NONLINEAR ANALYSIS OF FIBER-REINFORCED SELF-COMPACTING CONCRETE HOLLOW SHORT COLUMNS SUBJECTED TO CONCENTRIC AND ECCENTRIC LOADS

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Abstract:
This study examines the load capacity of fiber-reinforced self-compacting concrete hollow short columns under eccentric and concentric loads. Different opening sizes and longitudinal steel reinforcement are used for the columns. The finite element software ABAQUS was utilized to model and examine the columns. A verification analysis of the nonlinear finite element modeling is conducted using the experimental test result. The verification of the model is established by considering all specifications of the empirically tested columns in the modeling process. Upon comparing the modeling and test findings, it becomes evident that a strong concurrence exists between them. Consequently, the correctness of the modeling is demonstrated. Additionally, a parametric investigation conducted different longitudinal steel reinforcement ratios and opening sizes with the same modeling technique. The impact of these variables on the column load capacity is examined. It was found that increasing the hollowing ratio from 0% (solid) to 8.7% (opening size of 50 mm) to 19.6% (opening size of 75mm) reduced the ultimate Load by 11% and 19.56%, respectively. The increasing hollowing ratio causes an increase in axial displacement by 12.2% and 25.2% and lateral displacement by 9.9% and 28.6% in the same order mentioned above. The elevation of the longitudinal reinforcement ratio from 1% to 2% with different diameters of (8, 10, and 12) mm leads to an escalation in the ultimate Load by 7.39% and 8.47%, respectively. The elevation of the longitudinal reinforcement ratio from 1% to 1.53% causes an increase in axial displacement by 4.81% and axial displacement by 4.13%. In comparison, the elevation of the longitudinal reinforcement ratio from 1.53% to 2% causes an increase in lateral displacement by 5.0% and lateral displacement by 6.67%. 12. Finally, the numerical study conducted that when e/h increased (from 0 to 0.13 to 0.27 to 0.4), the models' ultimate Load, axial displacement, and lateral displacement decreased.

Keywords: Hollow Columns, Solid Columns, Steel reinforcement ratio, Opening Size, Nonlinear analysis, and Abaqus.

Introduction

Hollow concrete columns have many preferred features over solid columns, such as using hollow columns in tall bridges in seismic areas. On the other hand, hollow columns constructed of high-strength concrete will reduce the members' weight, reduce the foundation's dimensions, and save on cost [1]. Hollow-reinforced concrete columns are commonly employed as primary compression elements in contemporary structural designs. Consequently, it is imperative to research their load capability [2]. Transverse and longitudinal openings are commonly incorporated into reinforced concrete columns to facilitate the provision of utilities such as plumbing and electrical wiring. ABAQUS is the most robust software for this task. The real-world behaviour of concrete material is accurately represented by the concrete damage plasticity model employed in the simulation process, resulting in a strong agreement between experimental and finite element results [3]. The prior research conducted on reinforced concrete columns utilizing the finite element method can be referenced as follows:

In 2018, **Lotfy** [4] conducted a study investigating the behavior of thin reinforced concrete columns under eccentric loads when reinforced with CFRPs. The study focuses on three specific approaches, aiming to improve these columns' axial and flexural stiffness. The experiment entailed applying an eccentric compressive force to ten full-scale specimens with rectangular cross-sections measuring 210 mm x 150 mm until failure was seen. **Al-Shaarbaf et al**. [5] 2018 studied how well slender concrete columns with openings held up under concentric Load and uniaxial bending. The ANSYS computer program (version 16.1) was utilized to conduct a numerical analysis. The analysis considered two factors: the ratio of longitudinal steel in the column's longitudinal bars and the grade of the longitudinal steel reinforcement (fy). The findings indicated that enhancing the steel ratio significantly enhances the maximum Load.

Additionally, elevating the reinforcement ratio decreased the tensile steel stresses, especially at the tension face. This improved the structure's Ability to hold more weight. In their 2018 study, **Yonas** et al. [6] examined the response of thin concrete-filled steel tube columns under eccentric loading by applying finite element analysis. The load-carrying capacity of the composite columns was analyzed using the finite element program ABAQUS 6.13-1. The prediction of mid-height deflection and axial load-carrying capacity with variable eccentricity was achieved through the utilization of a general non-linear approach. The findings indicate composite columns with reduced eccentricity, increased cross-sectional area, and greater steel tube thickness can support a more significant maximum load. The load-carrying capacity experiences a decline from 0% to 32.71% due to the increase in eccentricity from 0 mm to 157 mm. In 2020, **Khamees et al**. [7] examined the impact of cross-sectional shape, hollowing ratio, and fiber form on the behavior of hollow and solid slurry-infiltrated fiber concrete (SIFCON) columns. The ABAQUS computer program was utilized to conduct nonlinear finite element analysis on the axially loaded (SIFCON) columns. The findings indicated a high degree of concordance between the predictions and the actual outcomes. The findings demonstrated that SIFCON columns exhibited outstanding load-bearing capacity, flexibility, and energy absorption despite their narrow cross-sectional area and longitudinal holes. This was remarkably accurate for columns strengthened by combining different fiber types. Conversely, the performance of the column declined as the hollowing ratio grew. The outcomes also indicated that circular columns outperformed square columns with the same cross-sectional area.

Abdulrahman and Al-Zuhairi [8] conducted a study in 2020 where they utilized nonlinear finite element analysis to showcase the structural performance of thin SSRC columns. They employed both experimental and computational approaches for their investigation. The study relies on nine specimens that underwent failure testing and eighteen finite element models analyzed using the Abaqus software. Compared to square-shaped columns of equivalent dimensions, using SSRC columns resulted in a notable enhancement of around 12% in strength and a substantial reduction of nearly 40% in deformations. Two design formulas have been utilized to calculate the compressive strength of columns under concentric loading conditions. The structural performance of columns is satisfactory when compared to square-shaped columns of equivalent dimensions. Only a few numerical studies have examined the presence of longitudinal openings in thin columns. This study aimed to examine the behavior of numerically hollow, slender, reinforced concrete columns under axial and eccentric stresses. In 2021, **Al-Maliki et al.** [9] conducted a study on the analysis of the short reinforced concrete columns with varying cross-sections along the column. They used the ANSYS V.15 software package to do a linear analysis. The variables examined encompassed the section type, whether solid or hollow, the ratio of steel reinforcement and ties, the hollowness ratio, and the comparison of numerical findings with those derived from the prior investigation. The simulation results of the numerical analysis of the models show a high level of concurrence with the findings of experimental studies. The findings demonstrated a reduction in lateral displacement when the proportion of reinforcement in the longitudinal direction was increased compared to the reinforcement in the transverse direction. In 2022, **Braidi and Abd Ali** [3] examined the Ability of slender hollow reinforced concrete columns to sustain the Load and how they fail when subjected to concentric and eccentric stresses. The ABAQUS computer program was utilized to create the nonlinear finite element models. The experimental study outcomes were used to conduct a validation investigation of the numerical modeling. It was discovered that when the slenderness ratio increased, the peak load decreased. The peak load capacity was reduced by increasing the moment of inertia of both sections. The concrete's enhanced strength led to an increase in the maximum bearing capacity. Moreover, the finite element analysis outcomes strongly correlate with experimental test results.

