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Nonlinear Finite Element Analysis of a Reinforced Concrete Flat Plates with Pre and Post Openings with an Edge Column

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Abstract: - The flat slab is a common structural system commonly used to construct a range of buildings. In contrast, the usage of flat slabs directly supported by columns indicates their sensitivity to a punched shear collapse, especially in earthquake-prone zones. Punching shear and slab behavior can be studied using nonlinear Finite Element studies. This work presents a 3-D analysis of the reinforced concrete slab utilizing the damage-plasticity model in the finite element program ABAQUS. This research investigates the punching shear behavior of reinforced flat plates with pre and post-openings. In comparison with the behavior of the test specimen, the findings of the FEA simulations reveal a suitable response. Simulations provide information on punching shear capacity and crack pattern. The purpose of this paper is to develop an innovative numerical modeling strategy for simulating and analyzing reinforced slabs with pre and post-opening. The proposed method for representing the flat slab with post openings and the drilling damage produced satisfactory results and can be used to represent similar cases. Numerical studies showed that slabs with post-openings had lower ultimate loads than slabs with pre-openings due to drilling damage.

Keywords: Finite Element Method (FEM), Punching Shear, Flat Slab, Post Openings, Pre Openings, Axial Loading

I. INTRODUCTION

A.General

The reinforced concrete flat floor system is a building technology often used to construct contemporary structures, such as car parks and residential buildings. This system has many benefits, such as a lower story height, easy placement of reinforcements, less complicated formwork, and lower construction costs. On the other hand, flat-plate systems have lower flexural rigidity and are more vulnerable to brittle punching shear failure than traditional concrete slab-beam systems. ACI Code (318-19) [1] recommends increasing slab thickness or using shear reinforcement to prevent catastrophic punching shear failure. Flat plate floor systems typically need the installation of additional services that require openings near columns. Ventilation, heating, air conditioning, and electrical conduits are the primary reasons for the openings. The opening decreases the punching shear capacity of the slab-column connection by removing some of the concrete volumes responsible for resisting shear force and unbalanced moments. consequently, it is more susceptible to brittle punching shear failure.
Engineering research has undergone a revolution due to digital computers, which has made Finite element analysis (FEA) numerical computations a common technique for structural analysis. FEA is a complex system of simultaneous algebraic equations that uses a stiffness matrix to explain the behaviour of a structure.

B. Punching Shear FEA Literature Review

The two-dimensional (2D) structures may be simulated with few degrees of freedom, requiring little computation. (2D) components cannot wholly describe the complicated tri-axial tension in the punching region. Advances in digital computers allow for increasingly complicated models using 3D solid components. These aspects enable flexibility and precision in discretizing reinforced concrete structures and contribute to the most realistic punching shear analysis [2]. Nana et al. [3] provided a numerical study of their punching shear of concrete slab experiments using the ABAQUS concrete damaged plasticity model. Their experiment examined how slab punching affects concrete strength and loading area. They evaluated nine different slab geometries. The FEA model has been verified using test results. The FEA model was used to assess the effects of slab thickness, concrete aggregate size, flexural reinforcement, and loaded area size. The only parameter that required calibration was the FEA dilation angle parameter used in the constitutive model. The authors recommend applying a (37^{o})dilation angle to resemble concrete with a compressive strength of less than (25)MPa. The dilation angle increases with concrete strength. The load-deflection response of the FEA model and the experimental results showed good agreement with one another when compared. Figure (1) provides a representation of some of the results that they obtained.

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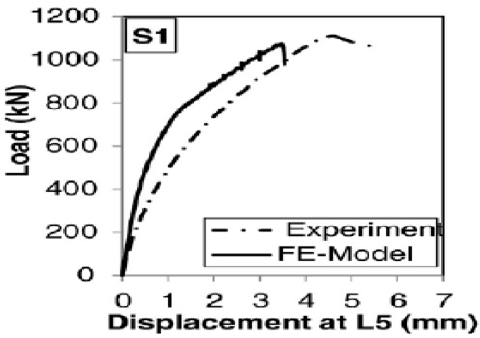


Fig. 1 Experimental results against FEA [3].

Youm et al. [4] The failure of lightweight aggregate concrete in punching stress was studied using a nonlinear finite element model and five full-size slabs. The damaged concrete plasticity model in ABAQUS was used for the test. The slabs were shown as solids with eight nodes, and the reinforcement was shown as two-dimensional trusses. Uniaxial tensile stress-strain was assumed linear up to cracking stress. The dilation angle is an essential parameter for defining the concrete-damaged plasticity model. The authors compared the load-deflection results for dilation angles of (20^o, 31^o, and 45^o), as in the Figure (2). The dilation angle of (31^o) had a nearly perfect correlation with the load. Generally, a significant correlation was shown between the finite element model and the experimental results for all five modelled slab specimens, as in the Figure (3).

