Three dial gauges of 0.01 mm accuracy and total capacity of 25 mm were used for measuring deflections. Figure 6 shows the arrangement of dial gages and the demic points for measuring the strain.

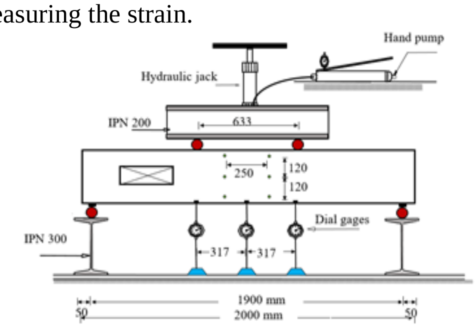

Fig. 6: Test set up and instrumentation

Table 2 defines concrete mix proportions and compressive strength after 7 and 28 days.
Table 3 shows the mechanical properties of steel reinforcement and strengthening steel plates and Table 4 identifies the mechanical properties of CFRP Plates [18].

Table 2: Concrete mix proportions and compressive strength

Mix No	Mix proportions kg/m^3				Unit Weight	C. A/ .F.A	%W/C	Slump (mm)	Compressive Strength N/mm^2 (MPa)	
	C	W	F.A	C.A					7days MPa	28 days MPa
1	350	158	640	1280	2440	2	45	31	23.0	30.73

Where: C= Portland cement from Suez Company
W = Water
F. A. = Fine aggregate
C. A. = Coarse aggregate (crushed dolomite with a nominal max. size of 25mm)

Table 3: Mechanical properties of steel reinforcement and strengthening plates

Steel Type	Yield Stress (MPa)	Tensile Strength (MPa)	Elongation %	Modulus of Elasticity (MPa)
High Tensile	360	520	15.0	205940
Mild Steel	248	366	22	198094
Steel Plates	221	235	24	205940

Table 4: Mechanical properties of CFRP Plates [18]

Property	CFRP Sika carbodur ® S1012
Thickness, mm	1.2
Plate width, mm	100
Density, g/cm^3	1.6
Tensile E-Modulus, MPa	165000
Tensile strength, MPa	Min. value =2800
Strain at break	Min. Value not less than 1.7%

5. Experimental Results

5.1 Crack Patterns

Figure 7 shows the crack pattern for reference specimens CB, CBSO and CBMO in Group 1. For the control specimen without opening, CB, cracks started at load 35 kN from the midspan of the beam at the tension side (bottom face) and directed upward in a vertical direction. With increasing load cracks spread in the middle third of the span. Before the failure, cracks directed with an inclined angle of about 45^o form the bottom surface toward the points of loading as shown in Fig. 7a.

The first cracking load for the beam with side opening, CBSO, starts at 20 kN from the support near the opening and directed to the nearest corner of the opening then directed to the adjacent loading point at the top surface of the beam. At cracking load, cracks started also at midspan. With increasing load cracks propagated in the middle third of the span from the tension side to upward as shown in Fig. 7b.

Cracks started for beam CBMO at 25 kN at the bottom surface from the midspan under the opening. When the load increased, cracks directed with inclination angle of about 45o from bottom surface toward the adjacent point of loading as shown in Fig. 7c.

Fig. 7a Crack pattern for CB

Fig. 7b Crack pattern for CBSO

Fig. 7c Crack pattern for CBMO

Fig. 7: Crack patterns for specimens in Group 1

Figure 8 shows the crack patterns for strengthened specimens with side openings in Group 2; BSOST1, BSOST2, BSOST3, BSOC1and BSOC2. Cracks started to propagate at loads 20, 25, 25, 20 and 25 kN for beams BSOST1, BSOST2, BSOST3, BSOC1and BSOC2 respectively. The different methods of strengthening for BSOST1 and BSOC1 were not effective for increasing the cracking loads in case of the side opening; this may be attributed to the propagation of cracks at the midspan of specimens.

Fig. 8a Crack pattern for BSOST1

Fig. 8b Crack pattern for BSOST2

Fig. 8c Crack pattern for BSOST3

Fig. 8d Crack pattern for BSOC1

Fig. 8e Crack pattern for BSOC2

Fig. 8: Crack patterns for specimens in Group 2

Figure 9 shows the crack patterns for strengthened specimens with midspan openings in Group 3; BMOST1, BMOST2, BMOST3, BMOC1, and BMOC2 and BMOC3. Cracks started to propagate at loads 45, 50, 25, 50, 50 and 40 kN for beams BMOST1, BMOST2, BMOST3, BMOC1, and BMOC2 and BMOC3 respectively. The different methods of strengthening by using CFRP Plates were effective for increasing the cracking loads in case of midspan opening.

