DESIGN SUMMARY AND PERFORMANCE PREDICTIONS

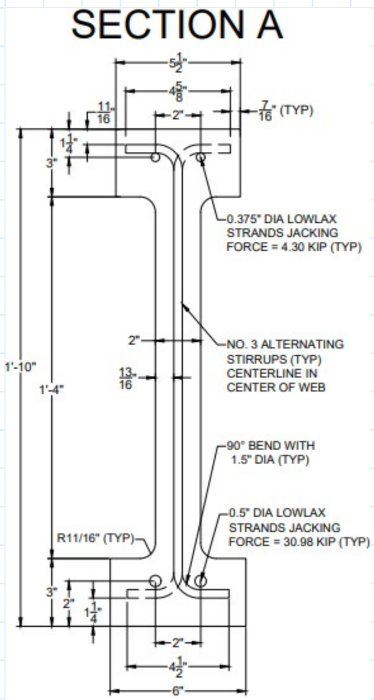


Figure 1: Cross-Section Profile

Beam Predictions

CrackingLoad = 21.27 ***kip***

BreakingLoad = 35.91 ***kip***

Deflection = 0.58 ***in*** @ 32 ***kip***

Test Results

Cracking Load = 22.50 ***kip***

Breaking Load = 38.20 ***kip***

Deflection = 0.85 ***in*** @ 32 ***kip***

Cost

DollarCost = 299.37

Weight

Weight = 1079.122 ***lbf***

CROSS SECTION PROPERTIES

$l := 18\ ft$ Total Beam Length

$l_s := 17\ ft$ Beam Span Length

$x := 0\ ft, 0.01\ ft .. l_s \quad AB := 8\ ft \quad BC := 3\ ft \quad CD := 6\ ft \quad AC := AB + BC = 11\ ft$

$t_{ft} := 3\ in$ Top Flange Thickness

$b_{ft} := 3\ in$ Bottom Flange Thickness

$t_{fw} := 5.5\ in$ Top Flange Width

$b_{fw} := 6\ in$ Bottom Flange Width

$w_d := 16\ in$ Web Depth/Height

$w_w := 2\ in$ Web Width

$c_r := 0.6875\ in$ One Chamfer Radius

$h := t_{ft} + w_d + b_{ft} = 22\ in$ Beam Height

$l_{perim} := 2 \cdot c_r \cdot \pi + \left(2 \cdot w_d + 2 \cdot t_{fw} + 2 \cdot t_{ft} + \left(2 \cdot b_{fw} + 2 \cdot b_{ft} - 8 \cdot c_r\right) - 2 \cdot w_w\right) = 61.82\ in$ Cross Sectional Perimeter

Cross Sectional Areas and Volume

$A_{tf} := t_{ft} \cdot t_{fw} = 16.5\ in^2$ Area of Top Flange

$A_{bf} := b_{ft} \cdot b_{fw} = 18\ in^2$ Area of Bottom Flange

$A_{webrect} := w_d \cdot w_w = 32\ in^2$ Area of Web Rectangle

$A_{ch} := c_r^2 - \frac{\pi \cdot c_r^2}{4} = 0.101\ in^2$ Area of Chamfers

$A_{web} := A_{webrect} + A_{ch} = 32.101\ in^2$ Area of Total Web

$A_{total} := A_{tf} + A_{web} + A_{bf} = 66.601\ in^2$ Total Cross Sectional Area

$V_{total} := A_{total} \cdot l = 0.308\ yd^3$ Cross Sectional Volume

Cross Sectional Centroids

$y_{tf} := \frac{t_{ft}}{2} + w_d + b_{ft} = 20.5\ in$ — Centroid of Top Flange

$y_{bf} := \frac{b_{ft}}{2} = 1.5\ in$ — Centroid of Bottom Flange

$y_{web} := b_{ft} + \frac{w_d}{2} = 11\ in$ — Centroid of Web Rectangle or Total Web

$y_{tcham} := b_{ft} + w_d - 4\ \frac{c_r}{3 \cdot \pi} = 18.708\ in$ — Centroid of Top Chamfers

$y_{bcham} := b_{ft} + 4\ \frac{c_r}{3 \cdot \pi} = 3.292\ in$ — Centroid of Bottom Chamfers

$y_{bmbot} := \frac{A_{tf} \cdot y_{tf} + A_{web} \cdot y_{web} + A_{bf} \cdot y_{bf}}{A_{total}} = 10.786\ in$ — Beam Centroid From Bottom

$y_{bmtop} := h - y_{bmbot} = 11.214\ in$ — Beam Centroid From Top

Moment of Inertia (MOI)

$I_{tf} := \frac{1}{12}\ t_{fw} \cdot t_{ft}^{3} + A_{tf} \cdot \left(y_{tf} - y_{bmbot}\right)^{2} = \left(1.569 \cdot 10^{3}\right)\ in^{4}$ — MOI of Top Flange

$I_{webrect} := \frac{1}{12}\ w_w \cdot w_d^{3} + A_{web} \cdot \left(y_{web} - y_{bmbot}\right)^{2} = 684.136\ in^{4}$ — MOI of Web Rectangle

$I_{tcha} := 2\left(\frac{\pi}{8}\ c_r^{4} + A_{ch} \cdot \left(y_{tcham} - y_{bmbot}\right)^{2}\right) = 12.907\ in^{4}$ — MOI of Top Chamfers

$I_{bcha} := 2\left(\frac{\pi}{8}\ c_r^{4} + A_{ch} \cdot \left(y_{bcham} - y_{bmbot}\right)^{2}\right) = 11.569\ in^{4}$ — MOI of Bottom Chamfers

$I_{bf} := \frac{1}{12}\ b_{fw} \cdot b_{ft}^{3} + A_{bf} \cdot \left(y_{bf} - y_{bmbot}\right)^{2} = \left(1.566 \cdot 10^{3}\right)\ in^{4}$ — MOI of Top Flange

$I_{total} := I_{tf} + I_{webrect} + I_{tcha} + I_{bcha} + I_{bf} = \left(3.844 \cdot 10^{3}\right)\ in^{4}$ — Total MOI

BEAM COMPOSITION

Concrete; Updated Based on Recorded Cylinder Test Data

$\rho := 124.1\ pcf$	Concrete Density
Lightweight	Concrete Type
$\lambda := 0.75$	Lightweight Factor
$d_{agr} := 0.5\ in$	Maximum Aggregate Diameter
$Rel_{hud} := 40$	Relative Humidity (%)
$f'_{ci} := 6334\ psi$	Initial Concrete Strength (at transfer)
$f'_c := 7808.64\ psi$	Strength of Concrete (ASTM C78)
$E_{ci} := 33 \cdot \left(\frac{\rho}{pcf}\right)^{1.5} \cdot \sqrt[2]{\frac{f'_{ci}}{psi}} \cdot psi = 3630.87\ ksi$	Initial Concrete Modulus of Elasticity
$E_c := 33 \cdot \left(\frac{\rho}{pcf}\right)^{1.5} \cdot \sqrt[2]{\frac{f'_c}{psi}} \cdot psi = 4031.432\ ksi$	Concrete Modulus of Elasticity

7-Wire Strand (Tension)

$f_{pu} := 270\ ksi$	Strand Ultimate Strength
$E_{ps} := 28500\ ksi$	Modulus of Elasticity of Strands
$d_{ps} := 0.5\ in$	Diameter of Tension Prestressing Strands
$w_{ps} := 0.52\ plf$	Weight of Prestressing Strands
$A_{ps} := 0.153\ in^2$	Nominal Area of 7-Wire Low-Lax Strands
$n_{ps} := 2$	Number of Prestressing Strands
$y_{ps1} := 2\ in$	Distance from Bottom of Beam to Strand 1
$y_{ps2} := 2\ in$	Distance from Bottom of Beam to Strand 2
$y_{ps3} := 0\ in$	Distance from Bottom of Beam to Strand 3
$s_{min1} := \max\left(2\ in, \frac{4}{3}\left(d_{agr} + d_{ps}\right)\right) = 2\ in$	Minimum Center to Center Spacing Pretensioned Strands (ACI 318-18, 25.2.4)

7-Wire Strand (Compression)

$d_{psc} := 0.375\ in$ — Diameter of Compression Prestressing Strands

$A_{psc} := 0.085\ in^2$ — Nominal Area of Compression 7-Wire Low-Lax Strands

$n_{psc} := 2$ — Number of Compression Prestressing Strands

$w_{psc} := 0.273\ plf$ — Weight of Compression Prestressing Strands

$y_{psc1} := 1.25\ in$ — Distance from Top of Beam to Strand 1

$y_{psc2} := 1.25\ in$ — Distance from Top of Beam to Strand 2

$s_{min2} := \max\left(1.75\ in, \frac{4}{3}\left(d_{agr} + d_{psc}\right)\right) = 1.75\ in$ — Minimum Center to Center Spacing Pretensioned Compression Strands (ACI 318-18, 25.2.4)

Steel Rebar (Compression)

$E_r := 29000\ ksi$ — Modulus of Elasticity of Steel Rebar

$d_r := 0\ in$ — Diameter of Steel Rebar

$w_r := 0\ plf$ — Weight of Steel Rebar

$A_r := 0\ in^2$ — Nominal Area of Steel Rebar

$n_r := 0$ — Number of Compression Reinforcement Bars

$y_{r1} := 0\ in$ — Distance from Bottom of Beam to Rebar 1

$y_{r2} := 0\ in$ — Distance from Bottom of Beam to Rebar 2

Steel Stirrups (Shear)

$f_y := 60\ ksi$ — Stirrup Strength

$d_{stir} := 0.375\ in$ — Diameter of Stirrup

$w_{stir} := 0.376\ plf$ — Weight of Stirrups

$A_{stir} := 0.110\ in^2$ — Nominal Area of Stirrup

$n_{legs} := 1$ — Number of Stirrup Legs

$n_{stir} := 29$ — Number of Stirrups

$l_{stir} := 23.4375\ in$ — Length of Stirrups

Eccentricity of Bottom Strands

$y_{stl} := \left(\left(A_{ps} \cdot y_{ps1}\right) + \left(A_{ps} \cdot y_{ps2}\right) + \left(A_{ps} \cdot y_{ps3}\right) + \left(A_r \cdot y_{r1}\right) + \left(A_r \cdot y_{r2}\right) \right) \div \left(A_{ps} \cdot n_{ps} + A_r \cdot n_r\right) = 2\ \mathbf{in}$

Centroid of Steel Within the Beam Designed to Resist Moment

$h_{barc} := h - y_{stl} = 20\ \mathbf{in}$

Height to Center of Bars

$e := h_{barc} - y_{bmtop} = 8.786\ \mathbf{in}$

Beam Eccentricity

Eccentricity of Top Strands

$y_{stlc} := \left(\left(A_{psc} \cdot y_{psc1}\right) + \left(A_{psc} \cdot y_{psc2}\right) + \left(A_r \cdot y_{r1}\right) + \left(A_r \cdot y_{r2}\right) \right) \div \left(A_{psc} \cdot n_{psc} + A_r \cdot n_r\right) = 1.25\ \mathbf{in}$

Centroid of Top Steel Within the Beam Designed to Resist Moment

$h_{cbarc} := y_{stlc} = 1.25\ \mathbf{in}$

Height to Center of Bars

$e_c := h_{cbarc} - y_{bmbot} = -9.536\ \mathbf{in}$

Beam Eccentricity

LOADING, MOMENT, AND SHEAR

Selfweight

$$w_{ship} := \left(\left(-A_{ps}-A_{psc}\right)\cdot\rho + n_{ps}\cdot w_{ps}+n_{psc}\cdot w_{psc}\right)\cdot l + \left(V_{total}-A_{stir}\cdot l_{stir}\right)\cdot\rho + l_{stir}\cdot n_{stir}\cdot w_{stir} = 1079.122\ \mathbf{lbf}$$

