Finite element Analysis of Large Span Continuous Two-Way Ribbed Slabs with Some Parametric Studies

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Abstract

This paper investigates the results of finite element analysis for three proposed full-scale two-way slabs. The aim of this study is to use finite element method (FEM) by using ANSYS-v15 program to analyze the proposed slabs and study the flexural behavior , especially load-deflection relationship and ultimate strength. Some parametric studies on these works are also done to cover the effect of some important parameters on the ultimate load capacity and deflection. Proposed slabs are divided into three groups with different dimensions to study the effect of using continuous large spans on the structural behavior of two-way ribbed (waffle) slabs as compared to solid slabs. In all three groups, each slab consists of three by three panels supported by concrete columns at corners. For the first group, when the void ratio (the ratio of volume of voids between ribs to total volume of ribbed slab) increases, the stiffness of waffle slab also increases. Increasing stiffness for waffle slab is continued up to some limit, and then will decrease with increasing void ratio. The best case in this example occurs when the void ratio equal to (0.667) which gives increase in stiffness of (0.347) as 3compared to solid slab with the same thickness. The results of ANSYS analysis shows that the best percentage of increase in deflection is (51%) with decreasing in concrete volume of (59%) for long to short span ratio of (1.5) and 4(300)mm thickness. For the third group of proposed models, the stiffness of two-way ribbed (waffle) slab is higher than the solid slab which has the same volume of concrete. The displacement of two-way ribbed (waffle) slab in the elastic range (at first crack) is lower than the solid slab. In this manner, it will give the maximum reduction in concrete weight with higher thickness.

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

التحليل بالعناصر المحددة للبلاطات المعصبة باتجاهين ذات الفضاءات الكبيرة المستمرة مع بعض الدراسات البارامترية

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الخلاصة:

تبحث هذه الورقة في نتائج تحليل العناصر المحددة لثلاث بلاطات مضلعة باتجاهين ذات فضاءات واسعة مقترحة. الهدف من هذه الدراسة هو استخدام طريقة العناصر المحددة (FEM) باستخدام برنامج ANSYS-v15 لتحليل السقوف المقترحة ودراسة سلوك الانحناء ، وخاصة علاقة انحراف التحميل والقوة النهائية. يتم أيضًا إجراء بعض الدراسات المعيارية حول هذه السقوف لمعرفة تأثير بعض المتغيرات المهمة على السعة القصوى للانحراف. تقسم البلاطات المقترحة إلى ثلاث مجموعات ذات أبعاد مختلفة لدراسة تأثير استخدام فضاءات كبيرة مستمرة على السلوك الهيكلي للبلاطات المضلعة باتجاهين مقارنة بالبلاطات الصلبة. في كل

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المجموعات الثلاث ، تتكون كل بلاطة من ثلاثة سقوف بثلاثة أعمدة مدعومة بأعمدة خرسانية في الزوايا. بالنسبة للمجموعة الأولى ، عندما تزيد نسبة الفراغ (نسبة حجم الفراغات بين الأضلاع إلى الحجم الكلي للبلاطة المضلعة) ، تزداد صلابة البلاطة المضلعة أيضًا، تستمر زيادة صلابة البلاطة إلى حد ما ، ومن ثم ستنخفض بزيادة نسبة الفراغ. أفضل حالة في هذا المثال تحدث عندما تكون نسبة الفراغ تساوي (٠.٦٦٧) والتي تعطي زيادة في الصلابة (٠.٣٤٧) مقارنة بالبلاطة الصلبة بنفس السماكة. أظهرت نتائج تحليل ANSYS أن أفضل نسبة زيادة في الانحراف هي (٥١ ٪) مع انخفاض في حجم الخرسانة من (٥٩ ٪) لفترة طويلة إلى قصيرة المدى من سمك (١.٥) و (٣٠٠) ملم. بالنسبة للمجموعة الثالثة من النماذج المقترحة ، تكون صلابة البلاطات المضلعة ذات الاتجاهين أعلى من الألواح الصلبة التي لها نفس الحجم من الخرسانة. إن إزاحة البلاطة المضلعة في اتجاهين في النطاق المرن (عند الكسر الأول) أقل من البلاطة الصلبة. بهذه الطريقة ، سيعطي الحد الأقصى للتخفيض في وزن البلاطة مع سمك أعلى.

1. Introduction

Two-Way Ribbed 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 slabs is to reduce the quantity of concrete and reinforcement are decreases. Some of previous studies on analysis and design of two-way ribbed (waffle) slabs will be presented here.

Kennedy (1983) tested three specimens of reinforced concrete waffle slab to study the effect of rib orientation on the carrying capacity of waffle slab. The specimens 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. Abdul-Wahab & KhaliI (2000)[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 specimens 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, Hájek et.al [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.. Ibrahim (2014) [4] 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. Lau & Clark (2007)[5] tested 20 models consisting major wide beams that are much wider than the supporting columns, wide beams are formed in the two orthogonal directions, while the ribs between beams in only one direction. Experimental work was very important to understand the behavior of punching failure and to help in shear design of wide beam ribbed slabs. This was because of the UK design code, BS 8110.5 does not cover adequately the shear design procedure for wide beam ribbed slabs. In case of the beams are very wide, the punching failure surface could form within the section of full depth, but if the beams are narrower, the punching failure surface could pass through the reduced depth section. As result, a smaller shear failure surface could be mobilized, which, consequently, would lead to a lower punching shear capacity. Olawale & Ayodele (2014) [6] compared the flexural behavior for waffle and solid slab models under concentrated load. This work had showed the difference between characteristics of waffle and solid slab models. Twenty test samples were presented to determine the deflections, crack width and bending moments. Each specimen was subjected to an incremental concentrated loading of 1.00 kN interval after 28 days of casting. The samples were divided into two groups, ten samples had been small size panels (900 mm × 300mm) supported on all four sides. While the others had been large size panels (1353 mm × 430 mm), supported on the two short sides. It was shown from the test results, that waffle slabs have a higher structural stiffness than solid slabs. However, through estimation the crack width for both the waffle and solid slabs, the results showed that the waffle slab have upper crack width if compared with solid slabs at service load. While, at the failure load, waffle slabs have lower crack width if compared with solid slabs. This was because of the presence of ribs in the waffle had reduced the effect of load on the slab portion by carrying the tensile forces and the results of flexural cracks were smallest failure load. Alaa & Zainab (2011) [7] presented and discussed the optimum design problem of reinforced concrete two-way ribbed(waffle) 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 main objective for the study was to specify the optimum values for the various design variables. The design variables included the effective depth of the slab, ribs width, the spacing between ribs, the top slab thickness, the width of band beams, and the area of steel reinforcement of the beams. The direct design method was used to analyze and design the slabs. It was applied according to requirements of ACI 318-05 code and the ultimate strength design method. The researchers used MATLAB computer program to accomplish the structural analysis and design of waffle slabs by the direct design method. Process of optimization was carried out by using the built-in genetic algorithm toolbox of MATLAB. 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 purpose of this study is to understand the behavior of two-way ribbed slabs under various loading conditions through the following objectives:

1. Use of finite element method by creating model in ANSYS program, to perform analysis of two way ribbed slabs by using real scale continuous slab with large size and studying the linear response for these slabs.

2. Parametric study using various parameters such as length to width ratio, spacing of ribs and total slab thickness and its influence on the mid span deflection as compared to solid slabs.

In the present study, the proposed slabs are divided into three groups:

(i) Frame consists of three by three panels with different dimensions (solid and two way ribbed slab) with the same thickness and different rib spacing.

(ii) Frame consists of three by three panels with different dimensions (solid and two way ribbed slab) with the same rib spacing and different thickness.

(iii) One panel with different dimensions (solid and two way ribbed slab) for the same volumes of concrete with variable rib spacing.

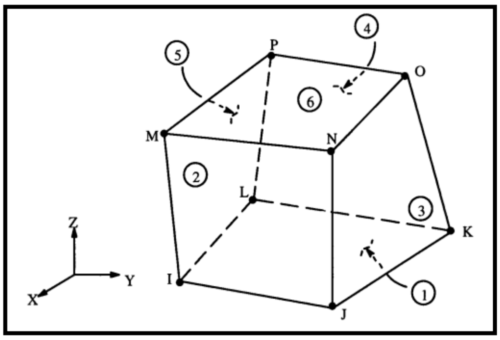
2- Finite Element Modelling & Analysis by ANSYS

ANSYS program is a general-purpose program for the finite element analysis and design. It contains over 100,000 lines of code and more than 284 different elements conducted in the package. Through the study of some of the general characteristics of the program ANSYS, it turns out that it can be used in many fields of engineering. ANSYS package has the ability to solve static (linear and nonlinear) and dynamic structural problems, steady-state and transient heat transfer problems.[8]

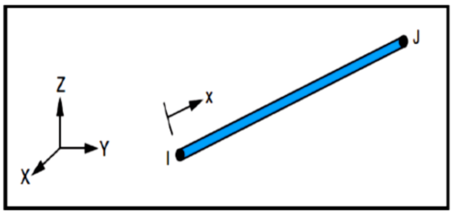
2.1 ELEMENT TYPES

2.1.1 For Concrete: An eight-node solid element, Solid65, was used to model the concrete. This element has eight nodes with three degrees of freedom at each node-translation in the nodal x, y and z directions. It has been used for the 3-D modelling of concrete solids with or without reinforcing bars (rebar). This element treats the nonlinear material properties. The concrete is capable of cracking (in three orthogonal directions), crushing, plastic deformation, and creep [8]. The geometry for the element type is shown in Figure(1- a).

