Minimum Slab Thickness of Two-way Edge-supported Slabs

As specified by ACI Code 9.5.3.3 and 9.5.3.2, for slabs with beams spanning between the supports on all sides, the minimum thickness shall be as follows:

a. For \( f_{\text{m}} \) equal to or less than 0.20, minimum slab thickness is determined from provisions on slabs without interior beams spanning between the supports, shown in Table (5), but not less than:
   - Slabs without drop panels: 12.5 cm
   - Slabs with drop panels: 10.0 cm

**Table (5): Minimum thickness of slabs without interior beams**

<table>
<thead>
<tr>
<th>Without drop panels</th>
<th>With drop panels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without edge beams</td>
<td>With edge beams</td>
</tr>
<tr>
<td>( l_n / 33^* )</td>
<td>( l_n / 36^* )</td>
</tr>
<tr>
<td>( l_n / 30^{**} )</td>
<td>( l_n / 33^{**} )</td>
</tr>
<tr>
<td>( l_n / 28^{***} )</td>
<td>( l_n / 31^{***} )</td>
</tr>
<tr>
<td>Without edge beams</td>
<td>With edge beams</td>
</tr>
<tr>
<td>( l_n / 36^* )</td>
<td>( l_n / 40^* )</td>
</tr>
<tr>
<td>( l_n / 33^{**} )</td>
<td>( l_n / 36^{**} )</td>
</tr>
<tr>
<td>( l_n / 31^{***} )</td>
<td>( l_n / 34^{***} )</td>
</tr>
</tbody>
</table>

* \( f_y = 2800 \text{ kg/cm}^2 \)
** \( f_y = 4200 \text{ kg/cm}^2 \)
*** \( f_y = 5200 \text{ kg/cm}^2 \)

In Table (5), \( l_n \) is the length of clear span in the long direction measured face-to-face of supports in slabs without beams and face-to-face of beams or other supports in other cases.

For \( f_y \) between the values given in the table, minimum thickness is determined by linear interpolation. Moreover, for slabs with beams between columns along exterior edges, the value of \( \alpha_f \) for the edge beam is not to be less than 0.80.

b. For \( f_{\text{m}} \) greater than 0.20 but not greater than 2.0, the thickness shall not be less than
\[ h = \frac{l_n \left(0.80 + \frac{f_y}{14000}\right)}{36 + 5 \beta (\alpha_{fm} - 0.20)} \geq 12.5 \text{ cm} \]  

(10)

c. For \(\alpha_{fm}\) greater than 2.0, the thickness shall not be less than

\[ h = \frac{l_n \left(0.80 + \frac{f_y}{14000}\right)}{36 + 9 \beta} \geq 9 \text{ cm} \]  

(11)

d. At discontinuous edges, an edge beam shall be provided with a stiffness ratio \(\alpha_f\) not less than 0.80 or the minimum thickness required by Eqn. (10) or Eqn. (11) shall be increased by at least 10\% in the panel with a discontinuous edge.

where

- \(h\) = overall thickness of slab
- \(\alpha_f\) = ratio of flexural stiffness of beam section to flexural stiffness of a width of slab bounded laterally by centerlines of adjacent panels, if any, on each side of beam determined analytically as follows:
  \[ \alpha_f = \frac{E_{cb} I_b}{E_{cs} I_s} \]
  - \(E_{cb}\) = modulus of elasticity of beam concrete
  - \(E_{cs}\) = modulus of elasticity of slab concrete
  - \(I_b\) = moment of inertia about centroidal axis of gross section of beam
  - \(I_s\) = moment of inertia about centroidal axis of gross section of slab

Another way of determining \(\alpha_f\) is graphically, using Figures 5 and 6.