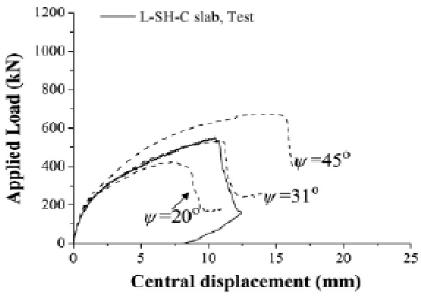


Fig. 2 Dilation angle parametric study [4].

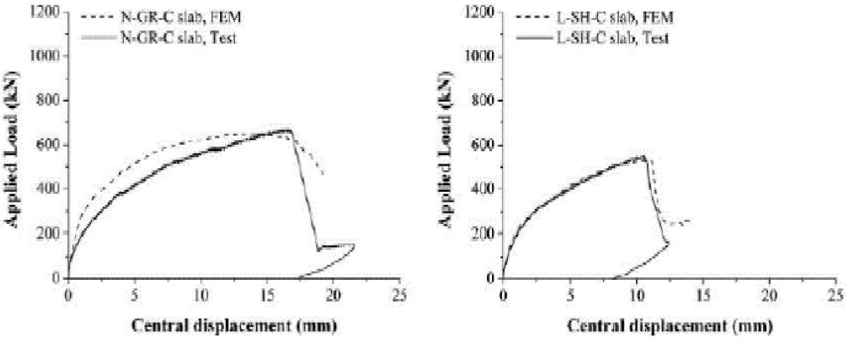


Fig. 3 Results of load-displacement [4]

Puddicome et al. [5] modelled the FRC slabs using ABAQUS. The nonlinear behaviour of concrete can be modelled with Damaged Concrete Plasticity. An exponential decay formula is used to estimate the tension-stiffening effect, with parameters including concrete strength, flexural reinforcement ratio, steel fibre content, and steel yield strength. Concrete is described using hexahedral (brick) components with eight nodes to represent reduced integration, while reinforcement is represented using linear truss elements with two nodes. Calibrating the model with nine slabs from the literature yields a range of (0.78 to 1.281), an average of (1.068), and a standard deviation of (0.195) for the numerical to experimental failure load ratio. Abdel-Rahman et al. [6] investigated fourteen reinforced concrete slabs strengthened longitudinally with 1.2% in both directions. Steel fibers dimensions (50×0.52×0.72 mm) and volume fractions of (0.5 to 1.5%) were utilized to examine the punching shear strength of slabs. Tests indicated a (24%) increase in punching shear strength. The numerical and experimental results are compared using ANSYS R14.5 nonlinear (FE) analysis. Eight node solid components, solid65, depict concrete, and 3D link elements 180 simulate reinforcing bars. The average numerical to experimental load ratio is (0.98 with a 0.14) standard deviation, indicating good agreement. Hawileh et al. [7] used ANSYS to simulate punching shear behavior. The model employed 3D solid components to represent concrete and steel reinforcement and ANSYS' tri-axial plastic concrete model. The tension stiffening curve was bilinear. Ascending branch is considered linear to the modulus of rupture. It fell promptly by (60%) of the tensile concrete strength and linearly to six times the tensile rupture strength. The element used to represent strengthening contained a component to imitate bond slip. The authors utilized CEB-FIP to determine the bond 50 stress slip. The phrase may be changed with different reinforcement ratios. Hawileh et al. found that the FEA model and the experimental data were very strongly in accord with the final punching shear loads and the mid-span deflection.

C. Objective and Scope of the Study

This paper presents a finite element model that predicts the punching shear behaviour of reinforced concrete slabs. The model predicts the ultimate load and load-deflection response of reinforced concrete slabs with different parameters such as concrete strengths, reinforcement ratios, opening size, and pre-and post-opening. There is no consistent method for including these factors into one FEA model for general punching shear. This paper will contribute to the field of study on FEA modelling of reinforced concrete by filling a gap in the literature with a punching shear model.

II. TEST SPECIMENS

Seven flat slab specimens of ordinary reinforced concrete have been made, with dimensions of (1650 x 1650 x 100) mm, connected to a square edge column of (500) mm height, with a (200 x 200) mm section. Each slab was reinforced with one layer of (Ø10) mm steel bars spaced at (200) mm center to center, with an effective depth of (75) mm. The edge column was also reinforced with eight (Ø10) mm steel bars, as required by the ACI318-19(ACI code 318-19) [8]. The slabs in this research were divided into two groups, presented in Table I. In the first group (G1), the concrete slab with pre-openings, the openings were created before casting using the molds. The openings have different dimensions to study the effect of these openings on the behavior of the punching shear strength. In the second group (G2), concrete slabs, the openings are created after (28) days of casting using the perforating cylinder installed in the drilling rig. Then the opening shape is modified using the drilling hammer. Openings have similar shapes, and dimensions to those in group 1.