2.1.2 For Steel Bars: LINK180 element was used for modelling of steel bars. It is a 3-D bar that is useful in a variety of engineering applications. The element can be used to model trusses, sagging cables, links, springs, and so on. The element is a uniaxial tension-compression element with three degrees of freedom at each node: translations in the nodal x, y, and z directions. Tension-only (cable) and compression-only (gap) options are supported. As in a pin-jointed structure, no bending of the element is considered. Plasticity, creep, rotation, large deflection, and large strain capabilities are included. The geometry for the element type is shown in Figure(1- b).



(a)



(b)

Figure 1. (a) 8-Nodes isoperimetric brick element (solid 65), (b) LINK180 Geometry [8]

2.1.3 For Steel Plate: SOLID185 is used for 3-D modelling of solid structures. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformations of nearly incompressible elastoplastic materials, and fully incompressible hyper elastic materials. The geometry, node locations, and the coordinate system for this element are shown in Figure (2).

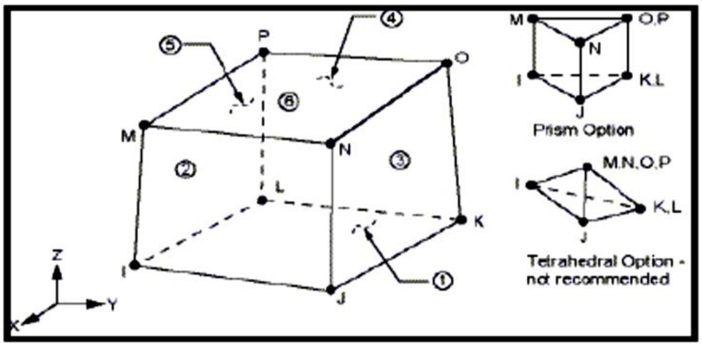


Figure 2. 8-Nodes brick element (solid 185)[8]

2.2 Material properties:

ANSYS requires input data to define the material properties of concrete as follows:

Ultimate uniaxial compressive strength (fc'). Elastic modulus (Ec). Ultimate uniaxial tensile strength (modulus of rupture, fr). Poisson's ratio (ν). Shear transfer coefficient (βt). Compressive uniaxial stress-strain relationship for concrete.

Use the following equations from ACI code [9]:

$Ec = 4700\sqrt{(fc')}$

$Fr = 0.62\sqrt{(fc')}$

Poisson's ratio for concrete in this study is taken as (0.2).

The shear transfer coefficient, βt, represents conditions of the crack face. The value of βt ranges from 0.0 to 1.0, with 0.0 representing a smooth crack (complete loss of shear transfer) and 1.0 representing a rough crack (no loss of shear transfer) [10].

For steel reinforcement, representation of the mechanical properties is very simple and it needs a single stress-strain relation to define the material properties in the analysis of the reinforced concrete members. The behavior of steel bar is the same in compression and tension loading.

In finite element method, representation of steel reinforcement can be implemented by two methods: discrete reinforcement connecting solid elements nodes or smeared reinforcement which means that some of solid elements containing a smeared reinforcement **[11]**. In this study, discrete model is used for modelling the reinforcement. Figure (3) shows reinforcement representation types.

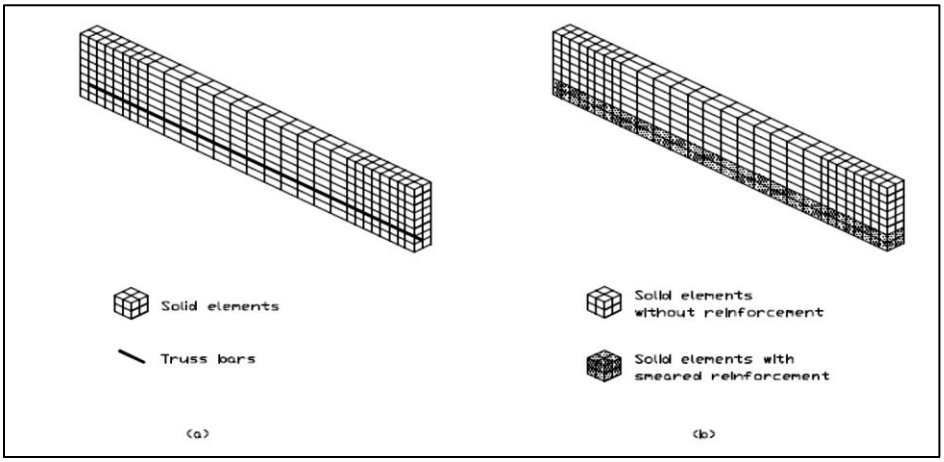


Figure 3. Types of reinforcement representation. [11]

The discrete model of reinforcing bars is generally modeled as separate elements commonly truss or cable elements. Representation of reinforcement bars is shown in Figure (4).

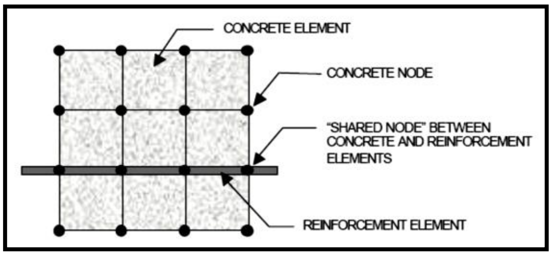


Figure 4. Discrete Representation of Reinforcement Bars. [11]

2.3 Modelling of Two-Way Ribbed Slabs:

The slabs were modelled according to ACI code [9].The dimensions of two-way ribbed slabs are illustrated in Figure (5) and their limits as per ACI 318 are summarized below.

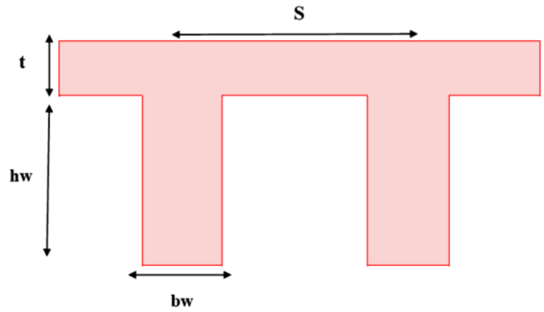


Figure 5. Dimensions of the Cross Section of the Ribs.

- Minimum thickness of structural toppings (t) is 50 mm or one-tenth (1/10) of the clear distance between ribs, whichever is greater.
- Clear ribs spacing (S) shall not exceed 750mm.
- Width of ribs (bw) shall be at least 100mm at any location along the depth.

slab model	Dimensions (mm) Long direction (Lx)	Short direction (Lz)	Total thickness (h)	Rib spacing (S)	Total load (kN/m^2)
R1*	9200	6200	250	600	6
R2	9200	6200	250	800	6
R3	9200	6200	250	1000	6
S1**	9200	6200	250	------	6

- The depth of ribs (hw) shall not exceed (3.5) Times the minimum width.

2.4 Modelling of proposed slabs:

2.4.1 **First Group:** Four slab models have been designed in this group. Arrangement and details of slab models are shown in Table (1).

Table 1. Arrangement and Details of Slab Models for Group -1

*R refers to ribbed slab.

** S refers to solid slab.

All models are supported by columns with dimensions (400*400*400) mm in (x, y, z) directions . ***Solid185*** element is used for modelling the columns.

Nonlinear analysis by 3D finite elements model is done using ANSYS. 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 [8]. The ANSYS program uses Newton-Raphson equilibrium iterations for updating the model stiffness. The real constants for this example are shown in Table (2).

Table 2. Real Constant.

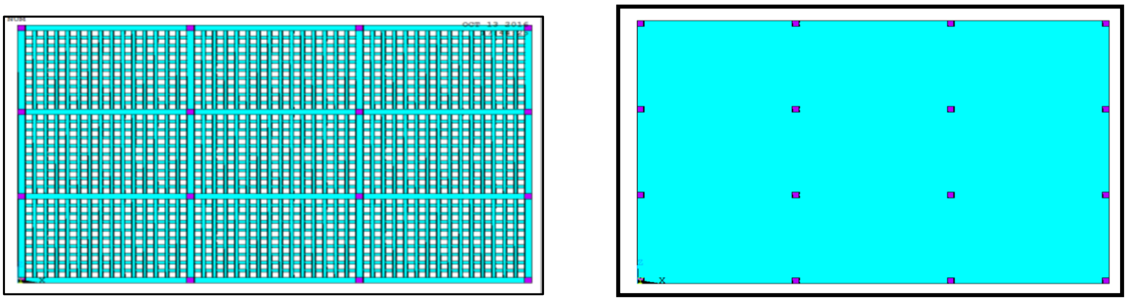
Real constant Set No.	Element Type	Material
1	Solid65	Concrete
2	Link180	Steel Bar(rib)
3	Link180	Steel Bar(slab)

Materials properties for specimens as used in ANSYS are summarized in Table (3).