Shipping Weight

$$w_{sw} := w_{ship} \div l = 59.951\ \mathbf{plf}$$

Selfweight

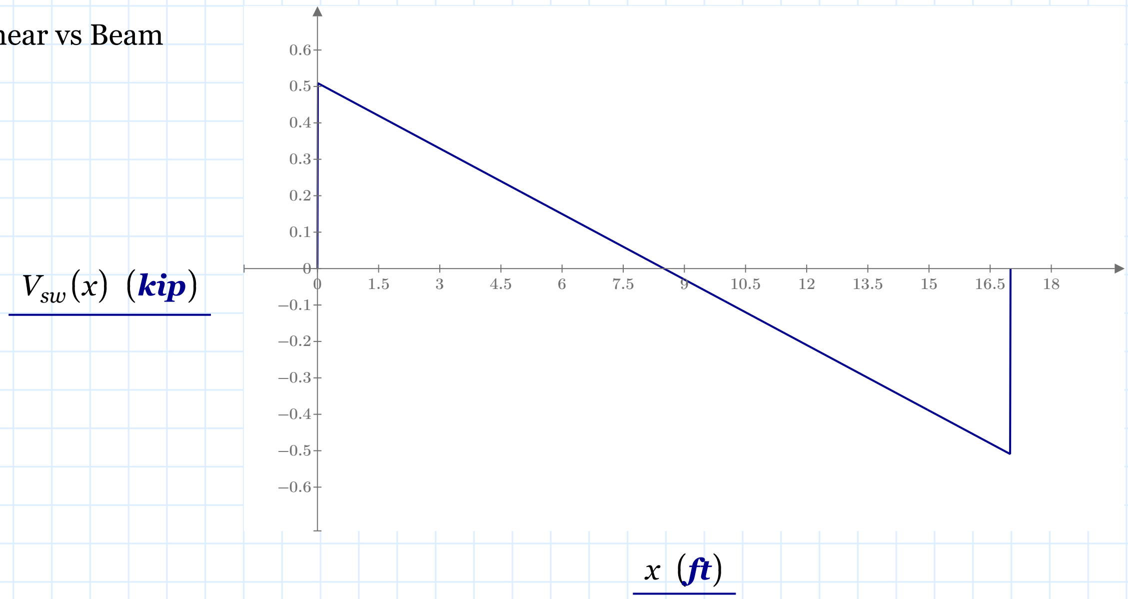
$$Weight \equiv 1079.122\cdot \mathbf{lbf}$$

$$check := \mathbf{if}\left(w_{ship} < 2000\ \mathbf{lbf}, \text{“OK”}, \text{“NG”}\right) = \text{“OK”}$$

Truck Capacity Check

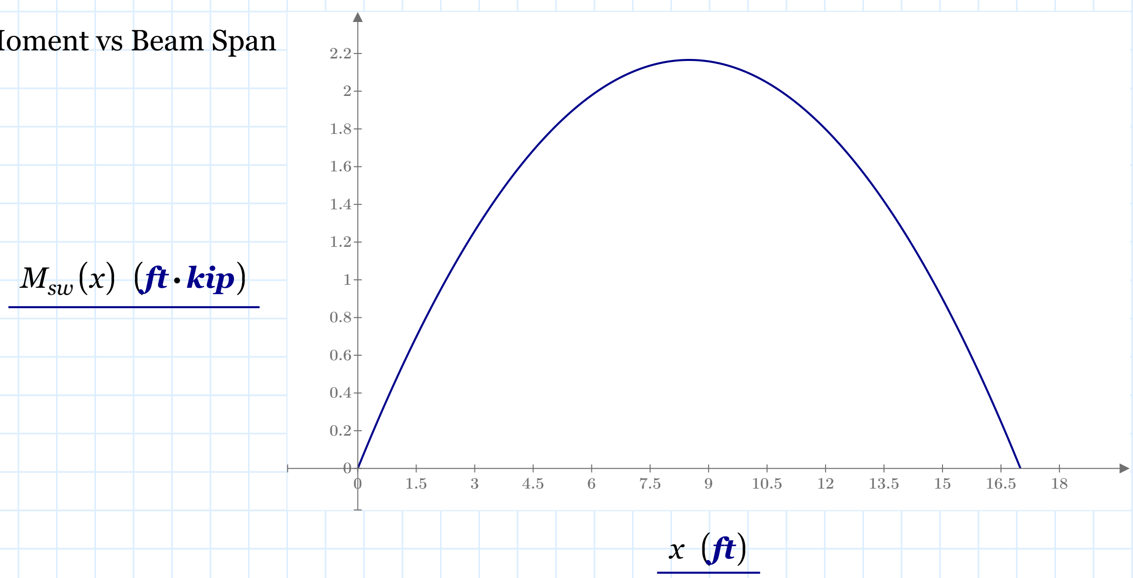
$$V_{sw}(x) := \mathbf{if}\left(0<x<l_s, w_{sw}\cdot\left(0.5\cdot l_s - x\right), 0\right)$$

Selfweight Shear vs Beam Span Length



$$M_{sw}(x) := \frac{w_{sw}\cdot x}{2}\left(l_s - x\right)$$

Selfweight Moment vs Beam Span Length



Live Load

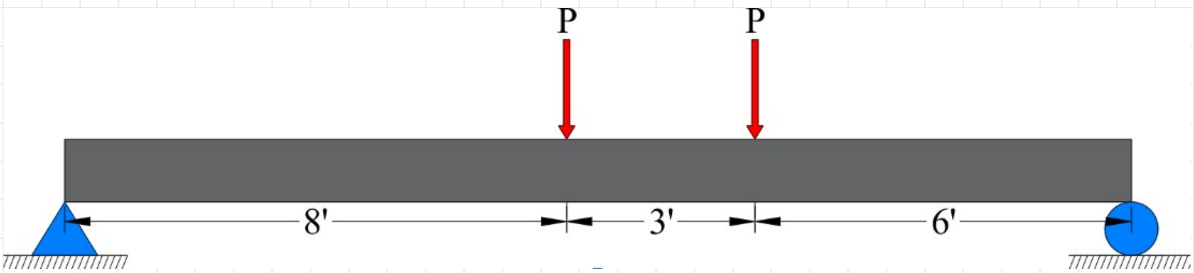


Figure 2: Competition Loading Diagram

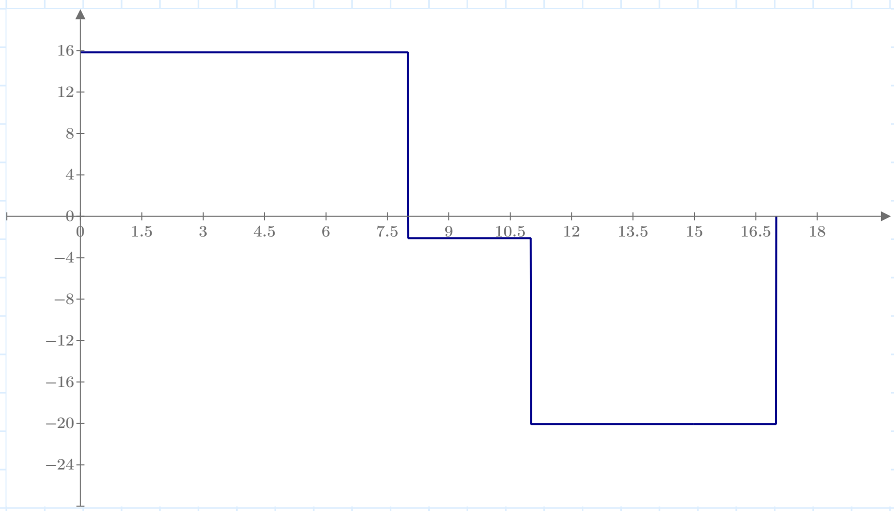
$P := 17.954\ \textbf{kip}$ $\qquad \Sigma M = 0\ kip \cdot ft$ $\qquad \Sigma F_y = 0\ kip$ $\qquad \Sigma F_x = 0\ kip$ $\qquad A_x = 0\ kip$

$D_y := \dfrac{P \cdot (AB) + P \cdot (AC)}{l_s} = 20.066\ \textbf{kip}$ $\qquad A_y := 2\ P - D_y = 15.842\ \textbf{kip}$

$$V_{LL}(x) := \textbf{if}\left(x \le AB, A_y, \textbf{if}\left(AB < x \le AC, \frac{P}{l_s} \cdot (CD - AB), \textbf{if}\left(AC < x < l_s, -D_y, 0\ \textbf{kip}\right)\right)\right)$$

Live Load Shear vs Beam Span Length

$V_{LL}(x)\ (\textbf{kip})$

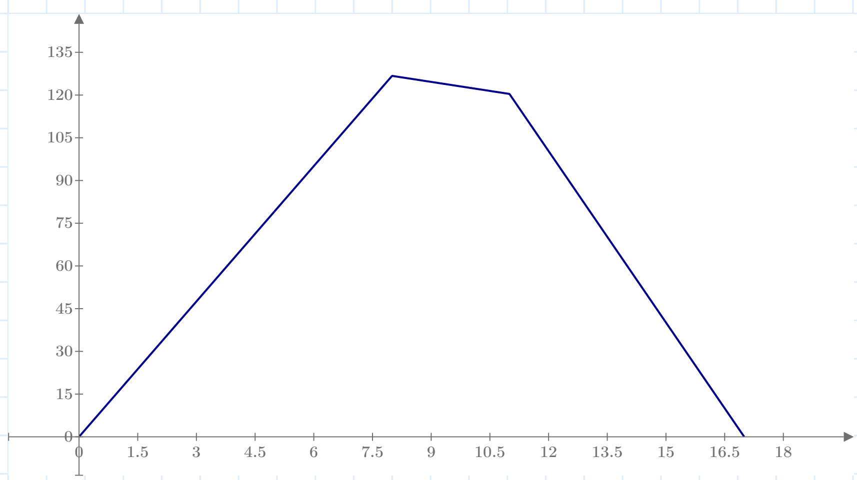


$x\ (\textbf{ft})$

$$M_{LL}(x) := \textbf{if}\left(x \le AB, A_y \cdot x, \textbf{if}\left(AB < x < AC, A_y \cdot x - P \cdot (x - AB), D_y \cdot CD - D_y \cdot (x - AC)\right)\right)$$

