

FINITE ELEMENT ANALYSIS OF TWO-WAY HOLLOW HIGH STRENGTH SELF-COMPACTING FIBER REINFORCED CONCRETE SLAB UNDER THE EFFECTS OF UNIFORM REPEATED LOAD (USING TWO-WAY PIPING SYSTEM)

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Abstract

This paper offers detailed data regarding the mechanical behaviour of two-way hollow high strength self-compacted fiber reinforced concrete slabs that were tested under the influences of uniform repeated loads. In this research, a comparison between the results of the numerical analysis and the experimental results of previous research is presented to confirm the suitability of the convergence study, material properties, elements types, and the real constants of the proposed model of two-way hollow slabs using an innovative two-way piping system. This new type of voiding system could be fabricated through placing continuous two-way plastic piping system, inside the reinforced concrete slabs to reduce the self-weight of the produced slabs along with offering continuous networks of voids that could be beneficial for passing service lines, including lines for communication, sewage, electricity, and water. The outcomes of this research proved that using the nonlinear finite element method showed acceptable precision with a maximum difference percentage of about 15% of the ultimate capacity between the proposed numerical model and the experimental results. Besides, it was shown that it is useful to produce two-way hollow slabs using the two-way piping system with keeping about 80% of the ultimate capacity. Finally, the results showed that the reduction in the strength of the two-way hollow reinforced concrete slabs could be reduced using high strength concrete, adding micro steel fiber, increasing the reinforcement ratio or by locating the piping systems far from the locations of maximum stresses.

Keywords: FEA, Two-way hollow, Two-way piping system, Uniform repeated load.

1. Introduction

Nowadays, it is required to produce multi-story buildings with a huge continuous distance between columns. This requirement could lead to several disadvantage points, including higher thickness, higher self-weight, more deflection and more expensive. Several options are available in practice, including increasing the slab depth, using prestressing or using hollow slab systems.

Increasing the depth of reinforced concrete slabs could help by increasing the stiffness, which could be useful in fulfils the serviceability requirements. However, using reinforced concrete slab with a higher thickness could also lead to several disadvantages, such as reducing the precious spacing between two adjacent floors along with increasing the dead loads and that requires using more oversized columns and foundations.

The other option of prestressing could be a good option, but it requires expensive special equipment and expert staffs. Finally, using hollow reinforced concrete slab systems could be an advance choice to avoid the previously mentioned issues [1, 2]. A hollow concrete slab could be constructed by inserting plastic moulds, styro-foam or polystyrene blocks into reinforced concrete slabs.

Engineers have been engaging in studying the mechanical behaviour of hollow slab. It was stated that producing precast hollow-core units by introducing styrofoam into reinforced concrete slabs showed better structural behaviour than using PVC pipes [3]. Reduction in the shearing strength, lower maximum loading capacity, and low ductility previously reported due to increasing the voiding ratio of hollow core two-way slab [4]. Also, utilizing steel pipes of (32 mm and 42 mm) in diameter led to enhance the mechanical behaviour by increasing ultimate loading capacity and cutting down the corresponding deflection [5].

Inserting cubes and spheres of recycled polypropylene into concrete slab led to similar or higher ultimate loading capacity than solid slabs and led to lower flexural stiffness by about 50% [6]. Moreover, increasing the depth of hollow-core reinforced concrete slab led to decrease the ultimate deflection by 50% and increase the shear resistance by about 50% while utilizing shear reinforcement in constructing hollow-slab led to an increase in the shear strength by about 50% and the maximum deflection by about 50% [7].

Most researchers have been interested in studying the mechanical performance of different types of hollow slab systems including hollow-core, BubbleDeck, Airdeck, U-boot, styro-foam and cobiax. Those systems are used to decrease the weight of solid slabs by replacing a percentage of the concrete volume by voids, but no one of those systems could be used for passing service lines.

On the other hand, the proposed new type of two-way hollow slab system could also be used to reduce the self-weight along with offering continuous two-way networks of voids, which could be used for service lines), as shown in Fig. 1.

This research contains detailed data regarding the finite element analysis (FEA) by ABAQUS/Standard 2017 of the new type of two-way hollow slab system.



Fig. 1. Constructing two-way hollow reinforced concrete slabs using two-way piping systems of plastic pipes and fittings.