Table 3. Material Properties.

Material Model Number	Element Type	Properties	
1	Solid 65	Linear Isotropic	
		Ex	25743
		PRXY	.2
		Concrete	
		Open Shear Transfer Coef.	.4
		Close Shear Transfer Coef.	.9
		Uniaxial Cracking Stress	3.4
		Uniaxial Crushing Stress	30
4	Solid185	Linear Isotropic	
		Ex	200000
		PRXY	.3

Modelling of slab models is shown typically in Figure (6).



(R1) (S1)

Figure 6. Modelling of R1 (Ribs With Hidden Beams) and S1 (Solid Flat Slab)

Table (4) shows the element size in(X-Y-Z) directions for slab models.

Table 4. Element Size in (X-Y-Z) Directions For Slab Models.

Slab Models	Element Size (mm)		
	X	Y	Z
R1	200	50	200
R2	200	50	200
R3	200	50	200
S1	200	50	200

Typical meshing and boundary conditions of slab models are shown in Figure (7) and (8) respectively.

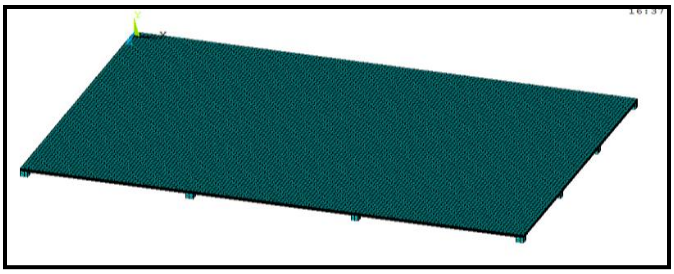


Figure 7. Typical Meshing for all Slabs.

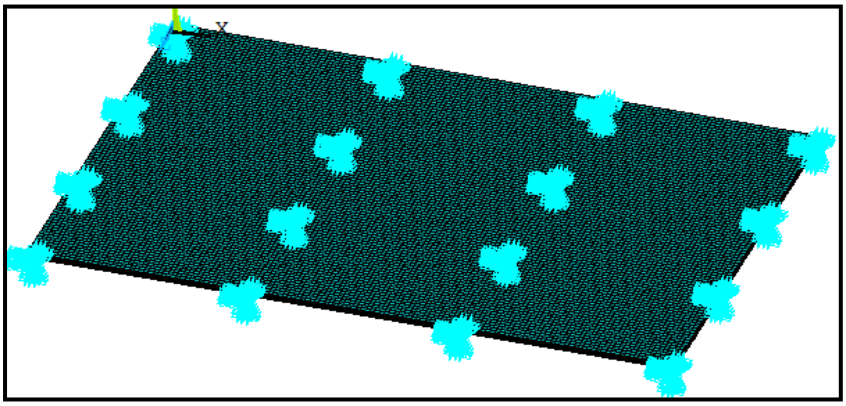


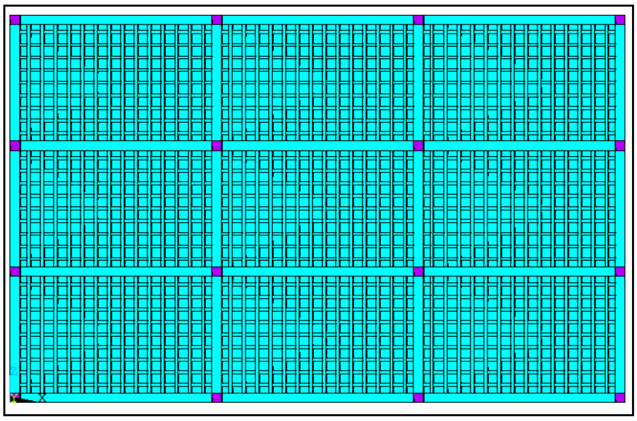
Figure 8. Typical Boundary conditions for all slabs.

2.4.2 Second Group : Twelve slab models have been designed in this group. Arrangement and details of slab models are shown in Table (5).

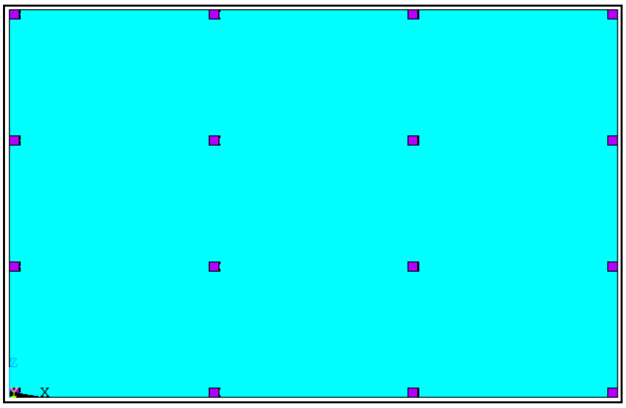
Table 5. Arrangement and details of Slab Models.

slab model	Dimensions (mm) Long direction (Lx)	Short direction (Lz)	Lx/Lz	Total thickness (h)	Rib spacing (S)	Total load (kN/m2)
RA1	12000	8000	1.5	250	800	7
RA2	12000	8000	1.5	300	800	7
RA3	12000	8000	1.5	350	800	7
SA1	12000	8000	1.5	250	-	7
SA2	12000	8000	1.5	300	-	7
SA3	12000	8000	1.5	350	-	10
RB1	16000	10000	1.6	250	800	6
RB2	16000	10000	1.6	300	800	6
RB3	16000	10000	1.6	350	800	6
SB1	16000	10000	1.6	250	-	6
SB2	16000	10000	1.6	300	-	6
SB3	16000	10000	1.6	350	-	6

All slab specimens are supported by columns with dimensions (600*600*600) mm in (x, y, z) directions and ***(Solid185)*** element is used for modelling them. Modelling of slab specimens are shown typically for ***RA1*** and ***SA1*** in Figure (9).



(RA1)



(SA1)

Figure 9. Modelling of RA1 and SA1

2.4.3 Third Group:

In this group, a single one panel solid slab has been transformed into two-way ribbed slab by assuming the volume of concrete to be constant for both. Dimensions of one of the models for solid slab are (12000*8000*300) mm. The thickness of two-way ribbed slab is determined by using the flowing equations:

Vt = (11.4*7.4*.3) = 25.308 m^3

Vslab = (11.4*7.4*.05) = 4.218 m^3 …… Where (Vslab)is the volume of top slab

Vr = Vt- Vslab …… Where (Vr) is the volume of ribs.

=25.308-4.218 =21.09 m^3

Ar = At - Av …… Where(Ar) is the area of rib, (At) is the total area; (Av) is the area of voids.

Av= (Ni Ai) ……… Where (Ni) is the number of voids, (Ai) is the area for each void.

=4(.2*.3) +36(.4*.3) +22(.2*.4) +11*18*(.4*.4) = 38 m^2 for (600mm) Rib spacing.

Ar = (11.4*7.4)-38 =46.36 m^2

tr = Vr/Ar =.454+thikness of slab (.05)

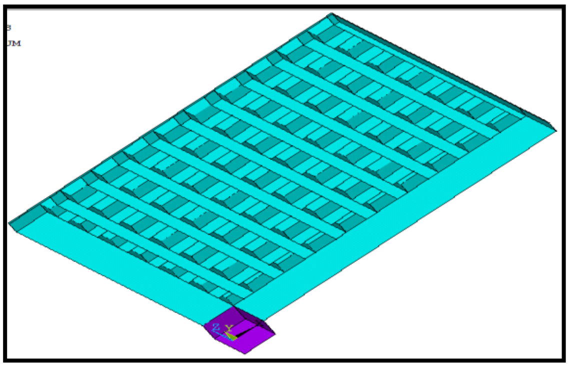
=.504 mm or 504 mm.

By the same procedure, Thickness of two-way ribbed slab for other models can be calculated. Twelve slab models have been designed in this group. Since the slab models are symmetric, quarter of slab model has been

modelled for the analysis**.** Arrangement and details of slab models are shown in Table (6). Typical modelling of slabs are shown in Figure (10). Finite element meshing of slab models is shown in Figure (11) and element sizes are shown in Table(7).

