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ABSTRACT

As a common practice, concrete core test is one of the most significant investigations that can reasonably predict the in-situ concrete compressive strength of existing reinforced concrete elements. This test is categorized as a destructive test and has a direct impact on the column strength. In general, the testing specifications do not mention on the influence of core test on the column strength reduction. This paper presents a numerical study to investigate the RC column loading carrying capacity after extracting the core specimen. The analytical program consists of forty five full-scale columns with height of 3000 mm. The aspect ratios for the utilized column cross sections are (a/b) equal to 1, 1.33, 1.5, 2.33 and 3. Effect of the length to diameter ratio of the core hole (L/D) of values 1, 1.5 and 2 was studied. In addition, different concrete compressive strength were used to study the effect of concrete strength. The columns are axially loaded till failure. Finite Element Analysis (FEM) are used to model the specimens using the ABAQUS program. The Numerical models present all the above varying parameters. In addition, traditional analysis are carried out to predict the column carrying load with and without the core hole for the above mentioned parameters. The prediction was done using the equations stated by the Egyptian Code of Practice (ECP 203-2018)[1] and (ACI 318)[2] to predict the compression strength with a hole due to coring.
The study showed good agreement of the results from the numerical models and the calculated code equations. Finally, recommendations are given for the reduction in the RC column load carrying capacity under the effect of core hole.

Keywords: ABAQUS, Core Test, Finite Element, Load Carrying Capacity, RC Column

INTRODUCTION

Nowadays, core drilling is one of the most common test to evaluate the strength of concrete material in existing buildings. Core test is classified as a destructive test because the core would reduce the element cross section. Accordingly, the occurrence of the hole will introduce a geometrical discontinuity in the evaluated element. Consequently, the stresses around the hole will be changed and the compressive strength of the element cross section will be reduced [10].

Many testing specifications recommend specific diameters and lengths for the cores' samples. American Standard Test Method (ASTM) [3], British Standard (BS) [4] and German code (DIN) [5] recommend either 100 or 150 mm for the core diameter. However, in Concrete Institute of Australia (CIA) [6], recommend the values between 30 and 150 mm for the core diameter. In addition, those specifications suggest values of L/D ratios from 1 to 2.

Kypros Pilakoutas 2006 [7], evaluate the effect of the drilled holes on the behavior of RC columns and found that holes in columns leads to a loss of the column load-bearing capacity. The analysis concluded that this loss is directly proportional to the loss of the area. The research recommended that the reduction in column capacity is assessed against the design actions, and if necessary, remedial strengthening in the region of the holes will need to take place. Furthermore, it was stated that holes may accelerate the instability effects of slender columns and, hence, it is recommended that codified slenderness bounds need to take into account the effect of large transverse holes. Ehab M. Lotfy 2006 [8], study the effect of holes on 21 RC column specimens using ANSYS [12] software. The research concluded that the hole with diameter more than 0.15 of columns length has significant effect on the column behavior by reducing the ductility and the toughness of tested columns. The increase of hole dimension to be more than 0.15 of columns length leads to reduction in the ultimate loads of the tested columns by ~ 80%. Using square hole in tested column has a significant effect on the behavior of tested columns. Holes can be made in middle third of columns with diameter up to 0.15 column length. ZHU Lei 2010 [9], has studied experimentally the RC column capacity which is affected by core drilling through testing nine short columns specimens. Those experimental studies present that the axial compression capacity of RC columns after core drilling is reduced by 5.63% to 22.14% while the ultimate displacement decreases from 1.88% to 26.14%. Giovanni Minafò 2012 [10], establish an analytical model to predict the load-carrying capacity of RC columns with core holes. The research concluded that the most damaging effect was reached when the center of the hole was placed along the column axis. In addition, great losses of load-carrying capacity occurred also for small-hole dimensions if low amount of transverse reinforcement was provided. Mohsen Falahatkar 2015 [11], studied the influences of cores with diameters of 100 and 150 mm and L/D ratio of 1,1.5 and 2 on load carrying capacity of RC column reinforced by three different longitudinal bars ratios using ABAQUS [13] software. The conclusion developed from the study is that the RC column load carrying capacity is affected by core hole drilling, but by increasing the longitudinal reinforcement ratio the effects of core hole would be less. Also, the results showed that the effect of core with diameter of 100 mm has an effect less than the core with diameter of 150 mm on the load carrying capacity.

