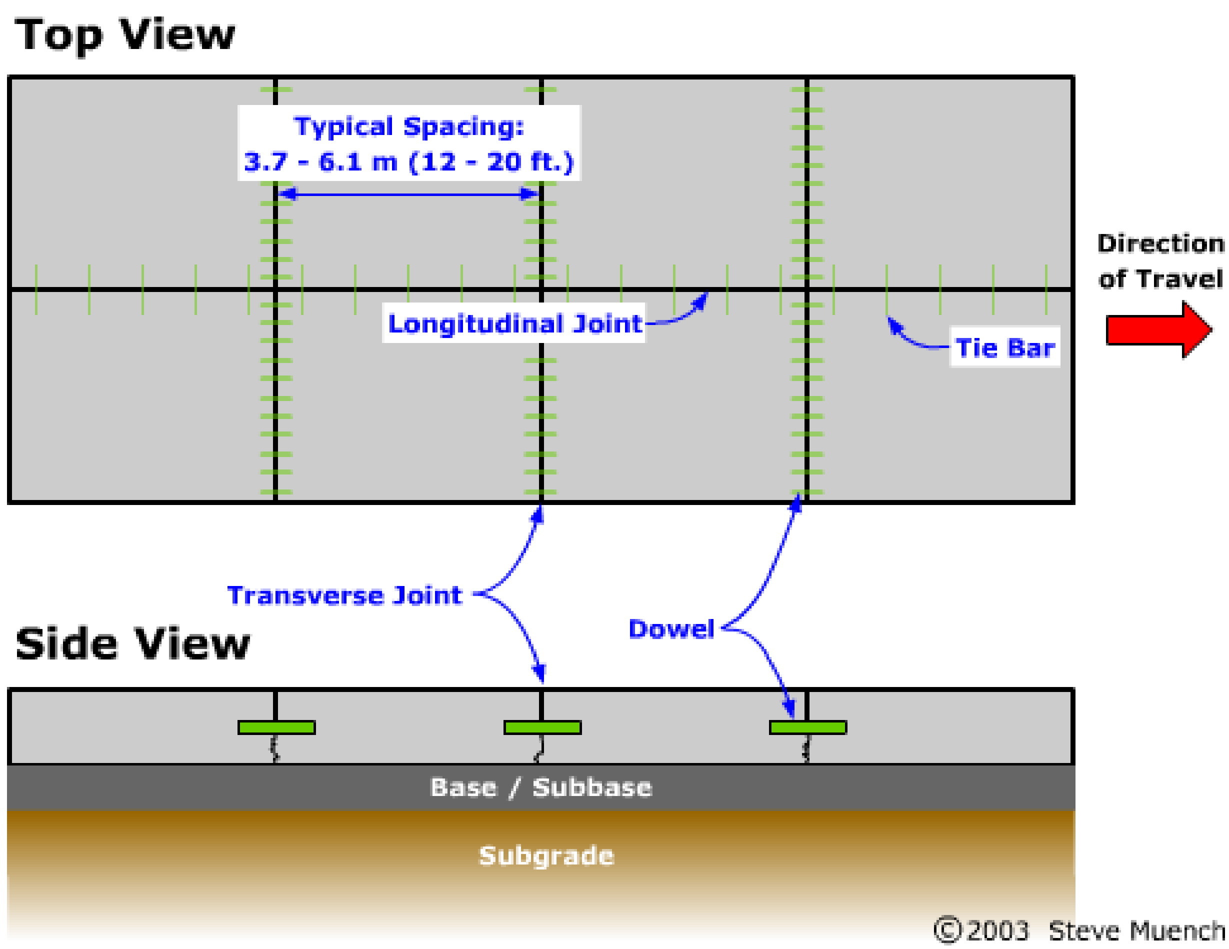
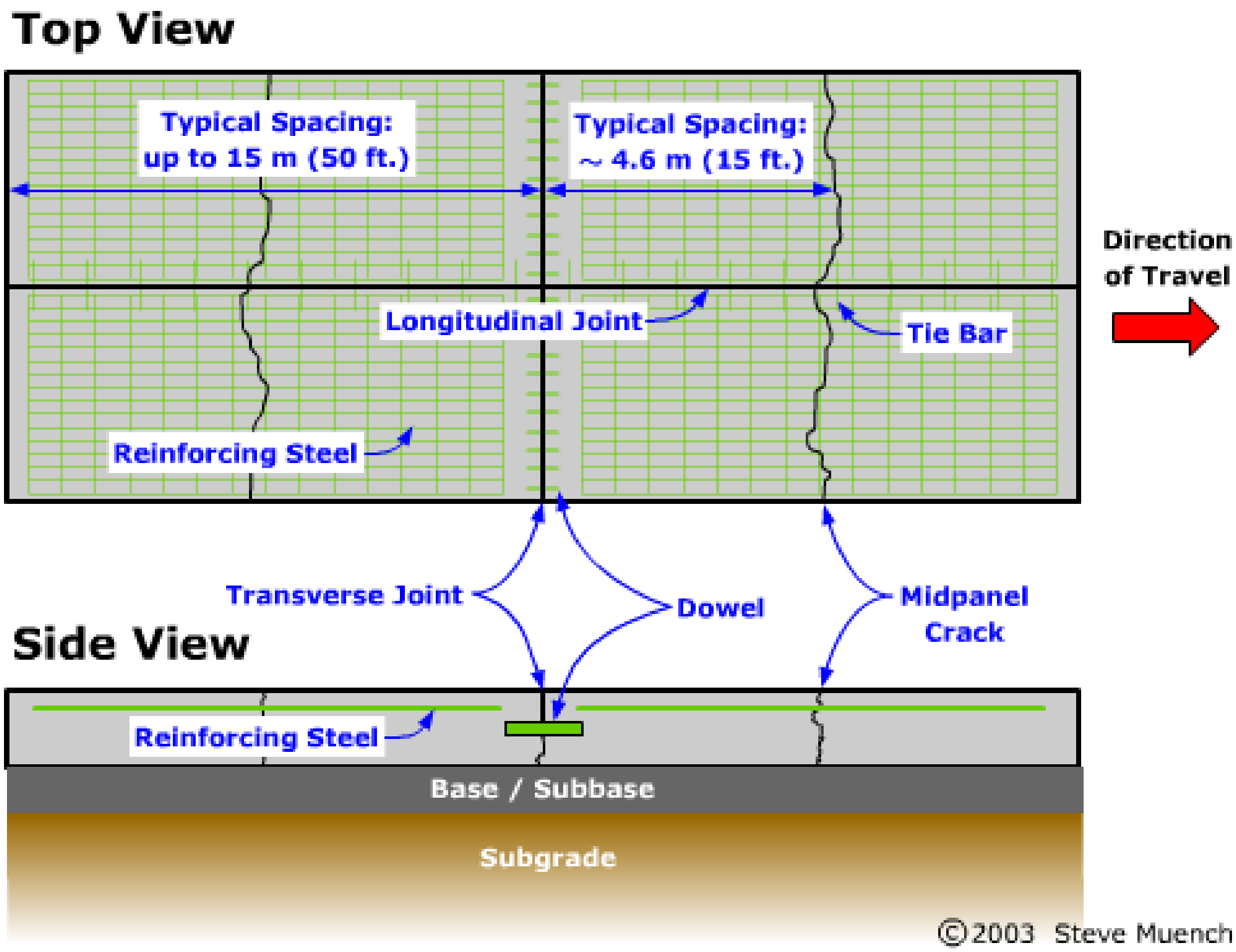
CRCP Reinforcement