Table 6. Arrangement and details of Slab Models for Third Group

slab models	Dimensions (mm) Long direction (Lx)	Short direction (Lz)	Total thickness (h)	Rib spacing (S)	Total load (kN/m2)
S250	12000	8000	250	-	15
R414	12000	8000	414	600	15
R516	12000	8000	516	800	15
R628	12000	8000	628	1000	15
S300	12000	8000	300	-	15
R505	12000	8000	505	600	15
R630	12000	8000	630	800	15
R774	12000	8000	774	1000	15
S350	12000	8000	350	-	20
R596	12000	8000	596	600	20
R750	12000	8000	750	800	20
R915	12000	8000	915	1000	20



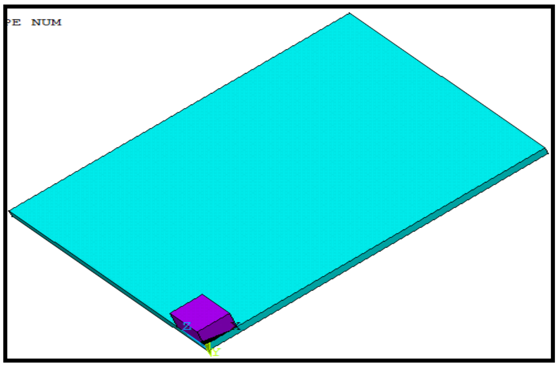
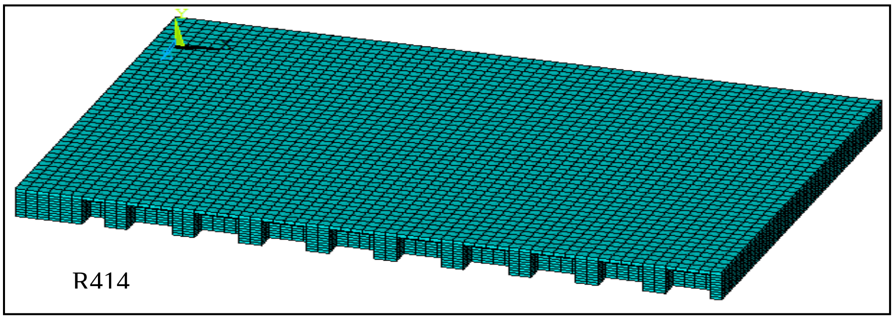


Figure 10.Typical Modelling of Slab Models (Quarter of Slab).



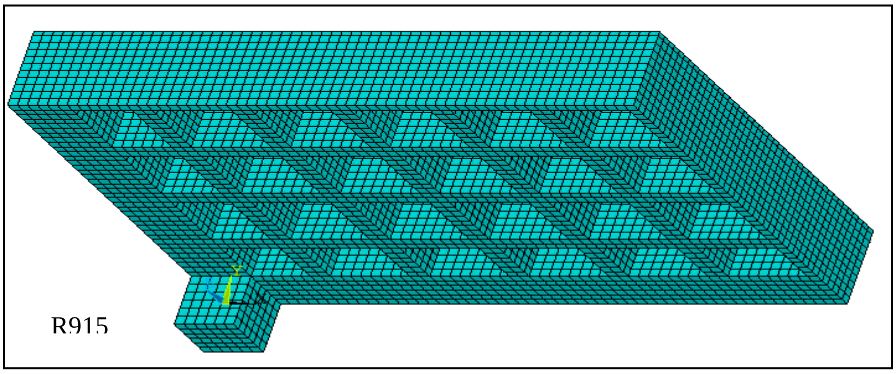


Figure 11.Typical Meshing of Slab Models (Quarter of Slab).

Table (7) Element Size in (X-Y-Z) Directions For Slab Models.

Slab Models	Element *Size* (mm)		
	X	Y	Z
S250	100	50	100
R414 (rib)	100	36.4	100
R414 (top slab)	100	50	100
R516 (rib)	100	46.6	100
R516 (top slab)	100	50	100
R628 (rib)	100	57.8	100
R628 (top slab)	100	50	100
S300	200	150	200
R505 (rib)	100	45.5	100
R505 (top slab)	100	50	100
R630 (rib)	200	58	200
R630 (top slab)	200	50	200
R774 (rib)	100	72.4	100
R774 (top slab)	100	50	100
S350	100	70	100
R596 (rib)	100	54.6	100
R596 (top slab)	100	50	100

Applying displacement boundary conditions at planes of symmetry which prevent the movement in the direction of (x and z) at the plans (x,z) respectively. This applies for all models.

3. Results and Discussions

The twenty-eight models explained in the previous section have been analyzed by using (ANSYS) (version 15.0) to study the effect of several important parameters on the behavior of two-way ribbed slab. ***In the first group***, the parameters include the effect of void ratio on stiffness of waffle slab and the effect of rib spacing (S) on the maximum stress under uniform loads. ***In the second group***, the parameters include influence of the depth of waffle slab on the maximum deflection for different span to width ratios (L/W) of waffle slab as compared with the solid slab with constant rib spacing (S) and influence of the depth of waffle slab on the maximum stress. ***In the third group***, the parameters include the influence of rib spacing (S) on the stiffness and maximum deflection for waffle slab as compared to Solid slab. Span to width ratio (L/W) and concrete volume are kept constant.

3.1. First Group: Figure (12) and (13) show Typical analysis results for first group.

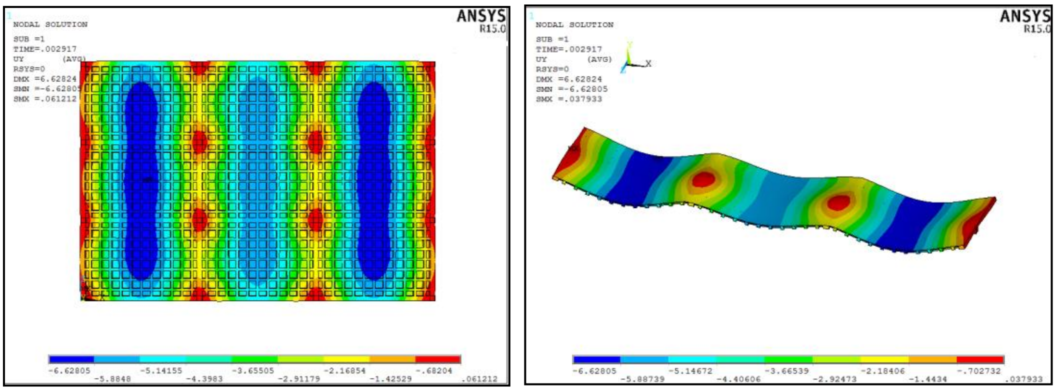


Figure 12. Vertical displacement for Model R2.

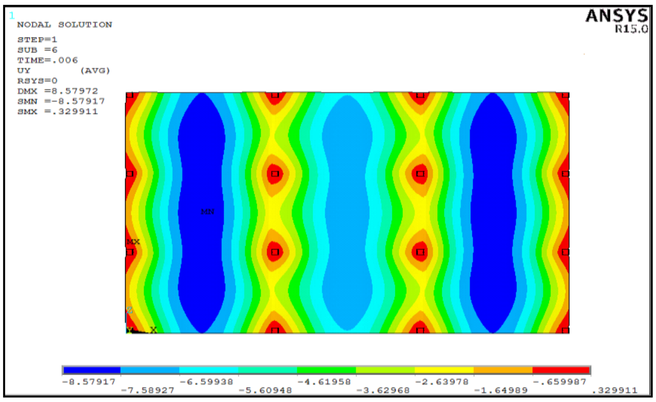


Figure 13. Vertical displacement for Model S1.

3.1.1. Load- Displacement Response: From analysis results, the effect of rib spacing on the maximum deflection is observed. Figure (14) and (15) show load-displacement response for slab models with different rib spacing and the effect of this spacing on the maximum deflection.

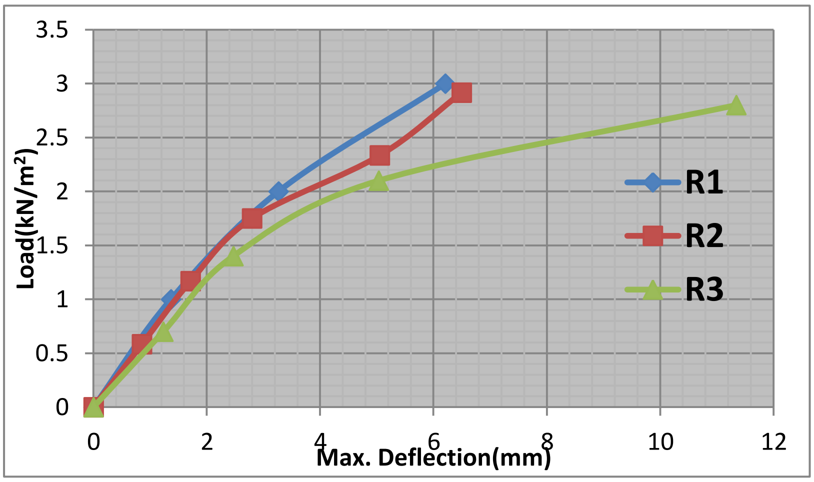


Figure 14. Load-Displacement Response for Ribbed Slab Models

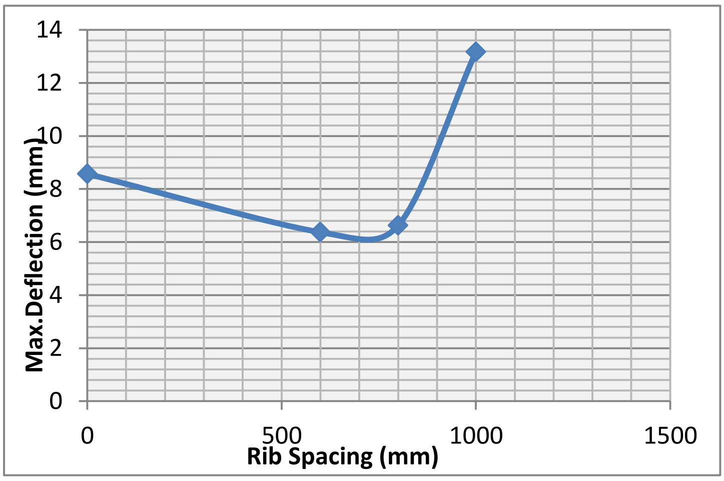


Figure 15. Effect of Rib Spacing on the Maximum Deflection.

