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Optimum Design of a Reinforced Concrete Ribbed Slab

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Abstract In this research, optimum design of reinforced cement concrete (RCC) ribbed slab, also known as waffle slab according to the Indian RCC code (IS 456:2000) is presented. The objective function is the combined cost of the reinforcement, concrete and formwork which sums up the cost of the ribbed slab. The structure is analyzed using the direct design method. The objective function is developed after studying the ribbed slab in detail. The optimization process is carried out for different grades of concrete. The comparative results for different grades of concrete are enumerated and laid out in the tabulated form. Optimization for reinforced cement concrete (RCC) ribbed slab is illustrated and the results of the optimum design and conventional design are compared. Optimization problem is a constrained nonlinear programming problem (NLPP). The mathematical model is analyzed by using MATHEMATICA software. From the analysis, it was found that savings up to 25 percent can be obtained by optimizing the reinforced concrete ribbed slab.

Keywords Ribbed slab, Reinforced concrete, Structural optimization, Effective depth

1. Introduction

A ribbed slab also called as waffle slab is a two-way joist or coffered slab, essentially consisting of a thin top slab acting compositely with a closely spaced orthogonal grid of beam ribs. In flat ribbed slabs, solid heads are formed around the columns to resist the high bending and shear stresses in these critical areas. In contrast to a joist which carries loads in a one-way action, a waffle or ribbed system carries the loads simultaneously in two directions. The system is more suitable for square bays than rectangular bays. [9]

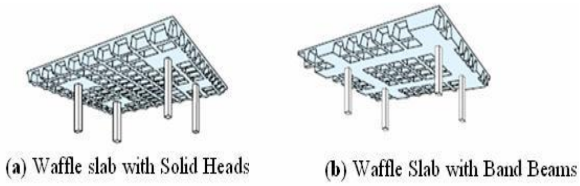

Figure 1. Waffle (Ribbed) Slab Types [1] *Source: IJCSE*

Optimum design of reinforced concrete elements plays a vital role in economical design of reinforced concrete structures. Thus, a designer has to perform a number of design-analyze cycles before converging on the best solution. In Ribbed Slab construction, as it involves, the slab, beams (ribs) running in both the directions beneath the slab (concrete, steel and formwork) in addition to safety, economic aspects also need to be considered as it is going to make a major impact on the overall cost of the structure. Hence, there is a need for an optimum design of ribbed slabs.

Research, on optimization of ribbed slabs is exceptionally scarce as there is little to none work done on the subject. The material consumption and economical aspects of ribbed slabs are often neglected by the designers. It is important to think about the importance and efficacy of optimization of such structural elements.

2. Objectives

2.1. To analyze and design three ribbed slabs manually of 10m square module, 12.6 m square module and 21 m square module with 1.4 m grid spacing.
2.2. To study the optimization of effective depth of the beams using MATHEMATICA and consequently the overall cost of the system.
2.3. To compare the cost with respect to the standard design principles.

3. Review of Related Literature

Research on optimization of ribbed slabs is very limited, as there is hardly any work done on the subject. Among the papers reviewed, one of the most important ones is the work done by Kiran Patil et al [2013] [2] who have investigated the optimum design of reinforced concrete flat slab with drop

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panel. The objective function considered is the total cost of the structure including the cost of slab and column. The cost of each structural element included, the material and labor for reinforcement, concrete and formwork. Comparative study was carried out for various grades of concrete and steel. The optimum and conventional design results are compared. The cost of the slab was found increasing rapidly with increase in grades of concrete and steel. The percentage reduction in optimum cost of the slab was found to be directly proportional to the number of spans.

Another important work was done by Alaa C Galeb, and Zainab F. Atiyah [2014] [1] who investigated the optimum design of reinforced concrete waffle slabs (two way ribbed) by using genetic algorithms. Two cases were studied, the first was waffle slabs with solid heads and the other, waffle slabs with band beams along column centrelines. Direct design method was used for the structural analysis and design of slabs. The objective function represented cost of concrete, formwork and reinforcement for the slab. The design variables were effective depth of slab, rid width, spacing between ribs and top slab thickness. Constraints included the dimensions of rib, top slab thickness and area of steel reinforcement, to satisfy flexural and minimum area requirements. Algorithm was developed using MATLAB to perform structural analysis and the optimization process was carried out using the built-in genetic algorithm toolbox.

4. Analytical Work

Formulations are done by following IS 456:2000 guidelines and results of ribbed slab for different depths and spans are calculated by using MATHEMATICA software.

