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Behavior of Reinforced Concrete Deep Beams with Large Openings Strengthened by External Post – Tensioning Strands

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Abstract: ***In this research, nine simply supported reinforced concrete deep beams with large web openings strengthened by using external post – tensioning strands have been cast and tested up to failure under one-point load. These beams were divided into three groups according to strengthening schemes by using external strands. Each of these groups consisted of three beams having different opening ratios (0.4, 0.6 and 0.8). Where the opening ratio is defined as the opening length divided by the overall depth of the section. All beams having the same dimensions of 150 mm width, 400 mm overall depth and 1600 mm total length with clear span equal to 1280 mm. All deep beams have been designed with same interior reinforcement (same design). The main variables in the present study were the external strands configurations (strengthening schemes) and the openings ratio. For all deep beams the height of opening was kept constant of 160 mm (0.4H). Since the pre-stressing force in strands was not a variable parameter in this study, so that the jacking stress was intended to be constant of 600 MPa for all strengthening beams. The results show that increasing openings ratio caused a decreasing in first cracking and ultimate loads and increasing in mid span deflection for all beams. While, for same openings ratio, the strengthening using horizontal post – tensioning strands scheme was more effective than using vertical strengthening scheme in increasing the first cracking and ultimate load capacities and reducing the deflection. The maximum percentages increasing in first cracking and ultimate loads were (57.1 and 53.3) % respectively for opening ratio equal to 0.8 when using horizontal strengthening scheme. Also, the results show insignificant effect of increasing openings ratio on strands stress for both strengthening schemes. In other hand, there is a significant decrease in bottom (tension) reinforcement when using horizontal strengthening scheme as compared with beams without strengthening at same load level and for same openings ratio. The maximum percentage decreasing in main steel bar stress was about 88 %.***

Keywords: deep beam, large web opening, strengthening, exterior post – tensioning, strands

1. Introduction

Beam in which its clear span is less than four times the overall depth of the section is called as deep beam [1]. Deep beams are often being used in reinforced concrete (RC) structures such as diaphragms and transfer girders. Bernoulli's theory is inapplicable to deep beams due to plane section would not remain plane after bending [8].

Prediction the behavior of deep beams with web openings is important due to strong development of construction work which is used for doors, windows and accommodate fundamentals services. Mansur and Tan[11] were classified the web openings in RC beams as small and large openings. They suggested that the opening could be considered small if the ratio of depth of web opening (h) to overall depth of the section (H) is less than 25%. Otherwise, the opening could be considered large [10]. The presence of web openings in RC beams caused reduction in their ultimate strength [5]. Therefore, there is a need to strengthen these beams with openings to compensate the reduction in strength due to presence of such openings. Strengthening by using external post – tensioning strands may be considering one of the lasted developments in strengthening technology in which strands are install outside the concrete section and anchorage at beam ends [9 and 12].This strengthening technique by using external post – tensioning strands may be undergone in two schemes. The first scheme is by using horizontal strands (longitudinal to beam axis) installing above and below the opening edges. While, the second scheme is by using vertical strands locating to the left and right of the opening edges.

2. Objective of the Study

The main objectives of this research are: -

- Investigating the behavior of RC deep beams with different sizes of large web openings (different opening ratios).
- Investigating the behavior of RC deep beams with large web openings strengthening by using external post – tensioning strands in two schemes of strengthening (horizontally and vertically).
- Discuss the effect of increasing the web opening sizes (i.e., opening ratios) on the behavior of of RC deep beams strengthening with horizontal and vertical external strands.

3. Experimental Work

3.1 Deep beams description

Nine RC deep beams with symmetric large web openings have been cast and tested up to failure. All beams having the same dimensions of (150 *x* 400 *x* 1600) mm. The main variables in this research are the web opening sizes (i.e., opening ratios) and the strengthening schemes using external post – tensioning strands. So that, these beams have been divided into three groups (three beams in each group) according to strengthening schemes.

Group **A** represents deep beams with large web openings without strengthening. Group **B** represents deep beams with large web openings strengthened by using horizontal post – tensioning strands. While, Group **C** represents deep beams with large web openings strengthened by using vertical post – tensioning strands. Three opening ratios have been considered for each group which are (0.4, 0.6 and 0.8). Where, the opening ratio is defined as the ratio of web opening length (*w*) divided by the overall depth of the deep beam section (H). The opening height (h) was kept constant of 160 mm for all tested beam (i.e., 0.4 H). Figures 1 to 3 show the layout of tested deep beams for each groups. While, full description for tested beams is listed in Table 1.

Table 1: Nomenclature of deep beams

Group	*Nomenclature*	*Opening Ratio*	*Opening dimension (h x w) mm*	*Type of strengthening*
Group A	R – DB – 160	0.4	(160 *x* 160)	Without strengthening
	R – DB – 240	0.6	(160 *x* 240)	
	R – DB – 320	0.8	(160 *x* 320)	
Group B	HS –DB – 160	0.4	(160 *x* 160)	Horizontal strengthening with exterior strands
	HS –DB – 240	0.6	(160 *x* 240)	
	HS –DB – 320	0.8	(160 *x* 320)	
Group C	VS –DB – 160	0.4	(160 *x* 160)	vertical strengthening with exterior strands
	VS –DB – 240	0.6	(160 *x* 240)	
	VS –DB – 320	0.8	(160 *x* 320)	

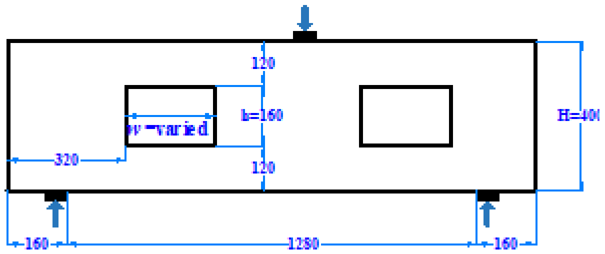


Figure 1: Layout of a typical tested beam for beams of Group **A** (beams without strengthening)