RESEARCH PLAN

A numerical analysis program consisted of modeling forty-five full-scale RC columns and divided into five groups is performed. The dimensions of columns' samples are 300x300, 300x400, 300x600, 300x700 and 300x900 mm with 3000 mm height. All columns were reinforced with longitudinal reinforcement ratio of 1 % and with transvers stirrups reinforcement equal to 5 stirrups for each one meter as shown in Figs.1a and 1b. The yield stress of the used longitudinal and transvers reinforcement was 400 and 240 MPa, respectively. Different cores' diameters were used equal to 50, 100 and 150 mm to study the parameter of the core hole L/D ratio effect on the RC column capacity. The cores lengths were 75, 100, 150 and 200 mm as shown in table 1.

Various values of the compressive strengths of the concrete cylinders were used to study the effect of core hole with L/D ratio equal to 1.5 when the concrete strengths are changed. The columns types C1, C4, C7, C10 and C13 were modeled with concrete strength equal to 25 MPa. However, concrete strength equal to 30 MPa was used for the columns types C2, C5, C8, C11 and C14. In addition, concrete strength equal to 40 MPa was used for the columns types C3, C6, C9, C12 and C15.

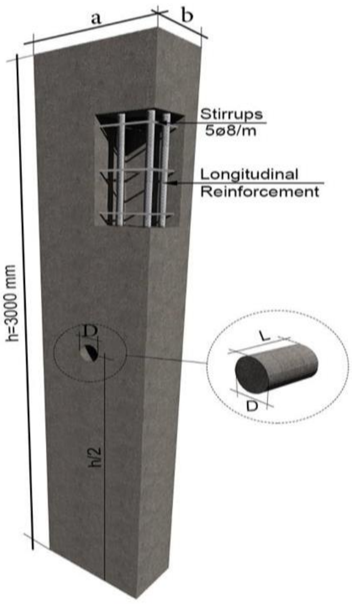

Fig. 1a Schematic Diagram for the Modeled Column

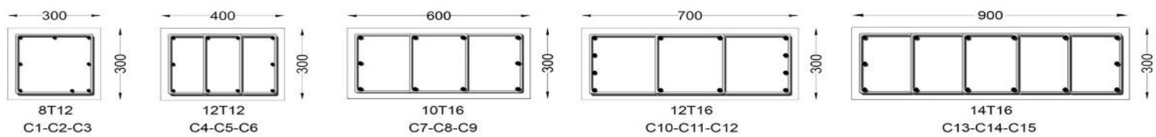

Fig. 1b Columns Dimensions and Reinforcement Details

Table 1: Modeled columns

Column Type	f'c (MPa)	Core Dimensions Length (mm)	Diameter (mm)	L/D Ratio	Column Type	f'c (MPa)	Core Dimensions Length (mm)	Diameter (mm)	L/D Ratio
C1-1	25	--	--	--	C10-1	25	--	--	--
C1-2		100	100	1	C10-2		100	100	1
C1-3		150	100	1.5	C10-3		150	100	1.5
C1-4		75	50	1.5	C10-4		75	50	1.5
C1-5		200	100	2	C10-5		200	100	2
C2-1	30	--	--	--	C11-1	30	--	--	--
C2-2		150	100	1.5	C11-2		150	100	1.5
C3-1	40	--	--	--	C12-1	40	--	--	--
C3-2		150	100	1.5	C12-2		150	100	1.5
C4-1	25	--	--	--	C10-1	25	--	--	--
C4-2		100	100	1	C10-2		100	100	1
C4-3		150	100	1.5	C10-3		150	100	1.5
C4-4		75	50	1.5	C10-4		75	50	1.5
C4-5		200	100	2	C10-5		200	100	2
C5-1	30	--	--	--	C11-1	30	--	--	--
C5-2		150	100	1.5	C11-2		150	100	1.5
C6-1	40	--	--	--	C12-1	40	--	--	--
C6-2		150	100	1.5	C12-2		150	100	1.5
C7-1	25	--	--	--	C13-1	25	--	--	--
C7-2		100	100	1	C13-2		100	100	1
C7-3		150	100	1.5	C13-3		150	100	1.5
C7-4		75	50	1.5	C13-4		75	50	1.5
C7-5		200	100	2	C13-5		200	100	2
C8-1	30	--	--	--	C14-1	30	--	--	--
C8-2		150	100	1.5	C14-2		150	100	1.5
C9-1	40	--	--	--	C15-1	40	--	--	--
C9-2		150	100	1.5	C15-2		150	100	1.5