JPCP



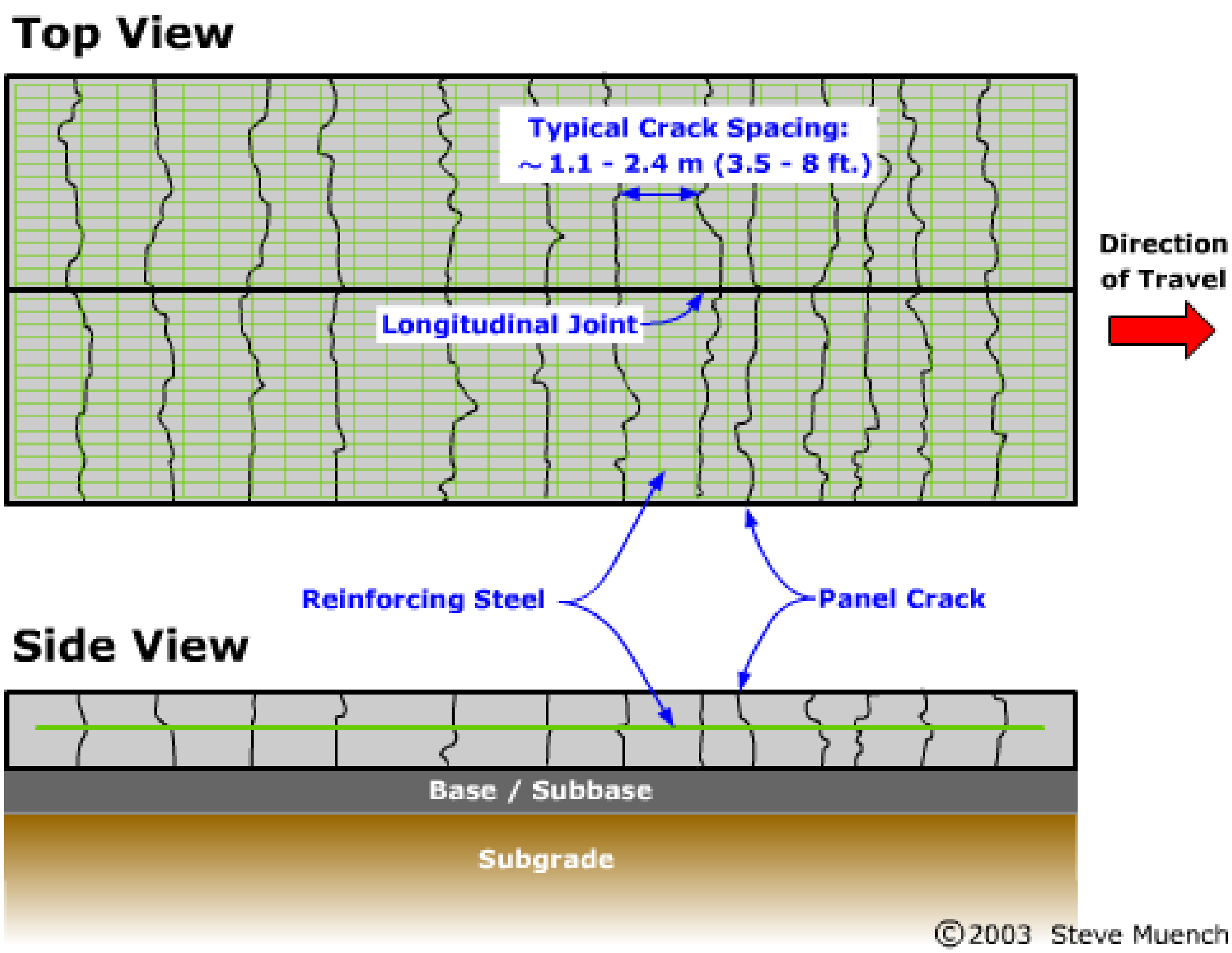
Source: WSDOT Pavement Guide Interactive CD-ROM

JRCP



Source: WSDOT Pavement Guide Interactive CD-ROM

CRCP



Source: WSDOT Pavement Guide Interactive CD-ROM

CRCP

Source: *CRCP Performance and Best Practices*, ACPT Tech Brief, FHWA-HIF-12-039

CRCP Reinforcement

CRCP Reinforcement

Design of CRCP Reinforcement

Goal: provide sufficient reinforcement to

– Produce a desirable crack pattern

  - Crack spacing between 3.5 and 8 ft

– Keep transverse cracks tightly closed

  - Maximum crack width less than 0.4 in

– Keep steel stresses within allowable levels

Design of CRCP Reinforcement

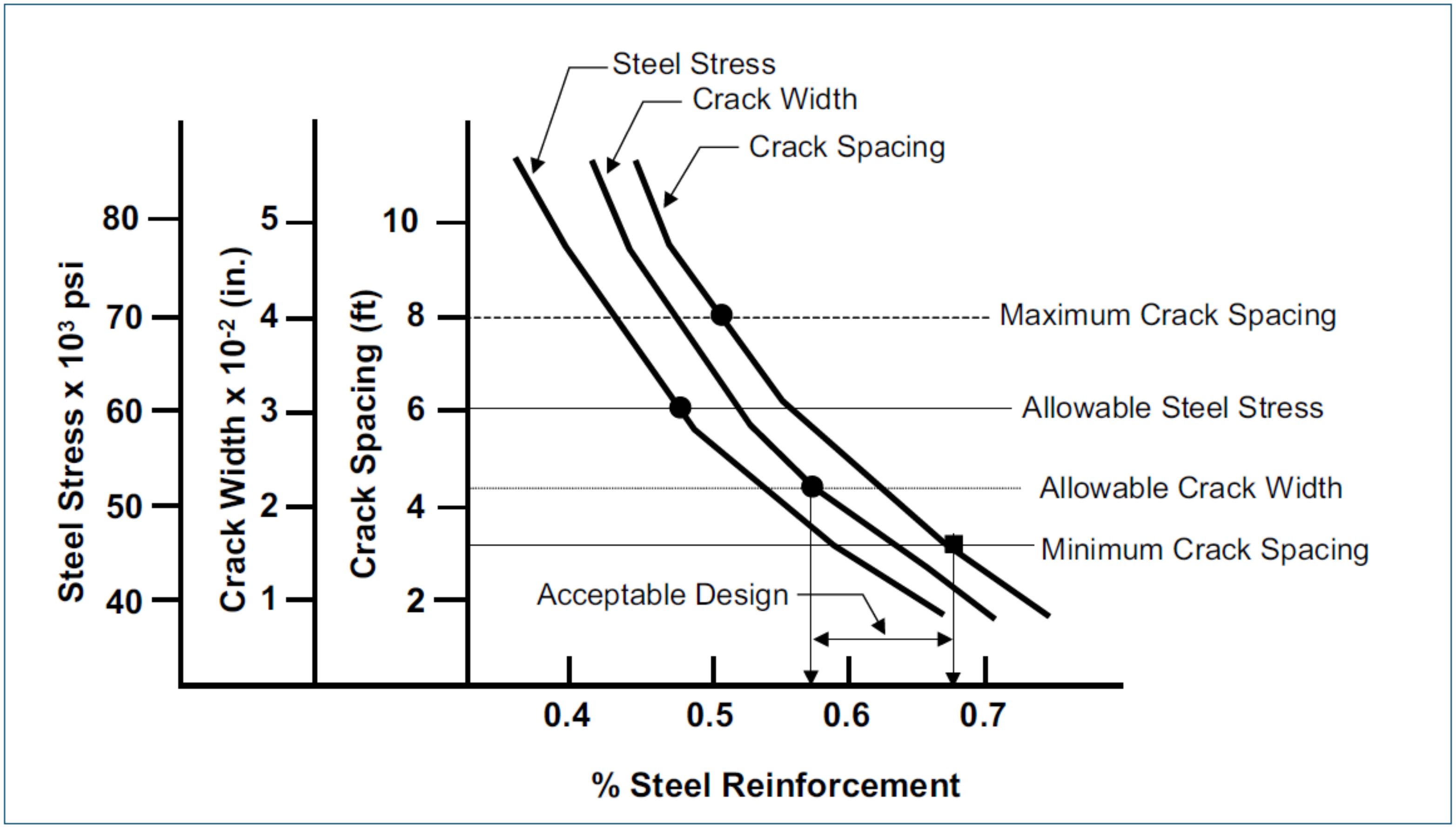


Figure 11. Conceptual representation of steel design for CRCP.[55]

Source: FHWA/CRSI *Continuously Reinforced Concrete Pavement Design & Construction Guidelines*

Design Variables

- Concrete tensile strength, f_t (psi)
- Concrete shrinkage strain, δ_c (in/in)
- Concrete thermal coefficient, α_c (in/in/°F)
- Rebar diameter, ϕ_b (in)
- Allowable steel working stress, σ_s (psi)
- Steel thermal coefficient, α_s (in/in/°F)
- Design temperature drop, ΔT_d (°F)
- Tensile stress due to wheel loads, σ_w (psi)

Concrete Shrinkage Strain

AASHTO Pavement Design Guide

Tensile Strength (psi)	Shrinkage Strain (in/in)
300 or less	0.0008
400	0.0006
500	0.00045
600	0.0003
700 or more	0.0002

Average 0.0005

Concrete Thermal Coefficient

Aggregate Type	Coefficient (10^{-6} in/in/^{o}F)
Quartz	6.6
Sandstone	6.5
Gravel	6.0
Granite	5.3
Basalt	4.8
Limestone	3.8
Average	5.0