TABLE I. SAMPLES DESCRIPTION AND GEOMETRY

SLAB ID	Group	Type of opening	Diameter of opening(mm)	Distance between opening and column(mm)	Description
CS	Reinforcement Concrete Flat Slab without Opening				
SWCO1	G1	pre	112.5	633.5	Reinforcement Concrete Flat Slab with pre circle Opening
SWCO2	G1	pre	225	582.5	
SWCO3	G1	pre	450	465	
SWPSO1	G2	post	112.5	633.5	Reinforcement Concrete Flat Slab with post circle Opening
SWPSO2	G2	post	225	582.5	
SWPS O3	G2	post	450	465	

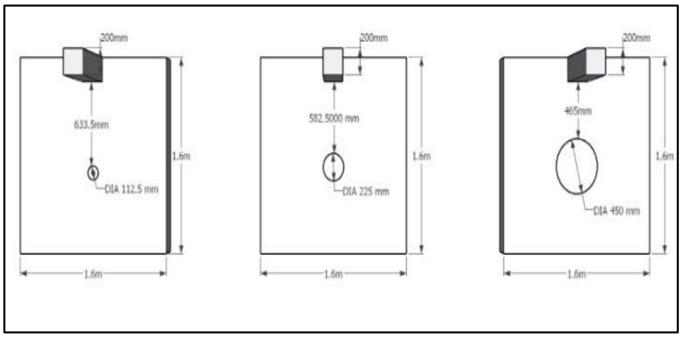


Fig. 4 Reinforcement details and geometry of flat slab

A. Supporting and Loading Condition

All specimens were tested under static loads through the column and on a supported span on all three sides (1600 x 1600mm). The upper face of the column is levelled if there are protrusions to create the plane of the column and avoid the distribution of ununiformed stress. The weight is applied in (10) kN increments for the static load. Each step deflections are measured, and the force is applied continuously until the specimen fails.

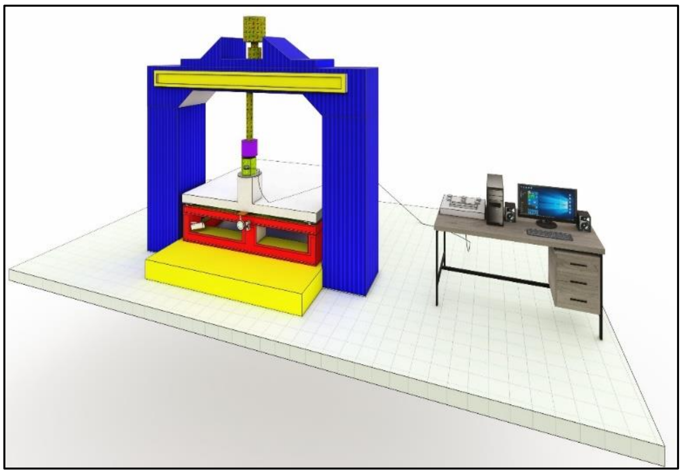


Fig. 5 Test device components

B. Experimental Results

The results of this study are discussed and presented here. Table II summarizes specimens' failure loads, initial cracks, and ultimate deflections for each group (G1 and G2).

TABLE II. TEST RESULTS

Slab ID	First crack Load(kN)	Failure load(kN)	The failure load decreased from the control slab. %	Maximum Deflection (mm)
CS	39.2	70	-----	23
SWCO1	24.4	58.08	17	23.625
SWCO2	24	52	25.7	24
SWCO3	19	45	35.78	22
WPCO1	21	50	28.14	24.15
SWPCO2	15	47	32.85	20
SWPCO3	13	41	42.42	23

III. Reinforced Concrete FEA Modeling

In this section, experimental data and finite element analysis are compared to check material properties and element types and to study the convergence of a model that represents the presence of (pre and post) openings in flat plates with normal concrete subjected to a specific load. The column-slab connections' nonlinear finite elements were investigated using ABAQUS/Standard 2017. Analyze the test specimens numerically to test the analytical finite element model's effectiveness and accuracy, then compare the findings to the same experimental data.

Cracking tension and crushing in compression are the main failure mechanisms of concrete. Therefore, the FEA model's description of the reinforced concrete structure's behavior under compression and tension must be precise for the model to simulate the structure's behavior successfully. A constitutive model including these features of behavior has been developed. Finite elements of the right type and size have been used to represent the concrete and reinforcement. The failure criterion must be specified, and the boundary conditions and load application must be precisely modelled.

A. Concrete Damage Plasticity (CDP) Model

The CDP model is a modification of the Drucker-Prager yield criteria, one of the most often used strength hypotheses for concrete. To modeling the concrete, the damaged plasticity of the available concrete in ABAQUS was used as it is able to model reinforced and unreinforced structural concrete and other quasi-brittle materials subject to any kind of loads (monotonic, periodic, dynamic, etc.). The damaged plasticity of concrete is based on the theory of coupled damage plasticity and the multi-axial response of concrete rule by a yield surface which was suggested by (Lubliner et al., 1989) [9] and developed by (Lee & Fenves, 1998) [10] to account for the different evaluation of strength under tension and compression, as in the Figure (6).

