6. Design of Slab Bridges

6.1. Structural View

Slabs are the simplest system of superstructures and used for short bridges where the span length is about $(15\ \mathrm{m})$ or less. Generally, the slab (deck) carries the traffic and other loads are subjected to and transmits them into abutments (exterior supports) or/and piers (interior supports). Also, the slab behaves as simply supported, continuous or cantilever span depending on the supports number and locations. Both the span length (S) and main reinforcement (A_s) shall be taken parallel to traffic direction. The slab edges shall either be strengthened or designed as edge beams. The edge beams are utilized to carry the curbs, parapets, and barriers at edges but not to carry the entire slab.

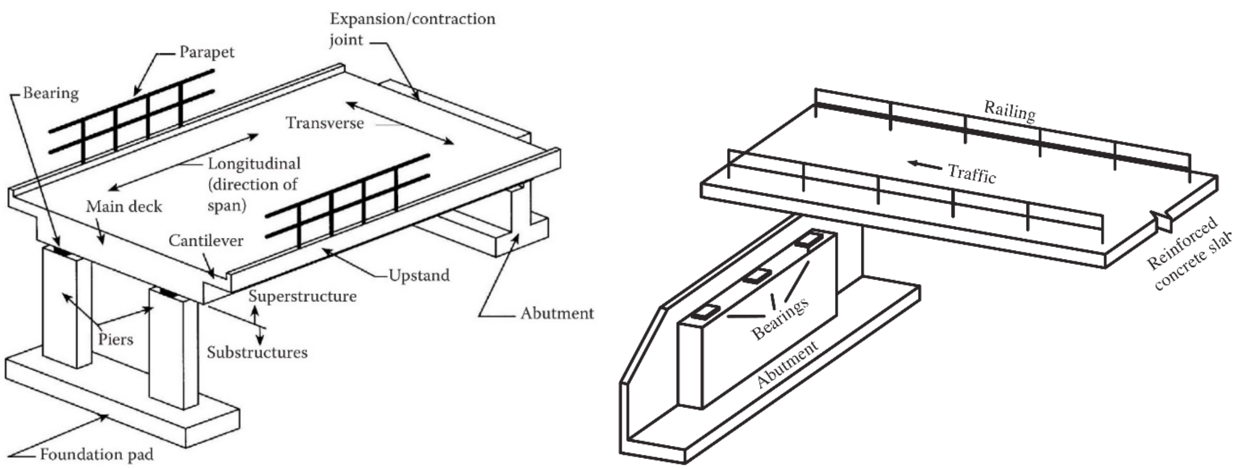

Figure 6.1: Slab Bridge Components

6.2. Design of Deck in Slab Bridges

In slab bridges, the deck slab is always designed as simple span in parallel direction to traffic. Thus, the main reinforcement of the deck is directed parallel to the traffic. For structural adequacy, the slab bridge is divided into interior strips to be designed at first and exterior strips to be designed then. The design procedure of the deck slab requires the following steps:

- Determine the minimum required slab thickness $(h_{min} \geq 165\ \mathrm{mm})$ to control deflection.
- Calculate the unfactored loads.
- Design the required main reinforcement for flexure according to Strength I Limit State and then detail all other distributed, shrinkage and temperature reinforcements.
- No need to check shear and bond stresses when the deck is designed as a slab.
- Determine the required camber from long-term deflection according to Service I limit State.
- Check fatigue stresses according to Fatigue I limit State.
- Check if the exterior strips need to be strengthened or designed as edge beam. However, beams need no distribution reinforcement but may be need stirrups to resist shear.

Example 6.1

Design the reinforced concrete slab bridge shown below using the followings:

Simple span effective length between centers of bearings $(S) = 10$ m.

Clear roadway width between the barriers $(w) = 9$ m.

Nonstructural overlay of a 50 mm thick is to be provided for the deck.

Area-wight of FWS $(q_{ws}) = 1.2$ kN/m².

Traffic barriers are 0.5 m wide at the base and weigh 7.5 kN/m each.

Flexural moment of moving tandem $(M_{Ta}) = 486$ kN.m

Fatigue moment of moving truck $(M_{fTr}) = 360$ kN.m

Specified 28-day compressive strength of concrete = 28 MPa

A706 Grade 420 reinforcement.

