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Strength and Serviceability of Reinforced Concrete Deep Beams with Large Web Openings Created in Shear Spans

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Abstract

Deep beams are used in wide construction fields such as water tanks, foundations, and girders in multi-story buildings to provide certain areas free of columns. In practice it is quite often occurring to create web opening in deep beams to supply convenient passage of ventilation ducts, cable channels, gas and water pipes. Experimental studies of ten 10 deep beams were carried out, where two of them are control specimens without openings and eight with large web openings in the shear spans. The variables that have been adopted are the ratio of the shear span to the overall depth of the member cross-section, location and dimensions of the opening. Test results showed that there was a decrease in the load carrying capacity of deep beams with openings compared to the control deep beams. This reduction may reach 66% in particular cases. It is clear that, the position of opening in shear span has less effect on the performance of structural concrete deep beams at different serviceability stages. Only 11% increase in load capacity at failure was observed in specimens with openings adjacent to the interior edges of shear spans in comparison with specimens with openings at the center of shear span because the discontinuity of the load path is less. Also the midspan deflection at service load level of the reference beam in specimens with openings adjacent to interior edge of shear spans was less than the midspan deflection of reference specimens by 10% - 33%. Evaluating all these advantages facilitates to recommend, if it is very required, the creation of openings at the interior edges of shear spans of the structural concrete deep beams.

Keywords: Deep Beam; Large Web Openings; Shear Span; Load Carrying Capacity.

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1. Introduction

Deep reinforced concrete beams are quite often used in multistory buildings, bridges and marine structures. There is frequently a need for creation openings in these beams to provide passage for electrical and mechanical ducts. Web openings reduce the load carrying capacity of structural concrete members, specifically the shear resistance. Mansur and Tan (1996) were classified the web openings in reinforced concrete beams as small and large openings [1]. They suggested that the web opening could be considered small when the ratio of the circular opening diameter or web opening depth to overall depth of the deep beam is less than or equal to 25%. Otherwise, web opening could be classified as large web opening. For large web opening, this ratio is limited to 40%. Several studies were conducted to determine the effect of openings on the shear resistance of deep beams [2-4].

Kong and Sharp (1977) conducted experimental work to evaluate the effect of the size and location of opening on the performance of reinforced concrete deep beams. According to their experimental results, series of empirical expressions were proposed to consider the effect of these parameters on the shear strength [5]. The influence of web openings on reinforced concrete deep beams were estimated experimentally and analytically by Yang et al., (2006) [6]. Thirty-two reinforced high-strength concrete deep beams with or without openings were tested under two-point static

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loading. Test variables included concrete strength, shear span-to-depth ratio, and the width and depth of the opening. Yang et al., (2006) mentioned that, the strengths at diagonal crack appearance stage and at failure load are closely related to the angle of the inclined plane joining the support and the corner of the web opening [6]. Also, the influence of concrete strength on the ultimate shear strength remarkably decreases in deep beams with openings rather than solid deep beams. Al-Khafaji et al., (2014) tested eight simply supported self-compacted concrete deep beams under two-point static loads, where the parametric study focused mainly on the shear span to effective depth ratio (a/d). Test results showed that, increasing the (a/d) ratio from 0.6 to 1 led to decrease the cracking and ultimate loads by average ratios of 28.6% and 23.3%, respectively [7].

Chin, et al., (2015), tested three specimens of reinforced concrete deep beams, where the first specimen was without openings, the second specimen was with large circular web opening. While, the third one was with the same opening size as in the second specimen but it strengthened with carbon fiber reinforced polymer strips (CFRP) in shear regions. They found that, the reduction of load carrying capacity for unstrengthen specimen with opening compared to solid reinforced concrete deep beam was 51%. Furthermore, surface strengthening around opening using CFRP resulted in increasing the ultimate load by 56% and 15.32% compared to unstrengthen beam with web opening and solid beam, respectively [8].

Al-Bayati, et al., (2016) tested eleven simply supported reinforced self-compacting concrete deep beams under symmetrically two-point load to investigate the influence of the circular web openings on their behavior. Variables which were investigated involve the location of opening, opening size, the area of the transverse inclined reinforcement around openings and the shear span to effective depth ratio (a/d). In this study, all beams had the same overall dimensions, concrete compressive strength and flexural reinforcement. Based on the test results presented in this work it was concluded that, as the opening was positioned at the center of the shear span, the behavior of the beams was significantly influenced regardless the value of the (a/d) ratio and the opening size. Also it was found that, when the opening of a large diameter shifted away from the load path either to the top or to the bottom regions of the beam, the cracking and ultimate loads were dramatically reduced [9].

Grande et al. (2008) and Sayed et al. (2013) considered in their studies the influence of the shear span to depth ratio (a/d) which selected to be between 2 and 3 while Li, et al., (2015) investigated the effect of (a/d), which varied from 1.0 to 3.5, on the behavior of reinforced concrete beams which strengthened with full-wrapping FRP strips in shear spans. Twelve specimens were tested up to failure, where six of them were un-strengthened, while the other six were strengthen by FRP strips. The test results indicated that, the FRP shear contribution increased initially with the increasing of (a/d) ratio, but decreased when the ratio was more than 2.5 [10-12]. Li, et al. (2015) mentioned that, the design guidelines for the fiber-reinforced polymer strengthening of reinforced concrete structures may exceed the shear-strengthening effectiveness at low (a/d) ratios, therefore they have to be used with caution [12].

Alsaad et al., (2017) presented an experimental study of five reinforced concrete deep beams with circular web openings to investigate the influence of CFRP strengthening on the behavior of these beams at different loading stages. All samples were with dimensions of 1200 mm clear span × 500 mm deep × 100 mm wide, respectively. Results of this work showed that, the diagonal configuration of CFRP strips around the opening was the best one, as the ultimate shear strength ratio with respect to the control solid beam was 0.97, while it was 0.86 for the same beam with openings but un-strengthened by CFRP. A significant positive effect was observed on the deformability of these beams that strengthened by CFRP strips. Also, CFRP sheet oriented diagonally around openings was the most appropriate for reducing the deflection [13].

Nie et al., (2018) tested eight full-scale reinforced concrete beams under center-point loading up to failure. Two of these specimens, (one with rectangular section and the other with T-section), were solid without openings, where the other six beams were with T-section and contained single rectangular web opening in the shear zone. Out of the six T-beams with openings, two specimens were un-strengthened and four beams were strengthened with externally bonded CFRP composite sheets. Test results showed that, a sizable web opening can effectively reduce the flexural capacity of the T-beam and the CFRP strengthening system is needed to avoid shear failure of the beam and confine the web chord created by the opening to ensure a ductile response at failure [14].

2. Experimental Work

2.1. Material Properties

The concrete mix was prepared to fabricate experimental specimens using cement Type I which tested according to the Iraqi specifications (I.O.S. 5/1984) [15], coarse aggregate of 10 mm maximum size and fine sand which tested according to the Iraqi specifications (No. 45/1984) [16]. Figure 1 shows the sieve analysis results for fine and coarse aggregate. The cement: sand: aggregate proportions by weight were (1: 1.13: 2.70) with a water/cement ratio of 0.62. To estimate the concrete compressive strength for each experimental specimen, three concrete cylinders with 150 × 300 mm dimensions were made and tested according to (ASTM C39-86 2002) [17].

The average cylinder compressive strength of concrete at 28 days age f_c' was 27 MPa. All deep beams were reinforced in tension zone by 3Ø16 mm longitudinal bars with f_y of 569.67 MPa which tested according to (ASTM A615/A615M-16) [18], and equally distributed transverse reinforcement of closed form bars Ø6 mm@ 86 mm c/c with (f_y) of 623.96 MPa along the span.