Where columns C1, C2, C3 have dimension of 300 x 300 mm,
columns C4, C5, C6 have dimension of 300 x 400 mm,
columns C7, C8, C9 have dimension of 300 x 600 mm,
columns C10, C11, C12 have dimension of 300 x 700 mm, and
columns C13, C14, C15 have dimension of 300 x 900 mm.

FINITE ELEMENT MODELING OF RC COLUMNS

Nonlinear finite element method (NFEM) is used to analyze the RC columns under variable parameters. Many factors are considered to model the behavior of the RC columns such as the material nonlinearity, the boundary conditions, and the interaction between the structure's constituents. ABAQUS [13] program was used to model the RC columns since it has the capability of modeling the nonlinear behavior of concrete and steel. In addition, it is also capable of treating steel as a separate input entity, allowing it to be modeled independently of concrete elements.

Three-dimensional 4-nodes first order fully integration continuum elements (tetrahedral elements C3D4) were used to model the concrete columns specimens as shown in Fig.3. However, 2-nodes first order truss elements (T3D2 - Truss) were used to model both the longitudinal and transverse reinforcement bars in the concrete column model as shown in Fig.4. A bilinear elastic–plastic model with the von misses yield criterion was used to describe the constitutive behavior of the steel reinforcement, which was used for the RC column.

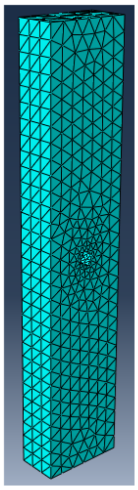

Fig.3 concrete part 3D Meshing

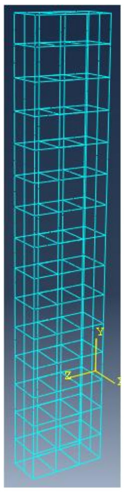

Fig.4 steel reinforcement

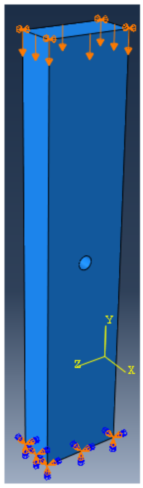

Fig.5 Loading and defined boundary conditions places.

Fig. 5 presents the boundary conditions for the models created with 3D solid elements and defined as follow:

Pin Support 1: bottom surface of columns were locked against translation in all directions vertical (Y-direction), transverse (X-direction) and longitudinal (Z-direction).

Pin support 2: nodes at top surface of column were locked against translation in two transverse directions (X-direction) and (Z-direction).

Centric uniform load-displacement is distributed on the loaded area as shown in Fig.5.

Figures 6a, 6b and 7 show the stress–strain relation for both concrete and steel reinforcement, respectively.

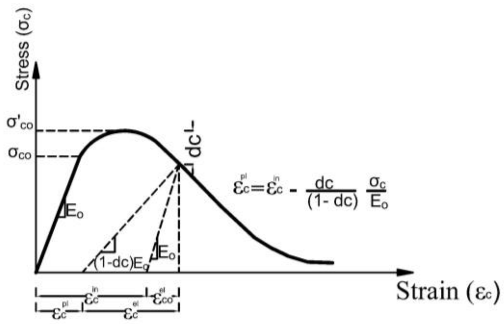

Fig.6a Concrete Compressive Stress-strain Relation in ABAQUS [13]

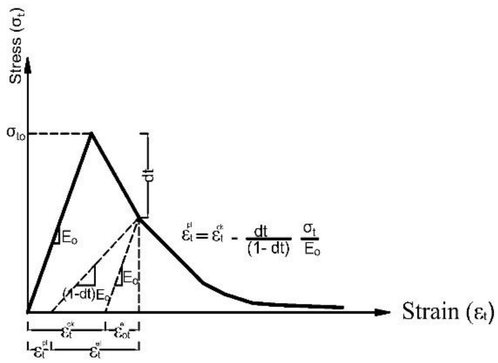

Fig.6b Terms for Tension Stiffening Model in ABAQUS [13]

