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Effect of Size and Location of Square Web Openings on the Entire Behavior of Reinforced Concrete Deep Beams

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Abstract

This paper presents an experimental and numerical study which was carried out to examine the influence of the size and the layout of the web openings on the load carrying capacity and the serviceability of reinforced concrete deep beams. Five full-scale simply supported reinforced concrete deep beams with two large web openings created in shear regions were tested up to failure. The shear span to overall depth ratio was (1.1). Square openings were located symmetrically relative to the midspan section either at the midpoint or at the interior boundaries of the shear span. Two different side dimensions for the square openings were considered, mainly, (200) mm and (230) mm. The strength results proved that the shear capacity of the deep beam is governed by the size and location of web openings. The experimental results indicated that the reduction of the shear capacity may reach (66%). ABAQUS finite element software program was used for simulation and analysis. Numerical analyses provided un-conservative estimates for deep beam load carrying capacity in the range between (5-21%). However, the maximum scatter of the finite element method predictions for first diagonal and first flexural cracking loads was not exceeding (17%). Also, at service load the numerical of midspan deflection was greater than the experimental values by (9-18%).

Keywords: Deep Beam; Large Openings; Shear Span; Abaqus.

1. Introduction

Deep beams are important construction elements that are often used in foundations, water tanks, beams in multi-story buildings, etc. Almost, reinforced concrete deep beams are extensively used in bridges and naval structures. Creation of openings in this type of structural members is frequently required for the passage of utility ducts. It is well known that the creation of openings in the web of reinforced concrete deep beam affects the loading carrying capacity, specifically shear resistance. Principally, the shear capacity of reinforced concrete deep beams is much greater than that of shallow beams. This is due to the tied-arch action in which the externally applied load is transmitted to the support by the diagonal concrete strut. Accordingly, the effect of concrete compressive strength becomes more significant for the shear strength of deep beams. The shear strength of deep beams was found to be effected by the value of the principal tensile strain of the diagonal concrete strut [1-4].

Mansur and Tan (1996) [1] were classified the web openings in reinforced concrete beams into two categories (small and large openings). 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

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were conducted to determine the effect of openings on the shear resistance of deep beams [2-4]. Al-Khafaji et al., (2014) [5] conducted an experimental study on eight simply supported reinforced self-compacting concrete deep beams under static two-point load. Authors focused on the shear span to effective depth ratio (a/d) as main variable in their work. Results of the aforementioned study indicated that, increasing shear span to effective depth ratio from (0.6) to (1.0) led to reduction in the values of the first cracking and failure loads by (28.6%) and (23.3%), respectively. Al-Bayati, et al., (2016) [6] investigated eleven simply supported reinforced self-compacting concrete deep beams subjected to two-point load to study the influence of circular web openings on the performance and response of deep beams. Variables which were investigated include the size and position of opening, the area of the transverse inclined reinforcement around openings and the shear span to effective depth ratio (a/d). In this research, all specimens had similar overall dimensions, flexural reinforcement, and concrete compressive strength. The results of the experimental analysis revealed that, when opening was positioned at the center of the shear span, the behavior of the beams was significantly affected regardless the value of the (a/d) ratio and the opening size. Also it was found that, the cracking and ultimate loads were dramatically reduced due to the creation of web openings. Grande et al., (2008) [7] and Sayed et al., (2013) [8] 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) [9] investigated the behavior of reinforced concrete beams, where the adopted variables the value of the (a/d) ratio, which ranged between (1.0) and (3.5). The specimens were strengthened by FRP strips around the shear span. Twelve specimens were tested up to failure, six of which were un-strengthened, and the other six were strengthened 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). Li et al., (2015) [9] mentioned that, the design guidelines for the fiber-reinforced polymer for strengthening reinforced concrete structures may exceed the shear-strengthening effectiveness at low (a/d) ratios, therefore they have to be used with caution.

Hawileh et al., 2012 [10] used the nonlinear finite element software ANSYS, to examine (12) reinforced concrete deep beams with web openings which strengthened in shear with (CFRP) composite sheets. The variables were: the location, size of web opening and the method of strengthening (parallels and around) the web openings. Web opening locations were varied at top (near loading point), the middle, and bottom (near support) of the deep beam. The considered sizes of opening were (200×200) mm, (250×250) mm and (150×150) mm. The proposed strengthening patterns were around strengthening (around the opening) and parallel strengthening (above and below the web opening). Two-point load and same reinforcement details were used for all tested beams. It was found that the around web opening strengthening method was considerably increased the ultimate load than the horizontal strengthening. Compared to beam without strengthening, the percentage of increase in ultimate load – carrying capacity was (74%).

Kassim et al., 2015 [11] implemented nonlinear finite element software (ANSYS) to examine ten reinforced concrete deep beams with single large web opening under one point loading. These beams were strengthened by using CFRP sheets except one which was referred as a reference beam (i.e., beams without strengthening). The dimension of single web opening was (381×381) mm and located near the left support of the beam. The considered variables were the CFRP sheets configuration and their thickness. The CFRP sheets configuration was vertical, horizontal and (U) type configuration. These CFRP sheets were varied in thickness which were (0.7, 1.4 and 2.8) mm. They found that the percentage of increasing in the ultimate load compared to the reference beam was (26, 53 and 59 %), (55, 78 and 90 %) and (86, 92 and 97%) for vertical, horizontal and (U) type configurations of CFRP sheets thickness of (0.7, 1.4 and 2.8) mm, respectively.

Due to the complexity of behavior for reinforced concrete deep beam, Akinpelu et al., 2018 [12] suggested analyze these type of structural concrete members based on a simplified approximated method. The complexity is rising from numerous parameters that affecting the response during exploitation. To evaluate some of these parameters, finite element study of the structural behavior of reinforced self-compacting concrete deep beam was conducted using ABAQUS finite element modeling tool. Concrete compressive strength, vertical web reinforcement ratio and horizontal web reinforcement ratio were used as parametrical factors to investigate their influence on the performance of deep beams. Eight different deep beams were tested under four point loads. Between the three investigated parameters, almost the concrete compressive strength showed to be the most powerful parameter that affected the beams' behavior. An average of (41.1%) and (49%) improvement in the diagonal cracking and failure loads, respectively, was attained due to the doubly increasing in the concrete compressive strength. However, increasing the horizontal web reinforcement ratio from (0.31%) to (0.63 %) led to an average increase of (6.24%) for the diagonal cracking load, while, the failure load and the load-deformability of the beams were not affected. Meanwhile, the variation in vertical web reinforcement ratio resulted in average of (2.4%) and (15%) increasing in the cracking and load carrying capacity, respectively, with no considerable change in the deformability response.

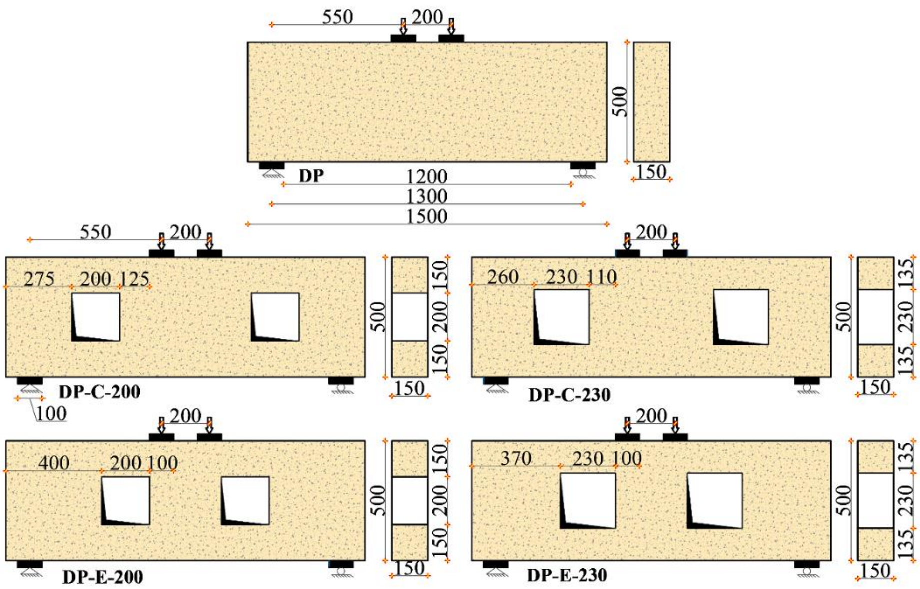
Tseng et al., 2017 [13] proposed an analytical method to predict the shear capacity of reinforced concrete deep beams with web openings. The goal of the proposed method was to define the shear-transfer paths based on the strut-and-tie method. According to the stiffness ratios, authors proposed to distribute the shears between the transfer paths which existed above and below the web openings. The suggested method has the ability to predict different modes of failure, including crushing of concrete, yielding of steel, and splitting of concrete. Parameters which included in this study were compressive strength of concrete strengths, reinforcement ratio, span-depth ratio, and sizes and positions of web openings. The comparison of results indicated that the proposed method can rationally evaluate the shear strength of reinforced concrete deep beams with web openings.