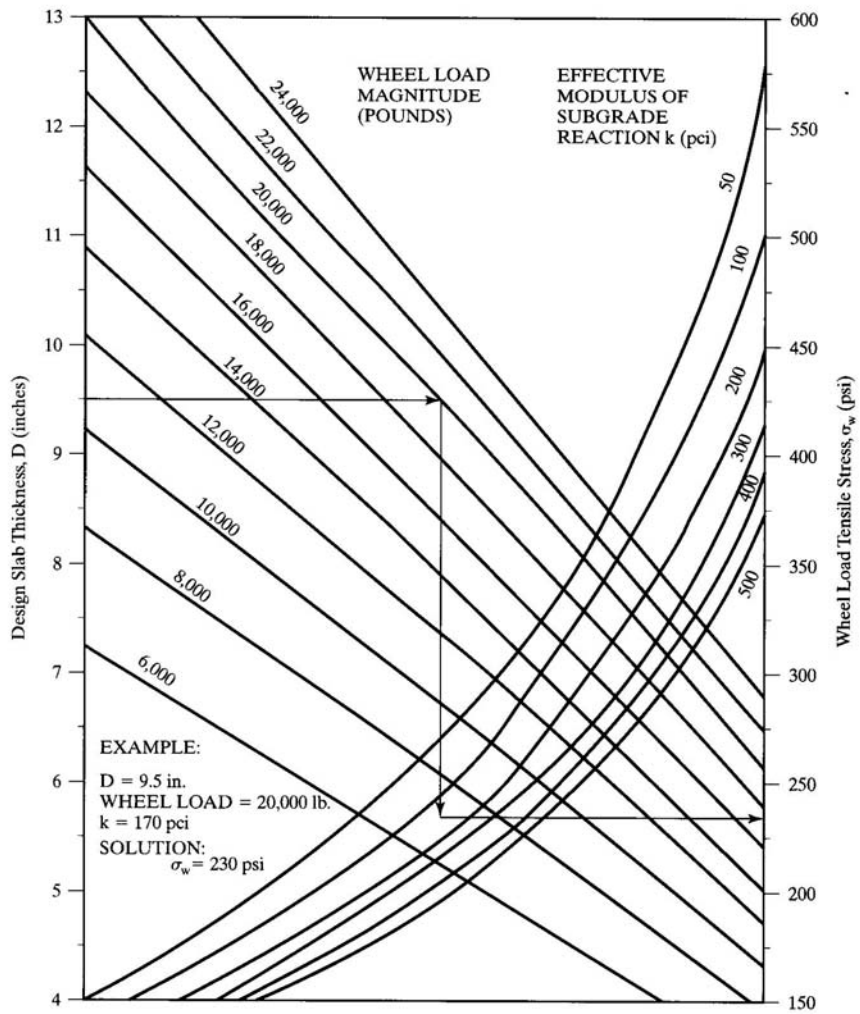
Allowable Steel Working Stress

Indirect Tensile Strength of Concrete at 28 days (psi)	Reinforcing Bar Size No. 4	No. 5	No. 6
300 or less	65,000	57,000	54,000
400	67,000	60,000	55,000
500	67,000	61,000	56,000
600	67,000	63,000	58,000
700	67,000	65,000	59,000
800 or more	67,000	67,000	60,000

Steel Thermal Coefficient

$$\alpha_s = 5\times10^{-6}\ \text{in/in/}^{o}\text{F}$$

Tensile stress due to wheel loads



σ_w

Crack Spacing

$$\bar{X} = \frac{1.32\left(1+\frac{f_t'}{1000}\right)^{6.70}\left(1+\frac{\alpha_s}{2\alpha_c}\right)^{1.15}\left(1+\phi_b\right)^{2.19}}{\left(1+\frac{\sigma_w}{1000}\right)^{5.20}\left(1+P\right)^{4.60}\left(1+1000\delta_c\right)^{1.79}}$$

$\bar{X}$ = average crack spacing (ft)

P = percentage steel needed

Crack Spacing

$$P = \frac{1.062\left(1+\frac{f_t'}{1000}\right)^{1.457}\left(1+\frac{\alpha_s}{2\alpha_c}\right)^{0.25}\left(1+\phi_b\right)^{0.476}}{\left(1+\frac{\sigma_w}{1000}\right)^{1.13}\left(\bar{X}\right)^{0.217}\left(1+1000\delta_c\right)^{0.389}} - 1$$

$\bar{X}$ = average crack spacing (ft)

P = percentage steel needed

Minimum Crack Spacing

$$P_{max} = \frac{1.062\left(1+\frac{f_t'}{1000}\right)^{1.457}\left(1+\frac{\alpha_s}{2\alpha_c}\right)^{0.25}\left(1+\phi_b\right)^{0.476}}{\left(1+\frac{\sigma_w}{1000}\right)^{1.13}\left(3.5\text{ ft}\right)^{0.217}\left(1+1000\delta_c\right)^{0.389}} - 1$$

Maximum Crack Spacing

$$P_{min}^{1} = \frac{1.062\left(1+\frac{f_t'}{1000}\right)^{1.457}\left(1+\frac{\alpha_s}{2\alpha_c}\right)^{0.25}\left(1+\phi_b\right)^{0.476}}{\left(1+\frac{\sigma_w}{1000}\right)^{1.13}\left(8.0\text{ ft}\right)^{0.217}\left(1+1000\delta_c\right)^{0.389}} - 1$$

Nomograph Solves:

$$\bar{X} = \frac{1.32\left(1+\frac{f_t}{1000}\right)^{6.70} \times \left(1+\frac{\alpha_s}{2\alpha_c}\right)^{1.15} \times \left(1+\phi\right)^{2.19}}{\left(1+\frac{\sigma_w}{1000}\right)^{5.20} \times \left(1+P\right)^{4.60} \times \left(1+1000Z\right)^{1.79}}$$

Example:

$\bar{X}$ = 3.5 ft.

α_s / α_c = 1.32

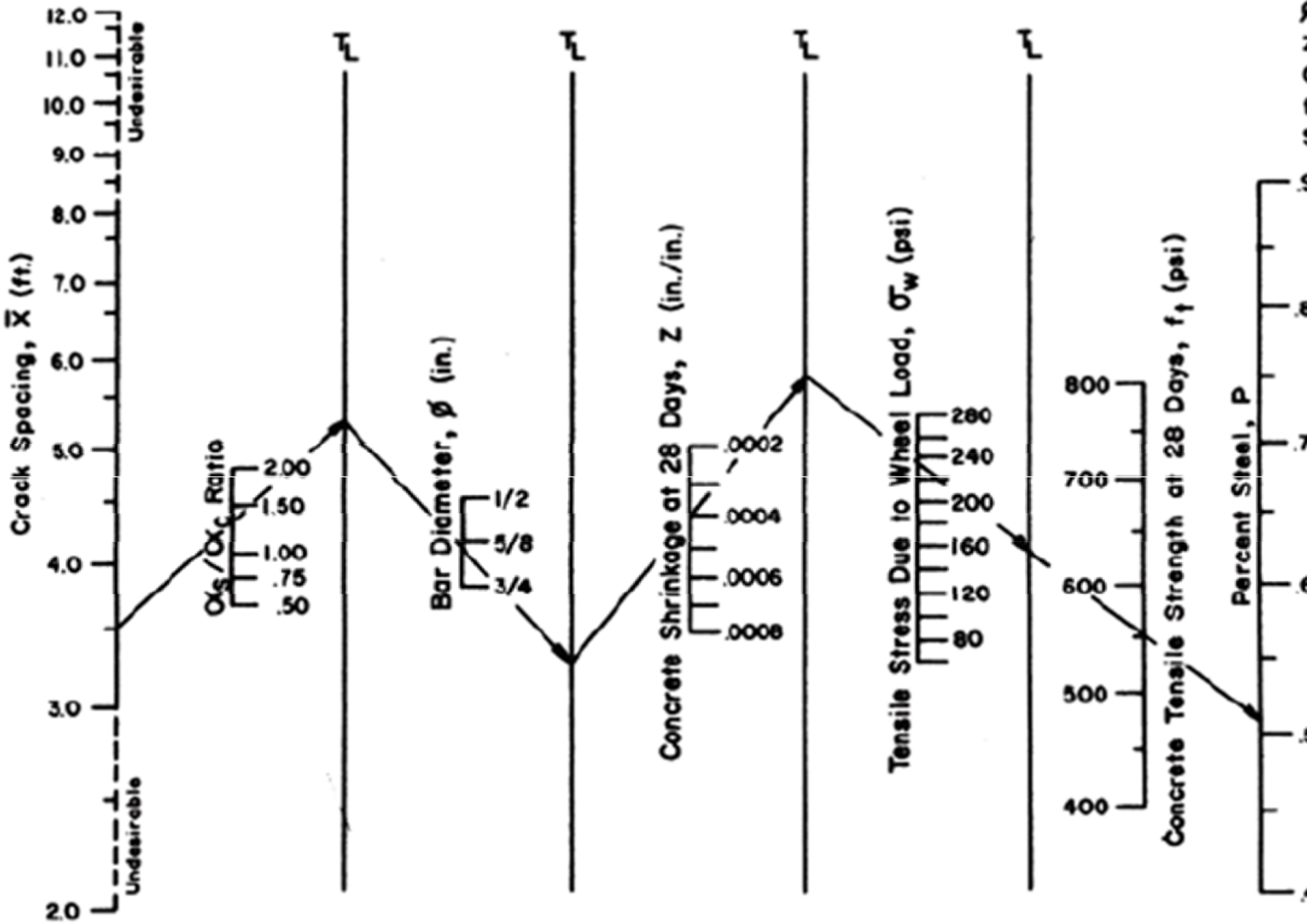
ϕ = 5/8 in.