Fig. 9a Crack pattern for BMOST1

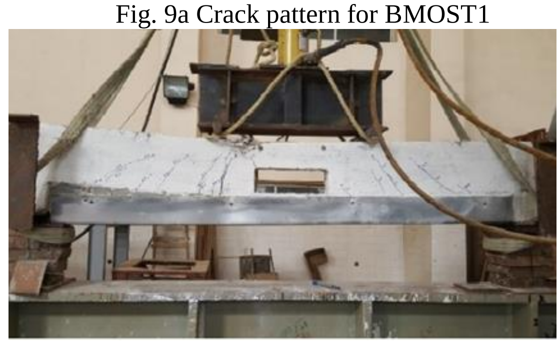

Fig. 9b Crack pattern for BMOST2

Fig. 9c Crack pattern for BMOST3

Fig. 9d Crack pattern for BMOC1

Fig. 9e Crack pattern for BMOC2

Fig. 9f Crack pattern for BMOC3

Fig. 9: Crack patterns for specimens in Group 3

5.2 Cracking and ultimate failure load

First cracks for beams CB, CBSO and CBMO were recorded at load 35, 20 and 25 kN respectively. It is noticed that the side opening decreased the cracking load by about 43% while the midspan opening decreased it by about 29%.

Ultimate failure loads for CB, CBSO and CBMO were recorded at load 120, 40 and 90 kN respectively. It is noticed that the side opening decreased the ultimate failure load by about 67% while the midspan opening decreased it by about 25%.

Ultimate failure loads for specimens BSOST1, BSOST2, BSOST3, BSOC1and BSOC2 were recorded at load 50, 80, 85, 50 and 115 kN respectively. It is noticed that the second method of strengthening for BSOC2 using horizontal and vertical CFRP Plates around the opening from both faces of the beam gave best results.

This technique increased the ultimate failure with respect to the corresponding specimen CBSO by about 188%, which approached to the ultimate failure of control beam without opening CB.

Ultimate failure loads for specimens BMOST1, BMOST2, BMOST3, BMOC1, and BMOC2 and BMOC3 in Group 3 were recorded at loads 100, 120, 95, 145, 135 and 130 kN respectively. All methods of strengthening were very effective in case of midspan opening. The ultimate loads for specimens BMOST1, BMOST2, BMOST3, BMOC1, and BMOC2 and BMOC3 were increased more than the corresponding control beam CBMO by about 11%, 33%, 6%, 61%, 50% and 44%. Using CFRP Plates gave better result than using steel plates. The ultimate failure loads were increased in case of using CFRP Plates than the control beam without opening CB. It is noticed that for specimen BMOC1, using CFRP Plates at the bottom face of the beam at the overall span length gave the best result in this group.

Figure 10 compares ultimate loads of all tested strengthened beams with respect to their reference beams.

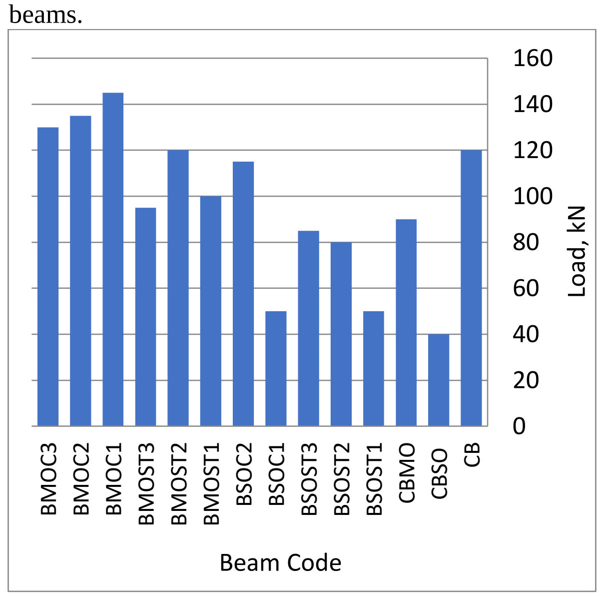

Fig. 10: Ultimate loads of all tested beams

5.3 Deflection

Ductility of beams can be defined as the ratio between the maximum deflection due to the ultimate load and the maximum deflection at the first cracking load. Energy absorption is always defined as the area under the load-deflection curve until failure.

Figure 11 compares the load-deflection curves for reference reinforced concrete beams in Group 1. The figure shows the reduction of the stiffness as well as the reduction in energy absorption due to openings. The reduction of the strength was affected by the opening locations. It can be seen that the side opening reduces the strength more than the midspan opening with respect to the control beam without opening as shown in Fig. 11.

Figure 12 shows the load-deflection curves for reinforced concrete beams strengthened by steel plates by the different techniques in Group 2. Figure 13 shows the load-deflection curves for reinforced concrete beams strengthened by CFRP plates in Group 2

Figure 14 shows the load-deflection curves for reinforced concrete beams strengthened by steel plates in Group 3. Figure 15 shows the load-deflection curves for reinforced concrete beams strengthened by CFRP plates by the different techniques.

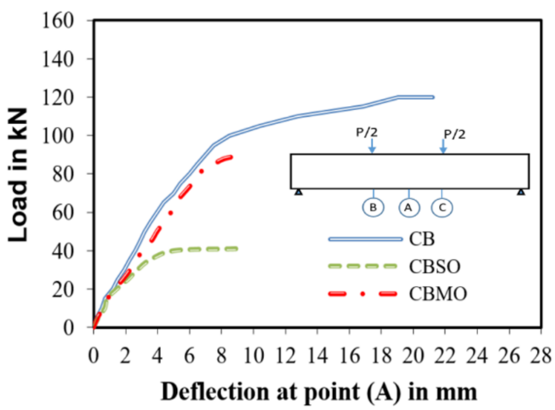

Fig. 11: Load deflection curves for reference specimens in Group 1.

