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## Analysis and Parametric Study of Waffle Slabs

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**ABSTRACT:** An arrangement of intersecting beams placed at regular interval and interconnected to a slab of nominal thickness is known as Grid slab or Waffle slab. These slabs are used to when a large column free area is the main requirement. There are various methods available for analyzing the grid slab system. In present study some of these methods are studied namely Rankine's Grashoff's method, Timoshenko's plate theory and stiffness method and compared with each other. The comparison is done on the basis of flexural parameters such as bending moments, shear forces and deflection obtained from various methods. The parameters considered for study include span to depth ratio, spacing of transverse beams, thickness of web and thickness of flange. The magnitude of span to depth ratio considered is 16 to 60. The spacing of transverse beams is varied from 0.75m to 1.75 m. Thickness of slab and the ribs are made constant and are equal to 0.1m and 0.15m respectively. The bending moment, the shear force and the mid span deflection developed in grid floor beams have been predicted by conventional and numerical methods and the results are compared and software validated. The parametric study is carried out using the model proposed by ETABS.15 software. More over the cost analysis is carried out with the help of MS.EXCEL program for finding economical design.

**KEYWORDS:** Waffle slab, orthotropic plate, plate theory, Rankine's method, stiffness method, cost analysis

### I.INTRODUCTION

Waffle slab system consists of beams spaced at regular interval in perpendicular directions, monolithic with slab. In these types of slab, a mesh or grid of beams running in both the directions is the main structure, and the slab is of nominal thickness. Grids (beams) are found to be very efficient in transferring load. Normally the sizes of grids running in perpendicular directions are generally kept the same.

Waffle slab are generally employed for architectural reasons for large rooms such as auditoriums, vestibules, theatre halls, show rooms of shops where column free space is often the main requirement. They are used for heavy loads and large span structures as they exhibit higher stiffness and smaller deflection. Void formed in the ceiling leads to reduction in dead load and is advantageously utilized for concealed architectural lighting. These slabs are also used as the foundation for many different types of buildings and structures, but are most commonly used in commercial or industrial buildings. Waffle foundations are resistant to cracking and sagging and can hold a much greater amount of weight than traditional concrete slabs.

Waffle slabs are conventionally analyzed by the method proposed by Rankine-Grashoff and Timoshenko's plate theory. Now a days software is used to carry out analysis. ETAB software will be used for analysis and design purpose. ETAB is found by Computers and Structures, Inc. (CSI) which is recognized globally as the pioneering leader in software tools for structural and earthquake engineering.

### II. RELATED WORK

Muhammed Yoosaf.K.T at.el (2013) [1] studied the influence of various parameters on the economical spacing of the transverse beams in grid floor. The parameters considered in this study are span to depth ratio, spacing of

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transverse beams, thickness of web and thickness of flange. The magnitude of span to depth ratio considered is 16 to 60. The spacing of transverse beams is varied from 0.5m to 2.0 m. The bending moment, the shear force and the mid span deflection developed in grid floor beams have been predicted by conventional and numerical methods and the results are compared. The parametric study is carried out using the model proposed by ANSYS software. They found out that Timoshenko's plate theory is in good agreement with ANSYS results.

Prof. Dr. S. A. Halkude and S. V. Mahamuni (2014) [2] studied and compared various approaches available for analyzing the grid slab system. The comparison is done on the basis of flexural parameters such as bending moments and shear forces obtained from various methods. A halls having constant width 10.00m and varying ratio of hall dimensions (l/b) from 1 to 1.5 are considered. STAAD.pro (stiffness method) is used for software analysis. The author concludes that up to  $L/B=1.2$ , bending moment is high according to Plate theory than stiffness method. Beyond  $L/B=1.3$ , bending moment is low according to Plate theory than stiffness method.

Anjaly Somshekhar and Preetha Prabhakaram (2015) [3] studied on the structural behavior of Waffle slab with and without opening and the effect of opening size and locations on the ultimate load. For that they considered a waffle slab with three square opening at different location with and without stiffening ribs. The parametric study was conducted using ANSYS. Use of stiffening ribs enables to restore its full load capacity and increased its ultimate load carrying capacity by 19%.