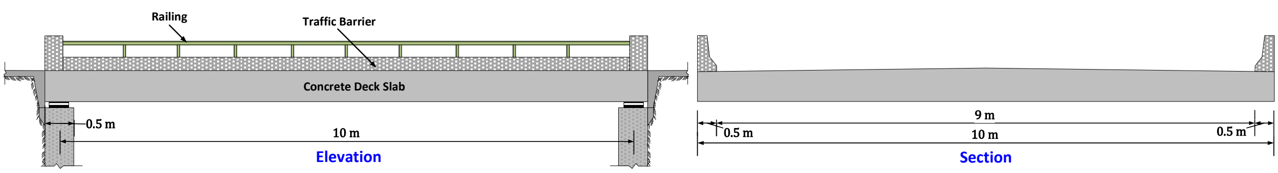

Figure 6.2: Details for the slab bridge.

Solution 6.1

Design of Interior Strip

$S = 10$ m

$h_{min} = 1.2(S + 3)/30 = 0.04(10 + 3) = 0.52$ m

use $h_d = 550$ mm

The design of the slab would be based on 1 m wide

Unfactored Loads Per Unit Width:

- Permanent loads:

$w_d = (h_d + h_{ns})b\Upsilon_c = (0.55 + 0.05)(1)(24) = 14.4$ kN/m

$w_{DC} = w_d = 14.4$ kN/m

$M_{DC} = w_{DC}L^2/8 = (14.4)(10)^2/8 = 180$ kN.m

$w_{ws} = q_{ws}b = (1.2)(1) = 1.2$ kN/m

$w_{DW} = w_{ws} = 1.2$ kN/m

$M_{DW} = w_{DW}L^2/8 = (1.2)(10)^2/8 = 15$ kN.m

- Transient loads:

$L = 10 \text{ m} < 12 \text{ m} \rightarrow M_{Mo} = M_{Ta}$

$M_{Ta} = 486$ kN.m

$w_{Ln} = 9.3$ kN/m

$M_{Ln} = w_{Ln}L^2/8 = (9.3)(10)^2/8 = 116.25$ kN. m

Equivalent strip width and distribution factor:

$N_L = \text{INT}(w/3.6) = \text{INT}(9/3.6) = 2$

$\because N_L = 2 \rightarrow \therefore$ check both E_{i1} and E_{i2}

$L_1 = L = 10$ m governs

≤ 18 m

$W_1 = W = 10$ m governs
≤ 18 m
$E_{i1} = 0.25 + 0.42\sqrt{L_1 W_1}$
$= 0.25 + 0.42\sqrt{(10)(10)} = 4.45$ m
$E_{i2} = 2.10 + 0.12\sqrt{L_1 W_1}$
$= 2.10 + 0.12\sqrt{(10)(10)} = 3.3$ m governs
$\leq W/N_L = 10/2 = 5$ m
$\therefore E_i = 3.3$ m
$DF_{im} = 1/E_i = 1/3.3 = 0.3$

Total live load:

$IM = 0.33$
$M_{LL+IM} = [M_{Ta}(1 + IM) + M_{Ln}]DF_{im}$
$= [(486)(1.33) + 116.25](0.3) = 228.79$ kN.m

Reinforcement for Flexure:

- Main reinforcements:

$A_s = 1.25M_u/f_y d_s$
$M_{u1} = \eta_i[1.25M_{DC} + 1.50M_{DW} + 1.75M_{LL+IM}]$
$\eta_i = 1.0$
$M_{u1} = 1.25(180) + 1.50(15) + 1.75(228.79) = 647.88$ kN.m
try $\emptyset_b = 30$ in $\rightarrow A_b = 707$ mm^2
$c_B = 25$ mm
$s_{min} = 1.5\emptyset_b = 1.5(30) = 45$ mm governs
$\geq 1.5d_{ag} = 1.5(19) = 28$ mm
≥ 38 mm
$s_{max} = 1.5h = 1.5(550) = 825$ mm
$= 3h = 3(550) = 1650$ mm $[A_{sh}]$
≤ 450 mm governs
$d_s = h_d - c_B - \emptyset_b/2 = 550 - 25 - 30/2 = 510$ mm
$A_{s,req} = 1.25M_u/f_y d_s = 1.25(647.88\text{x}10^6)/[(420)(510)] = 3780.81$ mm^2
$s_{req} = A_b\text{x}10^3/A_{s,req} = 707\text{x}10^3/3780.81 = 187$ mm
use Ø30 @ 150 mm c/c parallel to traffic at bottom
$A_s = A_b\text{x}10^3/s = 707\text{x}10^3/150 = 4713.33$ mm^2
$f_c' = 28$ MPa $\rightarrow \beta_1 = 0.85$
$c = A_s f_y/0.85 f_c' \beta_1 b = (4713.33)(420)/[(0.85)(28)(0.85)(1000)] = 97.85$ mm
$\varepsilon_t = [(d_t - c)/c]\varepsilon_{cu} = [(510 - 97.85)/97.85](0.003) = 0.013 > 0.005$ ∴ OK
$a = \beta_1 c = 0.85(97.85) = 83.17$ mm
$M_n = A_s f_y(d_s - a/2) = (4713.33)(420)(510 - 83.17/2) = 927.27$ kN.m
$M_r = \phi_f M_n = 0.9(927.27) = 834.54$ kN.m $> M_u = 647.88$ kN.m ∴ OK