Z = 0.0004

σ_w = 230 psi

f_t = 550 psi

Solution: P = 0.51%



Crack Width

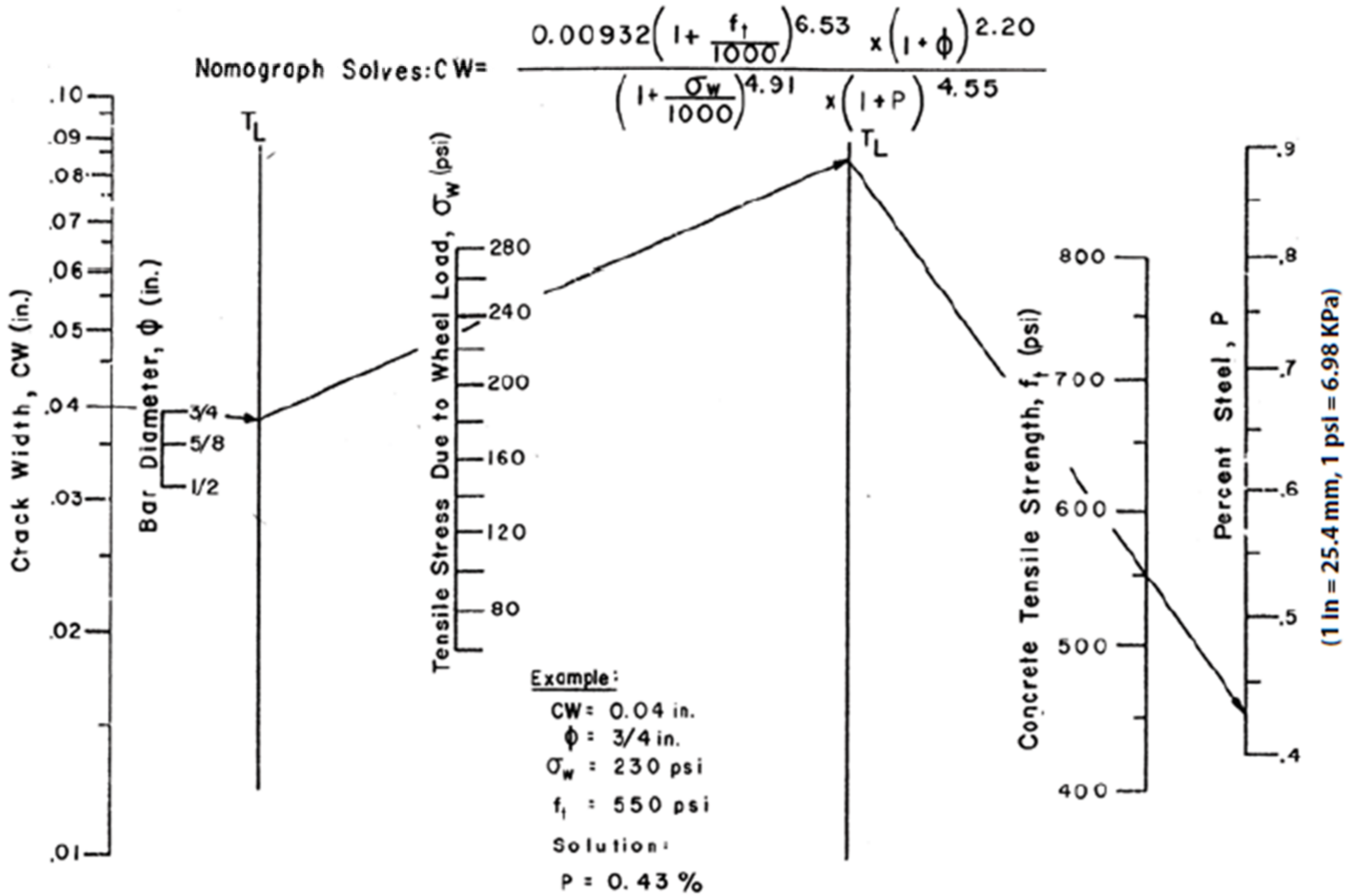
$$CW = \frac{0.00932\left(1+\frac{f_t'}{1000}\right)^{6.53}\left(1+\phi_b\right)^{2.20}}{\left(1+\frac{\sigma_w}{1000}\right)^{4.91}\left(1+P\right)^{4.55}}$$

Crack Width

$$P = \frac{0.358\left(1+\frac{f_t'}{1000}\right)^{1.435}\left(1+\phi_b\right)^{0.484}}{\left(1+\frac{\sigma_w}{1000}\right)^{1.079}\left(CW\right)^{0.220}} - 1$$

Maximum Crack Width

$$P_{min}^{2} = \frac{0.358\left(1+\frac{f_t'}{1000}\right)^{1.435}\left(1+\phi_b\right)^{0.484}}{\left(1+\frac{\sigma_w}{1000}\right)^{1.079}\left(0.04\text{ in}\right)^{0.220}} - 1$$



