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Analysis and Parametric Study of Reinforced Concrete Two-Way Ribbed Slabs by using ANSYS

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Abstract

This paper presents the results of finite element analysis for two experimental works (taken from other research works). The aim of this study is to use finite element method (FEM) by using ANSYS (v.15) software to analyse the specimens of experimental work to verify the validity of FEM by comparison with experimental results. In addition, some parametric studies on these works are done to cover the effect of some important variables on the ultimate load capacity and deflection which were not covered in the experimental work. The results of ANSYS software for chosen examples shows good agreement with the experimental results. Load-deflection curves for ANSYS models are higher than the experimental curves. The average value of correlation factor is (98.85%)for first example and (73.7%) for the second one. Results have shown that the percentage of increase in stiffness increases with increasing of slab thickness, but this increase is governed by the spacing between ribs.

Keywords: Ribbed slab; waffle slab; finite element analysis; ANSYS.

1. Introduction

Two-Way Ribbed (Waffle) slab system can be defined as the slab constructions having a flat flange plate, or deck, and equally spaced parallel beams in two orthogonal direction, or grillage. The main purpose of using two-way ribbed (waffle) slabs is to reduce the quantity of concrete and reinforcement and hence the weight

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Reference [1] tested three models of reinforced concrete waffle slab to study the effect of rib orientation on the carrying capacity of waffle slab. The models were different in the shape and construction method, but having the same volume of concrete and the same area of reinforcing steel bars. It was concluded from the experimental results that the shape and method of construction for reinforced concrete slab affected the ultimate load capacity and stiffness. Reference [2] used experimental study and theoretical analysis to discuss the effect of rib spacing and the depth of rib on the flexural rigidity resistance for waffle slabs, and compared between the results of different models. In the experimental work, six models of square panels of ribbed flat slabs in 1: 4 scale and two solid flat slabs had been tested. To study the effect of the bending and torsion the slabs were considered isotropic in shape and reinforced in two perpendicular directions, so that the resistant moments were identical in both directions. The test specimen was simply supported along the four edges and its dimensions were (1540 *1540) mm. It was concluded that increasing the number of ribs, or decreasing their spacing, stiffness of waffle slab was increased and the deflection in elastic uncracked range was decreased. In 2009, Large in [3] studied the effect of using high performance fiber concrete on the top slab in waffle slab structures. In this research, 11 various series were tested. The specimens are differed in types of fibers and concrete mixture used. They were subjected to different combinations of flexural and torsion loads. Test results showed higher shear and torsion capacity with using fibre concrete. Therefore, steel fibers can be placed instead of conventional shear reinforcement. Reference [4] presented and discussed the optimum design problem of reinforced concrete two-way ribbed slabs by using genetic algorithms. Two cases had been studied; the first was a waffle slab with solid heads, and the second was a waffle slab with band beams. The researchers concluded that the total cost of waffle slab with band beams was higher than that with solid head for slabs with the same span length. The ratio of the total costs was found to be within the range (1.10 - 2.12) and the cost ratio decreases as the span length increases. Reference [5] focused on analysis of two-way ribbed slabs with hidden beams. From the obtained results, the researcher concluded that the distribution of moments in two-way slabs with hidden beams was similar to the distribution of moments in slabs without beams if the stiffness of the hidden beams was small. In addition, using of three dimensional modelling by computer software provides a good solution for moment’s determination and distribution. In the present study, six specimens are chosen from reference [2] and one specimen is taken from reference [6]. The dimensions of these specimens are slightly changed for purpose of easy meshing. Nonlinear analysis by 3D finite elements model is done using ANSYS-v15. The total load applied to finite element model is divided into a series of load increments called load steps. At the completion of each incremental solution, the stiffness matrix of the model is adjusted to reflect nonlinear changes in the structural stiffness before proceeding to the next load increment [7]. The ANSYS program uses Newton-Raphson equilibrium iterations for updating the model stiffness.

2. Finite Element Modelling & Analysis by ANSYS

2.1 First Example

Reference [2] used experimental study and theoretical analysis to discuss the effect of rib spacing (S) and rib depth on the flexural rigidity of two-way ribbed (waffle) slabs, and compare between results for these methods. In experimental work, six models of square panels of ribbed flat slabs in 1: 4 scale and two solid flat slabs had been tested. The Slabs were considered isotropic in shape and reinforced in two perpendicular directions, so that the resistant moments were identical in both directions. Dimensions of test specimens were (1540 x 1540) mm and simply supported along the four edges. Figure (1) shows the details of slabs.

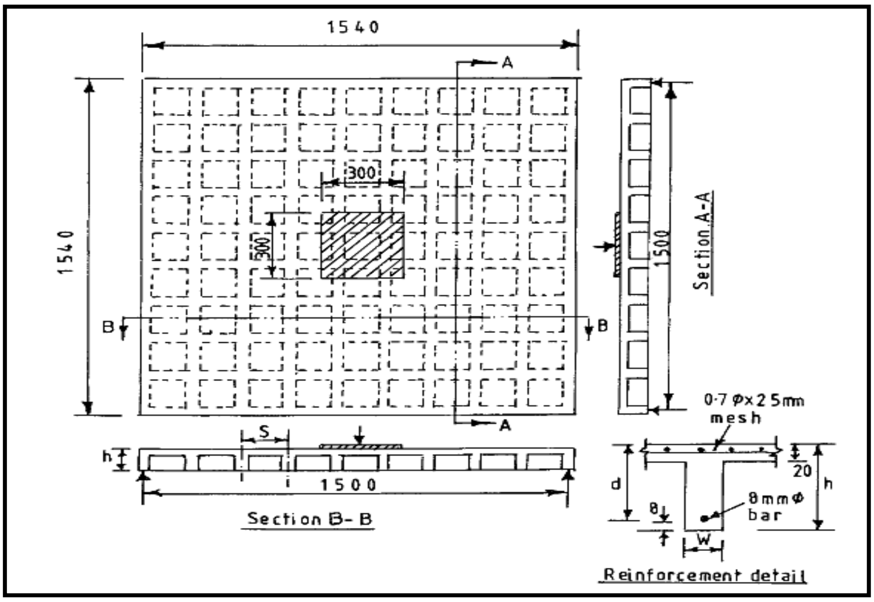


Figure 1: Geometry of Waffle Slabs, Loading Arrangement, and Reinforcement.[2]

In the present study, six specimens have been analysed by using ANSYS package (version 15), then compare the results with the experimental results of Reference [2]. Table (1) shows the six specimens analysed in this study.

Table 1: The Slab dimensions used in the present study**.**

Slab number (1)	*Bays (2)*	*S (mm) (3)*	*T (mm) (4)*	*W (mm) (5)*	*H (mm) (6)*	*h/t (7)*	*As (mm^2/m)*
S2	*9x9*	*170*	*20*	*50*	*95*	*4.75*	*301*
S4	*5x5*	*300*	*20*	*50*	*95*	*4.75*	*168*
S5	*9x9*	*165*	*20*	*60*	*125*	*6.25*	*301*
S6	*9x9*	*165*	*20*	*45*	*65*	*3.25*	*301*
S7	*Solid*	*—*	*—*	*—*	*75*	*1.00*	*301*

2.1.1 Real Constants

The real constants for this example are shown in Table (2).

Table 2: Real Constant.

Real constant Set No.	Element Type	Material	Value
1	Solid65	Concrete	N/A
2	Link180	Steel Bar(rib)	50.24 mm2
3	Link180	Steel Bar(slab)	.38465 mm2

2.1.2 Material Properties

Concrete properties for specimens as used in ANSYS are summarized in table (3).