Methodology

This study's foundation is validating concrete columns that were cast and subsequently tested within the Structures Laboratory of the Engineering College at Mustansiriyah University. (Experimental Investigation of Fiber-Reinforced Self-Compacting Concrete Hollow Short Columns under Axial Loads**)** [10]**.** All of those samples were cast using self-compacting concrete, silica fume and steel fibers [11]. The finite element approach was employed to simulate five columns. The first column was solid, while the remaining four columns were hollow and were designed with a corbel at the ends to withstand axial Load during testing, as illustrated in Fig. 1. The columns were distributed in two groups: the first group had different sizes of openings, and the second group had different longitudinal steel reinforcement ratios, as shown in Table 1.

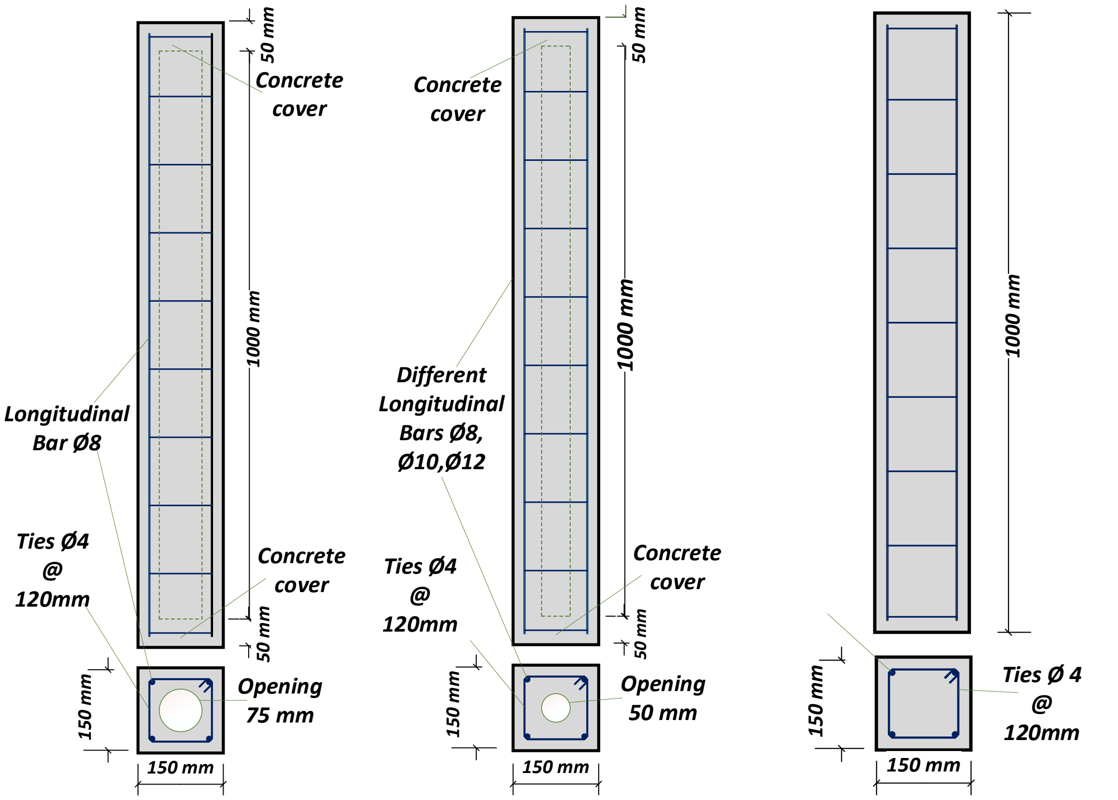

Fig (1) Column elevation and cross-section for Solid and Hollow Columns.

Table (1) Details of Experimental Columns [10]

Columns Designation	Variables	Size of Opening (mm)	Longitudinal Steel Reinforcement Ratio ρw %	Ultimate Load (kN)	Axial Disp. (mm)	Lateral Disp. (mm)
SCCH0R8	Size of Opening	0	1	818	1.96	0.096
SCCH50R8		50	1	728	2.16	0.104
SCCH75R8		75	1	658	2.41	0.123
SCCH50R8	Steel Reinforcement Ratio (ρw)	50	1	728	2.16	0.104
SCCH50R10		50	1.53	783	2.25	0.111
SCCH50R12		50	2.2	839	2.37	0.119

3. Finite Element Modeling

The finite element approach has emerged as a potent technique for the computational examination of various engineering issues. Applications encompass the examination of

deformation and stress in multiple structures, including buildings, bridges, and other civil engineering challenges. Utilizing current computer technology and computer-aided design techniques, intricate problems can be accurately represented with considerable ease [12].
To begin the analysis of solid and hollow reinforced concrete columns, the first step is to designate the element type. In ABAQUS, the model can be extended in any direction. Hence, a 3D solid element was generated in this study within the "modelling space," utilizing a deformable type specifically for the column. The 8-node linear brick element (C3D8R) was employed to construct the concrete column. This element can undergo plastic deformation, fracture in three mutually perpendicular directions, and crushing. The longitudinal and tie bars were modelled as a T3D2 truss element consisting of two nodes. Truss elements are rods that can carry only tensile or compressive loads. The concrete was modelled using the C3D8R linear hexahedron element. The T3D2 linear line element incorporated longitudinal (main bars) and tie reinforcement. The steel cups at the ends of the column capital were represented using the C3D8R linear hexahedron element.
The parameter value of the element was necessary for any tested columns that could be compared. They were utilized to approximate the properties and fundamental values of the material. Table (2) explains the element properties parameters.

Table (2) Element properties parameters

Element	Parameters	Description	Value
SCC Columns	f'c	Compressive Strength (MPa)	32.5
	ft	Tensile Strength (MPa)	5.3
	Ec	Young Modulus of Elasticity (MPa)	27545
	υ	Poisons Ratio	0.2
Steel Bars	Ab	Φ 4 mm	12.57
		Φ 8 mm	50.27
		Φ 10 mm	78.54
		Φ 12 mm	113.1
	fy	Yield Strength (Mpa)	582
	Es	Modulus of Elasticity (MPa)	200000
	υ	Poisons Ratio	0.3

3.1 Modeling and Meshing

The mesh size in finite element modeling has a noticeable effect on the accuracy of the results by dividing the model parts into many connected small units (these units are called elements). Within the present investigation, the meshes' dimensions were selected relative to the steel cup thickness of 2.5 mm to obtain accurate results, as shown in Figure (2). The column and steel cups have a mesh size of 2.5mm, while the steel bar is chosen to have a mesh size of 5mm.