2. Details of the testing platform

2.1. Testing parameters

Eleven reinforced concrete slabs (two solid slabs and the rest were two-way hollow slabs) of (800 × 800 mm) length of effective spans, (880 × 880 mm) overall length (80 mm) overall thickness were tested under the effects of equivalent uniformly distributed loads (EUDRL), as shown in Fig. 2. Different variables were considered in this research producing six parametric studies counting the following:

- Producing two-way hollow reinforced concrete slabs using two-way piping systems with various voiding ratio (0%, 16% and 24%) with a fixed number of pipe and fixed distance between pipes (140 mm c/c) was evaluated by C₆₅.F₀.H₁₆.D₃₂.R₁.A_u.L_u, C₆₅.F₀.H₀.D₀.R₁.A₀.L_u and C₆₅.F₀.H₂₄.D₄₀.R₁.A_u.L_u concrete slabs.
- Fabricating two-way hollow reinforced concrete slabs using two-way piping systems of different diameters (20 mm, 32 mm and 40 mm) with a fixed (8%) voiding ratio was inspected through C₆₅.F₀.H₈.D₄₀.R₁.A_u.L_u, C₆₅.F₀.H₈.D₃₂.R₁.A_u.L_u, C₆₅.F₀.H₈.D₂₀.R₁.A_u.L_u, and C₆₅.F₀.H₀.D₀.R₁.A₀.L_u concrete slabs.
- Fabricating two-way hollow fiber reinforced concrete slabs using two-way piping systems and (1.5%) volume fraction of micro steel fiber of (aspect ratio 75 and tensile strength 2600 MPa) was examined through C₆₅.F_{1.5}.H₁₆.D₃₂.R₁.A_u.L_u, C₆₅.F₀.H₁₆.D₃₂.R₁.A_u.L_u, and C₆₅.F₀.H₀.D₀.R₁.A₀.L_u concrete slabs.
- Constructing two-way hollow reinforced concrete slabs using two-way piping systems with various types of concrete (standard strength concrete with $f'_c = 35$ MPa and high strength concrete with $f'_c = 65$ MPa) was examined through C₃₅.F₀.H₂₄.D₄₀.R₁.A_u.L_u, C₆₅.F₀.H₂₄.D₄₀.R₁.A_u.L_u, C₃₅.F₀.H₀.D₀.R₁.A₀.L_u and C₆₅.F₀.H₀.D₀.R₁.A₀.L_u concrete slabs.
- Creating two-way hollow reinforced concrete slabs using two-way piping systems with a higher ratio of the primary reinforcement ($\rho = 0.004710$) for bottom layer instead of ($\rho = 0.002355$) was evaluated through C₆₅.F₀.H₁₆.D₃₂.R₂.A_u.L_u, C₆₅.F₀.H₁₆.D₃₂.R₁.A_u.L_u and C₆₅.F₀.H₀.D₀.R₁.A₀.L_u concrete slabs.
- Assembling two-way hollow reinforced concrete slabs using different configurations of two-way piping systems was evaluated through C₆₅.F₀.H₁₆.D₃₂.R₁.A_{nu}.L_u, C₆₅.F₀.H₁₆.D₃₂.R₁.A_u.L_u and C₆₅.F₀.H₀.D₀.R₁.A₀.L_u concrete slabs.