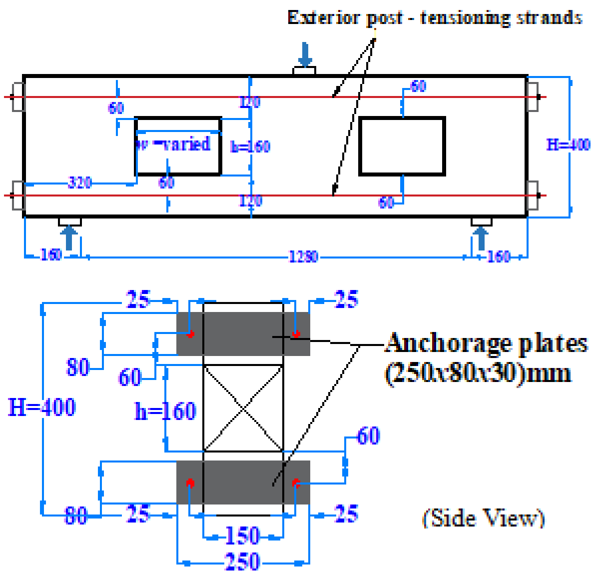


Figure 2: Layout of a typical tested beam for beams of Group **B** (beams strengthened with horizontal post – tensioning strands)

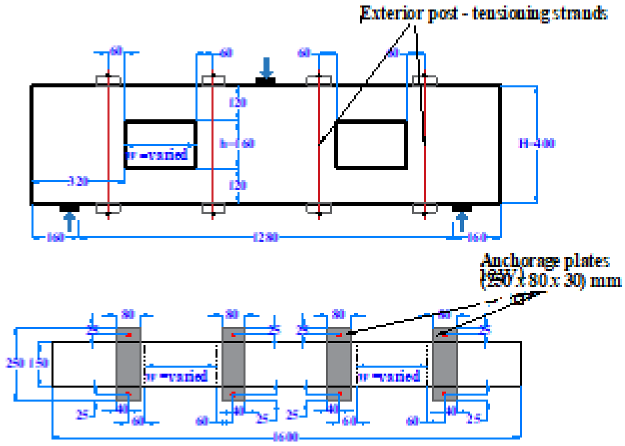


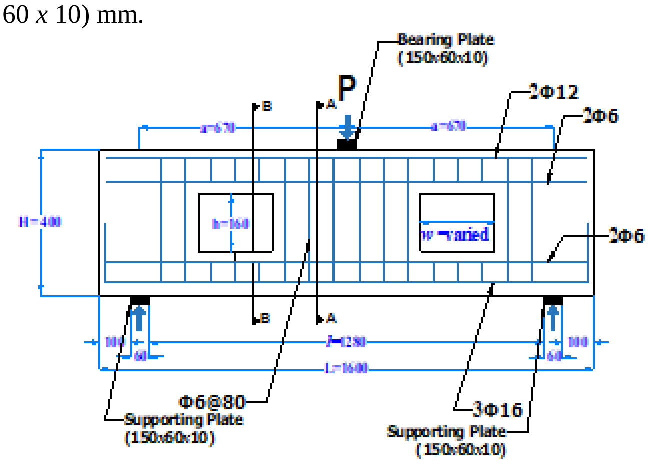
Figure 3: Layout of a typical tested beam for beams of Group **C** (beams strengthened with vertical post – tensioning strands)

3.2 Specimens details

All tested deep beams having the same design for interior reinforcement. The longitudinal reinforcement is design with 3∅16 mm and 2∅12 mm for bottom and top reinforcement respectively, ∅6 @ 80 mm is used for stirrups. While, 4 ∅6 mm (2 at each side face of beams cross section) is used for skin reinforcement as shown in Figure 4. All previous proposed reinforcement aspects have been checked with the (ACI318 -14) Code [1] exceptskin (nominal) reinforcement due to presence of web openings.

It is worth to mention that the beams of Group **B** (beams strengthened with horizontal strands) are strengthened with 4 external strands which equally arranged above and below the web opening. These strands are located horizontally at a distance of 60 mm above and below the web opening edges as previously shown in Fig. 2. While, the beams of Group **C** (beams strengthened with vertical strands) are strengthened with 8 external strands. Each 4 strands were equally divided to the left and right of each web opening. These strands are located vertically at a distance of 60 mm from the opening edges as previously shown in Fig. 3.

All anchorage plates that used to fixed the strands having a dimension of (250 *x*80 *x*30) mm. While, the supporting plates used to support beams having a dimension of (150 *x* 60 *x* 10) mm.



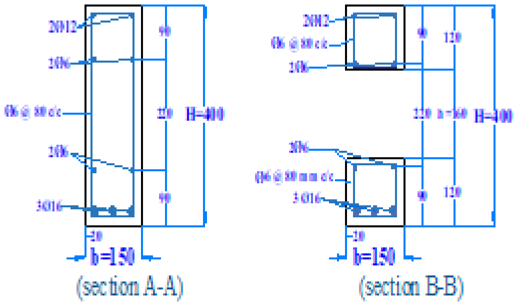


Figure 4: Typical reinforcement layout for tested deep beams (all dimensions are in mm)

3.3 Materials properties

The components of normal weight concrete used to cast the specimens in the present study are: cement, fine aggregates, coarse aggregates and tab water. For all tested deep beams, the concrete compressive strength (f'_c) was 30 MPa at 28 days. Medium workability with slump of (75 – 100) mm was archivedafter several trial mixes. Deformed steel bars and stress–relived strands have been used for interior reinforcement and for external post – tensioning strands respectively for tested deep beams.

3.3.1 Cement

Ordinary Portland cement (Type I) was used throughout this investigation. Cement was tested chemically and physically. These result were comparing with Iraqi Specifications (NO. 5/1984) [7] and ASTM C150 / C150 M -17[3] specifications.

