

Prestressing Effects on Full Scale Deep Beams with Large Web Openings

An Experimental and Numerical Study

Rafaa M. Abbas

Department of Civil Engineering
College of Engineering
University of Baghdad
Baghdad, Iraq
dr.rafaa@coeng.uobaghdad.edu.iq

Lara T. Hussein

Department of Civil Engineering
College of Engineering
University of Baghdad
Baghdad, Iraq
l.hussein1001@coeng.uobaghdad.edu.iq

Abstract—Most studies on deep beams have been made with reinforced concrete deep beams, only a few studies investigate the response of prestressed deep beams, while, to the best of our knowledge, there is not a study that investigates the response of full scale (T-section) prestressed deep beams with large web openings. An experimental and numerical study was conducted in order to investigate the shear strength of ordinary reinforced and partially prestressed full scale (T-section) deep beams that contain large web openings in order to investigate the prestressing existence effects on the deep beam responses and to better understand the effects of prestressing locations and opening depth to beam depth ratio on the deep beam performance and behavior. A total of seven deep beam specimens with identical shear span-to-depth ratio, compressive strength of concrete, and amount of horizontal and vertical web reinforcement ratios have been tested under mid-span concentrated load applied monotonically until failure. The main variables studied were the effects of depth of the web openings and the prestressing location on deep beam performance. The test results showed that the enlargement in the size of web openings substantially reduces the element's shear capacities, while prestressing strands location above the web openings have more effect at increasing the element's shear capacities. The numerical study considered three-dimensional finite element models that has been developed in Abaqus software to simulate and predict the performance of prestressed deep beams. The results of numerical simulations were in good agreement with the experimental ones.

Keywords—deep beam; large web openings; pre-stressing; finite element; shear strength; static loading

I. INTRODUCTION

Shear behavior of reinforced concrete members (slender members that have span-to-depth ratios greater than 2.5) is a complex phenomenon influenced by a large number of parameters [1, 2]. This complexity is more pronounced in deep beams (members that have small span-to-depth ratios, less than 2.5) because the applied load is transferred mainly through the formation of arching which causes a highly nonlinear strain distribution in the cross section so that the shear strain is dominant [3]. In deep beams, the strain distribution is nonlinear and the load is transferred to the support by a compression strut

joining the loading point and the support [1, 4-7]. The creation of web openings is often required for the accommodation of electrical and mechanical conduits. Enlargement of openings due to architectural/mechanical requirements reduces the element's shear capacity [8]. Openings' configuration was investigated in [9] and an increase in ultimate load capacity when circular openings were used was reported. Many studies investigated the pre-stressing effects [10]. Pre-stressing a deep beam can increase significantly its load carrying capacity [11].

Finite Element Modeling (FEM) is a powerful tool in simulating structural elements in a variety of fields. In FEM, the successful simulation of specific elements relies upon the realistic representation of the material properties. However, due to the complexity of the constitutive material properties, modeling the behavior of reinforced concrete, shear in particular, has been, and still is, a challenging issue [12]. In the current study, 7 deep beams were tested and a comparison was made with the results of the numerical analysis (FEM) that was implemented with the aid of Abaqus/CAE program in order to investigate the effect of openings and pre-stressing locations. The comparison included load-deflection relation, load-strain relation at specific locations, crack pattern, and failure stage load. From the experimental results a significant decrease in load carrying capacity can be noticed when large web openings are introduced, and that agrees with the statement that the further the opening is located from what can be called the loaded quadrant and the nearer to the unloaded quadrant, the strength of the beam increases [13] and the deep beam acts as an ordinary beam. Also, pre-stressing location above the openings has more effect above the soffit in increasing load carrying capacity of the deep beam. The experimental results showed a good agreement with the numerical ones and can predict the pre-stressed deep beam strength accurately.