Table 3: Concrete properties for specimens as used in ANSYS.

Slab Specimens	Compressive strength(f_c)	Modules of elasticity(Ec)	Poisson's ratio(*PRXY)*	B_t	B_c	F_t
S2	32	26587.21	.2	.5	1	3.5
S4	28.9	25266.5	.2	.4	.7	3.33
S5	29.9	25700	.2	.3	.6	3.4
S6	29.1	25353.87	.2	.5	1	3.34
S7	36	28200	.2	.4	.7	3.7
S8	28.5	25091.13	.2	.4	.7	3.33

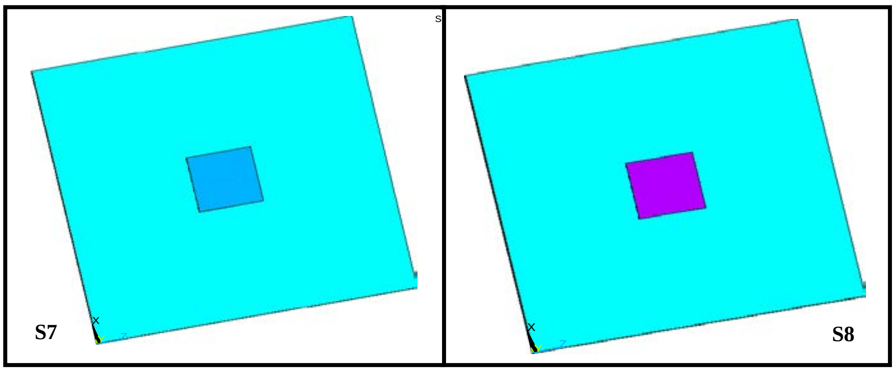


Figure 2: Modelling of Solid Slabs

For all specimens, steel plates have been added at the locations of supports and loading by using (solid185) elements. The steel plates were assumed to be linear elastic materials with an elastic modulus equal to 200,000 MPa and Poisson's ratio of (0.3). Flexural reinforcement consisted of 8-mm-diameter smooth steel bars with yield strength of 398 MPa. To satisfy temperature requirement, wire mesh with an average diameter of 0.7 mm and mesh size of 25 mm is used and link (180) is used to represent it with an elastic modulus equal to 200,000 MPa and Poisson's ratio of (0.3). Modelling of slab specimen is shown in Figure (2) and (3).

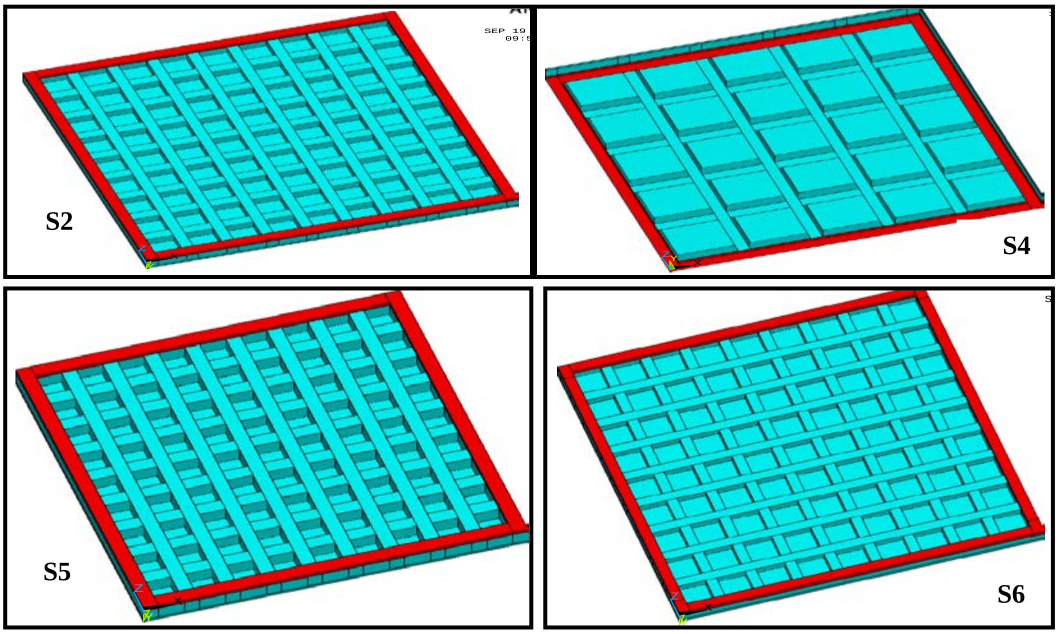
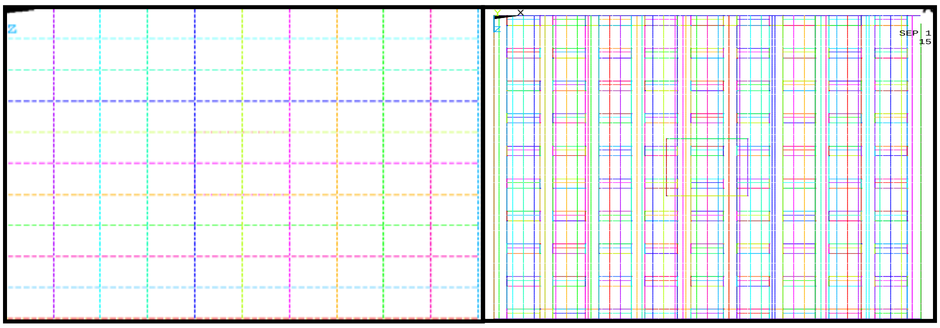


Figure 3: Modelling of Waffle Slabs.

Details of reinforcement bars in slabs are shown in Figure (4).



(S7) **(S2)**

Figure 4: reinforced concrete slabs.

2.1.3 Meshing

In some specimens, the width of ribs and spacing has been slightly changed to simplify and control the process of meshing. The reinforcement steel has been meshed as line element (using link 180) while the concrete is meshed as solid elements (solid 65).

Table (4) shows the element size in(X-Y-Z) directions for all specimens. Meshing of slab specimen is shown in figure (5).

Table 4: Element Size in(X-Y-Z) direction for the specimen

Slab	Element *Size*(mm)		
	X	Y	Z
(S2)	10	10	10
(S4)	25	10	25
(S5)	15	15	15
(S6)	15	15	15
(S7)	25	15	25
(S8)	50	9.5	50

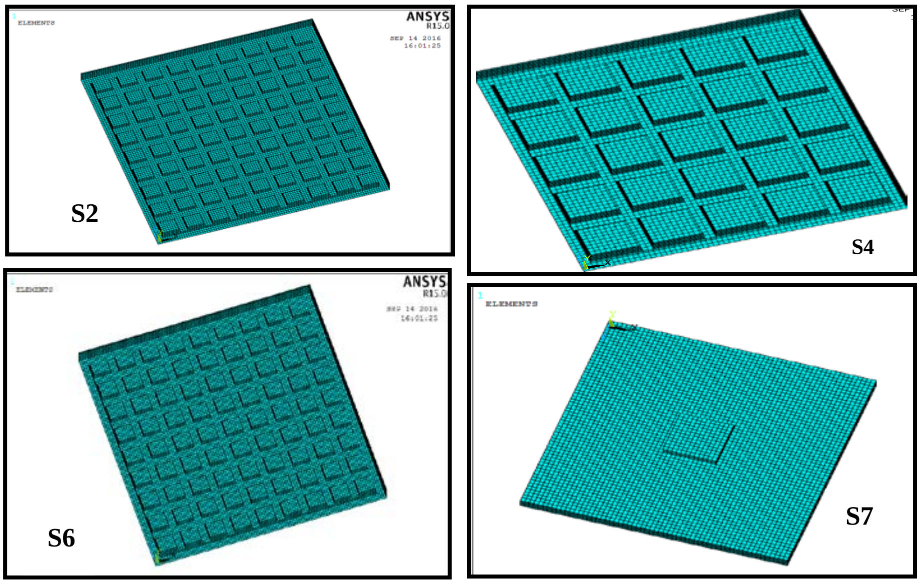


Figure 5: Meshing of Slab Specimens.