3.3.2 Fine aggregate

Natural sand from Al-Akhaidher quarries in Karbala city has been used for concrete mixes. The maximum size of fine aggregate was 4.75 mm. The sand has conformed to the Iraqi Specification No. 45/1984[6]and ASTM C33/ C33M -16e1[4] specifications.

3.3.3 Coarse aggregate

Crashed gravels with maximum size of aggregate equal to 12.5 mm have been used in this study. The gravel has conformed to Iraqi Specification No. 45/1984[6]and ASTM C33/ C33M -16e1 [4] specifications.

3.3.4 Steel reinforcement

Table 2below illustrates the sizes of deformed steel bars used in the present study with their yield strength. The modulus of elasticityfor steel barsis assumedto be 200000 MPa. The steel reinforcing bars hadconformed to ASTM A615/A615M-16[2].

Table 2: Steel reinforcement properties

Nominal Bar Diameter mm	Actual Bar Diameter mm	Yield Strength MPa	Ultimate Strength *MPa*
6	5.64	520	560
12	11.72	650	720
16	15.66	660	750

3.3.5 Strands

The size and area of strands used for strengthening deep beams with large web openings are 12.7 mm and 98 mm^2 respectively with ultimate strength of 1630 MPa. These strands were fabricated from seven wires twisted around a slightly larger central straight wire and that conform to ASTM standard A416-16 [2].

3.4 Fabrication and Casting of specimens

To fabricate each specimen, steel bars have been cut to required length then strain gaugeswere fixed at the center of longitudinal bottom reinforcement as well as at the left and right stirrups closed to opening edges as shown in Figure 5.

To fabricate web opening, styropor blocks were prepared according to required opening dimensions for each beam and inserted inside the steel cage at the required opening location.

Before casting, the molds were lubricated with oil for easy remove of specimen. The concrete was leveled when the adequate amount was placed into the mold so that the specimens were kept at the same height. Figure 6 shows the deep beam specimens after completing casting and curing process.

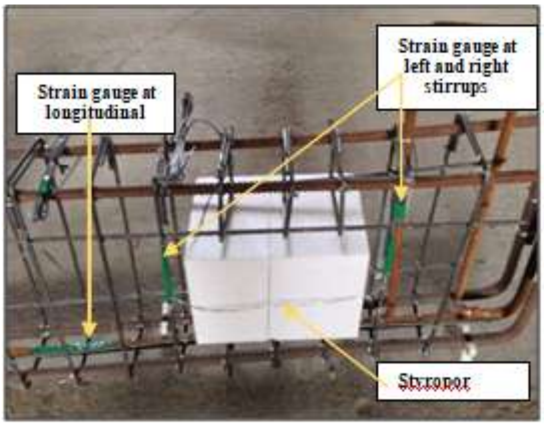


Figure 5: Strain gauges location on longitudinal bar and stirrups

Figure 6: Tested deep beams after completing casting and curing process

3.5 Jacking process

A hydraulic pre – stresses jack having a capacity of 23 Ton was used for pre-stressing the external strands. In the present study, jacking stress is not an investigation parameter so that it was intended to be constant with a value of 600 MPa in each strands for both horizontal and vertical strengthening schemes. Figure 7 shows the jacking process for external horizontal and vertical strands.

(a) Jacking stress process for beams with horizontal strengthening strands

(b) Jacking stress process for beams with vertical strengthening strands

Figure 7: Jacking process for both strengthening schemes

3.6 Testing procedure

After 28 days of curing, the specimens were painted with weight color to identify cracks during the loading process. Specimens were then placed inside the testing frame and adjusted so that the center line of point loading, supports and dial gauge were fixed in their correct locations as shown in Figure 8.

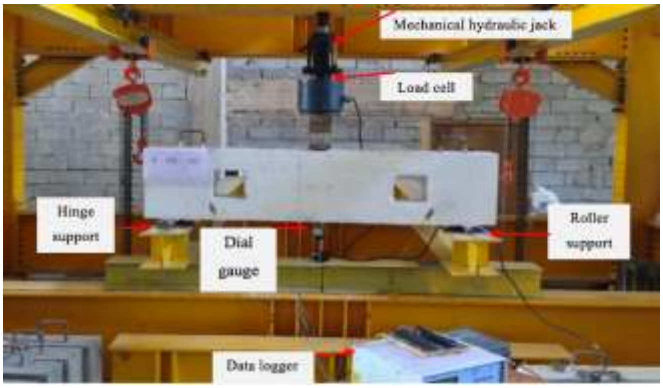


Figure 8: Setup of a typical tested beams

4. Results and discussion

4.1First cracking loads

It was observed from the experimental test that the diagonal cracks were formed first by 45° at the upper corner of web openings. While, the first flexure cracks were formed with increasing load increment. Table 3 summarizes the first diagonal cracking loads for all tested deep beams. From this table, it can be notice that increasing of web opening ratio lead to early appearance of the first diagonal cracks. For deep beams with large web openings without strengthening (i.e., Group **A**), the percentages decreasing in first diagonal crack loads as compared with deep beam having web opening ratio equal to 0.4 were (28.6 and 50.0) % for opening ratios 0.6 and 0.8 respectively. While, for deep beams strengthened with horizontal strands (i.e., Group **B**), the percentages decreasing in first diagonal crack loads compare with beam having opening ratio equal to 0.4 from this group were (16.7 and 38.9) % for beams with opening ratio equal to 0.6 and 0.8 respectively. Finally, for deep beam strengthened with vertical strands (i.e., Group **C**), these percentages were (25.0 and 50.0) % for same opening ratios.

