IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684, p-ISSN: 2320-334X, Volume 16, Issue 1 Ser. II (Jan. - Feb. 2019), PP 01-11
www.iosrjournals.org

Finite Element Analysis of Bottom Loaded Continuous Deep Beams with and without Web Openings

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Abstract : *This research presents a study for the prediction of the behavior of bottom loaded continuous deep beams (CDB) numerically by using finite element modeling (FEM). ABAQUS 2017 finite element software program is used for simulation the CDB. The results of FEM are calibrated and validated with experimental data by Farag A. (1999) [18]. A parametric study using the calibrated model is used to cover more parameters for predicting the behavior of bottom loaded continuous deep beams with openings. The results of FEM show that the increasing of ultimate capacity of bottom loaded continuous deep beams depends on position of web openings and percentage of either horizontal or vertical web reinforcement ratio. In addition, the vertical web reinforcement ratio is more efficient than horizontal web reinforcement ratio. Further, it observed from the results that, additional reinforcement around opening has small effect on ultimate capacity of CDB. Finally, a simplified strut-and-tie model is developed for each bottom loaded CDB.*

Keywords:*Finite Element (FEM), Bottom Loaded, Continuous Deep Beams (CDB), Web Openings.*

Date of Submission: 04-01-2019 Date of acceptance: 21-01-2019

I. Introduction

Reinforced concrete continuous deep beams are widely used in most special structures that carry high loads like bridges, pile caps, folded plates, and high-risebuildings. The behavior of top loaded simply supported deep beam with or without web openings were widely investigated [1-14]. Some researches were carried out to investigate the behavior of bottom loaded simply supported deep beam with/without opening. Mourad, etal., [11]suggests a modified truss model to estimate the bottom loaded deep beam capacity without web openings using into consideration variation of web reinforcement ratios.

Elzeiny, [14] investigates and evaluates the behavior of bottom loaded simply supported deep beams with square web openings experimentally and theoretically, and develops a modification for the shear friction truss model for prediction the ultimate shear capacity taking the effect of web openings into consideration.

In continuous deep beams, the mechanism of failure is different from that for simply supported deep beams, especially for bottom loaded continuous deep beams. Because of maximum shear and bending occurred at the same region in continuous deep beams (CDB). On the other hand, deep beams develop a truss or tied arch action, which can be used for estimating the ultimate capacity of deep beams. [15-19]

Farag. A.,[18] andEl-Attar, et al.,[19] investigate the behavior of bottom loaded (two span) continuous deep beams experimentally using different parameters. The results show that the ultimate capacity of bottom loaded deep beams is generally less than that of similar top loaded ones.

Recently, carry out a numerical analysis by using finite element modeling software program (ABAQUS[1]) for simulating reinforced concrete deep beams presents a good agreement with experimental results, due to its flexibility in creating 3D modeling with different material types.

In this study, the ABAQUS FEM software is used to predict the behavior of bottom loaded continuous deep beams with/without web openings considering the nonlinearity of materials and parameters affect the behavior of CDB such as; opening type and its position, web reinforcement ratio, and additional reinforcement around the web openings. A simplified strut-and-tie model for each previous CDB were obtained using FEM.

II. Material Modeling of RC Continuous Deep Beams

The finite element program ABAQUS was used to study the behavior of reinforced concrete continuous deep beams. The provided model was used to validate the results of experimental analysis of bottom loaded two-span continuous deep beams with web openings testedby Farag A. 1999[18], the detailing of the specimens isshown in Figure (1). The used concrete compressive strength was 25 MPa, and the yield strength for reinforcement was 460 MPa, While Pu is the ultimate capacity of each span in kN, and dash-line is the load path (strut) from top to support.

Note; all dimensions in meters (m) in Fig. (1).

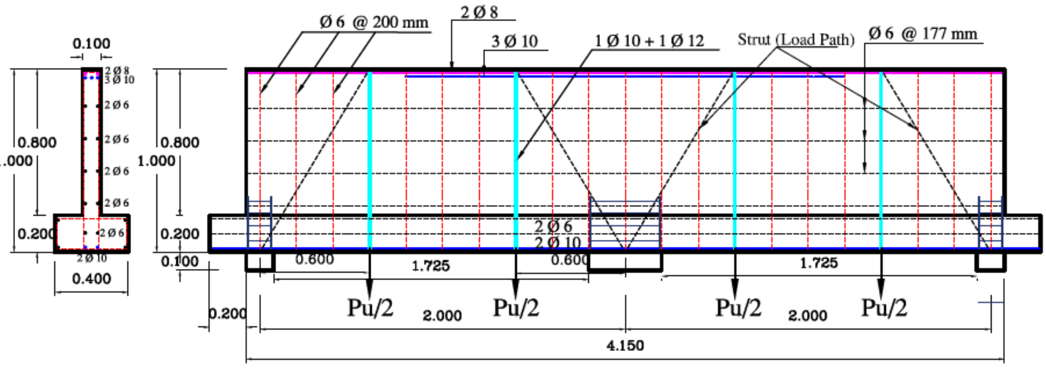


Fig. (1): Detailing of Bottom Loaded Continuous Deep Beams Without Web Openings Tested byFarag A. 1999[18].

2.1. Concrete

The concrete damage plasticity in ABAQUS software can beused for defining the material properties of concrete material of deep beams. The concrete damaged plasticity model assumes that the two main failure mechanisms in concrete are the tensile cracking and the compressive crushing. The evolution of the yield (or failure) surface is determined by two hardening variables, tension and compression equivalent plastic strains, respectively. Each of them is linked to degradation mechanisms under tensile or compressive stress conditions, as shown in figure (2).