2.1.4 Loads and Boundary Conditions

To confine the model and get an accurate solution, displacement boundary conditions are applied at planes that prevent the movement in (x-y) and (z-y) directions(simple support at the four edges are assumed). Boundary conditions have been applied after placing steel cushion with solid element mesh by using (solid185) elements, in the region of the supports and loading to prevent local failure under concentrated loads. Figure (6) shows boundary conditions for all specimens.

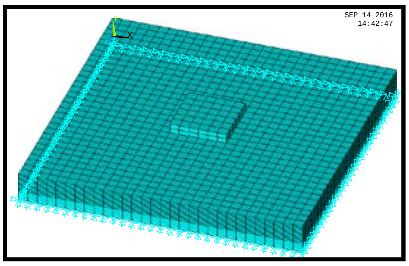


Figure 6: Boundary Conditions for All Specimens.

In this study, the number of sub steps changes according to applied load in the experimental program for each specimen. Maximum number of equilibrium iteration is limited to 100.

The convergence criteria is based on displacement. Achieving the convergence of the solutions for the models was difficult due to the nonlinear behavior of reinforced concrete. Therefore, to accelerate the solution, the value of tolerance was increased.

Allawi reported [8] that **Kachlakev and his colleagues (2001)** and **Dahmani and his colleagues (2010)** had efficiently used convergence tolerance limits of 0.005 and 0.05 for force and displacement respectively. Anyway, the tolerance for displacement used in this study is chosen as (0.02) for all specimens and shown to be satisfactory.

2.1.5 Parametric Study

The parametric study in this example is carried out by transformation of three specimens from waffle to solid slab. The specimens of waffle and solid slab have the same volume and properties of materials. The influence of thickness of slab on the mid span deflection and stiffness has been studied. In this example, waffle slab (**S2**) is transformed to solid slab keeping the concrete volume constant, t

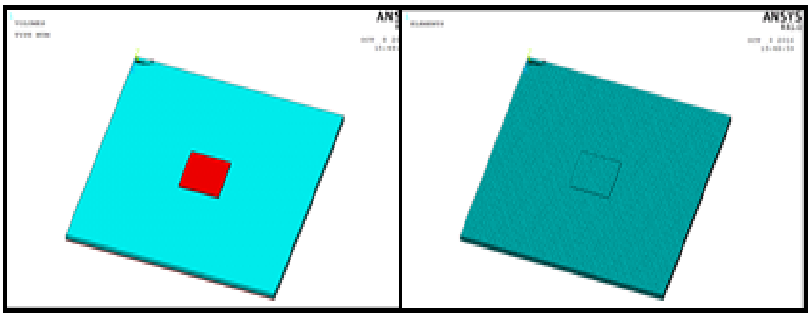


Figure 7: Modelling and Meshing of Solid Slab.

he slab thickness of equivalent solid slab is calculated for all models. Modelling, meshing, details of steel reinforcement and boundary condition of solid slabs are shown in Figures (7), (8), and (9) respectively**.**

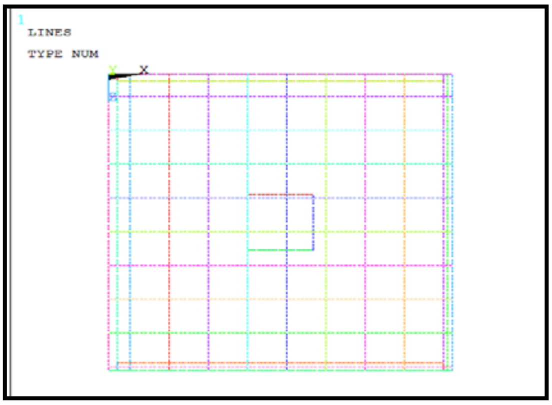


Figure 8: Details of Steel Reinforcement.

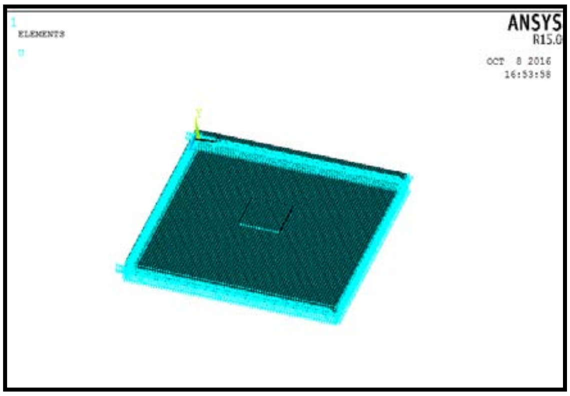


Figure 9: Boundary Condition of Solid Slab.

2.2 Second Example

In reference [6], the researchers tested six models of two-way ribbed slabs. One of these models contained solid portion in the center of the slab and without holes, while other models are containing one or two holes that vary in the shape and location for each model.

The dimensions of models are (1,800 x 1,800 x150) mm in length, width and thickness, respectively. The voids between ribs are Filled by Styrofoam (EPS), with dimensions (200 x 200 x 110) mm for length, width and height respectively.

In this study, one model without holes has been taken to analysis it by using ANSYS package (v.15) and compare the result with the experimental results presented in Ref. [6]. Figure (10) shows the details of two-way ribbed slab. In this model, flexural reinforcement steel were CA50 diameter Ø 8.0 mm.

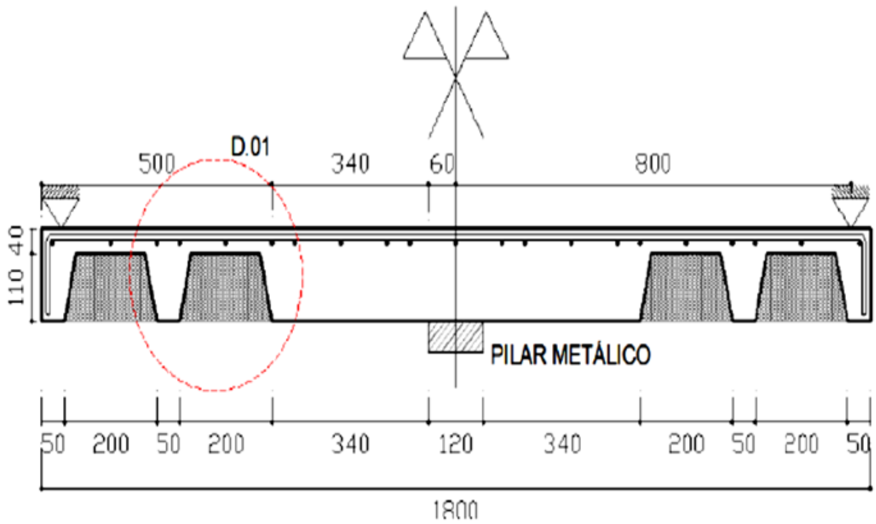


Figure 10: General Section of Ribs.[6]

Figure (11) shows the details of steel reinforcement.