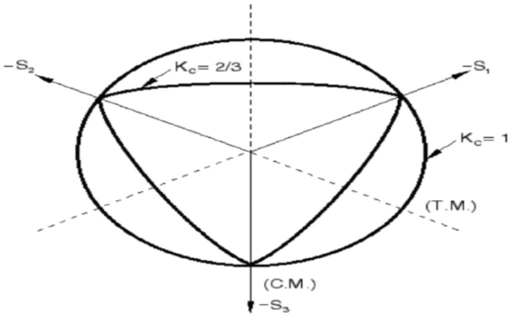


Fig. 6 The Yield Surface in Plane Stress

B. FINITE ELEMENT SIMULATIONS

This section is divided into three parts. The first part describes the geometry of the test specimens; the second part describes the loads and boundary conditions used in this investigation, and the third part is the convergence study and how to choose the best mesh for the study.

1) Assemblage of the RC slab parts

Many parts were modelled for seven flat slab specimens. A concrete slab, a concrete column, flexural reinforcement of the slabs, column reinforcing bars, and a bearing plate were among the parts. These parts were created independently, assembled, and mixed to form a modelling specimen. Figures (7) describe these parts' assembly methods. These sections (column, slab, and steel plate) have meshed into solid brick elements to distribute stress in the 3D Finite element analysis. ABAQUS offers a variety of solid brick parts. This study used C3D8 linear hexahedral elements with complete integration. Steel reinforcement for the slab and column formed a linear truss element (T3D2). The openings were modelled individually in the specimens of groups before and post openings, as they were in the experimental set-up, and then combined with the model components, it was chosen to use linear hexahedral elements with full integration (C3D8). Figures (8) and (9) show specimen modelling in ABAQUS.

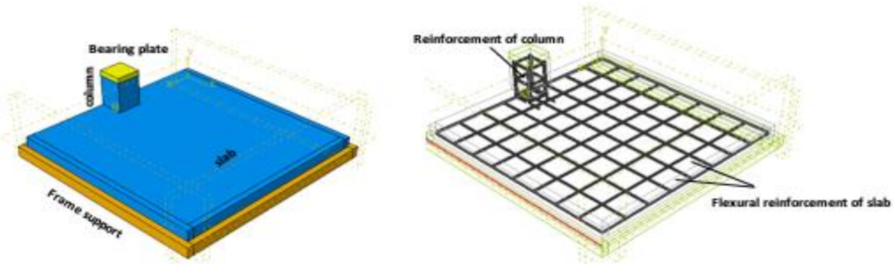
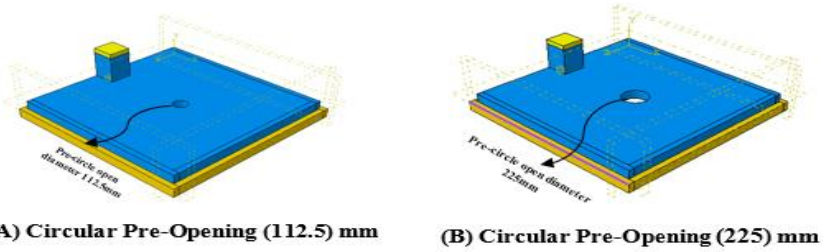
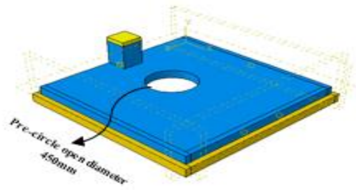


Fig. 7 flat slab Model's Assembly and Reinforcement Assembly



(A) Circular Pre-Opening (112.5) mm **(B) Circular Pre-Opening (225) mm**



(C) Circular Pre-Opening (450)