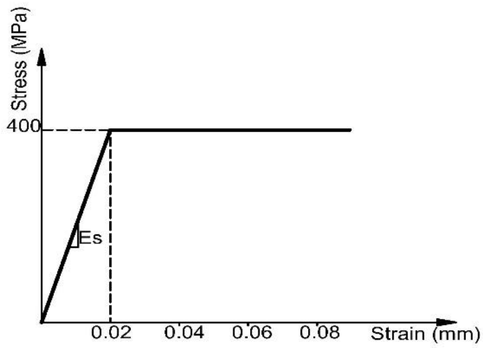

Fig.7 Steel Reinforcement Stress-Strain Relation in ABAQUS [13]

MODEL VALIDATION

Verification models are done on different samples to certify the validity of the models. That is done through numerical evaluation models for similar experimental ones. The utilized experimental models are done by ZHU Lei [9]. A benchmark test has been carried out using seven specimens of reinforced concrete columns, which were studied experimentally to evaluate the load carrying capacity of the RC columns with and without core drilling. Table 2 presents the configuration of those investigated columns. The analytical and experimental results are tabulated below.

Table 2: Comparison between the experimental and the analytical results

Group NO.	Specimen	Column Dimension	Location of drilled core	Experimental Ultimate load (P_{exp}) (kN)	Analytical Ultimate load (P_{Th}) (kN)	P_{Th}/ P_{Exp}
1*	C1	300x300	---	1616	1610	0.99
	C2	300x300	Offset center	1525	1455	0.95
2**	C3	400x400	---	2872	2920	1.01
	C4	400x400	Offset center	2236	2719	1.21
	C5	400x400	center	2448	2465	1
3**	C6	400x600	---	4446	4394	0.99
	C7	400x600	Offset center at short direction	4031	4136	1.03

Reinforcement ratio of all specimens is 1% except C6 and C7 are 0.84% from concrete column area.
* Reinforcement yield stress is 385 MPa, ultimate yield stress is 551 MPa and f'c is 19.5 MPa.
** Reinforcement yield stress is 367 MPa, ultimate yield stress is 525 MPa and f'c is 19.5 MPa.
Note: Column height is equal to1200-mm.

Studying the previous Table 2, it is found that the numerical models achieved good agreement with the experimental models results except for C4 sample. It is found that using concrete modulus of elasticity according to Euro code gives close results to the experimental results.

RESULTS OF THE NUMERICAL INVESTIGATED MODLES

The models, previously defined in Table 1, are numerically investigated and the results are

Load Carrying Capacity

Tables 3, 4, 5, 6 and 7 present the maximum calculated loads of columns types C1, C4, C7, C10 and C13 respectively. In addition, Figs. 8, 9, 10, 11 and 12 display the reduction ratio in the load carrying capacity.

The maximum calculated load (P_{max}) for columns types C1-1, C1-2, C1-3 and C1-5 were 2210, 2039, 1940 and 1855 kN consequently. In addition, the calculated maximum load for column C1-4 is 2144. The reduction ratio in the column capacity due to the existence of core holes for columns C1-2, C1-3, C1-4 and C1-5 are 7.7%, 12.2%, 3% and 16.1% consequently. It is found that increasing the aspect ratio of the core dimension, L/D, ratio could lead to increase the reduction ratio in the column capacity up to 16.1%. Also, one can notice that the reduction ratio in the column capacity of column C1-3 with core hole dimension of 100x150 more than column C1-4 with core hole dimension of 50x75.

The maximum calculated load (P_{max}) for columns C4-1, C4-2, C4-3 and C4-5 were 2943, 2723, 2674 and 2617 kN. However, the maximum load for column C4-4 is 2921 kN. The reduction ratio in the column capacity due to the effect of the core hole compared to the column without core hole for columns C4-2, C4-3, C4-4 and C4-5 are 7.5%, 9.1%, 0.7% and 11.1% respectively. It is found that increasing the L/d ratio leads to increase the reduction ratio in the column capacity up to 11.1%. Also, it is found that the reduction in the column capacity of column type C4-3 was more than column type C4-4. Since The dimension of the core hole in column C4-3 is 100x150mm and in column C4-4 is 50x75mm.