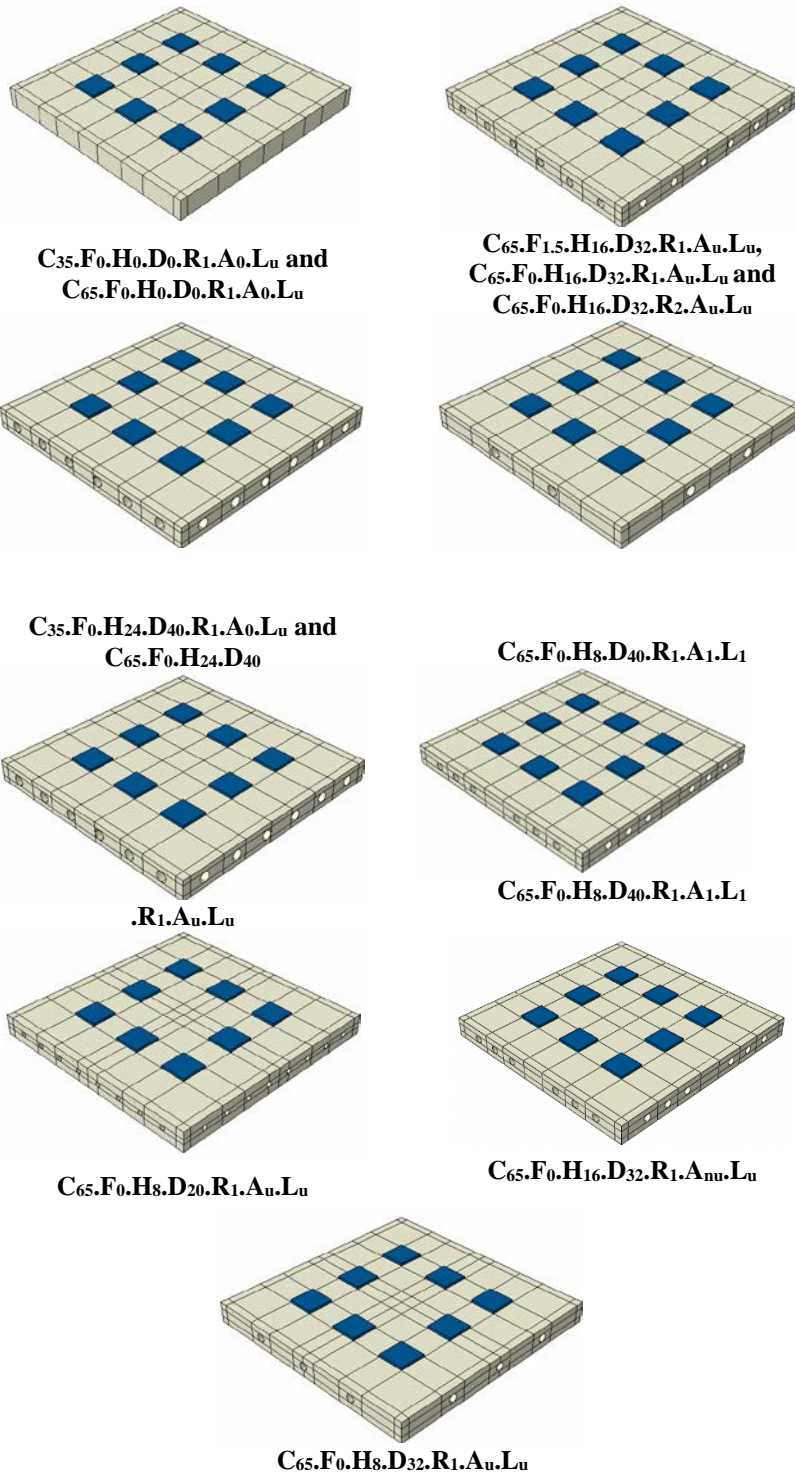


Fig. 2. Cross-section details for concrete slabs.

2.2. Materials

Ordinary Portland cement that satisfies IQS No.5 [8] specifications, fine aggregates with sieve analysis and properties that agreed with ASTM C136 / C136M – 14 and IQS No.45 standard tests [9, 10], coarse aggregates with structural properties and grading that were met the requirements of IQS No.45 standard tests [10], microsilica that conformed to the requirements of ASTM C1240 – 15 standard specifications [11] and high range water reducing admixture that agreed with ASTM C494 / C494M – 17 standard test [12] were used in producing self-compacting high strength concrete while limestone powder was used in making normal strength self-compacting concrete mixtures. Moreover, micro steel fibers of aspect ratio 75 and tensile strength 2600 MPa, which were manufactured by Jingjiang Hongtu Engineering Co., were used in producing fiber reinforced concrete. Steel rebar that satisfies ASTM A1064 / A1064M - 18a standard test [13] of (4 mm and 6 mm) diameters were used as (secondary and main reinforcement, respectively) in constructing both the top and bottom layers, respectively. Finally, plastic fittings and plastic pipes were utilized in assembling two-way piping systems, as shown in Fig. 1.

