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Comparative Study of Waffle Slabs with Flat Slabs and Conventional RCC Slabs

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***Abstract* – Waffle slab construction consists of concrete joists at right angles to each other with solid heads at the column which is needed for shear requirements or with solid wide beam sections on the column centerlines for uniform depth construction. Waffle slab construction allows considerable reduction in the dead load of the overall structure as compared to flat slabs and conventional RCC slabs. The thickness of waffle slabs can be minimized to great extent as compared to flat slabs and RCC slabs. The bottom portion of waffle slab has many square projections with ribs spanning in both directions. The ribs are reinforced with steel to resist flexural tensile stresses. The design of waffle slab is done in such manner so as to achieve better load distribution. This paper deals with the comparative study of Waffle slabs with flat slabs and conventional RCC slabs and highlights the advantage waffle slabs have over flat slabs and RCC slabs. This comparison is shown with the help of a case study by designing of waffle slabs along with flat slabs and RCC slabs with the help of IS 456-2000 and shown with comparison of various points.**
Keywords – Waffle Slabs, flat slabs, joists, flexural tensile stresses.

I. INTRODUCTION

Waffle Slabs can be defined as "A reinforced concrete slab with equally spaced ribs parallel to the sides, having a waffle appearance from below. A Waffle Slab is a type of building material that has two-directional reinforcement on the outside of the material, giving it the shape of the pockets on a waffle. The top of a waffle slab is generally smooth, like a traditional building surface, but underneath has a shape reminiscent of a waffle. Straight lines run the entire width & length of the slab, generally raised several inches from the surface. These ridges form the namesake square pockets of the entire length and width of slab. It helps insulate the floor since hot air gets trapped in the pockets. Waffle slabs have a thick solid-slab floor from which the bottom layer concrete in tension is partially replaced by their ribs along orthogonal directions. The ribs are reinforced with steel. This type of reinforcement is common on concrete, wood and metal construction. A waffle slab gives a substance significantly more structural stability without using a lot of additional material. This makes a waffle slab perfect for large flat areas like foundations or floors. Reinforced concrete floors and roof construction employing a square grid of deep ribs with coffers in the intertices.

II. OBJECTIVE OF STUDY

The basic aim of this study is to design and show the comparative benefits of Waffle slabs over flat slabs and RCC slabs. Waffle slabs have some advantages over Flat slabs and RCC Slabs which helps us to use the Waffle Slabs.

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The objectives are:-

i. Savings on weights and material
ii. Vertical penetration between ribs is easy.
iii. Attractive soffit appearance if exposed.
iv. Can be used for long span also.
v. Economical when reusable formwork used.
vi. Reduction in dead load of slab.
vii. Economical for structure having repeated works.

III. WHAT ARE FLAT SLABS?

Flat slabs system of construction is one in which the beams used in t he conventional methods of constructions are done away with. The slab directly rests on the column and load from the slab is directly transferred to the columns and then to the foundation. To support heavy loads the thickness of slab near the support with the column is increased and these are called drops, or columns are generally provided with enlarged heads called column heads or capitals. Absence of beam gives a plain ceiling, thus giving better architectural appearance and also less vulnerability in case of fire than in usual cases where beams are used. Plain ceiling diffuses light better, easier to construct and requires cheaper form work.

IV. CASE STUDY

In the following case study a typical plan of shopping centre is taken into consideration. The design of various slabs in the entire building is done by standard design steps from the IS 456-2000. The comparison of various slabs i.e. 1. Waffle Slabs; 2. Flat Slabs; 3. Conventional RCC Slabs are done with respect to its design and construction aspects.

V. DESIGN OF RCC SLAB – SIZE = 7.5 × 7.5 m

Given:-

$L_y = 7.5$m — $L_x = 7.5$m

Live Load, LL = 4 KN/m² — Floor Finish, F.F = 1 KN/m²

M20, fck = 20 MPa — Fe415, Fy = 415 MPa

Design Constants:-

fck = 20 MPa — Fy = 415 MPa

Pt max. = 0.95 — Ru = 2.76

Ld. = 47 Ø

Depth of Slab from Deflection Criteria:-

Let pt = 0.5

Refer Pg. 38, IS 456 – 2000, M.F = 1.2

$$\frac{\text{Short Span}}{d} = 26 \times \text{M.F}$$

$$d \text{ reqd.} = \frac{7500}{26 \times 1.2} = 240 \text{ mm}$$

dc = 20 mm

D = d + dc = 240 + 20

D = 260 mm

Load Analysis:-

D.L of Slab, DL = 0.24 × 25 × 1 = 6 KN/m²

Floor Finish, FF = 1 KN/m²

Live Load, LL = 4 KN/m²

Total Load = DL + FF + LL = W = 11 KN/m²

Total Factored Load = Wu = 1.5 × W = 1.5 × 11 = 16.5 KN/m²

Analysis of Slab:-

$$\frac{Ly}{Lx} = \frac{7.5}{7.5} = 1 < 2 \quad (\therefore \text{It is a two way slab.})$$

Refer Tb – 26, Case 4, IS 456-2000.