\(\alpha_{fm}\) = average value of \(\alpha_f\) for all beams on edgs of a panel

\(\beta\) = ratio of clear spans in long to short direction of slab.
Figure 5: Beam Stiffness (Interior Beams)
ACI Code 318-89 (Revised 92) included three different equations for determination of minimum slab thickness. Two of those equations will be given here for their simplicity, as they require no prior evaluation of $\alpha$. The smallest thickness $h_{\text{min}}$ is given as

$$h_{\text{min}} = \frac{(ba^3/12)f}{b/(a-h)} \leq b+4h$$
The largest thickness $h_{\text{max}}$ is given as

$$h_{\text{max}} = \frac{l_n (0.80 + f_y/14000)}{36 + 5\beta (1 + \beta_y)} \quad (13)$$

where $\beta_y = \text{ratio of length of the continuous edges to the total perimeter of the panel.}$

**Summary of Design Procedure for Two-way Edge-supported Solid Slabs Using the Simplified Methods**

Once design compressive strength of concrete and yield stress of reinforcement are specified, the next steps are followed:

1. Slab thickness is evaluated based on deflection control requirement.
2. The total factored load supported by the slab is calculated. The dead load includes own weight of the slab in addition to the covering materials it supports. The live load is dependent on the intended use of the slab.
3. The loads distributed in the short and long directions of each panel are determined as discussed in earlier sections.
4. Representative 1 $m$ wide design strips to span in the short and long directions are selected.
5. The shearing force and bending moment diagrams for each of the strips are drawn.
6. Strength of each of the strips in shear is checked.
7. Design the reinforcement at critical negative and positive bending moment sections for each of the strips. Reinforcement in the short direction is placed closest to the concrete surface in order to increase the effective depth $d$ in this direction.
8. Prepare design drawings showing the dimensions and the provided reinforcement.

**Example (1):**

Using the Grashoff coefficients design the simply supported solid slab shown in Figure 7.a. Assume that the beam webs are 25 $cm$ wide. Weight of flooring materials is 200 $kg/m^2$, and the live load is 500 $kg/m^2$. Use $f_c' = 250 \text{ kg/cm}^2$, $f_y = 4200 \text{ kg/cm}^2$. 

$$h_{\text{min}} = \frac{l_n (0.80 + f_y/14000)}{36 + 5\beta (1 + \beta_y)} \quad (12)$$
Solution:

1- Evaluate Slab thickness:

\( l_n = 5.0 - 0.25 = 4.75 \text{ m} \)

Since \( r = 5/4 = 1.25 < 2.0 \), the slab is classified as being two way.

The smallest slab thickness is given by

\[
\begin{align*}
    h_{\text{min}} &= \frac{l_n \left( 0.80 + f_y / 14000 \right)}{36 + 5 \beta (1 + \beta)} \\
    &= \frac{475 \left( 0.80 + 4200 / 14000 \right)}{36 + 5 (4.75 / 3.75)(1 + 0)} = 12.34 \text{ cm}
\end{align*}
\]

The largest slab thickness is given by

\[
\begin{align*}
    h_{\text{max}} &= \frac{l_n \left( 0.80 + f_y / 14000 \right)}{36} \\
    &= \frac{475 \left( 0.80 + 4200 / 14000 \right)}{36} = 14.51 \text{ cm}
\end{align*}
\]

Slab thickness will be taken as 14.0 cm.

2- Determine the total factored load per unit area of the slab:

Own weight of slab = 0.14 \times 2.50 = 0.35 \text{ ton/m}^2

\( w_u = 1.20 \left( 0.35 + 0.20 \right) + 1.60 (0.50) = 1.46 \text{ ton/m}^2 \)

3- Evaluate load distribution in both directions:

Rectangularity ratio \( r = 5/4 = 1.25 \)

Using Grashoff coefficients, \( \alpha = 0.71 \), and \( \beta = 0.29 \).
Load in the short direction \( w_s = 0.71 \cdot (1.46) = 1.03 \, t/m^2 \)

For a strip 1 m wide, \( w_s = 1.03 \, \text{ton/m} \)

Load in the long direction \( w_l = 0.29 \cdot (1.46) = 0.42 \, t/m^2 \)

For a strip 1 m wide, \( w_l = 0.42 \, \text{ton/m} \)

4- Select representative 1 m wide design strips to span in the short and long directions:

Two strips are used, one in the short direction and the other in the long direction.