2. Characteristics of Experimental Specimens

The experimental program was carried out on five simply supported reinforced concrete deep beams with two large web openings originated in shear regions. The experimental beams include one solid specimen which was used as a reference deep beam while the other four beams were with square openings located either at the middle or at the interior edge of the shear span. These two openings were placed symmetrically relative to the midspan section of the deep beam. Parameters which were studied involved the size and positions of openings in shear span. Two different side dimensions for the square openings were considered, mainly, (200) mm and (230) mm. All deep beams had rectangular cross-sectional dimensions of (150) mm x (500) mm and a total length of (1500) mm. The effective span during testing was considered to be (1300) mm including two shear spans each of (550) mm, accordingly, the shear span to overall depth ratio was used to be (1.1). The ratio of the opening side dimension to the web depth was adopted to be (40%) and (46%) for specimens with square opening of (200x200) mm and (230x230) mm dimensions, respectively. In this study, both square openings were treated as large opening because their dimensions were sufficient to introduce sizeable reduction in shear strength, since a web containing an opening of three-eighths the web depth does not result in strength degradation of the beam (ACI 426R-74 1973) [14]. Table 1 shows the parametric details of the tested deep beams, where the symbols D and P indicate deep beam, respectively and the subsequent symbol C or E denotes opening at the center or interior edge of the shear span, respectively. The last digit following the symbols represents the side dimension of the square opening. Schematic representation for the configuration of the tested specimens and the arrangement of reinforcement bars for the reference beam and the reinforced concrete deep beam with square web opening are shown in Figures 1 and 2.

Table 1. Experimental parametric details of experimental deep beams

Beam designation	Opening location	Opening size, (*mm*)
DP	Solid without opening	-
DP-C-200	center of shear region	200×200
DP-E-200	edge of shear region	
DP-C-230	center of shear region	230×230
DP-E-230	edge of shear region	



(All dimensions are in mm)

Figure 1. Configuration of experimental specimens

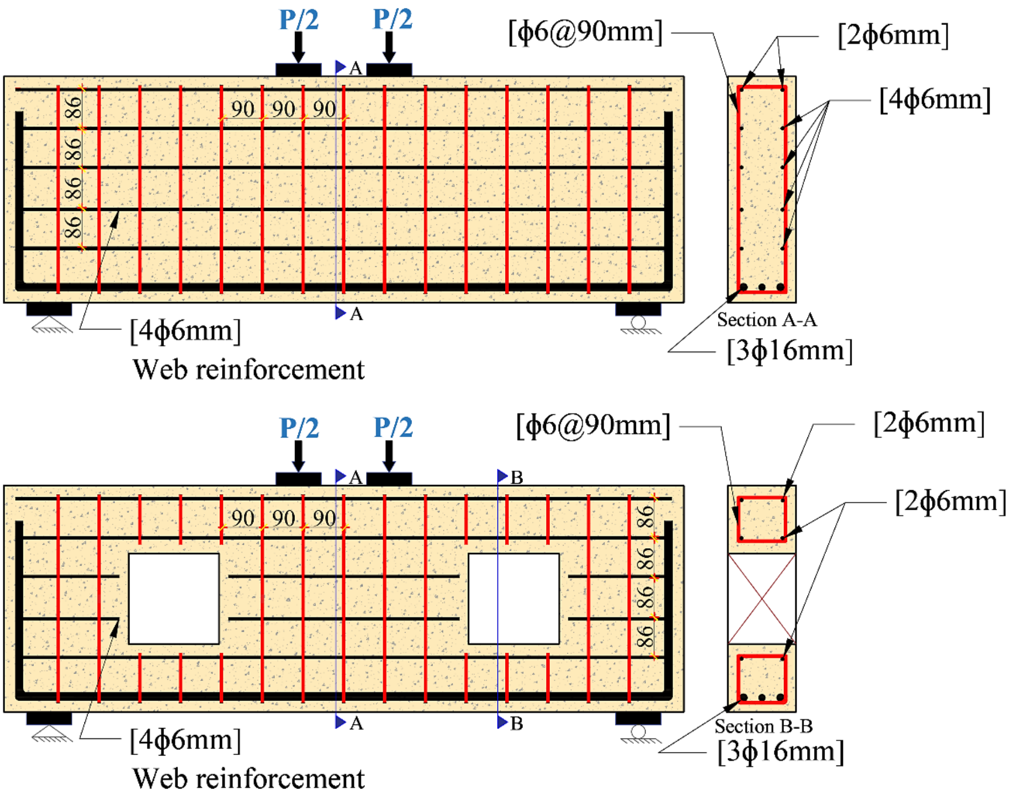


Figure 2. Reinforcement details of experimental specimens

3. Material Properties

All deep beams were designed according to ACI 318M-2014 code [15]. Beams initially were designed in such a way that shear failure will be attained prior to any flexural collapses. To achieve the uniformity of concrete strength, all tested beams were fabricated using the same batch of concrete. The beams were cast in plywood formworks (Figure 3). After one day, the specimens were removed from the formworks and cured for (28) days using wetted bags from gunny materials. Ordinary Portland cement (Type I) was used in the present study. Cement was tested chemically and physically according to the Iraqi specifications [I.O.S. 5/1984] [16] and [ASTM C150] [17] for Portland cement. Fine sand and graded crushed gravel of 10 mm maximum size were used in this experimental program. Their test results were complying with the Iraqi specification [No. 45/1984] [18] and [ASTM C33] [19]. By weight the aggregate: sand: cement proportion was (2.70: 1.13: 1.00) with a high water/cement ratio of (0.62). Three concrete cylinders with (150x300) mm were prepared from fresh mix for each deep beam to assess the concrete compressive strength at (28) days age. These cylinders were tested according to [ASTM C39-86 2002] [20], where the average compressive strength was found to be (27) MPa. The flexural reinforcement in tension and compression zones of the normal section consisted of 3Ø16 mm and 2Ø6 mm deformed steel bars, respectively. Perpendicular and parallel to the longitudinal axis of the specimen web reinforcement of Ø6 mm deformed bars was provided at (90) mm and (86) mm center-to-center spacing, respectively. For shear reinforcement, ∅6 mm steel bars were bent up to have the required stirrups configuration. To determine the mechanical properties, steel bars were tested according to [ASTM A615/A615M-16] [21]. Accordingly, for each diameter three bar pieces, of (500) mm length, were exposed to uniaxial tension in the Consulting Engineering Bureau/College of Engineering/University of Baghdad. Findings from these tests are given in (Table 2).

Table 2. Mechanical properties of steel reinforcement

Nominal diameter, *(mm)*	Measured diameter, *(mm)*	Area, *(mm²)*	Yield stress f'_c, *(MPa)*	Tensile strength f_u, *(MPa)*	Elongation at breaking, (%)
6	5.5	23. 75	623.96	684.5	8.5
16	16	200.96	569.67	668.79	12.5

Figure 3. Arrangement of Steel Reinforcement

4. Testing Setup

The experimental investigation on reinforced concrete deep beams was carried out in the Structural Engineering Laboratory at the University of Baghdad. Accordingly, the tested deep beams were subjected to static loading increased monotonically up to failure using load control testing system. During testing these beams were supported on simple supporting scheme which allowed for rotation and horizontal movement at one end and the angular movement only at the other end. Tests were conducted using self-equilibrating steel frame designed as closed loop ram which equipped with an actuator of (1000) kN capacity and (10) kN measuring accuracy (Figure 4), that used to expose the experimental specimens to four-point loading pattern in which the two symmetrical external loads creating pure bending moment region of (200) mm. Preparations and calibrations to all instrumentations and devices were provided prior to the start of testing. All surfaces of the tested beams were cleaned, accurately prepared, covered with white emulsion painting and then a square-cell mesh of fine black lines were drawn to ease investigating the cracking process starting from occurrence. The deflection of the tested deep beams was measured at midspan section only using mechanical dial gauge of (0.01) mm sensitivity and accuracy of (0.001) mm. Cracking, strains in steel and concrete in addition to midspan vertical displacement were monitored and measured systematically after the application of each loading step. External load was increased monotonically with (5) kN total increment value per stage.