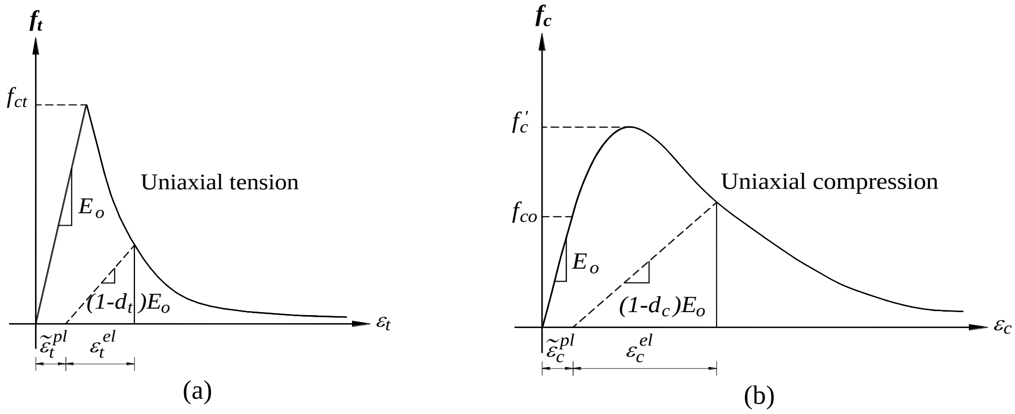


Fig. (2): Response of Concrete Due To (A) Uniaxial Tension, (B) Uniaxial Compression.

2.2. Steel

The constitutive behavior of steel can be predicted using an elastic perfectly plastic model, as described in (ABAQUS /CAE 2017) [1]. In this approach, the steel behavior is elastic up to the yield stress. At this point, the material yields under constant load, as shown in Figure (3). The steel reinforcement embedded to the concrete assuming that there is a perfect bond between the concrete and the steel reinforcement.

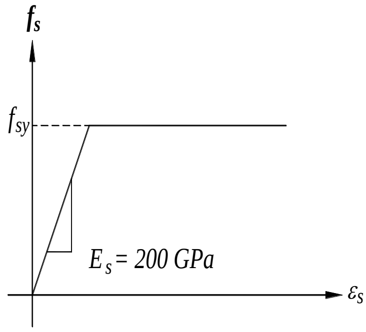
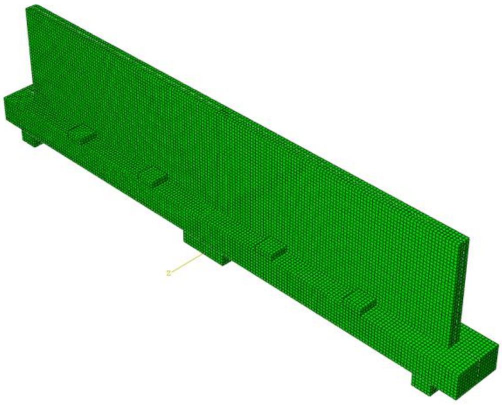


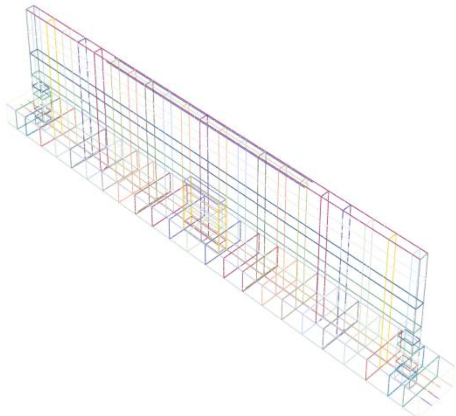
Fig. (3): Stress-Strain Relationship for Steel Reinforcement.

III. Model Validation

A three-dimensional finite element (FE) program 'ABAQUS' is used for the numerical analysis of reinforced concretebottom loaded two-span continuous deep beams experimentally tested by Farag A. 1999. In reinforced concrete deep beams to model the concrete in ABAQUS and steel plates under applied load, an8-node solid element, C3D8R was used. While longitudinal reinforcement, horizontal, and vertical reinforcement in reinforced concrete beams are model by using element T3D2.The load was applied at load-plates over the bottom web of the CDB, while the hinged supports were used. The details of FE model used in this validation is shown in Figure (4) and table (1).



(a) Mesh Used in Validation.



(b) Steel Reinforcement.

Fig. (4) Detail of FE Model Without Web Openings.

Table (1): Details ofFEM Bottom Loaded Deep Beams Without Web Openings.

Spec. No.	Opening position	F_{cu} MPa	Long. Bottom RFT		Long. Top RFT		Vl. Web RFT			Hz. Web RFT		
			A_S, mm^2	$\rho\% = \frac{A_s}{bd}$	A_S	$\rho\% = \frac{A_s}{bd}$	A_{SV}, mm^2	SV, mm	$\rho\% = \frac{A_{sv}}{bS_v}$	A_{sh}, mm	Sh, mm	$\rho\% = \frac{A_{sh}}{bS_h}$
CDB1	-----	25	214	0.218	336	0.342	56	200	0.28	56	177	0.316

The ultimate load obtained from FE model was compared with the results obtained from the experimental results by Farag A. 1999[18]. The modeled response verifies the ability of the selected model to capture the whole beam's behavior up to failure and shows a good agreement to the experimental results. The results of the model can be used in validating and guiding experimental work, in addition to exploring concrete response under complicated loading conditions such as the behavior of reinforced concrete deep beams with and without web openings introduced in the current study. Table (2) and figure (5)show the FE model results compared to experimental results

Table (2): Ultimate Load Comparison.

Spec. No.	Pu,Experimental kN	Pu, FE Modeling kN
CDB1	500	462.2

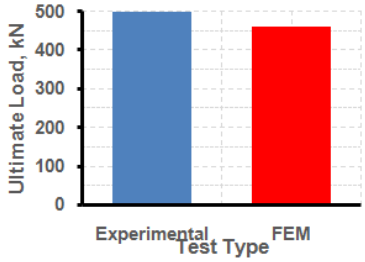


Fig.(5): Experimental vs FEM Ultimate Load.

IV. Parametric Study

A verified FE model was used to predict the behavior of bottom loaded two-span continuous deep beams with squarewebopenings at the center of load-path and had dimensions 200 mmx200 mm, considering different parameters. Table (3) shows details of parametric study. The detailing of dimensions and steel reinforcement of CDB2 shown in figure (6), while figure (7) shows the simulating FEM used in this study by ABAQUS software.