Check for minimum reinforcement:

$M_{cr} = \gamma_3\left[(\gamma_1 f_r + \gamma_2 f_{cpe})S_c - M_{dnc}(S_c/S_{nc} - 1)\right]$

$\gamma_3 = 0.75$

$\gamma_1 = 1.6$

$f_r = 0.62\lambda\sqrt{f_c'} = 0.62(1)\sqrt{28} = 3.28 \text{ MPa}$

$f_{cpe} = 0$ $\quad$ $[A_p = 0]$

$I_g = bh^3/12 = 1000(550)^3/12 = 13.865\text{x}10^9 \text{ mm}^4$

$y_t = h/2 = 550/2 = 275 \text{ mm}$

$S_c = S_{nc} = I_g/y_t = 13.865\text{x}10^9/275 = 50.42\text{x}10^6 \text{ mm}^3$

$M_{cr} = \gamma_3[(\gamma_1 f_r)S_c] = 1.2 f_r S_c = (1.2)(3.28)(50.42\text{x}10^6) = 198.45 \text{ kN.m}$

$1.33M_u = 1.33(647.88) = 861.68 \text{ kN.m} > M_{cr} = 198.45 \text{ kN.m}$

$M_r = 834.54 \text{ kN.m} > M_{cr} = 198.45 \text{ kN.m}$ $\quad \therefore$ OK

Check for reinforcement spacing:

$M_{s1} = M_{DC} + M_{DW} + M_{LL+IM} = 180 + 15 + 228.79 = 423.79 \text{ kN.m}$

$f_{Bs} = M_s/S_B = 423.79\text{x}10^6/50.42\text{x}10^6 = 8.41 \text{ MPa}$

$0.8f_r = 0.8(3.28) = 2.62 \text{ MPa}$

$f_{Bs} = 8.41 \text{ MPa} > 0.8f_r = 2.62 \text{ MPa}$ $\quad \therefore$ cracked section

$E_c = 4800\sqrt{f_c'} = 4800\sqrt{28} = 25.4\text{x}10^3 \text{ MPa}$

$n = E_s/E_c = 200\text{x}10^3/25.4\text{x}10^3 = 7.87$

$\rho = A_s/bd_s = 4713.33/(510\text{x}10^3) = 0.0092$

$n\rho = (7.87)(0.0092) = 0.072$

$k = \sqrt{n\rho^2 + 2n\rho} - n\rho = \sqrt{(0.072)^2 + 2(0.072)} - 0.072 = 0.314$

$j = 1 - k/3 = 1 - 0.314/3 = 0.895$

$jd = j(d_s) = (0.895)(510) = 456.45 \text{ mm}$

$f_{ss} = M_s/(A_s jd) = 423.79\text{x}10^6/[(4713.33)(456.45)] = 196.98 \text{ MPa}$

$0.6f_y = 0.6(420) = 252 \text{ MPa}$

$f_{ss} = 196.98 \text{ MPa} < 0.6f_y = 252 \text{ MPa}$ $\quad \therefore$ OK

$\gamma_e = 0.75$ $\quad$ [class 2 exposure]

$d_c = c_B + \emptyset_b/2 = 25 + 30/2 = 40 \text{ mm}$

$\beta_s = 1 + d_c/[0.7(h - d_c) = 1 + 40/[0.7(550 - 40)] = 1.11$

$s_{lim} = 123\text{x}10^3\gamma_e/(\beta_s f_{ss}) - 2d_c = (123\text{x}10^3)(0.75)/[(1.11)(196.98)] - 2(40)$
$= 341.91 \text{ mm}$