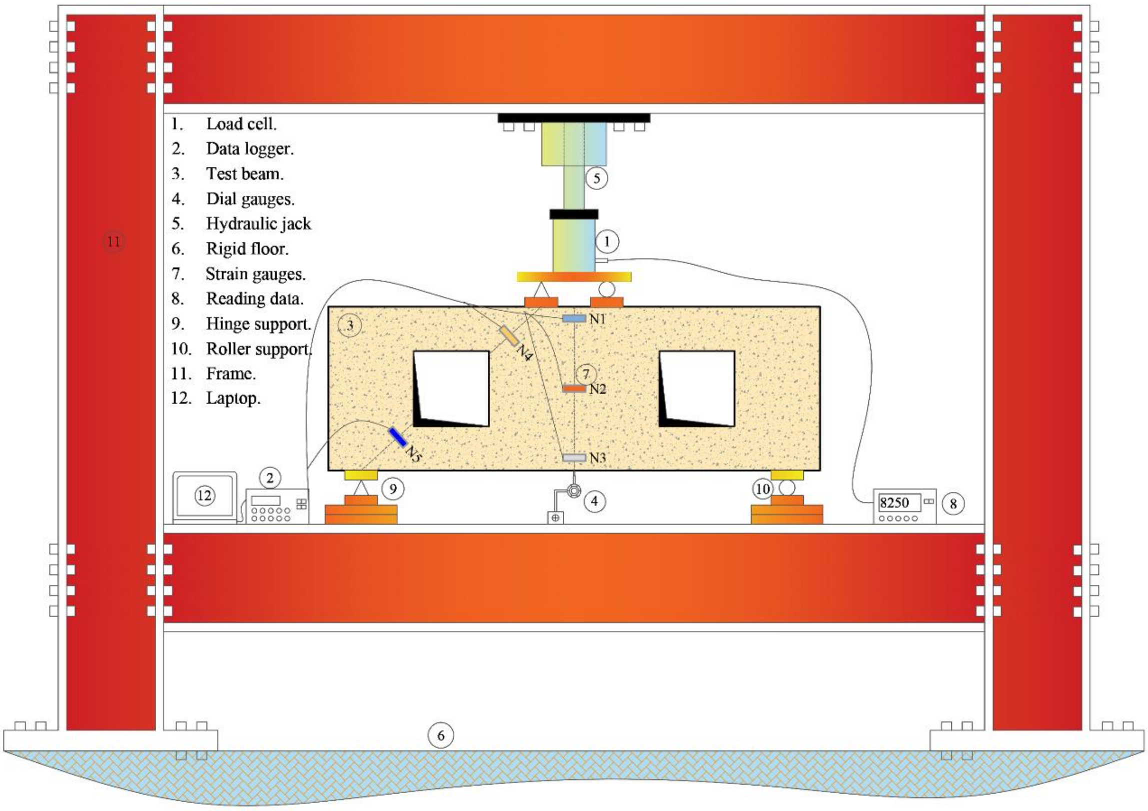


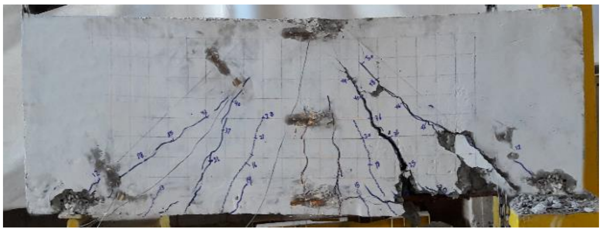
Figure 4. Test setup for deep beam with large web opening

5. Findings from Testing Outputs

5.1. Modes of Failure of Experimental Deep Beams

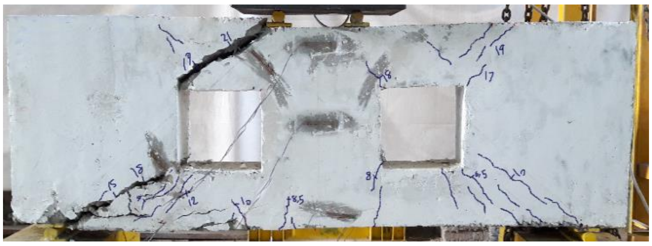
The cracking history of the tested deep beams started with the appearance of diagonal cracks at the corners of the square openings. As the structural concrete member then exposed to additional loading, it experienced occurrence of additional diagonal cracks in other sections besides the opening zone and flexure cracks in pure bending moment region. With further increase in the applied load, flexure cracks in the middle part of the member and extra shear cracks at the bottom chord below opening and the top chord above opening were propagated. As the applied load attained the failure value, intensive progress of the diagonal crack along the thrust joining the points of the applied load and the reaction force was monitored leading the deep beam to collapse.

The failure of the investigated deep beams was characterized by one of the following modes: diagonal splitting mode of failure, which was took place as the diagonal cracks at the opposite corners of the web openings progressively propagated and extended along the thrust joining the points of the application of external load and reaction force, or, shear-compression mode of failure, which was happened due to the propagation of diagonal crack in shear span that resulted intensive strains in the compression chord above opening near the applied concentrated load, see Figure 5.



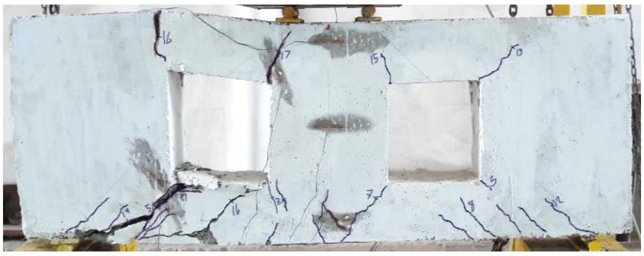
Diagonal splitting failure of (DP)

Diagonal splitting failure of (DP-C-200)



Shear-compression failure of (DP-E-200)

Diagonal splitting failure of (DP-C-230)



Diagonal splitting failure of (DP-E-230)

Figure 5. Crack pattern at failure stage for tested deep beams

5.2. Influence of Creating Large Web Openings on Deep Beam Resistance

Table 3 demonstrates how the creating of openings in shear regions affects the performance of reinforced concrete deep beams, mainly, in serviceability and ultimate stages. It is clear that, the cracking resistance of these structural concrete members including the capacity against diagonal and flexural cracks was less than the resistance of the solid deep beam against the appearance of the above mentioned cracks. Also, deep beams with openings experienced lower failure loads in comparison to the reference solid deep beam. Obviously, as the opening size increased from (200×200) mm to (230×230) mm the dropping in the load capacity was increased from (58%) to (66%).

Based on the location of opening relative to the profile of the shear region, it is very important to pay attention that, the worst location of opening is that location which exists at the midpoint of the shear span rather than the other locations (i.e., at the interior boundary of the shear region). Almost here openings were led to more degradation in the overall stiffness of the structural member and, consequently, the dropping of the failure load compared to specimens with openings at the interior boundaries of the shear spans. Meanwhile, large web openings in shear regions caused considerable decreasing in the overall stiffness of the reinforced concrete deep beams and, as a result, significant reduction in the first diagonal and first flexural cracking loads in the range of (46%-58%) and (41%-56%), respectively. It is worth to mention that, almost the deflection of midspan section at serviceability stage in beams with openings at the midpoint of the shear spans was greater than the deflection of the assigned section in deep beams with openings at the interior boundaries of the shear spans. Meanwhile, the deformability of deep beams with openings is considerably depending on the opening size (i.e., as the side dimension of the square opening was increased, the midspan deflection was increased at both serviceability and failure stages).

Table 3. Experimental cracking resistance, deformability and failure load capacity

Specimen designation	First diagonal cracking load, (*kN*)	First flexural cracking load, (*kN*)	Failure load, (*kN*)	Reduction of first diagonal cracking load, (%)	Reduction of first flexural cracking load, (%)	Reduction of failure load, (%)	Deflection at service load, (*mm*)	Deflection at failure load, (*mm*)
DP	120	135	500	Reference	Reference	Reference	1.68	9
DP-C-200	60	65	190	50	52	62	1.1	4
DP-E-200	65	80	210	46	41	58	0.88	4.8
DP-C-230	55	60	175	54	56	65	1.32	4.3
DP-E-230	50	70	170	58	48	66	0.93	5.1

5.3. Load – Deformability History during Testing of Deep Beams

Reinforced concrete deep beams with or without opening experienced three distinguished stages of performance during the loading process from the moment of application of external load up to failure. These stages can be clearly illustrated on the plots of load–midspan deflection, in which the slope of load–deflection diagram decreases upon the appearance and later the propagation of cracking along the member longitudinal axis. Linear relationship between the applied load and the measured midspan deflection was monitored during the first stage of performance that is characterized the elastic behavior of the materials.

The first stage of performance of deep beam completed at the moment of appearance of the first crack (diagonal or flexural). The second stage of performance is characterized by propagation of different flexural and diagonal cracks. The diagonal cracks which appeared at the top and bottom corners of the opening were progressively extended inclined to the member longitudinal axis along the thrust joining the points of the applied load and reaction force. Also, flexural cracks which appeared at the soffit of the beam and concentrated, mainly, in the pure bending moment region were progressively extended perpendicularly to the member longitudinal axis. As the applied load increased, all these cracks were progressively increased in numbers, depths and widths. As a result, the elastic behavior gradually converted to inelastic due to the degradation of the overall stiffness of the member. The second stage of performance was finalized as the slope of the second portion of the load-deflection curve started to decrease due to the significant increasing in the appeared cracking numbers and cracks width.

Finally as the applied load progressed, the load-deflection curves started to take a flat character due to the excessive degradation of the member stiffness resulted due to the reduction of cracking resistance and the performance of deep beams approached the failure point. At this point the deflection values at midspan sections showed sizeable change in comparison to the second stage. Figures 6 and 7, respectively, show the effect of the size and position of the openings created in shear regions on the load-midspan deflection response of deep beams. Obviously from (Figure 6) and (Table 4) that, the size of opening created in shear regions affected the cracking and deformability resistances of the reinforced concrete deep beams.