$\alpha x' = 0.047$ — $\alpha y' = 0.047$

$\alpha x = 0.035$ — $\alpha y = 0.035$

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$Wu.Lx^2 = 16.5 \times 7.5^2 = 928.13$ KN-m

$Mux = \alpha x \times Wu \times Lx^2$
$= 0.035 \times 928.13$
$= 32.48$ KN

$Mux' = \alpha x' \times Wu \times Lx^2$
$= 0.047 \times 928.13$
$= 43.62$ KN

$Muy = \alpha y \times Wu \times Ly^2$
$= 0.035 \times 928.13$
$= 32.48$ KN

$Muy' = \alpha y' \times Wu \times Ly^2$
$= 0.047 \times 928.13$
$= 43.62$ KN

Check for 'd':-

$Mu = Ru.b.d^2$

$43.62 \times 10^6 = 2.76 \times 1000 \times d^2$

d = 125.71 < 240 mm (∴ Safe)

Design Table:-

Span	Position	Mu	d prov.	Ast. reqd.	Ast. min.	Ø Spacing	Ast. prov.
Short	Midspan	32.48	240	388	288	10 Ø 200	390
	Continous	43.62	240	528	288	10 Ø 140	557
Long	Midspan	32.48	240	388	288	10 Ø 200	390
	Continous	43.62	240	528	288	10 Ø 140	557

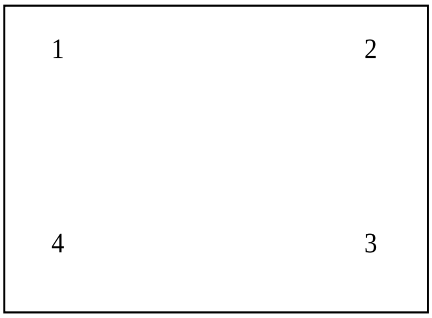
Provision of Torsion Steel at corners.:-

In this case,

Astx. = 388 mm²

$AT = \frac{3}{4} \times 388 = 291$ mm²

8 Ø – 3 nos.



Check for Shear.:-

$$Reaction = \frac{Wu.Lx}{2} + \frac{Mx}{Lx} = \frac{16.5 \times 7.5}{2} + \frac{43.62}{7.5}$$
$$= 67.69 \text{ KN}$$

$$Vu = 67.9 - 16.5\left(\frac{0.3}{2} + 0.24\right) = 61.26 \text{ KN}$$

$$\tau v = \frac{Vu}{bd} = \frac{61.26 \times 10^3}{1000 \times 240} = 0.26 < \tau c \max$$

$$\frac{100 \times Ast}{bd} = 0.16$$

Refer Tb. – 19, Pg. - 73, IS 456-2000,

$\tau c = 0.29$ N/mm²

Refer Pg. 72, IS 456-2000,

k = 1.10

k. $\tau c = 1.10 \times 0.29 = 0.319$ MPa

∴ $\tau v < k.\tau c$ (∴ Safe)

Check for Deflection:-

$$\frac{(\text{Short Span})}{d} = \frac{7500}{240} = 31.25$$

fs = 240 MPa , pt = 0.16

Refer Pg. – 38, Fig. – 4, IS 456-2000,

M.F = 2

∴ Basic Value × M.F = 26 × 2 = 52

∴ 31.25 ≯ 52

∴ Safe.

$$\frac{5}{384}\left(\frac{Wu \times L^4}{EI}\right) = \frac{5}{384} \times \left(\frac{16.5 \times 10^{-3} \times 7500^4}{22.36 \times 1.15 \times 10^9}\right) = 26.44 \text{ mm}$$

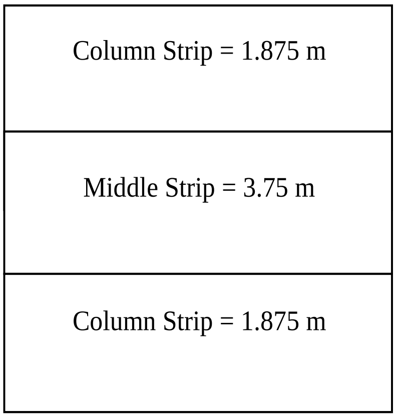
VI. DESIGN OF FLAT SLAB – SIZE = 7.5 × 7.5 m.

Given:-

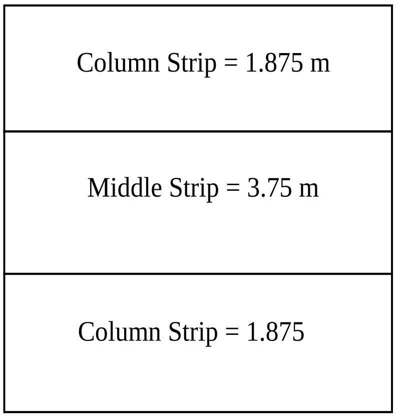
Ly = 7.5 m	Lx = 7.5 m
Live Load, LL = 4 KN/m²	Floor Finish, F.F = 1 KN/m²
M20, fck = 25 MPa	Fe415, Fy = 415 MPa

Division of slab into Column Strip and Middle Strip:-
As the length of slab in both directions is same i.e. Ly = Lx = 7.5 m (L1 = L2), no separate calculations needed for long span and short as the values would be identical.
∴ L1 = 7.5 m ; L2 = 7.5 m

Column Strip:-
= 0.25 × L2 = 0.25 × 7.5 = 1.875 m
But it should not be greater than 0.25L1 = 0.25 × 7.5 = 1.875 m
Middle Strip = 7.5 – (1.875 + 1.875) = 3.75 m



Along X – Direction



Along Y – Direction

Since, the span is large, it is desirable to provide drop.
∴ L1 = 7.5 m, L2 = 7.5 m
∴ It should not be less than, $\frac{L1}{3} = \frac{7.5}{3} = 2.5$ m
Hence provide a drop of size 2.5 × 2.5 m i.e. in column strip width.

Column Head:-
The diameter of column head should not be greater than $\frac{L1}{4} = \frac{7.5}{4} = 1.875$ m
∴ Adopting the diameter of Column Head = 1.875 m

Depth of Flat Slab:-
By considering the flat slab as a continuous slab over a span not exceeding 10 m .
∴ $\frac{L}{d} = 26 \rightarrow d = \frac{L}{26}$
∴ $d = \frac{7500}{26} = 288.46$ mm
∴ d = 290 mm
Taking effective cover = 25 mm
∴ D = 290 + 25 = 315 mm > 125 mm ... (125 mm = min. slab thck. as per IS 456-2000)
∴ It is safe to provide a depth = 315 mm.