Table 3: Effect of increasing opening ratio on first diagonal cracks loads

Group	Deep Beam	Opening Ratio	First Cracking Loads kN	% Decreasing In First Cracking Load *
Group A	R – DB – 160	0.4	70	---
	R – DB – 240	0.6	50	28.6
	R – DB – 320	0.8	35	50.0
Group B	HS –DB – 160	0.4	90	---
	HS –DB – 240	0.6	75	16.7
	HS –DB – 320	0.8	55	38.9
Group C	VS – DB – 160	0.4	80	---
	VS – DB – 240	0.6	60	25.0
	VS – DB – 320	0.8	40	50.0

$$* \, \% \, Decreasing = \left| \frac{\begin{matrix} deep\ beam\ with \\ web\ opening\ ratio\ 0.4 \end{matrix} - \begin{matrix} deep\ beam\ with \\ web\ opening\ ratio\ 0.6\ or\ 0.8 \end{matrix}}{\begin{matrix} deep\ beam\ with \\ web\ opening\ ratio\ 0.4 \end{matrix}} \right| x\ 100$$

In other hand, the strengthening of deep beams with large web openings using external post – tensioning strands would increase the first diagonal cracking loads for same opening ratio as it illustrated in Table 4.For deep beams with opening ratio equal to 0.4, the percentages increasing in first diagonal crack loads were (28.6 and 14.3) % for horizontal and vertical schemes of strengthening respectively as compared with their reference deep beam (i.e., deep beam without strengthening). While, for deep beams with opening ratio equal to 0.6, the percentages increasing in first diagonal crack loads were (50.0 and 20.0) % for horizontal and vertical schemes of strengthening respectively as compared with reference deep beam. Finally, for deep beams with opening ratio equal to 0.8, these percentages were (57.1 and 14.3) % for same strengthening schemes. From the previous comparisons, it can be concluded that the strengthening with external post –tensioning strands using horizontal scheme was more effective than using vertical scheme of strengthening.

Table 4: Effect of strengthening scheme on first diagonal cracks loads

Deep Beam	Opening Ratio	First Cracking Loads kN	% Increasing In First Crack *
R – DB – 160	0.4	70	Reference bean
HS –DB – 160		90	28.6
VS – DB – 160		80	14.3
R – DB – 240	0.6	50	Reference bean
HS –DB – 240		75	50.0
VS – DB – 240		60	20.0
R – DB – 320	0.8	35	Reference bean
HS –DB – 320		55	57.1
VS – DB – 320		40	14.3

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$$\% \, Increasing = \frac{strengthening \; beam \; with \; horizontal \; or \; vertical \; strands \; - Reference \; beam}{Reference \; beam} \, x \, 100$$

4.2 Crack pattern and failure mode

Diagonal cracks or shear crackscaused failure in most cases for tested deep beams with large web openings. It can benoticed that diagonal splitting failure and shear – compression failureare the modes of failure for tested deep beams. In which the first mode referred to failure due to diagonal crack at corner of web openings developed towards support and loading point. While, the second mode referred to diagonal crack developed in shear span and crushing in compression due to high stress in compression zone. Figures 9 to 17 show the crack pattern at ultimate load for tested deep beams.

Figure 9: Crack pattern at ultimate load for beam ***R– DB – 160***(Group **A**) (diagonal splitting failure)

Figure 10: Crack pattern at ultimate load for beam ***R– DB – 240(Group A)***(shear – compression failure)

Figure 11: Crack pattern at ultimate load for beam ***R– DB – 320(Group A)*** (diagonal splitting failure)

Figure 12: Crack pattern at ultimate load for beam ***HS–DB–160(Group B)*** (diagonal splitting failure)

Figure 13: Crack pattern at ultimate load for beam ***HS–DB–240(Group B)***(diagonal splitting failure)

Figure 14: Crack pattern at ultimate loadfor beam ***HS–DB–320(Group B)***(diagonal splitting failure)

Figure 15: Crack pattern at ultimate load for beam ***VS–DB–160(Group C)***(shear – compression failure)

Figure 16: Crack pattern at ultimate loadfor beam ***VS–DB–240(Group C)***(shear – compression failure)

Figure 17: Crack pattern at ultimate load for beam ***VS–DB–320 (Group B)***(shear – compression failure)

4.3 Load – deflection response

Central deflection has been recorded for each deep beam during the test by using dial gage located at midspan of deep beam. Figures 18 to 20show the effect of increasing openings ratio on load – deflection curves for tested deep beams of each group. It can be notice from these figures that the increased in opening ratio caused decreased in ultimate load and increased in mid span deflection. Table 5 summarizes the ultimate load and mid span deflection for all tested deep beams.

For deep beams without strengthening, the percentages decreasing in ultimate load were (22.7 and 31.8) % for beams with opening ratio equal to 0.6 and 0.8 respectively as compared with beam having opening ratio equal to 0.4. While, the percentages increasing in deflection were (30.0 and 110.0) % for same opening ratios corresponding to ultimate load of beam with opening ratio equal to 0.8. While, for deep beams strengthened with horizontal strands, the percentages decreasing in ultimate load were (10.3 and 20.7) % for beams with opening ratio equal to 0.6 and 0.8 respectively. While, the percentages increasing in deflection were (48.9 and 80.0) % for the same opening ratios. Finally, for deep beams strengthened with vertical strands, the percentages decreasing in ultimate load were (17.9 and 28.6)

% and the percentages increasing in deflection were (30.0 and 55.3) % for the same opening ratios.