Increasing the side dimension of the square opening from (200) mm to (230) mm was resulted in decreasing the first diagonal cracking load by (8-23%), the first flexural cracking load by (8-13%) and the failure load by (8-19%) depending on the position of the opening relative to the shear span. That is due to the fact that, the deep beam with smaller web openings was experienced less degradation in the overall stiffness than the specimen with larger web openings. Accordingly, the midspan deflection at service and failure loads for deep beams with larger web openings was increased by (46-51%) and (6-8%), respectively, compared to deep beams with smaller web openings

It is interesting to observe the second stage of performance on the load-deflection curves illustrated in Figure 6 that the deflection at midspan section of the deep beams with openings which located at the midpoint of the shear region is greater than the deflection of the deep beams with openings positioned at the interior boundaries of the shear span. Accordingly, shifting the web opening from the midpoint to the interior boundaries of the shear region was resulted in stiffer behavior that decreasing the midspan deflection at service load of the adopted reference deep beam by (27-29%)

depending on the size of openings. At the failure load level, it is clear that the deflection of the deep beams with web openings which located at the interior boundaries of the shear region was greater than the deflection deep beams with openings positioned at the center of the shear span by (18%-20%) due to the fact that these deep beams experienced higher load carrying capacity. Meanwhile, the shifting of openings toward the boundaries of the shear spans caused in changing the first diagonal cracking load by (8%-9%), increasing the first flexural cracking load by (17%-23%) and changing the failure load by (3%-11%), see Figure 7 and Table 5.

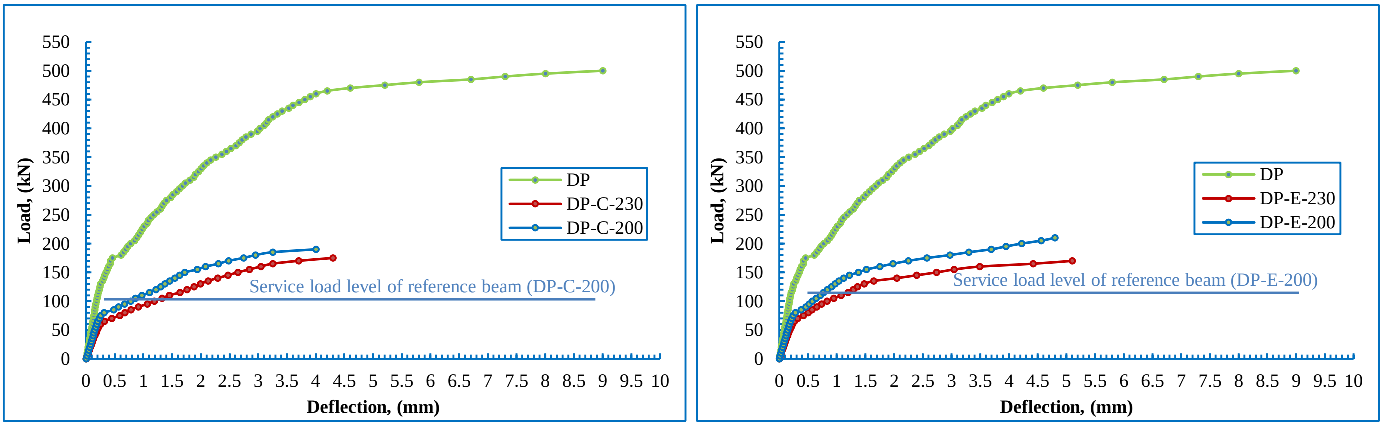


Figure 6. Influence of opening size on the load-deflection response

Table 4. Effect the opening size on strength, cracking resistance and deflection of deep beams

Specimen designation	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 level, (*mm*)	Change in deflection at failure load level of reference beam, (%)
DP-C-200	60	Reference	65	Reference	190	Reference	1.1	Reference	4	Reference
DP-C-230	55	-8	60	-8	175	-8	1.61	+46	4.3	+8
DP-E-200	65	Reference	80	Reference	210	Reference	0.9	Reference	4.8	Reference
DP-E-230	50	-23	70	-13	170	-19	1.36	+51	5.1	+6

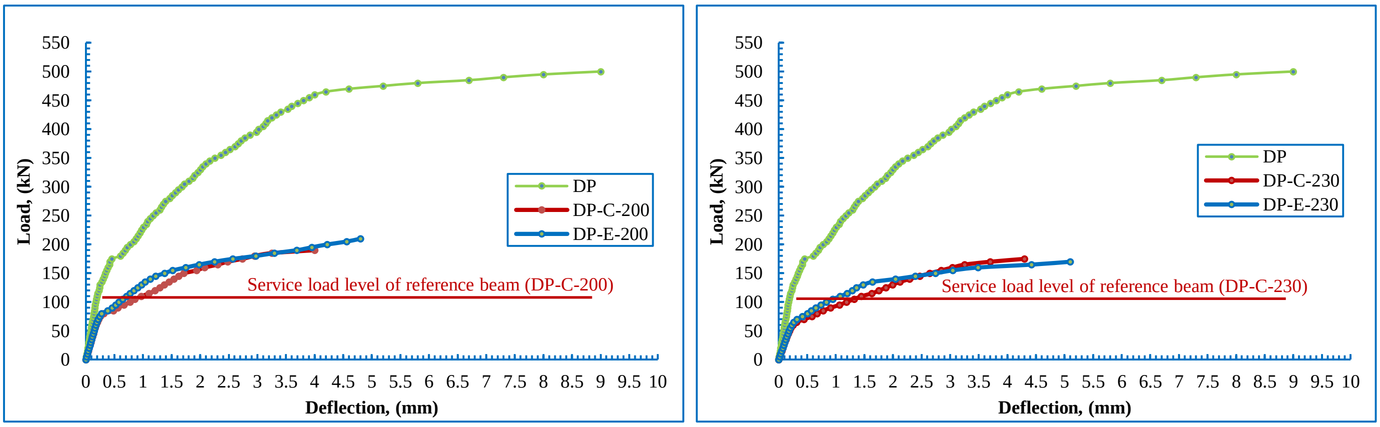


Figure 7. Influence of opening position on the load-deflection response

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

Specimen designation	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 level, (*mm*)	Change in deflection at failure load level, (*mm*)
DP-C-200	60	Reference	65	Reference	190	Reference	1.1	Reference	4.0	Reference
DP-E-200	65	+8	80	+23	210	+11	0.78	-29	4.8	+20
DP-C-230	55	Reference	60	Reference	175	Reference	1.32	Reference	4.3	Reference
DP-E-230	50	-9	70	+17	170	-3	0.96	-27	5.1	+18

6. Numerical Analysis of Tested Deep Beams by Finite Element Method

An analytical study was carried out to assess the structural performance of the five test deep beams implementing nonlinear modeling techniques of the finite element method. This method considered to be a reliable tool for investigating the nonlinear response of reinforced concrete structures. ABAQUS (6.13.1 package), general-purpose finite element software, was used for the numerical modeling of the reinforced concrete deep beams with or without web openings in shear regions. The symmetry was not considered that, the full scale tested beam was modeled. The typical finite element mesh of specimens DP and DP-C-200 (or DP-E-200) and DP-E-230 (or DP-C-230) are illustrated in Figure 8. The concrete volume was represented by eight-node solid brick element (C3D8R) with (2x2x2)-points integration (Figure 9). The finite element model of steel rebars for deep beams specimens is depicted Figure 8. The longitudinal and transverse steel rebars of these beams were modeled using an embedded truss reinforcement of 2-node linear 3-D truss element (T3D2). Eight-node solid elements were also used to model steel plates under the applied load and the resisting reactions (Figure 9). It is worth to mention that, in this numerical analysis, the perfect bond between the surrounding concrete and the steel rebars was assumed (i.e., full compatibility). Damaged plasticity model (DPM) has been used for the analysis. This model consists of the combination of non-associated multi-hardening plasticity and scalar (isotropic) elasticity to describe the irreversible damage that happens during fracturing process [22]. The main two failure mechanisms which adopted by this model are the tensile cracking and the compressive crushing of concrete.

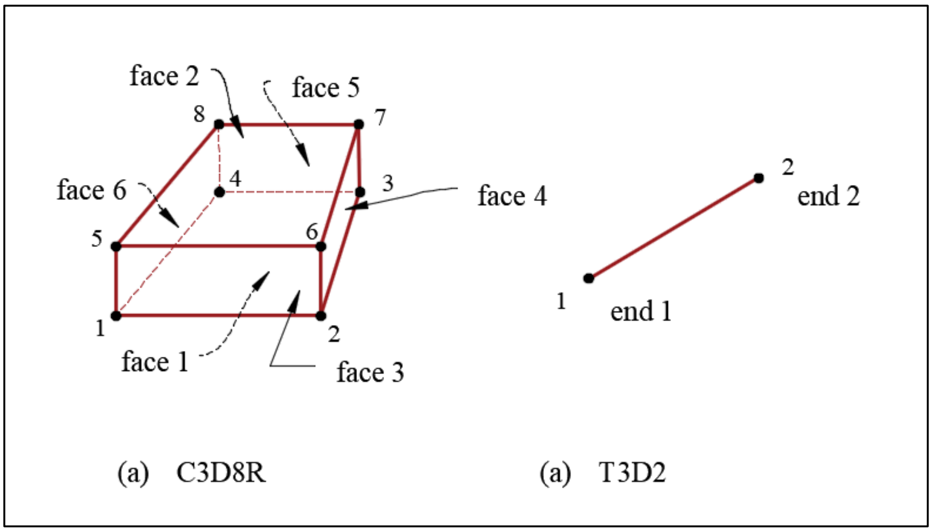


Figure 8. ABAQUS modeling for tested deep beams (concrete, steel bar and steel plate)