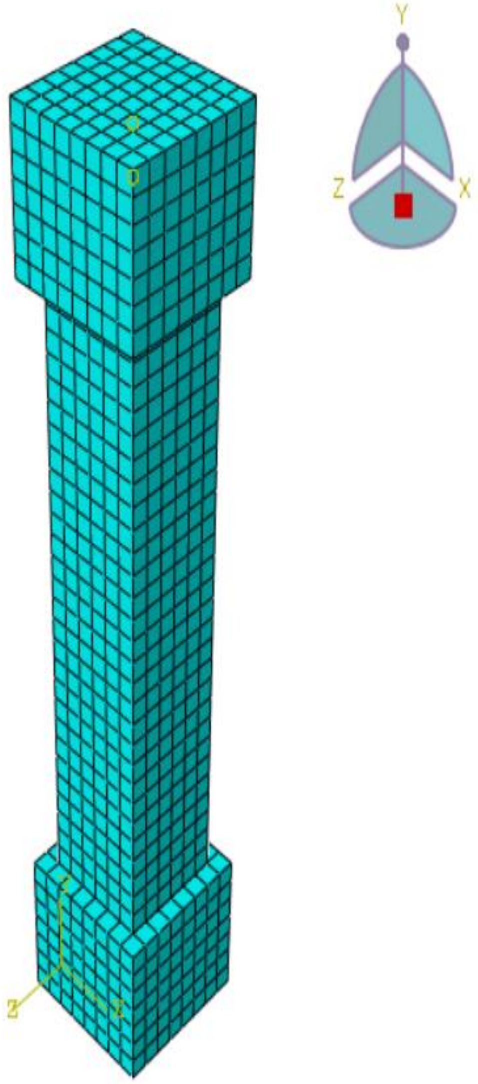

Figure (2) Meshing of Solid Concrete Column

3.2 Loading and Boundary Conditions

The support conditions were simulated as fixed-fixed-end conditions to replicate the experimental columns. To replicate these conditions, the lowest part of the column was chosen by restricting the movements along the x, y, and z axes of this base, as illustrated in Figure (3) Similarly, the boundary conditions for the top fixed end were specified, restricting only the displacement along the x and z axes.

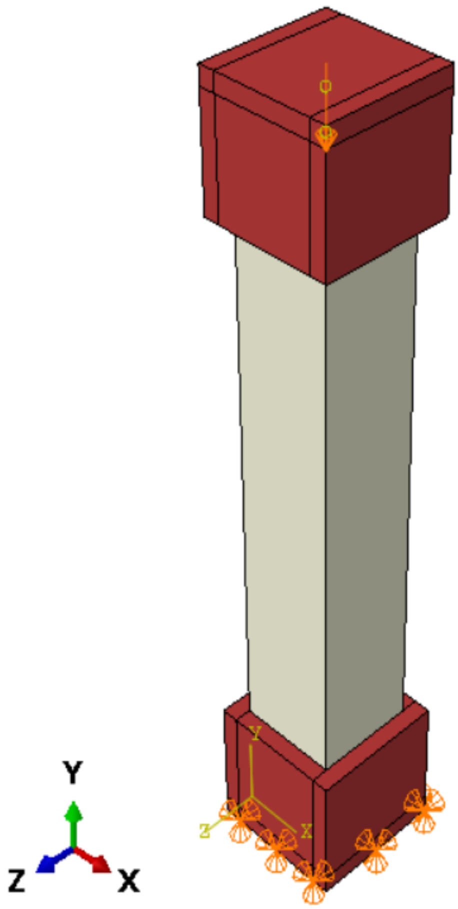

Figure (3) Locations of Load and Boundary Conditions

4. Results and Discussion

The ABAQUS program was executed to scrutinize the models after fulfilling all prerequisites and gathering the necessary data for the finite element simulation. The outcome was visually evaluated and conveyed through the load-displacement curve and deformed shape. The experimental results of the chosen specimen were compared with the numerical results of all examined samples to validate the numerical model. The comparison involved evaluating the maximum Load and maximum axial and lateral displacement. The following articles compare and discuss the theoretical and experimental maximum load and displacement results.

4.1 Load carrying capacity (Ultimate Load) of columns (Pu)

The ultimate load values of the tested concrete specimens were obtained and documented in Table (3) through finite element analysis (ABAQUS software) and experimental testing. A high degree of agreement (about 94-96%) exists between the experimental and finite element results for the ultimate Load. These percentages are deemed satisfactory.

Table (3) Numerical and Experimental Ultimate Load for SCC Columns

Columns	Pu (kN)		Maximum Axial Displacement (mm)		Maximum Lateral Displacement (mm)	
	EXP.	FEM	EXP.	FEM	EXP.	FEM
SCCH0R8	818	786	1.96	1.85	0.096	0.091
SCCH50R8	728	693	2.16	2.08	0.104	0.1
SCCH75R8	658	619	2.41	2.32	0.123	0.117
SCCH50R10	783	744	2.25	2.18	0.111	0.105
SCCH50R12	839	807	2.37	2.27	0.119	0.112

4.2 Load-Displacement Relationships for Models

Both the finite element and experimental load-axial displacement curves for the SCC concrete column SCCH0R50 are shown in Figure (4). The analysis of these curves demonstrates a high level of agreement with the experimental findings across the whole range of maximum Load, axial displacement, and lateral displacement. The numerical study reveals an increase of 3.9% for ultimate Load, 5.6% for axial displacement, and 5.2% for lateral displacement when comparing the two data sets.

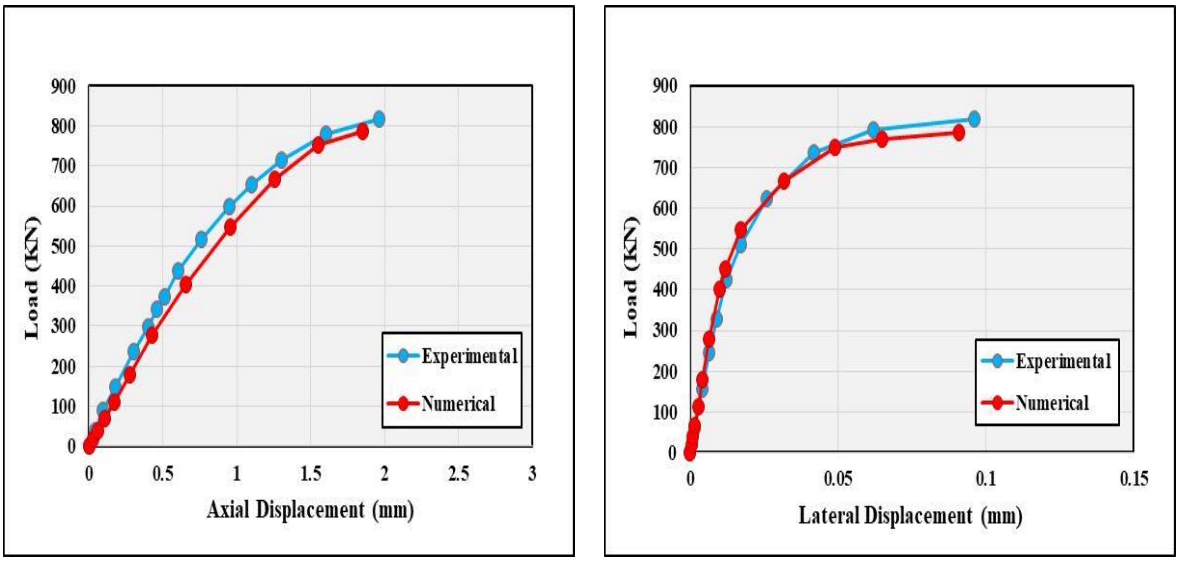

Figure (4) Comparison Between Experimental and Finite Element Load-Displacement for Column SCCH0R8

As shown in Figure (5), the ultimate Load experienced a growth of 4.8%, with axial displacement showing a 3.7% rise and lateral displacement exhibiting a 3.8% increase in the experimental results compared to the numerically simulated values for the concrete column SCCH50R8.