Note; all dimensions in meters (m) in Fig. (6).

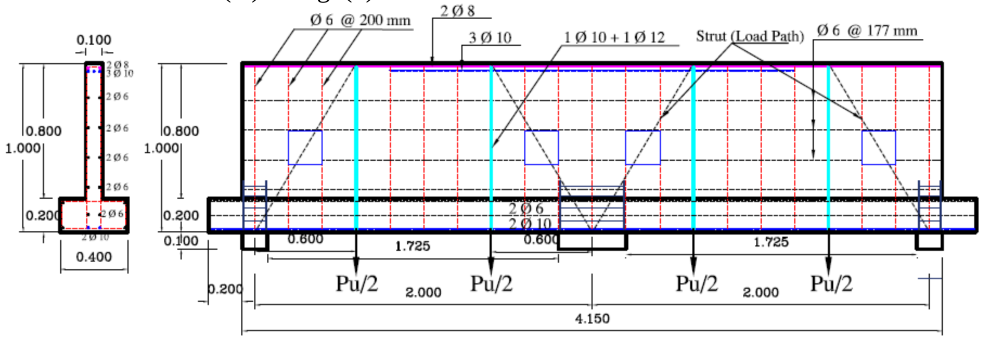
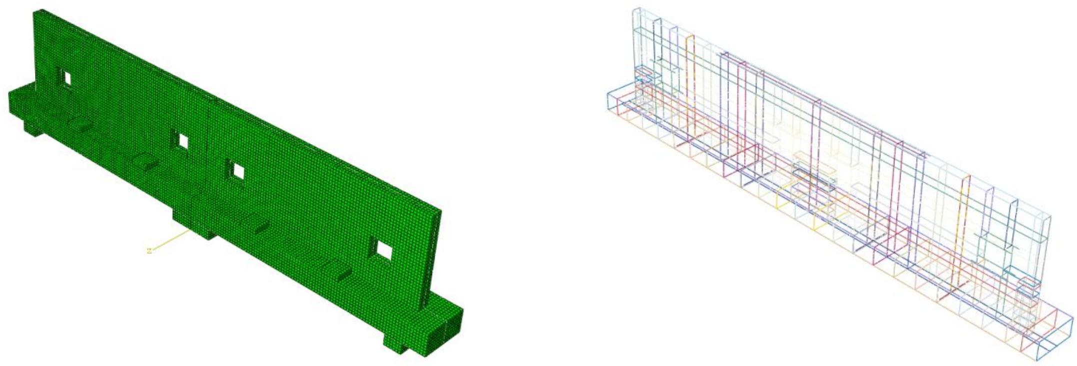


Fig. (6): Detailing of Bottom Loaded Continuous Deep Beams with WebOpenings at the Center



(a) Mesh Used in Validation. **(b) Steel Reinforcement.**

Fig. (7): Detail ofFE Model with Square Web Openings.

Table (3): Detailing of Paramedic Study Specimens.

Spec. No.	Opening position	Opening type	Opening dimensions, mm	F_{cu} MPa	Long. Bottom RFT		Long. Top RF.		Vl. Web RFT			Hz. Web RFT			Additional RFT around Opening
					A_S, mm^2	$\rho\% = \frac{A_s}{bd}$	A_S, mm^2	$\rho\% = \frac{A_s}{bd}$	A_{SV}, mm^2	SV	$\rho\% = \frac{A_{sv}}{bS_v}$	A_{Sh}, mm^2	Sh, mm	$\rho\% = \frac{A_{sh}}{bS_h}$	$\rho_{h,RFT}$ %= $\rho_{v,RFT}$ %
CDB2	center	Square	20 x 200	25	214	0.229	336	0.359	56	200	0.28	56	177	0.316	0
CDB3	above	Square	200 x 200	25	214	0.229	336	0.359	56	200	0.28	56	177	0.316	0
CDB4	below	Square	200 x 200	25	214	0.229	336	0.359	56	200	0.28	56	177	0.316	0
CDB5	center	Circle	D = 200	25	214	0.229	336	0.359	56	200	0.28	56	177	0.316	0
CDB6	center	Square	200 x 200	25	214	0.229	336	0.359	56	200	0.28	56	88.5	0.632	0
CDB7	center	Square	200 x 200	25	214	0.229	336	0.359	56	200	0.28	100	88.5	1.13	0
CDB8	center	Square	200 x 200	25	214	0.229	336	0.359	56	100	0.56	56	177	0.316	0
CDB9	center	Square	200 x 200	25	214	0.229	336	0.359	100	100	1	56	177	0.316	0
CDB10	center	Square	200 x 200	25	214	0.229	336	0.359	56	100	0.56	56	88.5	0.632	0
CDB11	center	Square	200 x 200	25	214	0.229	336	0.359	56	200	0.28	56	177	0.316	0.428
CDB12	center	Square	200 x 200	25	214	0.229	336	0.359	56	200	0.28	56	177	0.316	0.856
CDB13	center	Square	200 x 200	25	214	0.229	336	0.359	56	200	0.28	56	177	0.316	1.712

V. FEM Results

The FE modeling results shows that failure of CDB's were due to share. On the other hand, the ultimate capacity of the continuous deep beams with web openings CDB2 is less that without opening by 19%. Most results of FEM specimens show that the supports-reactions were 46% and 54% of total span-forces at external and internal supports respectively. The ultimate capacity improved when the opening position was far from the center of load path (strut), using circular opening, and increasing the ratio of horizontal and vertical web reinforcement. On the other hand, the capacity of the deep beams with web openings becomes near to that without web openings when increasing ratio of both horizontal and vertical web reinforcement (CDB10). While the additional reinforcement (RFT) ratio around the web openings hassmall effect on the ultimate capacity as shown in table (4) and figures (8, 9)

Table (4): FE Model Results.