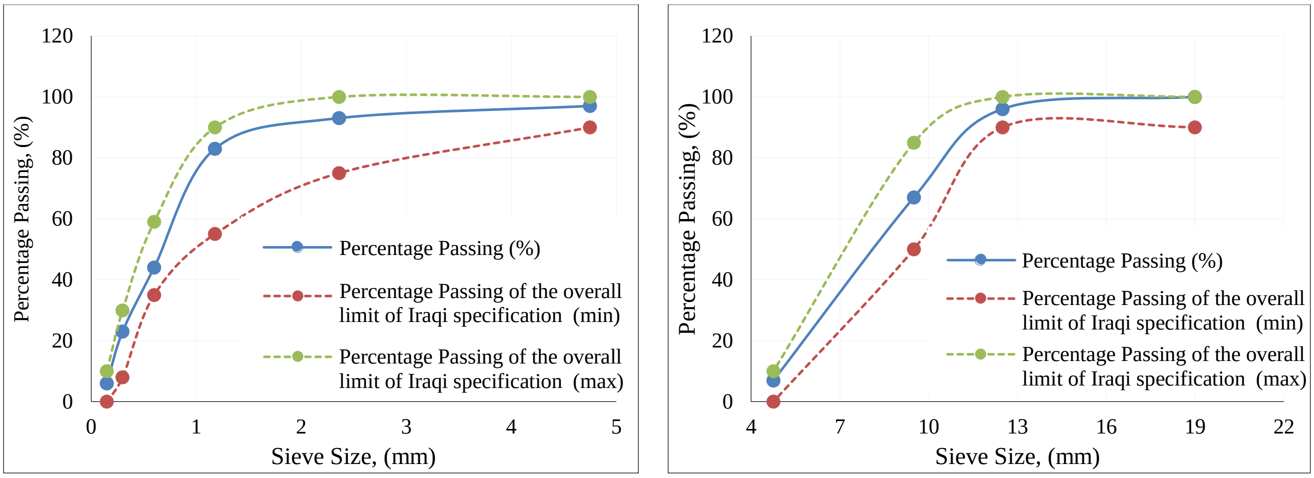


Figure 1. Sieve analysis results for fine and coarse aggregate

2.2. Designation for Specimens and Parameters for Deep Beams

To evaluate the effect of large web openings, which created in shear spans on the shear resistance of reinforced concrete deep beams, ten experimental deep beams were designed according to ACI 318M-2014 code [19] and fabricated with overall dimensions of 1500 mm clear span × 500 mm deep × 150 mm wide, respectively. Parameters which were investigated are the size of opening, position of opening and the shear span to overall depth of the member cross-section ratio. Two of those beams are control specimens, which were fabricated without openings, while the other eight specimens have large web openings in the shear spans. Two sizes for square openings were considered, mainly with 200 mm edge length or with 230 mm. The ratio of the square opening side dimension to the web depth was adopted to be 40% for specimens with 200 × 200 mm opening dimensions, and 46% specimens with 230 × 230 mm opening dimensions, which was sufficient to cause a sizeable reduction in shear capacity, since a web containing an opening of three-eighths the web depth does not reduce the strength of the specimen (ACI 426R-74 1973) [20].

Also, two locations for web opening were adopted, mainly at the center or at the interior edge of the shear span. The third parameter which considered was the (a/h) ratio, where (a) is the distance from the support to the applied concentrated load and (h) is overall depth of the member cross-section. This ratio was chosen to be 1.1 or 0.9. The designation of specimens can be explained as follows: the first two symbols (DP) indicates the deep beam specimen. The third symbol declares the shear span to depth ratio (i.e., S1 = when the ratio is 1.1 or S2 = when the ratio is 0.9). Meanwhile, the fourth symbol shows the location of the opening relative to the shear span (i.e., C = at the center or E = at the interior edge). The last symbol denotes the size of opening (i.e., O1 = 200 × 200 mm or O2= 230 × 230 mm), see Table 1 and Figures 2 and 3.

Table 1. Experimental parametric details of experimental deep beams

Beam designation	Opening location	Shear span/depth ratio (a/h)	Opening size, (*mm*)
DP-S1	-	1.1	-
DP-S1-C-O1	center of shear span	1.1	200 × 200
DP-S1-C-O2	center of shear span	1.1	230 × 230
DP-S1-E-O1	edge of shear Span	1.1	200 × 200
DP-S1-E-O2	edge of shear Span	1.1	230 × 230
DP-S2	-	0.9	-
DP-S2-C-O1	center of shear span	0.9	200 × 200
DP-S2-C-O2	center of shear span	0.9	230 × 230
DP-S2-E-O1	edge of shear Span	0.9	200 × 200
DP-S2-E-O2	edge of shear span	0.9	230 × 230