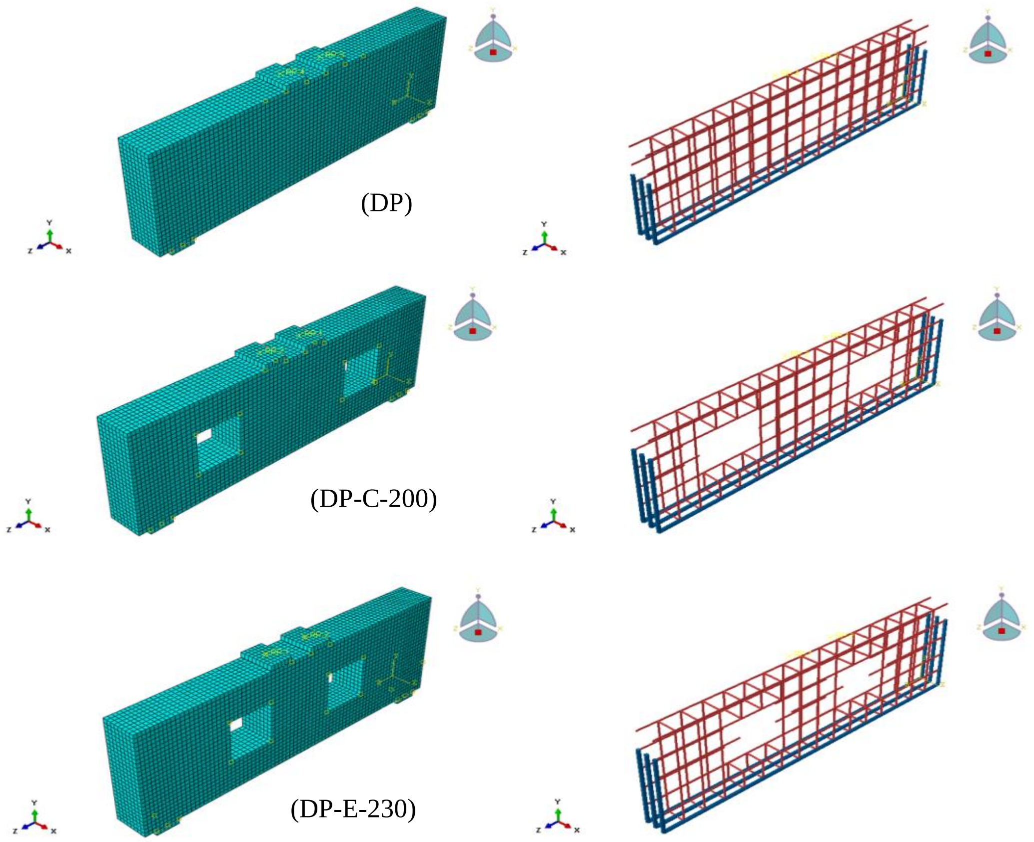


Figure 9. Applied finite elements for simulation of materials

Model verification has proved the good correlation between the numerical and the experimental results. Figure 10 demonstrated that the finite element models showed stiffer response of performance during the loading process up to failure because ABAQUS software program assumed idealized condition of bonding between steel and concrete in addition, it assumed that the concrete is isotropic material which is actually not exactly correct. Figure 11 illustrates the graphical visualization for the comparison between the experimental and numerical results concerning the first diagonal and first flexural cracking loads, the load carrying capacity and the deflection at service and failure loads. As shown from (Figure 11) the selected modeled response confirms the ability of the adopted model to simulate the entire behavior of the tested beams up to failure. The global failure modes of the analyzed, by ABAQUS software program, reinforced concrete deep beams are represented by the appearance and propagation of cracks and the crushing of concrete. The crack patterns showing the condition of deep beams after collapse are depicted in Figure 12. The observed crack pattern at the moment of collapse of deep beams provided excellent evidence that the flow of stresses within the deep beams was influenced by the opening size and layout. The presence of the opening at the midpoint of the shear region or at the interior boundaries of the shear region forced the compressive stresses in the specimen (between openings) to flow mainly in very narrow band. The width of this band was affected by the location of opening. So, in case the opening is located at the center of shear span the band width of the compressive stresses was greater. It is worth to mention that, the stress distribution in main steel reinforcement is an important index to prove of whether the tied-arch mechanism in reinforced concrete deep beam formed under loading and to what extension this mechanism was formed. Figure 13 shows that, the stress distribution along the main longitudinal bars in tension zone at different stages of applied loading. It is very interesting to note the following observations during investigating Figure 13 which illustrates the bottom reinforcement stress distribution at different stages of loading:

- In control deep beam (DP) without openings as the applied loading increased, the bottom reinforcement stresses became approximately similar over the entire effective span between the supports. The change of stresses at different sections followed steady character. Localized stress jumps were observed in specific sections that indicated cracks were appeared in the vicinity of these locations. As the diagonal cracks developed, joining the points of the loading application with supports, the beam action of the internal force flow was disrupted and converted to arch action. At failure stage the stress level in the steel bars was uniformly distributed from support to support, proving that a tied-arch mechanism had fully developed. The magnitude of stresses in main bars approximately reached the yielding capacity.

- In deep beams with openings as the loading progressed, the flow of stresses within the main longitudinal bars in tension zone were influenced by the opening size and the opening position, so, the distribution of stresses disturbed over the specimen effective span. High stress jumps were observed to be concentrated near the boundaries of the web opening. At failure stage the stress level in the steel bars was not constant between supports, proving that a tied-arch mechanism had partially developed. Obviously, in all reinforced concrete deep beams the stress in the steel bars over the region between openings was significantly lower than the stress magnitude at the boundaries of the web openings.

- Almost in deep beams with openings of different sizes and different layouts the tensile stresses in the steel reinforcement were not attained the yielding capacity because the concrete softening in the diagonal strut, joining the points of the application of the external load and the reaction force, was relatively insignificant.

- The value of the difference between the tensile stresses in the main longitudinal steel bars in the midspan section and in the section located at the boundary of opening depends on the opening position. This value was greater in the case when the web openings were positioned at the midpoint of the shear regions.

- Comparing the maximum magnitude of the tensile stresses in the bottom reinforcement for different deep beams with opening, it deserves to note that, as the size of opening increased the value of the attained stresses decreased at failure stage.

- It is observed that the stresses at the support location were on the order of (42) to (76) MPa for deep beams with openings, that approximately corresponding to (18%) to (25%) of the stress magnitude recorded at midspan at failure stage. Meanwhile, for the reference deep beam without opening (DP) the steel stress at the above mentioned location did not exceed at failure stage (12%) of the stress at midspan section for the same bar. These stress values should highlight the requirement to achieve adequate anchorage for main steel bars in tension zone near supports despite this zone is the zero bending moment region.

Figure 14 clearly shows the comparison between the experimental and the numerical progress, at midspan sections, of the tensile stresses in the bottom steel bars of all reinforced concrete deep beams. As previously mentioned, predictions of deep beam capacity were carried out using the finite element software program ABAQUS. Results of these analytical estimations are compared to the available experimental data of the tested beams in Table 6. It is important to note that, the findings presented in Table 6 show that all finite element analyses provided un-conservative estimates for deep beam load carrying capacity in the range between (5-21%). However, the maximum scatter in the predictions for first diagonal and first flexural cracking loads was not exceeding (17%). Meanwhile, almost at service load the numerical values of midspan deflection were greater than the experimental values by (9-18%).