Dr. A.C. Galeb and T.E. Ibrahim (2014) [4] conducted studies to find the optimum dimensions waffle slabs by conducting two Case studies –Waffle slab with solid heads, Waffle slab with band beams. They used MATLAB programme for optimum design considering design variables such as effective depth of the slab, ribs width, spacing b/w ribs, area of steel at moment critical sections, band beam width and its area by making use of a cost function. Cost function includes cost of concrete, steel, form work.

Chintha Santhosh and Venkatesh Wadki (2016) [5] analyzed and designed a G+5 Building with diagonal grid waffle slab. Both Gravity and lateral loads such as earth quake(zone IV &V) and wind loads are considered. And this is compared with the flat slab. The author concludes that maximum displacement is observed in flat slab with drop compare to grid slab with and without infills in both zones. Grid slab structures possess maximum base shear in comparison with flat slab with and without drop in both zones

Anurag Sharma , Claudia Jeya Pushpa (2016) [6] studied about the Seismic effect on multi storey building of G+9, G+14 and G+19 floors with waffle slab and flat slab were done using the software ETABS 2013. The seismic evaluation is performed by response spectrum analysis as per IS 1893 (2002). The author concludes that waffle slabs are advisable for structure with a height less than 40m and for structures of height above 40m flat slab is advisable.

Indrajit Chaudhary and Jitendra Singh (2012) [7] - This paper propose a semi analytical method for the analysis of waffle slab with any arbitrary boundary conditions; fixed, free and simply supported. To validate the results, selected cases are compared with finite element analysis by ANSYS. Two boundary conditions were selected; FEM results were lower bound by 12% with respect to Timoshenko's value for simply supported slab. Displacements for the proposed method are almost same as Timoshenko's analysis and shorter for analysis by FEM on ANSYS.

### III. OBJECTIVES AND METHODOLOGY

**1. Research Objectives:-**The objectives of this study include,

- To analyse a 9mx12m waffle slab using Rankine-Grashoff method, Timoshenko's plate theory and stiffness method (using ETABS 2015) and comparing the results of three methods .
- To check the validity of the application of ETABS 2015 software for the analysis of waffle slab.
- To conduct parametric study- considering, thickness of slab, rib width, rib depth and spacing b/w ribs as varying parameters.
- To carry out cost analysis for optimum design.

**2. Methodology:-**

1. Study of different methods of analysis of waffle slab.
2. Manual analysis using Rankine-Grashoff method and Timoshenko's plate theory.
3. Analysis using ETABS 2015 software (stiffness method)

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4. Comparison of analysis results of the three methods.
5. Carrying out Parametric study by varying rib depth and spacing between ribs, with constant rib width and slab thickness.
6. Preparation of MS EXCEL programme for design from results of parametric study.
7. Carry out cost analysis for optimum design.

## VI. METHODES OF ANALYSIS

Grid is highly redundant structural system and therefore statically indeterminate. Various approaches available for the analysis of grid floor frame are as listed below.

1. Analysis of grid by Rankine – Grashoff method.
2. Analysis by plate theory.
3. Stiffness method.

**1. Rankine - Grashoff Method:** This is an approximate method. In this method the slab is considered as simply supported on edges. It is based on equating deflections in either direction at the junctions of ribs. Figure 1 show the waffle slab of plan dimension (a x b) m and its deflection along x and Y axis.

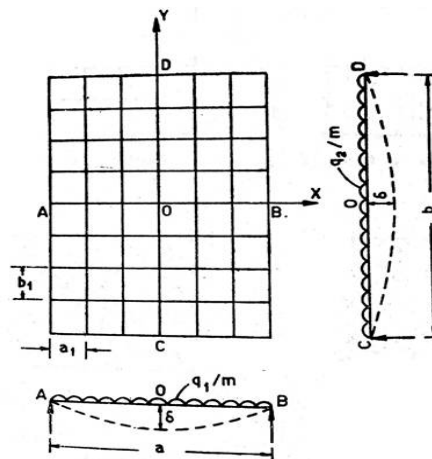


Figure1: Deflection of the ribbed slab [8]