$s = 150 \text{ mm} < s_{lim} = 341.91 \text{ mm}$ $\quad \therefore$ OK

- Distribution (lateral) reinforcement:

$\psi = 17.5/\sqrt{S} = 17.5/\sqrt{10\text{x}10^3} = 0.175 \leq 0.5$ $\quad \therefore$ OK

$A_{dis} = \psi A_s = (0.175)(4713.33) = 824.83 \text{ mm}^2$

try $\emptyset_b = 16 \text{ mm} \rightarrow A_b = 201 \text{ mm}^2$

$s_{dis} = A_b\text{x}10^3/A_{dis} = 201\text{x}10^3/824.83 = 243.69 \text{ mm}$

use Ø16 @ 200 mm c/c perpendicular to traffic at bottom

- Shrinkage and temperature reinforcement:

$A_{sh} = 750bh/[2(b+h)f_y] = 750(1000)(550)/[2(1550)(420)] = 316.28\text{ mm}^2$

$233 \leq A_{sh} \leq 1270\text{ mm}^2$

try $\emptyset_b = 12\text{ mm} \rightarrow A_b = 113\text{ mm}^2$

$s_{sh} = A_b\text{x}10^3/A_{sh} = 113\text{x}10^3/316.28 = 357.28\text{ mm}$

use Ø12 @ 350 mm c/c each side and each direction at top

Design for Camber:

Instantaneous dead load deflection on entire width:

$\Delta_{DL} = M_{DL}L^2/48E_cI_e$

$w_{DC} = 14.4(W) = (14.4)(10) = 144\text{ kN/m}$

$w_{DW} = 1.2(w) = (1.2)(9) = 10.8\text{ kN/m}$

$w_{DL} = 144 + 10.8 = 154.8\text{ kN/m}$

$M_a = M_{DL} = w_{DL}L^2/8 = (154.8)(10)^2/8 = 1935\text{ kN.m}$

$I_g = 13.865\text{x}10^9(W) = (13.865\text{x}10^9)(10) = 138.65\text{x}10^9\text{ mm}^4$

$M_{cr} = f_r(I_g/y_t) = (3.28)(138.65\text{x}10^9/275) = 1653.72\text{ kN.m}$

$M_{cr}/M_a = 1653.72/1935 = 0.85$

$kd = k(d_s) = (0.314)(510) = 160.14\text{ mm}$

$I_{cr} = [bkd^3/3 + nA_s(d-kd)^2](W)$

$= [(1000)(160.14)^3/3 + (7.87)(4713.33)(510-160.14)^2](10)$

$= 59.09\text{x}10^9\text{ mm}^4$

$I_e = (M_{cr}/M_a)^3I_g + [1-(M_{cr}/M_a)^3]I_{cr}$

$= (0.85)^3(138.65\text{x}10^9) + [1-(0.85)^3](59.09\text{x}10^9) = 107.95\text{x}10^9\text{ mm}^4$

$I_e = 107.95\text{x}10^9\text{ mm}^4 < I_g = 138.65\text{x}10^9\text{ mm}^4 \quad \therefore \text{OK}$

$\Delta_{DL} = (1935\text{x}10^6)(10\text{x}10^3)^2/[48(25.4\text{x}10^3)(107.95\text{x}10^9)] = 1.47\text{ mm}$

Long-term deflection:

$\Delta_{I_g} = \Delta_{DL}(I_e/I_g) = (1.47)(107.95\text{x}10^6/138.65\text{x}10^6) = 1.14\text{ mm}$

$\Delta_{LT} = 4\Delta_{I_g} = 4(1.14) = 4.56\text{ mm}$

$\geq 3\Delta_{I_e} = 3(1.47) = 4.41\text{ mm} \qquad [A'_s = 0]$

use $\Delta_{LT} = 4.56\text{ mm}$

Camber:

$\therefore$ Required Camber $= \Delta_{LT} = 4.56\text{ mm}$

Check for Fatigue:

Fatigue stress:

$M_{fTr} = 360\text{ kN.m}$

$DF_{ifm} = 1/m_1E_{i1} = 1/[(1.2)(4.45)] = 0.19$

$IM = 0.15$

$M_{f+IM} = \left[M_{fTr}(1+IM)\right]DF_{mif} = [(360)(1.15)](0.19) = 78.66\text{ kN.m}$

$M_f = 1.0M_{DC} + 1.0M_{DW} + 1.75M_{f+IM} = 180 + 15 + 1.75(78.66) = 332.66\text{ kN.m}$

$f_{Bf} = M_f/S_B = 332.66\text{x}10^6/50.42\text{x}10^6 = 6.6 \text{ MPa}$

$0.25\sqrt{f_c'} = 0.25\sqrt{28} = 1.32 \text{ MPa}$

$f_{Bf} = 6.6 \text{ MPa} > 0.25\sqrt{f_c'} = 1.32 \text{ MPa}$

$M_{f_1} = 1.75 M_{f+IM} = 1.75(78.66) = 137.66 \text{ kN.m}$ $\quad \therefore$ cracked section

$f_{sf} = M_{f_1}/(A_s jd) = 137.66\text{x}10^6/[(4713.33)(456.45)] = 63.99 \text{ MPa}$

Fatigue stress limit:

$(\Delta F)_{TH} = 166 - 0.33 f_{min}$ $\quad$ [reinforcing bars]

$M_{min} = M_{DC} + M_{DW} = 180 + 15 = 195 \text{ kN.m}$

$f_{min} = M_{min}/(A_s jd) = 195\text{x}10^6/[(4713.33)(456.45)] = 90.64 \text{ MPa}$

$(\Delta F)_{TH} = 166 - 0.33(90.64) = 136.09 \text{ MPa}$

$f_{sf} = 63.99 \text{ MPa} < (\Delta F)_{TH} = 136.09 \text{ MPa}$ $\quad \therefore$ OK

<u>Design of Exterior Strip (Edge Beam)</u>

Equivalent Strip Width:

$W_e = 0.5 \text{ m}$

$E_e = W_e + 0.3 + E_i/4 = 0.5 + 0.3 + 3.3/4 = 1.63 \text{ m}$

$\leq E_i/2 = 1.65 \text{ m}$

$\leq 1.8 \text{ m}$

$\therefore E_e = 1.63 \text{ m}$

Unfactored Loads Per Unit Width:

- Dead loads:

$M_{DC} = 180 \text{ kN.m}$

$w_{ws} = 1.2 \text{ kN/m}$

$w_{DW} = w_{ws}(E_e - W_e)/E_e = (1.2)(1.63 - 0.5)/1.63 = 0.83 \text{ kN/m}$

$M_{DW} = w_{DW} L^2/8 = (0.83)(10)^2/8 = 10.38 \text{ kN.m}$

- Live loads:

$M_{Ta} = 486/2 = 243 \text{ kN.m}$

$w_{Ln} = (3.1)(E_e - W_e) = (3.1)(1.63 - 0.5) = 3.5 \text{ kN/m}$

$M_{Ln} = w_{Ln} L^2/8 = (3.5)(10)^2/8 = 43.75 \text{ kN. m}$

Distribution factor:

$DF_{em} = 1/E_e = 1/1.63 = 0.61$

Total live load:

$M_{LL+IM} = [M_{Ta}(1.33) + M_{Ln}]DF_{em}$

$= [243(1.33) + 43.75](0.61) = 223.53 \text{ kN.m}$

Reinforcement for Flexure:

Check if the interior strips reinforcement is enough for the exterior strips

- Main reinforcements:

$M_{ri} = 834.54 \text{ kN.m}$

$M_{u1} = 1.25 M_{DC} + 1.50 M_{DW} + 1.75 M_{LL+IM}$

$= 1.25(180) + 1.50(10.38) + 1.75(223.53) = 631.75 \text{ kN.m}$

$M_{ri} = 834.54 \text{ kN.m} > M_u = 631.75 \text{ kN.m} \quad \therefore \text{OK}$

$\therefore$ use Ø30 @ 150 mm c/c parallel to traffic

Check of minimum reinforcement:

$M_{cr} = 198.45 \text{ kN.m}$

$1.33M_u = 1.33(631.75) = 840.23 \text{ kN.m} > M_{cr} = 198.45 \text{ kN.m}$

$M_r = 834.54 \text{ kN.m} > M_{cr} = 198.45 \text{ kN.m} \quad \therefore \text{OK}$