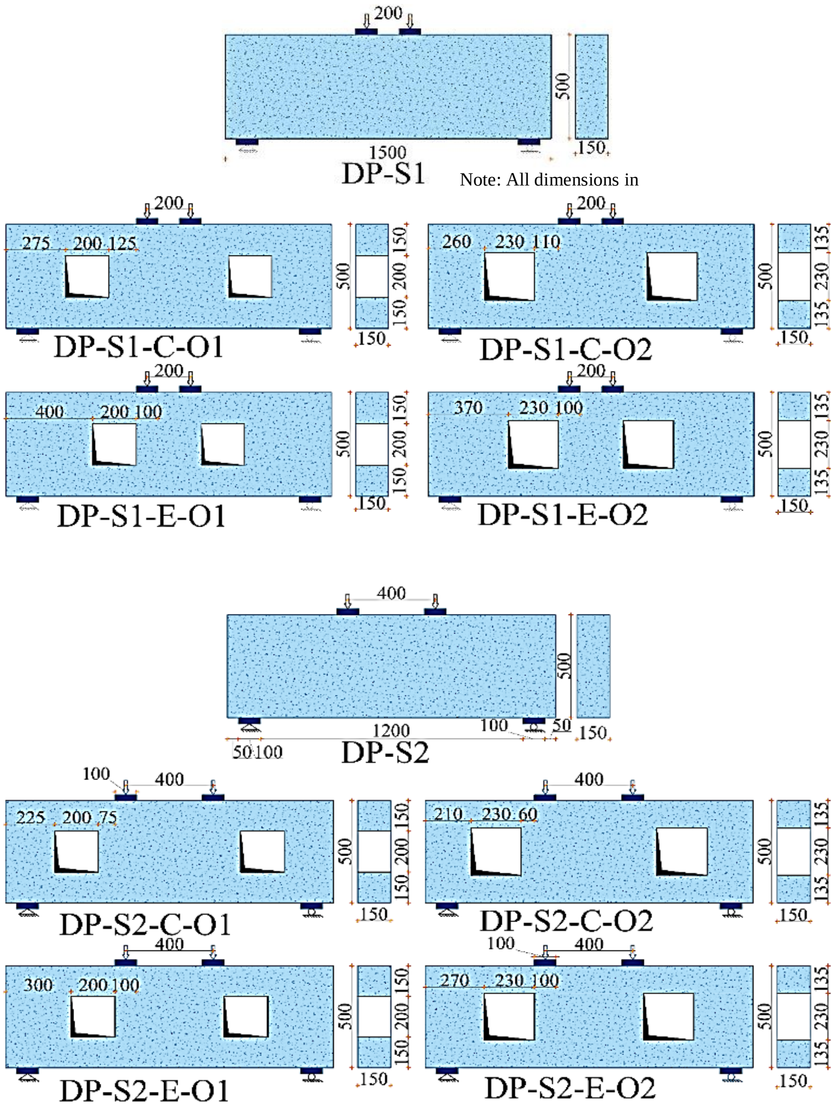


Figure 2. Configuration of experimental specimens

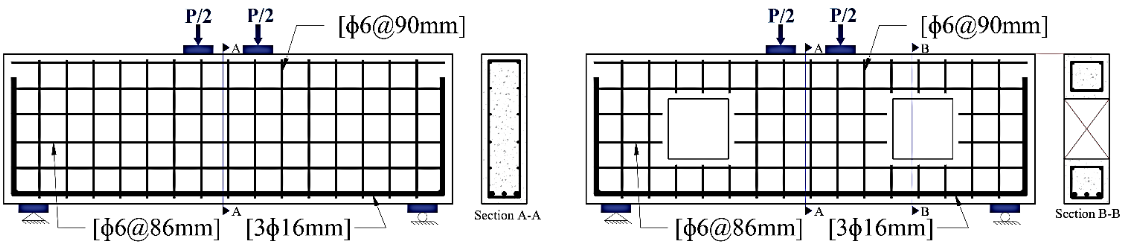


Figure 3. Reinforcement details of experimental specimens

2.3. Testing setup

All deep beams were exposed to monotonic static loading up to failure using a load control test. They were tested as simply supported beams, where one support allowed for horizontal movement and rotation only, and the second allowed for the angular movement only. The test was carried out in the Structural Engineering Laboratory at the University of Baghdad, using closed loop ram of 1000 kN capacity actuator with 10 kN measuring accuracy Figures 4 and 5, to expose the tested specimen to two symmetrical point loads with pure moment zone of 200 or 400 mm.

The tests were provided after preparing and calibrating all devices and equipment required for tests. Also, all concrete surfaces were prepared, painted with white emulsion and a mesh of 50 × 50 mm dimensions of light black lines were drawn to faciltate monitoring the crack appearance and propogation. The vertical displacement of the tested specimens was measured at midspan using mechanical dial gauge of 0.01 mm sensitivity and accuracy of 0.001 mm. The strain of concrete at compression face was recorded at each loading stage using five electrical strain gauges, type (PL-60-11-5L) of 60 mm base length, which were three of them located at midspan normal section and the other two strain gauges were distributed along the compression thrust joining the concentrated load and the reaction Figures 4 and 5. Also, the strain of steel reinforcement was measured using three strain gauges, type (FLA-6-11-5L) of 6 mm base length, which installed at midspan section on the main reinforcement and at the mid height of the section on the transverse reinforcement (stirrups) immediately before and after opening. All strain measuring devices were with resistanance of 120 Ω. All measurements, such as beam deflections, strains in concrete and steel were recorded after five minutes beyond the application of the load. Each loading stage consisted 5 kN load increment.

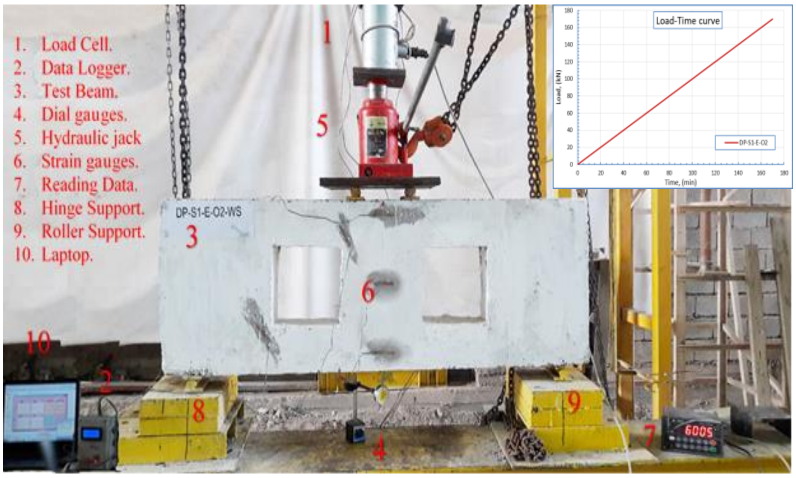


Figure 4. Testing Setup and applied load-time relationship

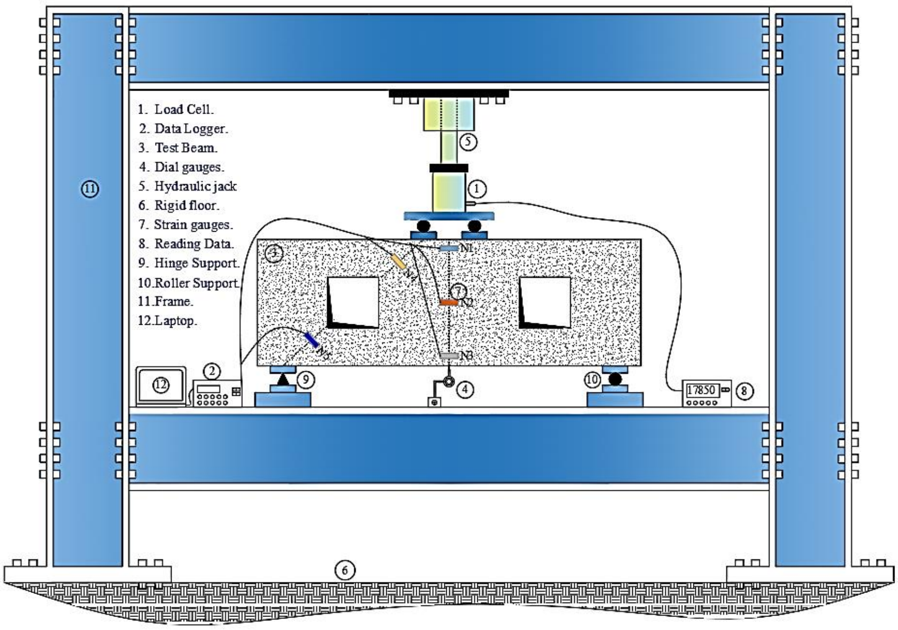


Figure 5. Schematic diagram of test setup for deep beam with large web opening

3. Test Results

3.1. Load - Deflection Response

During the test, the applied load and the midspan deflection have been recorded at each load step for each tested beam and plotted as load–midspan deflection curves. It is worth mentioning that, in all specimens three stages of behavior, during the entire loading process, have been distinguished. The first stage characterized the linear behavior of the member that reflected on the linear relationship between the applied load and the measured, at midspan, deflection value. This stage ended at the appearance of the first crack. Within this stage, materials (i.e., concrete and longitudinal steel bars) are still behave elastic and no cracks occur in the specimen. Through the second stage, diagonal and flexure cracks are initiated at the corners of openings and at the soffit of the specimens, respectively. These cracks were propagated and increased in numbers as the load progressed. Accordingly, the linear response tended to take nonlinear form where the nonlinearity was developed as the applied load increased. Finally, at the third stage, and as the load approached its maximum value, the rate of progressing of deflection attained a dramatically character. The influence of the shear span to depth ratio (a/h), the openings size and the openings location, on the mid-span deflection for all specimens is shown in Figures 6, 7 and 8 respectively.