Columns types C7, C10 and C13, which were modeled from concrete strength equal to 25 MPa, the reduction in the column capacity due to the effect of the core hole length and diameter, compared to the column without core hole was varied from 2.2% to 4.6%. This is leads to conclude that increasing the L/D ratio has a minor reduction effect on the column capacity for columns with dimension starting from 300x600 mm to 300x900 mm. This is mainly attributed to the increase in dimensions of column compared to the core hole dimensions as shown in Fig. 13.

Table 3: Maximum calculated loads for columns C1-1, C1-2, C1-3, C1-4 and C1-5

Column Type	P_{max} (kN)	Reduction Ratio (%)*
C1-1	2210	---
C1-2	2039	7.70
C1-3	1940	12.2
C1-4	2144	3.00
C1-5	1855	16.1

* Reduction Ratio: Is the maximum calculated load for the same column with core hole compared to the maximum calculated load without core effect (Control specimen).

Reduction Ratio= $\frac{P_{max-1}-P_{max-2}}{P_{max-1}}$

P_{max-1}: Maximum calculated load for the column without core hole

P_{max-2}: Maximum calculated load for the column with core hole

Table 4: Maximum calculated loads for columns C4-1, C4-2, C4-3, C4-4 and C4-5

Column Type	P_{max} (kN)	Reduction Ratio (%)
C4-1	2943	---
C4-2	2723	7.5
C4-3	2674	9.1
C4-4	2921	0.7
C4-5	2617	11.1

Table 5: Maximum calculated loads for columns C7-1, C7-2, C7-3, C7-4 and C7-5

Column Type	P_{max} (kN)	Reduction Ratio (%)
C7-1	4276	---
C7-2	4171	2.5
C7-3	4120	3.7
C7-4	4264	0.3
C7-5	4078	4.6

Table 6: Maximum calculated loads for columns C10-1, C10-2, C10-3, C10-4 and C10-5

Column Type	P_{max} (kN)	Reduction Ratio (%)
C10-1	4926	---
C10-2	4848	1.6
C10-3	4816	2.2
C10-4	4915	0.2
C10-5	4757	3.4

Table 7: Maximum calculated loads for columns C13-1, C13-2, C13-3, C13-4 and C13-5

Column Type	P_{max} (kN)	Reduction Ratio
C13-1	6329	---
C13-2	6231	1.5
C13-3	6182	2.3
C13-4	6301	0.4
C13-5	6147	2.9

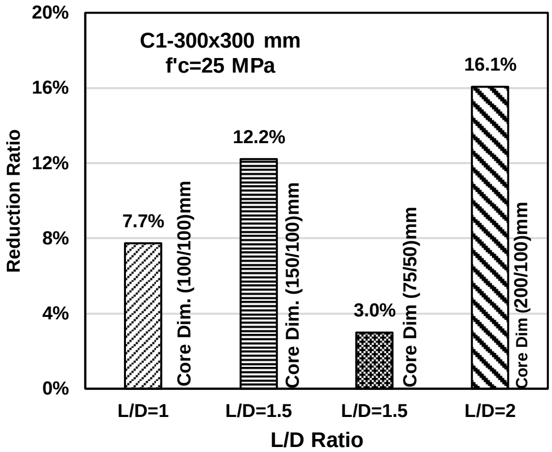

Fig 8: Effect of different L/D ratios on the reduction ratio for column C1-300x300

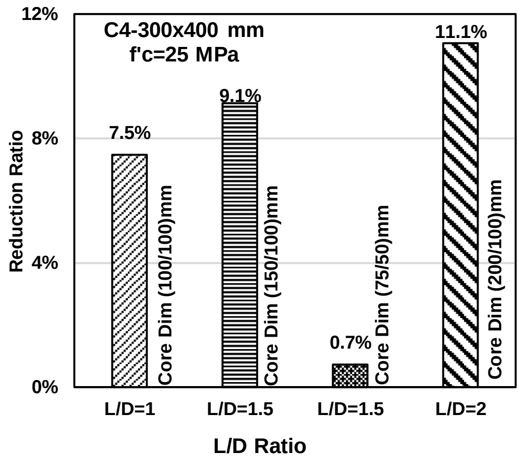

Fig 9: Effect of different L/D ratios on the reduction ratio for column C4-300x400