Check of reinforcement spacing:

$M_{s1} = M_{DC} + M_{DW} + M_{LL+IM} = 180 + 10.38 + 223.53 = 413.91 \text{ kN.m}$

$f_{Bs} = M_s/S_B = 413.91\text{x}10^6/50.42\text{x}10^6 = 8.21 \text{ MPa}$

$f_{Bs} = 8.21 \text{ MPa} > 0.8f_r = 2.62 \text{ MPa} \quad \therefore \text{cracked section}$

$f_{ss} = M_s/(A_s jd) = 413.91\text{x}10^6/[(4713.33)(456.45)] = 192.39 \text{ MPa}$

$f_{ss} = 192.39 \text{ MPa} < 0.6f_y = 252 \text{ MPa} \quad \therefore \text{OK}$

$\beta_s = 1.11$

$s_{lim} = 123\text{x}10^3\gamma_e/(\beta_s f_{ss}) - 2d_c = (123\text{x}10^3)(0.75)/[(1.11)(192.39)] - 2(40)$
$= 351.98 \text{ mm}$

$s = 150 \text{ mm} < s_{lim} = 351.98 \text{ mm} \quad \therefore \text{OK}$

$\therefore$ Amount of reinforcement in interior strip is enough for edge strip

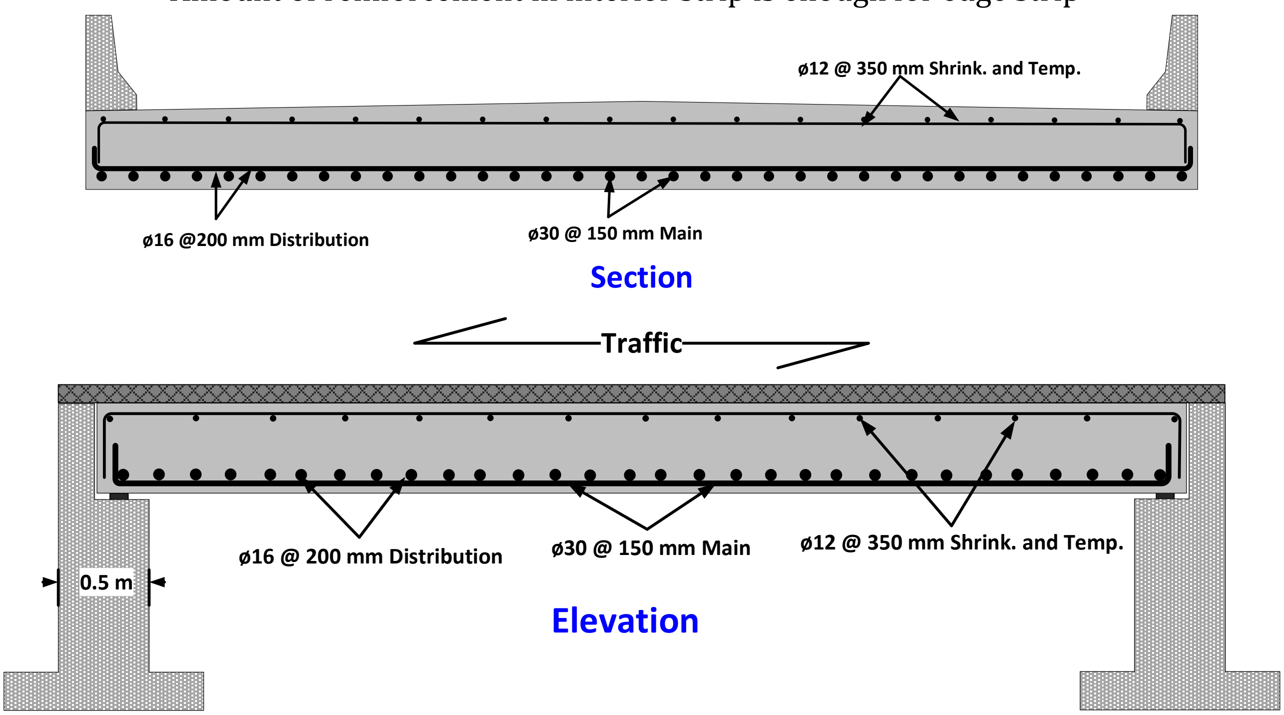

Figure 6.3: Reinforcement for the Slab Bridge of Example 6.1