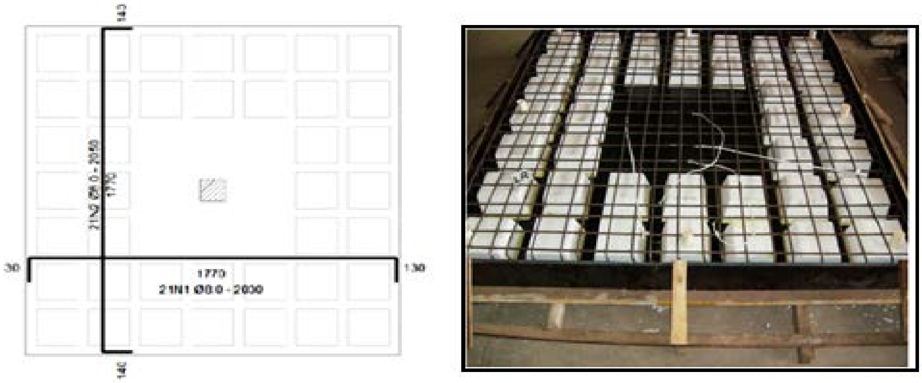


Figure 11: Details of Steel Reinforcement. [6]

2.2.1 Materials Properties

The properties of the materials used in finite element analysis are listed in table (9).

Table 9: Materials Properties for model

Material Model Number	Element Type		
1	Solid 65	Linear Isotropic	
		Ex	25600
		PRXY	.2
		Concrete	
		Open Shear Transfer Coef.	.001
		Close Shear Transfer Coef.	.5
		Uniaxial Cracking Stress	2.4
		Uniaxial Crushing Stress	43
		Tensile Crack Factor	1
2	Link 180	Linear Isotropic	
		Ex	284000
		PRXY	.3
		Bilinear	
		Yield strength	553
		Mod Tang	20
3	Solid185	Linear Isotropic	
		Ex	150000
		PRXY	.3

2.2.2 Modelling of two-way ribbed slab

In the modelling of two-way ribbed slab, some of the original dimensions of Ref [6] are slightly changed for purpose of easy meshing. Table (10) shows the dimensions of the model that used in this study**.**

Table 10: Model Dimensions

Slab model (1)	S (mm) (2)	t (mm) (3)	W (mm) (4)	h (mm) (5)	Total dimensions (mm) (6)
LR1	255	40	80	150	1860 x 1860

2.2.3 Meshing

Table (11) shows the element size in (X-Y-Z) direction for the Model. Modelling, meshing and boundary condition of two-way ribbed slab in the ANSYS package are shown in Figures (12) and (13) respectively.

Table 11: Element Size in (x-y-z) direction

LR1	**Element Size (mm)**		
	X	**Y**	**Z**
(Rib)	**15**	**10**	**15**
(Slab)	**15**	**20**	**15**

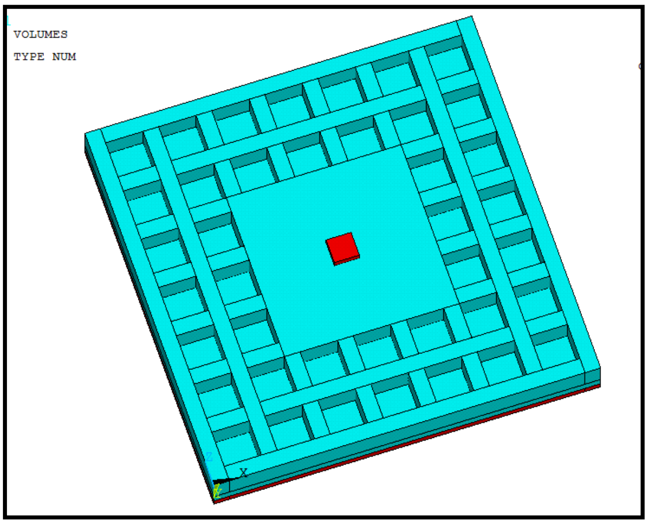


Figure 12: Modelling of Two-Way Ribbed Slab.

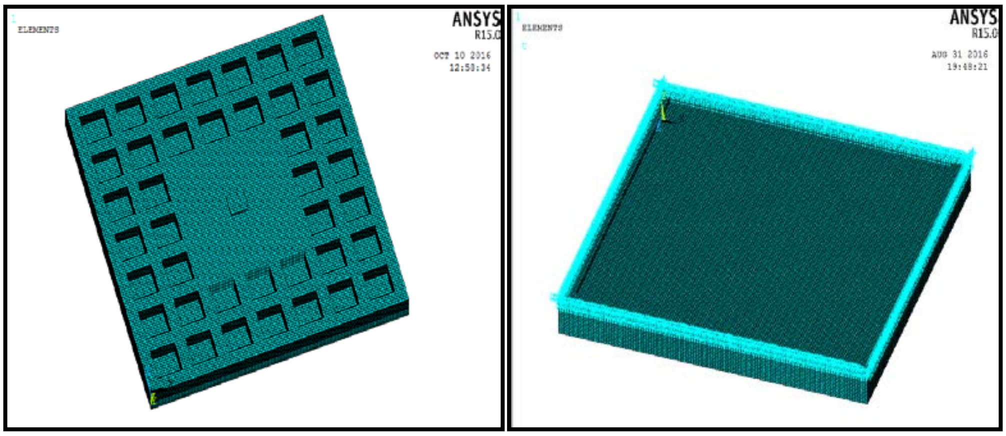


Figure 13: Meshing and Boundary Condition of Two-Way Ribbed Slab

2.2.4 Parametric Study

In this example, one solid slab and two-way ribbed slab without solid portion have been analyzed to carry out the parametric study. The two models have the same dimensions and materials properties of the original model. Modelling, meshing and boundary condition of solid and two-way ribbed slab in the ANSYS package are shown in Figures (14), (15) and (16) respectively**.**

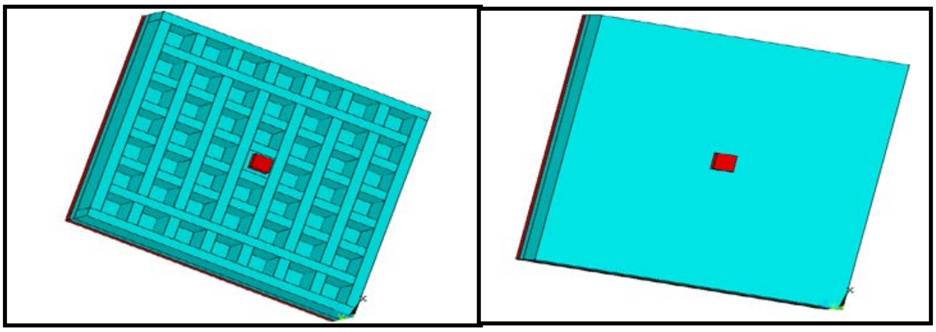


Figure 14: Modelling of Slabs (Bottom View).