II. FEM DESCRIPTION

A. Geometry and Element Types

In order to investigate the pre-stress effects on the response and performances of full scale T-section deep beams with large web openings under monotonic loading, three-dimensional (3D) FE models of simple supports that have been partially pre-

Corresponding author: Lara T. Hussein

stressed and reinforced were constructed as a reference. The geometry, dimensions, and configuration of the FE beams were identical to the actual tested specimens. Four partially pre-stressed concrete deep beams with web openings, two reinforced deep beams with web openings, and one-solid beam were designed according to the strut-and-tie approach [14]. The full scale (T-section) deep beam specimens had the same geometry with dimensions of 1950mm length, 1000mm height, 750mm flange width, 125mm flange thickness, and 250mm web thickness, having 900mm span, 25Mpa concrete compressive strength, and the same main reinforcement with the shear reinforcement. The specimens were tested and analyzed under monotonic loading at mid-span. The main variable was the size of web openings, and pre-stressing location (above the openings or above the soffit). The adopted pre-stress level was selected so that it satisfied the limit of $0.62 f_{pu}$ [15]. The objective of this study is to investigate experimentally and numerically the:

- Location of pre-stressed strand across the height of the section: Case (1) – pre-stressed strand above the soffit of the beam at 0.07H, where H is the height of the section Case (2) – pre-stressing strand above the top surface of openings at 0.07H.

- Height of opening D, adopting ratios of the height of the opening to the height of section D/H equal to 0.48 and 0.6.

The constants were:

- Concrete's compressive strength.
- Span length to height of the section ratio (L/H).
- Two openings symmetrically located relative to the center-line of the beam.
- The width of the opening D.
- The center of each opening was located at 0.45H from the soffit of the beam.

The practical program of this study was to investigate four deep beams with large web openings that were partially pre-stressed at various locations (0.07H mm) above the openings and above the soffit. The beams were designated with the DP-DE-OP symbols for partially pre-stressed deep beams with large web openings (480mm×480mm, 600mm×480mm) and different pre-stressing locations (OP- for above opening and SP- for above soffit). For more details of specimens and reinforcements properties, see Table I.

TABLE I. PROPERTIES OF THE REINFORCEMENTS OF THE POST TENSIONED DEEP BEAMS

Beam	Main reinf. A_s (mm ²)	Compression reinf. A_s (mm ²)	Pre-stressed A_p (mm ²)	Skin reinf. A_{sw} (mm ²)	ρ_w (%)	f_y (MPa)	Pre-stressing force F_{pe} (KN)
DP-48×48	3016	4010	---	50	0.2	430	286
DP-48×48-OP	3016	4010	2012.7	50	0.2	430	286
DP-48×48-SP	3016	4010	2012.7	50	0.2	430	286
DP-60×48	3016	4010	---	50	0.2	430	286
DP-60×48-OP	3016	4010	2012.7	50	0.2	430	286
DP-60×48-SP	3016	4010	2012.7	50	0.2	430	286
DP-Solid	3016	4010	2012.7	50	0.2	430	---

B. Numerical Modeling

The numerical investigations were carried out using the commercial FE tool Abaqus/Explicit finite element code. The concrete and the pre-stressed bars were modeled as three dimensional deformable bodies and the reinforcement as three dimensional truss. The interaction between concrete and steel was modeled using the constraint option available in Abaqus/CAE wherein the concrete was taken as the host region and the steel as the embedded region (Figure 1(a)). The element types that were used in the FE model for concrete were 8-noded linear bricks and 2-noded linear three dimensional trusses. The beam boundaries of the two ends were restrained with respect to all the degrees of freedom. The stresses for posttensioned strands were added in predefined fields as shown in Figure 1(b) and the loading applied was linearly varied to maximum, until failure occurred. Concrete Damaged Plasticity (CDP) modeling was used and the Johnson-Cook elastoviscoplastic material model available in Abaqus finite element code was employed for modeling the steel reinforcing bar material. The mesh sensitivity in concrete and steel was studied and the size of the elements was chosen based on the mesh convergence studied for concrete and reinforcements. The meshing of the elements of deep beams and reinforcement is shown in Figure 1(c)-(d).