Fig. 8 The Modeling of ABAQUS for a Flat Slab with Circular Pre-Opening

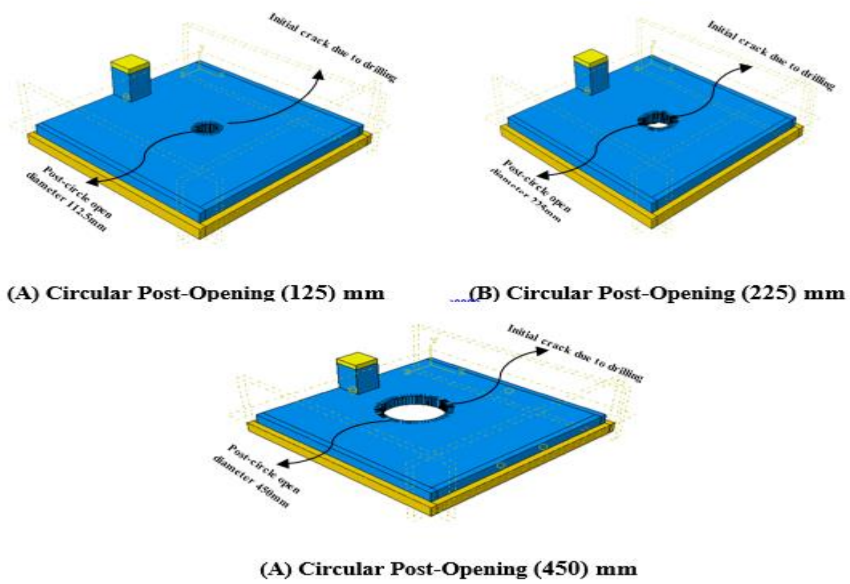


Fig. 9 The Modeling of ABAQUS for a Flat Slab with Circular Post-Opening

2) Loading and Boundary Conditions

The pressure load was generally static and uniformly distributed across the plate's loading zone. A uniformly applied pressure is calculated by dividing the load by the bearing plate area. Figure (10) shows the application load simulation. The simple supports of the RC slab were modelled using the displacement/rotation option in ABAQUS. This was completed to simulate the same boundary conditions as the experimental tests: Pin support: The node is fixed along the transverse line to the lower center of the support plate. It can't move in vertical (direction Y), horizontal (direction x), or longitudinal directions (z-direction). All axes allow rotation of the contract. Roller support: The nodes are fixed along the transverse line at the center bottom of the support plate and can only move in one direction (Z direction). All of the axes of the contract can be turned. Figure (10) shows the conditions of support and load.

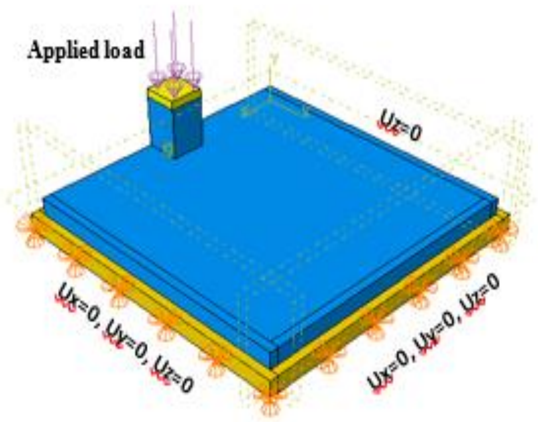


Fig. 10 Loading and Boundary Conditions

3) Meshing

The density of the mesh is one of the most important parameters influencing the model's accuracy. To select the optimum mesh size for the control slab, used four mesh sizes (25 mm, 30 mm, 40 mm, and 50 mm) and compared them with the experimental results as shown in Figure (11) and the analysis results are shown in Figure (12).

Figures (12) demonstrate that the mesh size of 30 mm gave good results and convergence relative to the experimental results and that this mesh size requires (15 to 25) minutes less time to complete the analysis.