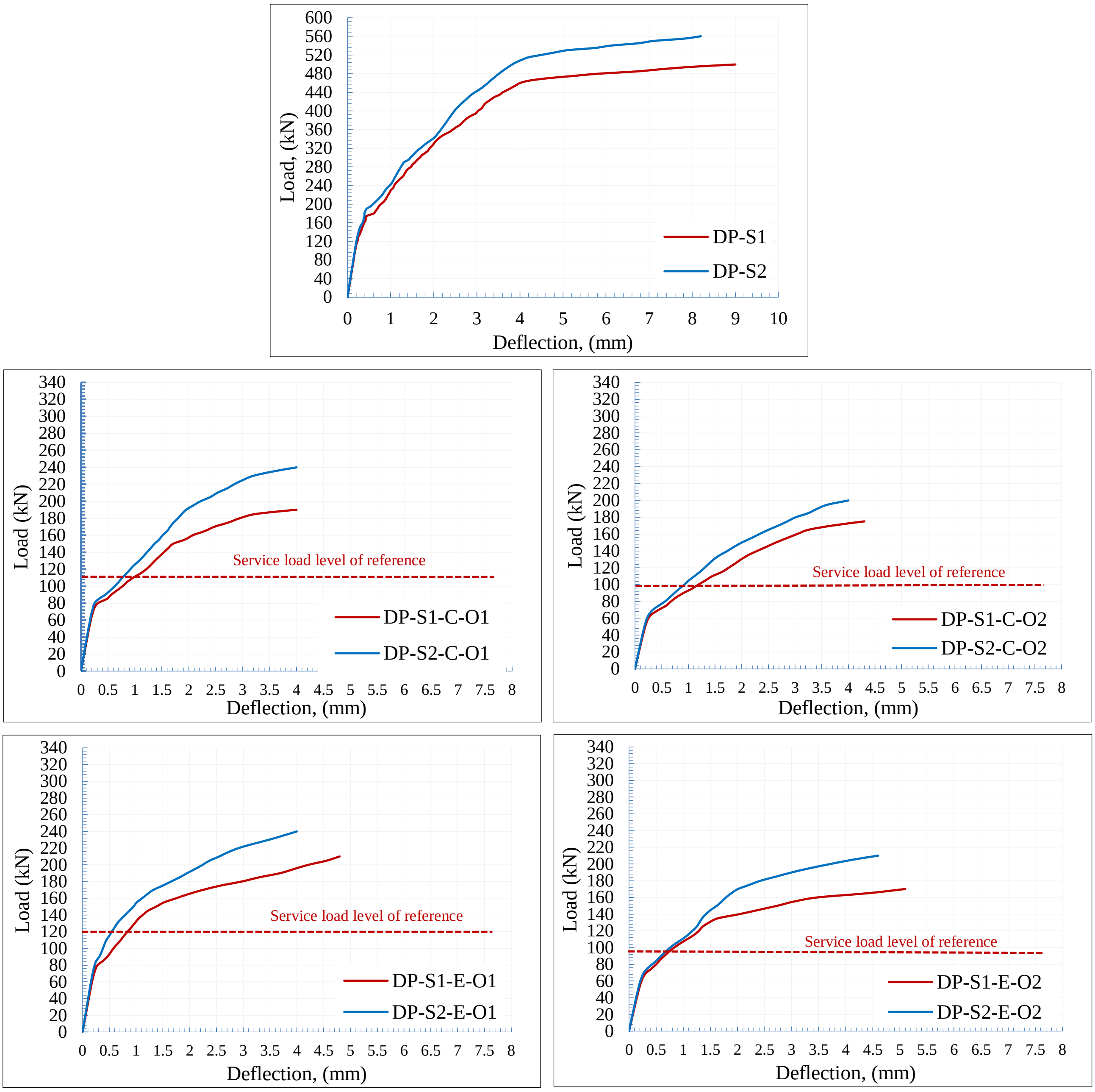


Figure 6. Influence of (a/h) ratio on the load-deflection response

Obviously from Figure 6 that, as the (a/h) ratio increased (i.e., the shear span increased) the overall stiffness of the tested specimen was more dropped down. Accordingly, at the same loading level, specimens with (a/h) equals 1.1 experienced more deflection than specimens with (a/h) of 0.9. Meanwhile, the effect of creation of openings in shear span influenced the rate of deformability of the specimen. Test results showed an increase in deflection values for specimens with openings in comparison with deep beams without openings. The increase of midspan deflections attained at ultimate service load (74% - 86%) and (67% - 85%), respectively, compared to deep beams without openings (DP-S1) and (DP-S2).

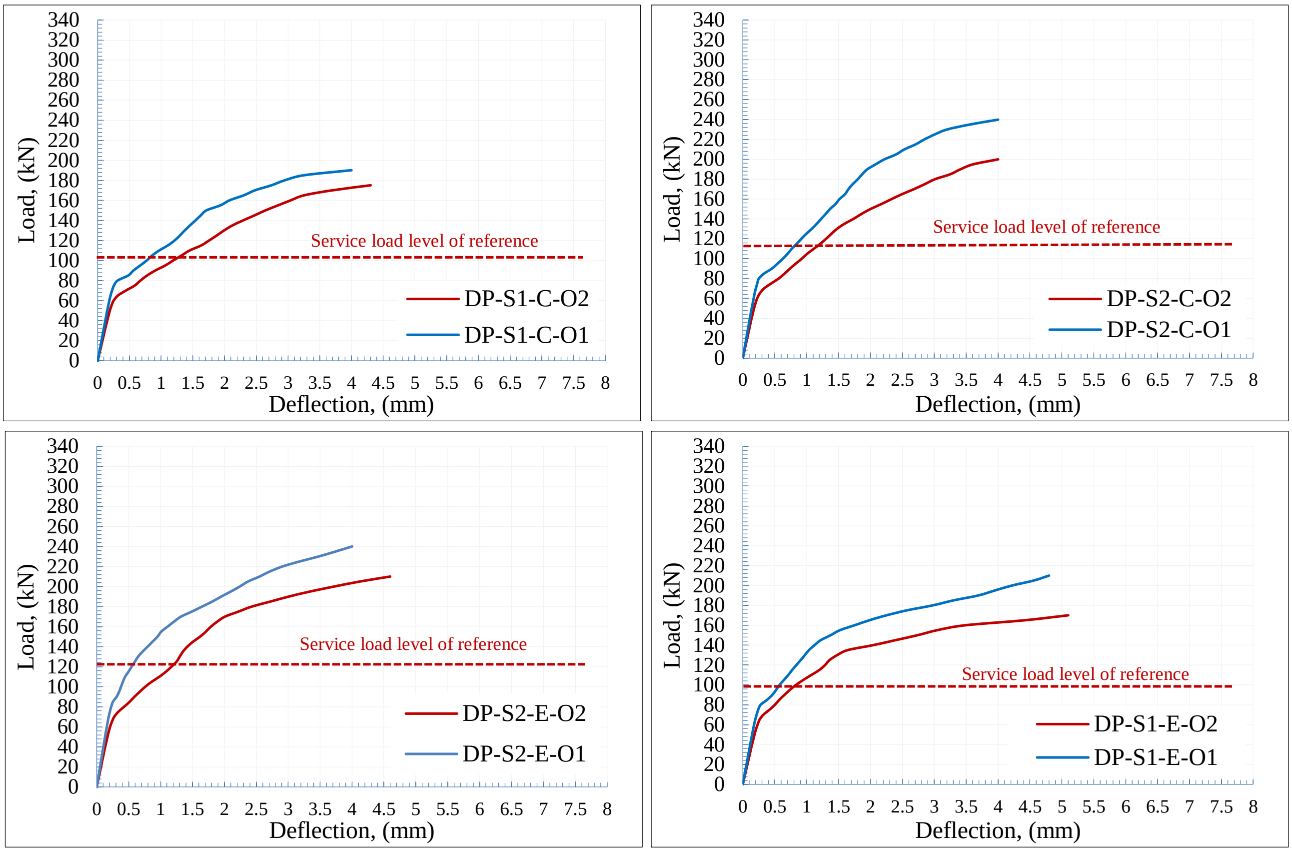


Figure 7. Influence of opening size on the load-deflection response

It is clear from Figure 7 that, the size of opening affected the performance of the tested specimen. It is worth mentioning that, the cracking and failure loads for deep beams with smaller size openings were more than the cracking and failure loads of deep beams with bigger size openings by 8% - 30% and 9% - 24%, respectively. Deep beams with smaller size openings were stiffer than speimens with bigger size openings. Obviously, from Figure 5 that, the midspan deflection at service loads for deep beams with smaller size openings was decreased by 30% -53% compared to deep beams with bigger size openings.