5- Evaluate shear and bending moment at critical section locations:

Maximum shear force in the short direction \( V_{u, max} = 1.03 \cdot (4/2) = 2.06 \, \text{ton} \)

Maximum shear force in the long direction \( V_{u, max} = 0.42 \cdot (5/2) = 1.05 \, \text{ton} \)

Maximum moment in the short direction \( M_{u, max} = 1.03 \cdot (4)^2 / 8 = 2.06 \, \text{t.m} \)

Maximum moment in the long direction \( M_{u, max} = 0.42 \cdot (5)^2 / 8 = 1.31 \, \text{t.m} \)

6- Check slab thickness for beam shear:

a. Short Direction:

Average effective depth \( d = 14 - 2 - 1.2 = 10.8 \, \text{cm} \), assuming \( \Phi 12 \) mm bars in both directions.

\( \Phi \ V_c = 0.75 \cdot (0.53) \sqrt{250 \cdot (100) \cdot (10.80)} / 1000 = 6.79 \, \text{ton} \)

i.e., slab thickness is adequate in terms of resisting beam shear in the shorter direction.

b. Long direction:

\( V_{u, max} < \Phi V_c \)

i.e., slab thickness is adequate in terms of resisting beam shear in the longer direction.

7- Design the reinforcement:

a. Short direction:

\[
\rho = \frac{0.85 \cdot (250)}{4200} \left[ 1 - \sqrt{1 - \frac{2.353 \times 10^5 \cdot (2.06)}{(0.9)100 \cdot (10.8)^2 \cdot (250)}} \right] = 0.0049
\]
Area of flexural reinforcement  \( A_f = 0.0049 \times 100 \times 10.8 = 5.29 \, \text{cm}^2/m \)

Use \( \phi \, 12 \, \text{mm} \) @ 20 cm at the bottom side of the slab.

For main reinforcement, spacing between bars is not to exceed the smaller of 3(14) = 42 cm and 45 cm, which is already satisfied.

b. Long direction:

\[
\rho = \frac{0.85(250)}{4200} \left[ 1 - \sqrt{1 - \frac{2.6353 \times 10^2 \times (1.31)}{(0.9)100 \times (10.8)^2 \times 250}} \right] = 0.003
\]

Area of flexural reinforcement  \( A_f = 0.003 \times 100 \times 10.8 = 3.24 \, \text{cm}^2/m \)

Use \( \phi \, 12 \, \text{mm} \) @ 30 cm on top of the short direction reinforcement.

Design of beam B1:

\( h_{\text{min}} = l/16 = 500/16 = 31.25 \, \text{cm} \)

Try 25 cm \( \times \) 50 cm cross section.

Factored own weight of beam = 1.2 \( \times \) (0.25) \( \times \) (0.5) \( \times \) (2.5) = 0.375 t/m

Maximum factored moment due to own weight of beam

\[
= 0.375 \times (5)^2 / 8 = 1.172 \, \text{t.m}
\]

Maximum factored shear due to own weight of beam = 0.375 \( \times \) 5 / 2 = 0.937 ton

Loads from the slab, shown in Figure 7.c:

\( w' = w_{u}(S/2) = 1.46 \times (4/2) = 2.92 \, \text{t/m} \)

Equivalent load due to shear = 2.92 \( \left[ 1 - \frac{1}{2(1.25)} \right] \) = 1.752 t/m

Equivalent load due to moment = 2.92 \( \left[ 1 - \frac{1}{3(1.25)^2} \right] \) = 2.297 t/m

Maximum factored shear = 1.752 \( \times \) 5 / 2 = 4.38 ton

Maximum factored moment = 2.297 \( \times \) 5 / 8 = 7.178 t.m

Total factored shear = 0.937 + 4.38 = 5.317 ton
Total factored moment = 1.172 + 7.178 = 8.35 ton.m

Assuming that φ 8 mm stirrups and φ 12 mm reinforcing bars are used,

\[ d = 50 - 4.0 - 0.80 - 0.60 = 44.6 \text{ cm} \]

\[ \rho = \frac{0.85 (250)}{4200} \left[ 1 - \sqrt{1 - \frac{2.353 \times 10^5 (8.35)}{(0.9) 25 (44.6)^2 (250)}} \right] = 0.0046 \]

\[ A_s = 0.0046 \times (25)(44.6) = 5.13 \text{ cm}^2 \text{, use 4 φ 14 mm bars.} \]

Check section for shear:

\[ \Phi \ V_c = 0.75 (0.53) \sqrt{250 (25)(44.6)} / 1000 = 7.0 \text{ ton} \]

Use φ 8 mm @ 20 cm as minimum shear reinforcement.