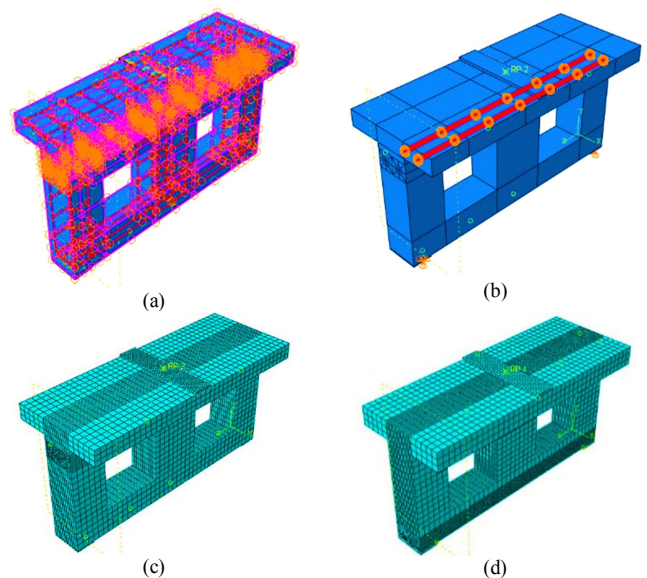


Fig. 1. (a) Embedded regions, (b) applying prestress, (c) meshing of the model DP-48×48-OP, (d) meshing of the model DP-48×48-SP.

III. RESULTS AND DISCUSSION

- The first crack appeared at the support regions toward the lower opening corner for the 48×48 and 60×48 specimens at 31% and 28% of the ultimate load respectively. The load-carrying capacity decreased as a result of the increasing opening depth [11].
- For the prestressed specimens 48×48-OP and 60×48-OP, the first crack was initiated at around 25%-26% of the ultimate load. The prestressing strands above the opening applied more compression stress and hence initial cracks above the openings appeared before the initiation of the first crack of the ordinary reinforced deep beams.
- At 48×48-SP and 60×48-SP specimens, the initial crack propagated at the upper corner of the openings toward the applied load region at 33%-34% of the ultimate load, as a result of the prestressing strand location at the tension zone [16].
- Flexure cracks appeared in all specimens, except specimens with prestressing above the soffit. There were no early flexure cracks as a result of tie action. They appeared at 34-44% whereas the flange shear cracks appeared at 33-52% of the ultimate load.
- As a result of large web openings, a typical crack pattern (column-beam) conjunction occurred. Horizontal cracks appeared at 32-47% of the ultimate load (Figure 2(a)-(b), crack number 3).
- The existence of web openings (480mm×480mm) can reduce the load carrying capacity by about 156KN (Figure 3).

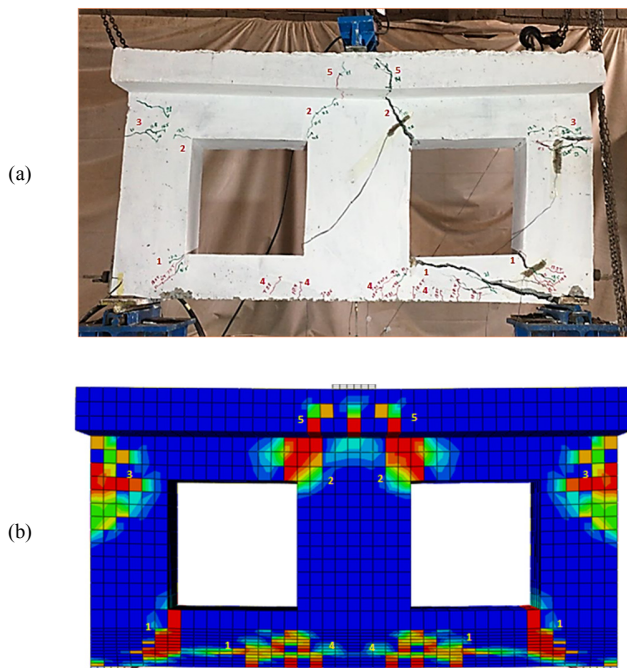


Fig. 2. Specimen DP-48×48-SP: (a) Experimental and (b) simulated crack patterns.