Here a, b is the span of slab in X and Y directions, respectively and  $q_1, q_2$  is the load per unit area shared in X and Y directions, respectively. Which is given by,

$$q_1 = q \left( \frac{b^4}{a^4 + b^4} \right), \quad q_2 = q \left( \frac{a^4}{a^4 + b^4} \right)$$

where, q is the total load the slab per unit area. The bending moments and shear for the central ribs are given by,

$$M_{AB} = \left( \frac{q_1 b_1 a^2}{8} \right), \quad M_{BD} = \left( \frac{q_2 a_1 b^2}{8} \right), \quad Q_x = \frac{q_2 a_1 b_1}{2}, \quad Q_y = \frac{q_1 b_1 a_1}{2}$$

where,  $M_{AB}, M_{BD}$  are bending moments and  $Q_x, Q_y$  are shear on strips of unit width spanning in x and y directions respectively.

**2. Analysis by plate theory:** This is a rigorous method of analysis. This is based on Timoshenko's analysis of orthotropic plate theory considering plane stress analysis. A reinforced concrete grid floor with ribs at close intervals in two mutually perpendicular directions connected by slab in between the ribs can be considered as an orthotropic plate freely supported on four sides. Deflection, moments and shear at any point on the slab is given by,

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Deflection, 
$$\Delta = \frac{16q}{\pi^6} \left( \frac{\sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{\pi y}{b}\right)}{\frac{D_x + 2H}{a^4} + \frac{D_y}{a^2 b^2} + \frac{D_y}{b^4}} \right)$$

Bending moments, 
$$M_x = D_x \left( \frac{\pi}{a} \right)^2 \frac{16q}{\pi^6} \left( \frac{\sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{\pi y}{b}\right)}{\frac{D_x + 2H}{a^4} + \frac{D_y}{a^2 b^2} + \frac{D_y}{b^4}} \right), \quad M_y = D_y \left( \frac{\pi}{b} \right)^2 \frac{16q}{\pi^6} \left( \frac{\sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{\pi y}{b}\right)}{\frac{D_x + 2H}{a^4} + \frac{D_y}{a^2 b^2} + \frac{D_y}{b^4}} \right)$$

Torsional moments, 
$$M_{yx} = C_y \left( \frac{\pi^2}{ab} \right) \frac{16q}{\pi^6} \left( \frac{\cos\left(\frac{\pi x}{a}\right) \cos\left(\frac{\pi y}{b}\right)}{\frac{D_x + 2H}{a^4} + \frac{D_y}{a^2 b^2} + \frac{D_y}{b^4}} \right), \quad M_{xy} = C_x \left( \frac{\pi^2}{ab} \right) \frac{16q}{\pi^6} \left( \frac{\cos\left(\frac{\pi x}{a}\right) \cos\left(\frac{\pi y}{b}\right)}{\frac{D_x + 2H}{a^4} + \frac{D_y}{a^2 b^2} + \frac{D_y}{b^4}} \right)$$

Shear, 
$$Q_x = \frac{16q}{\pi^5} \left( \frac{\cos\left(\frac{\pi x}{a}\right) \sin\left(\frac{\pi y}{b}\right)}{\frac{D_x + 2H}{a^4} + \frac{D_y}{a^2 b^2} + \frac{D_y}{b^4}} \right) \left( D_x \frac{\pi^5}{a^5} + C_y \frac{\pi^5}{ab^2} \right), \quad Q_y = \frac{16q}{\pi^5} \left( \frac{\sin\left(\frac{\pi x}{a}\right) \cos\left(\frac{\pi y}{b}\right)}{\frac{D_x + 2H}{a^4} + \frac{D_y}{a^2 b^2} + \frac{D_y}{b^4}} \right) \left( D_y \frac{\pi^5}{b^5} + C_x \frac{\pi^5}{ba^2} \right)$$

Where, x,y are the co-ordinates of points on the slab and a , b are the length of the span in x and y directions respectively. q is the load per unit area, Dx , Dy are the flexural rigidity per unit length of plate in x and y direction. Cx , Cy are the torsional rigidity per unit length of plate in x and y direction and  $2H = C_x + C_y$ .