2.3. Details of reinforcement

Concrete slabs were reinforced utilizing a layer of six rebar (6 mm in diameter) in two orthogonal directions at the bottom fiber and a layer of six rebar (4 mm in diameter) in two orthogonal directions at the top fiber with a uniform spacing of 150 cm c/c except for two-way hollow concrete slab model $C_{65}.F_{0}.H_{16}.D_{32}.R_{2}.A_{u}.L_{u}$ of 16% of voids was reinforced utilizing a layer of 12 deformed rebar of 6 mm in diameter in two orthogonal directions at the bottom fiber with uniform spacing of 75 cm c/c. A cover of 1 cm was adopted for all concrete slabs.

2.4. Loading and supporting conditions

A rigid I-section steel frame with four solid circular steel shafts (20 mm in diameter) was used as a supporting system to offer simply supporting condition, as presented in Fig. 3(a). The equivalent uniformly distributed repeated load was applied on the reinforced concrete slabs by dividing the applied load of the universal testing machine into eight regions of (100 mm × 100 mm) through utilizing I-section steel frame and eight rubber plates of dimensions (100×100×10 mm), as demonstrated in Fig. 3(b). The load was applied through five stages (from zero to the ultimate level) with a cycle of ten times, except for the last phase was up to failure, as illustrated in Table 1.

Table 1. The protocol the equivalent uniformly distributed repeated load.

Stage ID	*Start from (%)	*Increased to (%)	*Return to (%)	Increment Size (kN)	Number of Cycles
S ₁	0	20	0	25	10
S ₂	0	40	0	25	10
S ₃	0	60	0	25	10
S ₄	0	80	0	25	10
S ₅	0	100	End of Test	25	1

*as a percentage of the expected ultimate capacity

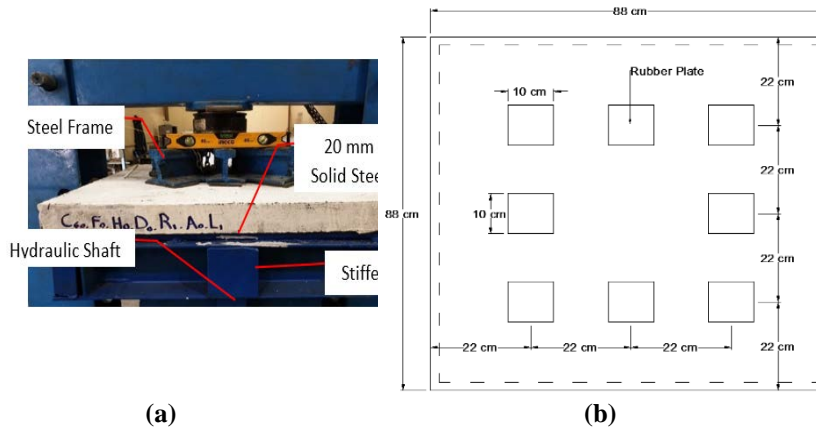


Fig. 3. Details of loading and supporting parameters.

3. Modelling of Two-Way Hollow RC Slab

ABAQUS/Standard 2017, which is a three-dimensional FE computer program, was adopted to perform a nonlinear FEA to determine the performance of two-way hollow reinforced concrete slabs under the effects of EUDRL.

3.1. Convergence study

A convergence study was performed to develop a suitable mesh size throughout assessing the influences of reducing the element size from (100 mm) to (15 mm), as shown in Fig. 4(a). As demonstrated in Fig. 4(a), negligible effects were developed on the load-carrying capacity by decreasing the size of the mesh from 30 to 15 mm. Therefore, a mesh size of 20 mm was selected in this study, as presented in Fig. 4(b).

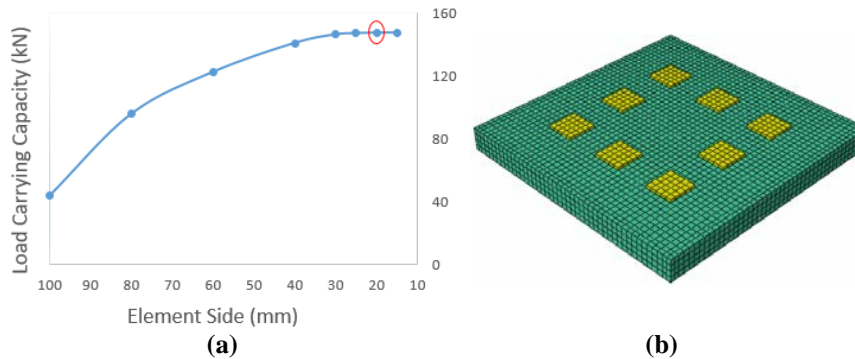


Fig. 4. Details of the convergence study.