Load Calculation:-
Dead Load, DL = 0.315 × 25 = 7.875 KN/m²
Live Load, LL = 6 KN/m²
Floor Finish, FF = 2 KN/m²
Total DL = DL + FF = 7.875 + 2 = 9.875 KN/m²

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Total LL = 6 KN/m^2
Total Load = DL + LL + FF = 7.875 + 6 + 2 = w = 15.875 KN/m^2
Total Factored Load, Wu = 1.5 × w = 1.5 × 15.875 = 23.81 KN/m^2
Check:- $\frac{LL}{DL} = \frac{6}{9.875} = 0.61 < 3$ … ∴ OK

Design Moment for span:-
$Mo = \frac{W.Ln}{8}$
Wu = 23.81 KN/m^2
$a = \left(\frac{\pi}{4}\right) \times d^2 = \left(\frac{\pi}{4}\right) \times 1.8^2$
a = 2.54 m^2
$Ln = 7.5 - \left(\left(\frac{1}{2}\right) \times 2.54\right) - \left(\left(\frac{1}{2}\right) \times 2.54\right)$
Ln = 4.96 m > (0.65.L1 = 0.65 × 7.5 = 4.875 m)
W = Wu × L1 × Ln = 23.81 × 7.5 × 4.96
W = 885.73 KN
$Mo = \frac{(W.Ln)}{8} = \frac{885.73 \times 4.96}{8}$
Mo = 549.15 KN-m ≅ 550 KN

Stiffness Calculation:-
Height of floor = 4.0 m
Clear ht. of column = ht. of floor – depth of drop – thickness of slab – thickness of head
= 4.0 – 0.16 – 0.315 – 0.415 = 3.11 m ≅ 3110 mm
Effective Ht. of Column = 0.8 × 3.11 = 2.49 m … (assuming one end hinged and other end fixed)
$\alpha c = \frac{\sum Kc}{Ks}$
$Kc = \left(\frac{4EI}{L}\right) bottom + \left(\frac{4EI}{L}\right) top$
α = 1.58
$\frac{L2}{L1} = 1$ … (from Tb. – 17)
$\frac{Wl}{Wd} = 1$
αc min. = 0.7
αc = 1.58 > αc min.
∴ Safe.

Distribution of BM across panel width:-

I. Column Strip

Negative BM at exterior support = $\left(\frac{-0.65Mo}{1+\left(\frac{1}{\alpha}\right)}\right) \times 1.0$
$= \left(\frac{-0.65 \times 550}{1+\left(\frac{1}{1.58}\right)}\right) \times 1.0 = 218.93$ KN-m

Positive Span BM = $\left(0.63 - \left(\frac{0.28}{1+\left(\frac{1}{\alpha}\right)}\right) \times Mo \times 0.60 \right)$
$= \left(0.63 - \left(\frac{0.28}{1+\left(\frac{1}{1.58}\right)}\right) \times 550 \times 0.60 \right) = 151.31$ KN-m

Negative Span BM at interior supports = $-\left(0.75 - \left(\frac{0.10}{1+\left(\frac{1}{\alpha c}\right)}\right) \times Mo \times 0.75 \right)$
$= -\left(0.75 - \left(\frac{0.10}{1+\left(\frac{1}{1.58}\right)}\right) \times 550 \times 0.75 \right) = -284.11$ KN-m

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II. MIDDLE STRIP

Negative BM at exterior support = $\left(\frac{-0.65\ Mo}{1+\left(\frac{1}{\alpha}\right)}\right) \times 0$ = 0 KN-m

Positive span BM = $(0.63 - \left(\frac{0.28}{1+\left(\frac{1}{\alpha}\right)}\right) \times Mo \times 0.40)$

= $(0.63 - \left(\frac{0.28}{1+\left(\frac{1}{1.58}\right)}\right) \times 550 \times 0.40)$ = 100.87 KN-m

Negative BM at interior support = $-\left(0.75 - \left(\frac{0.10}{1+\left(\frac{1}{\alpha}\right)}\right)\right) \times Mo \times 0.75$

= $-\left(0.75 - \left(\frac{0.10}{1+\left(\frac{1}{1.58}\right)}\right)\right) \times 550 \times 0.75$ = - 94.70 KN-m

∴ For effective depth of slab,
Maximum positive BM occurs in the column strip = 151.31 KN-m
∴ Mu = 0.138.fck.b.d²
∴ $151.31 \times 10^6 = 0.138 \times 25 \times 3750 \times d^2$
∴ d = 108.15 ≅ 120 mm
Using 12 mm Ø main bars
∴ D = 120 + 25 = 145 mm ≅ 160 mm

Depth (along longitudinal direction)

i. = $160 - 15 - \frac{12}{2}$ = 139 mm
ii. = 160 – 12 = 148 mm

Thickness of drop from maximum negative moment anywhere in the panel.
Maximum negative BM occurs in the column strip = 248.11 KN-m
Mu = 0.138.fck.b.d²
∴ $284.11 \times 10^6 = 0.138 \times 25 \times 1875 \times d^2$
∴ d = 209.57 mm ≅ 220 mm
Using 12 mm Ø main bars
∴ Overall thickness of Flat Slab, D = $220 + 15 + \frac{12}{2}$ = 241 mm ≅ 250 mm

Shear in Flat Slab:-
Check for shear stress developed in slab.

The critical section for shear for the slab will be at a distance $\frac{d}{2}$ from face of the drop.