Spec. No.	FEM results	
	P_u, kN	Deflection at ultimate load, mm
CDB1	462.17	5.03
CDB2	388.14	4.47
CDB3	456.88	6.41
CDB4	408.46	4.69
CDB5	403.37	5.13
CDB6	428.32	5.61
CDB7	448.66	5.17
CDB8	427.29	4.49
CDB9	465.88	5.13
CDB10	458.03	4.97
CDB11	389.58	5.42
CDB12	390.85	5.48
CDB13	392.50	4.61

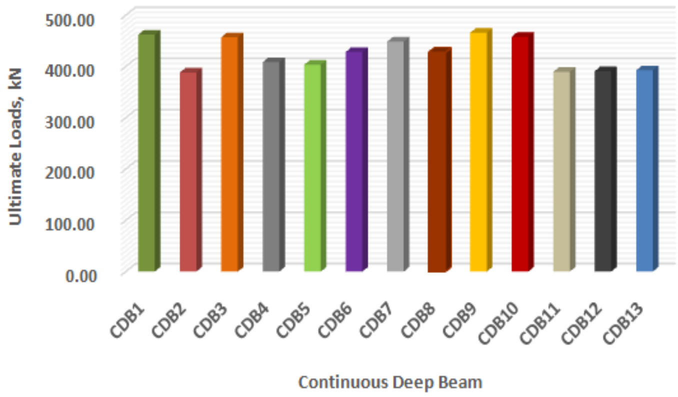


Fig. (8): Ultimate Capacity of All FEM Deep Beams.

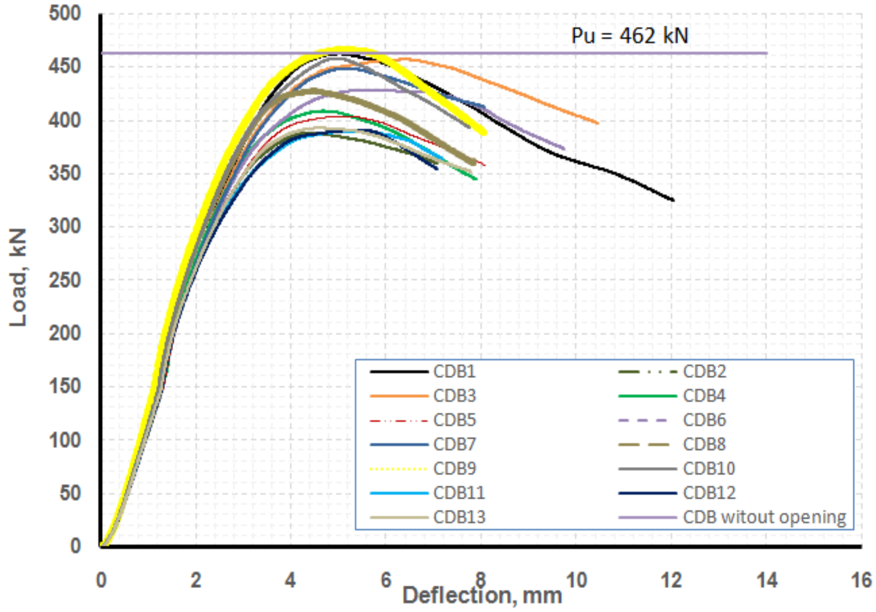


Fig. (9): Load – Deflection of All FE Models.

Table (5) showsthe web reinforcement strain at ultimate load for all deep beams. The results show that at ultimate load, the value of strain in vertical web RFT is greater than the corresponding value of horizontal web RFT. In addition, the vertical web reinforcement reaches the yield strain before the horizontal web reinforcement. The value of strain in horizontal web reinforcement increased when increasing the ratio of vertical web reinforcement, for CDB8 and CDB9.

Table (5): Strain in Web Reinforcement at Ultimate Load of ContinuousDeep Beams.

Spec. No.	Pu, kN	Web RFT Strain %	
		Horizontal Web RFT	Vertical Web RFT
CDB1	462.17	0.44	2.76
CDB2	388.14	0.57	1.03
CDB3	456.88	0.14	2.02
CDB4	408.46	0.57	1.23
CDB5	403.37	0.28	1.92
CDB6	428.32	0.24	1.59
CDB7	448.66	0.16	1.43
CDB8	427.29	0.69	2.91
CDB9	465.88	0.94	3.08
CDB10	458.03	0.46	3.53
CDB11	389.58	1.24	1.69
CDB12	390.85	1.26	1.7
CDB13	392.50	0.91	1.77

5.1. Effect of Web Openings Type and Position

Three deep beams were studied to predict the effect of web openings position on the ultimate capacity of continuous bottom loaded deep beams, the deep beams with opening on the center of strut (along the dotted line) was taken as a control beam, and the other two beams with opening above and below the previous opening were analyzed, as shown in figure (10). It can be concluded from the FE model that the increasing in ultimate capacity of continuous deep beams is very sensitive to the opening position. When the center of opening was on the top of center of load path by about 200 mm the ultimate capacity increased by about 17%, while this percentage of increasing on ultimate capacity decreased to about 5% when the center of opening was below the center of load path by about 200 mm, as shown in figure (11). It is very important to choose the position of opening above the center of load path as possible. In addition, figure (11) can be used to predict the increasing on ultimate capacity of CDB when changing the position of the opening above or below the center of load path.

On the other hand, one specimen with circular opening at the center of load path (along the dotted line, CDB5) is modeled, the results compared to that with square opening to investigate the effect of opening type on the behavior of continuous deep beams. The results show that the ultimate capacity of the CDB with circular opening is more than that with square opening by 3.9%, due to the concentrate of stress at the edges of square opening. Figure (12) shows the load-deflection curve for comparison between opening types on the capacity of CDB.