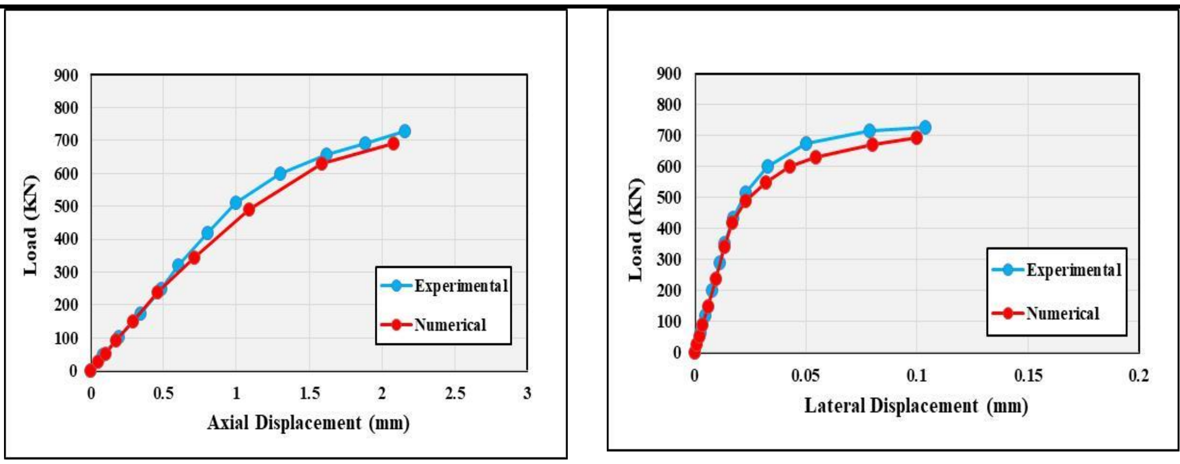

Figure (5) Numerical and Experimental Load-Displacement for Column SCCH50R8

By comparing the experimental and numerical results for a SCC concrete strength column SCCH75R8, it was found that the ultimate Load went up by 5.9%, the axial displacement increased by 3.7%, and the lateral displacement increased by 4.9%, as illustrated in Figure (6).

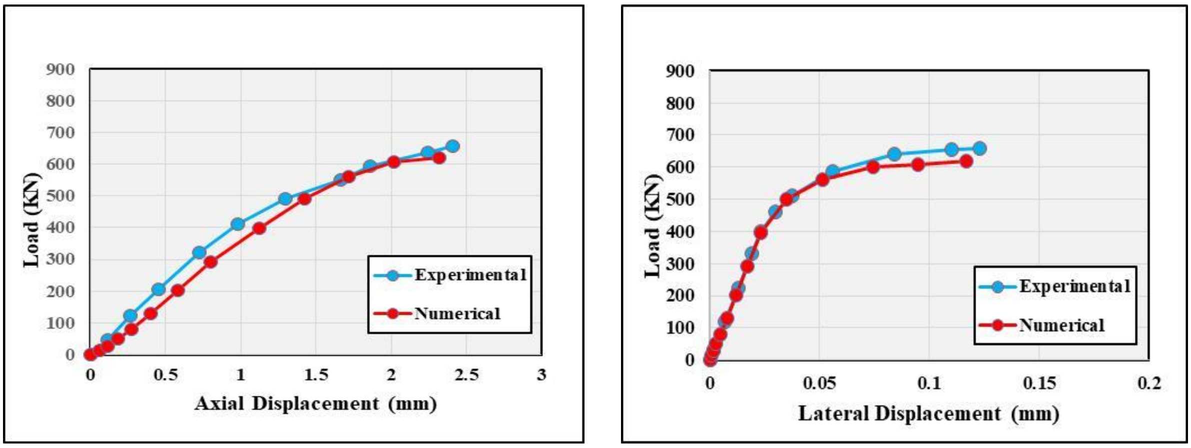

Figure (6) Numerical and Experimental Load-Displacement for Column SCCH75R8

The ultimate Load, axial, and lateral displacement increased in the experimental data for SCC concrete column SCCH50R10, going up by 5.0%, 3.1%, and 5.4%, respectively. This differed from the numerical concrete model, which had lower numbers, as seen in Figs. (7).

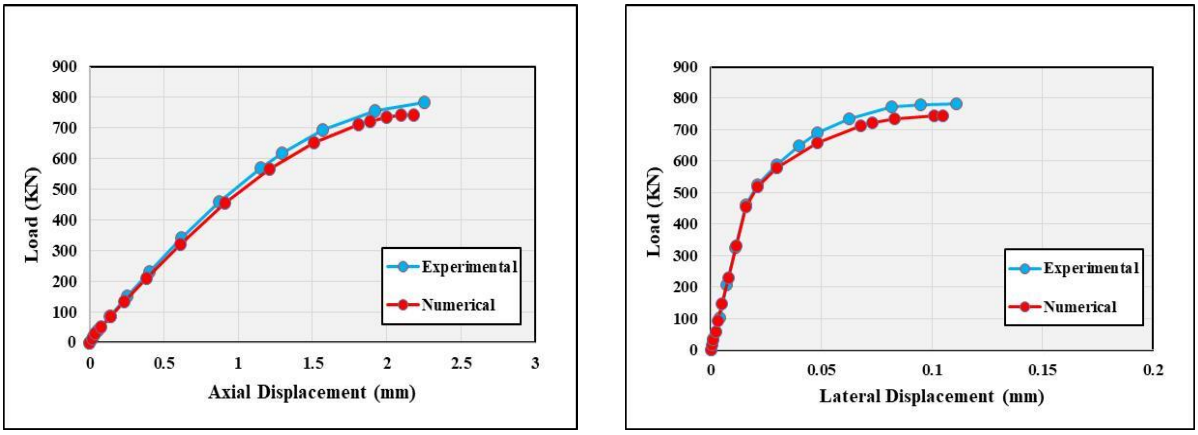

Figure (7) Numerical and Experimental Load-Displacement for Column SCCH50R10

It was discovered that for a SCC concrete column SCCH50R12, the ultimate Load increased by 3.8%, the axial displacement by 4.2%, and the lateral displacement by 5.9%. This can be seen in Figure (8).