Case 1: Ribbed slab of size 10000mm x 10000 mm square panel

Case 2: Ribbed slab of size 12600 mm x 12600 mm square panel

Case 3: Ribbed slab 21000 mm x 21000 mm square panel

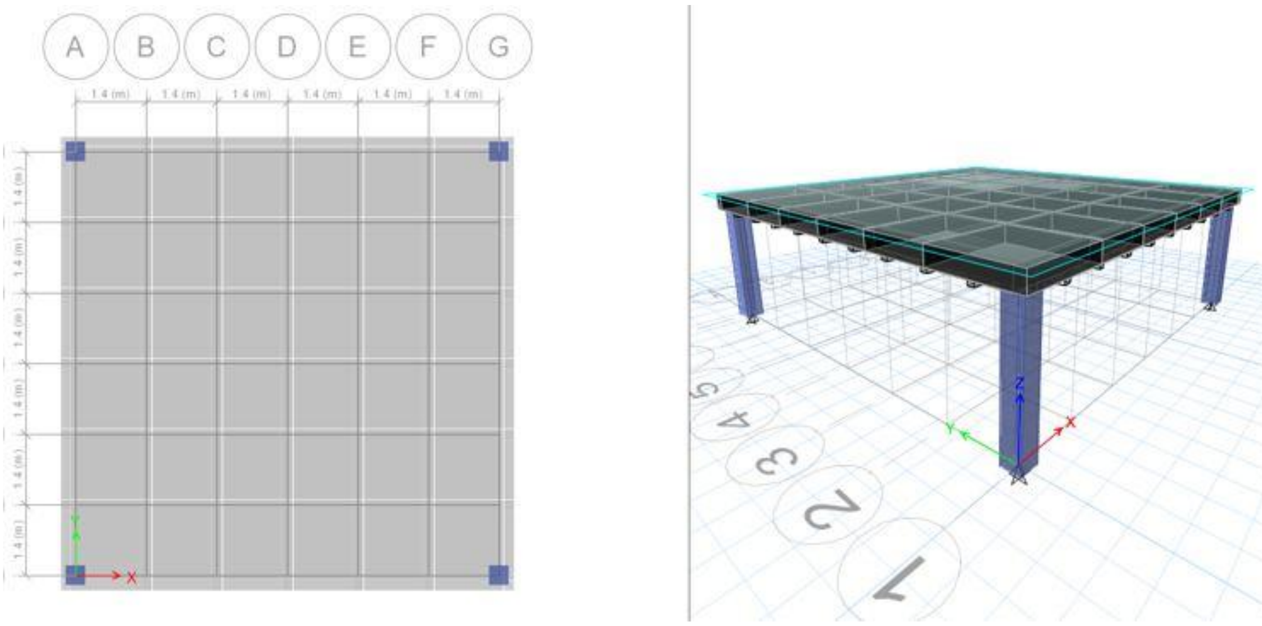

Figure 2. Modelling of 1000 0mm x 10000 mm span

The structural analysis of ribbed slab system is carried out using direct design method as per Bureau of Indian Standards, IS 456:2000.

In this method, a ribbed slab having a square column layout is divided into a series of longitudinal and transverse planes. Each frame consists of ribs and strips of slabs. In each direction, equivalent frames are structurally analyzed to obtain the total bending moments and shear forces at different sections of the slab. It is assumed that the width of the beams is divided into two strips namely column and middle strips. Negative and positive bending moments are determined in column and middle strips. The punching shear is checked in the solid head portion and the shear stress at the ribs is calculated. Then, the depth is checked to resist the bending moment. The bending moments and areas of steel at each section are calculated according to the design bending moment obtained in each section of column and middle strips.

This current analysis is constricted to rectangular form of slabs.

4.1. Objective Function (Cost Function)

The objective Function was developed after studying the ribbed slab in detail. It was formulated with respect to the design variable, effective depth.

$$\mathrm{Cc} * \left((L_1 * B_1 * D_1) + n_b * \left(L_2 * B_2 * (d + 0.025)\right)\right)$$
$$+\mathrm{Cs} * \left(\frac{\mathrm{Ast} * w * 4}{\pi * (D_2)^2 * 1000} + \frac{\mathrm{Ast} * w * 4}{\pi * (D_3)^2 * 1000}\right) +$$
$$\mathrm{Cf} * (70.56 + n_b * L_2 * (2 * d + 0.05 + B_2))$$

Where,

C_c is the cost of the concrete
C_s is the cost of the steel
C_f is the cost of the formwork
L_1 is the length of the Slab
L_2 is the length of the beam
B_1 is the breadth of the slab
B_2 is the breadth of the beam
D_1 is the depth of the topping slab
D_2 and D_3 are the diameters of the reinforcement bars
N_b is the number of ribs
A_{st} is the area of steel
25mm is the cover for beams
w is the unit weight of the reinforcement bar
d is the effective depth of the beam

4.2. Design Variables and Constraints

4.2.1. Design Variables

This optimization problem of a ribbed slab includes the following design variable which is an independent design variable

d = Effective depth of the beam.

Effective Depth: Effective depth is the depth of a beam as measured from the top of the member to the centroid of its tensile reinforcement.

The other independent variables are
f_{ck} = characteristic compressive strength of concrete.
Cost of the slab.

4.2.2. Constraint Equations

1. Shear Constraint: $\left(\frac{\tau_v}{\tau_c} - 1\right) < 0$

Here $\tau_v = \frac{v_u}{b_0 * d}$

$b_0 = 4 * (c + d)$

$v_u = w * (100 - (0.45 + d)^2)$

$\tau_c = 0.25 * \sqrt{f_{ck}}$

2. Minimum depth constraint: $\left(\frac{L}{28.8 * d}\right) - 1 < 0$

Where,
τ_v is the nominal shear stress
τ_c is the permissible shear stress
d is the design variable, effective depth
b_0 is the width of solid head of the slab
c is the width of solid portion of the slab
L is the span of slab in both directions
f_{ck} is the characteristic compressive strength of concrete.
w is the factored load acting on the slab

4.3. Design Optimization Procedure

The process of finding the conditions that give the maximum or minimum value of the function.

The optimum cost design of ribbed slab is formulated in which the objective (cost) function and the constraint functions are nonlinear functions of the design variable.

This nonlinear programming problem is solved by using fixed step size method. In fixed step size method, problem is checked for different values with constant step length. In this particular case, the step length considered is 25 mm. It is so considered, because the effective depth of the beam, which is the design variable in this problem is varied inch by 25 mm in practice. The effective depth is varied with the codal provisions and the optimization of the effective depth and the percentage of steel reinforcement is made to obtain the overall optimization of the ribbed slab.

Different Conditions and Parameters for Analysis and Design:

For comparative study consideration, the following parameters are considered for different results

f_{ck} = Characteristic Compressive Strength of concrete
= M25, M30
f_y = Characteristic Strength of steel
= Fe 415
Cost of Concrete:
M25 = Rs.9000 per Cum
M30 = Rs.10000 per Cum
M35 = Rs.10500 per Cum
Cost of Steel:
Fe415 = Rs.60000 per Metric Tonne
Cost of Formwork = Rs.400 per Sqm

Slab of sizes of 10000 mm x 10000 mm, 12600 mm x 12600 mm and 21000 mm x 21000 mm are considered in the research.