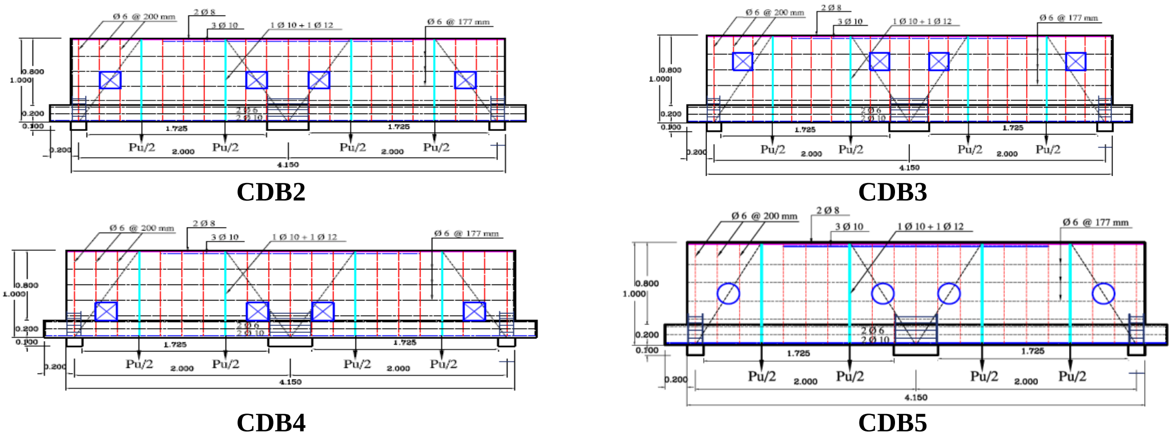


Fig. (10): Web Openings Type and Position Specmens Details.

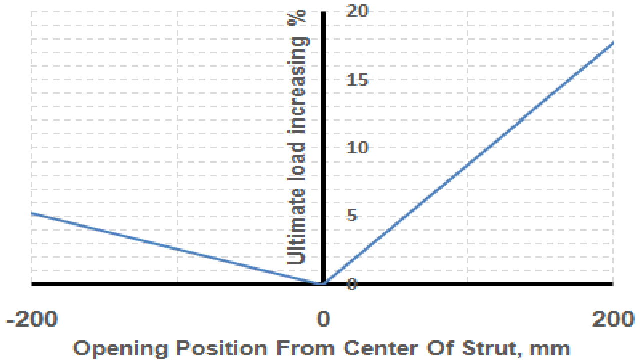


Fig. (11): Effect of Web Openings Position on CDB Ultimate Capacity.

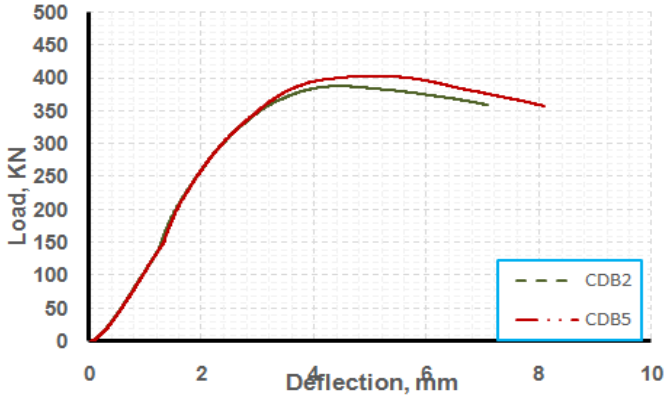
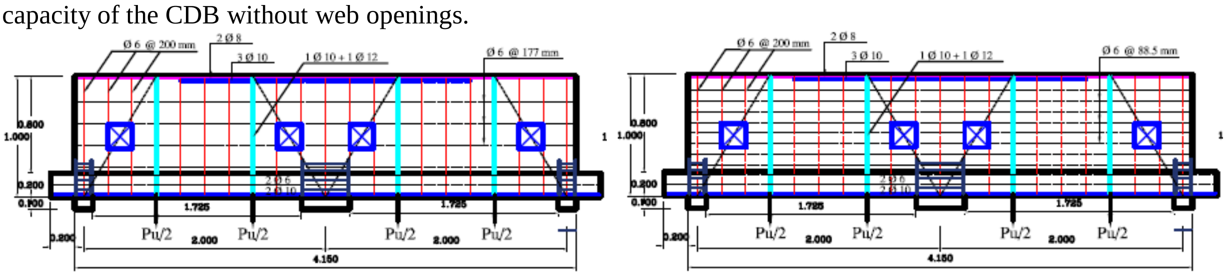


Fig. (12): Effect of Web Openings Type on CDB Capacity.

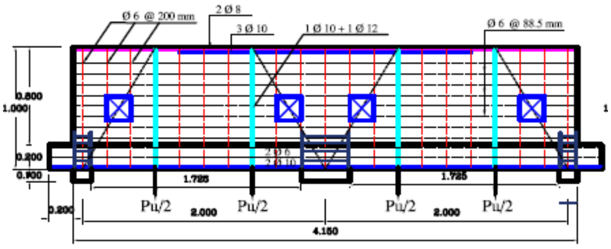
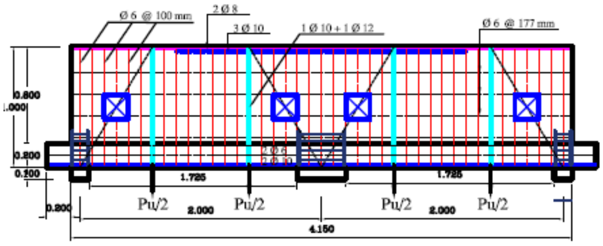
5.2. Effect of Web Reinforcement Ratio

To investigate the effect of web reinforcement ratio on the behavior of the bottom loaded continuous deep beams, twospecimenswithdifferent horizontal web reinforcement ratios of0.632, & 1.13% modeled, and anothertwobeamswith vertical reinforcement ratios of 0.56, & 1 % chosen for modeling and comparing the results obtained from FEM to the control CDB2. On the other hand, one beam with both 0.632% and 0.56% of horizontal and vertical web reinforcement ratio respectively was analyzed to investigate the effect of all web reinforcement ratio on the behavior of deep beams. The details of specimens shown in figure (13). The results show that the ultimate capacity increased by 10 % to 15%, and 10% to 20% with increasing of either horizontal or vertical web reinforcement ratiorespectively. It can be observed that the increasing of ultimate load is very sensitive to the vertical web reinforcement ratio due to the effect of increasing confinement of the section and the stresses redistribution on horizontal reinforcement. In addition, the stiffness of the beam was increased. Figure (14) shows the effect of web RFT on ultimate capacity of CDB.