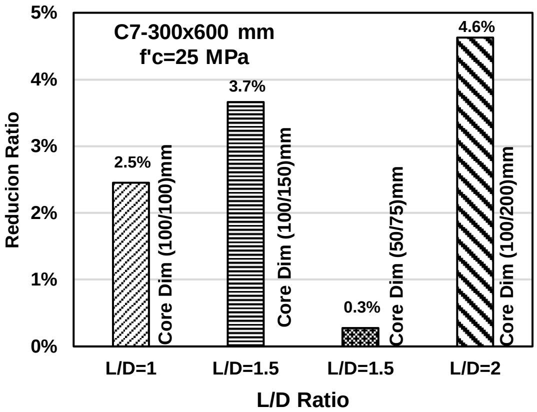

Fig 10: Effect of different L/D ratios on the reduction ratio for column C7-300x600

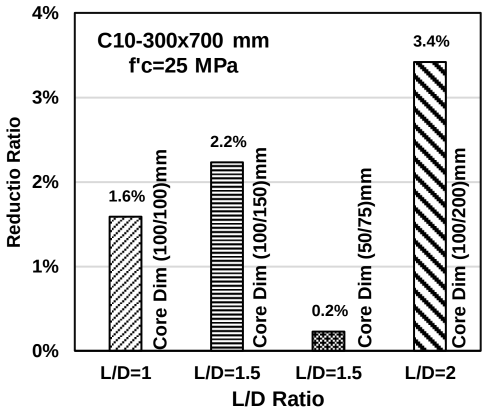

Fig 11: Effect of different L/D ratios on the reduction ratio for column C10-300x700

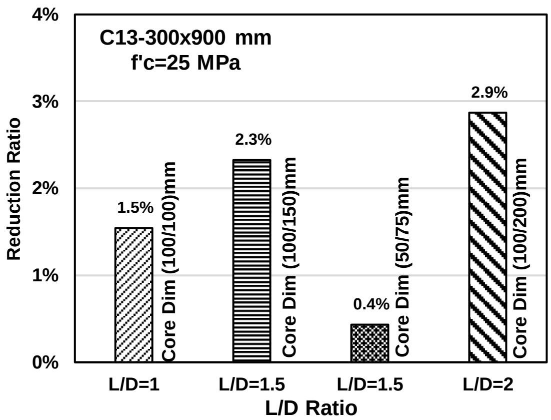

Fig 12: Effect of different L/D ratios on the reduction ratio for column C13-300x900

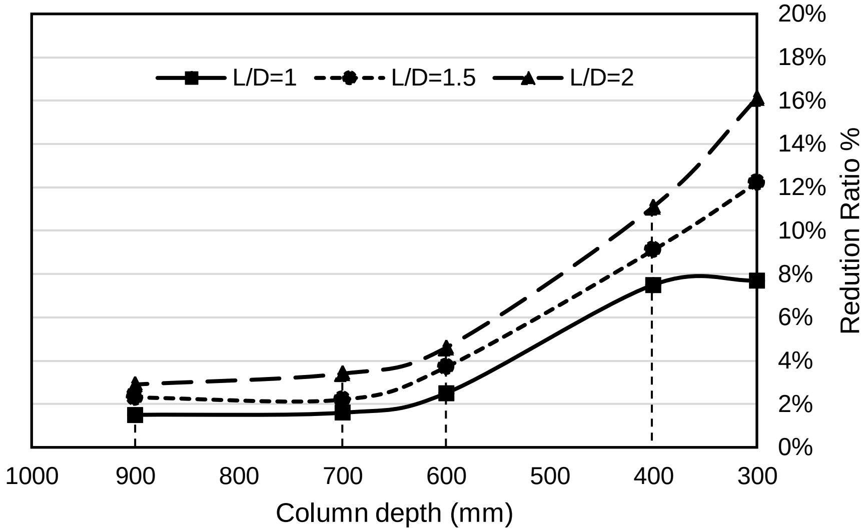

Fig 13: The strength reduction ratios for columns with width of 300 mm and different depths for several ratios of the core aspect ratio, L/D.