Side of critical section = $2500 + \frac{160}{2} + \frac{160}{2}$
= 2660 mm
∴ Perimeter of critical section = 2660 × 4 = 10640 mm
Vo = Wu (L1 × L2 – (Side)²)
= 23.81 (7.5 × 7.5 – 2.66²)
Vo = 1170.84 KN

Nominal Shear Stress = $\tau v = \frac{Vu}{bd} = \frac{1170.84 \times 10^3}{10640 \times 160}$
τv = 0.69 N/mm²
τc = 0.25√25 = 1.25 N/mm² ∴ τv < τc (∴ Safe.)

Check for shear in drop:-
bo = π (D + do) = π (1.8 + 0.29) = 6.57 m
V = $23.81\ (7.5 \times 7.5 - \frac{\pi}{4}\ (1.8 + 0.29)^2)$ = 1257.63 KN
$\tau v = \frac{1257.63 \times 10^3}{6570 \times 290}$ = 0.66 N/mm²
τc = 1.25 N/mm²
∴ τv < τc
∴ Safe.

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Reinforcement Details:-
As the lengths of both the spans are equal i.e. Ly = Lx = 7.5 m, the reinforcement in both the directions would be same. Hence, calculations would be same.
Ly = L× = 7.5 m

Negative Exterior Reinforcement:-
Mu = 0.87.Fy.Ast (d – 0.42xu)
$218.93 \times 10^6 = 0.87 \times 415 \times$ Ast. $\times$ (139 – (0.42 × 0.48 × 139))
∴ Ast. = 5463.9 mm ²
Use 12 mm ∅ bars
Number of bars = $\frac{5463.9}{113}$ = 48.35 ≅ 49 bars
Spacing = $\frac{1.875 \times 1000}{48}$ = 39 mm c/c

Positive Reinforcement:-
Mu = 0.87.Fy.Ast (d – 0.42xu)
$151.31 \times 10^6 = 0.87 \times 415 \times$ Ast. $\times$ (148 – (148 – (0.42 × 0.48 × 148))
Ast. = 3546.6 mm ²
Use 12 mm ∅ bars
Number of bars = $\frac{3546.6}{113}$ ≅ 31 bars
Spacing = $\frac{(3.75 \times 1000)}{31}$ = 120 mm c/c

Deflection Check:-
$E = 2.1 \times 10^5$ N/mm²
$I = \frac{bd^3}{12} = \frac{1000 \times 290^3}{12} = 2032.41 \times 10^6$ mm^4
$\left(\frac{5}{384}\right)\left(\frac{Wu.L^4}{EI}\right) = \left(\frac{5}{384}\right) \times \left(\frac{23.81 \times 7500^4}{(2.1 \times 10^5) \times (2032.41 \times 10^6)}\right) = 22.9$ mm
$\frac{Span}{250} = \frac{7500}{250} = 30$ mm
∴ 22.9 mm < 30 mm
∴ Safe.

VII. DESIGN OF FLAT SLAB – SIZE = 15 × 7.5 m.

Given:-

Ly = 15 m	Lx = 7.5 m
Live Load, LL = 4 KN/m²	Floor Finish, F.F = 1 KN/m²
M20, fck = 25 MPa	Fe415, Fy = 415 MPa

Division of slab into Column Strip and Middle Strip:-
Long Span
L1 = 15 m , L2 = 7.5 m
i. Column Strip = 0.25.L2 = 1.875 m (But not greater than (0.25L1 = 3.75 m)
ii. Middle Strip = 7.5 – (1.875 + 1.875) = 3.75 m

Short Span
L1 = 7.5 m , L2 = 15 m
i. Column Strip= 0.25.L2 = 3.75 m (But not greater than (0.25L1 = 1.875m)
ii. Middle Strip = 15 – (3.75 + 3.75) = 7.5 m

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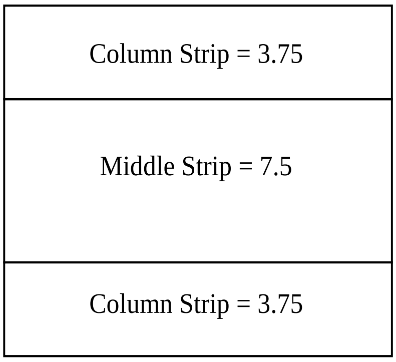
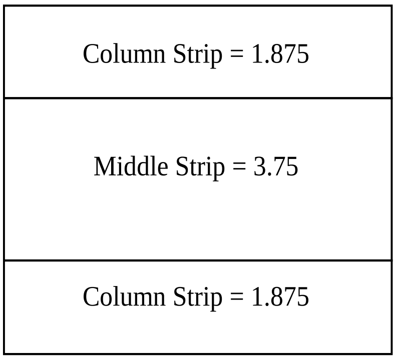


Along X – Direction = 7.5 m



Along Y – Direction = 15 m

Since the span is large, it is desirable to provide drop.

Long Span
L1 = 15 m , L2 = 7.5 m
Not less than $\frac{L1}{3} = \frac{15}{3}$ = 5 m

Short Span
L1 = 7.5 m , L2 = 15 m
Not less than $\frac{L1}{3} = \frac{7.5}{3}$ = 2.5 m
Hence, provide a drop of size 5 × 5 m in column strip width.

Column Head.:-
Long Span
L1 = 15 m , L2 = 7.5 m
Not greater than $\frac{L1}{4} = \frac{15}{4}$ = 3.75 m
Short Span
L1 = 7.5 m , L2 = 15 m
Not greater than $\frac{L1}{4} = \frac{7.5}{4}$ = 1.875 m
Adopting the diameter of column head = 1.75 m ≅ 1750 mm

Depth of Flat Slab:-
$\frac{L}{d} = 26 \rightarrow d = \frac{L}{26}$
Long Span
L1 = 15 m , L2 = 7.5 m
$d = \frac{L}{26} = \frac{15000}{26}$
d = 573.92 ≅ 575 mm
Short Span
L1 = 7.5 m , L2 = 15 m
$d = \frac{L}{26} = \frac{7500}{26}$
d = 288.46 mm
d ≅ 290 mm
Taking effective cover of 25 mm.
Overall depth of Flat Slab, D = 575 + 25 = 600 mm.