5. Results

Case 1: i) Span of size 10000 mm x 10000 mm
Grade of concrete=M25
Cost of concrete = Rs.9000 per Cum.
Cost of steel = Rs.60000 per MT
Cost of formwork= Rs.400 per Sqm

Table 1. Parameters of the Ribbed Slab for M25 Grade Concrete – 10000 mm x 10000 mm

S.NO	effective depth (d) in mm	Area of Steel in mm^2	Weight of steel in g/mm	Cost of Slab in INR
1	549	2507	0.02	317364
2	524	2623	0.02	308319
3	499	2751	0.02	299279
4	474	2893	0.02	290246
5	449	3054	0.02	281222
6	424	3237	0.03	272208
7	399	3450	0.03	263209
8	374	3704	0.03	254229
9	349	4024	0.03	245280

From the above Table 1: for M25 grade of concrete, it is observed that area of steel is increasing by 60 percent with decrease in effective depth.

Also from Figure 3(a), it is observed that, the weight of steel is increasing by 50 percent with decrease in effective depth.

The cost of the slab is increasing by 29 percent with increase in effective depth as observed from Figure 3(b):

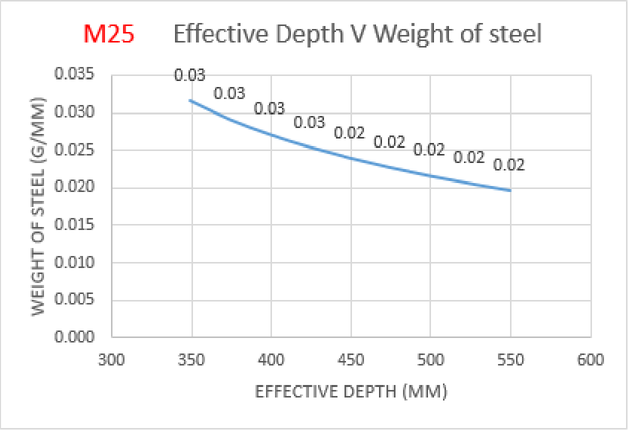

Figure 3(a). Variation of effective depth to weight of steel for M25 Grade Concrete

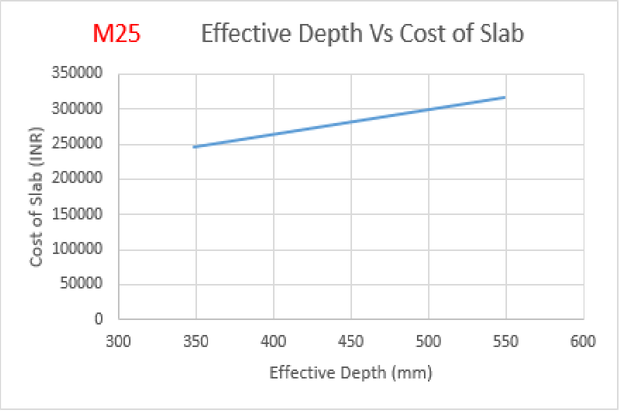

Figure 3(b). Variation of effective depth to cost of slab for M25 Grade Concrete

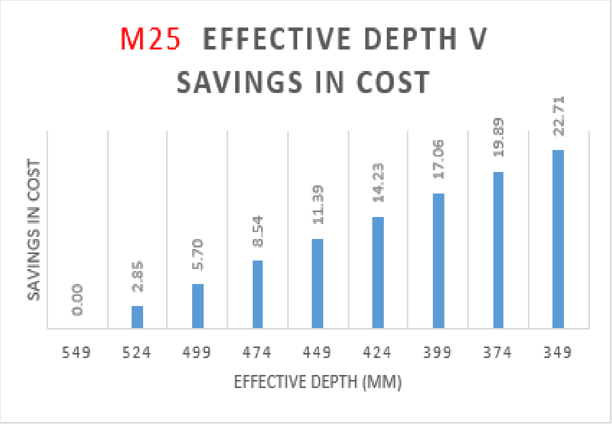

Figure 3(c). Variation of effective depth to savings in cost for M25 Grade Concrete

Case 1: **ii)** Span of size 10000 mm x10000 mm
Grade of concrete=M30
Cost of concrete = Rs.10000.00 per cum
Cost of steel = Rs.60000.00 per MT
Cost of formwork= Rs.400.00 per Sqm

Table 2. Parameters of the Ribbed Slab for M30 Grade Concrete- 10000 mm x 10000 mm

S. No.	Effective depth (d) in mm	Area of Steel in mm^2	Weight of steel in g/mm	Cost of slab in INR
1	549	2515	0.020	340940
2	524	2630	0.021	331194
3	499	2758	0.022	321454
4	474	2898	0.023	311721
5	449	3056	0.024	301995
6	424	3234	0.025	292279
7	399	3438	0.027	282575
8	374	3675	0.029	272887
9	349	3959	0.031	263221

From the above Table 2: for M30 grade of concrete, it is observed that area of steel is increasing by 57 percent with decrease in effective depth.

Also from Figure 4(a), the weight of steel is increasing by 50 percent with decrease in effective depth.

The cost of the slab is increasing by 29.5 percent with increase in effective depth as observed from Figure 4(b):

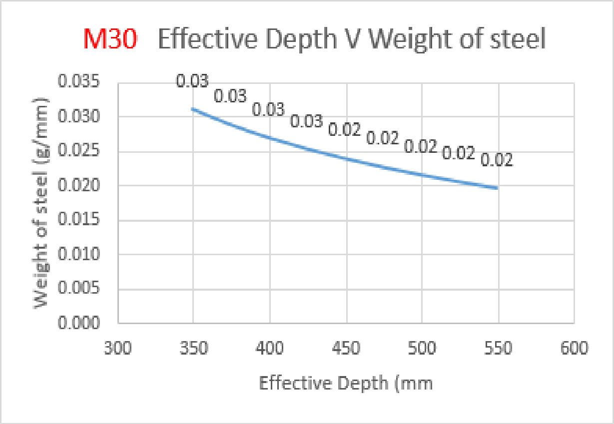

Figure 4(a). Variation of effective depth to weight of steel for M30 Grade concrete