From figures above, it is concluded that when the rib spacing increases, the maximum deflection increases. That is because increasing rib spacing will decrease the slab rigidity.

3.1.2. Effect of Void Ratio on Stiffness of Waffle Slab: Figure (16) shows the influence of ''void ratio'' (*S*-*W*)/*S* that obtained from different rib spacing on the stiffness of waffle slab. From this figure, it is found that when the void ratio increases, stiffness of waffle slab also increases. Increasing stiffness for waffle slab continues up to some limit. Then will decrease with increasing void ratio. The best case in this example occur when the void ratio equal (0.667) which gives increase in stiffness (0.347) as compared to solid slab with the same thickness.

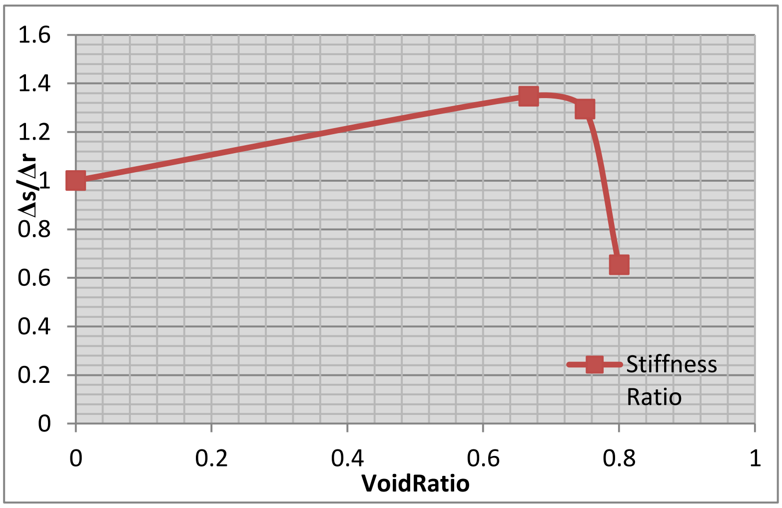


Figure 16. Effect of Void Ratio on Stiffness.

3.1.3. Effect of Rib spacing (S) on Maximum Stress : Numerical analysis for slab models is carried out by using (ANSYS) to predict the equivalent stress (Von-Mises) for slab models to study the effect of rib spacing(S) on the maximum stress. Figure (17) shows maximum stress for two-way ribbed slab.

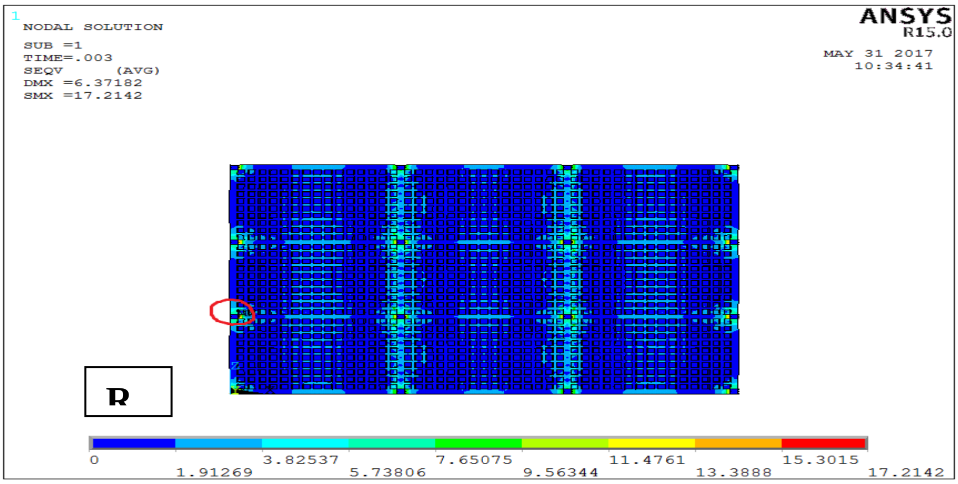


Figure17. Value and Location of Maximum Stress for R1 Slab (bottom view).

From analysis results for slab models which have different rib spacing(S), it is found that the maximum stress increases when the rib spacing increases. Table (4.5) shows the value and location of maximum stress for slab models.

The stress distribution along the slab models is shown in figures (4.24),(4.25) and(4.26) respectively.

Table 8. Value And Location of Maximum Stress.

Slab Model	Maximum Stress (MPa)	Location		
		X	Y	Z
R1	17.2142	397.981	0.439103	6400.19
R2	18.9115	9196.56	198.652	398.776
R3	24.0858	398.186	0.643365	12600.1

The stress distribution along the slab models is shown typically for slab R1 in figures (18)

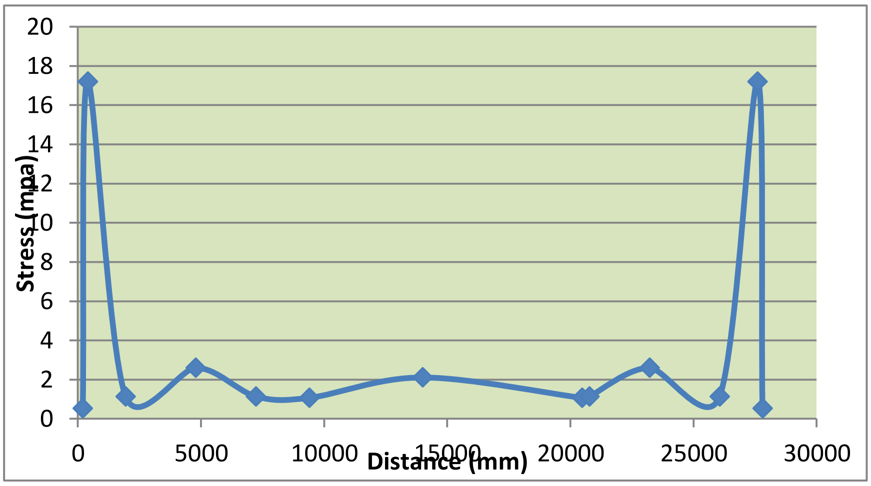


Figure 18. Von-Mises Stress distribution along the slab (R1).

3.2. Second Group: In this group, analysis results have been done to study the influence of the depth of waffle slab on the maximum deflection for different span to width ratios (L/W) of waffle slab with constant rib spacing (S) as compared with the solid slab. Also, the percentage of increase in deflection for waffle slab as compared to solid slab is studied to arrive to the case that gives the best percentage of decreasing in concrete volume. The span to width ratios (L/W) for slab specimens are ranged from (1.5) for panel (12*8) m dimensions to (1.6) for (16*10) m dimensions. Rib spacing(S) is taken (800) mm for all models. Figures (19) to (22) show typical analysis results for models.