Less effect on the cracking load and load-midspan deflection response has the position of opening relative to the shear span. Regardless the opening was located at the center or at the interior edge of the shear span, almost the same cracking load was observed for specimens (DP-S1-C-O1) and (DP-S1-C-O1), (DP-S1-C-O2) and (DP-S1-C-O2), (DP-S2-C-O1) and (DP-S2-C-O1), also, (DP-S2-C-O2) and (DP-S2-C-O2). Figure 6 shows that, creation of an opening at the center of shear span has more impact on the midspan deflection than creation of an opening beside the interior edge of the shear span. Deep beams with openings at the center of shear spans experienced more midspan deflection at service load than beams with edge openings by 10%-33%. Meanwhile, at failure stage the midspan deflection was greater for specimens with edge openings than for specimens with openings at the center of shear span by approximately 20%. This behavior can be argumented by the fact that, the load carrying capacity for beams with edge opening was almost exceeding the capacity of the beams with openings located at the center of the shear spans, see Figure 8.

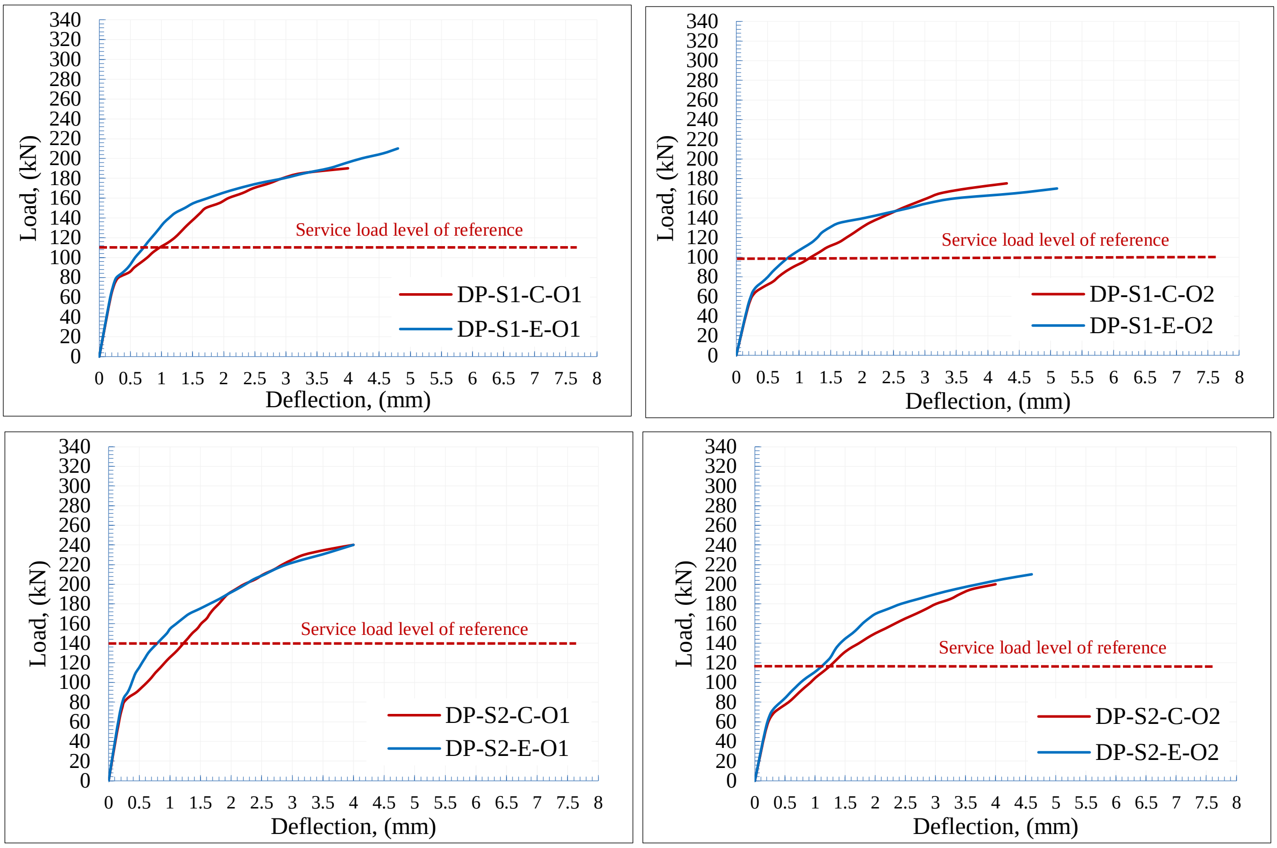


Figure 8. Influence of opening position on the load deflection response

3.2. Strain in Longitudinal Steel Bars

Normal strain in longitudinal steel bars have been recorded during the process of testing for all deep beams using data logger. These records were based on data collected from strain gauge which fixed on the steel bar at the midspan section. It is clear from Figures 9 and 10 and Table 2, that there was a reduction in the normal strains of the main steel bars of deep beam with large web opening compared to those of deep beams without openings. This decrease can be interpreted by the fact that, due to the presence of web openings the load carrying capacity for beams with openings in shear spans was less than the capacity of solid deep beams. Obviously, the normal strain in longitudinal steel bars was considerably affected by the presence of such openings.

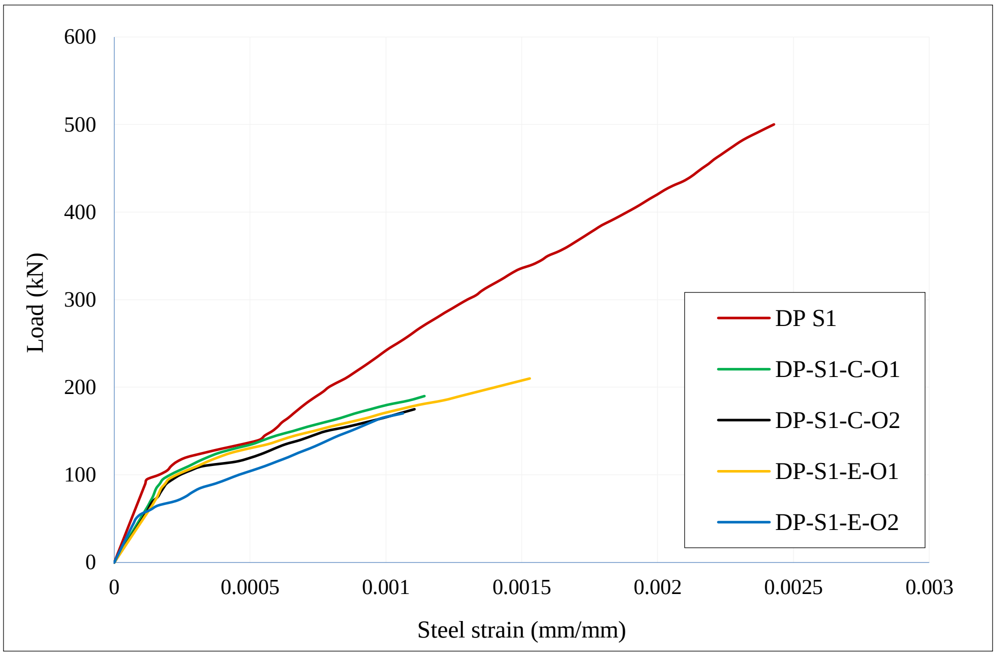


Figure 9. Load – normal strain of longitudinal steel bar curves for (DP-S1-C-O1), (DP-S1-C-O2), (DP-S1-E-O1), (DP-S1-E-O2) compared with (DP-S1)