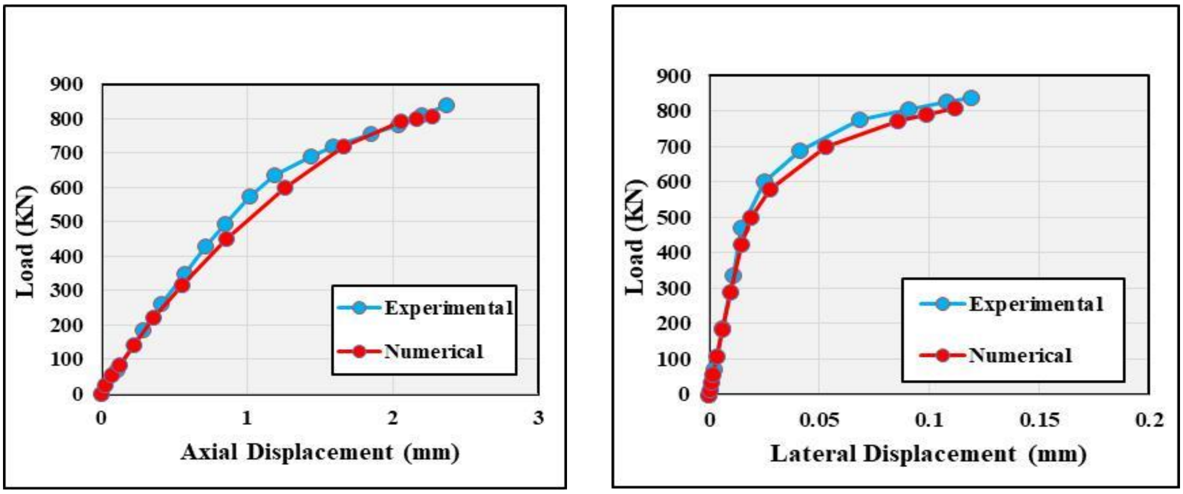

Figure (8) Numerical and Experimental Load-Displacement for Column SCCH50R12

4.3 Effect of Opening Size on Load-Displacement Behavior

This section discusses how different opening sizes affect the ultimate Load, axial displacement, and lateral displacement of columns under axial loading, with all other parameters staying the same. The openings in these columns had diameters of 0 mm, 50 mm, and 75 mm, respectively. The opening size was the only variable; all three tested columns shared consistent material composition and geometric characteristics.

4.3.1 Effect of Opening Size on Load-Displacement Behavior for SCC Concrete Columns

For the three SCC concrete columns (SCCH0R8, SCCH50R8, and SCCH75R8), the axial load was reduced as the opening size increased from 0 to 75 mm. There was an 11.8% decrease for 50 mm holes and a 21.3% decrease for 75 mm openings compared to the reference column (SCCH0R8), a solid column with no opening. Axial displacement increases proportionally with opening size. The percentage increase reached 12.2% for the column with a 50 mm opening compared to the solid column and 25.2% for the column with a 75 mm opening compared to the reference column. These percentage changes closely align with the increase in the opening ratio, as shown in Figure (9).

It is observed that solid columns present a lower magnitude of axial deflection when compared to hollow columns, emphasizing the enhanced structural stiffness associated with solid columns.

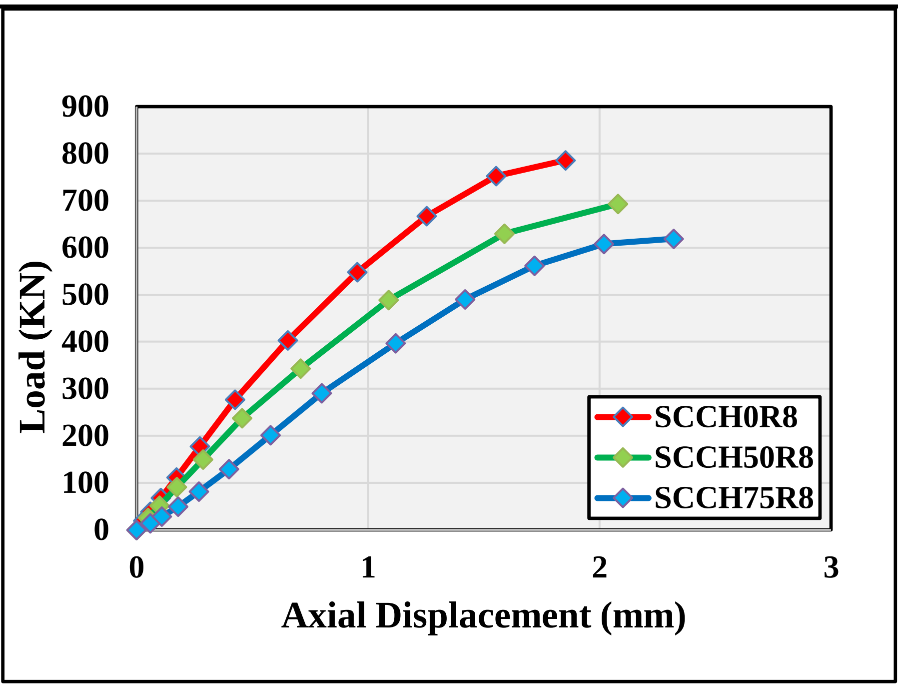

Figure (9) Load-Axial Displacement Relation for SCC Concrete Specimens

When the opening size increases from 0 to 75 mm, lateral displacement directly correlates with the opening size. The percentage increase reached 9.9% for column SCCH50R8 and 28.6% for column SCCH75R8 compared to the reference column SCCH0R8. As illustrated in Figure (10) The cross-sectional area affects the stiffness of the hollow column. A larger area results in a stiffer column, which means it can resist deformation more effectively under Load. This can be important for minimizing lateral deflection and maintaining the structure's overall stability.

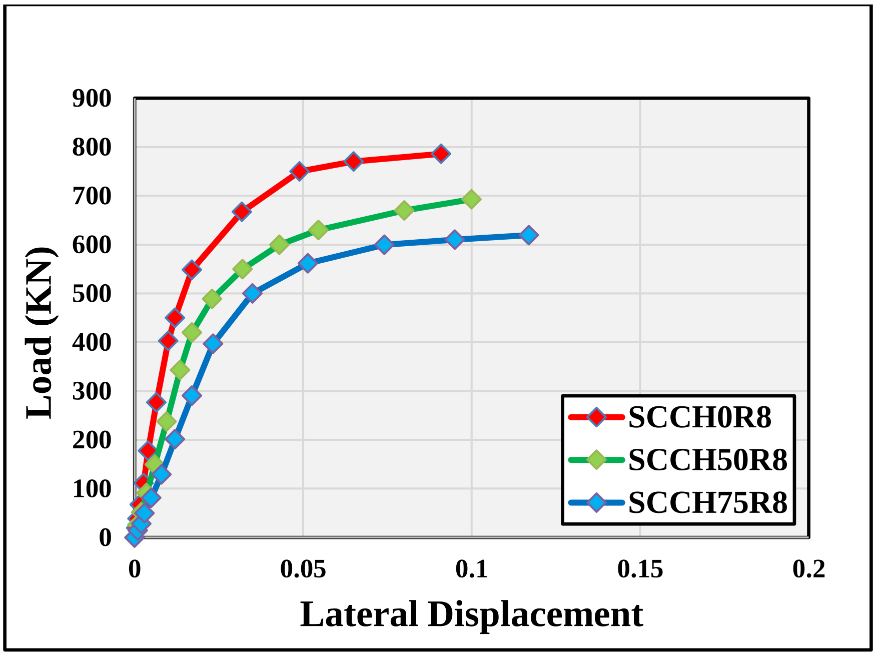

Figure (10) Load-Lateral Displacement Relation for SCC Concrete Specimens

4.3.2 Effect of Steel Reinforcement on Load-Displacement Behavior for SCC Concrete Columns

The data presented in Figure (11) provide compelling evidence of a pronounced enhancement in the axial load-displacement relationship associated with the progressive increase in longitudinal steel bar diameter.