Live Load Moment vs Beam Span Length

$M_{LL}(x)\ (\textbf{kip} \cdot \textbf{ft})$

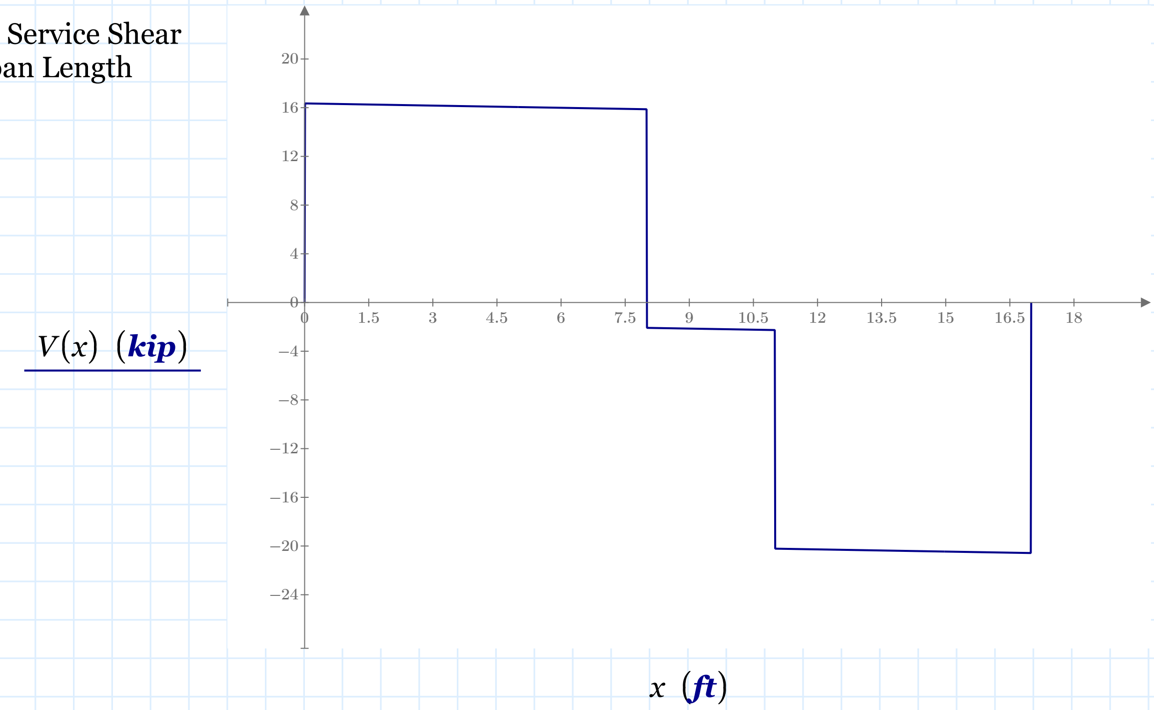


$x\ (\textbf{ft})$

Total Factored Shear

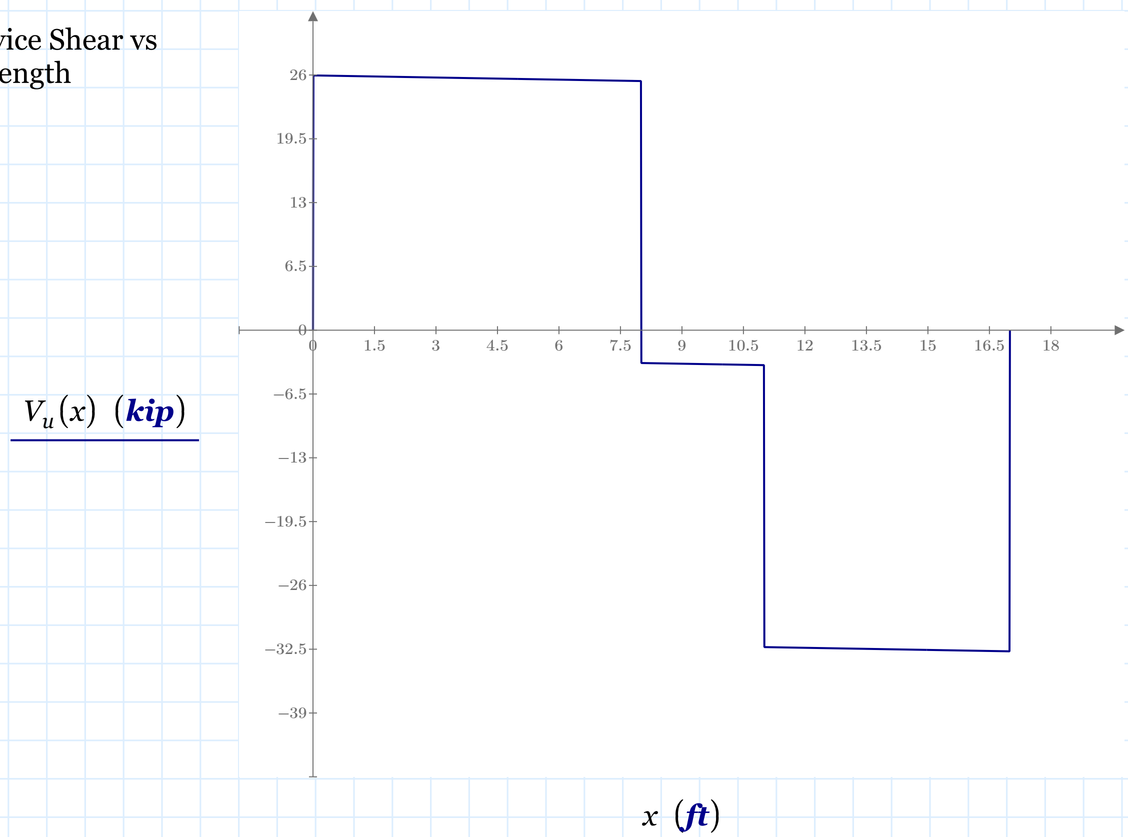
$V(x) := \textbf{if}\left(0 < x < l_s, V_{sw}(x) + V_{LL}(x), 0\ \textbf{kip}\right)$

Unfactored Service Shear vs Beam Span Length



$V_u(x) := \textbf{if}\left(0 < x < l_s, 1.2\ V_{sw}(x) + 1.6\ V_{LL}(x), 0\ \textbf{kip}\right)$

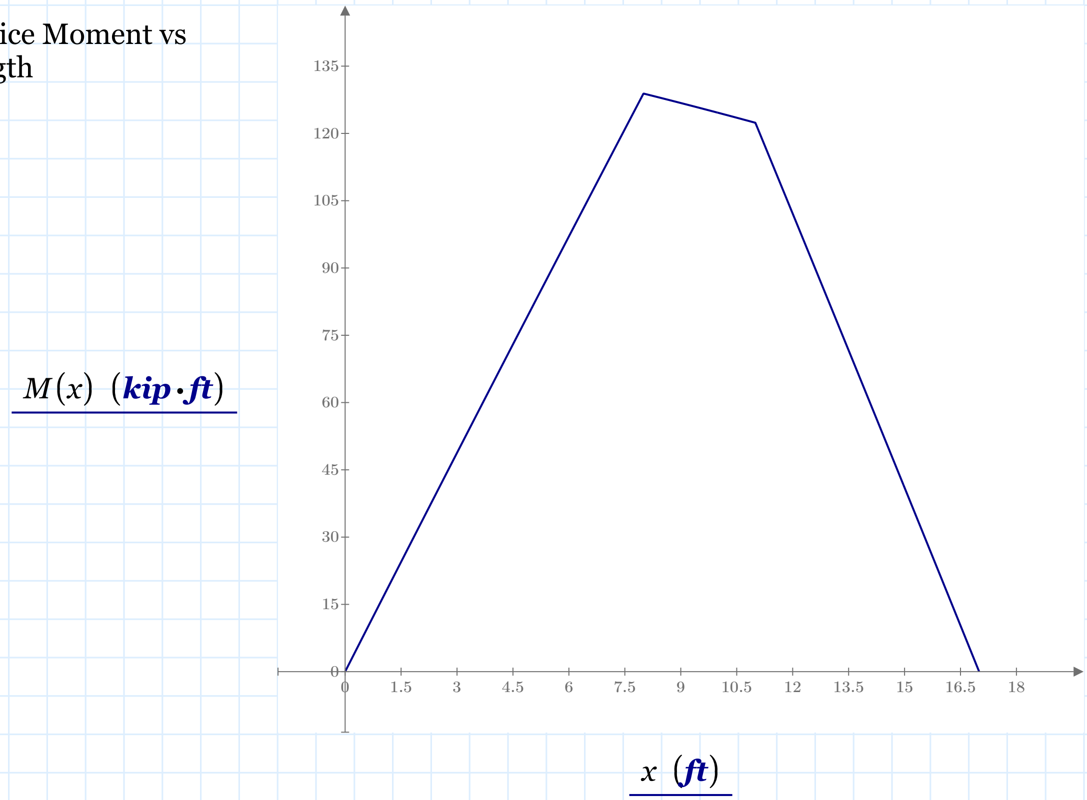
Factored Service Shear vs Beam Span Length



Total Factored Moment

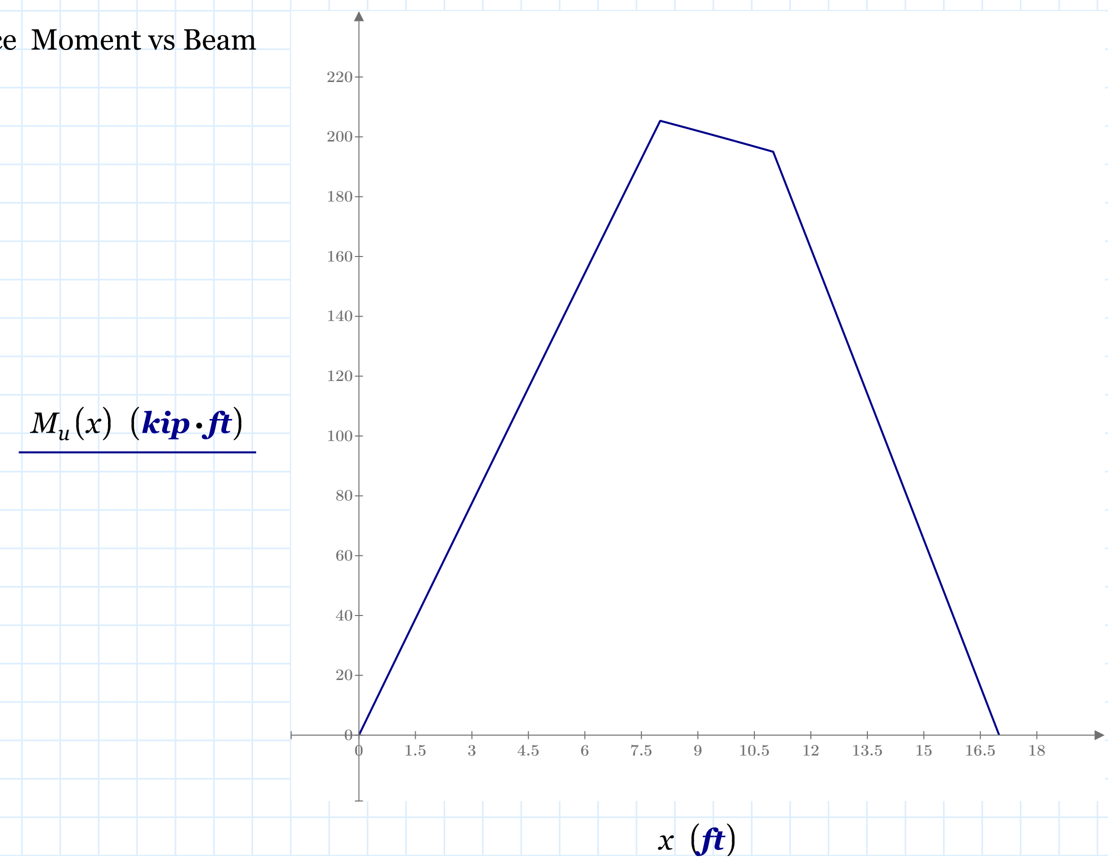
$M(x) := M_{sw}(x) + M_{LL}(x)$

Unfactored Service Moment vs Beam Span Length



$M_u(x) := 1.2\ M_{sw}(x) + 1.6\ M_{LL}(x)$

Factored Service Moment vs Beam Span Length



LOSSES

Elastic Shortening

$f_j := 0.75 \cdot f_{pu} = 202.5\ ksi$ — Jacking Stress

$P_j := f_j \cdot A_{ps} \cdot n_{ps} = 61.965\ kip$ — Jacking Force

$P_{j.ind} := \frac{P_j}{n_{ps}} = 30.983\ kip$ — Individual Jacking Force per Strand

$k_{cir} := 0.9$ — Elastic Shortening Coefficient

$k_{es} := 1.0$ — Initial Camber Coefficient

$M_{midsw} := \frac{w_{sw} \cdot l^2}{8} = 29.136\ kip \cdot in$ — Maximum Moment of the Beam due to Selfweight

$f_{cir} := k_{cir} \cdot \left(\frac{P_j}{A_{total}} + \frac{P_j \cdot e^2}{I_{total}}\right) - \frac{M_{midsw} \cdot e}{I_{total}} = 1.891\ ksi$ — Strand Stress at the Strand Centroid

$ES := \frac{E_{ps}}{E_{ci}} \cdot k_{es} \cdot f_{cir} = 14.842\ ksi$ — Elastic Shortening

Creep

$k_{cr} := \mathbf{if}(\lambda < 1, 1.6, 2) = 1.6$ — Lightweight/Normalweight Concrete Cracking Coefficient

$CR := k_{cr} \cdot \left(\frac{E_{ps}}{E_c}\right) \cdot (f_{cir}) = 21.387\ ksi$ — Concrete Creep

Shrinkage

$V_{overS} := \frac{A_{total}}{l_{perim}} = 1.077\ in$ — Effective Thickness for Shrinkage

$k_{sh} := 1.0$ — Shrinkage Constant

$SH := 8.2 \cdot 10^{-6} \cdot k_{sh} \cdot E_{ps} \cdot (1\ ft - 0.06 \cdot V_{overS}) \cdot (100 - Rel_{hud}) \cdot \frac{1}{ft} = 13.946\ ksi$ — Concrete Shrinkage

Steel Relaxation

$K_{re} := 5\ ksi$ — Initial Relaxation Stress

$J := 0.04$ — Relaxation Curve Factor

$C := 1.0$ — Strand Adjustment Coefficient

$ju_{ps} := \frac{f_j - ES}{f_{pu}} = 0.695$ — Normalized Jacking Stress Factor

$C_{ps} := \mathbf{if}\left(ju_{ps} \ge 0.54, \frac{ju_{ps}}{0.21} \cdot \left(\frac{ju_{ps}}{0.9} - 0.55\right), \frac{ju_{ps}}{4.25}\right) = 0.736$ — Stress Dependent Relaxation Factor

$RE := C_{ps} \cdot (K_{re} - J \cdot (SH + CR + ES)) = 2.202\ ksi$ — Steel Relaxation

Stress After Losses

$L_{short} := ES = 14.842\ ksi$ — Short Term Losses

$L_{long} := CR + SH + RE = 37.535\ ksi$ — Long Term Losses

$L_{total} := L_{short} + L_{long} = 52.377\ ksi$ — Total Losses

$f_{pi} := f_j - L_{short} = 187.658\ ksi$ — Initial Stress After Elastic Shortening

$f_{pe} := f_j - L_{long} = 164.965\ ksi$ — Final Stress After Creep, Shrinkage, and Steel Relaxation