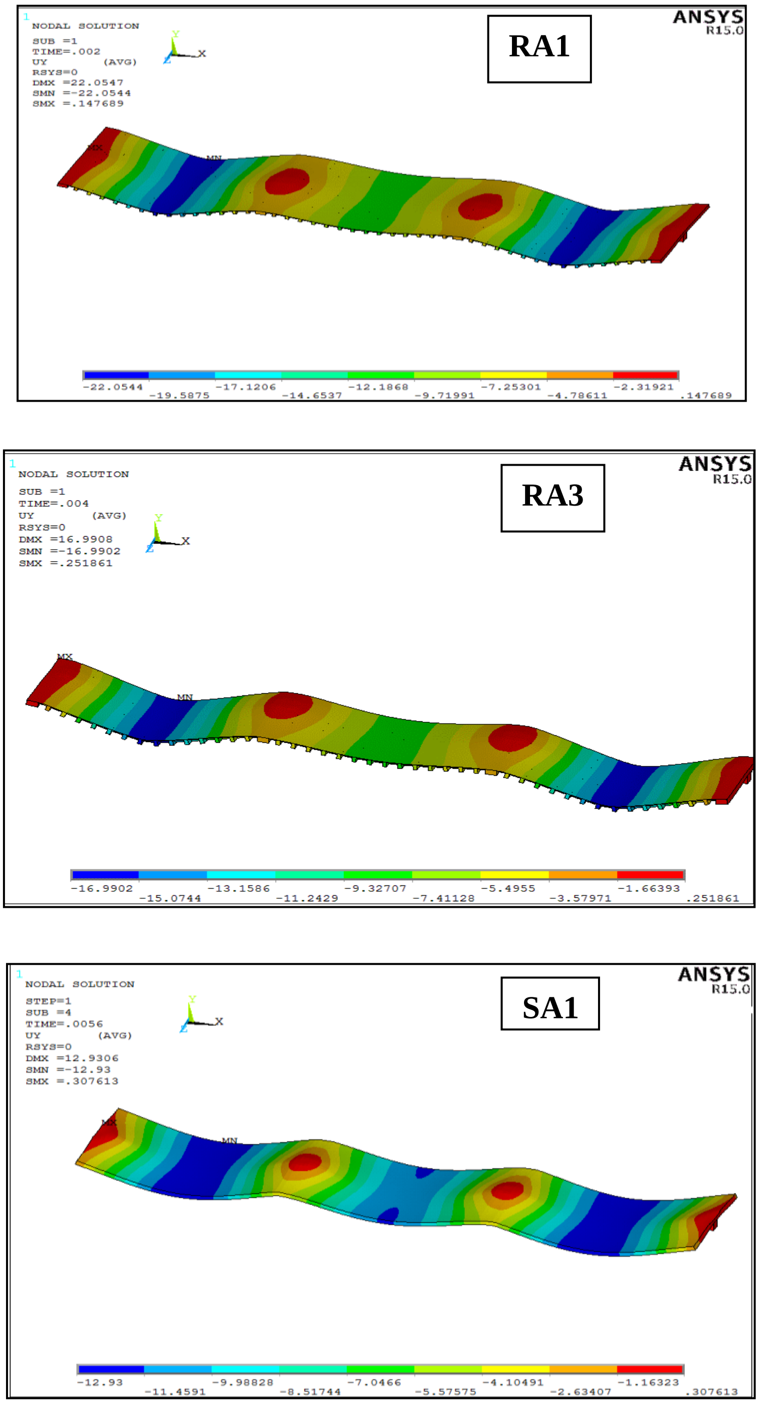


Figure 19. Deformed Shape of Models (RA1), (RA3) and (SA1), (Sectional View)

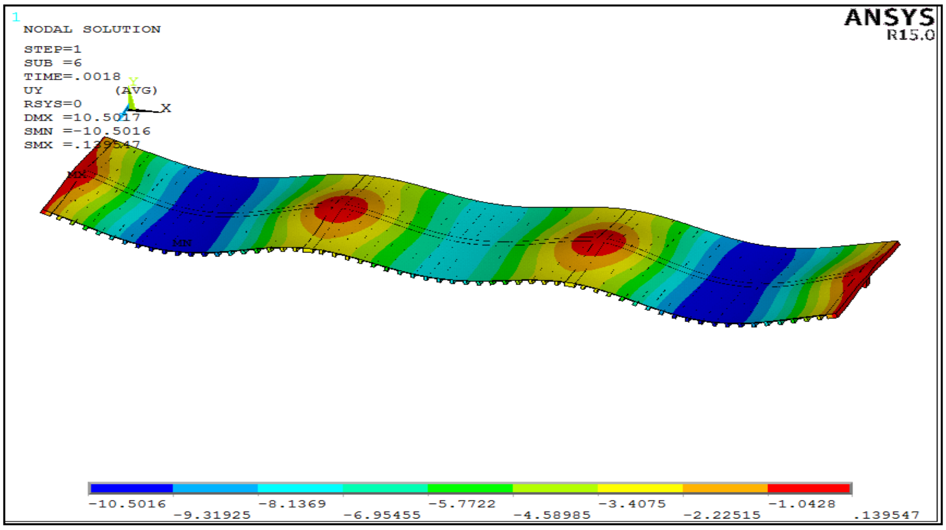


Figure 20. Deformed Shape for (RB1), (Sectional View)

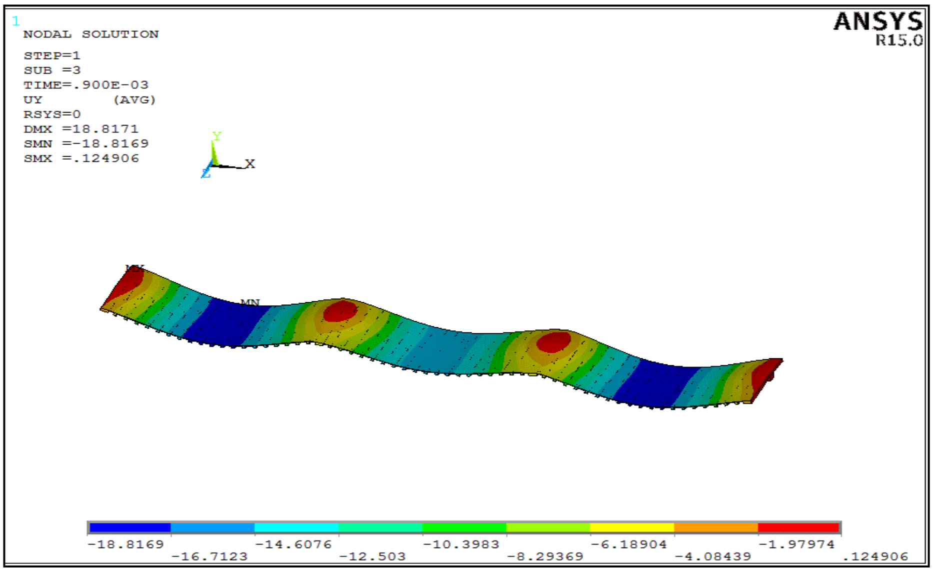


Figure 21. Deformed Shape for (RB3), (Sectional View)

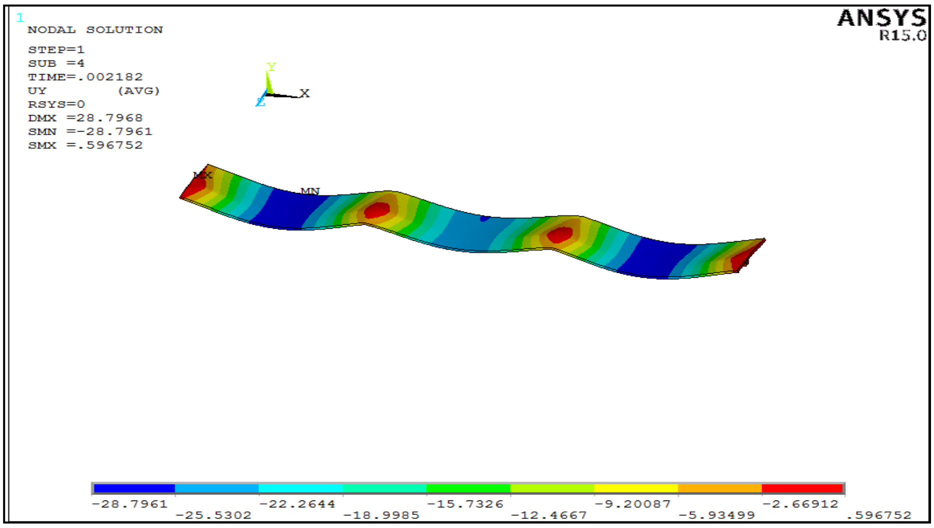


Figure 22.Deformed Shape for (SB1), (Sectional View)

After analysis, the maximum deflection values due to the application of uniform load to the twelve models have been determined according to the present ANSYS model. The load-deflection response for all models is shown in figures (23) and (24).