**3 Stiffness Method:** This method is based on matrix formulation of the stiffness of the structure and gives closed form solution. By using this method the analysis can be done by considering rigid supports as well. Various application software's are available to carry out analysis by this method. In the present work while analyzing grid floor frame by stiffness method, the simple supports are considered at closer distance so as to simulate the support conditions similar to Rankine-Grashoff method and Plate theory. Here ETABS.15 software is used. The modeled structure and stress diagram are given in Fig.2 and Fig.3. Details of the analytical model are given in table 1.

**Table 1:** Details of structure

Structure	Waffle slab (9mx12m)
Number of storey	Single
Storey height	3 m
Column	0.6 m x 0.3 m
Floor finishes	1.0 kN/m <sup>2</sup>
Roof load (Live load)	1.5 kN/m <sup>2</sup> (IS 875-part 2 (1987))
Thickness of waffle slab	100 mm
Width of rib	150 mm
Depth of rib	550mm
Center to center spacing of ribs	1500 mm
Grade of concrete for beam and slab	M <sub>20</sub>
Grade of steel	Fe 415
Restraints	Simply supported

The analytical results are given in table2. The results obtained by Rankine Grashoff theory is not in good agreement with the results obtained by numerical method. However the results predicted by the numerical method are in good agreement with the results predicted Timoshenko's plate theory. This indicates that the application of ETABS.15 software is valid for further parametric study.

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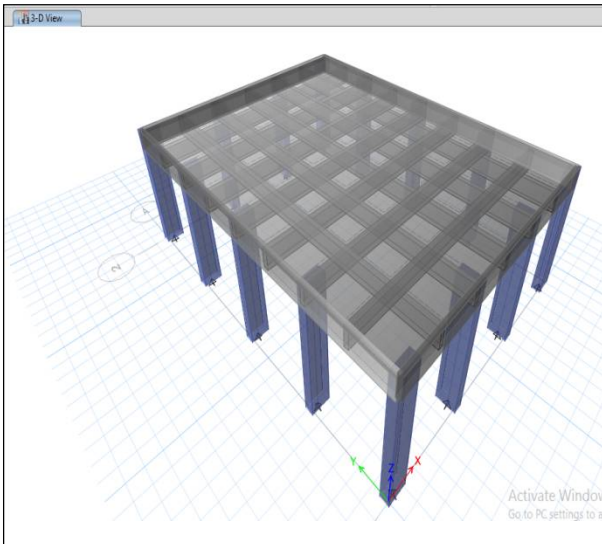


Figure2: 3D model of waffle slab

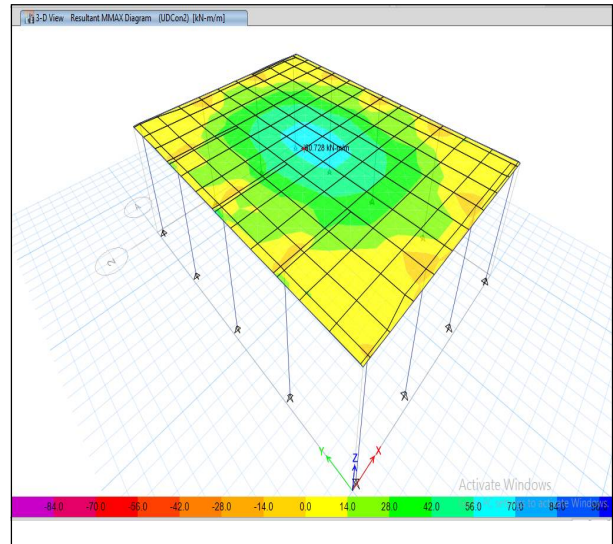


Figure3: Stress diagram of waffle slab

Table 2: Comparison of analysis methods

Maximum values	ANALYSIS METHOD			Average% variation with ETABS	
	Rankines Grashoff theory	Timoshenko's plate theory	Stiffness method ETABS 15	Rankines Grashoff theory	Timoshenko's plate theory
Deflection (mm)	6.30	4.40	3.20	29.08%	11.06%
Bending Moment Mx (kN-m/m)	84.29	69.55	60.77		
Bending Moment My(kN-m/m)	47.25	40.02	38.84		
Shear force Qx (kN/m)	37.46	25.15	21.10		
Shear force Qy (kN/m)	15.75	10.91	10.10		
Torsional moments (kN-m/m) Mxy	-	1.85	1.16		