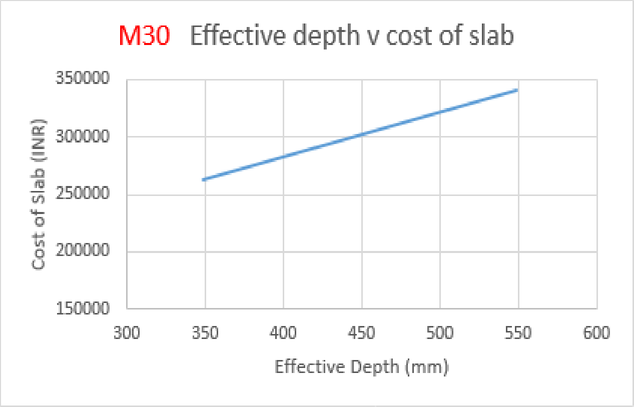

Figure 4(b). Variation of effective depth to cost of slab for M30 Grade Concrete

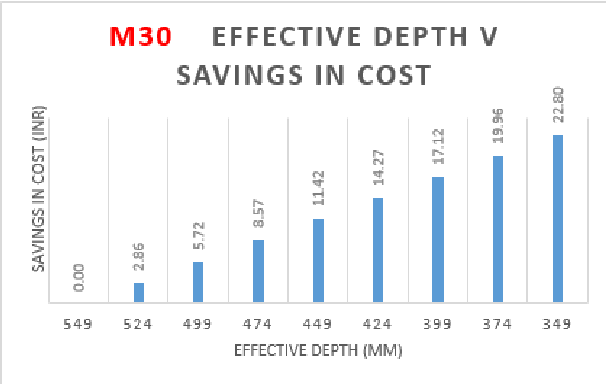

Figure 4(c). Variation of effective depth to savings in cost for M30 Grade Concrete

Case 1 iii) Span of size 10000 mm x 10000 mm
Grade of concrete=M35
Cost of concrete = Rs.10500.00 per Cum
Cost of steel = Rs.60000.00 per MT
Cost of formwork= Rs.400.00 per Sqm

Table 3. Parameters of the Ribbed Slab for M35 Grade Concrete -10000 mm x 10000 mm

S. No.	Effective depth (mm)	Area of steel in mm²	Weight of steel in g/mm	Cost of slab in INR
1	549	2522	0.0043	351799
2	524	2638	0.0041	341637
3	499	2765	0.0039	331475
4	474	2906	0.0037	321313
5	449	3062	0.0035	311152
6	424	3238	0.0033	300990
7	399	3437	0.0031	290828
8	374	3666	0.0029	280666
9	349	3936	0.0027	270504

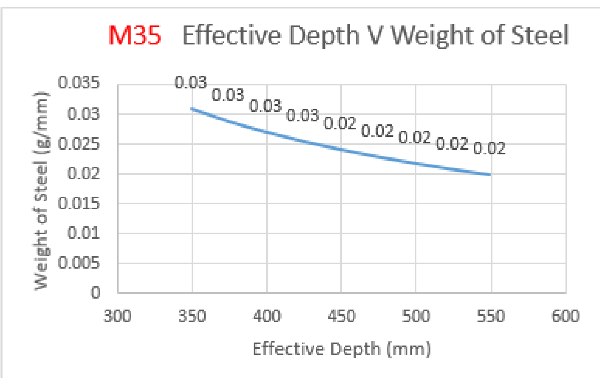

Figure 5(a). Variation of effective depth to weight of steel for M35 Grade Concrete

From the above Table 3:, for M35 grade of concrete, it is observed that area of steel is increasing by 56 percent with decrease in effective depth.

Also from Figure 5(a):, the weight of steel is increasing by 56 percent with decrease in effective depth.

The cost of the slab is increasing by 30 percent with increase in effective depth as observed from Figure 5(b):

The optimum point here is observed to be 349 mm (effective depth) as it results in savings of 23.11 % over normal design.

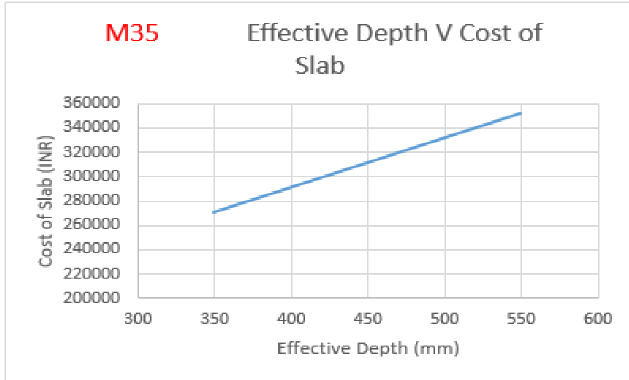

Figure 5(b). Variation of effective depth to cost of slab for M35 Grade Concrete

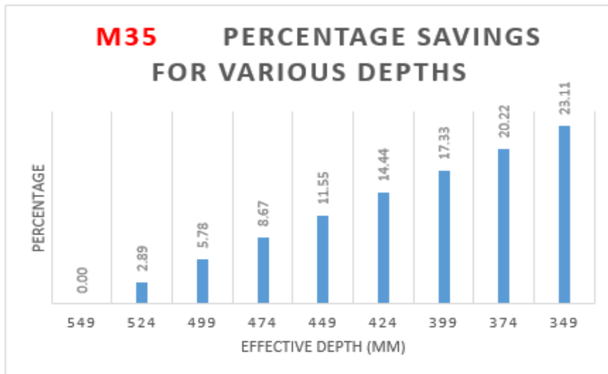

Figure 5(c). Variation of percentage savings for M35 Grade Concrete

Case 2: **i)** Span of size 12600 mm x12600 mm
Grade of concrete=M25
Cost of concrete = Rs.9000 per Cum
Cost of steel = Rs.60000 per MT
Cost of formwork= Rs.400 per Sqm