See Figure 7.c for reinforcement details.

Design of beam B2:

\[ h_{\text{min}} = l / 16 = 400 / 16 = 25.0 \text{ cm} \]

Try 25 cm × 50 cm cross section.

Factored own weight of beam = 1.2 (0.25) (0.5) (2.5) = 0.375 t/m

Maximum factored moment due to own weight of beam
Maximum factored shear due to own weight of beam
\[ = 0.375 \times (4)^2 / 8 = 0.75 \text{ t.m} \]

Loads from the slab, shown in Figure 7.e:

Equivalent load due to shear = \[ 2.92 / 2 = 1.46 \text{ t/m} \]
Equivalent load due to moment = \[ 2.92 \times (2/3) = 1.95 \text{ t/m} \]
Maximum factored shear = \[ 1.46 \times (4) / 2 = 2.92 \text{ ton} \]

Maximum factored moment = \[ 1.95 \times (4)^2 / 8 = 3.90 \text{ t.m} \]

Total factored shear = \[ 0.75 + 2.92 = 3.67 \text{ ton} \]
Total factored moment = \[ 0.75 + 3.90 = 4.65 \text{ t.m} \]

Assuming that \( \phi = 8 \text{ mm} \) stirrups and \( \phi = 12 \text{ mm} \) reinforcing bars are used,

\[ d = 50 - 4.0 - 0.80 - 0.60 = 44.6 \text{ cm} \]

\[ \rho = \frac{0.85 \times 250}{4200} \left[ 1 - \sqrt{1 - \frac{2.353 \times 10^5 \times (4.65)}{(0.9) 25 (44.6)^2}} \right] = 0.00254 < \rho_{\text{min}} \]

\[ A_t = 0.0033 \times 25 \times 44.6 = 3.68 \text{ cm}^2 \], use 4 \( \phi = 12 \text{ mm} \) bars.

Check section for shear:

\[ \Phi V_c = 0.75 \times (0.53) \sqrt{250 \times (25) (44.6) / 1000} = 7.0 \text{ ton} \]

Use \( \phi = 8 \text{ mm} \) @ 20 cm as minimum shear reinforcement.

See Figure 7.g for reinforcement details.

8- Prepare design drawings showing the dimensions and the provided reinforcement:

Design drawings are shown in Figure 7.g.
Figure 7: (continued); (e) equivalent loads on beam B2; (f) beam reinforcement details; (g) slab reinforcement details

Example (2):
Design the two-way solid slab shown in Figure 8.a. The covering materials weigh 258 kg/m², and the live load is 300 kg/m². Also, calculate the factored load acting on beam C3-C7-C11-C15 due to slab loads. Use $f' = 250$ kg/cm² and $f_y = 4200$ kg/cm². All beams are 25 cm wide.
Solution:

1- Evaluate Slab thickness:

The largest slab thickness is given by

\[
h_{\text{max}} = \frac{l_n (0.80 + f_y / 14000)}{36}
\]

\[
= \frac{475 (0.80 + 4200 / 14000)}{36} = 14.51 \text{ cm}
\]

Use a slab thickness of 14.0 cm.

2- Determine the total factored load per unit area of the slab:

\[
w_f = 1.2 \left[ 0.14 (2.5) + 0.258 \right] + 1.6 (0.30) = 1.21 \text{ t/m}^2
\]

3- Evaluate load distribution in both directions:

Load distributions, shown in Figure 8.b, are based on Egyptian code load coefficient given in Table (3).
For panels S1, S2 and S8:

\[ r' = \frac{5.0 (0.87)}{4.0 (0.87)} = 1.25, \alpha = 0.475 \text{ and } \beta = 0.230. \]

For panels S3 and S6:

\[ r' = \frac{4.0 (0.87)}{3.0 (0.87)} = 1.33, \alpha = 0.517 \text{ and } \beta = 0.190. \]

For panel S4:

\[ r' = \frac{5.0 (0.76)}{4.0 (0.76)} = 1.25, \alpha = 0.475 \text{ and } \beta = 0.230. \]

For panel S5:

\[ r' = \frac{5.0 (0.87)}{4.0 (0.76)} = 1.43, \alpha = 0.565 \text{ and } \beta = 0.174. \]

For panel S7:
\[ r' = \frac{5.0 \times (0.76)}{4.0 \times (0.87)} = 1.092, \alpha = 0.396 \text{ and } \beta = 0.295. \]

4- Select representative 1 m wide design strips to span in the short and long directions:

Six design strips are used, three in the short direction and three in the long direction.