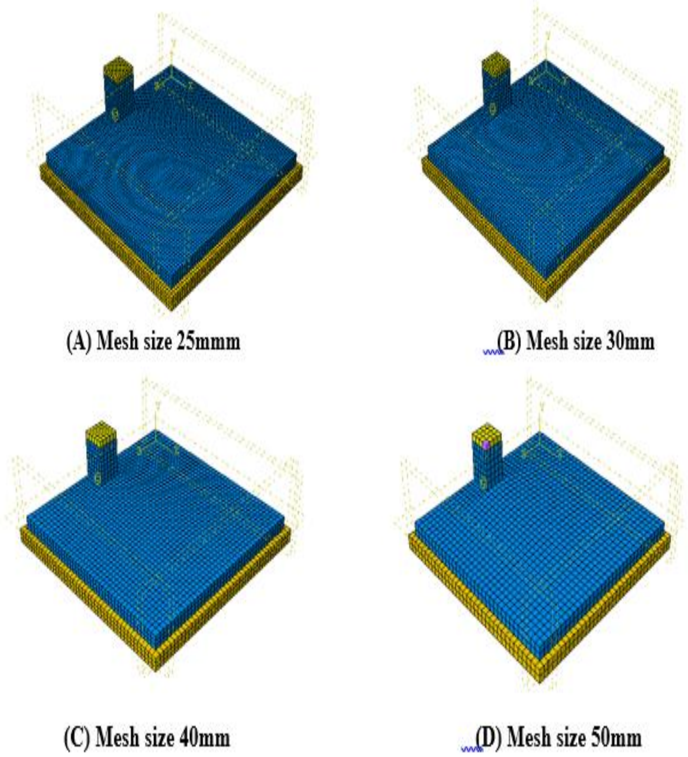


Fig. 11 Element mesh sizes considered in mesh sensitivity analysis

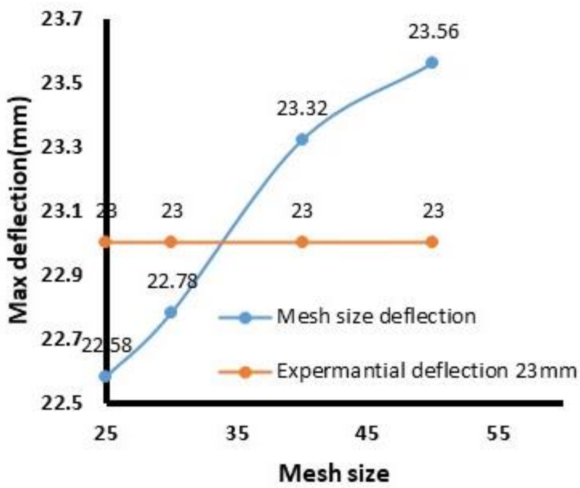


Fig. 12 Mesh size vs ultimate displacement for control slab.

IV. Numerical and Experimental Results

This section compares the FEA (Finite Element Analysis) findings to the experimental test results. A comparison was done between the failure crack pattern, the ultimate load, the ultimate deflection, and the load-deflection curve.

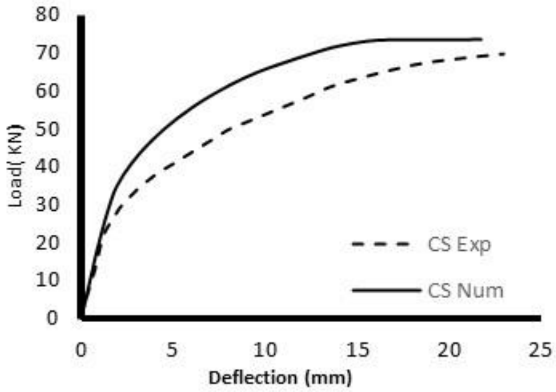
A. Comparison Between Experimental and Numerical Results for the Flat Plates with Circular Pre-Openings.

Figure (13) and Table (5) compare the numerical and experimental test results. Figure (13) shows that the experimental and numerical load deflections are in good agreement, with slightly stiffer numerical behavior than experimental data. The numerical analysis showed high stiffness regarding the load-deflection curves than it is in the experimental analysis. Many factors in finite element analysis explain the high stiffness of the crack stages. Some of these factors were found:

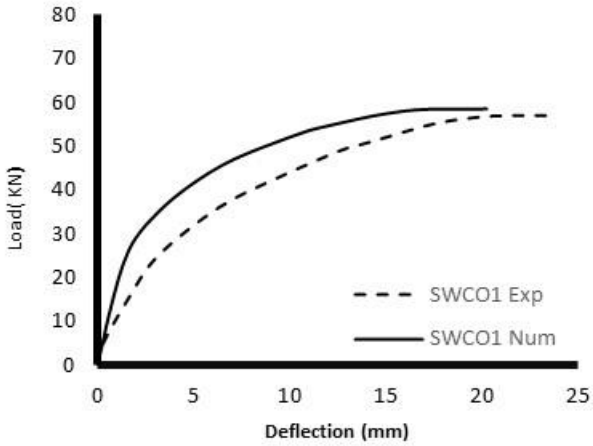
1-In finite element analysis, concrete is considered as a homogenous material, however it is not (heterogeneous material).

2- Small (micro-cracks) created in the concrete as a result of (drying shrinkage and handling) reduced the stiffness of the real concrete slab, but this impact was not detected by the FEA.

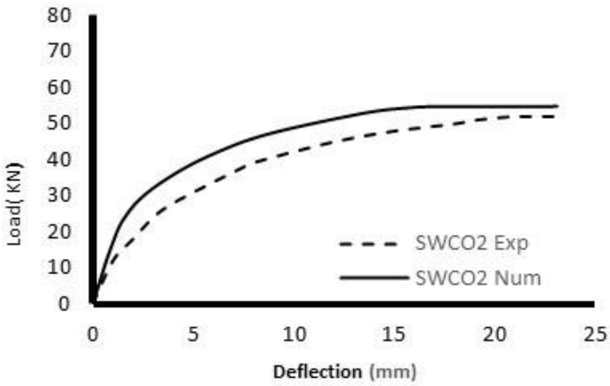
3- The FEA assumed an ideal connection between reinforcing bars and concrete, as well as between steel plates and concrete.