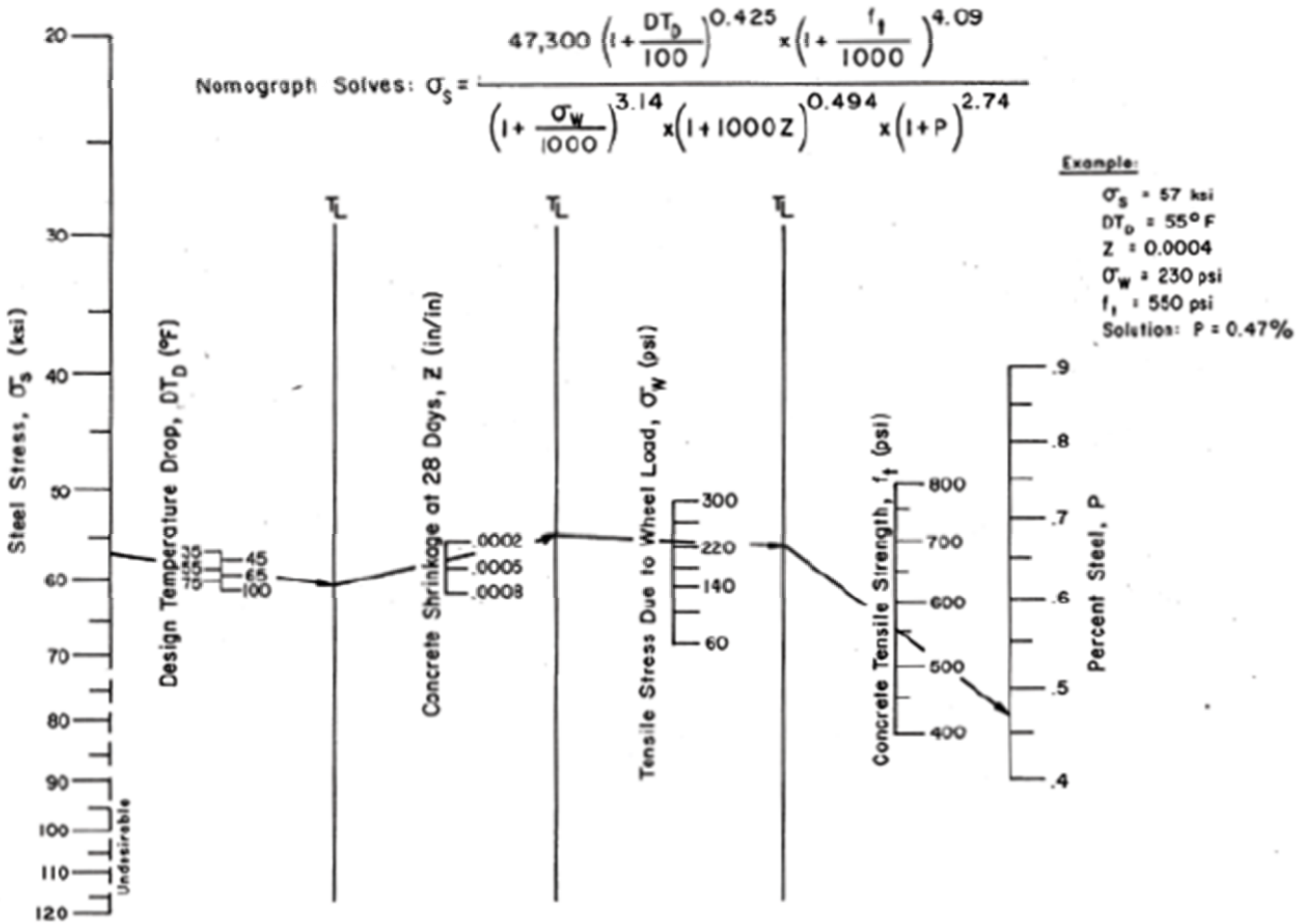
Nomograph Solves: $CW = \dfrac{0.00932\left(1+\frac{f_t}{1000}\right)^{6.53} \times \left(1+\phi\right)^{2.20}}{\left(1+\frac{\sigma_w}{1000}\right)^{4.91} \times \left(1+P\right)^{4.55}}$
Crack Width, CW (in.)
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
Bar Diameter, ϕ (in.)
3/4
5/8
1/2
T_L
Tensile Stress Due to Wheel Load, σ_w (psi)
280
240
200
160
120
80
T_L
Concrete Tensile Strength, f_t (psi)
800
700
600
500
400
Percent Steel, P
.9
.8
.7
.6
.5
.4
(1 in = 25.4 mm, 1 psi = 6.98 KPa)
Example:
CW = 0.04 in.
ϕ = 3/4 in.
σ_w = 230 psi
f_t = 550 psi
Solution:
P = 0.43 %

Steel Working Stress

$$\sigma_s = \frac{47{,}300\left(1+\frac{f_t'}{1000}\right)^{4.09}\left(1+\frac{\Delta T_d}{100}\right)^{0.425}}{\left(1+\frac{\sigma_w}{1000}\right)^{3.14}\left(1+P\right)^{2.74}\left(1+1000\delta_c\right)^{0.494}}$$

Maximum Steel Stress

$$P_{min}^{3} = \frac{50.834\left(1+\frac{f_t'}{1000}\right)^{1.493}\left(1+\frac{\Delta T_d}{100}\right)^{0.155}}{\left(1+\frac{\sigma_w}{1000}\right)^{1.146}\left(\sigma_s\right)^{0.365}\left(1+1000\delta_c\right)^{0.180}} - 1$$



Nomograph Solves: $\sigma_S = \dfrac{47{,}300\left(1+\dfrac{DT_D}{100}\right)^{0.425} \times \left(1+\dfrac{f_t}{1000}\right)^{4.09}}{\left(1+\dfrac{\sigma_W}{1000}\right)^{3.14} \times \left(1+1000Z\right)^{0.494} \times \left(1+P\right)^{2.74}}$
Example:
σ_s = 57 ksi
DT_D = 55° F
Z = 0.0004
σ_W = 230 psi
f_t = 550 psi
Solution: P = 0.47%
Steel Stress, σ_S (ksi)
20
30
40
50
60
70
80
90
100
110
120
Undesirable
Design Temperature Drop, DT_D (°F)
35
45
55
65
75
100
TL
Concrete Shrinkage at 28 Days, Z (in/in)
.0002
.0005
.0008
TL
Tensile Stress Due to Wheel Load, σ_W (psi)
300
220
140
60
TL
Concrete Tensile Strength, f_t (psi)
800
700
600
500
400
Percent Steel, P
.9
.8
.7
.6
.5
.4

Required Steel

$$P_{min} = \max\left(P_{min}^{1}\ , P_{min}^{2}\ , P_{min}^{3}\right)$$

$$N_{min} = \frac{\left(P_{min}/100\right) W_s D}{\left(\pi/4\right) {\phi_b}^2}$$

$$N_{max} = \frac{\left(P_{max}/100\right) W_s D}{\left(\pi/4\right) {\phi_b}^2}$$

Example

D = 9.5 in (from design equation)

W_s = 144 in (12-ft slab)

ΔT_d = 60°F (from weather data)

f'_t = 600 psi (from AASHTO T198)

k_{eff} = 170 pci (from Figure 3.6)

ϕ_b = 0.75 in (No. 6 bar assumed)

Step 1

$\delta_c =$

$\alpha_c =$

$\alpha_s =$

$\sigma_s =$

Concrete Shrinkage Coefficient

Indirect Tensile Strength at 28 days (psi)	Shrinkage Coefficient (in/in)
300 or less	0.0008
400	0.0006
500	0.00045
600	0.0003
700 or more	0.0002

Concrete Thermal Coefficient

$$\alpha_c = 5\times10^{-6}\ \text{in/in/}^{o}\text{F}$$

Allowable Steel Working Stress

Indirect Tensile Strength of Concrete at 28 days (psi)	Reinforcing Bar Size		
	No. 4	No. 5	No. 6
300 or less	65,000	57,000	54,000
400	67,000	60,000	55,000
500	67,000	61,000	56,000
600	67,000	63,000	58,000
700	67,000	65,000	59,000
800 or more	67,000	67,000	60,000

Steel Thermal Coefficient

$$\alpha_s = 5\times10^{-6} \text{ in/in/}^o\text{F}$$

Step 1

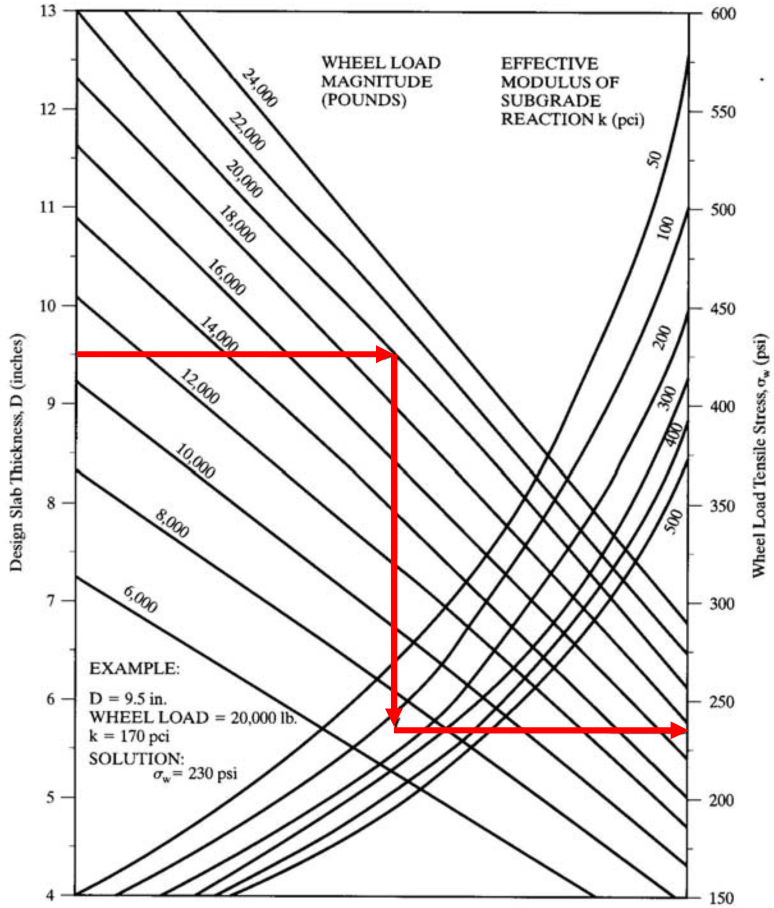
δ_c = 0.0003 in/in

α_c = 5×10^{-6} in/in/°F

α_s = 5×10^{-6} in/in/°F

σ_s = 58,000 psi

Step 2 – Tensile Stress



Step 3 – Min Crack Spacing

$$P_{max} = \frac{1.062\left(1+\frac{f_t'}{1000}\right)^{1.457}\left(1+\frac{\alpha_s}{2\alpha_c}\right)^{0.25}\left(1+\phi_b\right)^{0.476}}{\left(1+\frac{\sigma_w}{1000}\right)^{1.13}\left(3.5\ \text{ft}\right)^{0.217}\left(1+1000\delta_c\right)^{0.389}} - 1$$

$$P_{max} = \frac{1.062\left(1+0.6\right)^{1.457}\left(1+0.5\right)^{0.25}\left(1+0.75\right)^{0.476}}{\left(1+0.23\right)^{1.13}\left(3.5\ \text{ft}\right)^{0.217}\left(1+0.3\right)^{0.389}} - 1 = 0.66\%$$