The column SCCH50R10, with 10mm longitudinal steel reinforcement, demonstrated a 7.39% higher ultimate load and a 4.81% greater axial displacement than SCCH50R8, which had 8mm longitudinal steel reinforcement. SCCH50R12, which had 12mm of longitudinal steel reinforcement, had an 8.47 % higher ultimate load and a 4.13 % higher axial displacement than SCCH50R10.

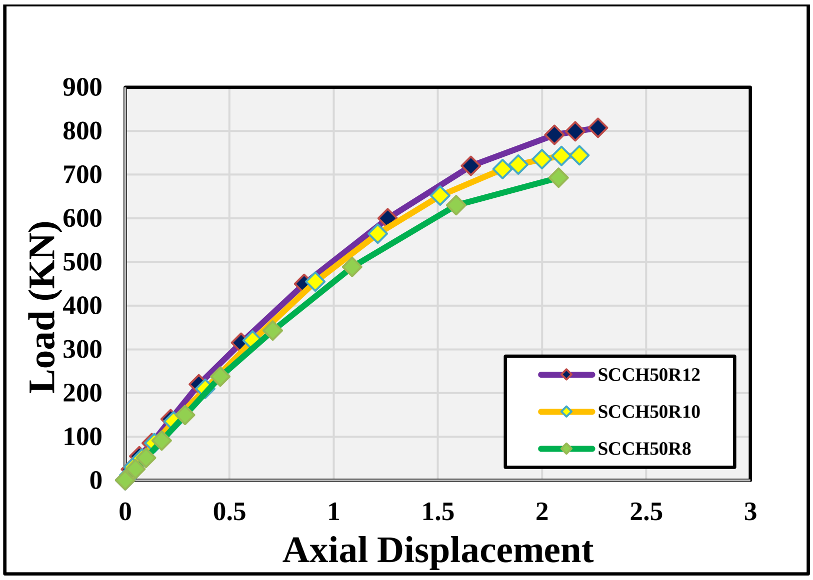

Figure (11) Load-Axial Displacement Relation for SCC Concrete Specimens

The increase in the diameter of the reinforcement steel bars from 8mm to 10mm has led to a 5.0% increase in lateral displacement. Similarly, the increase in the diameter of the reinforcement steel bars from 10mm to 12mm has resulted in a 6.67% increase in lateral displacement, as shown in Figure (12).

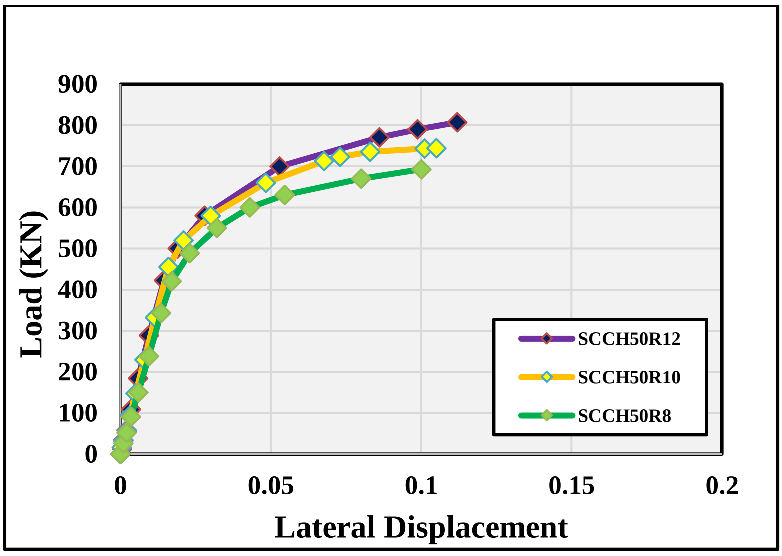

Figure (12) Load-Lateral Displacement Relation for SCC Concrete Specimens

4.4. Effect of Load Eccentricity on SCC Concrete Models

Most compression members in concrete structures experience axial loads and moments. These issues may arise from the Load on the column needing to be distributed appropriately or from the column bearing some of the unbalanced moments at the extremities of the beams supported by the columns [13].

Eccentric loading applies a load or force to a structure or component that deviates from perfect alignment with the central or major axis. The force is exerted at a certain distance from the axis, generating a moment or torque.

This section examines the impact of load eccentricity ratios on the load-carrying capacity, vertical displacement, and lateral displacement of numerically SCC concrete columns. Four load eccentricities were examined, precisely 20mm (e = 0.13 h), 40mm (e = 0.27 h), and 60mm (e = 0.40 h).

To show how the ratio of the distance between the axis of the Load and the centerline of the column to the section width (e/h) affects the Ability to carry loads, Fig. (13) shows that when increasing e/h (from 0 to 0.4), the ultimate Load of the models decreased.