3.2. Parts and assembly

Five parts, including rebar for main and secondary reinforcement, concrete slab, solid steel shaft for supports and bearing plates for loading conditions were involved in modelling two-way hollow reinforced concrete slabs. Solid brick elements that are Linear Hexahedral elements (C3D8R) of 8-node linear brick were

used in meshing steel plates, hollow reinforced concrete slabs and solid reinforced concrete slabs. Moreover, 3-D linear (T3D2) truss that is 2-node was utilized for meshing steel rebar.

3.3. Interaction

Different categories of constraints were used to enable the parts to interact with each other to construct a successive composite system based on experimental observations. An embedded constrain region was selected to represent the interaction between the reinforcing rebar and the surrounding model of concrete while a tie constraint was adopted between the concrete slab and the bearing steel plate along with the concrete slab and the supporting solid steel shafts, as shown in Fig. 5.

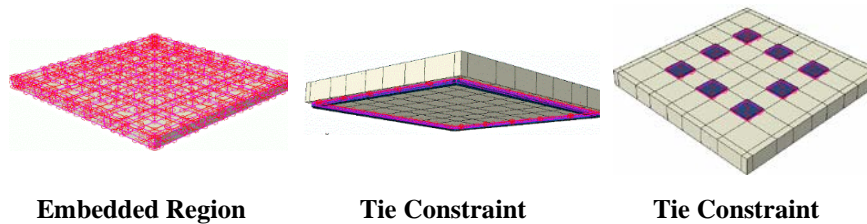


Fig. 5. Details of the constraint types.

3.4. Boundary Conditions

Displacement constrained were assigned at the lower surface of the solid steel shafts in both y-direction and z-direction through the edges of x-axis along with displacement were constrained in both y-direction and x-direction along the edges of z-axis to represent the simple supporting condition, as presented in Fig. 6(a). EUDRL was applied similarly as in the experimental program by applying uniform pressure on the bearing plates (as shown in Fig. 6(b)) using tabular type amplitudes to define the protocol of the EUDRL.

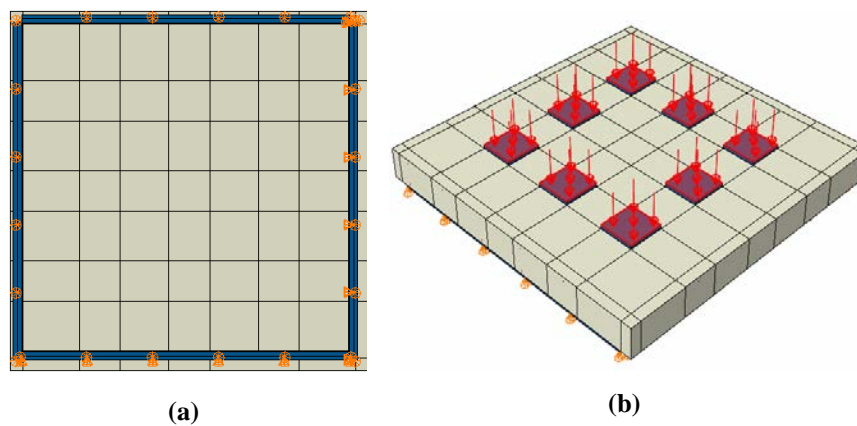


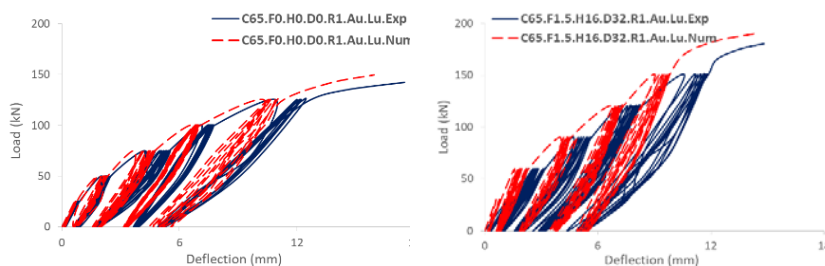
Fig. 6. Details of the boundary conditions.