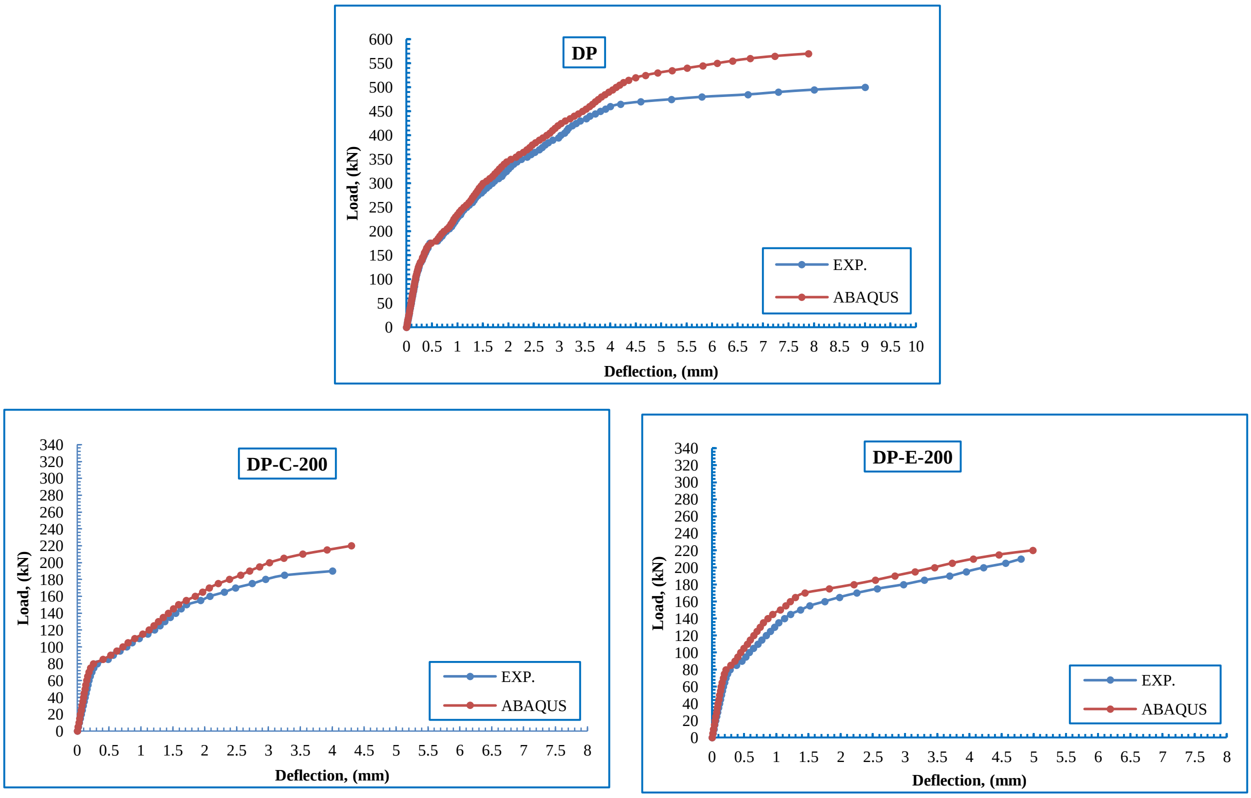


Figure 10. Load-deflection curves at midspan section constructed based on the experimental data and FEM results

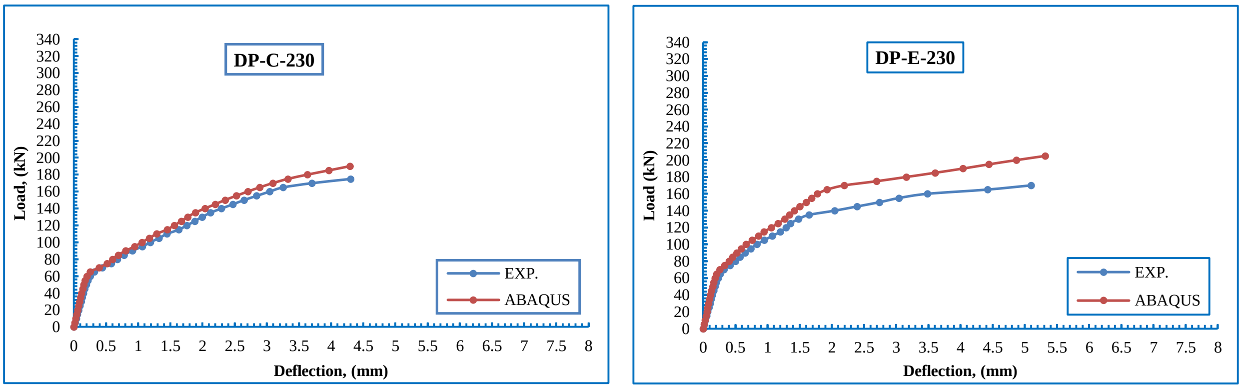


Figure 10. (Continued) Load-deflection curves at midspan section constructed based on the experimental data and FEM results

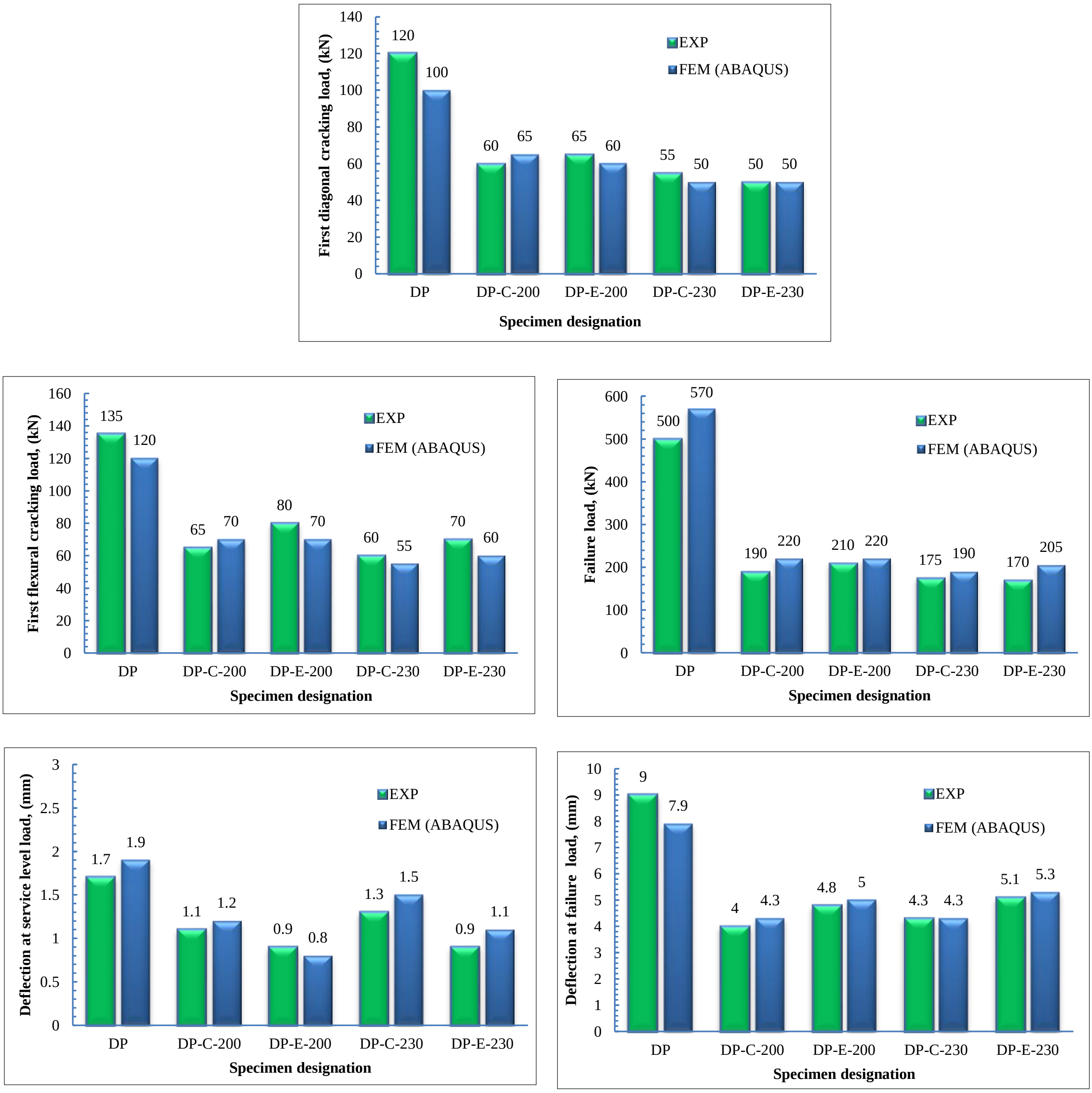


Figure 11. Graphical visualization for the difference between the experimental and numerical results of strength, cracking resistance and deformability