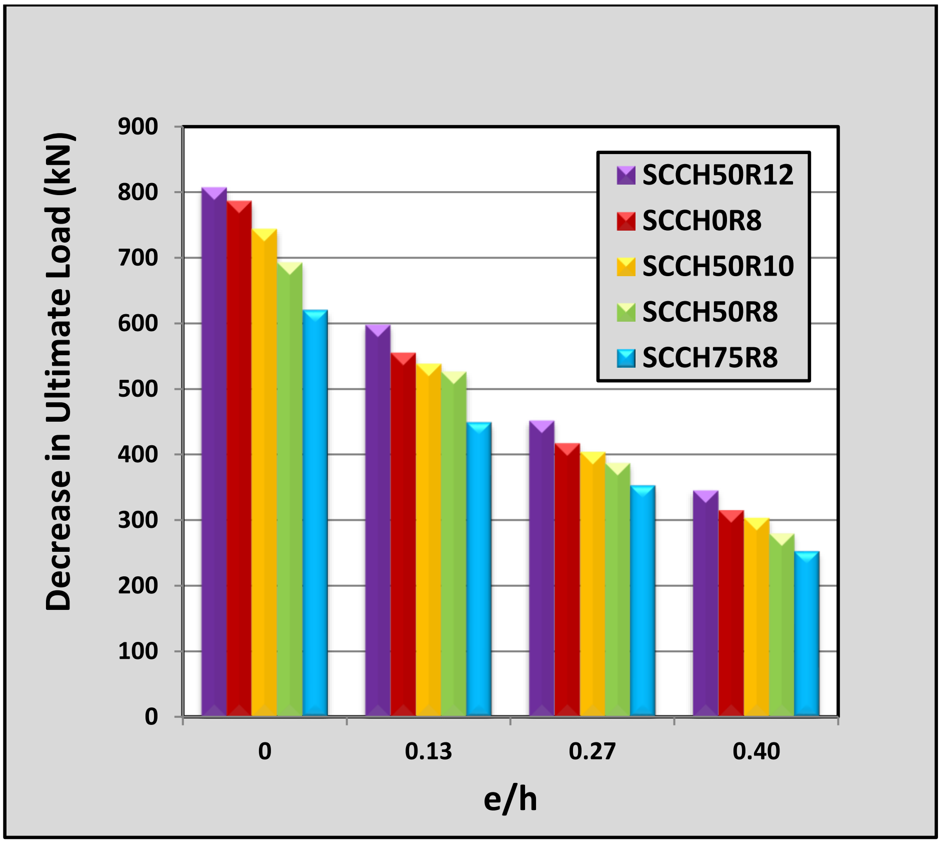

Figure (13) Decrease in Ultimate Load According to (e/h) for SCC Concrete Models

Figs. (14- 19) show the impact of eccentricity on the axial displacement and lateral displacement for columns (SCCH0R8, SCCH50R8, SCCH50R10, SCCH50R12, and SCCH75R8), where the load eccentricities of columns were (20, 40, and 60) mm, respectively.

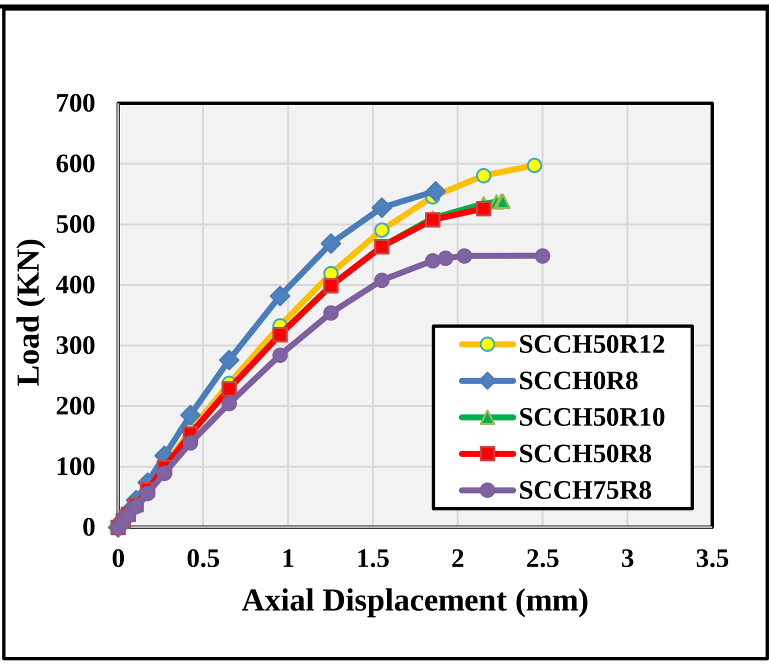

Figure (14) Axial Load- Axial Displacement for SCC Concrete Models with 20mm Eccentricity

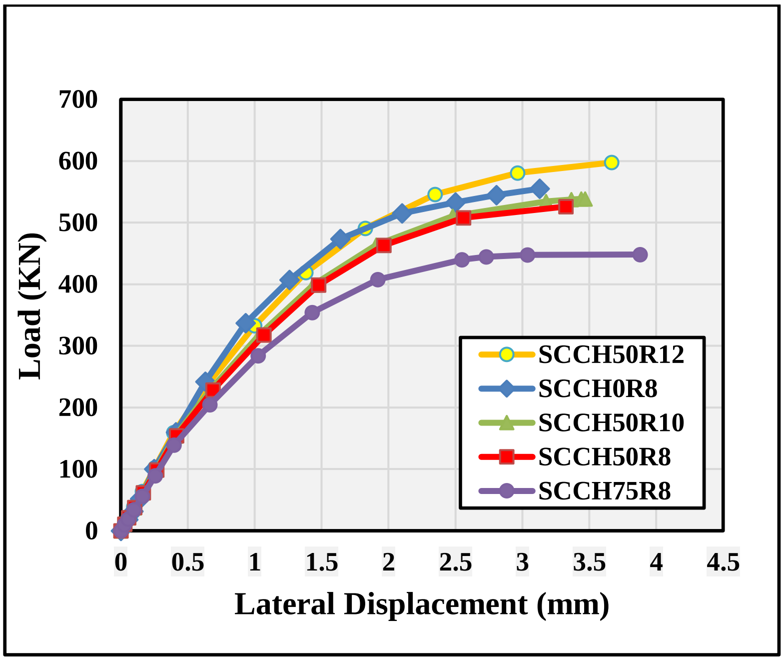

Figure (15) Axial Load- Lateral Displacement for SCC Concrete Models with 20mm Eccentricity

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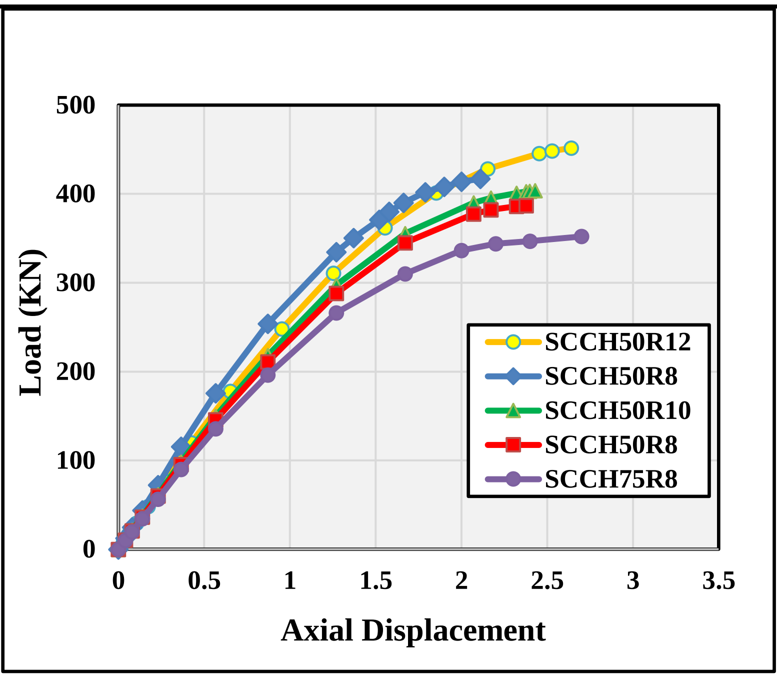

Figure (16) Axial Load- Axial Displacement for SCC Concrete Models with 40mm Eccentricity