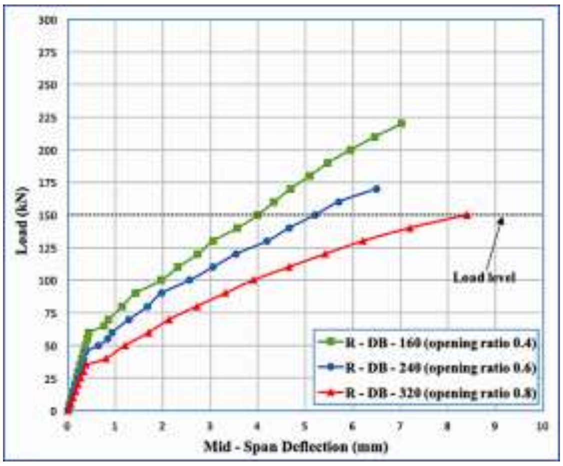

Figure 18: Load – deflection curves for deep beams without strengthening (Group **A**)

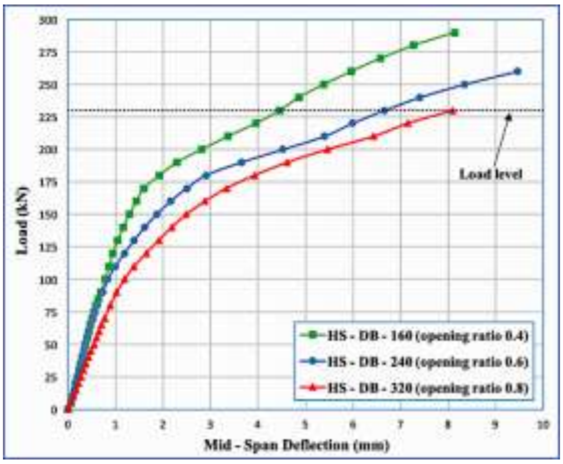

Figure 19: Load – deflection curves for deep beams strengthened with horizontal strands (Group **B**)

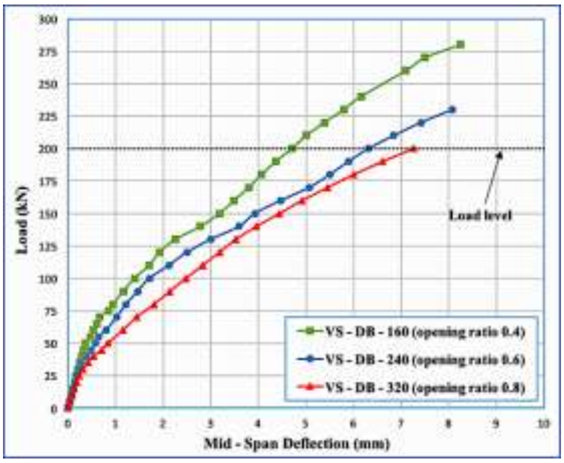

Figure 20: Load – deflection curves for deep beams strengthened with vertical strands (Group **C**)

Table 5: Effect of increasing of opening ratio on ultimate load and mid span deflection

Group	Deep Beam	Opening Ratio	Ultimate Loads (kN)	% Decreasing In Ultimate Loads *	Mid Span Deflection (mm) **	%Increasing In Mid Span Deflection *
Group A	R-DB-160	0.4	220	---	4.0	---
	R-DB-240	0.6	170	22.7	5.2	30.0
	R-DB-320	0.8	150	31.8	8.4	110.0
Group B	HS-DB-160	0.4	290	---	4.5	---
	HS-DB-240	0.6	260	10.3	6.7	48.9
	HS-DB-320	0.8	230	20.7	8.1	80.0
Group C	VS-DB-160	0.4	280	---	4.7	---
	VS-DB-240	0.6	230	17.9	6.3	30.0
	VS-DB-320	0.8	200	28.6	7.3	55.3

$$\% = \left| \frac{\begin{matrix}\text{deep beam with} \\ \text{web opening ratio 0.4}\end{matrix} - \begin{matrix}\text{deep beam with} \\ \text{web opening ratio 0.6 or 0.8}\end{matrix}}{\begin{matrix}\text{deep beam with} \\ \text{web opening ratio 0.4}\end{matrix}} \right| x\ 100$$

** corresponding to ultimate load level of deep with opening ratio equal to 0.8

In other hand, the strengthening of deep beams with large web openings by using external post – tensioning strands would increase the ultimate load and decreased the mid span deflection as shown in Figures 21 to 23. It can be notice form these figures that using horizontal post – tensioning strands in strengthening is more effective than using vertical strands compared with beams without strengthening under same opening ratio.

The percentages increasing in ultimate load as compared with reference beam were (31.8, 53.0 and 53.3) % for deep beam with web opening ratios (0.4, 0.6 and 0.8) respectively when they strengthened with horizontal post – tensioning strands. While, these percentages become (27.3, 35.3 and 33.3) % when using vertical post – tensioning strands.

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While the percentages decreasing in mid span deflection as compared with ultimate load level deflection of reference beam were (43.7, 61.7 and 70.4) % for deep beam with web opening ratios (0.4, 0.6 and 0.8) respectively when they strengthened with horizontal post – tensioning strands. While, these percentages are (23.4, 22.0 and 47.1) % when using vertical post – tensioning strands as they summarized in Table 6.

Table 6: Effect of strengthening schemes on the ultimate load and mid span deflection for tested beams

Deep Beam	Opening Ratio	Ultimate Loads (kN)	% Increasing In Ultimate Loads *	Mid Span Deflection (mm)**	%Decreasing In Mid Span Deflection*
R-DB-160	0.4	220	Reference Beam	7.02	Reference Beam
HS-DB-160		290	31.8	3.95	43.7
VS-DB-160		280	27.3	5.38	23.4
R-DB-240	0.6	170	Reference Beam	6.5	Reference Beam
HS-DB-240		260	53.0	2.49	61.7
VS-DB-240		230	35.3	5.07	22.0
R-DB-320	0.8	150	Reference Beam	8.40	Reference Beam
HS-DB-320		230	53.3	2.49	70.4
VS-DB-320		200	33.3	4.44	47.1

$$* \ \% = \frac{strengthening \ beam \ with \ horizontal \ or \ vertical \ strands - Reference \ beam}{Reference \ beam} \ x \ 100$$