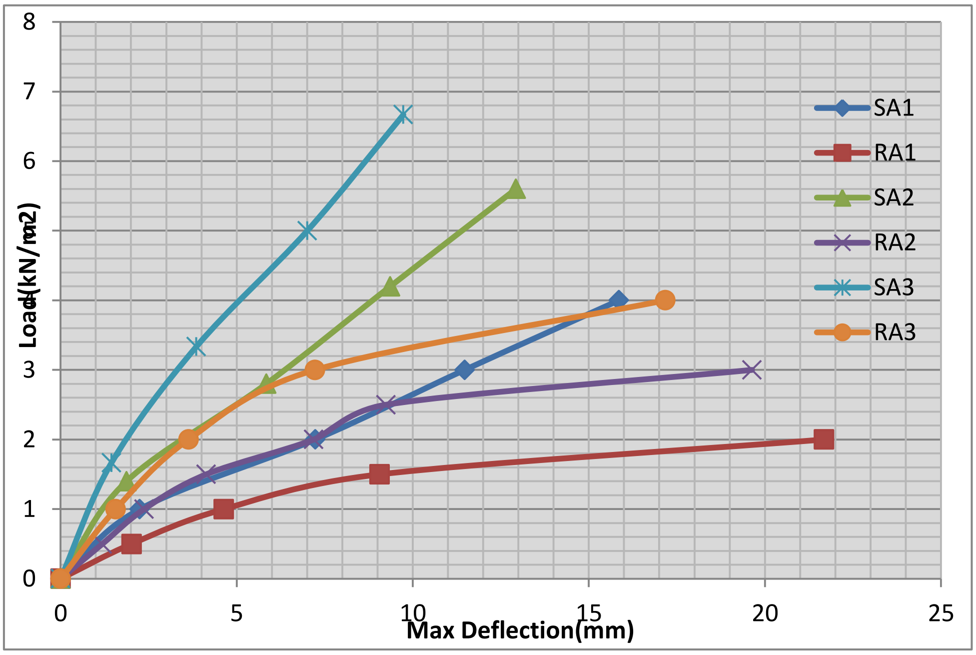


Figure 23. Load-Displacement Response for Span to Width Ratio =1.5

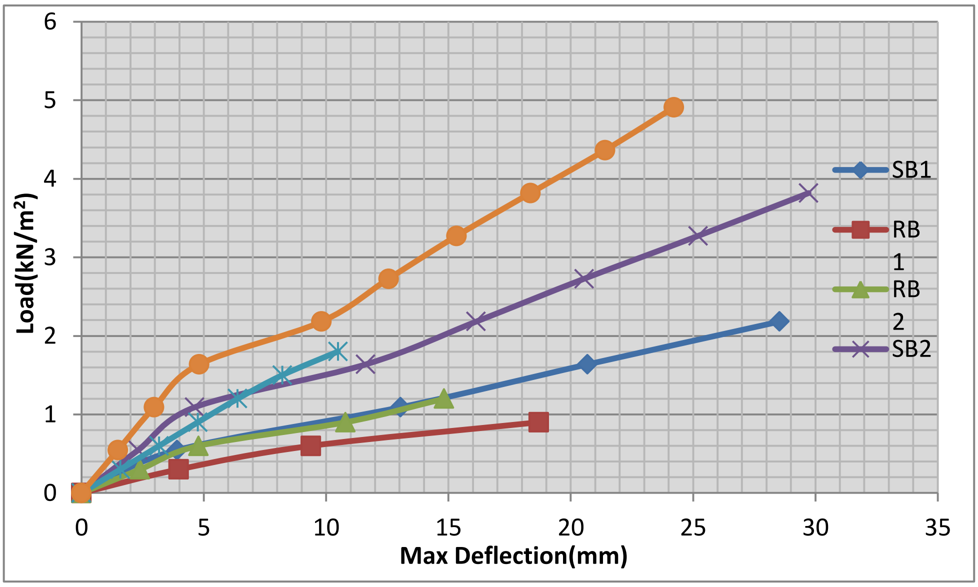


Figure24. Load-Displacement Response for Span to Width Ratio =1.6

Table (9) shows the influence of the depth of waffle slab on the maximum deflection for different span to width ratios (L/W) of waffle slab as compared with the solid slab with constant rib spacing(S). The best case for this example with span to width ratio (1.5) and (300) mm depth.

Table 9. The Influence of The Depth of Waffle Slab on The Maximum Deflection for Different Span to Width Ratios

Slab Models	Depth (mm)	Percentage of Increase in Max. Deflection	Percentage of Decrease in Concrete Volume
RA1& SA1	250	(88%)	(61%).
RA2& SA2	300	(51%)	(59%).
RA3& SA3	350	(76%)	(58%).
RB1& SB1	250	(73%)	(61%)
RB2& SB2	300	(111%)	(60%).
RB3& SB3	350	(74%)	(58%).

study the influence of the depth of waffle slab on the maximum stress, from the results shown typically in Fig(25) , it is found that the maximum stress for span to depth ratio = (1.5) is increased with increasing the depth of slab specimens; this is because the distribution and location of maximum stress is different for each specimen. For span to depth ratio = (1.6), all specimens have been the same location of maximum stress approximately. So, the depth of waffle slab will effect on the value of maximum stress where it decreases with increasing of depth.
Table (10) shows values and Locations of maximum Stresses for all slab models.

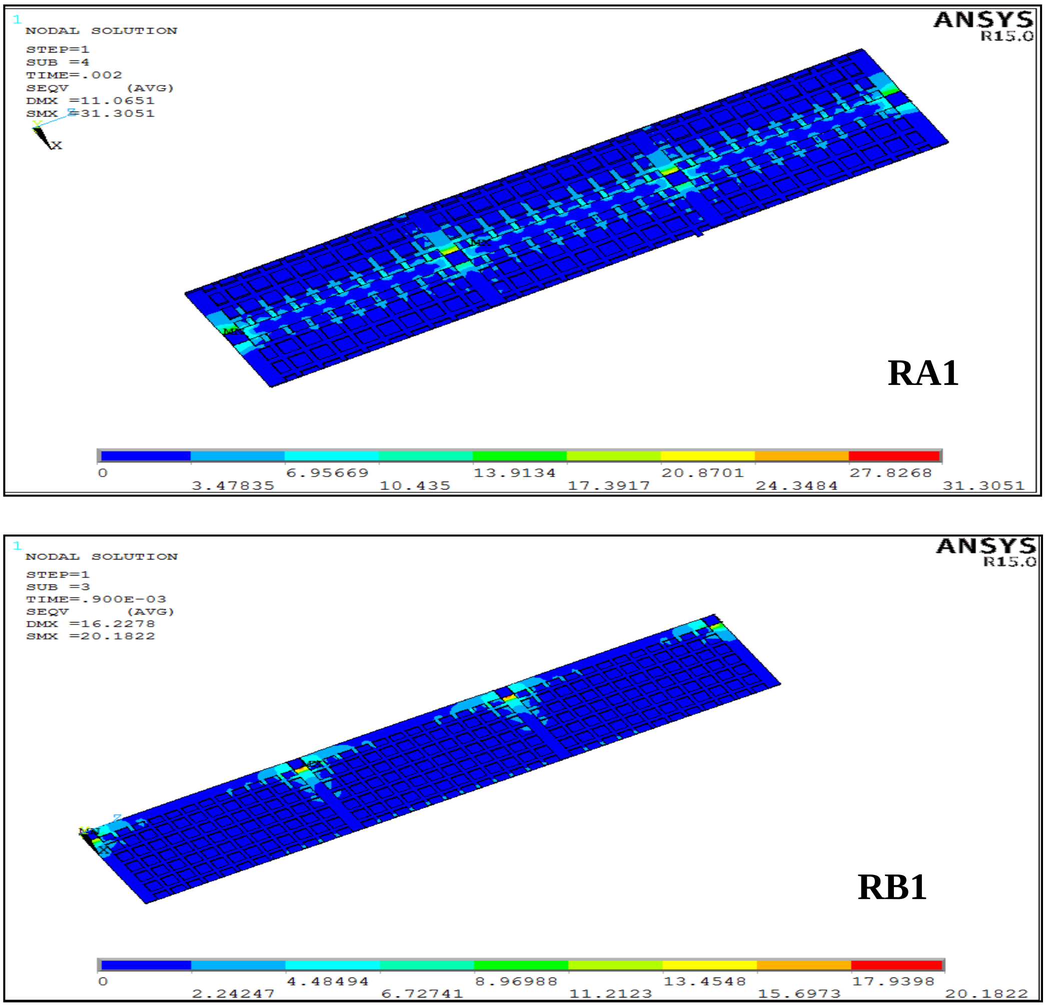


Figure 25. Maximum Stress of Two-Way Ribbed Slab.(Typical Results)

Table 10. Value and Location of Maximum Stress

Slab Specimens	Total Depth (mm)	Maximum Stress (MPa)	Location (mm) X	Y	Z
RA1	250	31.3051	12007.5	-35.1926	8992.48
RA2	300	31.7537	597.746	.57447	7999.42
RA3	350	35.4283	597.595	.902402	8400.12
RB1	250	20.1822	598.75	.405867	10400.3
RB2	300	19.5876	598.362	.452881	10199.9
RB3	350	14.8975	599.091	-.813993	10200.1

3.3. Third group: In this group, volume of concrete is considered constant for both waffle and solid slab. One panel with dimensions (12*8) m have been analyzed with different values of rib spacing (S) (600, 800 and 1000 mm) to study the influence of rib spacing on the stiffness and mid-span deflection of waffle slab as compared to solid slab. Span to width ratio (L/W) and concrete volume are kept constant. Results of ANSYS analysis are shown in figures (4.42) to (4. 45).