Table 8 shows the maximum load and the reduction ratio in the load carrying capacity of RC columns with the same concrete compression strength and variable column sizes: columns C2, C5, C8, C11 and C14. Also, table 9 shows the maximum load and reduction ratio in the load carrying capacity of RC columns with compression strength of 40 MPa of columns titled C3, C6, C9, C12 and C15.

Studying the results in the shown table one can notice that specimens with core aspect ratio of L/D =1.5 (core dimension is 100x150) the reduction ratio for columns C1-3, C2-2, C3-2 are 12.2%, 12.7%, and 13.4% where the compressive concrete strength varied as 25, 30, 40 MPa.

In addition, columns with larger dimension and core aspect ratio of L/D =1.5 of columns C4-3, C5-2 and C6-2 have reduction ratio of 9.1%, 8.7%, and 10.5%, respectively where the compressive concrete strength varied as 25, 30, 40 MPa. You may notice that the reduction ratios are decreased with the increase of column sizes and increased with the increase of concrete compression strength.

Moreover, columns types C9, C12 and C15, which are modeled from concrete strength equal to 40 MPa, the reduction in the column capacity due to the effect of the core hole length and diameter, compared to the column without core hole is ~8%. Figures 14, 15, 16, 17 and 18 present the reduction ratios for columns types C1-3, C2-2, C3-2, C4-3, C5-2, C6-2, C7-3, C8-2, C9-2, C10-3, C11-2, C12-2, C13-3, C14-2 and C15-2 for various concrete strengths.

Table 8: Maximum calculated loads for columns C2-1, C2-2, C5-1, C5-2, C8-1, C8-2, C11-1, C11-2, C14-1 and C14-2

Column Type	f'c (MPa)	P_{max} (kN)	Reduction Ratio (%)*
C2-1	30	2647.2	---
C2-2	30	2310.4	12.7%
C5-1	30	3517	---
C5-2	30	3211.5	8.7%
C8-1	30	5275.8	---
C8-2	30	4844	8.2%
C11-1	30	6030	---
C11-2	30	5727	5%
C14-1	30	7716	---
C14-2	30	7346	4.8%

* Reduction Ratio: Is the maximum calculated load for the same column with core hole compared to the maximum calculated load without core effect (Control specimen).

Reduction Ratio= $\frac{P_{max-1}-P_{max-2}}{P_{max-1}}$

P_{max-1}: Maximum calculated load for the column without core hole

P_{max-2}: Maximum calculated load for the column with core hole

Note: L/D ratio equal to 1.5 with core dimension equal to 150-mm for length and 100-mm for the diameter.

Table 9: Maximum calculated loads for columns C3-1, C3-2, C6-1, C6-2, C9-1, C9-2, C12-1, C12-2, C15-1 and C15-2

Column Type	f'c (MPa)	P_{max} (kN)	Reduction Ratio (%)
C3-1	40	3255	---
C3-2	40	3054	13.4%
C6-1	40	4693	---
C6-2	40	4202	10.5%
C9-1	40	6979	---
C9-2	40	6408	8.2%
C12-1	40	8028	---
C12-2	40	7487	6.7%
C15-1	40	1030	---
C15-2	40	9599	6.8%

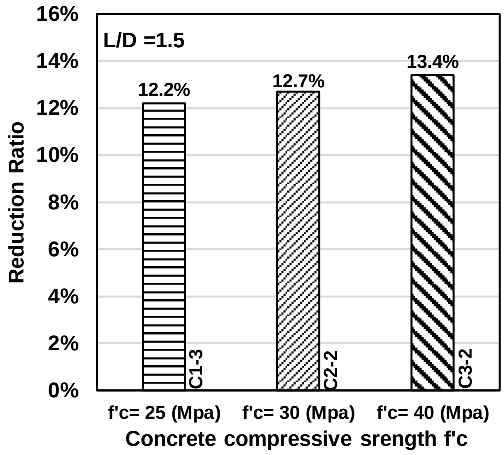

Fig 14: Reduction ratio for columns C1-3, C2-2 and C3-2 under effect of core hole with L/D ratio of 1.5