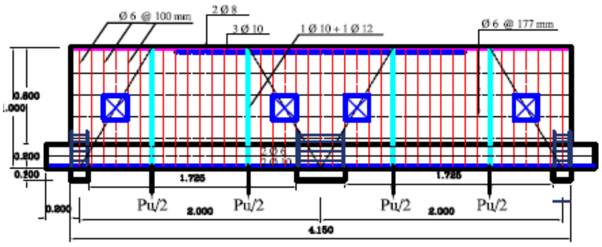
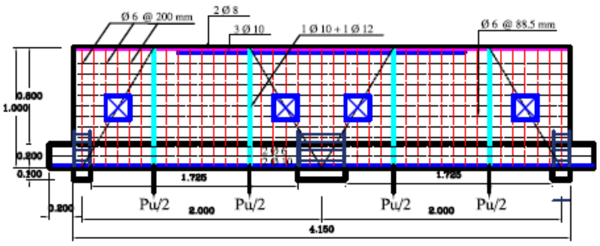
From the results, it can be concluded that the vertical web reinforcement ratio is the more efficient than the horizontal web reinforcement ratio and increasing both horizontal and vertical web reinforcement on the same specimen, the ultimate capacity of CDB with web openings is approximately similar to the ultimate capacity of the CDB without web openings.



CDB2 **CDB6**

CDB7 CDB8

CDB9 CDB10

Fig. (13): Effect of Horizontal and Vertical RFT Ratio Specimens Details.

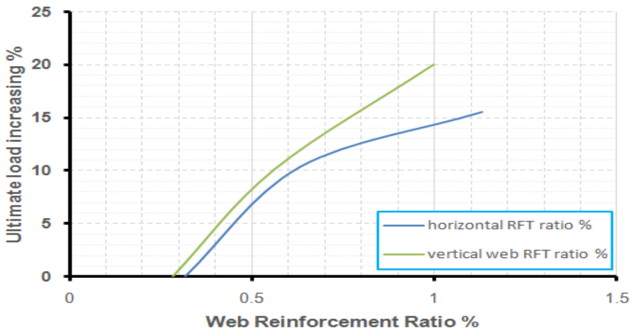
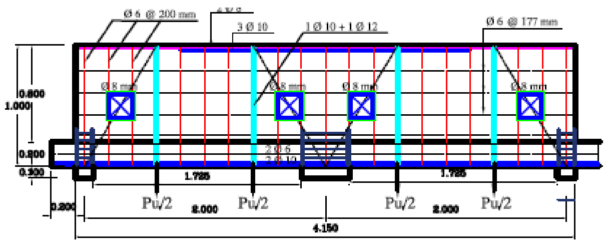
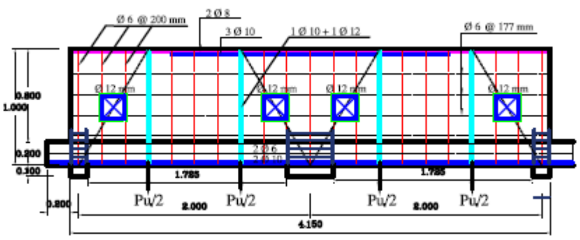


Fig. (14): Effect of Web Reinforcement Ratio on Capacity Of CDB.

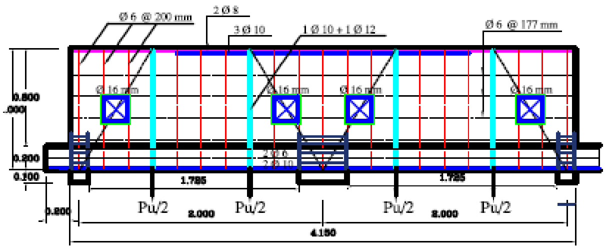
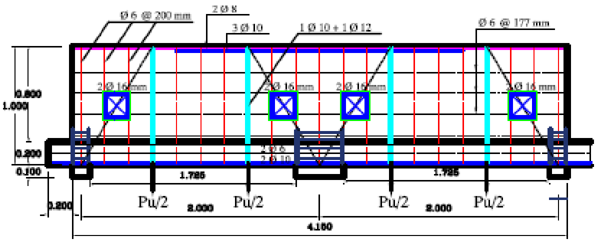
5.3. Effect of Additional RFT Around the Web Openings

Three different additional RFT ratios were used to investigate their effect on behavior of CDB, the ratios were 0.428%, 0.856%, and 1.712%. The reinforcement was added in two layers around the opening with equal diameter and numbers for each ratio. Figure (15) shows the detailing of FEM analyzed with ABAQUS software.

The increasing on ultimate capacity of CDB using each ratio was compared were changed from 0.37% to 1.12%, and it is observed that it has insignificant effect on ultimate capacity of CDB as shown in figure (16).

CDB2 CDB11

CDB12 CDB13

Fig. (15): Effect of Additional RFT Ratio Around Web Openings Specimens Details.