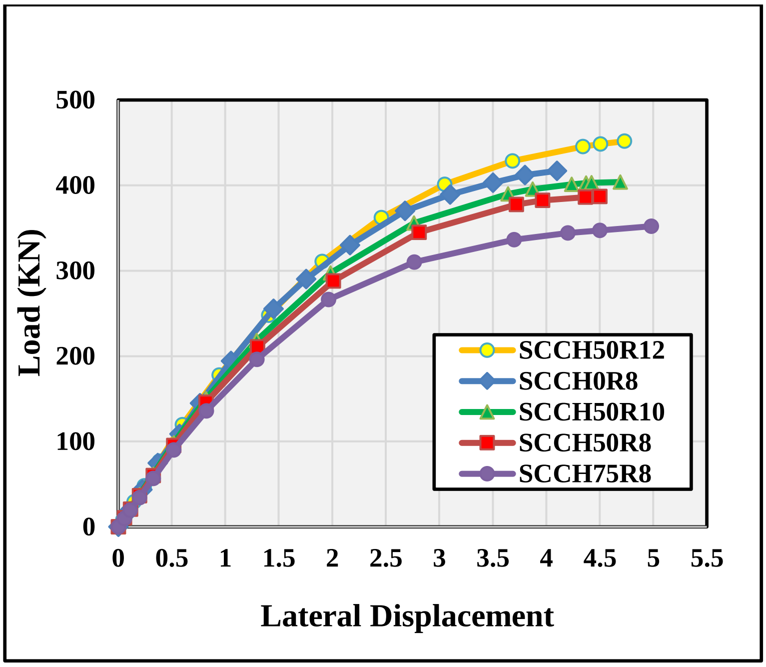

Figure (17) Axial Load- Lateral Displacement for SCC Concrete Models with 40mm Eccentricity

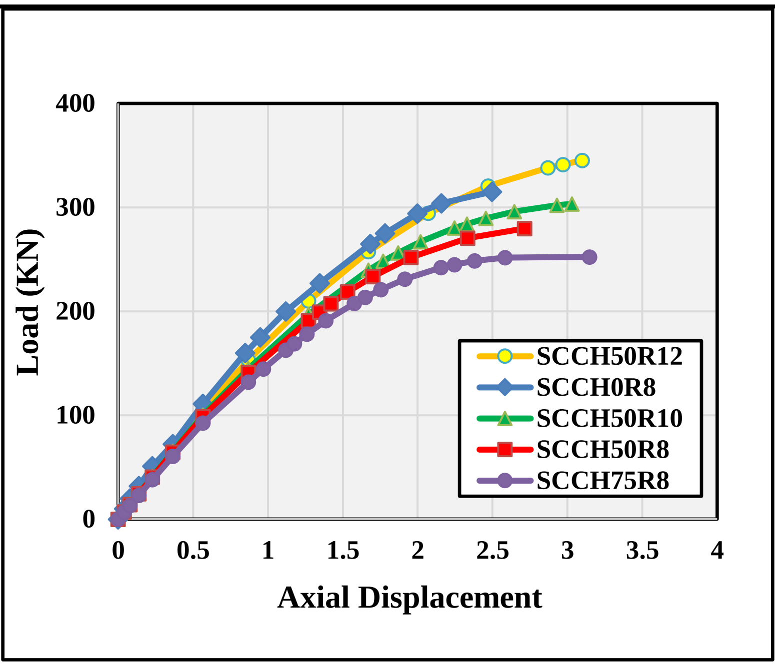

Figure (18) Axial Load- Axial Displacement for SCC Concrete Models with 60mm Eccentricity

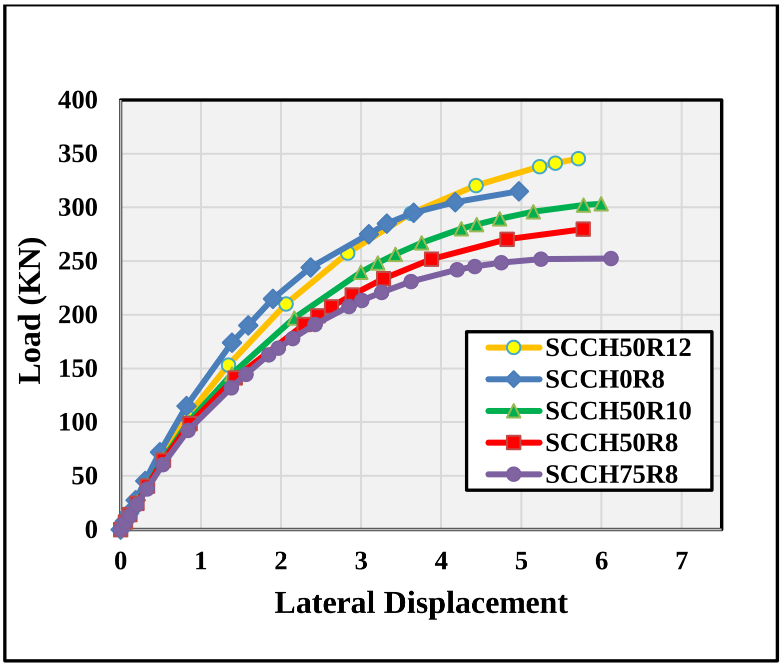

Figure (19) Axial Load- Lateral Displacement for SCC Concrete Models with 60mm Eccentricity

6. Conclusion

1. In comparison between the ultimate load values of the experimental and numerical models, there is a high degree of agreement (about 94-96%). These percentages are deemed satisfactory and agree with the test results compared to the numerical results.

2. when keeping the longitudinal steel diameter fixed (8mm), the ultimate Load decreased as the opening size increased from 0 to 50 to 75 mm. Compared to the reference solid column, when considering the opening sizes of 50 mm and 75 mm, the decrease amounted to 11.8% and 21.3%, respectively, for SCC concrete models. That indicates a lower load capacity of the column specimen due to the column's cross-sectional area reduction.
3. An increase in opening size causes an increase in axial displacement for the same longitudinal steel ratio. There is an increase of 12.2% for the SCC concrete model with a 50 mm opening and a rise of 25.2% for the SCC concrete model with a 75 mm opening compared to the solid reference column.
4. When the opening size increases from 0 to 75 mm, lateral displacement directly correlates with the opening size. The percentage increase reached 9.9% for columns with 50mm opening and 28.6% for columns with 50mm opening compared to the reference solid column.
5. For the fixed opening size (50mm), the increase in the longitudinal steel reinforcement ratio results in a rise in the strength of the study columns. Increasing the ratio of longitudinal steel reinforcement from 1% to 1.53% correlated with a 7.39% increase in the ultimate Load of SCC concrete columns. The rise to 2.2% showed an 8.47% increase in the ultimate load compared to the column with a 1.53% steel reinforcement ratio.
6. The axial displacement for a SCC concrete column with 10 mm steel reinforcement was 4.81% greater than that for an 8 mm steel reinforcement column. Meanwhile, the SCC concrete column with a 12 mm steel reinforcement demonstrated 4.13% increased axial displacement compared to the 10 mm steel reinforcement column.
7. Increasing the reinforcement ratio from 1 to 2.2 increased lateral displacement for SCC concrete columns. About 5.0% and 6.67%, respectively. These results indicate that the lateral displacement is generally tiny.
8. 12. When e/h increases (from 0 to 0.13 to 0.27 to 0.4), the models' ultimate Load, axial, and lateral displacement decrease.

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