Table 4. Parameters of the Ribbed Slab for M25 Grade Concrete – 12600 mm x 12600 mm

S. No.	Effective Depth in mm	Weight of steel in g/mm	Cost of slab in INR	Area of Steel in mm2
1	749	0.026	630273	3355
2	724	0.027	615585	3469
3	699	0.028	600900	3590
4	674	0.029	586220	3722
5	649	0.030	571545	3865
6	624	0.031	556876	4021
7	599	0.033	542215	4192
8	574	0.034	527562	4382
9	549	0.036	512920	4595
10	524	0.038	498293	4839
11	499	0.040	483685	5125
12	474	0.043	469108	5476

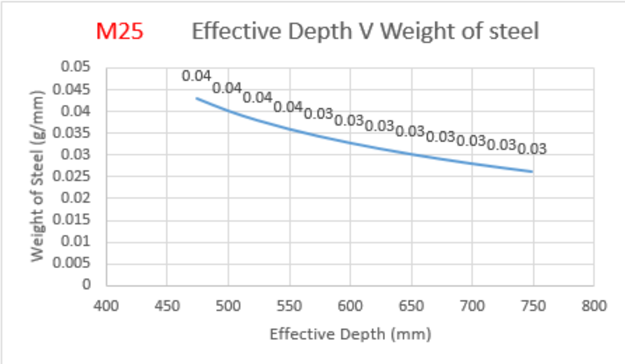

Figure 6(a). Variation of effective depth to weight of steel for M25 Concrete Grade

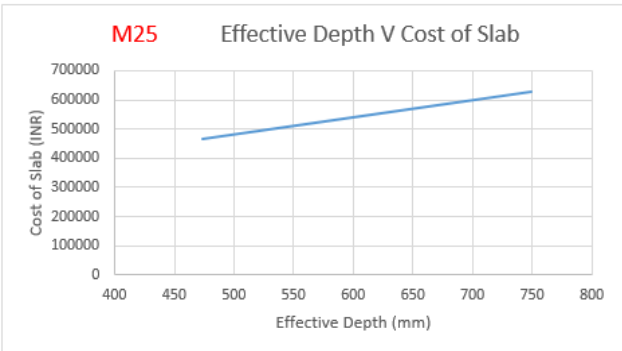

Figure 6(b). Variation of effective depth to cost of slab for M25 Concrete Grade

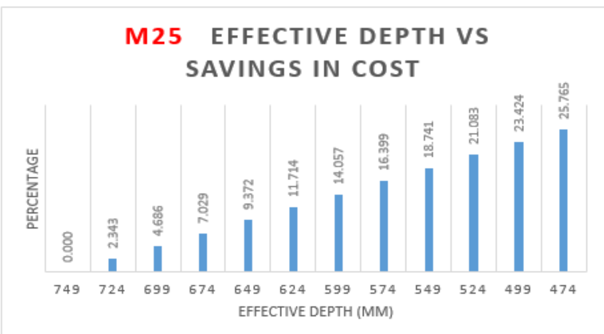

Figure 6(c). Variation of effective depth to savings in cost for M25 Concrete Grade

From the above Table 4:, for M25 grade of concrete, it is observed that area of steel is increasing by 63 percent with decrease in effective depth.

Also from Figure 6(a):, the weight of steel is increasing by 65 percent with decrease in effective depth.

The cost of the slab is increasing by 34 percent with increase in effective depth as observed from Figure 6(b):.

The optimum point here is observed to be 474 mm (effective depth) as it results in savings of 25.76% over normal design.

Case 2: **ii)** Span of size 12600 mm x 12600 mm

Grade of concrete=M30

Cost of concrete = Rs.10000 per Cum

Cost of steel = Rs.60000 per MT

Cost of formwork= Rs.400 per Sqm

Table 5. Parameters of the Ribbed Slab for M30 Grade Concrete – 12600 mm x 12600 mm

S. No.	Effective depth in mm	Weight of steel in g/mm	Cost of slab in INR	Area of Steel in mm^2
1	749	0.0263	677293	3363
2	724	0.0272	661470	3476
3	699	0.0281	645651	3597
4	674	0.0291	629836	3727
5	649	0.0302	614026	3868
6	624	0.0314	598222	4020
7	599	0.0327	582424	4187
8	574	0.0342	566634	4370
9	549	0.0358	550853	4573
10	524	0.0391	535178	4999
11	499	0.0396	519329	5057
12	474	0.0447	503762	5715

From Table 5:, for M30 grade of concrete, it is observed that area of steel is increasing by 69 percent with decrease in effective depth.

Also from Figure 7(a):, the weight of steel is increasing by 70 percent with decrease in effective depth.

The cost of the slab is increasing by 34 percent with increase in effective depth as observed from Figure 7(b):.

The optimum point here is observed to be 474 mm (effective depth) as it results in savings of 25.82% over normal design.

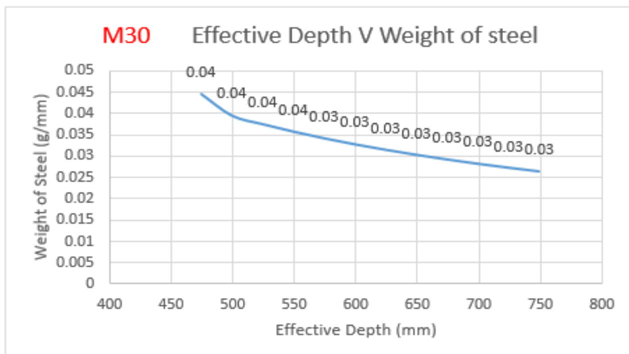

Figure 7(a). Variation of effective depth to weight of steel for M30 Concrete Grade