Forces After Losses

$P_i := A_{ps} \cdot n_{ps} \cdot f_{pi} = 57.423 \ \mathbf{kip}$ Prestress Force After Short Term Losses

$P_e := A_{ps} \cdot n_{ps} \cdot f_{pe} = 50.479 \ \mathbf{kip}$ Prestress Force After Long Term Losses

Elastic Shortening Top Strands

$f_{jc} := 0.1875 \cdot f_{pu} = 50.625 \ \mathbf{ksi}$ Jacking Stress

$P_{jc} := f_{jc} \cdot A_{psc} \cdot n_{psc} = 8.606 \ \mathbf{kip}$ Jacking Force

$P_{j.indc} := \dfrac{P_{jc}}{n_{psc}} = 4.303 \ \mathbf{kip}$ Individual Jacking Force per Strand

$k_{circ} := 0.9$ Elastic Shortening Coefficient

$k_{esc} := 1.0$ Initial Camber Coefficient

$M_{midswc} := \dfrac{w_{sw} \cdot l^2}{8} = 29.136 \ \mathbf{kip} \cdot \mathbf{in}$ Maximum Moment of the Beam due to Selfweight

$f_{circ} := k_{cir} \cdot \left(\dfrac{P_{jc}}{A_{total}} + \dfrac{P_{jc} \cdot {e_c}^2}{I_{total}} \right) - \dfrac{M_{midsw} \cdot e_c}{I_{total}} = 0.372 \ \mathbf{ksi}$ Strand Stress at the Strand Centroid

$ES_c := \dfrac{E_{ps}}{E_{ci}} \cdot k_{es} \cdot f_{circ} = 2.919 \ \mathbf{ksi}$ Elastic Shortening

Creep Top Strands

$k_{crc} := \mathbf{if}\left(\lambda < 1, 1.6, 2\right) = 1.6$ Lightweight/Normalweight Concrete Cracking Coefficient

$CR_c := k_{cr} \cdot \left(\dfrac{E_{ps}}{E_c} \right) \cdot \left(f_{circ} \right) = 4.206 \ \mathbf{ksi}$ Concrete Creep

Steel Relaxation Top Strands

$K_{rec} := 5 \ \mathbf{ksi}$ Initial Relaxation Stress

$J_c := 0.04$ Relaxation Curve Factor

$C_c := 1.0$ Strand Adjustment Coefficient

$ju_{psc} := \dfrac{f_{jc} - ES}{f_{pu}} = 0.133$ Normalized Jacking Stress Factor

$C_{psc} := \mathbf{if}\left(ju_{psc} \ge 0.54, \dfrac{ju_{psc}}{0.21} \cdot \left(\dfrac{ju_{psc}}{0.9} - 0.55 \right), \dfrac{ju_{psc}}{4.25} \right) = 0.031$ Stress Dependent Relaxation Factor

$RE_c := C_{psc} \cdot \left(K_{re} - J \cdot \left(SH + CR_c + ES_c \right) \right) = 0.13 \ \mathbf{ksi}$ Steel Relaxation

Stress After Losses Top Strands

$L_{shortc} := ES_c = 2.919 \ \mathbf{ksi}$ Short Term Losses

$L_{longc} := CR_c + SH + RE_c = 18.282 \ \mathbf{ksi}$ Long Term Losses

$L_{totalc} := L_{shortc} + L_{longc} = 21.201 \ \mathbf{ksi}$ Total Losses

$f_{pic} := f_{jc} - L_{shortc} = 47.706 \ \mathbf{ksi}$ Initial Stress After Elastic Shortening

$f_{pec} := f_{jc} - L_{longc} = 32.343 \ \mathbf{ksi}$ Final Stress After Creep, Shrinkage, and Steel Relaxation

Forces After Losses Top Strands

$P_{ic} := A_{psc} \cdot n_{psc} \cdot f_{pic} = 8.11 \ \mathbf{kip}$ Prestress Force After Short Term Losses

$P_{ec} := A_{psc} \cdot n_{psc} \cdot f_{pec} = 5.498 \ \mathbf{kip}$ Prestress Force After Long Term Losses

FLEXURAL CAPACITY

Whitney Stress Block Method

$check := \textbf{if}\left(f_{pe} \geq 0.5\, f_{pu}, \text{"OK"}, \text{"NG"}\right) = \text{"OK"}$ — Minimum Steel Stress Requirement

$$\rho_r := \frac{A_{ps} \cdot n_{ps}}{t_{fw} \cdot h_{barc}} = 0.003$$

Prestress Reinforcement Ratio

$\gamma := 0.28$ — Prestressing Reinforcement Factor

$$\beta := \max\left(0.65, min\left(0.85, 0.85 - 0.05 \cdot \left(\frac{f'_c - 4\ ksi}{1\ ksi}\right)\right)\right) = 0.66$$

Whitney Stress Block Depth Factor

$$f_{ps} := f_{pu} \cdot \left(1 - \frac{\gamma}{\beta} \cdot \left(\rho_r \cdot \frac{f_{pu}}{f'_c}\right)\right) = 258.975\ ksi$$

Strength to Compute Flexural Capacity

$$a := \frac{A_{ps} \cdot n_{ps} \cdot f_{ps}}{0.85\, f'_c \cdot t_{fw}} = 2.171\ in$$

Depth of Whitney Stress Block

$$c := \frac{a}{\beta} = 3.291\ in$$

Initial Guess; Depth Towards the Neutral Axis

Refine Guess With Strain Compatibility

$$\varepsilon_{losses} := \frac{f_{pe}}{E_{ps}} = 5.788 \cdot 10^{-3}$$

Strain Due to Long Term Losses

$$\varepsilon_{decomp} := \frac{P_e}{A_{total} \cdot E_c} \cdot \left(1 + \frac{e^2 \cdot A_{total}}{I_{total}}\right) = 4.395 \cdot 10^{-4}$$

Steel Strain From Concrete Elastic Shortening

$\varepsilon_{cult} := 0.003$ — Concrete Ultimate Strain

$$\varepsilon_{stlcrsh} := \varepsilon_{cult} \cdot \left(\frac{h_{barc} - c}{c}\right) = 1.523 \cdot 10^{-2}$$

Steel Strain At Concrete Ultimate Strain Limit

$$\varepsilon_{str} := \varepsilon_{losses} + \varepsilon_{decomp} + \varepsilon_{stlcrsh} = 2.146 \cdot 10^{-2}$$

Combined Prestressed Strand Strain During Failure

$$f_{ps2} := \textbf{if}\left(\varepsilon_{str} < 0.0085, 28500\ ksi \cdot \varepsilon_{str}, 270\ ksi - \frac{0.04}{\varepsilon_{str} - 0.007}\ ksi\right)$$

$f_{ps2} = 267.233\ ksi$

Refined Strength to Compute Flexural Capacity

$$c_2 := \frac{A_{ps} \cdot n_{ps} \cdot f_{ps2}}{0.85 \cdot f'_c \cdot \beta \cdot t_{fw}} = 3.396\ in$$

Refined Guess; Depth Towards the Neutral Axis

$$a_2 := \frac{A_{ps} \cdot n_{ps} \cdot f_{ps2}}{0.85 \cdot f'_c \cdot t_{fw}} = 2.24\ in$$

Refined Depth of Whitney Stress Block

$check := \textbf{if}\left(a < t_{ft}, \text{"OK"}, \text{"NG"}\right) = \text{"OK"}$ — Check to See if Compression Block is Deeper Than Flange Thickness

$$M_n := \textbf{if}\left(a_2 > t_{ft}, \left(\left(0.85 \cdot f'_c \cdot t_{ft} \cdot (b_{fw} - w_w) \cdot \left(\frac{a_2}{2} - \frac{t_{ft}}{2}\right)\right) + A_{ps} \cdot n_{ps} \cdot f_{ps2} \cdot \left(h_{barc} - \frac{a_2}{2}\right)\right), A_{ps} \cdot n_{ps} \cdot f_{ps2} \cdot \left(h_{barc} - \frac{a}{2}\right)\right)$$

$M_n = 128.893\ kip \cdot ft$ — Nominal Moment Capacity

TRANSFER AND DEVELOPMENT LENGTH

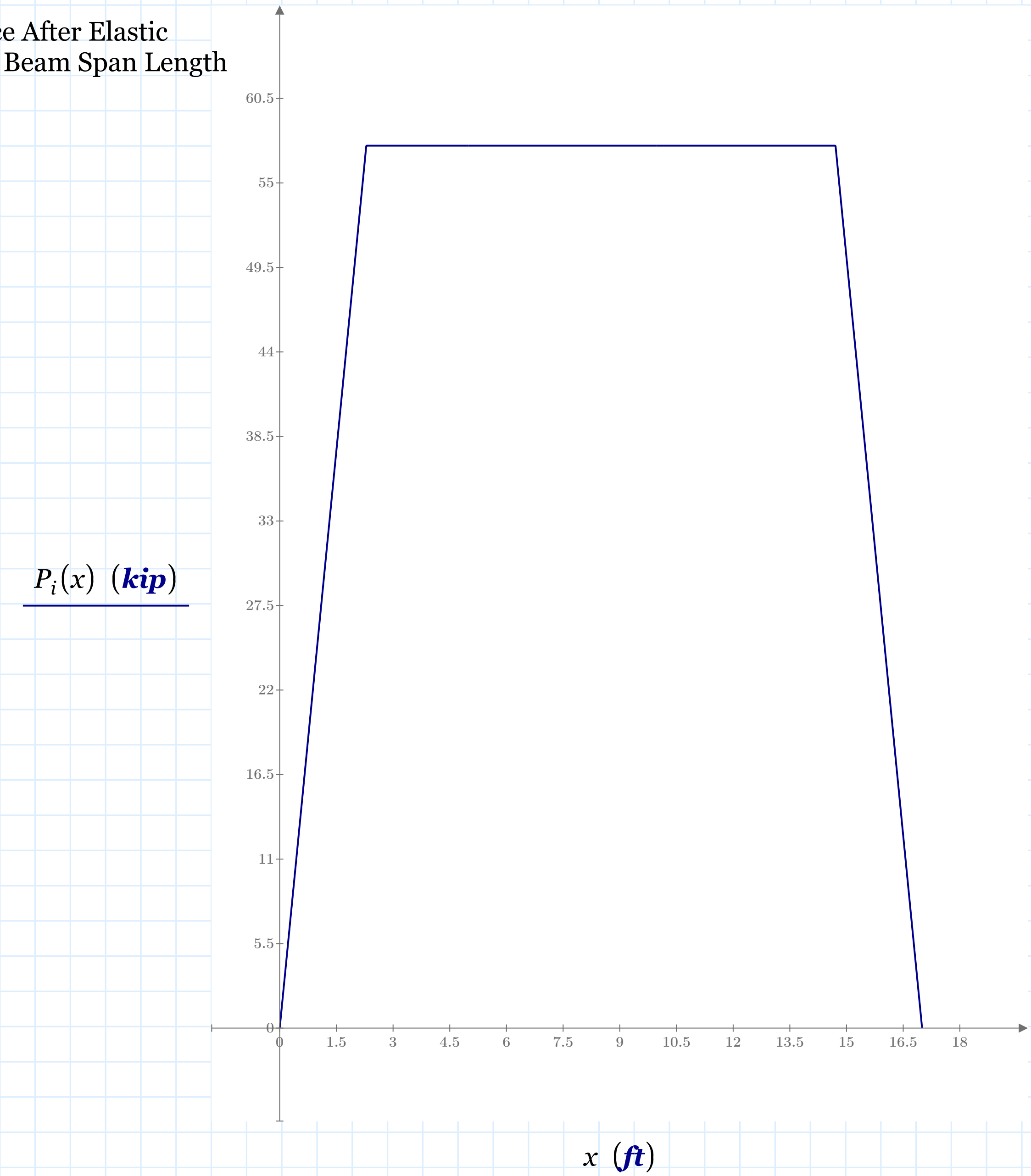
Prestress Force Function After Elastic Shortening

$l_t := \frac{f_{pe}}{3\ \mathbf{ksi}} d_{ps} = 2.291\ \mathbf{ft}$ Transfer Length

$$P_i(x) := \mathbf{if}\left(x \le l_t, \frac{x}{l_t} \cdot P_i, \mathbf{if}\left(l_t < x < l_s - l_t, P_i, P_i - \frac{P_i}{l_t} \cdot \left(x - \left(l_s - l_t\right)\right)\right)\right)$$

Prestress Force After Elastic Shortening Function (Short Term Losses)