## V.PARAMETRIC STUDY

In this study a rectangular waffle slab is assumed. The span of the grid beam in both X and Y direction  $L_x$  and  $L_y$  are made constant and is equal to 9m and 12m respectively. The spacing of grid beams is varied from 0.75m to 1.75 m at an interval of 0.25m. And for each spacing the depth of the grid beam (D) is varied from 0.55m to 0.15m.. Hence the span to depth (L/D) ratio is varied from 16 to 60. Thickness of slab and the rib width are made constant and are equal to 0.1m and 0.15m respectively. There by 30 models were generated and corresponding variations in maximum values of bending moments and mid span deflections have studied.

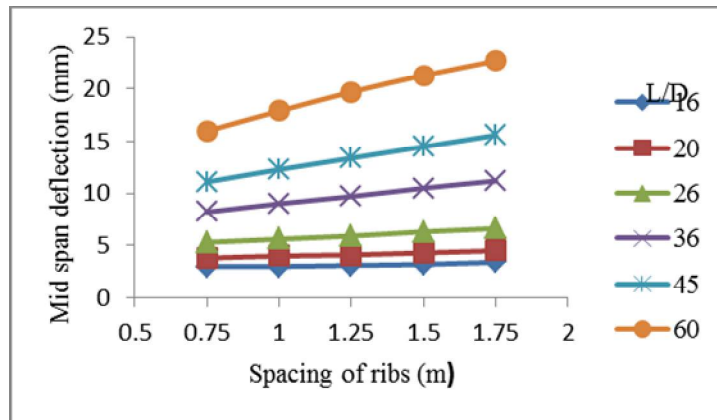
**1. Influence of spacing of ribs and span to depth ratios on mid span deflection:**Figure4. shows the influence of spacing of grid beams on the mid span deflection response of grid floor beams for different span to depth ratios (L/D) .

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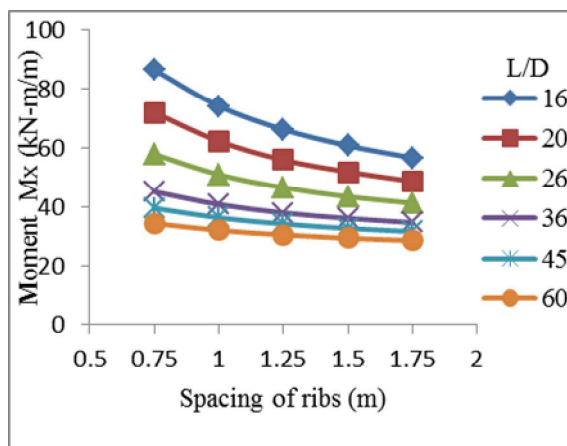


**Figure4:** Spacing of ribs vs. Mid span deflection

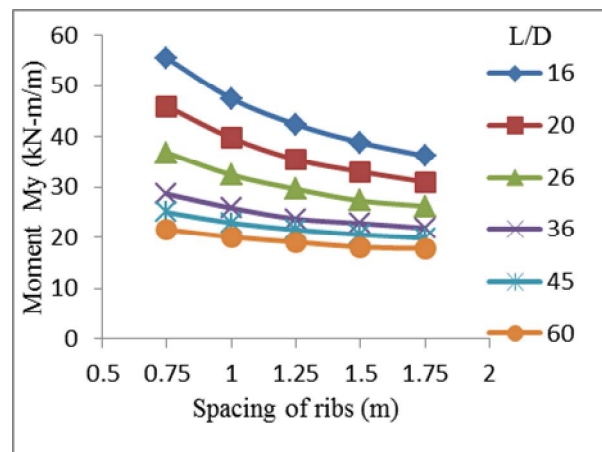
From figure5, it is found that when the spacing of grid beam increases, the mid span deflection also increases. The deflection is found to be more when the span to depth ratio (L/D) is increased to 60. The deflection is found to be depleting when the span to depth ratio (L/D) is reduced to 16.