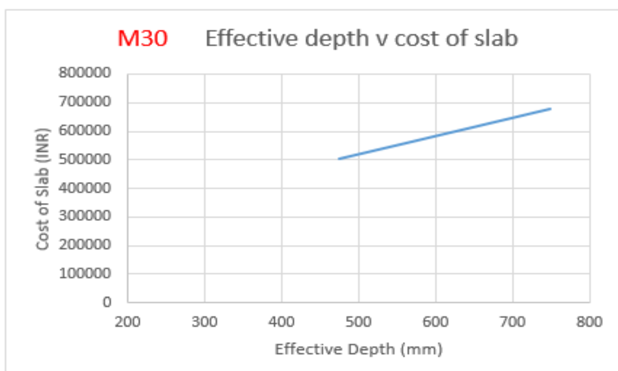

Figure 7(b). Variation of effective depth to cost of slab for M30 Concrete Grade

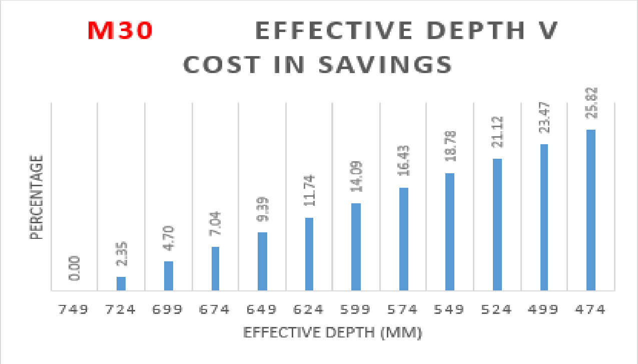

Figure 7(c). Variation of effective depth to cost savings for M30 Concrete Grade

Case 2: **iii)** Span of size 21000 mm x 21000 mm
Grade of concrete=M35
Cost of concrete = Rs.10500 per Cum
Cost of steel = Rs.60000 per MT
Cost of formwork= Rs.400 per Sqm

Table 6. Parameters of the Ribbed Slab for M35 Grade Concrete – 12600 mm x 12600 mm

S. No.	Effective depth in mm	Area of steel in mm²	Weight of steel in g/mm	Cost of slab in INR
1	749	3371	0.0265	700810
2	724	3484	0.0274	684420
3	699	3605	0.0283	668034
4	674	3734	0.0293	651653
5	649	3874	0.0304	635276
6	624	4026	0.0316	618904
7	599	4190	0.0329	602539
8	574	4370	0.0343	586180
9	549	4568	0.0359	569831
10	524	4788	0.0376	553491
11	499	5034	0.0396	537164
12	474	5313	0.0418	520853
13	449	5637	0.0443	504563

From Table 6:, for M35 grade of concrete, it is observed that area of steel is increasing by 67 percent with decrease in effective depth.

Also from Figure 8(a), the weight of steel is increasing by 67 percent with decrease in effective depth.

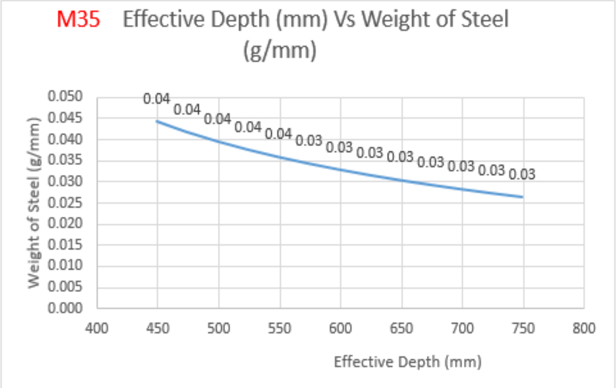

Figure 8(a). Variation of effective depth to weight of steel for M35 Concrete Grade

Figure 8(b). Variation of effective depth to cost of slab for M35 Concrete Grade

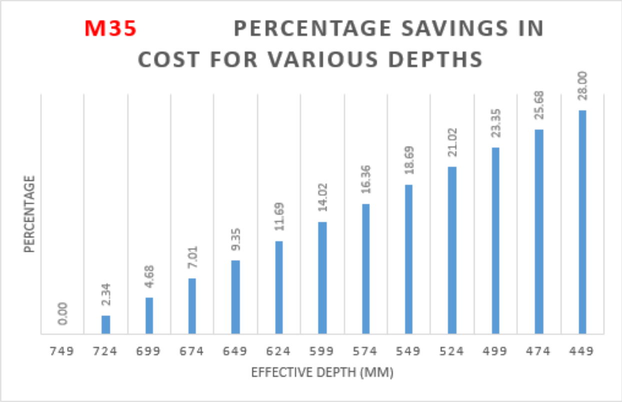

Figure 8(c). Variation of percentage of savings to cost of varying depths

The cost of the slab is increasing by 38 percent with increase in effective depth as observed from Figure 8(b):

The optimum point here is observed to be 449 mm (effective depth) as it results in savings over normal design.

Case 3: **i)** Span of size 21000 mm x 21000 mm
Grade of concrete=M30
Cost of concrete = Rs.10500 per Cum
Cost of steel = Rs.60000 per MT
Cost of formwork= Rs.400 per Sqm

Table 7. Parameters of the Ribbed Slab for M30 Grade Concrete – 21000 mm x 21000 mm

S. No.	Effective Depth in mm	Area of steel in mm2	Weight of steel in g/mm	Cost of slab in INR
1	949	9600	0.075	2553134
2	924	9900	0.078	2501300
3	899	10300	0.081	2449513
4	874	10600	0.083	2397679
5	849	11100	0.087	2345939
6	824	11500	0.090	2294153
7	799	12200	0.096	2242507
8	774	13300	0.104	2191049