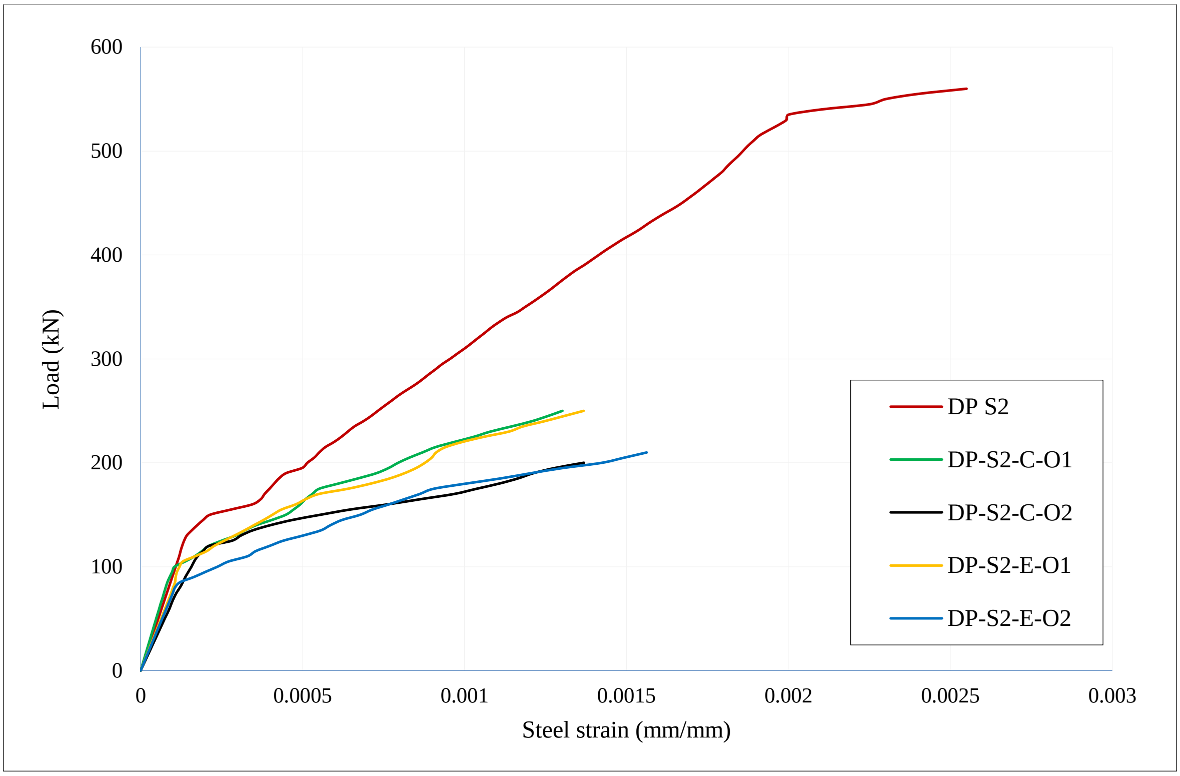


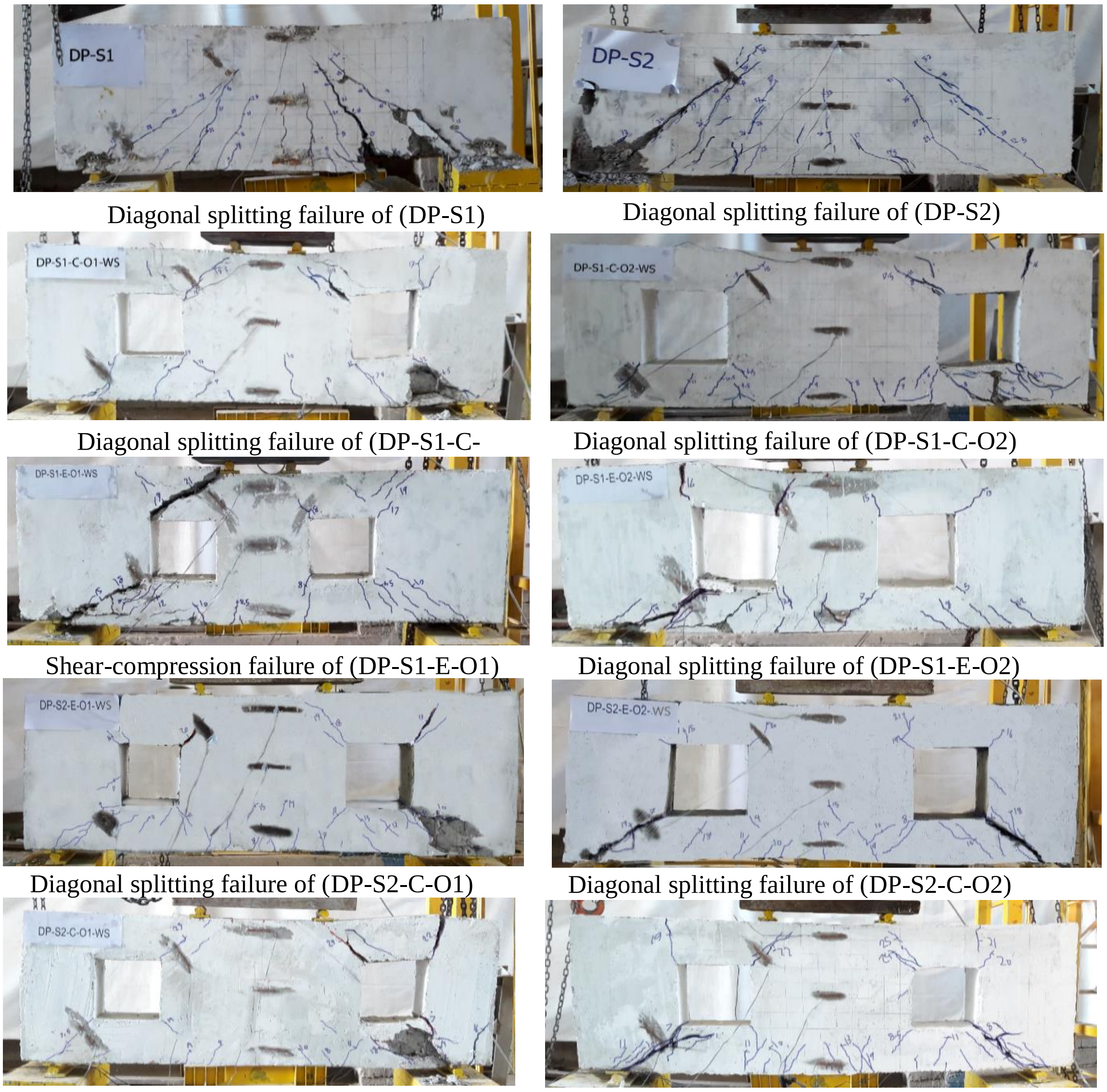
Figure 10. Load – normal strain of longitudinal steel bar curves for (DP-S2-C-O1), (DP-S2-C-O2), (DP-S2-E-O1), (DP-S2-E-O2) compared with (DP-S2)

Table 2. Normal strain in longitudinal steel bars at failure stage for all tested beams

Specimen designation	Failure load, (*kN*)	Normal strain in longitudinal steel bar x 10^{-6}	Change in normal strain, (%`)
DP-S1	500	2428.45	Reference
DP-S1-C-O1	190	1141.49	53
DP-S1-C-O2	175	1104.74	55
DP-S1-E-O1	210	1529.02	37
DP-S1-E-O2	170	1062.93	56
DP-S2	560	2550.00	Reference
DP-S2-C-O1	240	1302.36	49
DP-S2-C-O2	200	1368.27	46
DP-S2-E-O1	250	1368.00	46
DP-S2-E-O2	210	1562.89	39

3.3. Modes of Failure of Experimental Deep Beams

In all tested deep beams diagonal cracks, at the corner of web opening, were formed firstly. With further increase in the applied load, flexure cracks and another diagonal cracks below and above the openings were appeared. Also, the diagonal cracks were propagated in the direction toward the bearing plate under the applied concentrated load and then back towards the supports. Almost, diagonal cracks caused the failure of the tested specimens. Two different modes of failure were observed mainly, diagonal splitting failure, which was happened when the diagonal cracks at the corner of the web openings developed and moved toward the applied load and then extended back toward the supports and shear-compression failure, which was happened after diagonal cracks propagation in shear spans causing high strains that developed in the compression zone above the web opening near the point load see Figure 11.