Step 4 – Max Crack Spacing

$$P_{min}^{1} = \frac{1.062\left(1+\frac{f_t'}{1000}\right)^{1.457}\left(1+\frac{\alpha_s}{2\alpha_c}\right)^{0.25}\left(1+\phi_b\right)^{0.476}}{\left(1+\frac{\sigma_w}{1000}\right)^{1.13}\left(8.0\text{ ft}\right)^{0.217}\left(1+1000\delta_c\right)^{0.389}} - 1$$

$$P_{min}^{1} = \frac{1.062\left(1+0.6\right)^{1.457}\left(1+0.5\right)^{0.25}\left(1+0.75\right)^{0.476}}{\left(1+0.23\right)^{1.13}\left(8.0\text{ ft}\right)^{0.217}\left(1+0.3\right)^{0.389}} - 1 = 0.39\%$$

Step 5 – Max Crack Width

$$P_{min}^{2} = \frac{0.038\left(1+\frac{f_t'}{1000}\right)^{1.435}\left(1+\phi_b\right)^{0.484}}{\left(1+\frac{\sigma_w}{1000}\right)^{1.079}\left(0.04\text{ in}\right)^{0.220}} - 1$$

$$P_{min}^{2} = \frac{0.358\left(1+0.6\right)^{1.435}\left(1+0.75\right)^{0.484}}{\left(1+0.23\right)^{1.079}\left(0.04\text{ in}\right)^{0.220}} - 1 = 0.50\%$$

Step 6 – Max Steel Stress

$$P_{min}^{3} = \frac{50.834\left(1+\frac{f'_t}{1000}\right)^{1.493}\left(1+\frac{\Delta T_d}{100}\right)^{0.155}}{\left(1+\frac{\sigma_w}{1000}\right)^{1.146}\left(\sigma_s\right)^{0.365}\left(1+1000\delta_c\right)^{0.180}} - 1$$

$$P_{min}^{3} = \frac{50.834\left(1+0.6\right)^{1.493}\left(1+0.6\right)^{0.155}}{\left(1+0.23\right)^{1.146}\left(58{,}000\right)^{0.365}\left(1+0.3\right)^{0.180}} - 1 = 0.52\%$$

Step 7 – Required Steel

$$P_{min} = \max\left(0.39\%\,,\,0.50\%\,,\,0.52\%\right) = 0.52\%$$

$$N_{min} = \frac{\left(P_{min}/100\right)W_s D}{\left(\pi/4\right)\phi_b{}^2} = \frac{\left(0.52/100\right)\left(144\right)\left(9.5\right)}{\left(\pi/4\right)\left(0.75\right)^2} = 16.1$$

$$N_{max} = \frac{\left(P_{max}/100\right)W_s D}{\left(\pi/4\right)\phi_b{}^2} = \frac{\left(0.66/100\right)\left(144\right)\left(9.5\right)}{\left(\pi/4\right)\left(0.75\right)^2} = 20.4$$

Solution

$$16.1 < N < 20.4$$

$$\text{Choose } N = 18 \text{ bars}$$

$$P = \frac{N(\pi/4)\phi_b{}^2}{(0.01)W_s D} = \frac{(18)(\pi/4)(0.75)^2}{(0.01)(144)(9.5)} = 0.58\%$$

Crack Spacing

$$\bar{X} = \frac{1.32\left(1+\frac{f_t'}{1000}\right)^{6.70}\left(1+\frac{\alpha_s}{2\alpha_c}\right)^{1.15}\left(1+\phi_b\right)^{2.19}}{\left(1+\frac{\sigma_w}{1000}\right)^{5.20}\left(1+P\right)^{4.60}\left(1+1000\delta_c\right)^{1.79}}$$

$$\bar{X} = \frac{1.32(1+0.6)^{6.70}(1+0.5)^{1.15}(1+0.75)^{2.19}}{(1+0.23)^{5.20}(1+0.58)^{4.60}(1+0.3)^{1.79}} = 4.3'$$

Crack Width

$$CW = \frac{0.00932\left(1+\frac{f_t'}{1000}\right)^{6.53}\left(1+\phi_b\right)^{2.20}}{\left(1+\frac{\sigma_w}{1000}\right)^{4.91}\left(1+P\right)^{4.55}}$$

$$CW = \frac{0.00932\left(1+0.6\right)^{6.53}\left(1+0.75\right)^{2.20}}{\left(1+0.23\right)^{4.91}\left(1+0.58\right)^{4.55}} = 0.03''$$

Steel Working Stress

$$\sigma_s = \frac{47{,}300\left(1+\frac{f_t'}{1000}\right)^{4.09}\left(1+\frac{\Delta T_d}{100}\right)^{0.425}}{\left(1+\frac{\sigma_w}{1000}\right)^{3.14}\left(1+P\right)^{2.74}\left(1+1000\delta_c\right)^{0.494}}$$

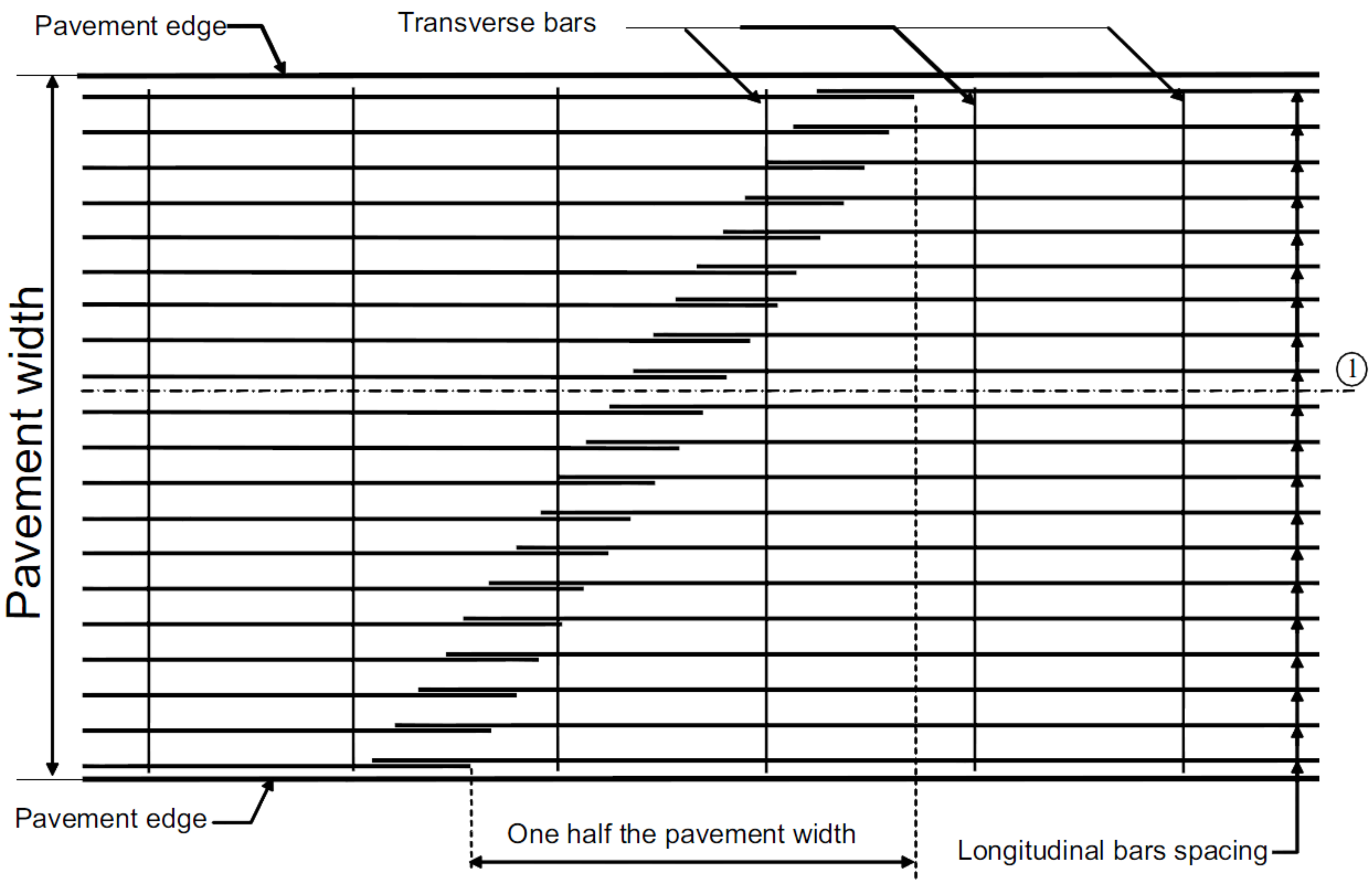
$$\sigma_s = \frac{47{,}300\left(1+0.6\right)^{4.09}\left(1+0.6\right)^{0.425}}{\left(1+0.23\right)^{3.14}\left(1+0.58\right)^{2.74}\left(1+0.3\right)^{0.494}} = 51{,}707 \text{ psi}$$