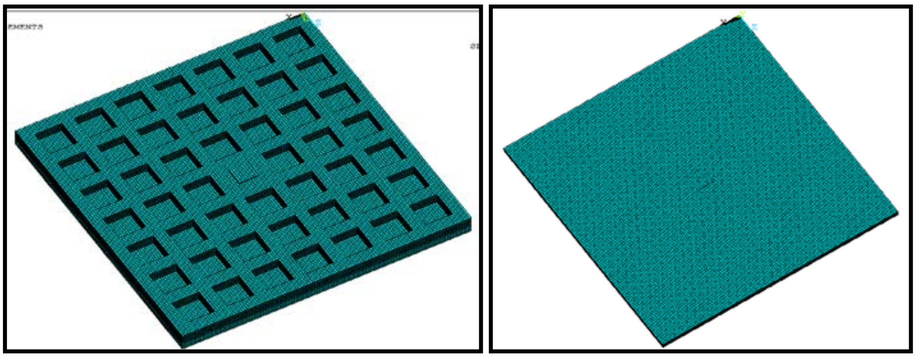


Figure 15: Meshing of Slab.

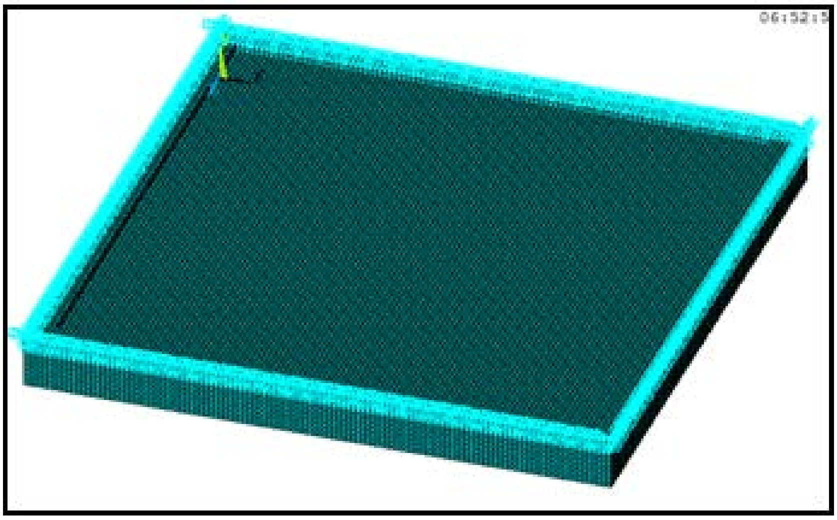


Figure 16: Boundary Condition (Top View).

In addition, parametric study is carried out by using the equation (3) and (4) in (ACI and NBR code respectively) to compute the modules of elasticity for concrete and input these values to analyse the original model by using **ANSYS**. Then, comparison of the results with the experimental work is done.

$E_c=4700\sqrt{f_c'}$ (ACI 318- 2014) ……(3)

$E_c=5600\sqrt{f_c'}$ (NBR 6118 -2003) .... (4)

3. Results and Discussions

3.1 General

The main reason for the use of the ANSYS (v.15) is the capability of the program to analyse simple and complex, linear and non-linear, static and dynamic problems.

In this study, ANSYS (v.15) has been used to create six specimen models (S2, S4, S5, S6, S7, S8) for the first example and one specimen model (LR1) for the second example.

The comparisons between the experimental work and results of FE analysis including load- displacement curves are presented and discussed in the following sections.

3.2 First Example

3.2.1 Load- Displacement Response

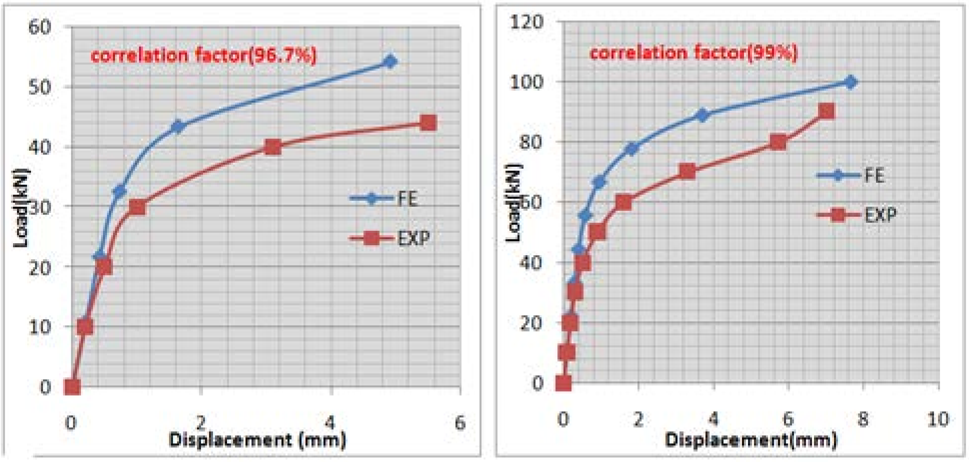


Figure18: Load-Displacement response for solid slab

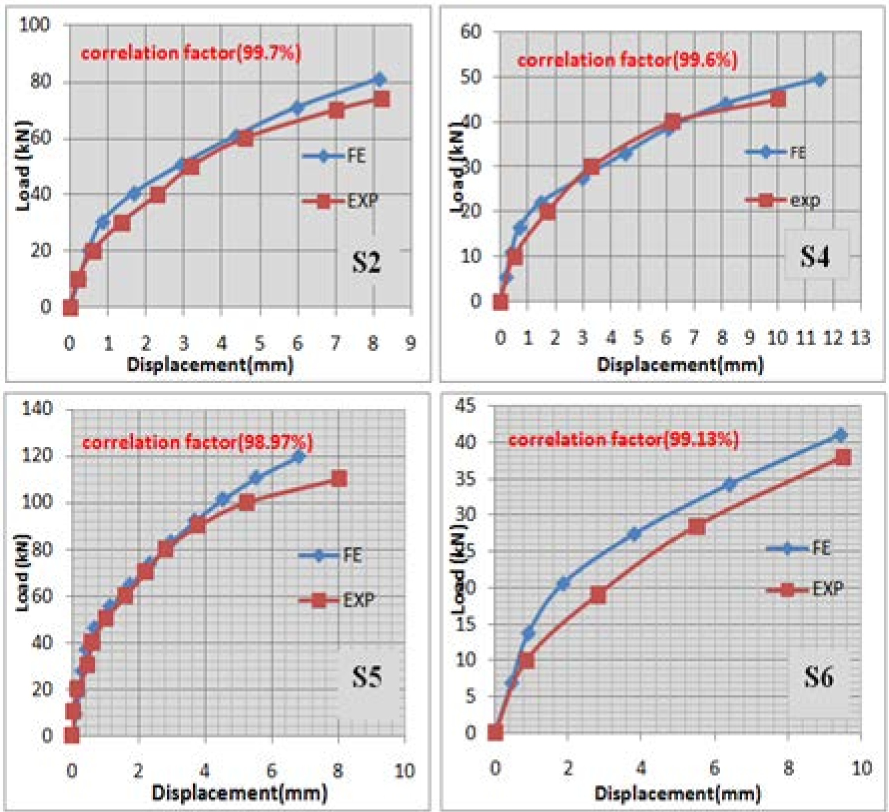


Figure 17: Load-Displacement response for waffle slab

The relationship between the load and deflection for concrete structures is important to understand the general behaviour of thesis specimens because each specimen has different behaviour. In ANSYS program, Newton–Raphson method has been used for the incremental load analysis. The load-deflection response for first example is shown graphically in Figures (17) and (18).

In ANSYS model, representation of variation of maximum deflection for slab specimens under the effect of ultimate loads is shown in Figure (19).