Diagonal splitting failure of (DP-S1) Diagonal splitting failure of (DP-S2)

Diagonal splitting failure of (DP-S1-C- Diagonal splitting failure of (DP-S1-C-O2)

Shear-compression failure of (DP-S1-E-O1) Diagonal splitting failure of (DP-S1-E-O2)

Diagonal splitting failure of (DP-S2-C-O1) Diagonal splitting failure of (DP-S2-C-O2)

Shear-compression failure of (DP-S2-E-O1) Diagonal splitting failure of (DP-S2-E-O2)

Figure 11. Crack pattern at failure stage for all tested deep beams

4. Effect of Different Test Variables

The main goal of the present research study is to investigate the effect of creation large web opening in shear spans of reinforced concrete deep beams on their strength and performance during the exposure to monotonic static loading. To achieve this goal, three parameters were considered, as mentioned previously, the size of opening, position of opening and the shear span to overall depth of the member cross-section ratio (a/h).

All experimental deep beams were subjected to two-point monotonic static loading up to failure with load increment of 5 kN. First cracking load, load-midspan deflection response, failure load, failure mode, and crack pattern have been monitored and recorded at each applied load stage.

4.1. Effect of Inducing Openings in Deep Beams on Strength and Cracking Resistance

Table 3 demonstrates the influence of inducing openings in shear spans on the behavior and capacity of reinforced concrete deep beams. Obviously, the first diagonal cracking, the first flexural cracking and the failure loads of the deep beams with large web openings in shear spans were lower than that of the reference solid deep beam. As the opening dimensions increased the dropping in the load capacity was increased. Also, as the shear span to overall depth of the member cross-section ratio (a/h) increased the degradation in the load capacity was increased. Thus comparing with solid deep beams without openings, the maximum dropping in the load capacity may attain 66%.

It is interesting to note that, almost creation of openings at the center of shear spans in deep beams resulted in more dropping in the failure load compared to specimens with openings at the interior edges of the shear spans. Meantime in comparison with reference solid beams, it was observed that the maximum decrease in the first diagonal and first flexural cracking load values were 58% and 56%, respectively. This evidence concluded the fact of the serious degradation of the strength and the cracking resistance of reinforced concrete deep beams.

It is worth also mentioning that, the overall stiffness and deformability of the reinforced concrete deep beams with openings in shear spans was dramatically dropped after the occurrence of diagonal and flexural cracks in comparison with solid deep beams. Thus, comparatively the midspan section deflection was larger in these specimens.

Table 3. First cracking load, failure load and deflection for experimental deep beams

Specimen designation	First diagonal cracking load, *(kN)*	Decreasing of first diagonal cracking load, *(%)*	First flexural cracking load, *(kN)*	Decreasing of first flexural cracking load, *(%)*	Failure load, *(kN)*	Decreasing of failure load, *(%)*	Deflection at service load, *(mm)*	Deflection at ultimate load, *(mm)*
DP-S1	120	Ref.	135	Ref.	500	Ref.	1.68	9
DP-S1-C-O1	60	50	65	52	190	62	1.10	4
DP-S1-C-O2	55	54	60	56	175	65	1.32	4.3
DP-S1-E-O1	65	46	80	41	210	58	0.88	4.8
DP-S1-E-O2	50	58	70	48	170	66	0.93	5.1
DP-S2	125	Ref.	145	Ref.	560	Ref.	2.25	8.2
DP-S2-C-O1	70	44	80	45	240	57	1.30	4
DP-S2-C-O2	65	48	70	52	200	64	1.31	4
DP-S2-E-O1	70	44	85	41	250	55	0.95	4
DP-S2-E-O2	60	52	80	45	210	63	1.26	4.6

4.2. Effect of (a/h) Ratio on Strength, Cracking Resistance and Deformability of Deep Beams with Large Openings

Table 4 focuses on the demonstration of the effect of the ratio of the shear span to overall depth of the member cross-section (a/h). It is worth mentioning that, this ratio was affected inversely the strength of the structural member at different stages of its exploitation. Based on the gathered test results it can be concluded that, as (a/h) ratio increased the first diagonal cracking, the first flexural cracking and the failure loads decreased. Accordingly, as the (a/h) ratio decreased from 1.1 to 0.9 the first diagonal cracking load was increased by 8%-20%, also, the first flexural cracking load was enhanced by (7%-23%), and the failure load was improved by 14%-26%. If consider the beams with (a/h) ratio of 1.1 as reference beams, it is interesting to note that, the midspan deflection at service load level of the reference beam in specimens with (a/h) ratio of 0.9 was less than the midspan deflection of reference beams by 11% - 33%. This important evidence confirms the riskiness of enlargement of (a/h) ratio in structural concrete deep beams with large openings which created in shear spans.

Table 4. Effect of (a/h) ratio on strength, cracking resistance and deflection of deep beams with large openings

Specimen designation	Shear span/depth ratio (a/h)	First diagonal cracking load, *(kN)*	Change in first diagonal cracking load, *(%)*	First flexural cracking load, *(kN)*	Change in first flexural cracking load, *(%)*	Failure load, *(kN)*	Change in failure load, *(%)*	Deflection at service load level of reference beam, *(mm)*	Change in deflection at Service load level of reference beam, *(%)*	Deflection at failure load, *(mm)*
DP-S1-C-O1	1.1	60	Ref.	65	Ref.	190	Ref.	1.1	Ref.	4
DP-S2-C-O1	0.9	70	+17	80	+23	240	+26	0.8	-27	4
DP-S1-C-O2	1.1	55	Ref.	60	Ref.	175	Ref.	1.32	Ref.	4.3
DP-S2-C-O2	0.9	65	+18	70	+17	200	+14	1	-24	4
DP-S1-E-O1	1.1	65	Ref.	80	Ref.	210	Ref.	0.88	Ref.	4.8
DP-S2-E-O1	0.9	70	+8	85	+7	250	+20	0.59	-33	4
DP-S1-E-O2	1.1	50	Ref.	70	Ref.	170	Ref.	0.93	Ref.	5.1
DP-S2-E-O2	0.9	60	+20	80	+14	210	+24	0.83	-11	4.6

4.3. Effect of Opening Size on Strength, Cracking Resistance and Deformability of Deep Beams

The evaluation of data gathered from experimental tests and illustrated in Table 5 shows the importance of limiting the dimensions of the created openings in shear spans of the structural concrete deep beams. Obviously, the strength and serviceability of such members are dramatically affected by the size of openings. Based on the test data it can be concluded that, as the edge length of the square opening decreased from 230 to 200 mm the first diagonal cracking, the first flexural cracking and the failure loads were increased by 8% - 30%, 6% - 14% and 9% - 24% respectively.