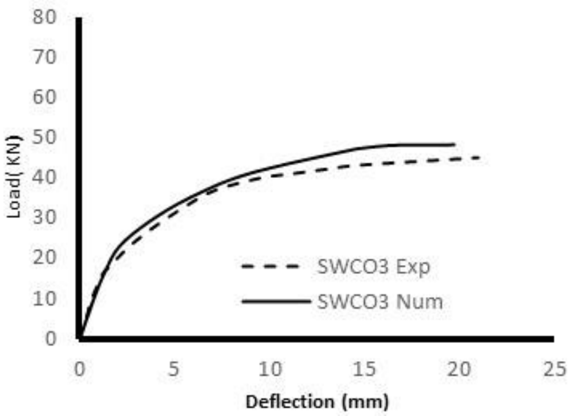
(A) **CS**



(B) **SWCO1**



(C) **SWCO2**



(D) SWCO3

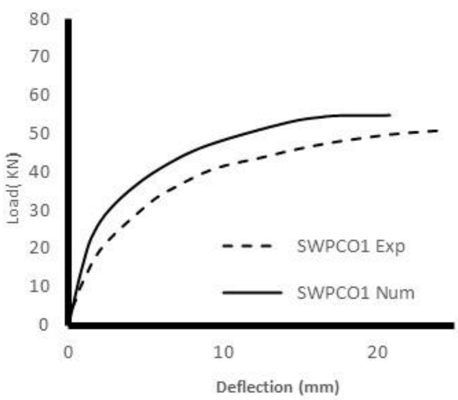
Fig. 13 The Experimental and Numerical Load-Deflection Curves for The Slabs with Circular Pre-Openings.

TABLE III. THE EXPERIMENTAL AND NUMERICAL RESULTS FOR SLABS WITH CIRCULAR PRE-OPENINGS

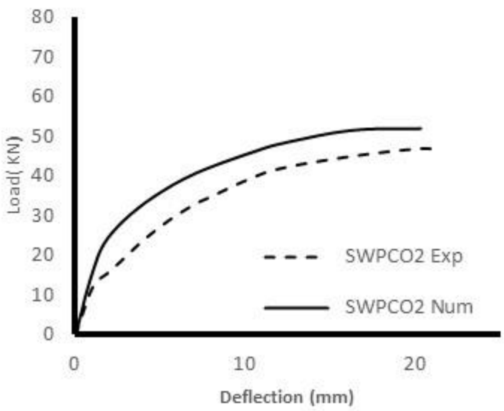
Slab ID	**Load Failure load(kN)**		$\frac{Pu,FEM - Pu,EXP}{Pu,EXP}\%$	**Maximum Deflection (mm)**		$\frac{\Delta u,FEM - \Delta u,EXP}{\Delta u,EXP}\%$
	Exp.	**FEA**		**Exp.**	**FEA**	
CS	70	74	5.71	23	21.76	5.4
SWCO1	57	59	3.5	23.625	20.25	15.55
SWCO2	52	55	5.77	23	23.5	2.1
SWCO3	45	49	8.16	21	19.7	6.1

B. Comparison Between Experimental and Numerical Results for the Flat plates with Circular Post-Openings.

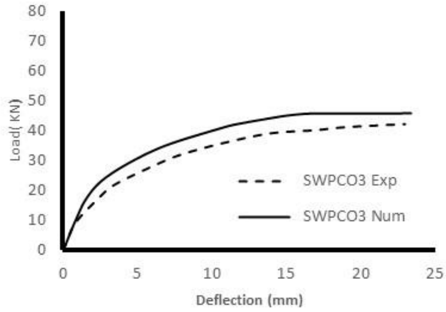
When comparing the load-deflection curves of pre- and post-opening specimens, the latter showed less agreement between the experimental and numerical data. Because the work of the post-openings causes damage to the concrete around the openings, the appearance of micro-cracks, and the cutting of reinforcement steel in various locations, all of these reasons make it difficult to guess and represent in FEA. To represent the damage caused to the concrete by the formation of micro-cracks surrounding the opening as a consequence of the drilling operation, micro-cracks with a thickness of (0.01) mm, an extension of 30 mm, and a depth of (5) mm were simulated. It was found that the extension of the mentioned damage around the openings gave results that are more in agreement with the experimental results, as shown in Figure (14), and thus it was relied upon in the study.



(A) SWPCO1



(B) SWPCO2



(C) SWPCO3

Fig. 14 The Experimental and Numerical Load-Deflection Curves for The Slabs with Circular Post-Openings

Slab ID	Failure load(kN)		$\frac{Pu,FEM - Pu,EXP}{Pu,EXP}$ %	Maximum Deflection (mm)		$\frac{\Delta u,FEM - \Delta u,EXP}{\Delta u,EXP}$ %
	Exp.	FEA		Exp.	FEA	
WPCO1	51	55	7.84	24.2	20	17.35
SWPCO2	47	53	12.765	21.15	20.3	4
SWPCO3	42	47	11.9	23.12	23	0.5

TABLE IV. THE EXPERIMENTAL AND NUMERICAL RESULTS FOR SLABS WITH CIRCULAR POST-OPENINGS

C. Cracking propagation

Seven specimens failed in a brittle, sudden punching mode. After applying the axial loads of the first group (G1) and the second group (G2) until failure, it was observed that all of the specimens cracked by punching shear, with fractures appearing 45 degrees from the column's exterior edges. The cracks started as diagonal cracks running from the corners of the column end to the slab edges on the tension side. Under various loading conditions, the control slab specimen developed the first cracks that occurred at (56%) of the ultimate load. The first cracks that occurred were (G1) between (34% and 40%) of the ultimate load and (G2) between (31% and 40%) of the ultimate load. In Finite Element Analysis, the slab crack was extended from the side closest to the column, as in experimental testing. The sudden crack opening causes it to start near the punching cone. Positive maximum primary plastic stresses show cracking in FEA for concrete damaged plasticity model. The Finite Element Analysis can show crack patterns using the principal tensile stress, but the maximum primary plastic strain gives a better crack description. Therefore, the strain will exhibit all test specimens' crack patterns. Figures show the specimen punching cone and slab stress surface crack pattern.