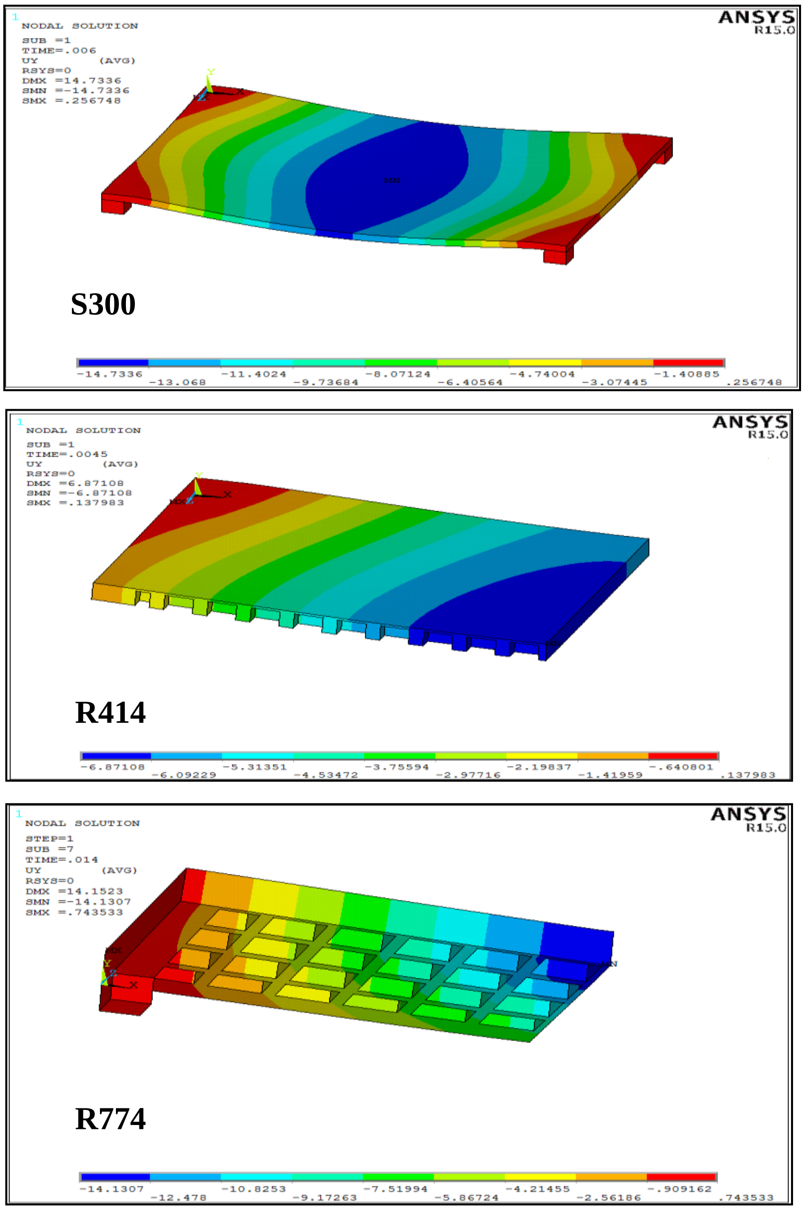


Figure 26. Typical Results of Deformed Shape of Slab Models

To compare between FE results for slab models, the values of mid-span deflection due to application of uniform load to models are shown in figure (27).

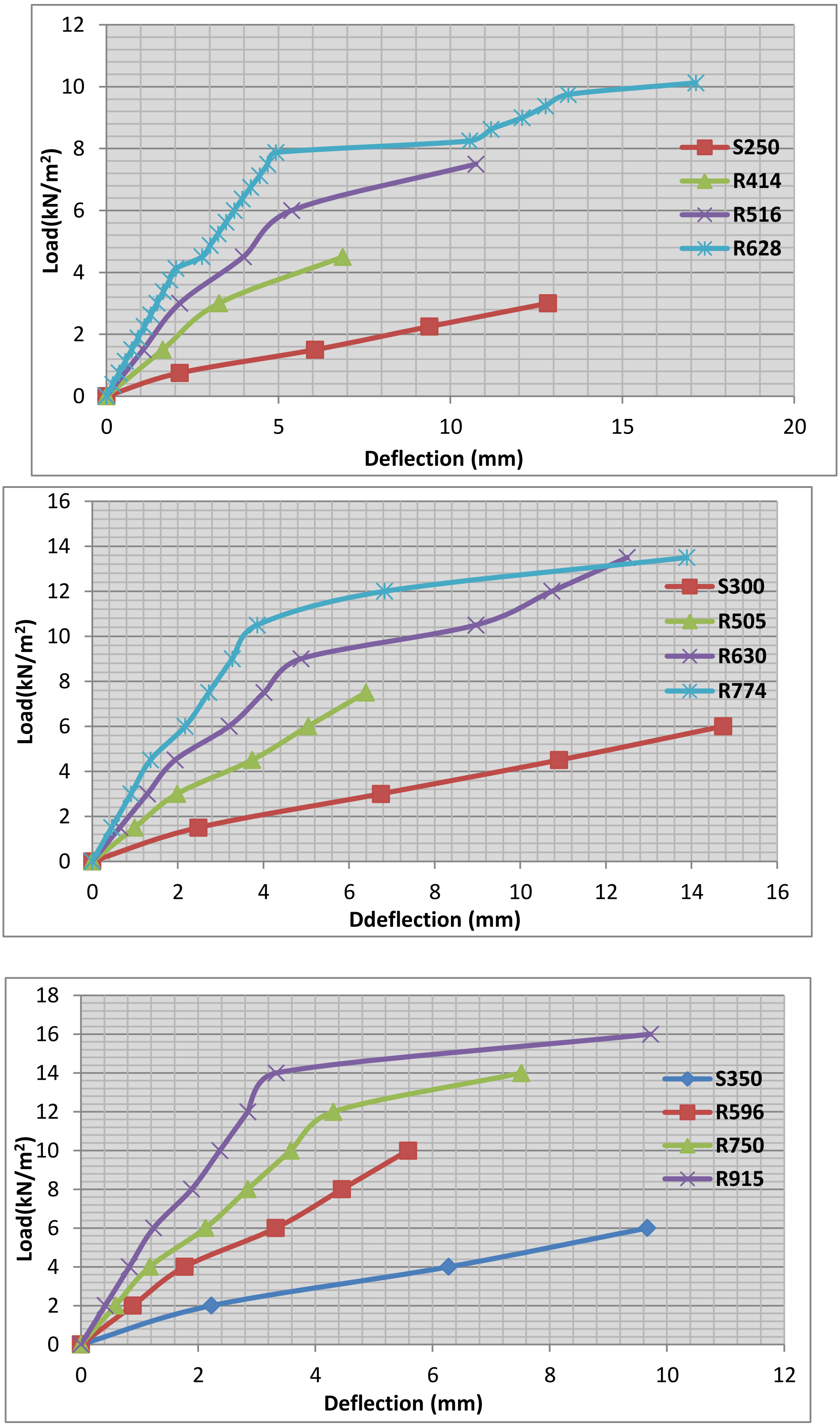


Figure 27. Load-Midspan Deflection Curves of Slab Models

From figure above, results of analysis shows that the stiffness of two-way ribbed slab is higher than the solid slab that has the same volume of concrete. The displacement of two-way ribbed slab in the elastic range (at first crack) is lower than the solid slab. In this manner, it will give the maximum reduction in concrete volume with higher thickness. Table (11) shows the comparison between the loads and displacement at the first crack and the load, displacement at the failure load.

Table (11) Comparison Between the Loads and Displacements for Slab Models.

Slab Models	P crack (kN/m^2)	Δ at first crack (mm)	P failure (kN/m^2)	Δ at failure load (mm)
S250	1.5	6.05965	3	12.8328
R414	4.5	6.87108	4.5	6.87108
R516	4.5	3.98346	7.5	10.742
R628	4.5	2.784	10	17.1348
S300	3	6.74125	6	14.7336
R505	4.5	3.73425	7.5	6.39267
R630	6	3.20786	13.5	12.4969
R774	6	2.17413	13.5	13.8898
S350	4	6.27508	6	9.66064
R596	6	3.32516	10	5.68073
R750	6	2.12654	14	7.51474
R915	8	1.89258	16	9.71999

4. Conclusions and Recommendations

4.1 Conclusions: Based on the results of Finite Element analysis in this study, the main conclusions can be summarized as follows:

1- Applying the finite element method by using ANSYS to model and analyze the two way-ribbed slabs of large sizes, it is found that when the void ratio increases, stiffness of waffle slab also increases. Increasing stiffness for waffle slab is continued up to some limit. Then it will decrease with increasing void ratio, the best case in this study occurs when the void ratio equal to (0.67) which gives increase in stiffness of (34.69%) as compared to solid slab with same thickness.

2- For the models which have length to width ratio of (1.5), the percentage of increase in deflection is (88%) for (250) mm depth with decreasing in concrete volume of (61%). For (300) mm depth slab, the percentage of increase in deflection is (51%) with decreasing in concrete volume of (59%). For (350) mm depth slab, the percentage of increase in deflection is (76%) with decreasing in concrete volume of (58%).

3- For models which have length to width ratio of (1.6), the percentage of increase in deflection is (73%) for (250) mm depth with decreasing in concrete volume of (61%). For (300) mm depth, the percentage of increase in deflection is (111%) with decreasing in concrete volume of (60%). For (350) mm depth, the percentage of increase in deflection is (74%) with decreasing in concrete volume of (58%). The best case for this study occurs with length to width ratio (1.5) and (300) mm depth.

4- Regarding the maximum Von-Mises stress, the maximum stress for length to width ratio of (1.5), increased with increasing the thickness of slab specimens. However, for length to width ratio of (1.6), all specimens have approximately the same location of maximum stress.

5- The stiffness of two-way ribbed slab is higher than the solid slabs that have the same volume of concrete. The deflection of two-way ribbed slab in the elastic range (at first crack) is lower than that of solid slab. In this manner, it will give the maximum reduction in concrete weight with larger thickness.

4.2 Recommendations for Future studies

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

2- Analysis of curved waffle slab.
3- Analysis of waffle slab under low-speed and high-speed impact load.
4- Experimental and theoretical analysis of lightweight concrete waffle slab.

5. References

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