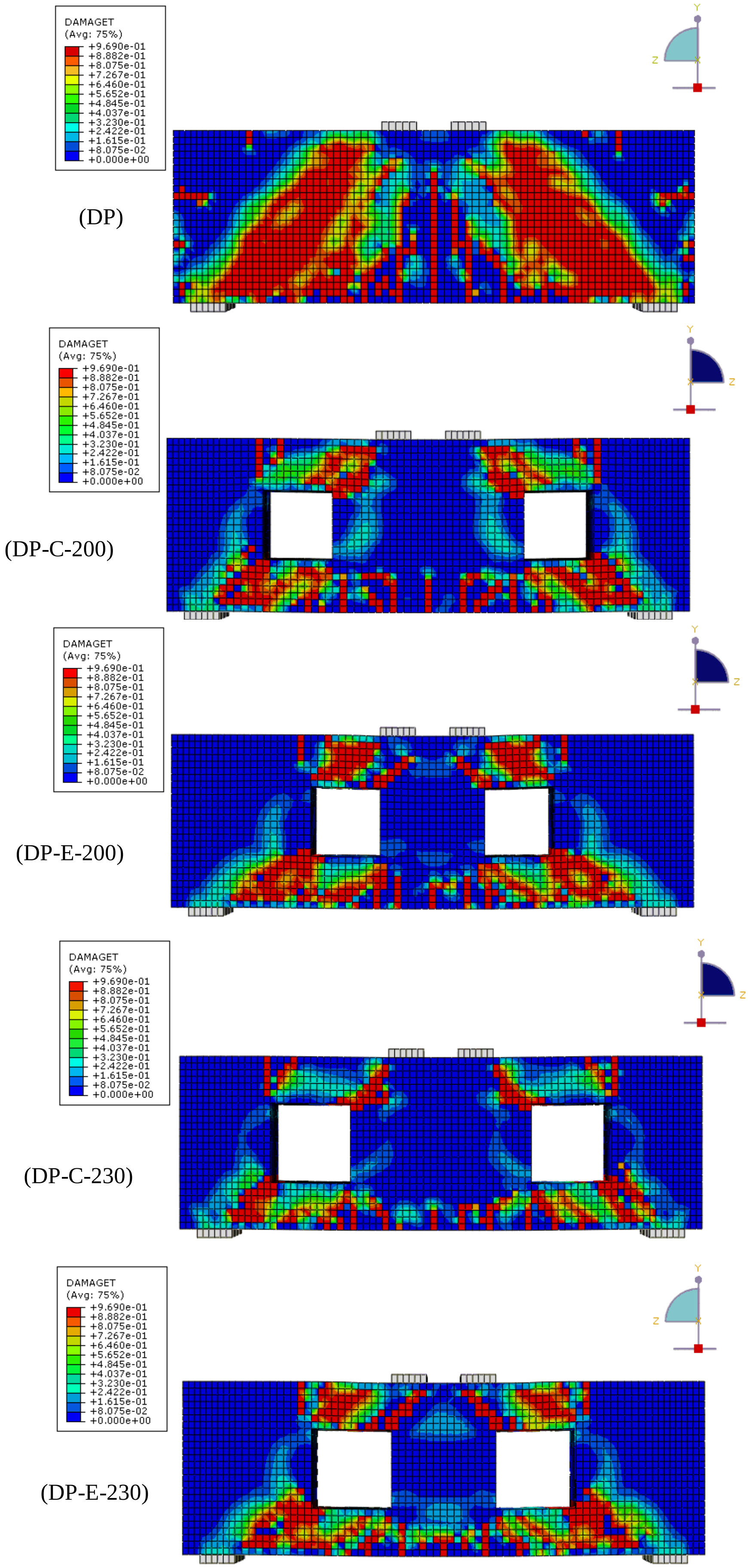


Figure 12. Crack pattern at the moment of collapse of deep beam models

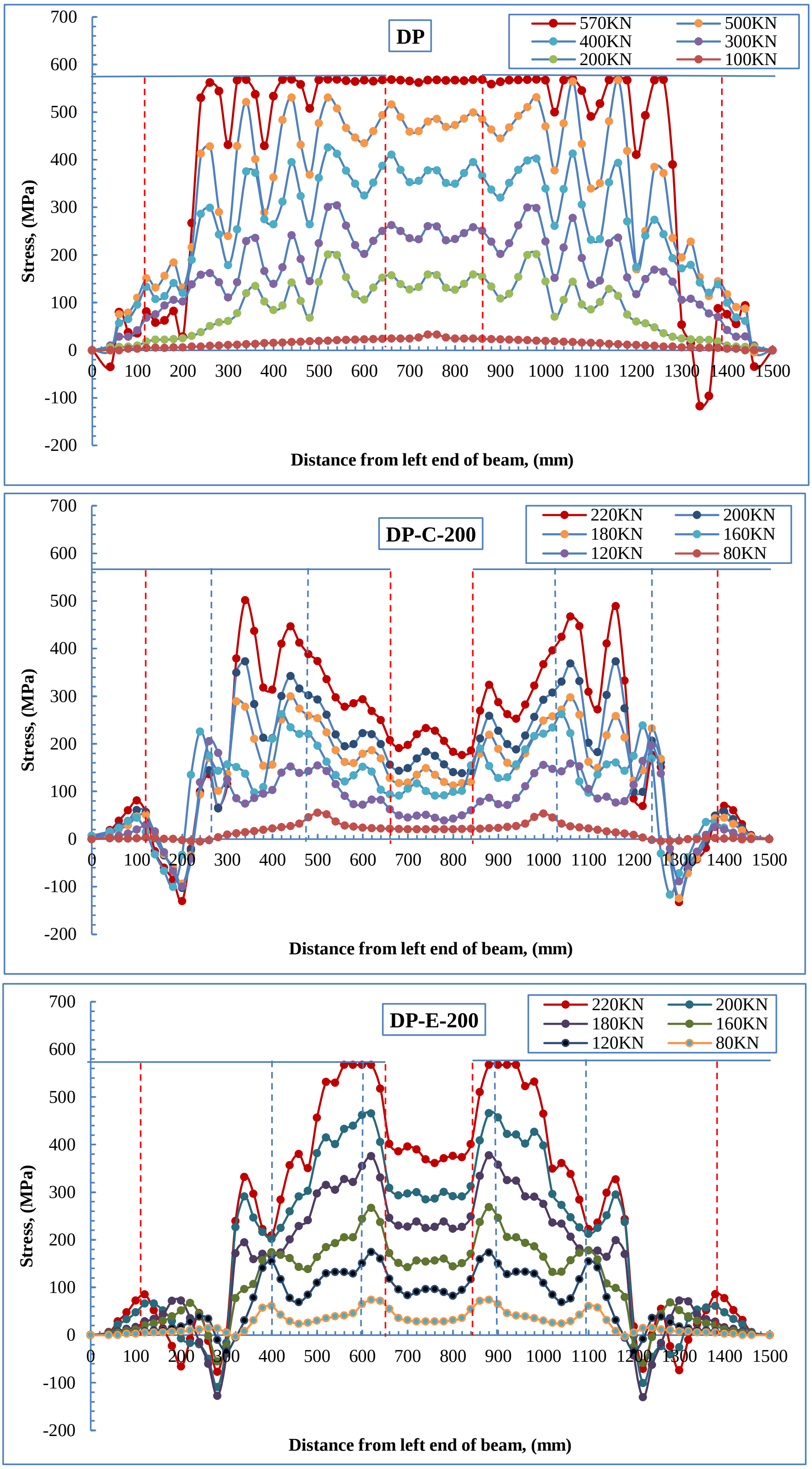


Figure 13. Bottom steel reinforcement stress distribution at different stages of loading

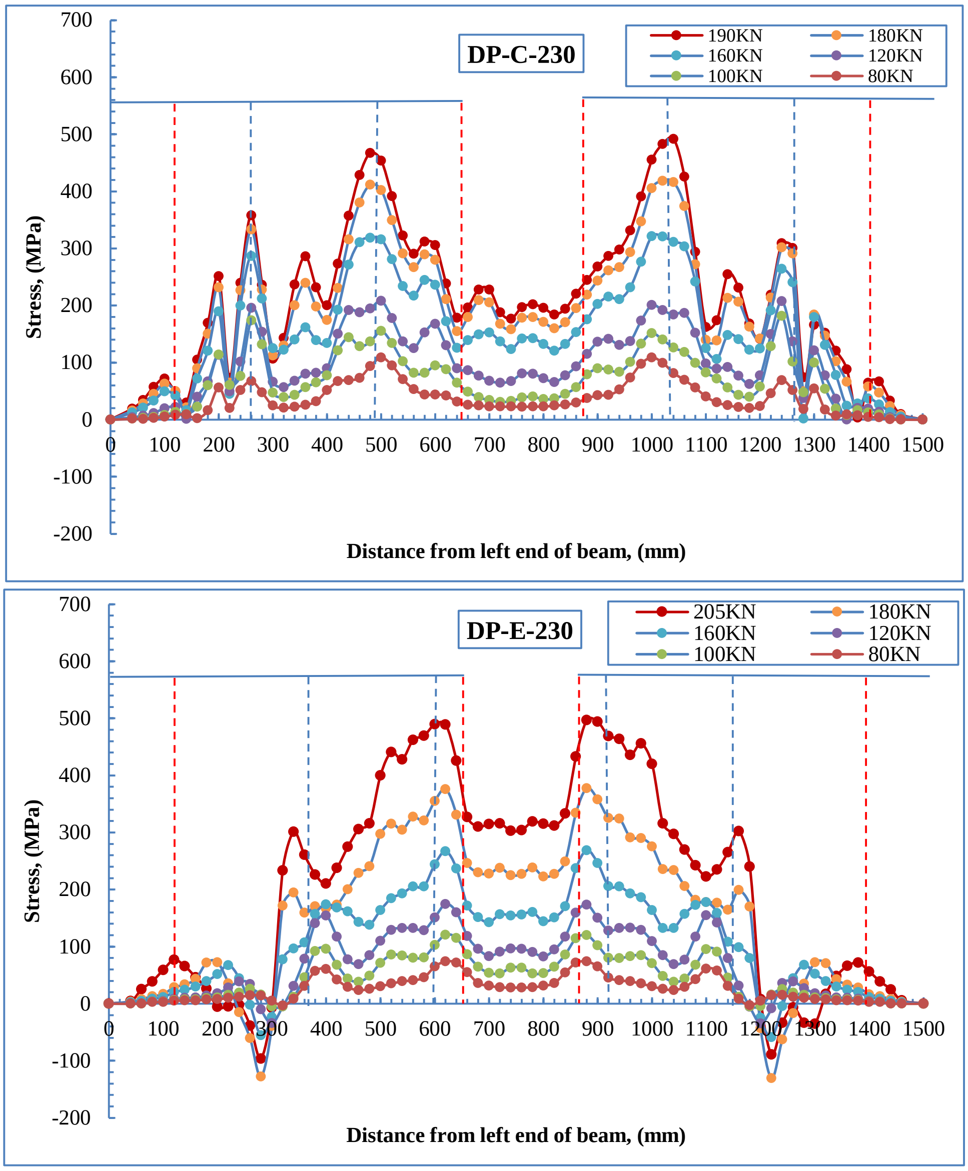


Figure 13 (Continued). Bottom steel reinforcement stress distribution at different stages of loading