4. Results and Discussion

General behaviour was observed for two-way hollow reinforced concrete slabs under the effects of equivalent uniformly distributed repeated loads following three key levels of deformations. The first level found within the elastic range where linearly relationships were observed between load-deflection curves. The second level (elastic-plastic stage) started as soon as the first crack initiated in the tension face that was ranging between 0.037 mm to 0.12 mm and corresponding to load level ranged between about 15% and 26% of the ultimate level. In this level, more cracks were initiated and propagated at the tension face as the number of cycles or the magnitude was increased. In addition, a linear correlation was detected in this level between load-deflection curves with different slopes. Cracks number, as well as cracks width, was raised and moved to the corners of the reinforced concrete slabs. Finally, a further increase in the numbers of cycles of the repeated load or the magnitude of the applied load was resulting in an excessive reduction in the stiffness followed by collapse.

The experimental outcomes showed that constructing two-way hollow slabs with voiding ratio up to 24% using two-way piping systems led to reducing the ultimate loading capacity by about 20% [14]. Furthermore, the results showed that is possible to compensate the weakness that occurs in the structural performance of two-way hollow reinforced concrete slabs by different options including using fiber reinforced concrete, increasing the main reinforcement, using mixtures of high strength concrete or distributing the two-way piping systems out of the location of the maximum stresses [15].

The nonlinear FEA of two-way hollow reinforced concrete slabs showed acceptable agreement with the experimental behaviour. The results also demonstrated that the FE first cracking loads were higher than the experimental cracking loads by about 4% to 14%. That could be due to the higher the homogenous of FE models. Moreover, FE ultimate loads were higher than the ultimate experimental loads by about 2% to 15% while the FE central deflections at the ultimate level were lower than those of the experimental study by about 3% to 13%, except for C₃₅.F₀.H₂₄.D₄₀.R₁.A₀.L_u that had higher FE central deflection than experimental results by about 6%. Besides, the models of finite element method showed stiffer behaviour than real models in the pre-cracking segment of the load-deflection curve and showed either similar or stiffer performance in the post-cracking segment, as presented in Table 2 and Fig. 7. Finally, A deflection profile was also drawn at different levels of loading for the experimental and FE methods for two-way hollow slab (C₆₅.F₀.H₁₆.D₃₂.R₁.A_u.L_u that had ultimate experimental deflection of 14.20 mm and ultimate numerical deflection of 12.60 mm) as an example to check the efficiency of the offered model, are shown in Fig. 8.