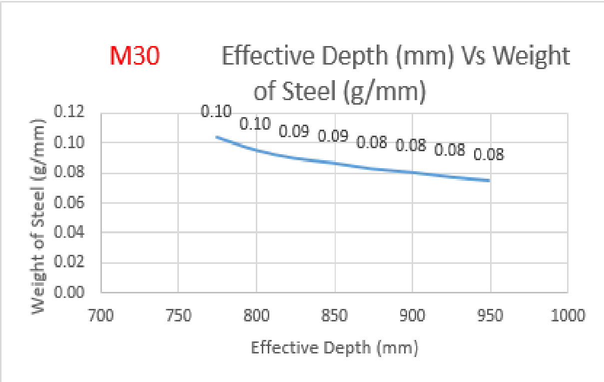

Figure 9(a). Variation of effective depth to weight of steel for M30 Concrete Grade

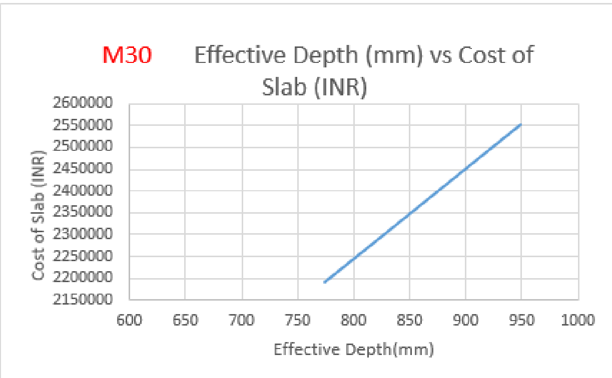

Figure 9(b). Variation of effective depth to cost of slab for M30 Concrete Grade

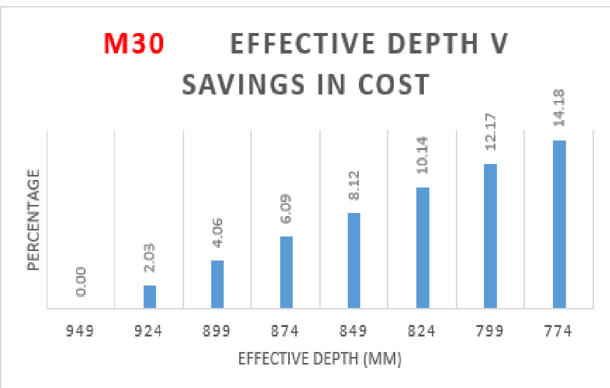

Figure 9(c). Variation of effective depth to savings in cost for M30 Concrete Grade

From the above Table 7:, for M30 grade of concrete, it is observed that area of steel is increasing by 39 percent with decrease in effective depth.

Also from Figure 9(a):, the weight of steel is increasing by 39 percent with decrease in effective depth.

The cost of the slab is increasing by 17 percent with increase in effective depth as observed from Figure 9(b):

The optimum point here is observed to be 774 mm (effective depth) as it results in savings of 14.18% over normal design.

Case 3: ii) Span of size 21000 mm x 21000 mm
Grade of concrete=M35
Cost of concrete = Rs.10500 per Cum
Cost of steel = Rs.60000/MT
Cost of formwork= Rs.400 per Sqm.

Table 8. Parameters of the Ribbed Slab for M25 Grade Concrete – 21000 mm x 21000 mm

S. No	Effective depth in mm	Area of Steel in mm^2	Weight of steel in g/mm	Cost of slab in INR
1	949	9623	0.075	2646384
2	924	9930	0.078	2592585
3	899	10267	0.080	2538800
4	874	10645	0.083	2485034
5	849	10823	0.085	2431174
6	824	11231	0.088	2377422
7	799	11694	0.092	2323696
8	774	12236	0.096	2270007

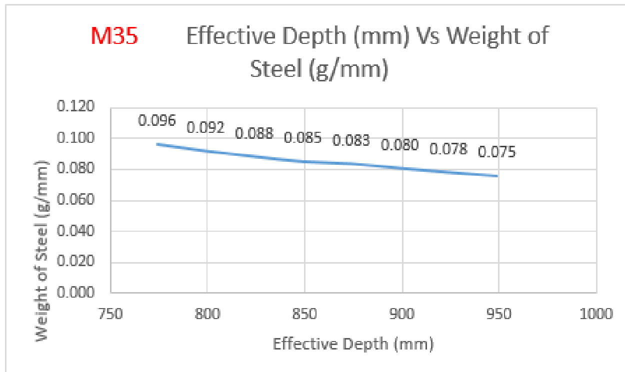

Figure 10(a). Variation of effective depth to weight of steel for M35 Concrete Grade

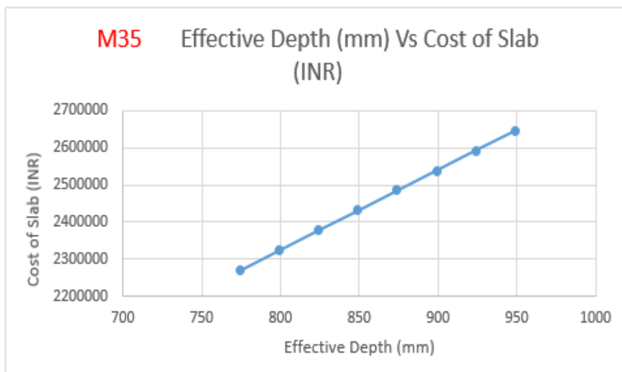

Figure 10(b). Variation of effective depth to cost of slab for M35 Concrete Grade

From the above Table 8:, for M35 grade of concrete, it is observed that area of steel is increasing by 27 percent with decrease in effective depth.

Also from Figure 10(a):, the weight of steel is increasing by 28 percent with decrease in effective depth.