If consider the beams with openings in shear spans of 230 × 230 mm dimensions as reference specimens, it is worth to observe that, the midspan deflection at service load level of the reference beam in specimens with 200 × 200 mm opening dimensions was considerably less than the midspan deflection of reference specimens by 30% - 53%. This fact confirms the importance of limiting the size of openings to reserve the overall stiffness of the structural concrete deep beams.

Table 5. Effect the opening size on strength, cracking resistance and deflection of deep beams

Specimen designation	Opening size, *(mm)*	First diagonal cracking load, *(kN)*	Change in first diagonal cracking load, *(%)*	First flexural cracking load, *(kN)*	Change in first flexural cracking load, *(%)*	Failure load, *(kN)*	Change in failure load, *(%)*	Deflection at service load level of reference beam, *(mm)*	Change in deflection at Service load level of reference beam, *(%)*	Deflection at failure load, *(mm)*
DP-S1-C-O2	230x230	55	Ref.	60	Ref.	175	-	1.32	Ref.	4.3
DP-S1-C-O1	200x200	60	+9	65	+8	190	+9	0.81	-39	4.0
DP-S1-E-O2	230x230	50	Ref.	70	Ref.	170	-	0.93	Ref.	5.1
DP-S1-E-O1	200x200	65	+30	80	+14	210	+24	0.61	-34	4.8
DP-S2-C-O2	230x230	65	Ref.	70	Ref.	200	-	1.31	Ref.	4
DP-S2-C-O1	200x200	70	+8	80	+14	240	+20	0.92	-30	4
DP-S2-E-O2	230x230	60	Ref.	80	Ref.	210	-	1.26	Ref.	4.6
DP-S2-E-O1	200x200	70	+17	85	+6	250	+19	0.59	-53	4

4.4. Effect of Opening Location on Strength, Cracking Resistance and Deformability of Deep Beams

Another scenario can be seen by investigating Table 6, which described the comparison between experimental specimens depending on the location of openings in shear spans (i.e., at the center or adjacent to the interior edge of shear span). It is clear that, this parameter has less effect on the performance of structural concrete deep beams with openings in shear span at different exploitation stages. Slight increase in load capacity during failure stage was fixed in specimens with openings adjacent to the interior edges of shear spans. In comparison with specimens with openings at the center of shear span, this increase was not exceed 11%. The interpretation of this increase can be relied to the fact that the solid part of the load path, which is connected the applied concentrated load and the reaction force, is greater in case when the opening is adjacent to the interior edge of the shear span than in case when the opening is located at the center of shear span (i.e., the discontinuity of the load path is less).

Due to the same reason the first flexural cracking load in these deep beams was exceed that for specimens with opening at the center of shear span by 6% - 23%. It should be mentioned that, almost the first diagonal crack appeared earlier in specimens with openings adjacent to the interior edge of shear span approximately by 8%. If consider the beams with openings at the center of shear spans as reference specimens, it is very useful to pay attention to the fact that, the midspan deflection at service load level of the reference beam in specimens with openings adjacent to interior edge of shear spans was less than the midspan deflection of reference specimens by 10% - 33%. Evaluating all these advantages facilitates to recommend, if it is very required, the creation of openings at the interior edges of shear spans of the structural concrete deep beams.

Table 6. Effect of opening location on strength, cracking resistance and deflection of deep beams

Specimen designation	Opening location	First diagonal cracking load, (*kN*)	Change in first diagonal cracking load, (%)	First flexural cracking load, (*kN*)	Change in first flexural cracking load, (%)	Failure load, (*kN*)	Change in failure load, (%)	Deflection at service load level of reference beam, (*mm*)	Change in deflection at Service load level of reference beam, (%)	Deflection at failure load, (*mm*)
DP-S1-C-O1	C	60	Ref.	65	Ref.	190	Ref.	1.1	Ref.	4.0
DP-S1-E-O1	E	65	+8	80	+23	210	+11	0.78	-29	4.8
DP-S1-C-O2	C	55	Ref.	60	Ref.	175	Ref.	1.32	Ref.	4.3
DP-S1-E-O2	E	50	-9	70	+17	170	-3	0.96	-27	5.1
DP-S2-C-O1	C	70	Ref.	80	Ref.	240	Ref.	1.30	Ref.	4
DP-S2-E-O1	E	70	0	85	+6	250	+4	0.87	-33	4
DP-S2-C-O2	C	65	Ref.	70	Ref.	200	Ref.	1.31	Ref.	4
DP-S2-E-O2	E	60	-8	80	+14	210	+5	1.18	-10	4.6

5. Conclusions

Based on the gathered experimental data and the evaluation process for different test variables, the following conclusions can be presented:

- It was observed that, after the appearance of cracking the degradation of the stiffness of structural concrete deep beams with opening was highly depending on the ratio of the shear span to overall depth of the member cross-section (a/h). Gathered test data showed an increase in deflection values for specimens with openings in comparison with deep beams without openings. The increase of midspan deflections attained at ultimate service load 74%-86% and 67%-85%, respectively, compared to deep beams without openings DP-S1 and DP-S2.

- Structural concrete deep beams with smaller openings located in shear spans showed stiffer behavior, at load stages beyond the cracking level, than deep beams with larger openings. The midspan deflection at service loads for deep beams with smaller size openings was decreased by 30%-53% compared to deep beams with bigger size openings.

- Deep beams with openings at the center of shear spans experienced more midspan deflection at serviceability stage than beams with edge openings by 10%-33%. While, at failure stage the midspan deflection was greater for specimens with edge openings than for specimens with openings at the center of shear span by approximately 20%.

- Clear reduction in the values of the first diagonal cracking, the first flexural cracking and the failure loads of the deep beams with large web openings located in shear spans compared to those of the reference solid deep beams. This reduction attained 58%, 56%, and 66% respectively.

- As the (a/h) ratio decreased from 1.1 to 0.9 the first diagonal cracking, the first flexural cracking, and the failure loads were increased by 8%-20%, 7%-23% and 14%-26% respectively. Also, the midspan deflection at service load level of the reference beam in specimens with (a/h) ratio of 0.9 was less than the midspan deflection of reference beams by 11%-33%. This important evidence confirms the riskiness of enlargement of (a/h) ratio in structural concrete deep beams with large openings which created in shear spans.

- As the edge length of the square opening decreased from 230 to 200 mm the first diagonal cracking, the first flexural cracking and the failure loads were increased by 8%-30%, 6%-14% and 9%-24% respectively. Also, the midspan deflection at service load level of the reference beam in specimens with 200 × 200 mm opening dimensions was considerably less than the midspan deflection of reference specimens by 30%-53%. This fact confirms the importance of limiting the size of openings to reserve the overall stiffness of the structural concrete deep beams.

- It is clear that, the position of opening in shear span has less effect on the performance of structural concrete deep beams at different serviceability stages. Only 11% increase in load capacity at failure was observed in specimens with openings adjacent to the interior edges of shear spans in comparison with specimens with openings at the center of shear span because the discontinuity of the load path is less. Also, the midspan deflection at service load level of the reference beam in specimens with openings adjacent to interior edge of shear spans was less than the midspan deflection of reference specimens by 10%-33%. Evaluating all these advantages facilitates to recommend, if it is very required, the creation of openings at the interior edges of shear spans of the structural concrete deep beams.

- The normal strain in longitudinal steel bars was decreased in the deep beams with large web openings in shear spans compared to main bars in deep beam without opening .The maximum observed reduction was 56% due to the fact that, the load carrying capacity of beams with openings in shear spans was less than the capacity of solid deep beams.

- All tested reinforced concrete deep beams with or without large web openings in shear spans were failed by shear. The shear failure took place by diagonal splitting and shear-compression failure modes.

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7. Conflicts of Interest

The authors declare no conflict of interest.

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