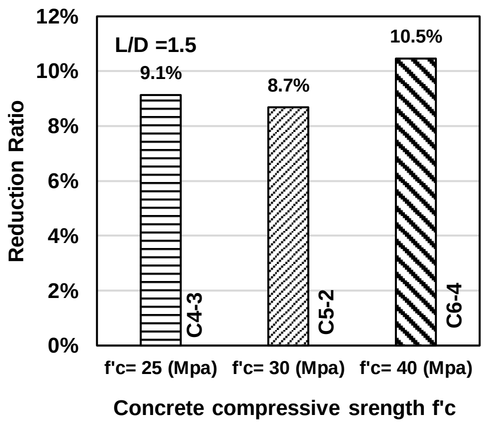

Fig 15: Reduction ratio for columns C4-3, C5-2 and C6-2 under effect of core hole with L/D ratio of 1.5

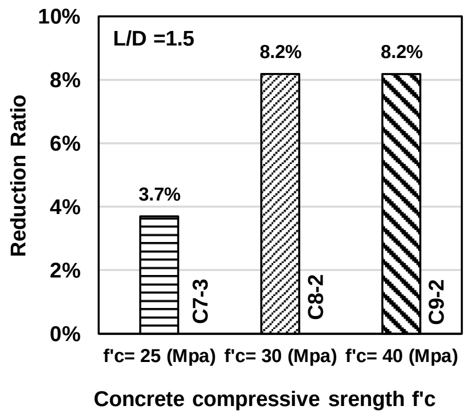

Fig 16: Reduction ratio for columns C7-3, C8-2 and C9-2 under the effect of core hole with L/D ratio of 1.5

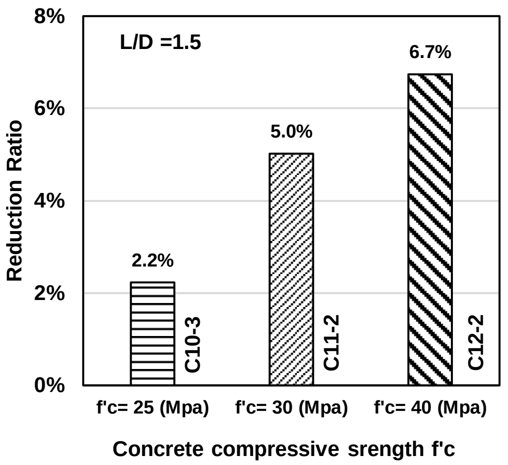

Fig 17: Reduction ratio for column C10-3, C11-2 and C12-2 under effect of core hole with L/D ratio of 1.5

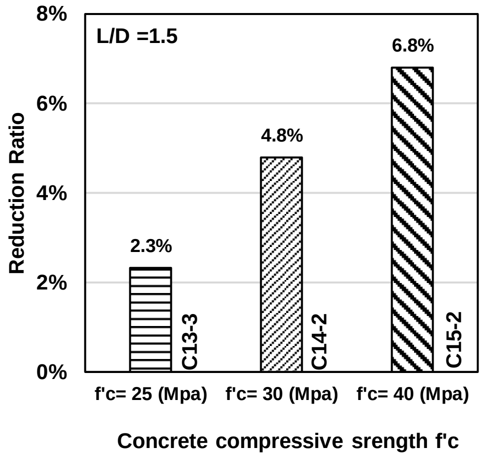

Fig 18: Reduction ratio for column C13-3, C14-2 and C15-2 under effect of core hole with L/D ratio of 1.5

CONCLUSIONS

Based on the previous data, the following conclusions can be drawn:

1. In general, the core drilling with different L/D ratio reduces the RC column Load carrying capacity.
2. The reduction of the column strength is pronounced for columns with small dimensions (less than 300x600mm) however samples with larger diameters (larger than 300x600mm) have minimum strength reduction ratio (less than ~4%). That conclusion is drawn for samples with L/D equal to 2. Reduction ratio of 12% is found for columns with dimension of 300x400m and 16% is found for columns with dimension of 300x300mm.
3. In RC columns with small dimensions, it is preferred to drill core with L/D equal to 75/50 mm to avoid a relatively large loss in column capacity taking into consideration that max aggregate size is equal 15 mm or less.
4. The strength reduction ratio of using core drilling in RC columns is increased with the increase of the concrete strength.

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