Prestress Force After Elastic Shortening vs Beam Span Length



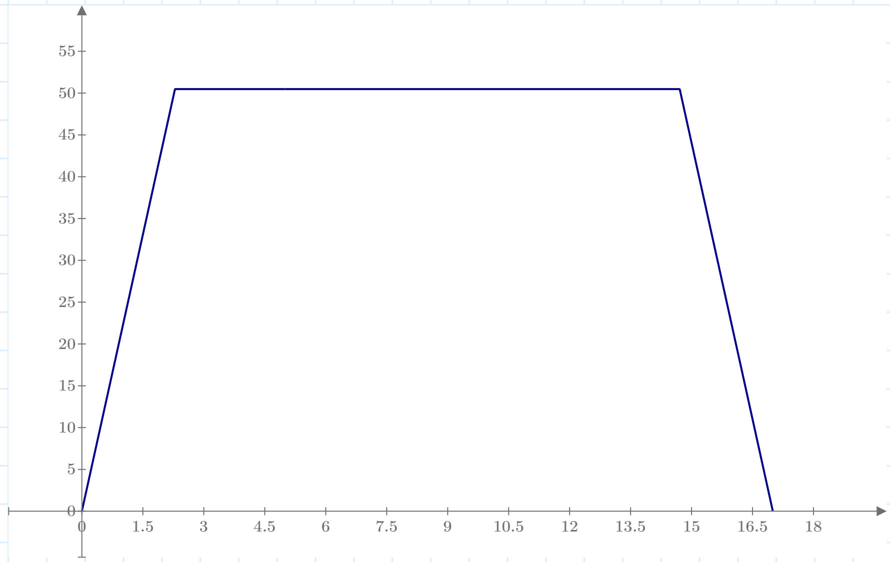
Prestress Force Function After Creep, Shrinkage, and Steel Relaxation

$$P_e(x) := \mathbf{if}\left(x \le l_t, \frac{x}{l_t} \cdot P_e, \mathbf{if}\left(l_t < x < l_s - l_t, P_e, P_e - \frac{P_e}{l_t} \cdot \left(x - \left(l_s - l_t\right)\right)\right)\right)$$

Prestress Force After Creep, Shrinkage, and Steel Relaxation Function (Long Term Losses)

Prestress Force After Creep, Shrinkage, and Steel Relaxation vs Beam Span Length

$P_e(x)$ $(\mathbf{kip})$



x $(\mathbf{ft})$

Top Strands Prestress Force Function After Elastic Shortening

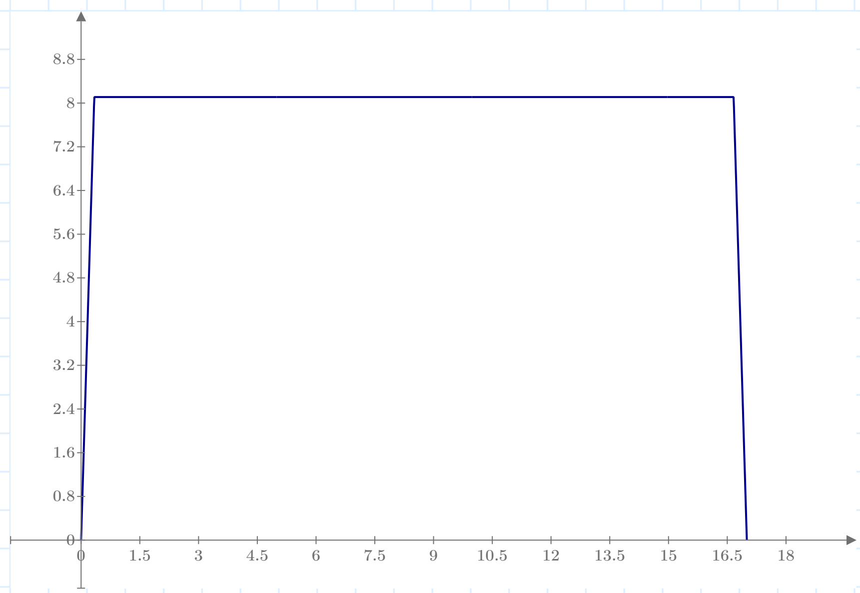
$l_{tc} := \frac{f_{pec}}{3\ \mathbf{ksi}} d_{psc} = 0.337\ \mathbf{ft}$ Transfer Length

$$P_{ic}(x) := \mathbf{if}\left(x \le l_{tc}, \frac{x}{l_{tc}} \cdot P_{ic}, \mathbf{if}\left(l_{tc} < x < l_s - l_{tc}, P_{ic}, P_{ic} - \frac{P_{ic}}{l_{tc}} \cdot \left(x - \left(l_s - l_{tc}\right)\right)\right)\right)$$

Prestress Force After Elastic Shortening Function (Short Term Losses)

Prestress Force After Elastic Shortening vs Beam Span Length

$P_{ic}(x)$ $(\mathbf{kip})$



x $(\mathbf{ft})$

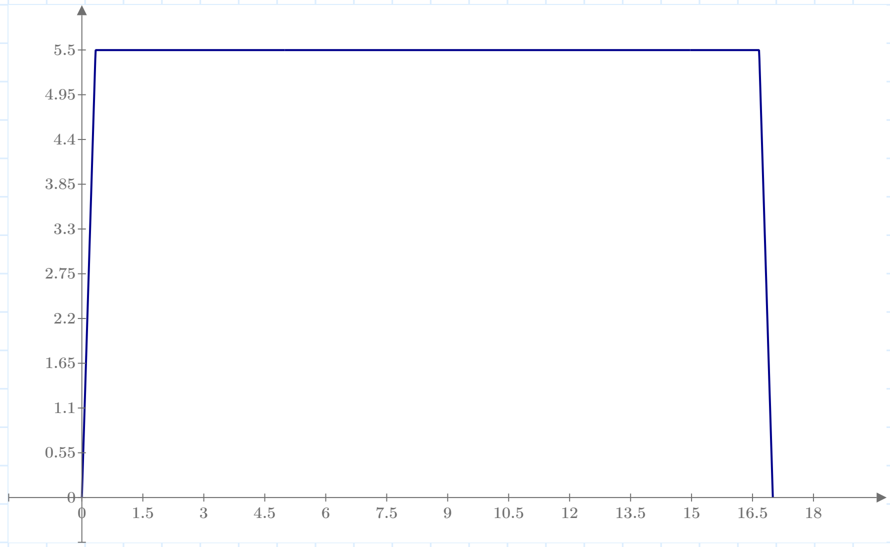
Top Strands Prestress Force Function After Creep, Shrinkage, and Steel Relaxation

$$P_{ec}(x) := \mathbf{if}\left(x \le l_{tc}, \frac{x}{l_{tc}} \cdot P_{ec}, \mathbf{if}\left(l_{tc} < x < l_s - l_{tc}, P_{ec}, P_{ec} - \frac{P_{ec}}{l_{tc}} \cdot \left(x - \left(l_s - l_{tc}\right)\right)\right)\right)$$

Prestress Force After Creep, Shrinkage, and Steel Relaxation Function (Long Term Losses)

Prestress Force After Creep, Shrinkage, and Steel Relaxation vs Beam Span Length

$P_{ec}(x)\ (kip)$



$x\ (ft)$

Transfer and Development Length Factor

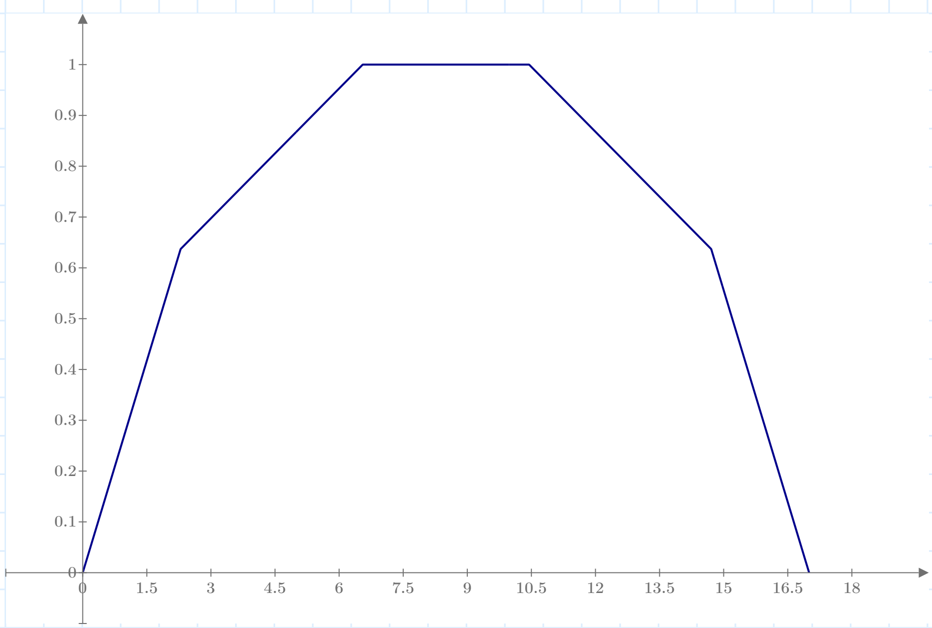
$$l_d := l_t + \frac{(f_{ps2} - f_{pe})}{1\ ksi}\, d_{ps} = 6.552\ ft$$

Development Length

$$k_{td}(x) := \text{if}\left(x < l_t, \frac{x}{l_t} \cdot \frac{f_{pe}}{f_{ps}}, \text{if}\left(l_t \le x \le l_d, \frac{x - l_t}{l_d - l_t} \cdot \left(1 - \frac{f_{pe}}{f_{ps}}\right) + \frac{f_{pe}}{f_{ps}}, \text{if}\left(l_d < x \le l_s - l_d, 1, \text{if}\left(l_s - l_d < x \le l_s - l_t, 1 - \frac{x - (l_s - l_d)}{l_d - l_t} \cdot \left(1 - \frac{f_{pe}}{f_{ps}}\right), \frac{f_{pe}}{f_{ps}} - \frac{x - (l_s - (l_t))}{l_t} \cdot \frac{f_{pe}}{f_{ps}}\right)\right)\right)\right)$$

Development Length Factor vs Beam Span Length

$k_{td}(x)$



$x\ (ft)$

ALLOWABLE STRESSES

Transfer Stress Limits

$f_{tTm} := 3 \cdot \sqrt[2]{f'_{ci}} \cdot \sqrt[2]{psi} = 238.759\ psi$ Transfer Tensile Limit at Midspan

$f_{tTe} := 6 \cdot \sqrt[2]{f'_{ci}} \cdot \sqrt[2]{psi} = 477.519\ psi$ Transfer Tensile Limit at Ends

$f_{tTPCI}(x) := \text{if}\left(x < 0.25 \cdot l_s, -0.7 \cdot f'_{ci}, \text{if}\left(0.25 \cdot l_s < x < 0.75 \cdot l_s, -0.6 \cdot f'_{ci}, -0.7 \cdot f'_{ci}\right)\right)$

PCI Tension Limit Function

$f_{tCe} := -0.7 \cdot f'_{ci} = -4433.8\ psi$ Transfer Compression Limit at Ends

$f_{tCm} := -0.6 \cdot f'_{ci} = -3800.4\ psi$ Transfer Compression Limit at Midspan

$f_{tCPCI}(x) := \text{if}\left(x < 0.25 \cdot l_s, 6 \cdot \sqrt[2]{f'_{ci}} \cdot \sqrt[2]{psi}, \text{if}\left(0.25 \cdot l_s < x < 0.75 \cdot l_s, 3 \cdot \sqrt[2]{f'_{ci}} \cdot \sqrt[2]{psi}, 6 \cdot \sqrt[2]{f'_{ci}} \cdot \sqrt[2]{psi}\right)\right)$