Evaluate shear and bending moment at critical section locations:

Shear force and bending moment diagrams for each of the six strips are shown in Figures 8.c through 8.h.

\[ d_{\text{avg}} = 14 - 2 - 1.2 = 10.8 \text{ cm}, \] assuming \( \phi 12 \text{ mm} \) reinforcing bars.

5- Check slab thickness for shear:

\[ \Phi V_c = (0.75)(0.53)\sqrt{250}(100)(10.8)/1000 = 6.79 \text{ ton O.K} \]

6- Design the reinforcement:

Strip 1-1:

For \( M_u = -0.87 \text{ t.m} \)

\[
\rho = \frac{0.85(250)}{4200} \left[ 1 - \sqrt{1 - \frac{2.353 \times 10^5 (0.87)}{(0.9)(100)(10.8)^2 (250)}} \right] = 0.002
\]

\[ A_y = 0.002(100)(10.8) = 2.16 \text{ cm}^2/\text{m} \]

\[ A_{\chi_{\text{min}}} = 0.0018(100)(14.0) = 2.52 \text{ cm}^2/\text{m}, \] use \( \phi \text{ mm} @ 30 \text{ cm} \).

\[
0.278 \text{ t/m} \\
\begin{align*}
\text{SFD} & \quad \begin{align*}
0.52 \text{ t} & \quad 0.87 \text{ m} \\
0.87 \text{ t} & \quad 0.87 \text{ t.m}
\end{align*} \\
\text{BMD} & \quad \begin{align*}
0.49 \text{ m} & \quad 0.49 \text{ t.m}
\end{align*}
\end{align*}
\]

Figure 8.c: S.F.D and B.M.D for strip 1-1
For $M_u = 0.49 \, t.m$

$A_{x_{min}} = 0.0018 \times (100) \times (14.0) = 2.52 \, cm^2/m$, use $\phi \, 10 \, mm @ 30 \, cm.$

Strip 2-2:

Figure 8.d: S.F.D and B.M.D for strip 2-2

For $M_u = -0.62 \, t.m$

$A_{x_{min}} = 0.0018 \times (100) \times (14.0) = 2.52 \, cm^2/m$, use $\phi \, 10 \, mm @ 30 \, cm.$

For $M_u = 0.43 \, t.m$

$A_{x_{min}} = 0.0018 \times (100) \times (14.0) = 2.52 \, cm^2/m$, use $\phi \, 10 \, mm @ 30 \, cm.$

Strip 3-3:
For $M_u = -0.82 \text{ t.m}$

$$\rho = \frac{0.85(250)}{4200} \left[ 1 - \sqrt{1 - \frac{2.353 \times 10^5 (0.82)}{(0.9)(100)(10.8)^2 (250)}} \right] = 0.00189$$

$A_{x_{\min}} = 0.0018 (100)(14.0) = 2.52 \text{ cm}^2 / \text{m}$, use $\phi 10 \text{ mm} @ 30 \text{ cm}$.

For $M_u = 0.51 \text{ t.m}$

$A_{x_{\min}} = 0.0018 (100)(14.0) = 2.52 \text{ cm}^2 / \text{m}$, use $\phi 10 \text{ mm} @ 30 \text{ cm}$.

**Strip 4-4:**

For $M_u = -0.46 \text{ t.m}$

$A_{x_{\min}} = 0.0018 (100)(14.0) = 2.52 \text{ cm}^2 / \text{m}$, use $\phi 10 \text{ mm} @ 30 \text{ cm}$.