As the depth of Flat Slab for the overall dimensions of 15 × 7.5 m is 600 mm, it is not practically feasible to provide a slab of such great depth. Also it is would not be economical to provide slab of such depth. Besides economical and practical problems, this may also have problems during execution stage as the concrete required would be great so the concrete batches would be more & also the heat of hydration would be very large.

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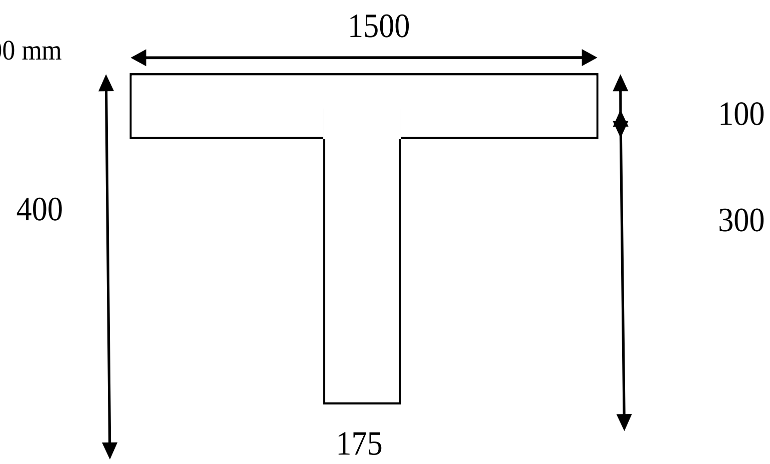
So, for providing slab of such greater spans Waffle Slabs are the alternative for flat slabs. The slab depth in waffle slabs is very much less as compared to Flat Slabs and any other slabs such conventional RCC slabs, etc. Due to decrease in the depth of slab it is practically more feasible to provide Waffle Slabs instead of Flat Slabs. The execution would also be easier in Waffle Slabs in comparison to Flat Slabs. Though the formwork required for Waffle Slabs is more it can be re-used many times as well as the construction is fast.

Hence, in this case study in comparison for Conventional RCC Slabs and Flat Slabs, we are comparing Waffle Slabs to lighten the benefits of using Waffle Slabs for large spans of slabs in replacement of other slabs. The construction, cost and practical benefits of Waffle Slabs in comparison with other slabs can be clearly elaborated from these case studies.

VIII. DESIGN OF WAFFLE SLAB – SIZE = 7.5 × 7.5 m

Given:-
Size of Grid = 7.5 × 7.5 m
Spacing of ribs = 1.5 m → a1 = 1500 mm ; b1 = 1500 mm
M20, fck = 20 N/mm²
Fe415, Fy = 415 N/mm²
Live Load, LL = 4 KN/m²
Floor Finish, FF = 1 KN/m²

Dimensions of Slab & Beam:-
Adopt thickness of slab = 100 mm
Depth of Rib = $\frac{\text{Span}}{26} = \frac{7500}{26}$ = 288.46 mm ≅ 400 mm
Width of Rib = 175 mm
Number of beams in X – Direction, Nx = 6
Number of beams in Y – Direction, Ny = 6
E = 5000√fck × 1000
= 5000 × √20 × 1000
E = 22.36 × 10^6



Load Calculations:-
Total weight of slab
= 25 × Df × Lx × Ly
= 25 × 0.1 × 7.5 × 7.5 = 140.63 KN
Total weight of beams in X – Direction
= 25 × bw × D × Nx × L×
= 25 × 0.175 × 0.40 × 6 × 7.5 = 78.75 KN
Total weight of beams in Y – Direction
= 25 × bw × D × Ny × (Ly – (bw × Nx))
= 25 × 0.175 × 0.40 × 6 × (7.5 – (0.175 × 6)) = 67.73 KN
Total Live Load, LL = LL × Ly × Lx = 4 × 7.5 × 7.5 = 225 KN
Total Floor Finish, FF = FF × Ly × Lx = 1 × 7.5 × 7.5 = 56.25 KN
Total Load = 140.63 + 78.75 + 67.73 + 225 + 56.25 = 568.38 KN
Total Load / m² = q = $\frac{568.75}{7.5 \times 7.5}$ = 10.10 KN/m²
Total Factored Load = Q = 1.5 × q = 1.5 × 10.10 = 15.15 KN/m²

Design Parameters:-

$$\frac{\text{Df}}{\text{D}} = \frac{100}{400} = 0.25$$

$$\frac{\text{bf}}{\text{bw}} = \frac{1500}{175} = 8.57$$

Moment of Inertia:-

$I = \frac{Kx \times bw \times D^3}{12} = \frac{3 \times 0.175 \times 0.4^3}{12}$ … (Kx = 3 → SP – 16, Tb. – 18)

$I = 2.8 \times 10^{-3}\ m^4 \cong 2.8 \times 10^9\ mm^4$

Flexural Rigidity of Ribs:-

$Dx = \frac{E \times I}{a1} = \frac{22.36 \times 10^6 \times 2.8 \times 10^9}{1500}$

$Dx = 4.7 \times 10^4$

$Dy = \frac{E \times I}{b1} = \frac{22.36 \times 10^6 \times 2.8 \times 10^9}{1500}$

$Dy = 4.7 \times 10^4$

Modulus of Shear:-

$G = \frac{E}{2\,(1+\mu)} = \frac{22.36 \times 10^6}{2\,(1+0.15)}$ … (μ = 0.15 → assume)