PCI Compression Limit Function

Transfer Applied Stress

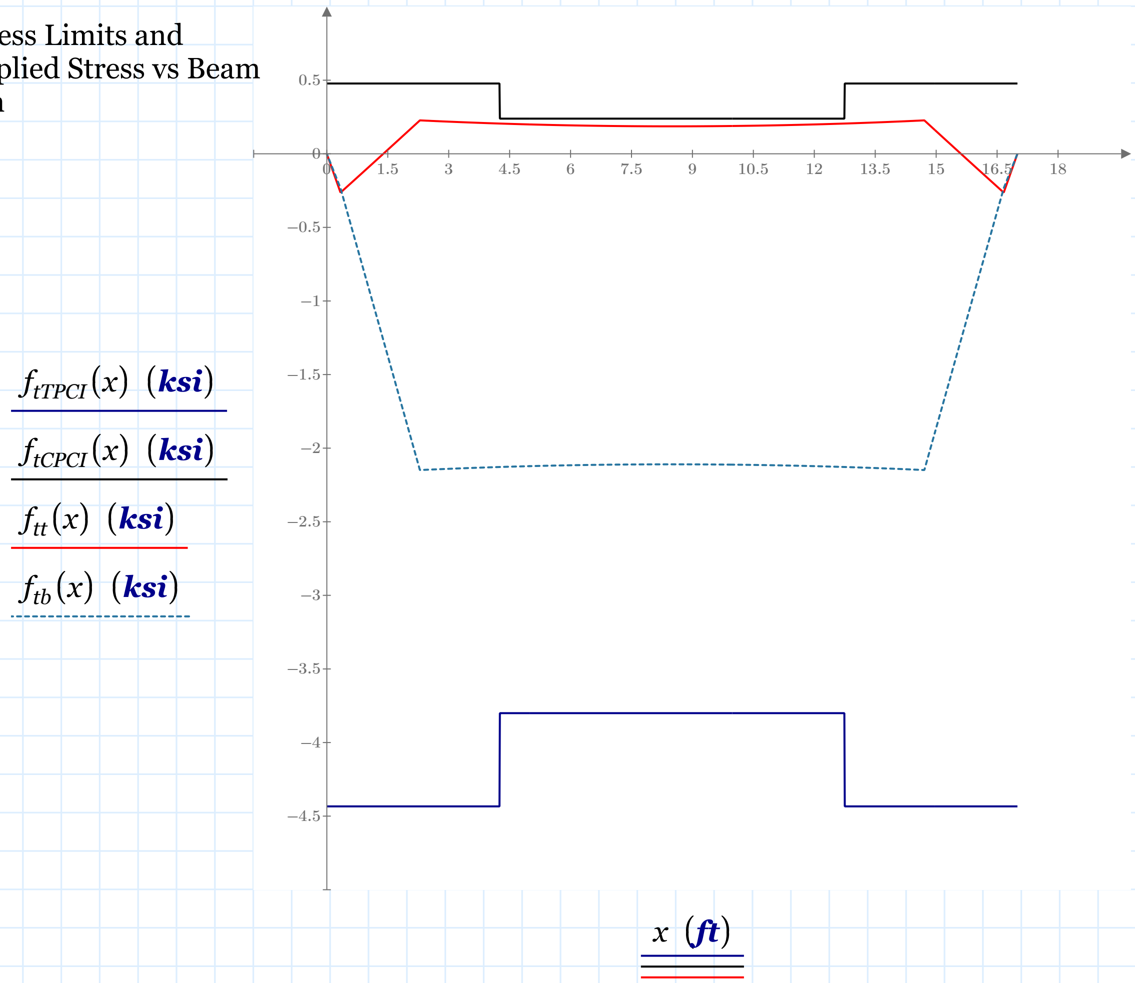
$$f_{tt}(x) := -\frac{P_i(x)}{A_{total}} + \frac{P_i(x) \cdot e \cdot y_{bmtop}}{I_{total}} - \frac{M_{sw}(x) \cdot y_{bmtop}}{I_{total}} - \frac{P_{ic}(x)}{A_{total}} + \frac{P_{ic}(x) \cdot e_c \cdot y_{bmtop}}{I_{total}}$$

Stress at Transfer Top of Beam

$$f_{tb}(x) := -\frac{P_i(x)}{A_{total}} - \frac{P_i(x) \cdot e \cdot y_{bmbot}}{I_{total}} + \frac{M_{sw}(x) \cdot y_{bmbot}}{I_{total}} - \frac{P_{ic}(x)}{A_{total}} - \frac{P_{ic}(x) \cdot e_c \cdot y_{bmbot}}{I_{total}}$$

Stress at Transfer Bottom of Beam

Transfer Stress Limits and Transfer Applied Stress vs Beam Span Length



Service Stress Limits

$f_{sT.PCI} := 7.5 \cdot \sqrt[2]{f'_c} \cdot \sqrt[2]{psi} = 0.663\ ksi$ Service Tensile Limit

$f_{sC.PCI} := -0.6 \cdot f'_c = -4.685\ ksi$ Service Compression Limit

Service Applied Stress

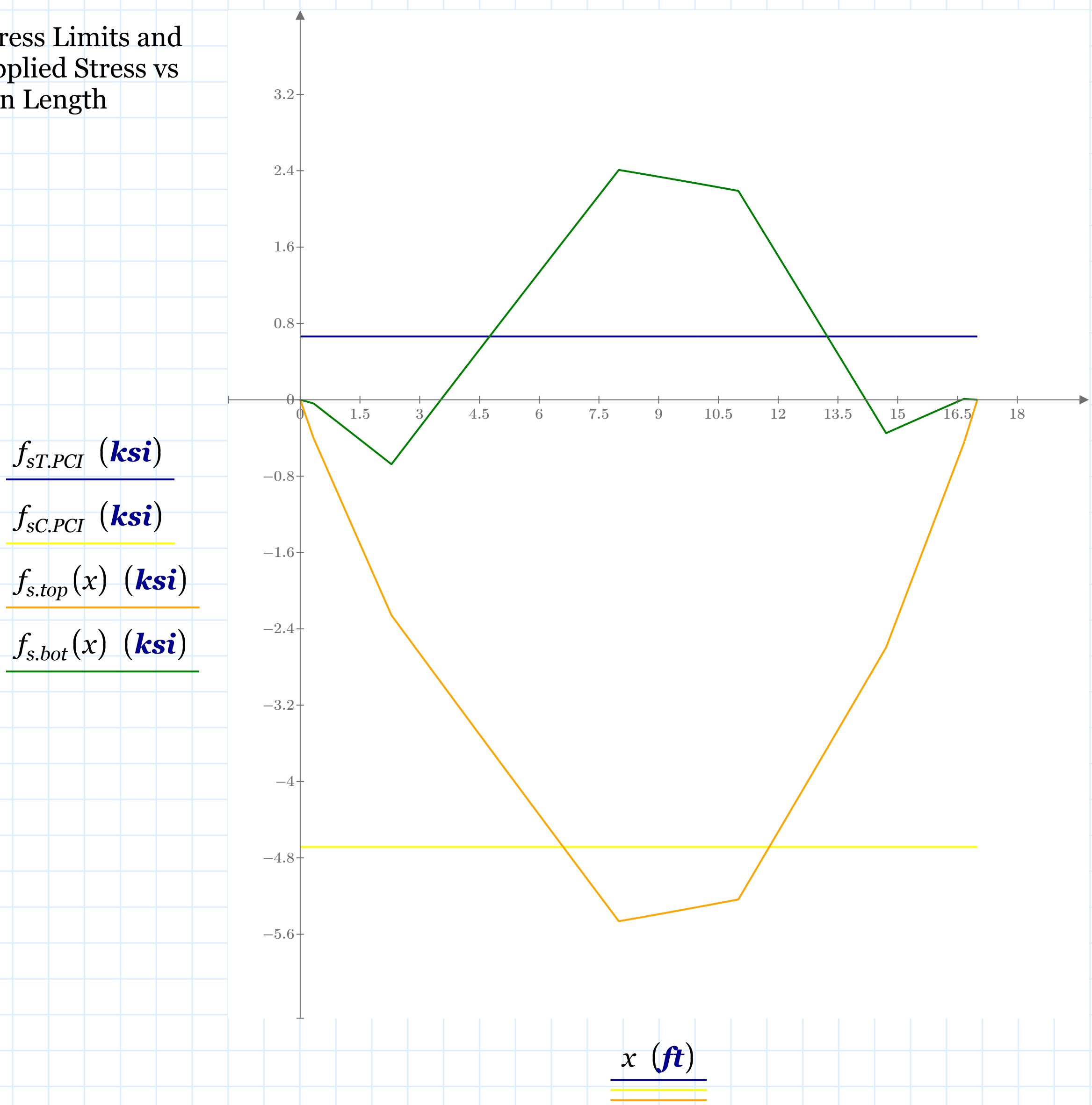
$$f_{s.top}(x) := -\frac{P_e(x)}{A_{total}} + \frac{P_e(x) \cdot e \cdot y_{bmtop}}{I_{total}} - \frac{M_{sw}(x) \cdot y_{bmtop}}{I_{total}} - \frac{M_{LL}(x) \cdot y_{bmtop}}{I_{total}} - \frac{P_{ec}(x)}{A_{total}} + \frac{P_e(x) \cdot e_c \cdot y_{bmtop}}{I_{total}}$$

Applied Stress At Top of Beam

$$f_{s.bot}(x) := -\frac{P_e(x)}{A_{total}} - \frac{P_e(x) \cdot e \cdot y_{bmbot}}{I_{total}} + \frac{M_{sw}(x) \cdot y_{bmbot}}{I_{total}} + \frac{M_{LL}(x) \cdot y_{bmbot}}{I_{total}} - \frac{P_{ec}(x)}{A_{total}} - \frac{P_{ec}(x) \cdot e_c \cdot y_{bmtop}}{I_{total}}$$

Applied Stress At Bottom of Beam

Service Stress Limits and Service Applied Stress vs Beam Span Length



MOMENT CAPACITY

Cracking Moment

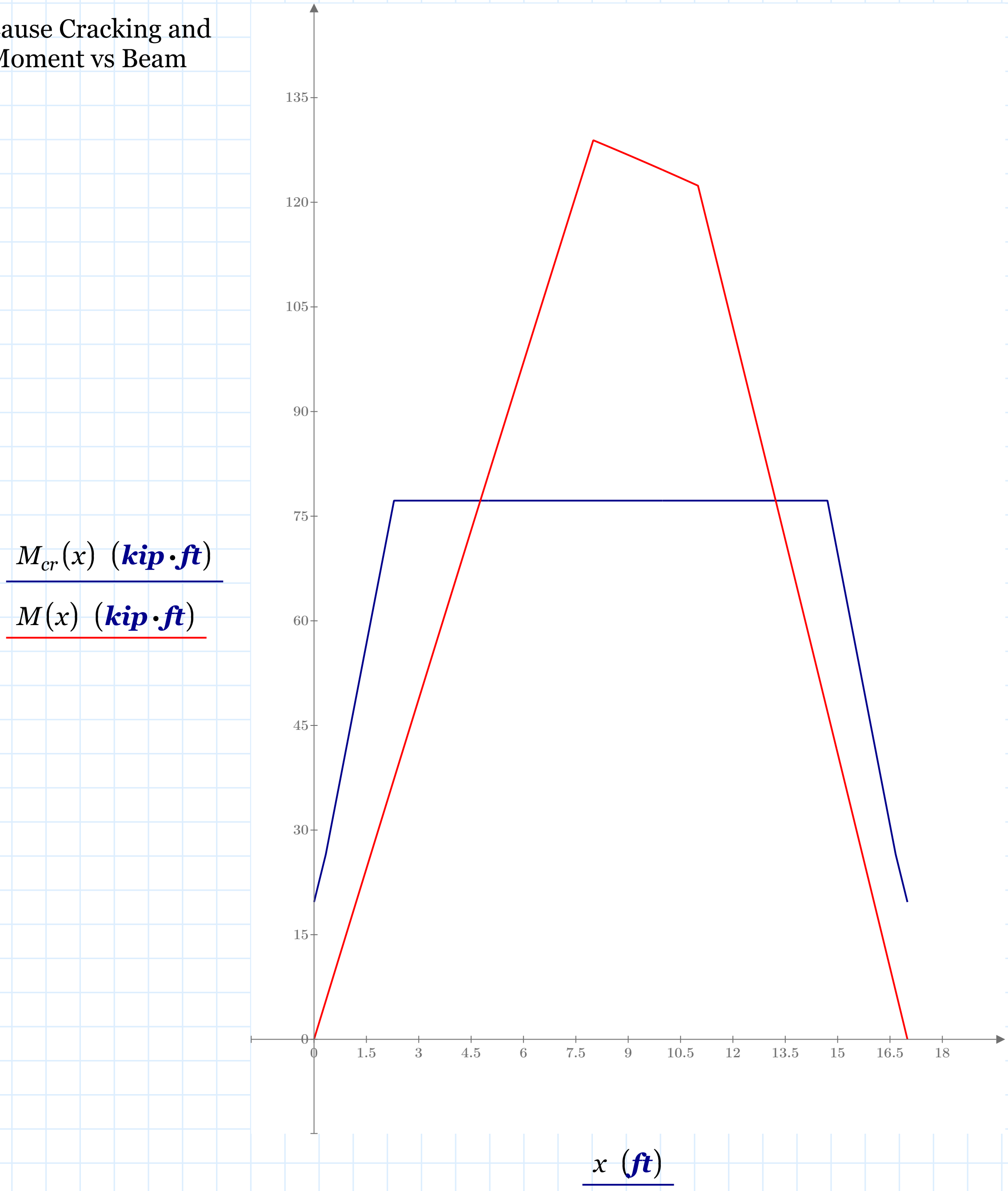
$f_r := f_{sT.PCI} = 662.749\ psi$

Modulus of Rupture, Based on Cylinder Tests

$$M_{cr}(x) := \left(f_r + \frac{P_e(x)}{A_{total}} + \frac{P_e(x) \cdot e \cdot y_{bmbot}}{I_{total}} + \frac{P_{ec}(x)}{A_{total}} + \frac{P_{ec}(x) \cdot e_c \cdot y_{bmbot}}{I_{total}} \right) \cdot \frac{I_{total}}{y_{bmbot}}$$