For $M_u = 0.26 \text{ t.m}$
Figure 8.f: S.F.D and B.M.D for strip 4-4

\[ A_{t, \text{min}} = 0.0018 \times 100 \times 14.0 = 2.52 \text{ cm}^2 / m, \text{ use } 10 \text{ mm @ 30 cm.} \]

Strip 5-5:

For \( M_u = -0.95 \text{ t.m} \)

\[ \rho = \frac{0.85 \times 250}{4200} \left[ 1 - \sqrt{1 - \frac{2.35 \times 10^{-5} \times 0.95}{(0.9)(100)(10.8)^2(250)}} \right] = 0.0022 \]

\[ A_{t, \text{min}} = 0.0018 \times 100 \times 14.0 = 2.52 \text{ cm}^2 / m, \text{ use } 10 \text{ mm @ 30 cm.} \]
For $M_u = 0.73 \, t.m$

$A_{\chi_{\text{min}}} = 0.0018 \, (100) \, (14.0) = 2.52 \, cm^2/m$, use $\phi 10 \, mm \, @ \, 30 \, cm$.

**Strip 6-6:**

![SFD and BMD diagram for strip 6-6](image)

**Figure 8.h: S.F.D and B.M.D for strip 6-6**

For $M_u = -1.01 \, t.m$

$$
\rho = \frac{0.85 \, (250)}{4200} \left[ 1 - \sqrt{1 - \frac{2.6353 \times 10^5 \, (1.01)}{(0.9)(100)(10.8)^2 \, (250)}} \right] = 0.00234
$$

$A_v = 0.00234 \, (100) \, (10.8) = 2.53 \, cm^2/m$

$A_{\chi_{\text{min}}} = 0.0018 \, (100) \, (14.0) = 2.52 \, cm^2/m$, use $\phi 10 \, mm \, @ \, 30 \, cm$.

For $M_u = 0.70 \, t.m$

$A_{\chi_{\text{min}}} = 0.0018 \, (100) \, (14.0) = 2.52 \, cm^2/m$, use $\phi 10 \, mm \, @ \, 30 \, cm$.

**7- Prepare design drawings showing the dimensions and the provided reinforcement:**

Design drawings are shown in Figure 8.i.
Load on beam C3-C7-C11-C15:

\[ w_u = 1.21 \left( \frac{4}{2} \right) (2) = 4.84 \, \text{t/m} \], as shown in Figure 8.j.

Summary of Design Procedure for Two-way Edge-supported Ribbed Slabs, Using the Simplified Methods

Once design compressive strength of concrete and yield stress of reinforcement are specified, the next steps are followed:
1. Determine the overall slab thickness $h$ based on deflection control requirement. Also, thickness of topping slab $t$, rib width $b$, and hollow block size are to be determined based on code requirements.

2. Calculate the total factored load per unit area.

3. Distribute the loads in the short and long directions of each panel, as discussed in earlier sections.

4. Select representative design strips to span in the short and long directions. The width of each of these strips is equal to center-to-center spacing between ribs in each of the two directions.

5. Draw shearing force and bending moment diagrams for each of the strips.

6. Check rib width for beam shear in the two directions.

7. Design the reinforcement at critical negative and positive bending moment sections of the ribs in each of the two directions. Reinforcement in the short direction is placed closest to the concrete surface in order to increase the effective depth $d$ in this direction.

8. Prepare design drawings showing arrangement of ribs and details of the reinforcement.

**Example (3):**

Design the two-way ribbed slab shown in Figure 9.a. The covering materials weigh 150 kg/m$^2$, equivalent partition load is equal to 73 kg/m$^2$, concrete hollow blocks are 40 cm $\times$ 25 cm $\times$ 17 cm in dimension, each 17 kg in weight and the live load is 400 kg/m$^2$. Use $f'_c = 300$ kg/cm$^2$, $f_y = 4200$ kg/cm$^2$. All beams are 30 cm wide.
**Solution:**

1- **Evaluate overall slab thickness and key ribbed slab components:**

The smallest slab thickness is given by

\[
h_{\text{min}} = \frac{l_n (0.80 + f_s / 14000)}{36 + 5 \beta (1 + \beta_s)} = \frac{770 (0.80 + 4200/14000)}{36 + 5(1.0)(1.5)} = 19.47 \text{ cm}
\]

The largest slab thickness is given by

\[
h_{\text{max}} = \frac{l_n (0.80 + f_s / 14000)}{36} = \frac{770 (0.80 + 4200/14000)}{36} = 23.53 \text{ cm}
\]

Use an overall slab thickness of 23.0 cm.

Topping slab thickness = 23 – 17 = 6 cm

Let width of web be equal to 12 cm

Area of shrinkage reinforcement \( A_s = 0.0018(100)(6) = 1.08 \text{ cm}^2/m \)

Use 5 φ 6 mm/m in both directions.