Reinforcement Spacing

	Bar Size	#5			#6					#7				#8			
	Spacing (in)	5	6	7	5	6	7	8	9	6	7	8	9	6	7	8	9
Slab Thickness (in)	8	0.77%	0.64%	0.55%		0.92%	0.79%	0.69%	0.61%			0.94%	0.84%				
	9	0.68%	0.57%		0.98%	0.82%	0.70%	0.61%			0.95%	0.84%	0.74%				0.97%
	10	0.61%	0.51%		0.88%	0.74%	0.63%			1.00%	0.86%	0.75%	0.67%			0.98%	0.87%
	11	0.56%			0.80%	0.67%	0.57%			0.91%	0.78%	0.68%				0.89%	0.79%
	11.5	0.53%			0.77%	0.64%				0.87%	0.75%	0.65%			0.98%	0.85%	0.76%
	12	0.51%			0.74%	0.61%				0.84%	0.72%				0.93%	0.82%	
	13				0.68%	0.57%				0.77%	0.66%			1.01%	0.86%	0.76%	

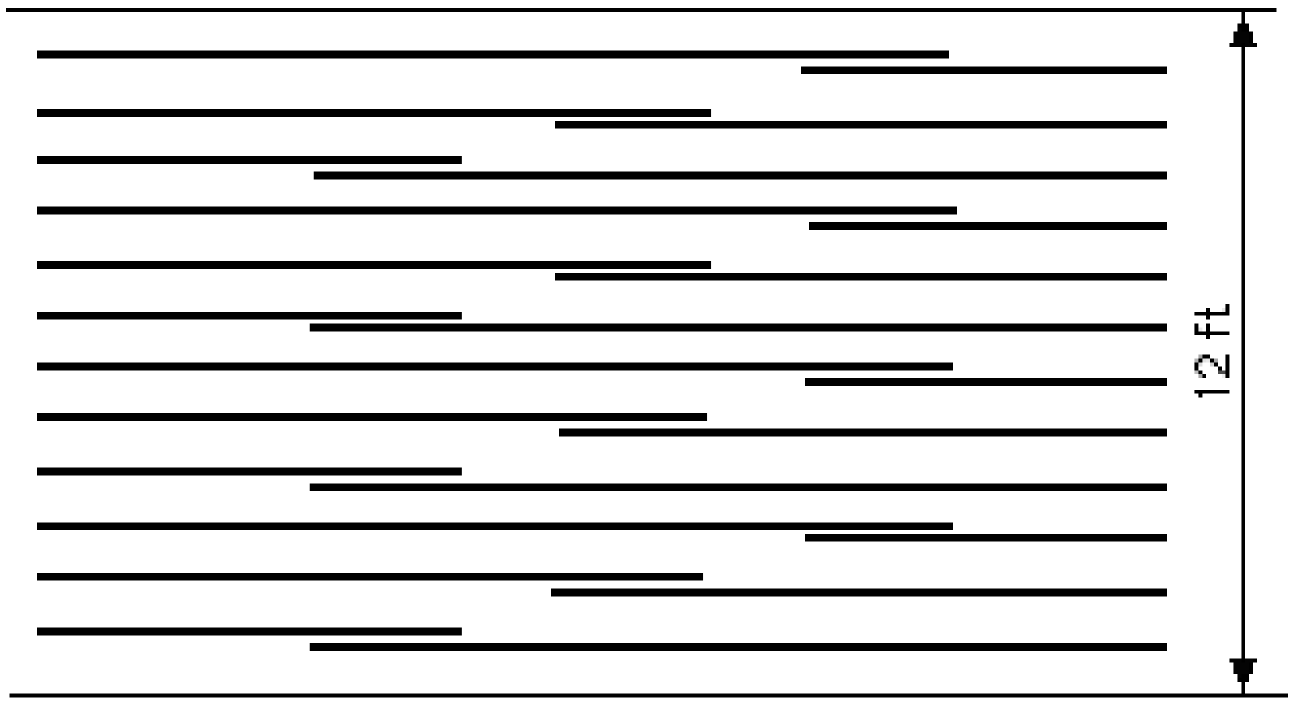
Source: FHWA/CRSI *Continuously Reinforced Concrete Pavement Design & Construction Guidelines*

Skewed Lap Splices



Source: FHWA/CRSI *Continuously Reinforced Concrete Pavement Design & Construction Guidelines*

Staggered Lap Splices



Source: Caltrans *Continuously Reinforced Concrete Pavement (CRCP) Design & Construction Guide*

Tie Bars

Tie
Bar

Tie Bars

Tie
Bar

Tie Bar Spacing

$$A_s = \frac{A_{bar}}{s_{bar}} = \frac{\gamma_c L' f_{avg} h}{f_s}$$

$$\frac{2}{3} f_y$$

Steel Reinforcing Bar

f_y = 40,000 or 60,000 psi

Tie Bar Spacing

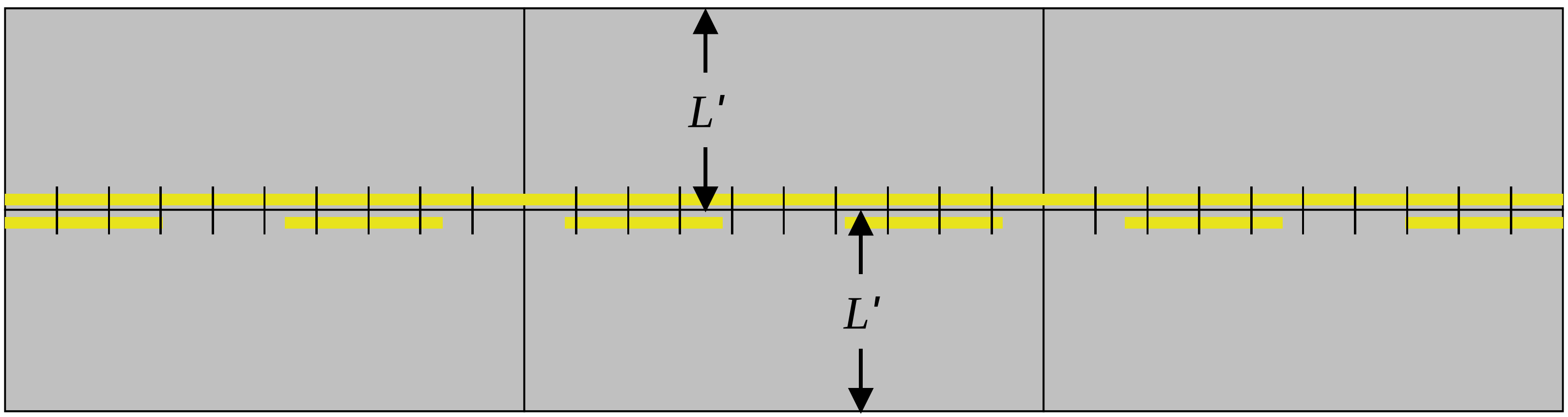
$$A_s = \frac{A_{bar}}{s_{bar}} = \frac{\gamma_c L' f_{avg} h}{f_s}$$

$$s_{bar} = \frac{f_s A_{bar}}{\gamma_c L' f_{avg} h} = \frac{\pi d^2 f_s}{4\gamma_c L' f_{avg} h}$$