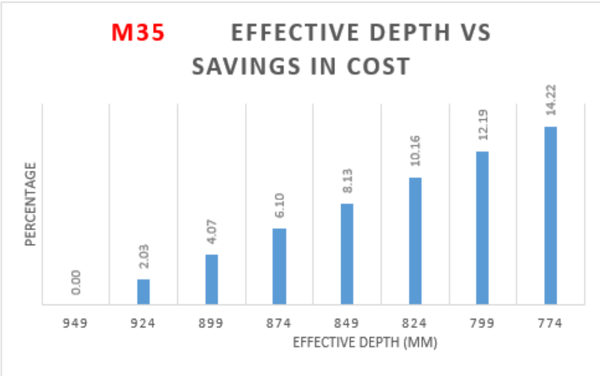

Figure 10(c). Variation of effective depth to savings in cost for M35 Concrete Grade

The cost of the slab is increasing by 16.5 percent with increase in effective depth as observed from Figure10 (b):

The optimum point here is observed to be 774 mm (effective depth) as it results in savings of 14.25 % over normal design.

Comparison

Case 1: Slab of size 10000 mm x 10000 mm

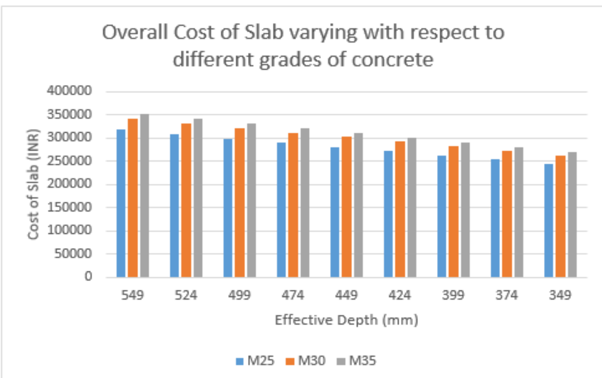

Figure 11. Cost of slab Vs different grades of concrete

Figure 11, shows the graphical representation cost values for ribbed slab for different grades of concrete.

M30 grade of concrete shows 7 percent increase in overall cost over M25 whereas M35 shows 11 percent increase.

Case 2: Slab of size 12600 mm x 12600 mm

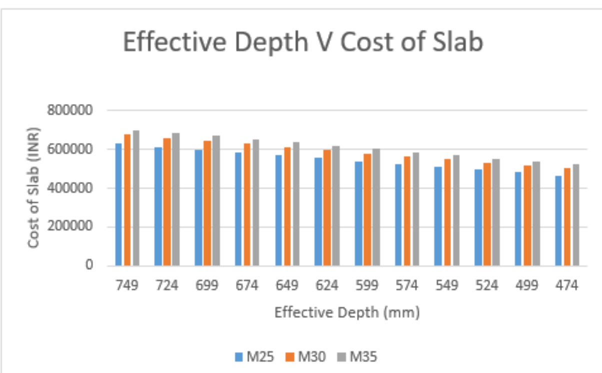

Figure 12. Effective depth Vs cost of slab for various grades of concrete

The overall cost of the slab increases as the grade of concrete increases.

Case 3: Span of size 21000 mm x 21000 mm

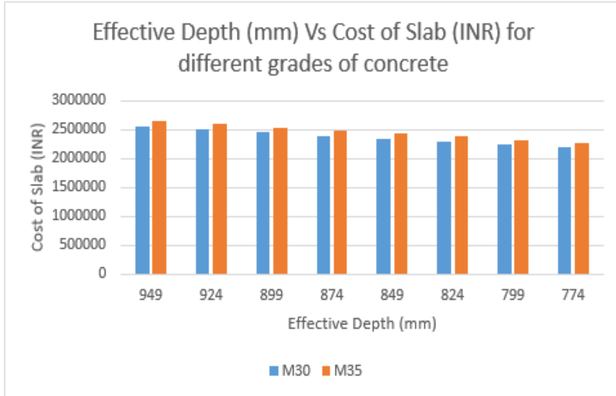

Figure 13. Effective depth Vs cost of slab for various grades of concrete

M35 grade of concrete shows 4 percent increase in overall cost over M30.

Depths for different spans

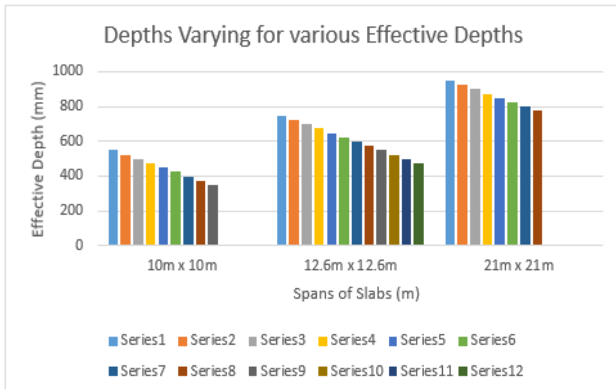

Figure 14. Variation of effective depths with spans

Figure 14: shows that the effective depth increases with increase in span for 12600 mm x 12600 mm span. Further, it is observed that 36 percent increase in depth over 10000 mm x 10000 mm span and 21000 mm x 21000 mm span shows 26 percent increase in depth over 12600 mm x 12600 mm span.

6. Conclusions

1. It is possible to formulate and obtain the optimum design of a ribbed slab by optimizing the effective depth and the percentage of reinforcement within the codal provisions, complying to the minimum depth and the minimum percentage of steel.
2. Maximum cost savings of 22.71%, 22.80% and 23.11% can be obtained over the normal design in case of ribbed slab with 10000 mm x 10000 mm span for M25, M30 and M35 grades of concrete respectively.
3. Cost savings of 25.57%, 25.62% and 25.71% are

obtained in case of ribbed slab with 12600 mm x 12600 mm span for M25, M30 and M35 grades of concrete respectively.

4. The overall cost of the ribbed slab increases by as much as 39 percent as the depth of slab increases.
5. The overall cost of the ribbed slab is directly proportional to depth of the slab and inversely proportional to the area and the weight of the steel.
6. As the panel size of the ribbed slab increases, the depth of the slab increases, consequently the cost of the ribbed slab also increases.
7. Ribbed slab of span 10000 mm x 10000 mm shows 26 percent increase in depth over 12600 mm x 12600 mm span whereas 12600 m x 12600 mm span shows 36 percent increase in depth over 21000 mm x 21000 mm span.

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