$G = 9.72 \times 10^6\ KN/m^2$

Torsional Constants (Polar Sectional Modulus):-

$C1 = 1 - \left(0.63 \times \left(\frac{bw}{D}\right)\right)\left(bw^3 \times \left(\frac{D}{3}\right)\right) = 1 - \left(0.63 \times \left(\frac{0.175}{4}\right)\right)\left(0.175^3 \times \left(\frac{0.4}{3}\right)\right) = 5.18 \times 10^{-4}\ m^3$

$C2 = 1 - \left(0.63 \times \left(\frac{bw}{D}\right)\right)\left(D^3 \times \left(\frac{bw}{3}\right)\right) = 1 - \left(0.63 \times \left(\frac{0.175}{0.4}\right)\right)\left(0.4^3 \times \left(\frac{0.175}{3}\right)\right) = 2.7 \times 10^{-3}\ m^3$

Torsional Rigidity:-

$Cx = \frac{(G \times C1)}{b1} = \frac{9.72 \times 10^6 \times 5.18 \times 10^{-4}}{1.5} = 3.35 \times 10^3$

$Cy = \frac{G \times C2}{a1} = \frac{9.72 \times 10^6 \times 2.7 \times 10^{-3}}{1.5} = 1.75 \times 10^4$

$\therefore 2H = Cx + Cy = (3.35 \times 10^3) + (1.75 \times 10^4) = 2.09 \times 10^4$

$\frac{Dx}{Lx^4} = \frac{4.75 \times 10^4}{7.5^4} = 13.9$

$\frac{Dy}{Ly^4} = \frac{4.75 \times 10^4}{7.5^4} = 13.9$

$\frac{2H}{Lx^2 \times Ly^2} = \frac{2.09 \times 10^4}{7.5^2 \times 7.5^2} = 6.60$

Deflection Check:-

$\omega = \frac{16 \times \left(\frac{Q}{\pi}\right)}{\frac{Dx}{Lx^4}} + \left(\frac{2H}{Lx^2 \times Ly^2}\right) + \left(\frac{Dy}{Ly^4}\right) = \frac{16 \times \left(\frac{15.15}{\pi}\right)}{13.19} + 6.60 + 13.19 = 7.65\ mm$

Long Term Deflections:-

Lt defl. = 3 × ω = 3 × 7.65 = 22.94 mm

$\frac{Span}{250} = \frac{7500}{250} = 30\ mm$ (Lt defl. < $\frac{Span}{250}$ ∴ Safe.)

Maximum Moment and Shear Values:-

$Mx = Dx \times \left(\frac{\pi}{Lx}\right)^2 \times \omega = 4.74 \times 10^4 \times \left(\frac{\pi}{7500}\right)^2 \times 7.65 = 56\ KN\text{-}m$

$My = Dy \times \left(\frac{\pi}{7500}\right)^2 \times \omega = 4.7 \times 10^4 \times \left(\frac{\pi}{7500}\right)^2 \times 7.65 = 56\ KN\text{-}m$

Maximum Torsional Moment:-

$Mxy = \frac{Cx \times \pi^2 \times \omega}{Ly \times Lx} = \frac{3.35 \times 10^3 \times \pi^2 \times 7.65}{7500 \times 7500} = 5\ KN\text{-}m$

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Shear Force:-

$$Qx = \left(\left(Dx \times \left(\frac{\pi}{Lx}\right)^3 \right) + \left(Cy \times \left(\frac{\pi^3}{a1 \times b1^2}\right) \right) \right) \times \omega$$

$$= \left(\left(4.74 \times 10^4 \times \left(\frac{\pi}{7500}\right)^3 \right) + \left(1.75 \times 10^4 \times \left(\frac{\pi^3}{1500 \times 1500^2}\right) \right) \right) \times 7.65 = 25 \text{ KN}$$

$$Qy = \left(\left(Dy \times \left(\frac{\pi}{7500}\right)^3 \right) + \left(Cx \times \left(\frac{\pi^3}{a1^2 \times b1}\right) \right) \right) \times \omega$$

$$= \left(\left(4.74 \times 10^4 \times \left(\frac{\pi}{7500}\right)^3 \right) + \left(3.35 \times 10^4 \times \left(\frac{\pi^3}{1500^2 \times 1500}\right) \right) \right) \times 7.65 = 25 \text{ KN}$$

Reinforcement Details:-

$$Astx = Asty = \frac{0.5 \times fck}{fy} \times \left(1 - \sqrt{1 - \frac{4.6Mu}{fck.b.d^2}} \right) \times b \times d \ldots \text{(as Ly = Lx = 7.5 m)}$$

$$= \frac{0.5 \times 20}{415} \times \left(1 - \sqrt{1 - \frac{4.6 \times 56 \times 10^6}{20 \times 175 \times 370^2}} \right) \times 175 \times 370$$

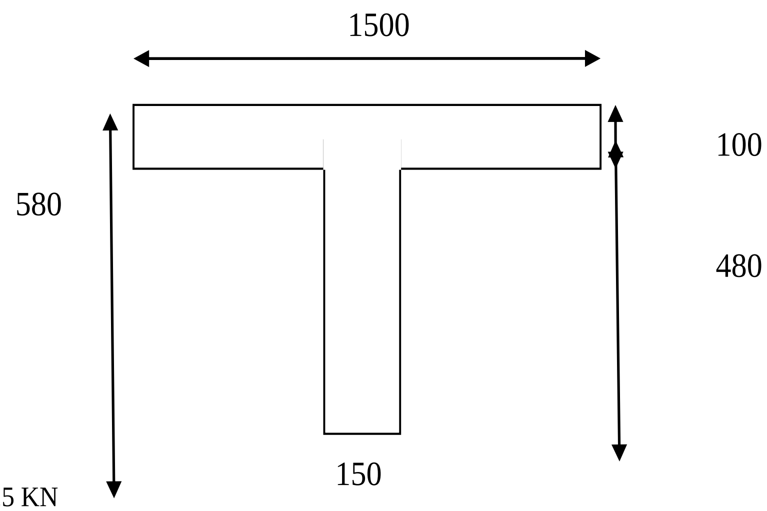
∴ Astx = Asty = 499.29 mm^2
Use 12 mm ∅ bars
∴ Provide 5 bars of 12 mm ∅.
Provide minimum steel in slab portion i.e. flange of waffle slab.