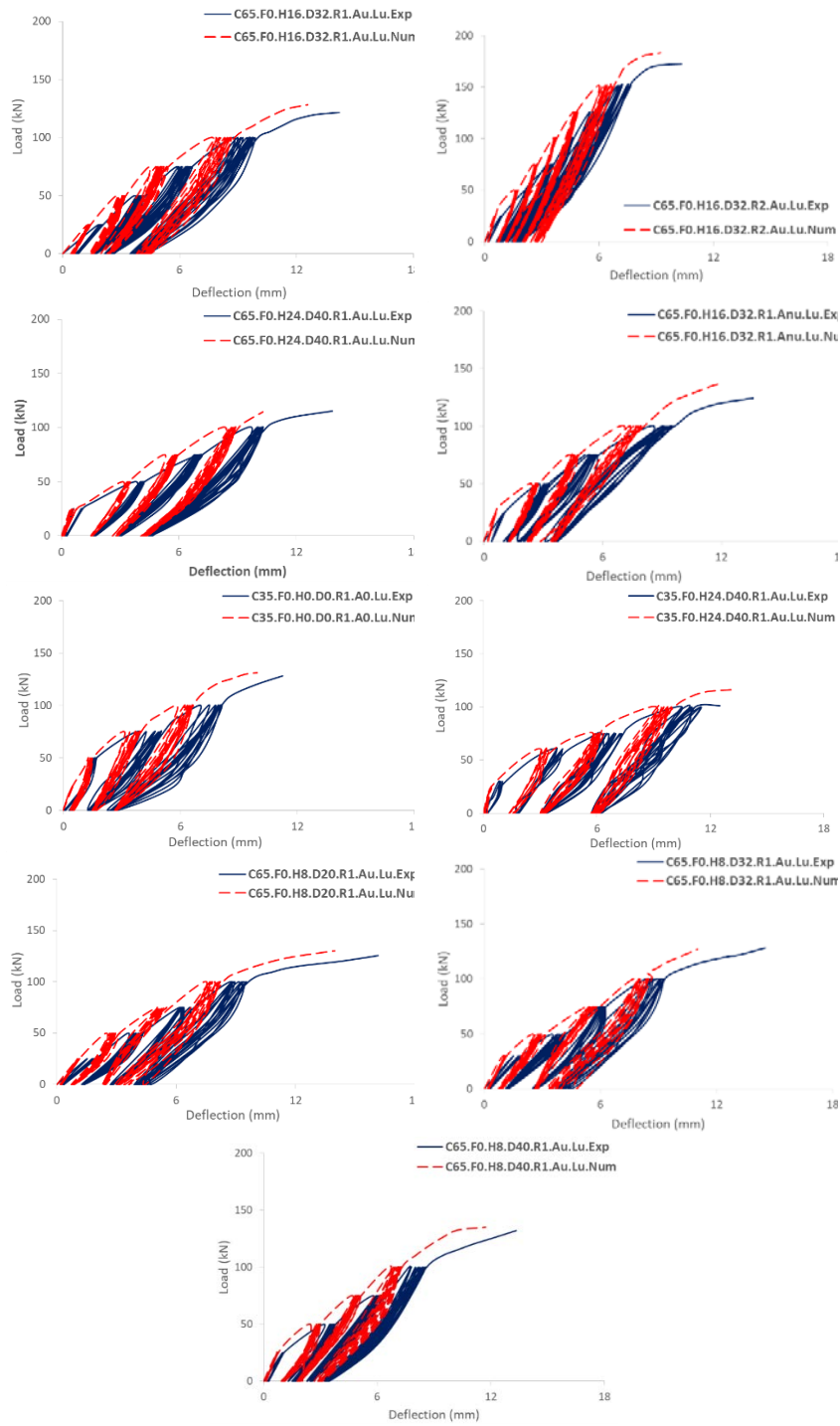
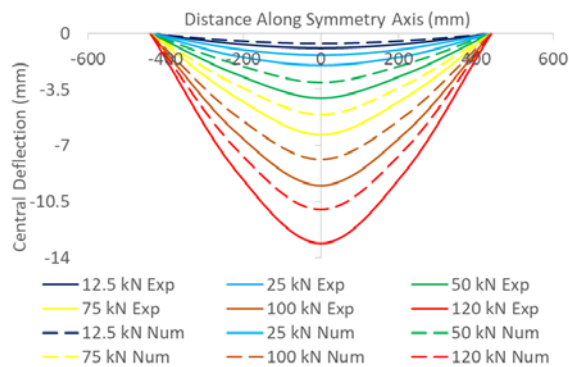


Fig. 7. Experimental vs. numerical load-deflection curves of two-way hollow RC slabs.

Table 2. Experimental vs. numerical mechanical behaviour of two-way RC slabs.

Model ID	$\frac{P_{cr_Num}}{P_{cr_Exp}}$	P_{u_Exp} (kN)	P_{u_Num} (kN)	$\frac{P_{u_Num}}{P_{u_Exp}}$	δ_{cu_Exp} (kN)	δ_{cu_Num} (kN)	$\frac{\delta_{cu_Num}}{\delta_{cu_Exp}}$
	C ₆₅ .F ₀ .H ₀ .D ₀ .R ₁ .A ₀ .L _u	1.042	142.4	149.81	1.052	17.52	15.96
C ₆₅ .F ₀ .H ₈ .D ₂₀ .R ₁ .A _u .L _u	1.094	125.5	130.02	1.036	16.14	13.97	0.87
C ₆₅ .F ₀ .H ₈ .D ₃₂ .R ₁ .A _u .L _u	1.102	128.3	131.91	1.028	14.52	12.84	0.88
C ₆₅ .F ₀ .H ₈ .D ₄₀ .R ₁ .A _u .L _u	1.101	132.1	134.89	1.021	13.34	11.71	0.88
C ₆₅ .F ₀ .H ₁₆ .D ₃₂ .R ₁ .A _u .L _u	1.066	121.6	128.23	1.054	14.20	12.60	0.89
C ₆₅ .F _{1.5} .H ₁₆ .D ₃₂ .R ₁ .A _u .L _u	1.064	180.3	190.43	1.056	14.82	14.35	0.97
C ₆₅ .F ₀ .H ₁₆ .D ₃₂ .R ₂ .A _u .L _u	1.055	172.6	183.23	1.06	10.32	9.22	0.89
C ₆₅ .F ₀ .H ₁₆ .D ₃₂ .R ₁ .A _{nu} .L _u	1.113	124.5	137.31	1.102	13.60	12.08	0.89
C ₆₅ .F ₀ .H ₂₄ .D ₄₀ .R ₁ .A _u .L _u	1.122	115.2	125.22	1.087	13.83	12.74	0.92
C ₃₅ .F ₀ .H ₀ .D ₀ .R ₁ .A ₀ .L _u	1.134	128.2	131.38	1.025	11.23	9.94	0.88
C ₃₅ .F ₀ .H ₂₄ .D ₄₀ .R ₁ .A ₀ .L _u	1.125	101.1	116.21	1.149	12.51	13.20	1.06