Friction Coefficient

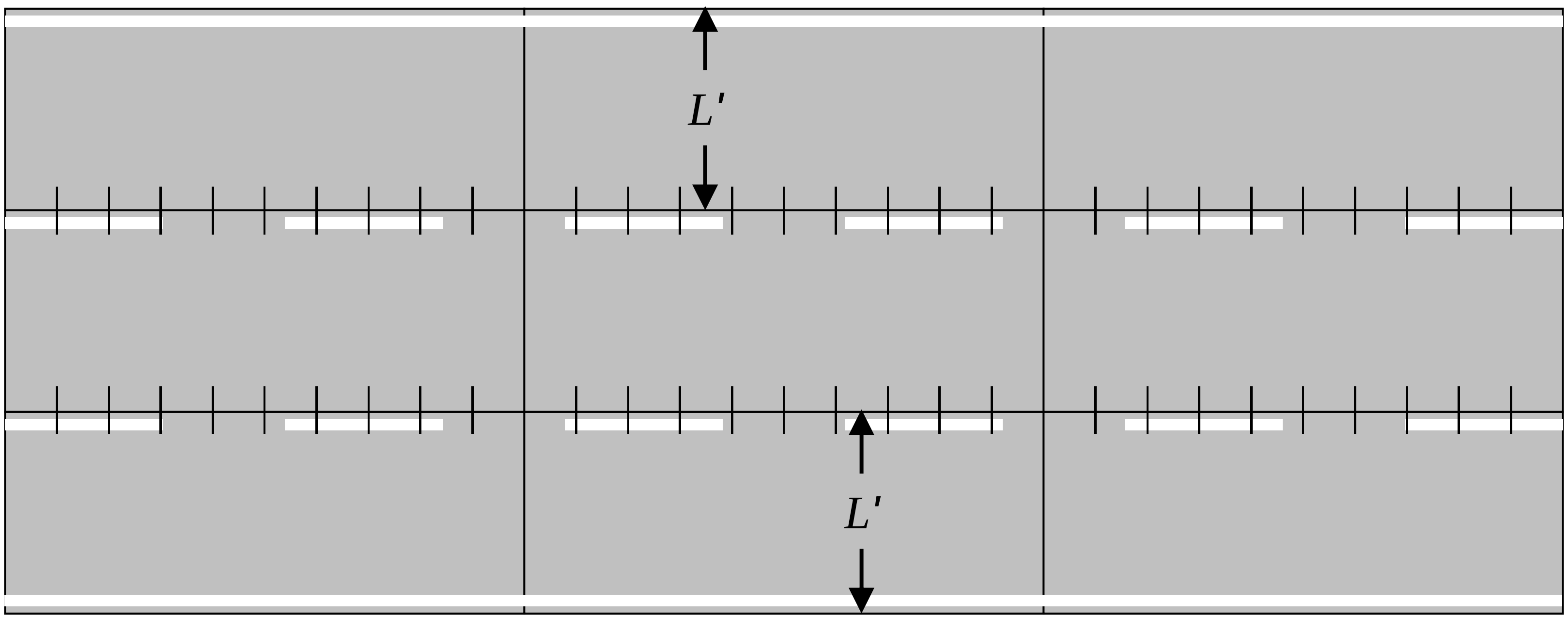
Type of Material Beneath Slab	f_{avg}
Lime stabilized soil	1.8
Asphalt stabilized soil	1.8
Cement stabilized soil	1.8
River gravel	1.5 } standard
Crushed stone	1.5 } standard
Sandstone	1.2
Natural subgrade	0.9

Tie Bar Spacing



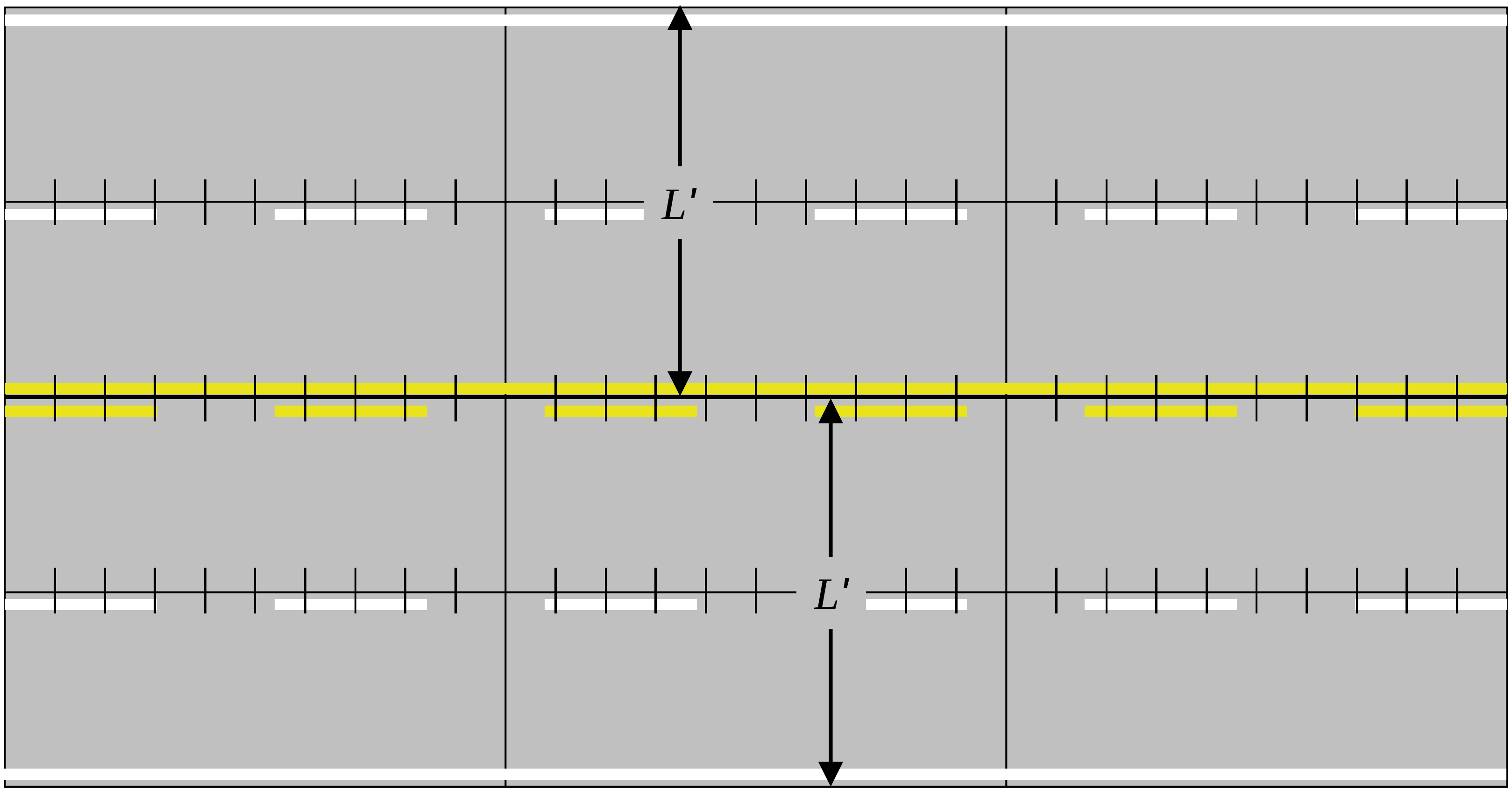
$L' = \textit{distance to nearest free edge}$

Tie Bar Spacing



$L' = distance\ to\ nearest\ free\ edge$

Tie Bar Spacing



L' = distance to nearest free edge

Tie Bar Length

$$t = \frac{1}{2}\left(\frac{f_s d}{\mu}\right) + \ell_a$$

μ = allowable bond stress (assume 350 psi)

f_s = allowable bar stress (2/3 of yield stress)

d = bar diameter (in)

ℓ_a = additional length for misalignment (3 in)

Transverse Reinforcement

Transverse
Steel

Transverse Reinforcement

Percent Transverse Steel

$$A_s = \frac{A_{bar}}{s_{bar}} = \frac{\gamma_c W_s f_{avg} h}{2 f_s}$$

$$P_s = \frac{A_s}{h} = \frac{\gamma_c W_s f_{avg}}{2 f_s} \times 100\%$$

Transverse Steel Spacing

$$s_{bar} = \frac{\pi d^2}{4P_s h} = \frac{\pi d^2 f_s}{2\gamma_c W_s f_{avg} h}$$

$d =$ bar diameter

$h =$ slab thickness (in)

$W_s =$ slab width (in)