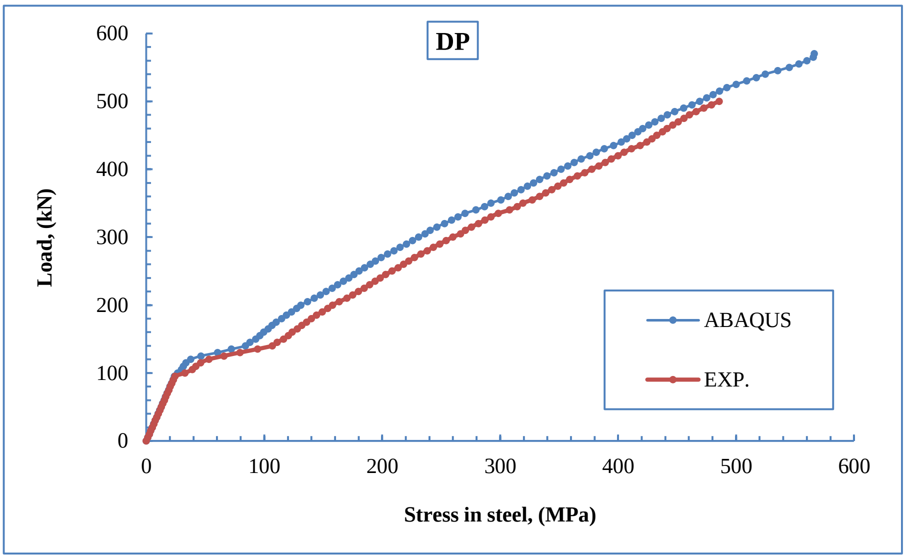


Figure 14. Load- stress curves in main steel bars at midspan section constructed based on the experimental data and FEM results

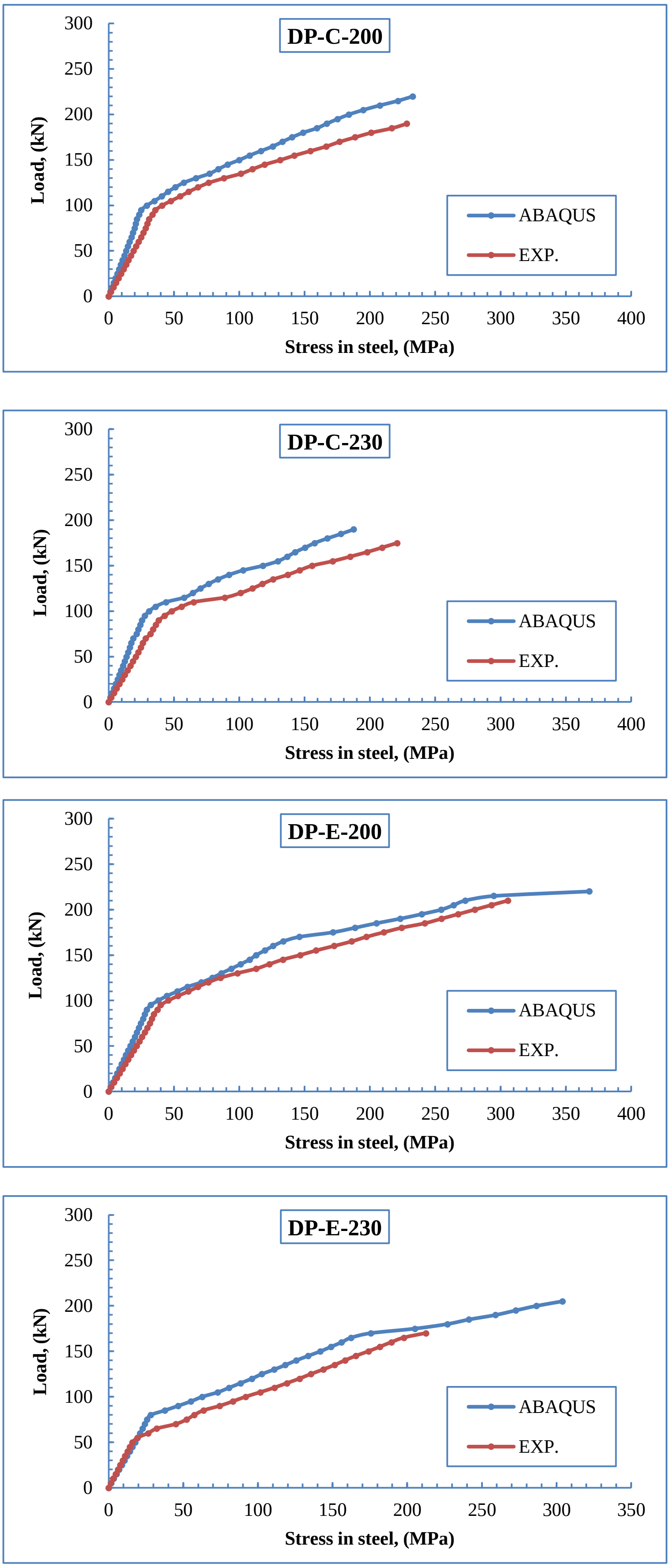


Figure 14. (Continued) Load- stress curves in main steel bars at midspan section constructed based on the experimental data and FEM results

Table 6. Comparison between experimental and numerical results for cracking, deformability and carrying capacity

		Specimen designation				
		DP	DP-C-200	DP-E-200	DP-C-230	DP-E-230
First diagonal cracking load	P_{EX}, (*kN*)	120	60	65	55	50
	P_{FE}, (*kN*)	100	65	60	50	50
	$(P_{EX} - P_{FE})/P_{EX}$*100%	17	-8	8	9	0
First flexure cracking load	P_{EX}, (kN)	135	65	80	60	70
	P_{FE}, (kN)	120	70	70	55	60
	$(P_{EX} - P_{FE})/P_{EX}$ *100%	11	-8	13	8	14
Failure load	P_{EX}, (*kN*)	500	190	210	175	170.0
	P_{FE}, (*kN*)	570	220	220	190	205
	$(P_{EX} - P_{FE})/P_{EX}$*100%	-14	-16	-5	-9	-21
Stress in main bottom bars at failure load	σ_{EX}, (*MPa*)	485	228	305	221	213
	σ_{FE}, (*MPa*)	٥٦٧	232	3٦٨	18٠	303
	$(\sigma_{EX} - \sigma_{FE})/\sigma_{EX}$*100%	-١7	-2	-21	+1٨	-42
Deflection at service level load	Δ_{EX}, (*mm*)	1.7	1.1	0.9	1.3	0.9
	Δ_{FE}, (*mm*)	1.9	1.2	0.8	1.5	1.1
	$(\Delta_{EX} - \Delta_{FE})/\Delta_{EX}$*100%	-14	-9	14	-17	-18
Deflection at failure load	Δ_{EX}, (*mm*)	9.0	4.0	4.8	4.3	5.1
	Δ_{FE}, (*mm*)	7.9	4.3	5.0	4.3	5.3
	$(\Delta_{EX} - \Delta_{FE})/\Delta_{EX}$*100%	12	-8	-4	0	-4

7. Conclusions

Based on the experimental results and the numerical analysis the following conclusion can be drawn:

- In comparison to the solid deep beam, obviously, as the opening size increased from (200×200) mm to (230×230) mm the dropping in the load capacity was increased from (58%) to (66%), respectively. Also, this increasing led to considerable decreasing in the overall stiffness of the reinforced concrete deep beams and, as a result, significant reduction in the first diagonal and first flexural cracking loads in the range of (46-58%) and (41-56%), respectively.
- In comparison to the deep beam with the smaller web opening, increasing the side dimension of the square opening from (200) mm to (230) mm was resulted in decreasing the first diagonal cracking load by (8-23%), the first flexural cracking load by (8-13%) and the failure load by (8-19%) depending on the position of the opening relative to the shear span. Accordingly, the deep beam with smaller web openings was experienced less degradation in the overall stiffness than the specimen with larger web openings. So, the midspan deflection at service and failure loads was increased by (46-51%) and (6-8%), respectively.
- Shifting the web openings from the midpoint to the interior boundaries of the shear regions was resulted in stiffer behavior that decreasing the midspan deflection at service load of the deep beam with web opening located at the midpoint of the shear regions by (27-29%) depending on the size of openings. This shifting led to changing the first diagonal cracking load by (8-9%), increasing the first flexural cracking load by (17-23%) and changing the failure load by (3-11%).
- Modeling of reinforced concrete deep beams were carried out by the finite element software program ABAQUS. Findings from this program showed that all numerical analyses provided un-conservative estimates for deep beam load carrying capacity in the range between (5-21%). However, the maximum scatter in the predictions for first diagonal and first flexural cracking loads was not exceeding (17%). Almost at service load the numerical values of midspan deflection were greater than the experimental values by (9-18%).

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9. Conflicts of Interest

The authors declare no conflict of interest.

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