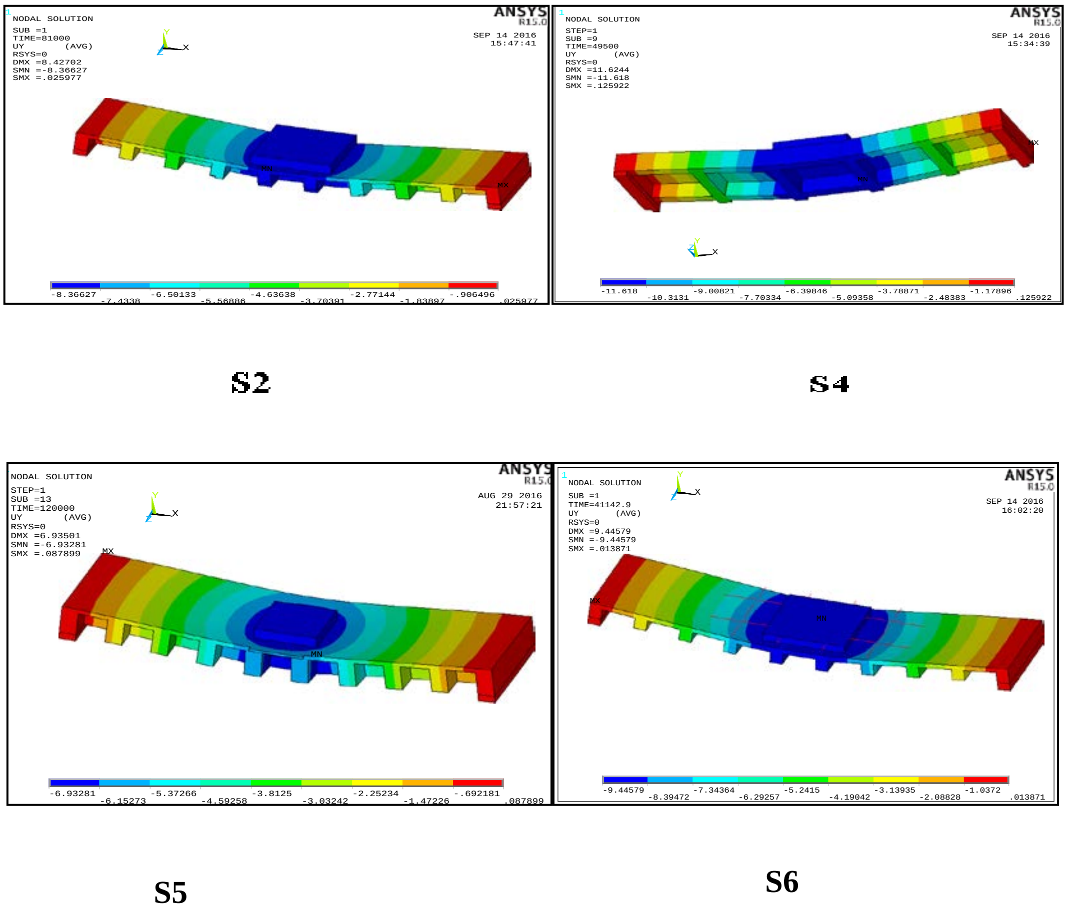


Figure19: Vertical Displacement for Slab Specimens**.**

3.2.2 Comparison between Experimental and Finite Element Results

To verify the validity of the finite element method, a comparison must be done between the Experimental and numerical analysis values of ultimate load and displacement. Table (12) shows the failure load of the experimental and the numerical model. It also shows the ratio between them. From analysis by using (ANSYS) program, the mid span deflection and the failure load values at failure are agreed with the measured values by expermental work with a little difference as shown in the table.

For waffle slab specimens, the comparison between the Experimental and numerical results showed good agreement for three stages of load-midspan deflection curves, before cracking (Elastic stage), cracking stage (till yielding of steel), and yielding of steel and crushing of concrete. While the result of solid slab specimens is showed a good agreement between experimental and finite elements result in elastic range only .Then, the difference between finite elements and experimental curves increases after first crack. The average value of correlation factor was *(98.85%)*.The difference between experimental work and numerical results due to the assumptions made in the FE (ANSYS) modelling. Some of these assumptions are following.

Table 12

Slab Specimen	*FEA Failure load P(FEA) (kN)*	*Experimental Failure load P(Exp)(kN)*	*P(Exp)/ P(FEA)*	*FEA Ultimate Displacement Δ(FEA)(mm)*	*Experimental Ultimate Displacement Δexp(mm)*	*Δ(FEA)/Δexp*
S2	*81*	*74*	*.91*	*8.12662*	*8.2*	*.99*
S4	*49.5*	*45*	*.90*	*11.5*	*10*	*1.15*
S5	*120*	*110*	*.91*	*6.8*	*8*	*.85*
S6	*41.143*	*38*	*.92*	*9.44*	*9.5*	*.99*
S7	*54.167*	*65*	*1.19*	*4.9*	*5.5*	*.89*
S8	*100*	*90*	*.90*	*7.66*	*7*	*1.09*

1. The concrete is assumed to be homogenous material.

2. Perfect bond between concrete and reinforcement.

3. The reinforcement is assumed to carry stress along its longitudinal axis only.

3.2.3 Analysis Results of Parametric Study

The parametric study in this example is carried out by assuming the volume of concrete for solid slab is the same volume for waffle slab. The main purpose of this study is to investigate the effect of thickness of slab on the stiffness and ultimate load capacity for waffle and solid slab with common constant volume. When the volume is constant, thickness of waffle slab is greater than the solid slab. This is leads to increasing the flexural rigidity (EI) for waffle.

Analysis results are shown in Figure (20).

3.2.4 Percentage of increase in stiffness of waffle slab as compared to solid slab with the same volume of concrete

From analysis results, the percentage of increase in Stiffness is observed with varying ratios for each model. Table (13) shows the percentage of increase in stiffness for each model.

Load-displacement response for slab specimens is shown in Figure (21). The numerical FE analysis Results show that the percentage of increase in stiffness increases with increasing of slab thickness. However, this increase is governed by the rib spacing.

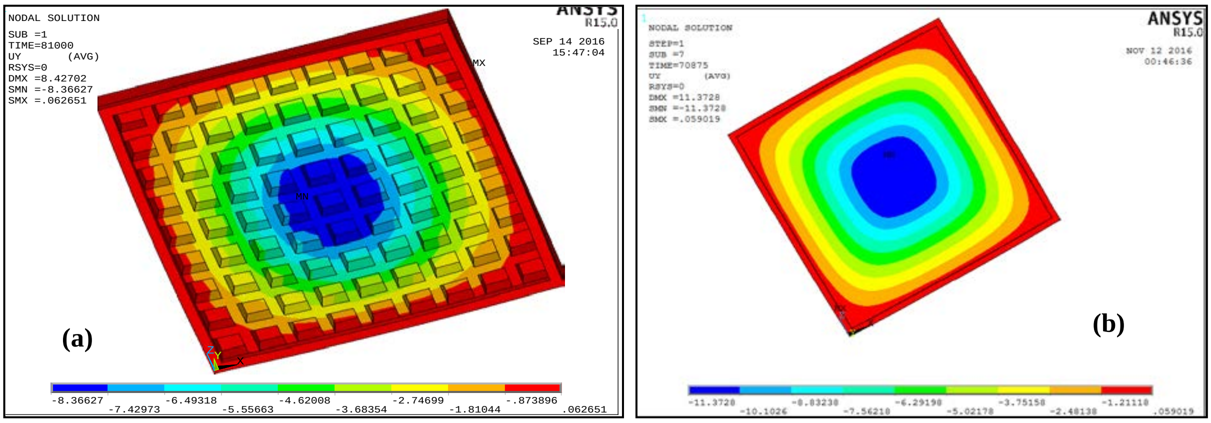


Figure 20: Analysis Results For (a)(S2)Original Model(b) Equivalent Model

Table 13: The Ratio of Increase in Stiffness for Each Model.