2- **Determine the total factored load on the slab:**

Load per rib, shown in Figure 9.b:
Total volume (hatched) = $0.52 \times 0.62 \times 0.23 = 0.074152 \text{ m}^3$
Volume of hollow blocks = $0.4 \times 0.17 \times 0.5 = 0.034 \text{ m}^3$
Net concrete volume = $0.074152 - 0.034 = 0.040152 \text{ m}^3$
Weight of concrete /m$^2$ = $0.040152 (2.5) / (0.52) (0.62) = 0.311 \text{ ton/ m}^2$
Weight of hollow blocks /m$^2$ = $17 (2) / (0.52) (0.62) (1000) = 0.105 \text{ ton/ m}^2$

\[ w_u = 1.20 (0.311 + 0.105 + 0.073 + 0.15) + 1.60 (0.40) = 1.407 \text{ ton / m}^2 \]

**Figure 9.b:** Loads per rib

3- **Determine load distributions in the two principal directions:**

Load distribution according to *Egyptian Code* coefficients:

\[ r = (8 \times 0.87) / (8 \times 0.87) = 1.0 \]
\[ \alpha = \beta = 0.35 \]
\[ w_1 = w_2 = 0.35 (1.407) = 0.492 \text{ t / m}^2 \]

Load per rib in the first direction:

\[ w_u / rib = 0.492 (62/100) = 0.305 \text{ t/m} \]

Load per rib in the second direction:

\[ w_u / rib = 0.492 (52/100) = 0.256 \text{ t/m} \]

4- **Select representative design strips in the two principal directions:**

One design strips is selected (with the larger loads).

5- **Draw shear force and bending moment diagrams:**
Analyzing the strip shown in Figure 9.c using the BENARI structural analysis software, one gets the shown shear force and bending moment diagrams.

Figure 9.c: Internal forces

6- Check web width for beam shear:
For reinforcement in the first direction (the closest to the outside surface of concrete):

Effective depth \( d = 23 - 2 - 0.60 - 0.8 = 19.6 \text{ cm} \), assuming \( \phi \) 16 mm reinforcing bars and \( \phi \) 6 mm stirrups.

\[
1.1 \Phi \ V_c = 1.1 \ (0.75) (0.53) \sqrt{300} \ (12) \ (19.6) / 1000 = 1.78 \text{ ton} > V_u
\]

Though shear reinforcement is not required, 4\( \phi \) 6 mm U-stirrups per meter run are to be used to carry the bottom flexural reinforcement.

7- Design rib reinforcement:
Positive moment reinforcement:
Assuming that \( a < 6 \text{ cm} \), compressive force in concrete is:

\[
C = 0.85 \ (f'_c) (b_e) (a)
\]

\[
C = 0.85 \ (300) (62) (a) / 1000 = 15.81 \text{ a ton}
\]

\[
M_u = \Phi \ M_u = \Phi \ (C) \ (d - a / 2)
\]

\[
1.37 = 0.9 (15.81 a) (19.6 - a / 2) / 100
\]
Solving this equation gives $a = 0.5 \text{ cm}$, which means that the assumption made before is valid, and the other root is too large to be considered.

From equilibrium, $C = T$

Area of flexural reinforcement

$$A_s = \frac{15.81 \times 0.50 \times 1000}{4200} = 1.88 \text{ cm}^2$$

Use 1 φ 10 mm and 1 φ 12 mm reinforcing bars in each rib.

**Negative moment reinforcement:**

Since the factored negative moment creates compression in the web, the section at corresponding location is to be designed as a rectangular section.

For $M_u = -2.44 \text{ t.m}$

$$\rho = \frac{0.85 \times 300}{4200} \left[ 1 - \sqrt{1 - \frac{2.635 \times 10^{-5} \times 2.44}{(0.9)(12)(19.6)^2(300)}} \right] = 0.0161$$

$$A_s = 0.0161 \times (12)(19.6) = 3.79 \text{ cm}^2$$, use 2 φ 16 mm per rib.

**8- Prepare design drawings:**

Figure 9.e shows required rib reinforcement and concrete dimensions.
Figure 9.e: Reinforcement layout