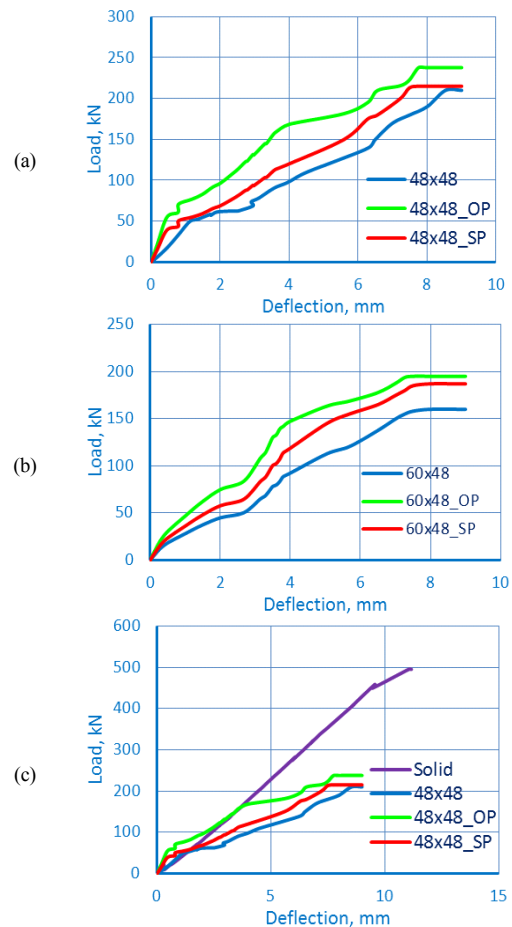


Fig. 3. Comparison of reinforced and pre-stressed deep beams with the solid deep beam.

- The stresses paths and strut-and-tie configurations are shown clearly in Figure 2(a)-(b) [17].
- The comparison of the ultimate load according to the prestress location shows that the prestressing strands above the web openings increase the load carrying capacity by about 14% in the case of 480mm depth and by 22% in the case of 600mm depth (Figure 3). When the pre-stressing strands are above the soffit the load carrying capacity increases by about 2.38% and 17% for 480mm depth and 600mm depth respectively (Figure 3).
- Introducing web openings reduces the solid deep beam strength by about 136-209KN for 48×48 and 60×48 respectively (Figure 3). Increasing the web opening depth, from 480mm to 600mm, decreases the load carrying capacity by about 31% for reinforced deep beams and 15% for pre-stressed deep beams (Figure 3), as a result of intersecting the load path [8].
- Introducing large web openings in the deep beam transforms it into an ordinary beam-column (Figure 2(a)-(b), crack number 3) [17].

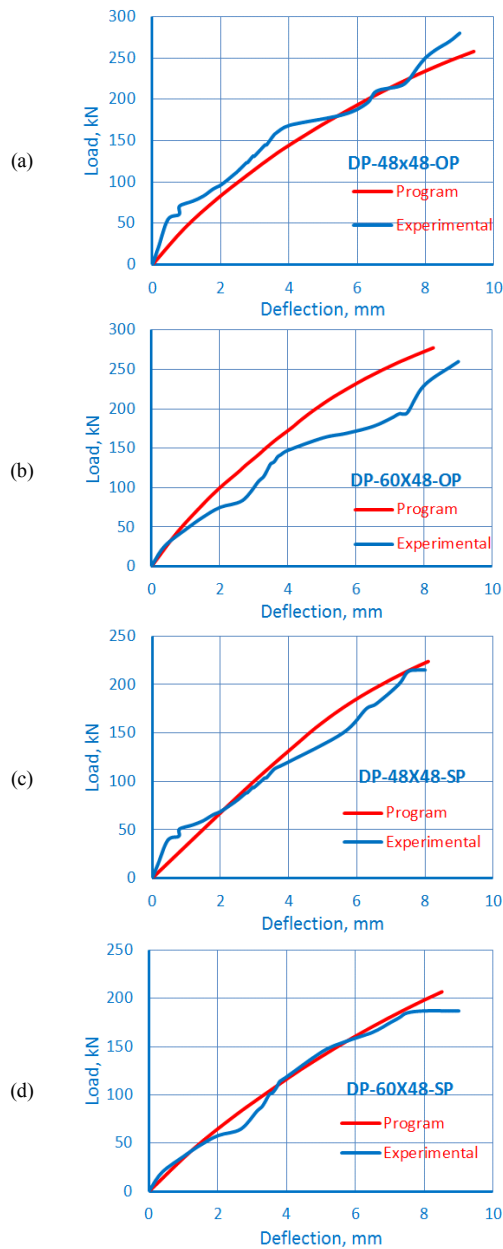


Fig. 4. Comparison of load versus deflection between experiments and simulations.