Waffle slab(Original Model)	S (mm)	Solid Slab Equivalent Model	Total Thickness waffle slab (mm)	Total Thickness Solid slab (mm)	Δ Waffle (mm)	Δ Solid (mm)	$\frac{h_{waffle}}{h_{solid}}$	$\frac{\Delta_{Solid}}{\Delta_{Waffle}}$
S2	170	S2eq	95	60	8.12	11.3	1.58	1.39
S4	300	S4eq	95	47	11.5	13.92	2.021	1.21
S5	165	S5eq	125	86	6.79	9.3	1.45	1.37

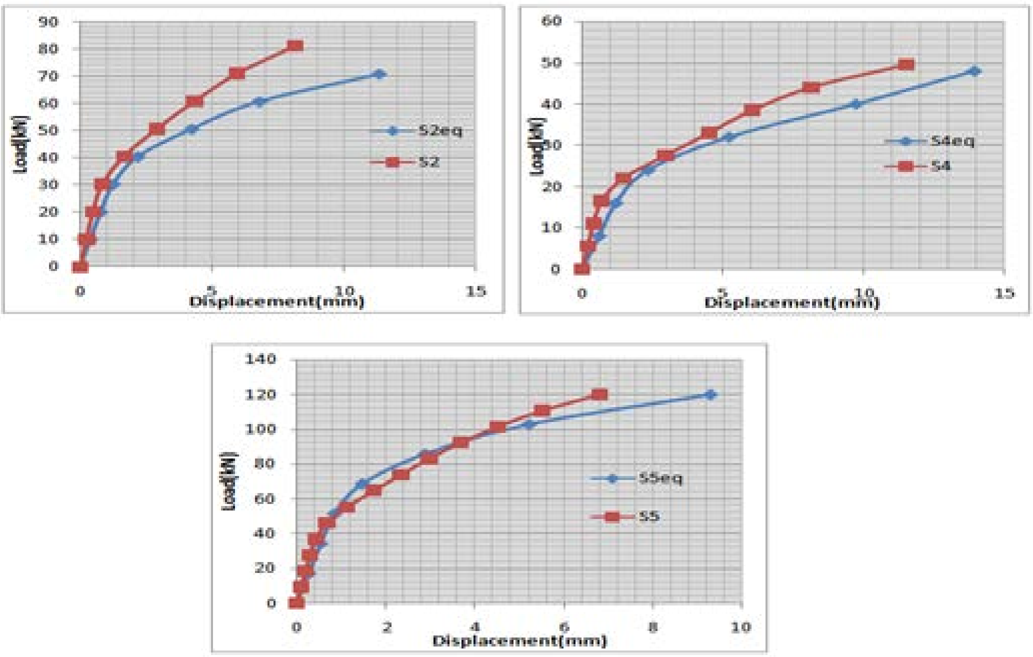


Figure 21: Load-Displacement response for slap slab

3.3. Second Example

3.3.1 Load-Displacement Response

Details and dimensions of slab specimen are given in section (2.2). Analysis results by ANSYS program and load-displacement response for slab specimen are shown in Figures (22) and (23) respectively. Table (14) shows the comparison between finite element and experimental work.

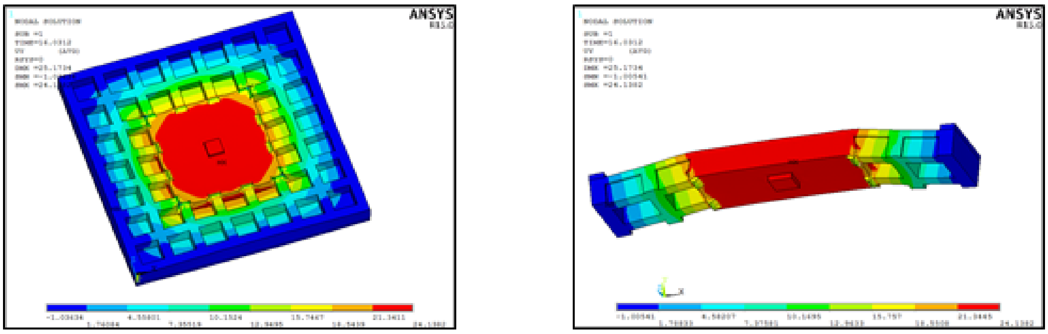


Figure 22: Vertical Displacement for Slab Specimen

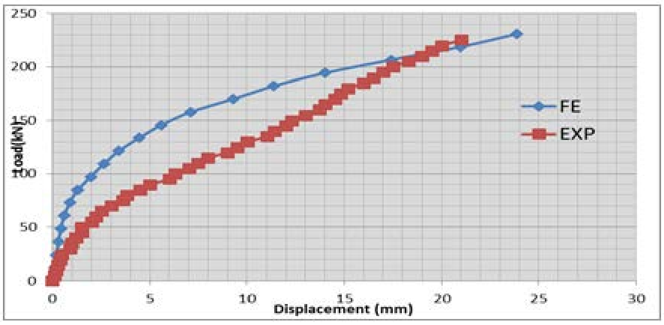


Figure 23: Load-Displacement Response for Slab Spaicmen

Table 14: Comparison between experimental work and finite element results (Ultimate Load and Ultimate Displacement)

Slab Specimen	FEA Failure load P(FEA)(kN)	Experimental Failure load P(Exp) (kN)	P(Exp) / P(FEA)	FEA Ultimate Displacement Δ(FEA) (mm)	Experimental Ultimate Displacement Δ(Exp)(mm)	Δ(FEA) / Δ(Exp)
LR1	*230.8464*	*225*	*.97*	*23.8854*	*21*	*1.13*

From analysis results, the ultimate load and ultimate displacement in the ANSYS model are slightly higher than the experimental work in the elastic range. In the cracking stage, the difference between experimental work and Finite Element result is increased. This difference may be due to the existence of errors in experimental work or the measure of deflection is not accurate. In addition to the imposition of perfect bond in numerical analysis. The correlation factor value is found to equal (73.7%).

3.3.2 Analysis Results of Parametric Study

In this example, parametric Study is carried out by adding two models to the origin model. The two models are solid slab and two-way ribbed (waffle) slab without solid portion. They have the same dimensions and materials properties of the original model. Figure (24) shows the results of analysis for models.