## 2. Influence of spacing of ribs and span to depth ratios on the moment $M_x$ and $M_y$ developed

The influence of spacing of grid beams on the bending moment  $M_x$  and  $M_y$  developed in grid beams for different span to depth ratios (L/D) is given in Figure5 and Figure6 respectively.



**Figure5:** Spacing of ribs v/s moment  $M_x$



**Figure6:** Spacing of ribs vs. Moment  $M_y$

It is found that from Figure5 and Figure6, when the spacing of grid beam increases bending moment developed in the beams decreases. This is because as the spacing increases the number of ribs decreases and there will be a reduction in dead load. This will decrease the bending moment. The bending moments is found to be increasing when the span to depth ratio (L/D) is reduced to 16 and decreasing in nature when the span to depth ratio (L/D) is increased to 60.

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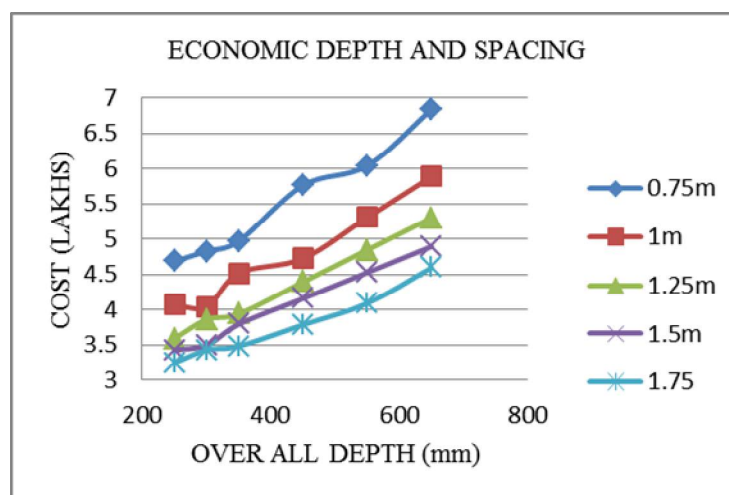
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### VILCOST ANALYSIS

Cost analysis for the waffle slab can be done by using making an excel program. After inputting the dimensions and moments in both direction the output material costs are noted for each case and tabulated in table.3. Figure7 is the graph plotted between overall depth of rib in x axis and material cost in lakhs along y axis for different spacing. The lower most point in the graph which corresponds to minimum cost gives the economic depth and spacing of ribs..

**TABLE 3:** Cost of slab for various depth and spacing

Spacing (mm) Depth (mm)	750	1000	1250	1500	1750
650	684039	588757	530050	489630	459661
550	604707	530751	484839	452950	409382
450	576447	472745	439629	416270	378795
350	497116	452082	394418	379590	348208
300	482986	404407	386366	349442	342760
250	468856	407255	359422	342909	324446



**Figure7:** Cost vs. overall depth

From Figure7, it is found that as the spacing between the ribs increases, material cost decreases since number of ribs decreases .also as the depth increases, material cost increases. For the given 9m x 12m waffle slab, from the graph the point with minimum material cost (Rs 3,24,446 ) corresponds to overall depth of 250mm and a rib spacing of 1.75m. But as per IS456-2000 , the maximum spacing between ribs is limited to 1.5m. So other than 1.75m spacing , from the graph the point with minimum material cost ( Rs 342909) corresponds to overall depth of 250mm at a rib

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spacing of 1.5m Thus the optimum design for 9m x12m waffle slab is the one with rib spacing is 1500mm at an overall depth of 250 mm .

## VIII.CONCLUSIONS

The conclusions drawn from the present work are given below:

1. Rankine-Grashoff method overestimates critical bending moment ( $M_x$ ) and shear force ( $Q_x$ ).
2. Analytical results of plate theory are in good agreement with that of ETAB result.
3. The spacing of grid beams influences the mid span deflection and the bending moments developed in the grid beams .
4. As spacing of the ribs increases mid span deflection decreases.
5. As the depth of the ribs increases mid span deflection increases.
6. Cost analysis can be carried out to for optimum design.
7. For slab with dimensions 9m x 12m , 250 mm ribs at 1500 spacing is found to be most economical .

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