** corresponding to ultimate load level of reference beam

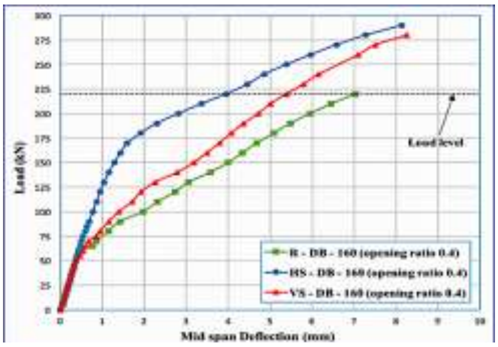


Figure 21: Load – deflection curves for deep beams with openings ratio equal to 0.4

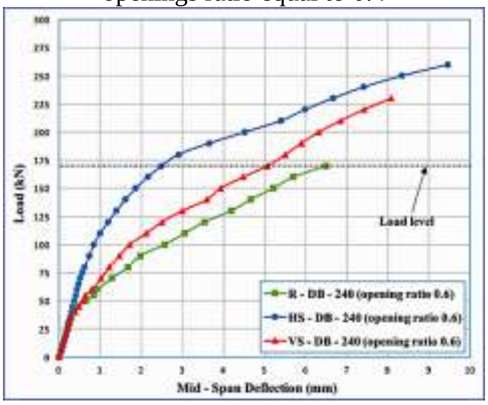


Figure 22: Load – deflection curves for deep beams with openings ratio equal to 0.6

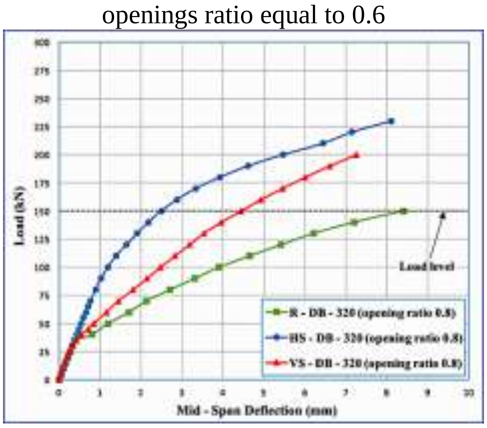


Figure 23: Load – deflection curves for deep beams with openings ratio equal to 0.8

4.4 Stresses in Main Steel Bars

Stresses on main steel bar have been recorded for each deep beam during the test by using strain gauge placed on mid length of main reinforcement steel bar. Figures 24 to 26 show the load – stresses in main steel bar curves for each tested group. It can be observed form these figure that changing in main steel bars stress has insignificant effect when the opening ratio was increased at same load level of ultimate load of beam with opening ratio equal to 0.8.

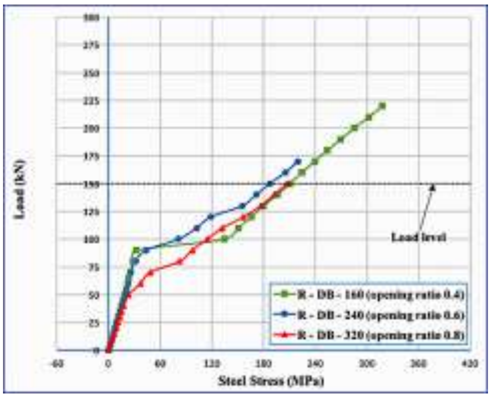


Figure 24: Load – stresses in main steel bars curves for deep beams without strengthening (Group **A**)

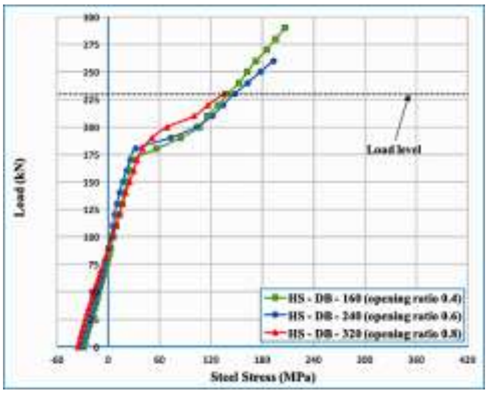


Figure 25: Load – stresses in main steel bars curves for deep beams strengthened with horizontal strands (Group **B**)

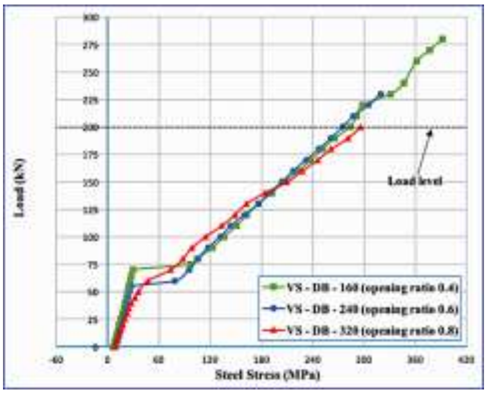


Figure 26: Load – stresses in main steel bars curves for deep beams strengthened with vertical strands (Group **C**)

While, Figures 27 to 29 show the effect of strengthening schemes on the stresses in main steel bars for tested beam. It can be notice form these figures that the external horizontal strands have a significant effect on decreasing the stresses in main steel bars compared with beams without strengthening. While, when using external vertical strands, the stresses in main steel bars were not affected under same load level corresponding to reference beam from each group. Also, from these figures it is shown that the stresses in main steel bar at early stages of loading have negative sign (compression) for all beams of Group **B** (beams strengthened with horizontal post – tensioning strands). This is because of high compression force delivered from exterior bottom strands. Table 7 summarizes the stresses in main steel bars for tested deep beams. From this table it could be concluded that the percentages decreasing in main steel bars stresswere (59.5, 88.2 and 88.0) % for deep beams with opening ratio (0.4,0.6 and 0.8) respectively when they strengthened with horizontal post – tensioning strands. While, when using external vertical strengthening, the change in main steel bars stresses were insignificant.