**Fig. 8. Numerical vs. experimental deflection profile of C₆₅.F₀.H₁₆.D₃₂.R₁.A_u.L_u.**

5. Conclusions

This paper was designed to examine the structural performance of two-way hollow high strength reinforced concrete slabs using finite element analysis by ABAQUS/Standard 2017 under the influences of uniformly distributed repeated loads. Eleven models of dimensions (880 × 880 × 80 mm) consisting of two solid reinforced concrete slabs and nine two-way hollow reinforced concrete slabs that were made-up using an innovative type of two-way plastic piping system, were considered in this paper. This new type of two-way piping system could be fabricated using networks of plastic pipes and their fittings. Main findings include:

- It is possible to construct two-way hollow reinforced concrete slabs with voiding ratio up to 24% using two-way piping systems with keeping about 80% of the original ultimate loading capacity.
- It is possible to compensate the reduction that occurs in the strength of two-way hollow reinforced concrete slabs by using fiber reinforced concrete, increasing the ratio of main reinforcement, using mixtures of high strength concrete or distributing the two-way piping system out of the location of the maximum stresses.

- Using nonlinear finite element analysis by ABAQUS/Standard 2017 in conducting the mechanical behaviour of two-way hollow reinforced concrete slabs showed acceptable results with a maximum difference in cracking loads, ultimate loading capacity and central deflection of about 14%, 15% and 13%, respectively in comparison with the experimental results.

Nomenclatures

A_{nu}	Distributing the two-way piping system out of the location of maximum stresses
A_u	Distributing the two-way piping uniformly
C_{35}	Concrete with normal strength
$C3D8R$	An 8-node linear brick with reduced integration and hourglass control
C_{65}	Concrete with high strength
D_0	Solid slab
D_{32}	Pipe diameter equal to 32 mm
D_{40}	Pipe diameter equal to 40 mm
F_0	Concrete slab with no fibers
$F_{1.5}$	Concrete slab with (1.5%) micro steel fiber
H_0	Solid slab
H_{16}	Two-way hollow slab with 16% of voids
H_{24}	Two-way hollow slab with 24% of voids
L_u	Load type is equivalent uniformly distributed repeated load
$P_{(cr_Exp)}$	Experimental first cracking load, kN
$P_{(cr_Num)}$	Numerical first cracking load, kN
$P_{(u_Exp)}$	Experimental ultimate load, kN
$P_{(u_Num)}$	Numerical ultimate load, kN
R_1	The ratio of main reinforcement equal to 0.002355
R_2	The ratio of main reinforcement equal 0.004710
$T3D2$	A 2-node linear 3-D truss

Greek Symbols

ρ	The ratio of main reinforcement
δ_{cu_Exp}	Experimental ultimate deflection, mm
δ_{cu_Num}	Numerical ultimate deflection, mm

Abbreviations

ABAQUS	Finite element package
ABAQUS	Finite element package
ASTM	American Society for Testing and Materials
EUDRL	Equivalent uniformly distributed repeated load
EUDRL	Equivalent uniformly distributed repeated load
FEA	Finite element analysis
FEA	Finite element analysis
IQS	Iraqi Quality Standardization

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