- The load-deflection curve behaves semi-linearly, which shows that the deep beams act as ordinary beams more than as deep beams, as a result of the large web openings at the shear zone which change their geometry (Figure 3) [17].
- The comparison of the load-deflection relation results of the tested specimens with the FEM results is shown in Figure 4. It is noted that the numerical load deflection responses are stiffer than the experimental ones and there is a good agreement in both trend and amplitude which varies from 5 to 10%.
- The deflection reaches 8mm-10mm and stresses at the failure stage (Figure 5).

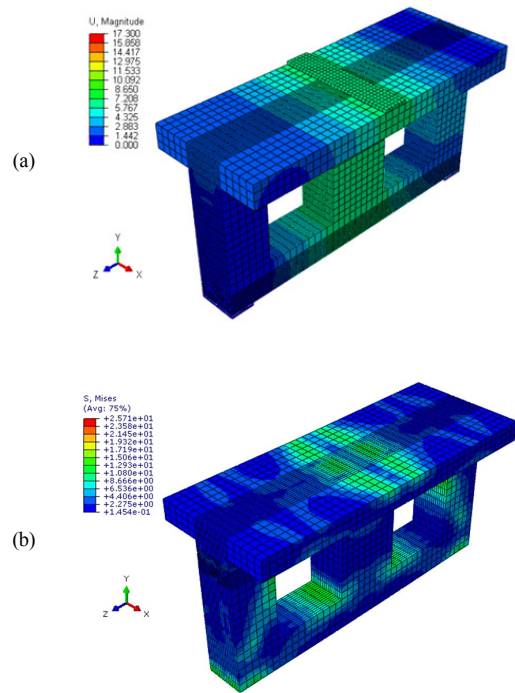


Fig. 5. Specimen DP-48x48-OP: (a) Deflection counter, (b) stresses at the failure stage.

IV. CALIBRATION WITH THE PRESTRESSED SOLID MODEL

Based on the FEM results, a calibration of solid deep beams with a pre-stressed solid deep (pre-stress location at $d_p=930$ mm) beam in finite element analysis using Abaqus was done. The obtained crack patterns of the pre-stressed solid deep beam are presented in Figure 6. The comparison with the simulated model shows that the existence of pre-stressing in the case of the solid deep beam increased the ultimate strength by about 37% than ordinary reinforced solid deep [16] (Figure 7).

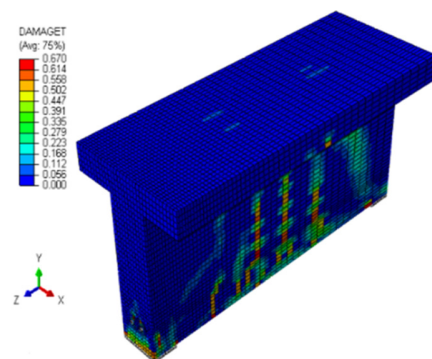


Fig. 6. Showing the crack patterns of the solid deep beam.

The load-deflection curve for prestressed and ordinary reinforced solid deep beams is linear. As a result of the under-reinforcement, the steel reaches its yield strain before the concrete reaches the failure strain which is 0.0035. Figure 7 shows the significant crack patterns in tension. The

compression zone does not show any kind of failure which can lead to a ductile failure. The influence of the longitudinal reinforcement on ductility is defined by the relative neutral axis position along the cross section of the element. For lower values of neutral axis position, the beams have higher cross section heights and, consequently, lower longitudinal reinforcement rates, which grant more ductility to these beams at the ultimate limit state. When the concrete resistance increases, the amount of longitudinal reinforcement required to maintain the same ductility also increases. Therefore, a direct dependence between the ductility factor and the longitudinal reinforcement rate was observed [18].