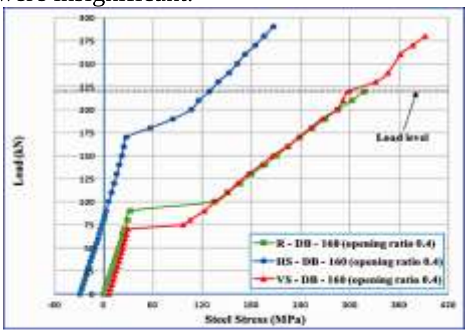


Figure 27: Load – stresses in main steel bar curves for deep beams with openings ratio equal to 0.4

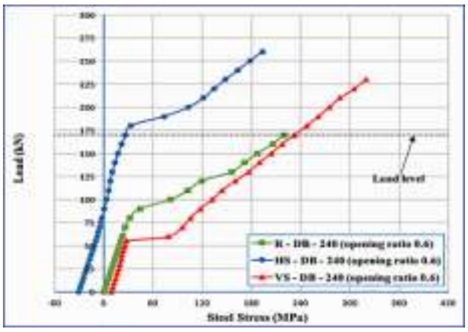


Figure 28: Load – stresses in main steel bar curves for deep beams with openings ratio equal to 0.6

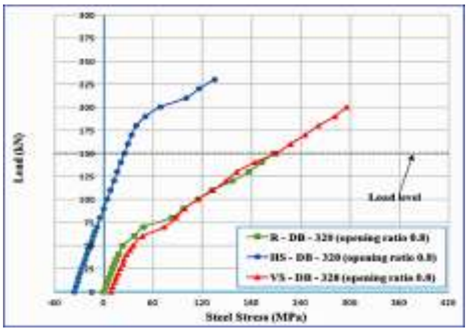


Figure 29: Load – stresses in main steel bar curves for deep beams with openings ratio equal to 0.8

Table 7: Effect of strengthening schemes of main steel bars stresses

Deep Beams	Opening Ratio	Stresses In Main Steel Bar (MPa) **	% Decreasing in Stress in Main Steel bar*
R – DB – 160	0.4	317.6	Reference beam
HS – DB – 160		128.7	59.5
VS – DB – 160		298.4	6.0
VS – DB – 240	0.6	219.6	Reference beam
HS – DB – 240		26.0	88.2
VS – DB – 240		231.92	5.6 ***
R – DB – 320	0.8	207.4	Reference beam
HS – DB – 320		24.9	88.0
VS – DB – 320		209.7	1.1***

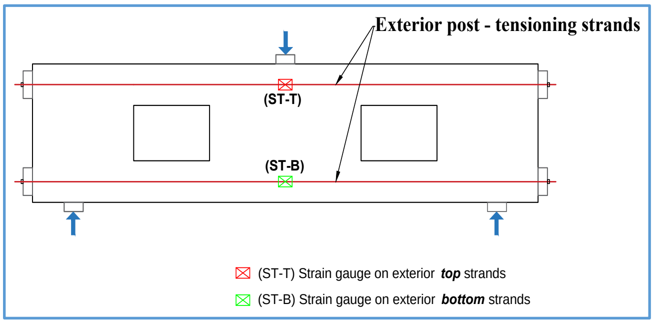
*

$$\% = \frac{strengthening\ beam\ with\ horizontal\ or\ vertical\ strands\ - Reference\ beam}{Reference\ beam}\ x\ 100$$

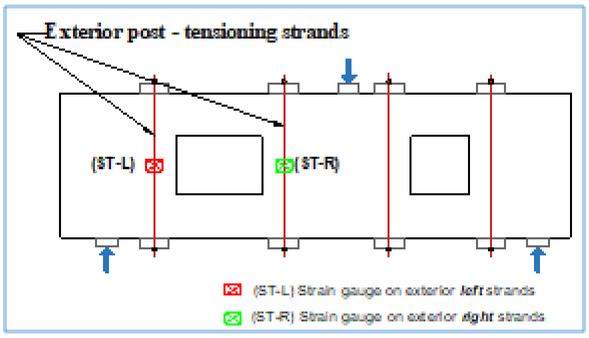
** corresponding to ultimate load level of reference beam
*** Increasing in steel stress

4.5 Stresses in Strands

Stresses that developed in strands have been recorded for each strengthened deep beams during the test by using strain gauge placed on the middle of bottom and top strands when using horizontal strengthening. While, for vertical strengthening, strain gaugeswere placed on the right and left of strands as shown in Figure 30.



(a) Position of strain gauges on the exterior horizontal strands (above and below the web openings).

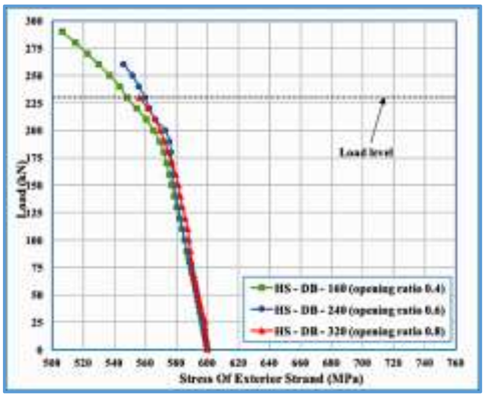


(b) Position of strain gauges on the exterior vertical strands (to the right and left of web openings).

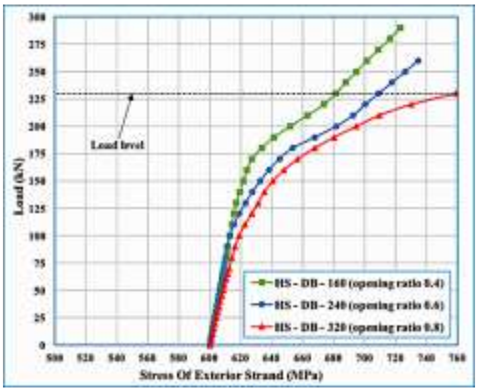
Figure 30: Positions of strain gauges on exterior strands for both strengthening schemes

4.5.1 Stresses in exterior horizontal strands

Figure 31 shows the load – stresses in top and bottom strands curves for beams of Group **B**. It can be noticed that the stresses in the top strands weredecreased from the initial stress (i.e., from 600 MPa) when the load is increased for all beams of this group. While, the stresses in bottom stands were increased form the initial stress as the load increased. This is because of increasing curvature of beams through the test (increasing positive bending moment). From Figure 31-a, it can be notice that the increasing of opening ratio was not affectedon changing in the top strand stresses as compared with ultimate load level top strand stress of beam with opening ratio equal to 0.8. While, Figure 31-b shows a slight increasing in bottom strand stress.