Moment to Cause Cracking

Moment to Cause Cracking and Unfactored Moment vs Beam Span Length



$check := \textbf{if}\left(M(AB) > M_{cr}(AB), \text{“Crack”}, \text{“No Crack”}\right) = \text{“Crack”}$

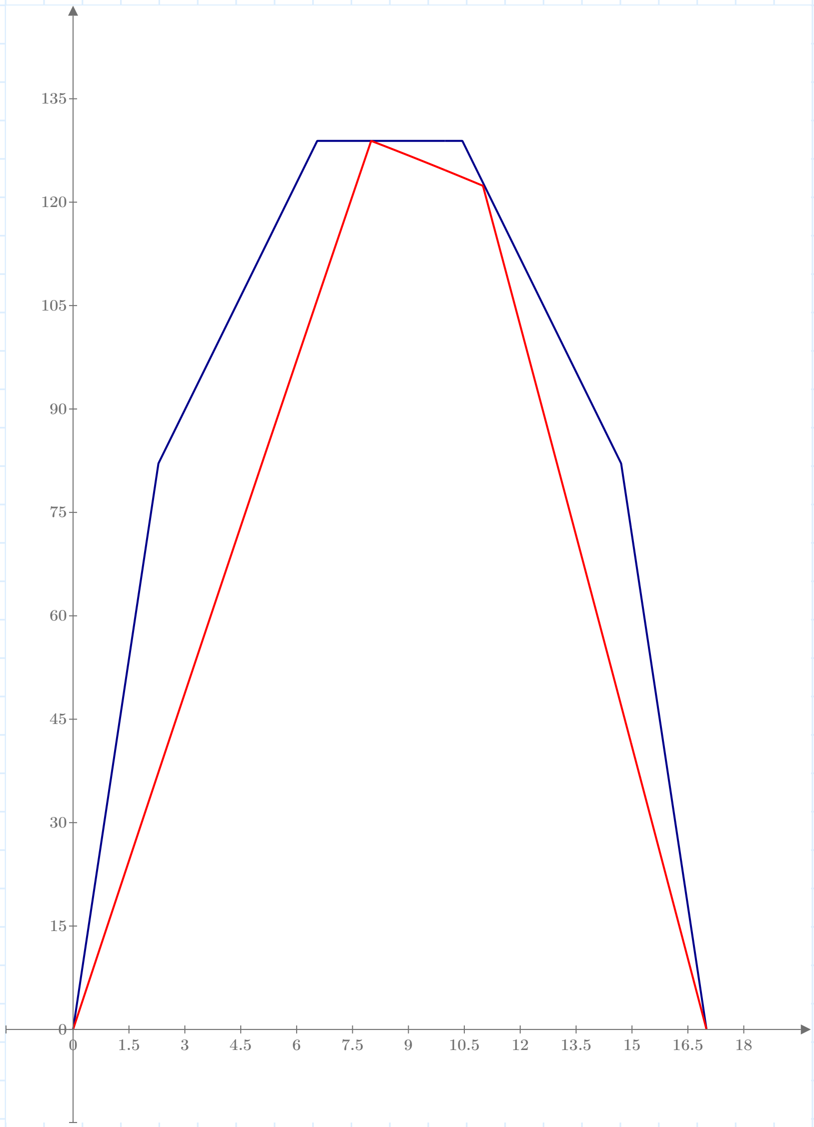
Check To See If Beam Will Crack When the Unfactored Moment is Applied

Unreduced Nominal Flexural Capacity

$\Phi := 1$ — Unreduced Safety Factor

$\Phi M_n(x) := \Phi \cdot k_{td}(x) \cdot M_n$ — Unreduced Factorized Nominal Flexural Capacity

Unreduced Nominal Flexural Capacity and Unfactored Moment vs Beam Span Length



Demand Compared to Nominal Flexural Capacity

$M(AB) = 128.892$ **kip·ft** — Critical Unfactored Service Moment

$\Phi M_n(AB) = 128.893$ **kip·ft** — Critical Unreduced Factorized Nominal Flexural Capacity

$check := \textbf{if}\left(M(AB) \ge \Phi M_n(AB), \text{“Fails”}, \text{“Doesn't Fail”}\right) = \text{“Doesn't Fail”}$

Check To See If Beam Will Crack When the Unfactored Moment is Applied

SHEAR CAPACITY

Simplified Shear Method

$check := \text{if}\left(A_{ps} \cdot f_{ps} > 0.4 \cdot A_{ps} \cdot f_{pu}, \text{"OK"}, \text{"NG, Fix"}\right) = \text{"OK"}$ — Verify Method Validity

$\Phi := 1$ — Unreduced Safety Factor

$l_{psdl} := 50 \cdot d_{ps} = 2.083\ \mathbf{ft}$ — Prestressing Strand Development Length

$check := \text{if}\left(V_u(h) \le 2 \cdot \lambda \cdot \sqrt{f'_c \cdot \mathbf{psi}} \cdot w_w \cdot h + 8 \cdot \sqrt{f'_c \cdot \mathbf{psi}} \cdot w_w \cdot h, \text{"OK"}, \text{"NG"}\right) = \text{"OK"}$

Check Section Size Adequacy

$$V_{cstr}(x) := \left(0.6\ \lambda \cdot \sqrt[2]{f'_c \cdot \mathbf{psi}} + 700 \cdot \mathbf{psi} \cdot min\left(\frac{|V_u(x)| \cdot h_{barc}}{|M(x)|}, 1\right)\right) \cdot w_w \cdot \max\left(h_{barc}, 0.8 \cdot h\right)$$

Concrete Shear Strength

$V_{cmin} := 2 \cdot \lambda \cdot \sqrt{f'_c \cdot \mathbf{psi}} \cdot w_w \cdot h_{barc} = 5.302\ \mathbf{kip}$ — Minimum Concrete Contribution

$V_{cmax} := 5 \cdot \lambda \cdot \sqrt{f'_c \cdot \mathbf{psi}} \cdot w_w \cdot h_{barc} = 13.255\ \mathbf{kip}$ — Maximum Concrete Contribution

$V_c(x) := \max\left(min\left(V_{cmax}, V_{cstr}(x)\right), V_{cmin}\right)$ — Concrete Shear Capacity

Spacing Calculations

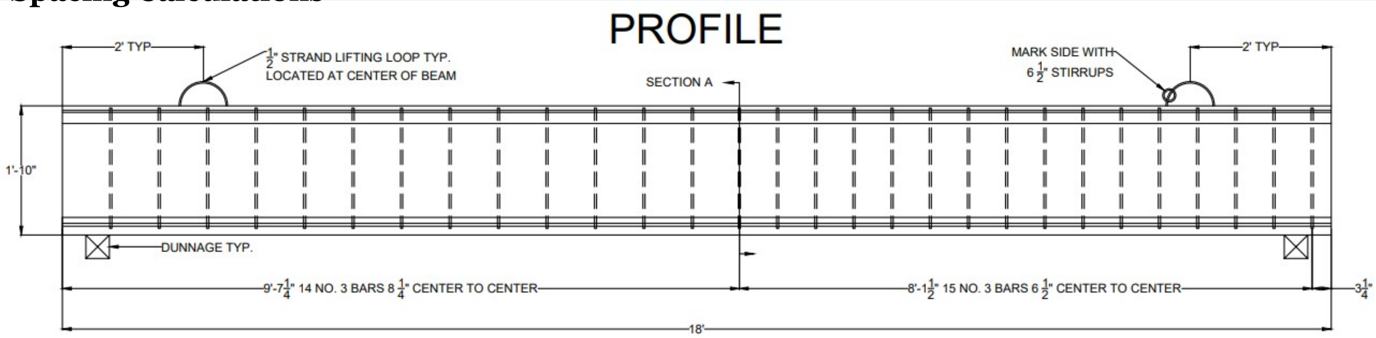


Figure 3: Stirrup Pattern Outlined in Shop Drawings

$s_1 := 8.25\ \mathbf{in}$ $\quad s_2 := 8.25\ \mathbf{in}$ $\quad s_3 := 6.5\ \mathbf{in}$

$l_{\Delta s1} := s_1 \cdot 11 = 90.75\ \mathbf{in}$ $\quad l_{\Delta s2} := l_{\Delta s1} + s_2 \cdot 3 = 115.5\ \mathbf{in}$ $\quad l_{\Delta s3} := l - l_{\Delta s2} = 100.5\ \mathbf{in}$

$V_{s1} := \frac{A_{stir} \cdot n_{legs} \cdot f_y \cdot h_{barc}}{s_1} = 16\ \mathbf{kip}$ — Steel Shear Strength at Spacing Interval 1

$V_{s2} := \frac{A_{stir} \cdot n_{legs} \cdot f_y \cdot h_{barc}}{s_2} = 16\ \mathbf{kip}$ — Steel Shear Strength at Spacing Interval 2

$V_{s3} := \frac{A_{stir} \cdot n_{legs} \cdot f_y \cdot h_{barc}}{s_3} = 20.308\ \mathbf{kip}$ — Steel Shear Strength at Spacing Interval 3

$s_{cc} := \frac{3}{8}\ \mathbf{in}$ — Specified Concrete Cover (ACI 318-19, 20.5.1.3.3)

$s_{max1} := \text{if}\left(V_{s1} > 4 \cdot \lambda \cdot \sqrt{f'_c \cdot \mathbf{psi}} \cdot w_w \cdot h_{barc}, min\left(0.375 \cdot h, 12\ \mathbf{in}\right), min\left(0.75 \cdot h, 24\ \mathbf{in}\right)\right)$

$s_{max1} = 8.25\ \mathbf{in}$ Maximum Spacing at Spacing Interval 1

$s_{max2} := \mathbf{if}\left(V_{s2} > 4 \cdot \lambda \cdot \sqrt{f'_c \cdot \mathbf{psi}} \cdot w_w \cdot h_{barc}, min(0.375 \cdot h, 12\ \mathbf{in}), min(0.75 \cdot h, 24\ \mathbf{in})\right)$

$s_{max2} = 8.25\ \mathbf{in}$ Maximum Spacing at Spacing Interval 2

$s_{max3} := \mathbf{if}\left(V_{s2} > 4 \cdot \lambda \cdot \sqrt{f'_c \cdot \mathbf{psi}} \cdot w_w \cdot h_{barc}, min(0.375 \cdot h, 12\ \mathbf{in}), min(0.75 \cdot h, 24\ \mathbf{in})\right)$