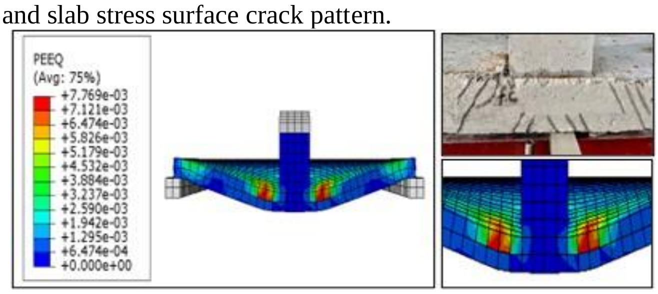


Fig.15 Crack Pattern for the Specimen CS

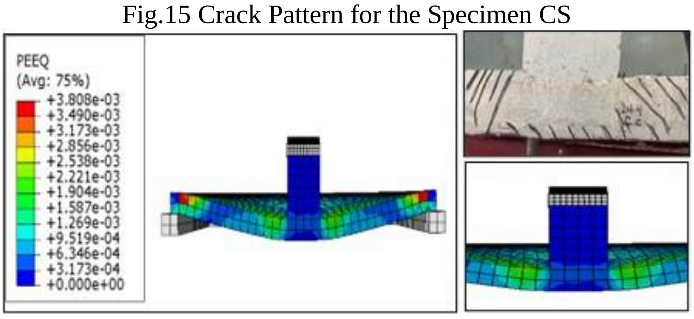


Fig. 16 Crack Pattern for the Specimen SWCO1

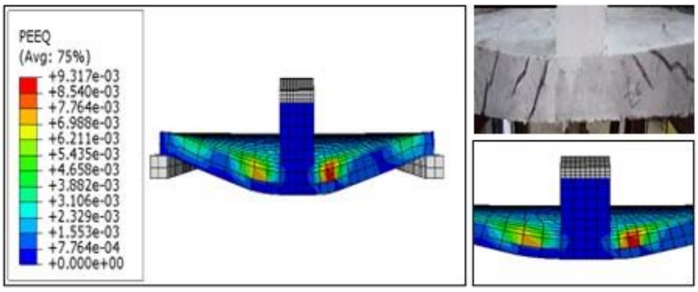


Fig. 17 Crack Pattern for the Specimen SWPCO1

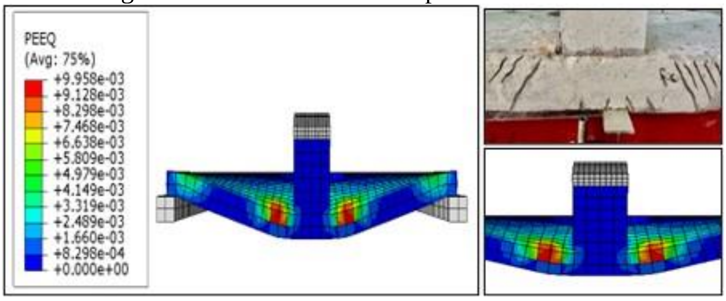


Fig. 18 Crack Pattern for the Specimen SWPCO3

V. Conclusion

The models that were created with the use of the ABAQUS software are able to provide accurate predictions about the behavior of reinforced concrete slabs in terms of the relationship between load and deflection, the ultimate load, and crack patterns.

1-The ABAQUS software uses specifications and boundary conditions as standard determinants, therefore the numerical models had more stiffness and the same or lesser deflections than the experimental models under the influence of the same load.

2-There was a good agreement of concord between the analytical and experimental results for the flat slab with pre-openings models, showing that the program accurately performed the analysis.

3-For specimens with pre-openings, reducing the reinforcement around them decreased the ultimate load and increased the center deflection during punching shear tests in numerical analysis.

4-The proposed method for depicting the flat slab with post openings and the damage resulting from the drilling procedure produced relatively acceptable results and may be utilized to represent cases similar to those.

5-The numerical results showed that the slab with post-openings had a lower ultimate load than the slab with pre-openings, as a result of the drilling operation causing damage.

6-According to the numerical result, all of the slabs' ultimate loads exceeded the experimental result and ranged between (3.5% to12.765%) for specimens.

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