(a) Top strand



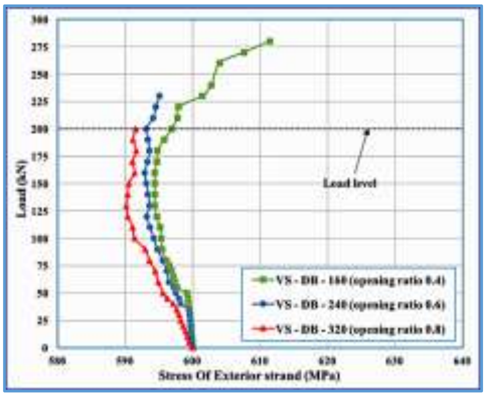
(b) Bottom strand

Figure 31: Load – stresses in top and bottom strands curves for deep beams strengthened with horizontal post – tensioning strands (beams of Group **B**)

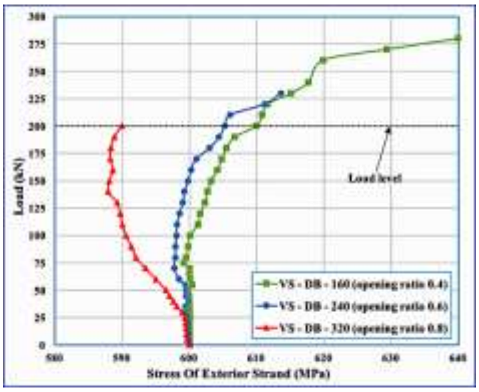
4.5.2 Stresses in exterior vertical strands

Figure 32 shows the load – stresses in left and right strands for beams of Group **C**. It can be noticed from Figure 32 –a that the stressinleft strand was slightly decreased from initial stress (i.e., from 600 MPa) when opening ratio was increased.

While, Figure 32-b shows a slightly increased in right strand stresses with increasing the opening ratio except when opening ratio was 0.8, the right strands show decreasing in stresses



(a) Left strand



(b) Right strand

Figure 32: Load – stresses in left and right strands curves for deep beams strengthened with vertical post – tensioning strands (beams of Group **C**)

It can be notice from the previous figures and comparisons for both schemes of strengthening to deep beam with large web opening, that the increasing in opening ratio has insignificant effect on in strands stress.

5. Conclusions

1. Presence of large web opening in RC deep beams caused decreasing in their first cracking and ultimate load capacities and increasing the mid span deflection.For deep beams without strengthening and for opening ratios 0.6 and 0.8,the percentages decreasing in first cracking and ultimate loads were (28.6 and 50.0) % and (22.7 and 31.8) % respectively as compared with beam having opening ratio equal to 0.4. While, the percentages increasing in mid span deflection for the same opening ratios were (30.0 and 110.0) %.

For deep beams strengthened by horizontal strands and for opening ratios 0.6 and 0.8, the percentages decreasing in first cracking and ultimate load were (16.7 and 38.8) % and (10.3 and 20.7) % respectively. While, the percentages increasing in mid span deflection for same opening ratios were (48.9 and 80.0) %.

While, for deep beam strengthened by vertical strands and for same opening ratio these percentages were (25.0 and 50.0) %, (17.2and 28.6) % and (30.0 and 55.3) % for decreasing in first cracking and ultimate loads and for increasing in mid span deflection respectively.

2. Strengthening of RC deep beams by using external post – tensioning strands in both horizontal and vertical schemes caused a significant enhancement in their first cracking and ultimate load capacities and reducing the mid – span deflection specially for beams strengthened by using horizontal post – tensioning strands as compared with beams without strengthening for same opening ratio.

For opening ratio equal to 0.4, the percentages increasing in first cracking and ultimate loads were (28.6 and 31.8) % respectively and the percentage decreasing in deflection was as 43.7 % when using horizontal strengthening schemes. While, when using vertical strengthening schemes these percentages were (14.3 and 27.3) % for first and ultimate loads respectively and 23.4 % for deflection.
While, for opening ratio equal to 0.6, the percentages increasing in first cracking and ultimate loads were (50.0 and 53.0) % respectively and the percentage decreasing in deflection was 61.7 % when using horizontal strengthening schemes. However, when using vertical strengthening schemes these percentages were (20.0 and 35.3) % for first and ultimate loads respectively and 22.0 % for deflection.

Finally, for opening ratio equal to 0.8, these percentages were (57.1 and 53.3) % for first cracking and ultimate loads respectively and 70.4 % when using horizontal strengthening schemes. While, when using vertical strengthening schemes these percentages were (14.3 and 33.3) % for first and ultimate loads respectively and 47.1 % for deflection.

3. As opening ratio was increased, the stress in main steel bars (bottom reinforcement) showed insignificant change under same ultimate load level of beams with opening ratio equal to 0.4. While, for the same opening ratio, the stress in main steel bar has decreased significantly when using horizontal post – tensioning strands schemes for strengthening compare with beams without strengthening. But insignificant change in this stress was occurred when using vertical scheme. For opening ratios (0.4,0.6 and 0.8) the percentages decreasing in main steel bar stresses by using horizontal strengthening scheme were (59.5, 88.2 and 88.0) % respectively.

4. Increasing opening ratio has insignificant effect on strands stress for both strengthening schemes under same load level.

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