$$\text{Ast min.} = \frac{0.12}{100} \times b \times d = \frac{0.12}{100} \times 1000 \times 100$$

Ast min. = 120 mm^2

IX. DESIGN OF WAFFLE SLAB – SIZE = 15 × 7.5 m

Given:-
Size of Grid = 15 × 7.5 m
Spacing of ribs = 1.5 m → a1 = 1500 mm ; b1 = 1500 mm
M20, fck = 20 N/mm^2
Fe415, Fy = 415 N/mm^2
Live Load, LL = 4 KN/m^2
Floor Finish, FF = 1 KN/m^2



Dimensions of Slab & Beam:-
Adopt thickness of slab = 100 mm

$$\text{Depth of Rib} = \frac{Span}{26} = \frac{15000}{26} = 580 \text{ mm}$$

Width of Rib = 150 mm
Number of beams in X – Direction, Nx = 6
Number of beams in Y – Direction, Ny = 11
E = 5000√20 × 1000 = 5000 × √20 × 1000
E = 22.36 × 10^6

Load Calculation:-
Total weight of slab = 25 × Df × Lx × Ly
= 25 × 0.10 × 7.5 × 15 = 281.25 KN
Total weight of beams in X – Direction = 25 × bw × D × Nx × Lx = 25 × 0.150 × 0.580 × 6 × 7.5 = 97.88 KN
Total weight of beams in Y – Direction = 25 × bw × D × Ny × (Ly – (bw × Nx))
= 25 × 0.15 × 0.25 × 11 × (15 – (0.15 × 6)) = 337.34 KN
Total Live Load, LL = LL × Lx × Ly = 4 × 7.5 × 15 = 450 KN
Total Floor Finish, FF = FF × Lx × Ly = 1 × 7.5 × 15 = 112.5 KN
Total Load = 281.25 + 97.88 + 337.34 + 450 + 112.5 = 1278.97 KN

$$\text{Total Load / } m^2 = q = \frac{1278.97}{7.5 \times 15} = 11.37 \text{ KN/m}^2$$

Total Factored load / m^2 = Q = 1.5 × q = 1.5 × 11.37 =17.05 KN/m^2

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Design Parameters:-

$\frac{Df}{D} = \frac{100}{580} = 0.17$

$\frac{bf}{bw} = \frac{1500}{150} = 10$

Moment of Inertia:-

$I = \frac{Kx \times bw \times D^3}{12} = \frac{2.3 \times 150 \times 580^3}{12}$ … (Kx = 2.3, SP - 16, Tb. – 88)

$I = 5.60 \times 10^9\ mm^4 = 5.61 \times 10^{-3}\ m^4$

Flexural Rigidity of Ribs:-

$Dx = \frac{E \times I}{a1} = \frac{22.36 \times 10^6 \times 5.60 \times 10^9}{1500} = 8.35 \times 10^{13}$

$Dy = \frac{E \times I}{b1} = \frac{22.36 \times 10^6 \times 5.60 \times 10^9}{1500} = 8.35 \times 10^{13}$

Modulus of Shear:-

$G = \frac{E}{2(1+\mu)} = \frac{22.36 \times 10^6}{2(1+0.15)}$ … (μ = 0.15 → assume) $= 9.72 \times 10^6$

Torsional Constants (Polar Sectional Modulus):-

$C1 = 1 - 0.63\left(\frac{bw}{d}\right)\left(bw^3 \times \left(\frac{D}{3}\right)\right) = 1 - 0.63\left(\frac{150}{580}\right)\left(150^3 \times \left(\frac{580}{3}\right)\right) = 5.46 \times 10^{-4}\ m^3$

$C2 = 1 - 0.63\left(\frac{bw}{D}\right)\left(D^3 \times \left(\frac{bw}{3}\right)\right) = 1 - 0.63\left(\frac{150}{580}\right)\left(580^3 \times \left(\frac{150}{3}\right)\right) = 8.17 \times 10^{-3}\ m^3$

Torsional Rigidity:-

$Cx = \frac{G \times C1}{b1} = \frac{9.72 \times 10^6 \times 5.46 \times 10^{-4}}{1.5} = 3.54 \times 10^3$

$Cy = \frac{G \times C2}{a1} = \frac{9.72 \times 10^6 \times 8.17 \times 10^{-3}}{1.5} = 5.29 \times 10^4$

$\therefore 2H = Cx + Cy = (3.54 \times 10^3) + (5.29 \times 10^4) = 5.65 \times 10^4$

$\frac{Dx}{Lx^4} = \frac{8.36 \times 10^4}{7.5^4} = 26.43$

$\frac{Dy}{Ly^4} = \frac{8.36 \times 10^4}{15^4} = 1.65$

$\frac{2H}{Lx^2 \times Ly^2} = \frac{5.65 \times 10^4}{7.5^2 \times 15^2} = 4.46$

Deflection Check:-

$\omega = \frac{16 \times \left(\frac{Q}{\pi}\right)}{\frac{Dx}{Lx^4}} + \left(\frac{2H}{Lx \times Ly^2}\right) + \left(\frac{Dy}{Ly^4}\right) = \left(\frac{16 \times \left(\frac{17.05}{\pi}\right)}{26.43}\right) + 4.46 + 1.65 = 8.72\ mm$

Long Term Deflection:-

Lt defl. = 3 × ω = 3 × 8.72 = 26.16 mm

$\frac{Span}{250} = \frac{7500}{250} = 30\ mm$

$\therefore$ Lt defl. $< \frac{Span}{250}$

$\therefore$ Safe.