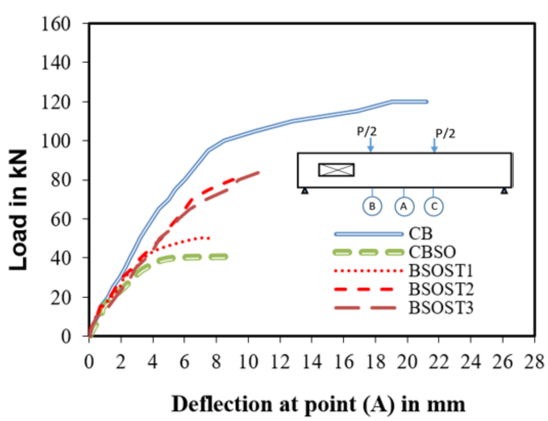

Fig. 12: Load deflection curves for specimens strengthened by steel plates in Group 2.

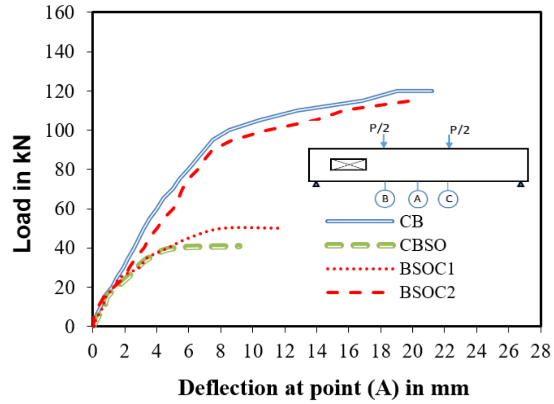

Fig. 13: Load deflection curves for specimens strengthened by CFRP plates in Group 2.

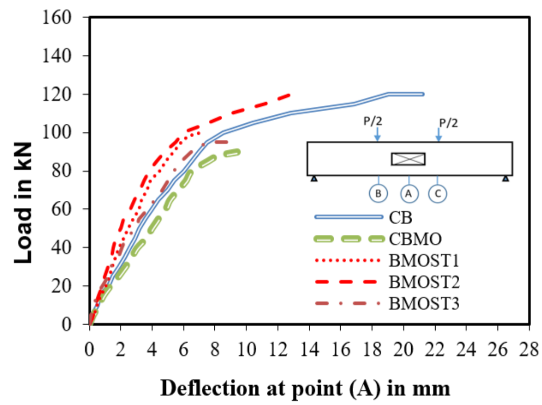

Fig. 14: Load deflection curves for specimens strengthened by steel plates in Group 3.

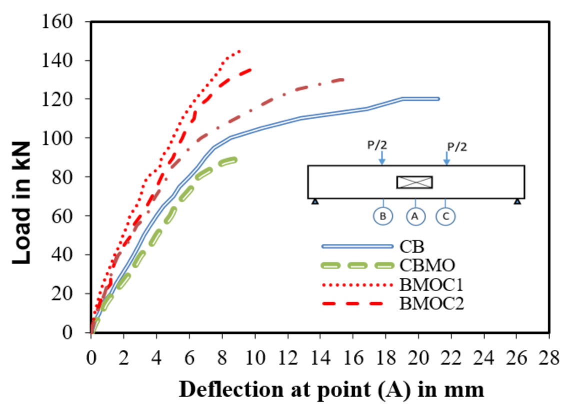

Fig. 15: Load deflection curves for specimens strengthened by CFRP plates in Group 3.

6. **Conclusions**

Based on the test results, the following conclusions can be obtained:

Large side opening in beam depth decreases the stiffness as well as the strength of the beam more than the midspan opening.

All strengthened techniques applied in this research improved the results of the strength, ductility, and energy absorption with the corresponding reference specimens.

First cracking loads for reference specimens CBSO and CBMO decreased by about 43% and 29% with respect to, the control beam without opening CB.

Ultimate failure loads for reference specimens CBSO and CBMO decreased by about 67% and 25% compared to, the beam without opening CB.

The method of strengthening for BSOC2 using horizontal and vertical CFRP plates around the opening from both faces of the beam gave best results. This technique increased the ultimate failure with respect to, the corresponding specimen CBSO by about 188%, which approached to the failure load of the control beam CB.

The ultimate loads for specimens in Group 3; BMOST1, BMOST2, BMOST3, BMOC1, and BMOC2 and BMOC3 were increased more than the corresponding control beam CBMO by about 11%, 33%, 6%, 61%, 50% and 44%.

The ultimate failure loads increased in the case of using CFRP Plates more than the ultimate failure load of the control beam CB. It is noticed that for specimen BMOC1, using CFRP Plates at the bottom face of the beam at the overall span length gave the best result in case of midspan opening.

Using CFRP Plates gave a better result than using steel plates for strengthening reinforced concrete beams with midspan openings.

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