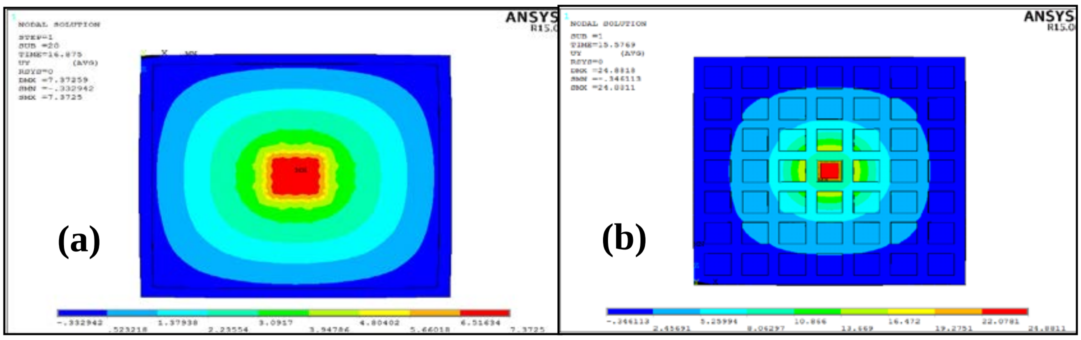


Figure 24: Analysis Results for(a) Top View of Solid Slab (b) Bottom View of Waffle Slab

To compare between results, Figure (25) shows load- deflection response for models.

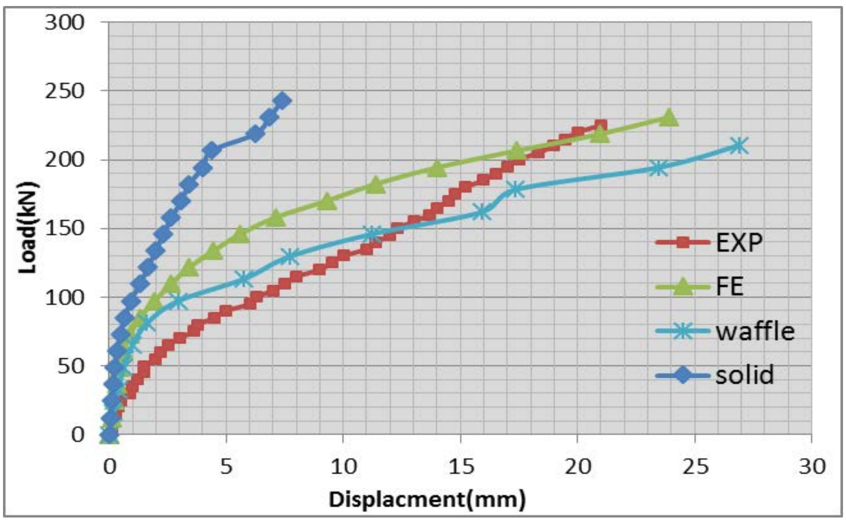


Figure 25: Comparison between original model and others models**.**

3.2.2 Study of structural behaviour (i.e. load-deflection curve) between waffle and solid slab with common constant thickness

After analysis, the results for the two proposed models have been compared with the original model. The results showed that the solid slab has higher stiffness because the thickness for all specimens is equal. Two way ribbed (waffle) slab has higher stiffness up to (150) kN loading. Beyond this limit, the stiffness for this model is slightly decreased.

3.2.3 Effect of modules of elasticity values (Ec) on structural behavior of waffle slab

This study is conducted to study the effect of modules of elasticity on the behavior of waffle slab. Two models have been analyzed by using two equation (3) and (4) in (ACI and NBR code respectively).

Analysis results showed that increasing modules of elasticity changed the location and value of maximum deflection .This leads to improve the behavior of waffle slab and increased the stiffness. Figure (28) shows load-deflection response for slab specimens.

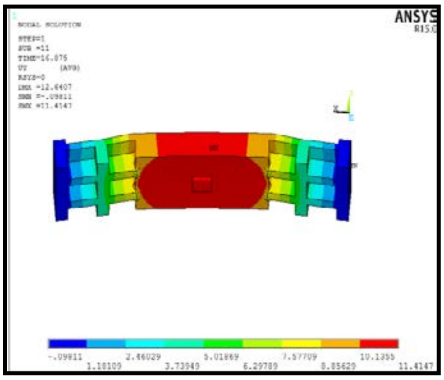


Figure 26: Analysis Results for (Ec=30820 N/mm^2)

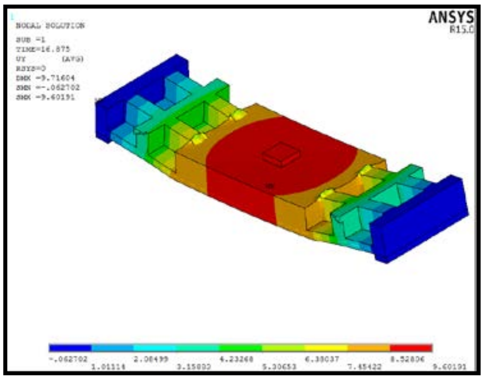


Figure 27: Analysis Results for (Ec=36721 N/mm^2)

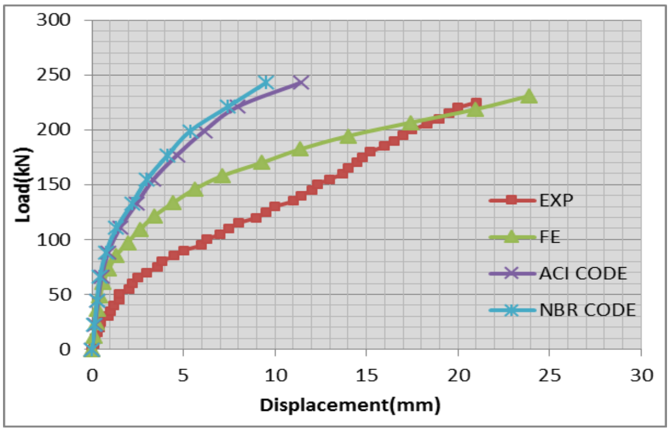


Figure 28: Load-Displacement Response for Slab Spaicmens

Increasing modulus of elasticity from (25600) to (30820) N/mm^2 (ACI CODE) decreased the deflection from (21) to (11.4) mm. Increasing modules of elasticity from (25600) to (36721 N/mm^2) (NBR CODE) decreased the deflection from (21) to (9.5) mm. Table(15) shows the location and value of maximum deflection for slab specimens.

Table 15: Location and Value of Maximum Deflection for Slab Specimens.

Slab Specimens	Maximum Deflection (mm)	***Location(mm)***		
		X	Y	Z
Exp(LR1)	***24.1382***	*930*	*219.176*	*854.767*
ACI CODE	***11.4147***	*884.615*	*233.98*	*837.653*
NBR CODE	***9.6019***	*868.862*	*241.908*	*668.862*

4. Conclusions

Based on the results of numerical analysis in this study, some conclusions can be summarized as follows:

1- Applying the finite element method by using ANSYS (V.15) to analyze the specimens of two experimental works showed good agreement with the experimental results regarding the deflection and ultimate load capacity. The results of FE analysis by using ANSYS15 software for verification examples showed good agreement with the experimental results; load-deflection curves of numerical model are stiffer than the experimental curves. The average value of correlation factor was *(98.85%)* for first example. For the second example, the correlation factor value was (73.7%).

2- The Percentage of increase in Stiffness increased with increasing of slab thickness. However, this increase is governed by the spacing between ribs.

3- The two- way ribbed (waffle) slab without solid portion in the region of loading has higher stiffness the two-way ribbed (waffle) slab with solid portion up to same limit. Beyond this limit, the stiffness for this model is slightly decreased.

4- Increasing modules of elasticity for verification example (2) leads to improve the behavior of waffle slab and increases the slab stiffness.

5. Recommendations for Future studies

a- Analysis of skew waffle slab as compared with Right angle slab.

b- Analysis of curved waffle slab.

c- Analysis of prestressed waffle slab.

d- Analysis of waffle slab under low-speed and high-speed impact load.

e- Experimental and theoretical study of light weight concrete waffle slab.

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