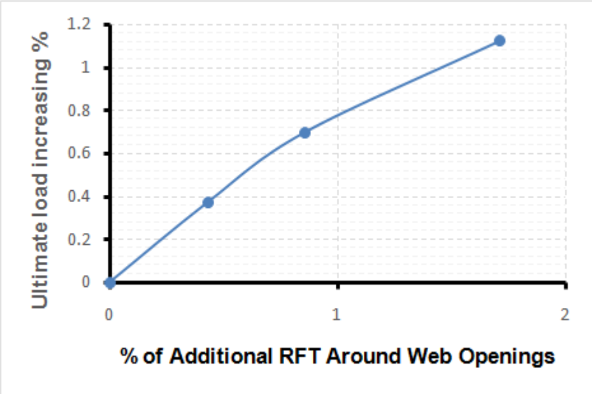
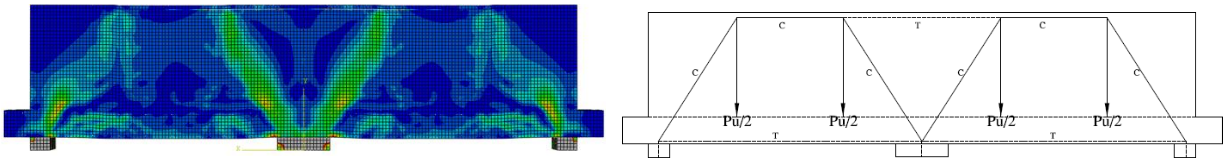


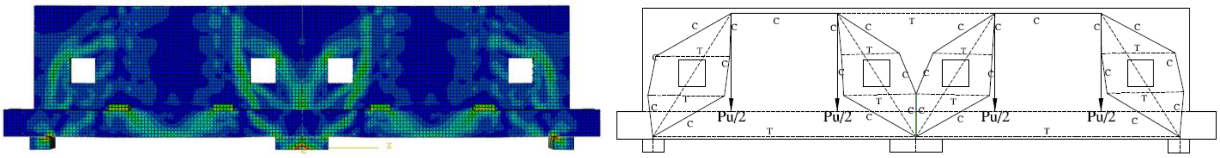
Fig. (16): Effect of Additional RFT Ratio Around Opening on CDB Capacity.

5.4. Strut-And-Tie Model Prediction for Bottom Loaded Continuous Deep Beams

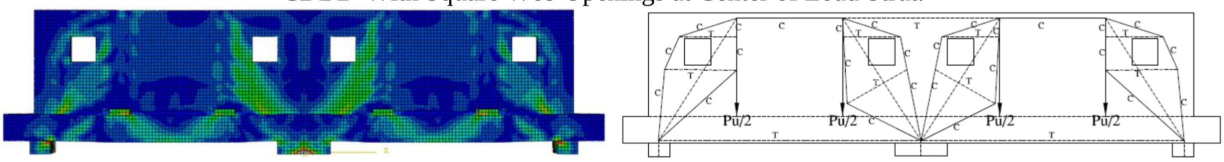
Using the stress distribution obtained from FEM along the CDB, simplest strut-tie models can be obtained, as shown in figure (17). The opening type & position and web reinforcement ratio specially the vertical web RFT ratio, affect the shape of strut-tie model. For CDB with web openings, approximately same simplified strut-tie model can be used for all specimens unless for specimens with different web openingspositions.



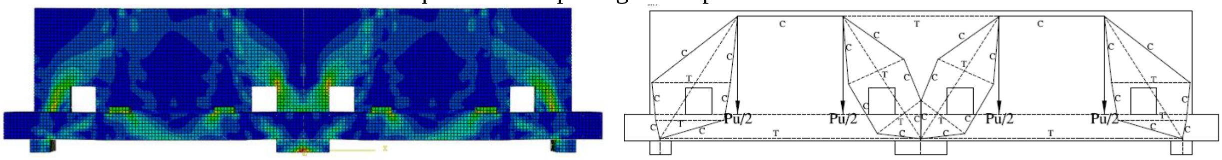
CDB1- Without Web Openings.



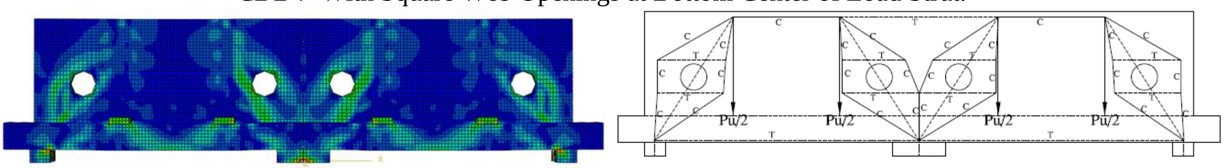
CDB2- With Square Web Openings at Center of Load Strut.



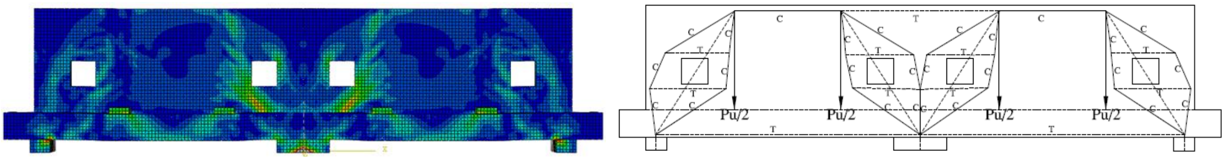
CDB3- With Square Web Openings at Top Center of Load Strut.



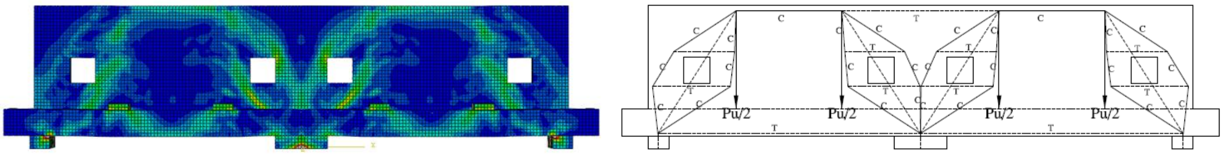
CDB4- With Square Web Openings at Bottom Center of Load Strut.



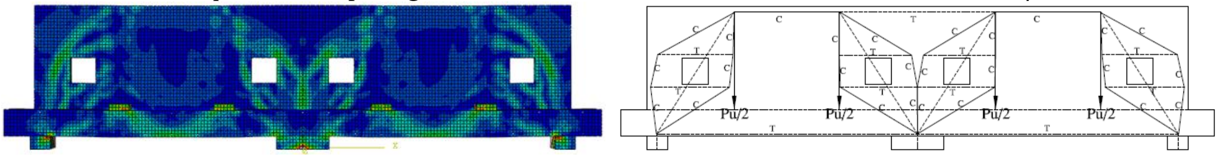
CDB5- With Circular Web Openings at Center of Load Strut.