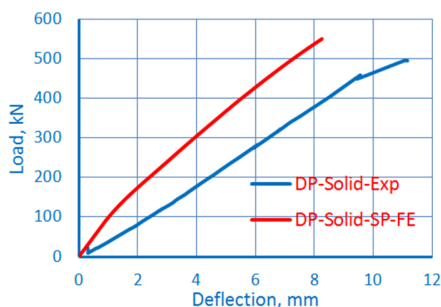


Fig. 7. Load-deflection relations of simulated and experimentally examined pre-stressed solid deep beams.

V. COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

The numerical models which simulate the actual tested specimens were able to predict the accurate shear capacity of each specimen with error varying around 10% (Table II). The highest shear capacity was observed with the solid deep beam (Figure 8).

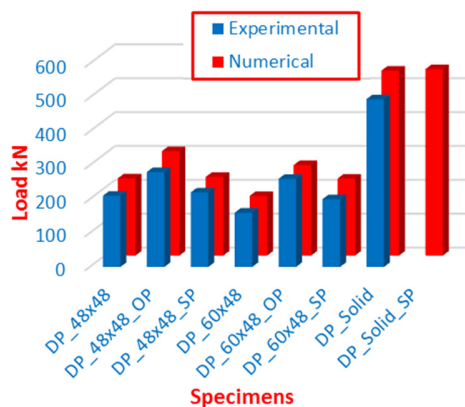


Fig. 8. Experimental and numerical shear capacity results.

As the opening depth increased, the shear capacity will decrease simultaneously. The DP-60×48 deep beam has the lesser shear capacity. The enlargement of the opening size reduces the shear capacity [11]. Introducing prestressing strands can increase the load-carrying capacity by about 35% [16]. It is observed that a prestressed solid deep beam has greater load carrying capacity than ordinary reinforced solid

deep beams by around 37%. When the prestressing location is above the web opening, it provides greater shear capacity than when it is above the soffit. Adding prestressing strands above the openings increased the compression struts and hence increased the shear capacity [14]. Introducing web openings intersects the stresses paths and changes the geometry of the deep beam affecting its behavior and shear capacity [17]. The existence of web openings (480mm×480mm and 600mm×480mm) can reduce the load carrying capacity (by about 135 and 209KN respectively). More details about each specimen's simulated and experimentally tested shear capacity can be seen in Figure 8 and Table II.

TABLE II. EXPERIMENTAL AND NUMERICAL RESULTS

Specimens	Shear strength (kN)		
	Experimental	Numerical	Num/Exp ratio
DP-48×48	210	228	1.08
DP-48×48-OP	280	308	1.1
DP-48×48-SP	220	232	1.05
DP-60×48	160	176	1.32
DP-60×48-OP	260	267	1.02
DP-60×48-SP	200	227	1.13
DP-Solid	495	546	1.1
DP-Solid-SP	---	550	---

VI. CONCLUSION

In this paper, seven beam specimens with large web openings and different pre-stressing locations were examined. The numerical model predictions were compared with the experimental results and the following conclusions can be drawn:

- Introducing pre-stress at a location above the opening can increase the load carrying capacity by 14% and 22%, whereas when the pre-stressing location is above the soffit, the load carrying capacity is increased by 2.3% and 17% for DP-48×48 and DP-60×48 respectively.
- Pre-stressing on beams with larger opening depth increases more the ultimate load capacity.
- Introducing web openings can reduce significantly the load carrying capacity by at least 136KN (480mm×480mm web openings), in comparison with the solid beam.
- The solid deep beam has bigger strength than the pre-stressed deep beam with openings.
- The numerical results comparison showed that, in the case of pre-stressed solid deep beam, as the location of the pre-stressing d_p decreases, its effects on increasing the beam strength decrease. In the case of pre-stressed deep beams with openings, the load carrying capacity of deep beam increased when the pre-stressing location d_p decreased.
- From the FEM result analysis, it can be seen that the models are stiffer than the experimental specimens.

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