$s_{max3} = 8.25\ \mathbf{in}$ Maximum Spacing at Spacing Interval 3

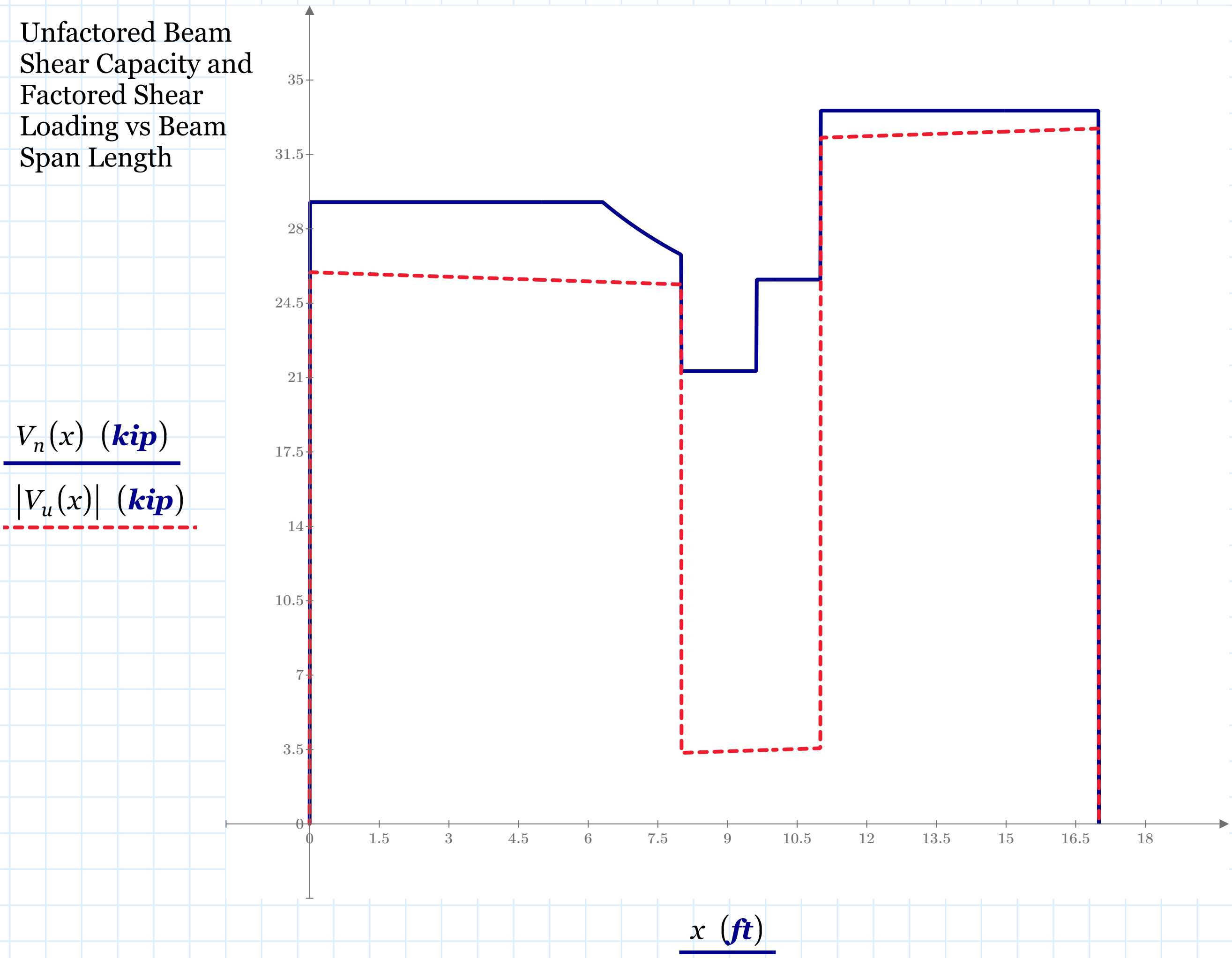
$$A_{vmin} := min\left(\frac{A_{ps} \cdot n_{ps} \cdot f_{pu}}{80 \cdot f_y \cdot h_{barc}} \cdot min(s_1, s_2, s_3) \cdot \sqrt{\frac{h_{barc}}{w_w}}, \max\left(0.75 \cdot \sqrt{f'_c \cdot \mathbf{psi}} \cdot \frac{w_w}{f_y} \cdot min(s_1, s_2, s_3), 50\ \mathbf{psi} \cdot \frac{w_w}{f_y} \cdot min(s_1, s_2, s_3)\right)\right) = 0.014\ \mathbf{in}^2$$

Minimum Stirrup Area

$$V_n(x) := \mathbf{if}\left(0 < x \le l_{\Delta s1}, (V_c(x) + V_{s1}), \mathbf{if}\left(l_{\Delta s1} < x \le l_{\Delta s2}, (V_c(x) + V_{s2}), \mathbf{if}\left(l_{\Delta s2} < x < l_s, (V_c(x) + V_{s3}), 0\right)\right)\right)$$

Unfactored Beam Shear Capacity

Unfactored Beam Shear Capacity and Factored Shear Loading vs Beam Span Length



$check := \mathbf{if}\left(V_n(AC) > |V_u(AC)|, \text{“OK”}, \text{“NG”}\right) = \text{“OK”}$

Final Maximum Shear Spacing Check

DEFLECTION

Superposition

$$\Delta_{cam} := \frac{-\left(\left(A_{ps} \cdot n_{ps} \cdot f_{pi}\right) \cdot l^2 \cdot e\right)}{8 \cdot E_{ci} \cdot I_{total}} = -0.211 \ \mathbf{in}$$

Cambering Deflection

$$\Delta_{sw} := \frac{5 \cdot w_{ship} \cdot l^4}{384 \cdot E_c \cdot I_{total}} \cdot \left(\frac{1}{1 \ \mathbf{ft}}\right) = 0.164 \ \mathbf{in}$$

Selfweight Deflection

$$\Delta_{P8} := \frac{P \cdot (BC + CD)^2 \cdot AB^2}{3 \cdot E_c \cdot I_{total} \cdot l} = 0.192 \ \mathbf{in}$$

Point Load From 8 feet of the Pin Support's Deflection

$$\Delta_{P11} := \frac{P \cdot CD^2 \cdot AB^2}{3 \cdot E_c \cdot I_{total} \cdot l} = 0.085 \ \mathbf{in}$$

Point Load From 11 feet of the Pin Support's Deflection

$$\Delta_{tot} := \Delta_{cam} + \Delta_{sw} + \Delta_{P8} + \Delta_{P11} = 0.231 \ \mathbf{in}$$

Total Deflection of the Beam

Virtual Work

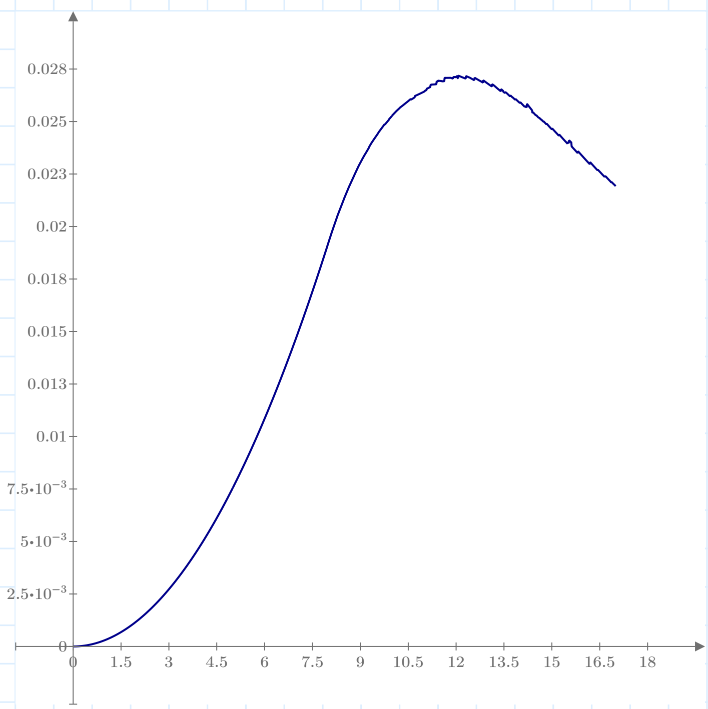
$$m(x) := \mathbf{if}\left(x \le AB, 0.5 \cdot x, \mathbf{if}\left(AB < x < AC, 0.5 \cdot x - 1 \cdot (x - AB), 0.5 \cdot CD - 0.5 \cdot (x - AC)\right)\right)$$

$$\Delta_{virt} := \int_0^l \frac{m(x) \cdot M(x)}{E_c \cdot I_{total}} \, dx = 0.374 \ \mathbf{in}$$

Total Deflection of the Beam Calculated Through Virtual Work During Service Loading

Deflection of the Beam Calculated Through Virtual Work vs Beam Span Length

$$\frac{\int_0^x \frac{m(x) \cdot M(x)}{E_c \cdot I_{total}} \, dx}{x} \left(\frac{\mathbf{in}}{\mathbf{ft}}\right)$$



$x \ (\mathbf{ft})$

$Deflection \equiv 0.58 \ \mathbf{in}$

*Deflection Will Be Calculated More Accurately With a Separate Software

ITERATION CHECKS

Cracking and Breaking Loads

$M_{cr}(AB) = 77.23\ kip \cdot ft$ — Maximum Cracking Moment

$M_{sw}(AB) = 2.16\ kip \cdot ft$ — Maximum Selfweight Moment

$$l_{maxcrack} := \left(\frac{\left(\frac{1}{l_s} \left\langle l_s - AB + CD \right\rangle \right) AB}{2} \right) = 3.5294\ ft$$

Location of Maximum Cracking Moment

$$P_{crack} := \frac{M_{cr}(AB) - M_{sw}(AB)}{l_{maxcrack}} = 21.27\ kip$$

Load to Cause Failure in Flexure

$CrackingLoad \equiv 21.27\ kip$

$$P_{break} := \frac{\Phi M_n(AB) - M_{sw}(AB)}{l_{maxcrack}} = 35.908\ kip$$

Load to Cause Failure in Rupture

$BreakingLoad \equiv 35.908\ kip$

$$\frac{M_{cr}(AB)}{M(AB)} = 0.599$$

Unfactored Service Moment vs Unreduced Nominal Capacity (Cracking Method Validity Verification)

$$\frac{M(AB)}{\Phi M_n(AB)} = 1$$

Unfactored Service Moment vs Unreduced Nominal Capacity (Breaking Method Validity Verification)

COST

MATERIAL COSTS AND BEAM WEIGHT

The following unit cost shall be used to determine the beam cost. Concrete cost is based on actual strength, not design strength.

Material	Cost	Notes/Instructions
Concrete Cost (yd^3):	maximum ($85 + $10*(concrete strength, ksi), $145) / cubic yard	Round concrete strength down to nearest ksi
Ultra-High-Performance Concrete	$400/$yd^3$	
Prestressing Strand: ⅜ in. diameter ½ in. diameter ½ in. special 0.6 in. diameter 0.7 in. diameter	 $0.27/ft $0.30/ft $0.33/ft $0.42/ft $0.55/ft	Use estimated lengths used in the beam
Steel: A615/A706 Welded Wire (deformed or smooth; for shear) Epoxy Coated A1035 Plate Steel	 $0.45/lb $0.60/lb $0.50/lb $0.70/lb $0.55/lb	Use estimated lengths and nominal unit weights in this calculation as provided in the *PCI Design Handbook*
Forming	$1.25/$ft^2$ of formwork (include all contact surfaces)	

- There is no need to include cost of steel fabrication, concrete fabrication, curing, inserts, etc. Concrete cost is based on actual strength.
- The beam weight shall be estimated by using the measured unit weight of the concrete or by actually weighing the beam. If the beam weight is estimated, it is estimated based on the gross concrete cross section only, ignoring reinforcement, bearing plates, etc. * Special circumstances or special materials not addressed in these rules must be reviewed by the chair of the committee and/or PCI staff.

Figure 4: Material Costs and Beam Weight per PCI Big Beam Competition 2025-2026

Concrete

$$C_{conc} := \max\left(85 + \frac{10 \cdot in^2}{kip} \cdot f'_c , \frac{145}{yd^3} \cdot V_{total}\right) = 163.09$$

Cost of Concrete in $

Formwork

$$C_{form} := \left(l_{perim} - t_{fw}\right) \cdot l \cdot \frac{1.25}{ft^2} + A_{total} \cdot \frac{1.25}{ft^2} = 106.18$$

Cost of Formwork in $

Prestressing Strand

$$Cd_{ps} := \text{if}\left(d_{ps} \ge 0.7\ in , 0.55 , \text{if}\left(d_{ps} \ge 0.6\ in , 0.42 , \text{if}\left(d_{ps} \ge 0.5\ in , 0.3 , 0.27\right)\right)\right) = 0.3$$

$$Cd_{psc} := \text{if}\left(d_{psc} \ge 0.7\ in , 0.55 , \text{if}\left(d_{psc} \ge 0.6\ in , 0.42 , \text{if}\left(d_{psc} \ge 0.5\ in , 0.3 , 0.27\right)\right)\right) = 0.27$$

$$C_{strand} := \frac{Cd_{ps}}{ft} \cdot l \cdot n_{ps} + \frac{Cd_{psc}}{ft} \cdot l \cdot n_{psc} = 20.52$$

Total Cost of Strand in $

Stirrups

A615/A706 — Stirrup Material

$$C_{stir} := n_{stir} \cdot l_{stir} \cdot w_{stir} \cdot \frac{0.45}{lbf} = 9.58$$

Total Cost of Stirrups in $

Total Cost

$$C_{total} := C_{conc} + C_{form} + C_{strand} + C_{stir} = 299.37$$

Total Cost of NAU PCI Big Beam 2025-2026's Beam in $

$DollarCost \equiv 299.37$