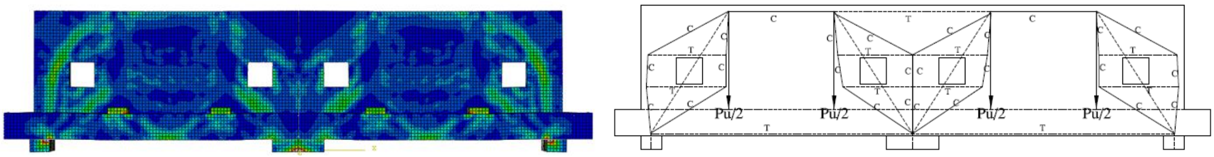
CDB6- With Square Web Openings at Center of Load Strut and Horizontal web RFT ratio, ρ_h = 0.632 %.



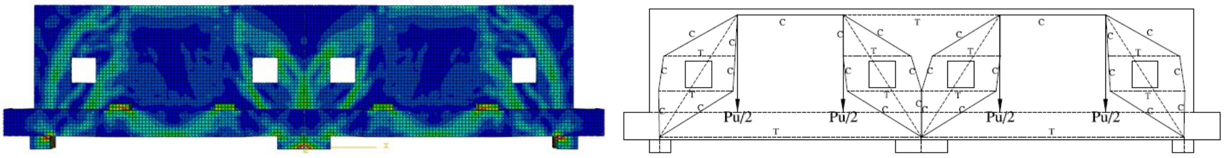
CDB7- With Square Web Openings at Center of Load Strut and Horizontal web RFT ratio, ρ_h = 1.13 %.



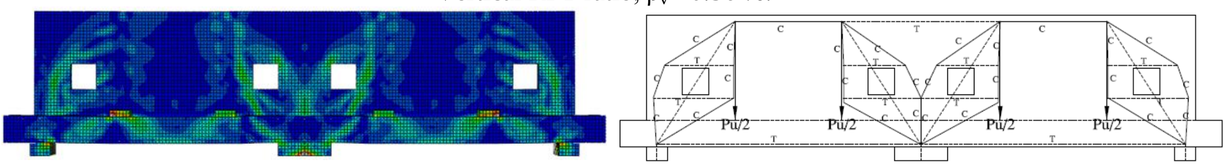
CDB8- With Square Web Openings at Center of Load Strut and Vertical web RFT ratio, ρ_v = 0.56 %.



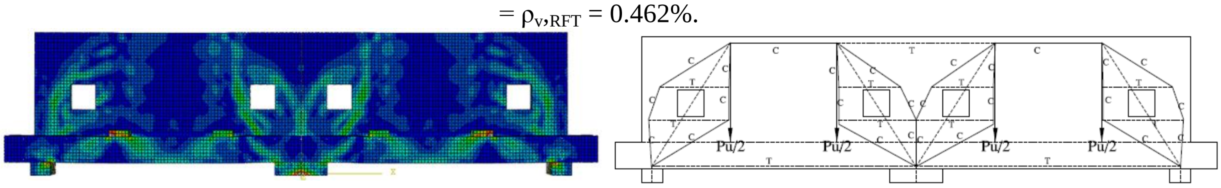
CDB9- With Square Web Openings at Center of Load Strut and Vertical web RFT ratio,ρ_v = 1 %.



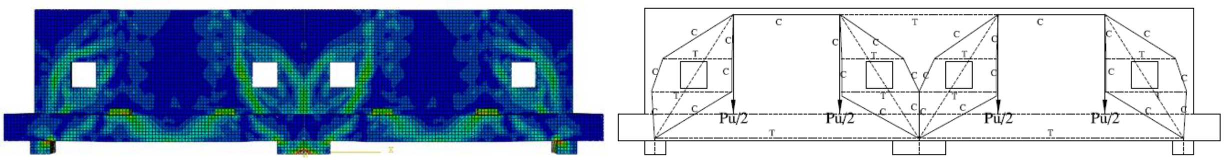
CDB10- With Square Web Openings at Center of Load Strut and Horizontal RFT ratio,ρ_h = 0.632 %, and Vertical RFT ratio, ρ_v =0.56 %.



CDB11- With Square Web Openings At Center Of Load Strut and Additional RFT Around Web Openings$\rho_{h,RFT}$ = $\rho_{v,RFT}$ = 0.462%.



CDB12- With Square Web Openings at Center of Load Strut and Additional RFT Around Web Openings$\rho_{h,RFT}$ = $\rho_{v,RFT}$ =0.82%.



CDB13- With Square Web Openings at Center of Load Strut and Additional RFT Around Web Openings$\rho_{h,RFT}$ = $\rho_{v,RFT}$ = 1.64%.

Fig. (17): Simplified Strut-And-Tie Model Developed for Each Bottom Loaded CDB.

VI. Conclusions

This research presents a prediction of behavior of bottom loaded continuous deep beams with web openings using calibrated finite element model developed by ABAQUS software program. Based on the results obtained from FEM, the next conclusions observed:

- The results obtained from FEM model had good agreement with experimental results from literature and the model can be used for investigation the behavior of CDB with or without opening.
- The ultimate capacity of CDB with web openings increased when the position of web openingswasat either the top or bottom of the center of load path.On the other hand, the top position of the web openings is more sufficient than bottom web openings.
- Opening types has insignificant effect on ultimate capacity of CDB.
- By increasing either horizontal or vertical web reinforcement ratio, the ultimate capacity of CDB increased.
- Vertical web reinforcement ratio is more sufficient than horizontal web reinforcement ratio
- Additional reinforcement around the opening had insignificant effect on ultimate capacity of CDB.
- Generated simplified Strut-tie model based on FEM result for different case of studiesin this research can be used to investigatethe ultimate capacity of CDB analytically.

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