Maximum Moment and Shear Values:-

$Mx = D \times \times \left(\frac{\pi}{L\times}\right)^2 \times \omega = 8.64 \times 10^4 \times \left(\frac{\pi}{7.5}\right)^2 \times 8.72 = 128$ KN-m

$My = Dy \times \left(\frac{\pi}{Ly}\right)^2 \times \omega = 8.36 \times 10^4 \times \left(\frac{\pi}{15}\right)^2 \times 8.72 = 32$ KN-m

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Maximum Torsional Moment:-

$$Mxy = \frac{C\times \times \pi^2 \times \omega}{Lx \times Ly} = \frac{3.54 \times 10^3 \times \pi^2 \times 8.72}{7.5 \times 15} = 3 \text{ KN-m}$$

Shear Force:-

$$Qx = \left(\left(D \times \times \left(\frac{\pi}{Lx}\right)^3\right) + \left(Cy \times \left(\frac{\pi^3}{a1 \times b1^2}\right)\right)\right) \times \omega$$

$$= \left(\left(8.36 \times 10^4 \times \left(\frac{\pi}{7.5}\right)^3\right) + \left(5.29 \times 10^4 \times \left(\frac{\pi^3}{1.5 \times 1.5^2}\right)\right)\right) \times 8.72 = 54 \text{ KN}$$

$$Qy = \left(\left(Dy \times \left(\frac{\pi}{Ly}\right)^3\right) + \left(C \times \times \left(\frac{\pi^3}{a1^2 \times b1}\right)\right)\right) \times \omega$$

$$= \left(\left(8.36 \times 10^4 \times \left(\frac{\pi}{15}\right)^3\right) + \left(3.54 \times 10^3 \times \left(\frac{\pi^3}{1.5^2 \times 1.5}\right)\right)\right) \times 8.72 = 8 \text{ KN}$$

Reinforcement Details:-

For X – Direction,

Mu = 128 KN-m, b= 150 mm, d = 550mm

$$Astx = \frac{0.5 \times fck}{Fy} \times \left(1 - \sqrt{1 - \left(\frac{4.6Mu}{fck.b.d^2}\right)}\right) \times b \times d$$

$$= \frac{0.5\times 20}{415} \times \left(1 - \sqrt{1 - \left(\frac{4.6 \times 128 \times 10^6}{20 \times 150 \times 550^2}\right)}\right) \times 150 \times 550$$

∴ Astx = 810 mm^2

Use 16 mm Ø bars.

∴ Provide 4 bars of 16 mm Ø.

For Y – Direction,

Mu = 32 KN-m, b = 150 mm, d = 550 mm

$$Asty = \frac{0.5 \times fck}{Fy} \times \left(1 - \sqrt{1 - \left(\frac{4.6Mu}{fck.b.d^2}\right)}\right) \times b \times d$$

$$= \frac{0.5 \times 20}{415} \times \left(1 - \sqrt{1 - \left(\frac{4.6 \times 32 \times 10^6}{20 \times 150 \times 550^2}\right)}\right) \times 150 \times 550$$

∴ Asty = 168.36 mm^2

Use 10 mm Ø bars.

∴ Provide 3 bars of 10 mm Ø.

Provide minimum steel in slab portion i.e. flange of waffle slab.

$$\text{Ast min.} = \left(\frac{0.12}{100} \times b \times d\right) = \left(\frac{0.12}{100} \times 1000 \times 100\right)$$

Ast min. = 120 mm^2

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X. DESIGN SUMMARY

	Size (m)	Slab Thickness (mm)	Deflection (mm)	Total Ast (mm^2)	Max. Moment (KN-m)	Max. Shear (KN)	Factored Load ($\frac{KN}{m^2}$)	Economy & Construction	Uses
Waffle Slab	7.5 × 7.5	100	7.65	1118.58	56	25	15.15	Economical for repetitive works, requires more time for construction as compared to RCC slabs.	Suitable for large loads, large spans, repetitive works, aesthetic appearance, etc.
Waffle Slab	15 × 7.5	100	8.72	1160	128	54	17.05	Economical for large spans and repetitive works, skilled labors required, aesthetically more useful structures, no need of finishing in various cases	. Suitable for large loads, large spans, repetitive works, aesthetic appearance, etc.
Flat Slab	7.5 × 7.5	315	22.9	9010.5	284.11	1170.84	23.81	Suitable for medium spans, beam-less construction, difficulty while construction pods and post-tensioning, complicated designs	Beam-less construction, aesthetics, less complication while construction
Flat Slab	15 × 7.5	600	-	-	-	-	-	Not for large spans, Suitable for medium spans, beam-less construction, difficulty while construction pods and post-tensioning, complicated designs	Beam-less construction, aesthetics, less complication while construction & suitable for medium spans
Conventional RCC Slab	7.5 × 7.5	260	31.25	1894	43.62	61.26	16.5	Suitable for short spans, most easiest way of construction, skilled labors not required, can be constructed in rural areas very easily.	Easiest way of construction, less complicated designs, residential buildings, etc.

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XII. CONCLUSION

From the following paper with the help of the case study, we conclude that waffle slabs are more advantageous as compared to other slabs such as flat slabs and RCC slabs, in terms of loading, large spans, aesthetic appearance, etc.

XIII. REFERENCE

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