CFRP-PC Training Course

Design Example

FIB-36

For Training Purposes Only, NOT To Be Used For Construction

UNIVERSITY of HOUSTON
CULLEN COLLEGE of ENGINEERING
Department of Civil & Environmental Engineering

DESIGN OF DECKED FIB-36 PRETENTIONED (INTERIOR) GIRDER WITH STRAIGHT CFRP CABLES

Geometry from "SR 687/4th Street, NB bridge"

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1. REFERENCES

LRFD: AASHTO LRFD Bridge Design Specifications, 8th Edition, 2017

AASHTO CFRP: Guide Specifications for the Design of Concrete Bridge Beams Prestressed with Carbon Fiber-Reinforced Polymer (CFRP) Systems, 1st Edition, 2018

AASHTO GFRP: AASHTO LRFD Bridge Design Guide Specifications for GFRP-Reinforced Concrete, 2nd Edition, 2018

SDG: FDOT Structures Manual, Volume 1 -Structures Design Guidelines

FRPG: FDOT Structures Manual, Volume 4 -Fiber Reinforced Polymer Guidelines

FDOT Standard Specifications For Road and Bridge Construction, January 2020

ACI 440.1R: Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars, 2015

ACI 440.4R: Prestressing Concrete Structures with FRP Tendons, 2011

NCHRP Report 907: Design of Concrete Bridge Beams Prestressed with CFRP systems

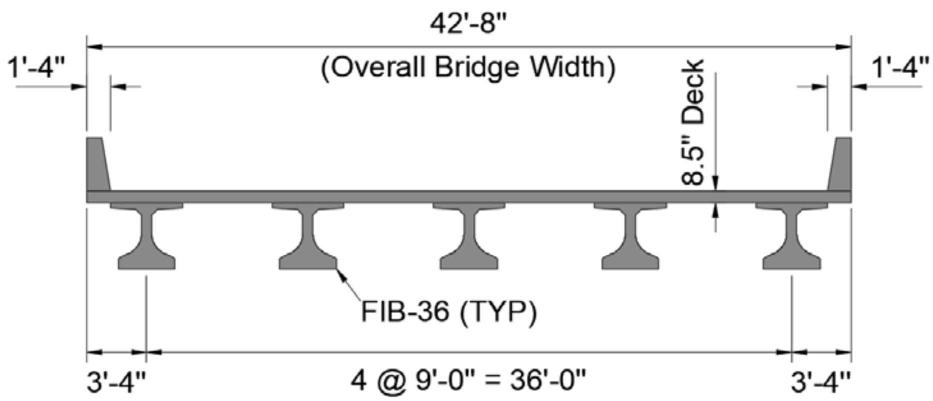
FDOT Design Example: LRFD Design Example #1, Prestressed Precast Concrete Beam Bridge Design

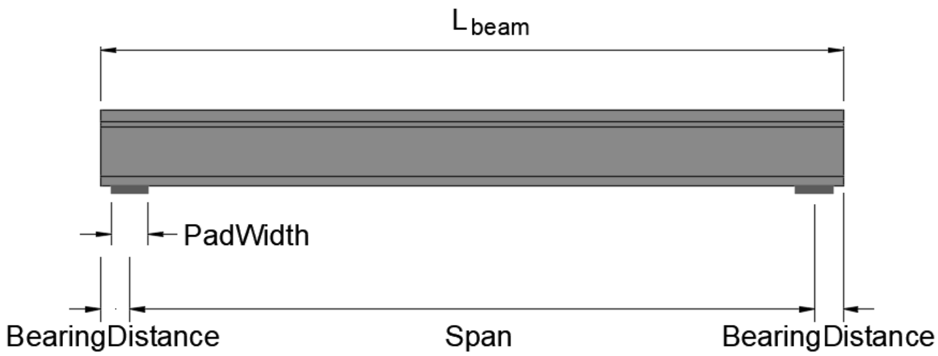
FDOT Design Example: LRFDPBeamV5.2 (MathCAD)

2. GEOMETRY AND MATERIAL INPUTS

2.1 Bridge Layout and Dimensions

$kcf \equiv \frac{kip}{ft^3}$





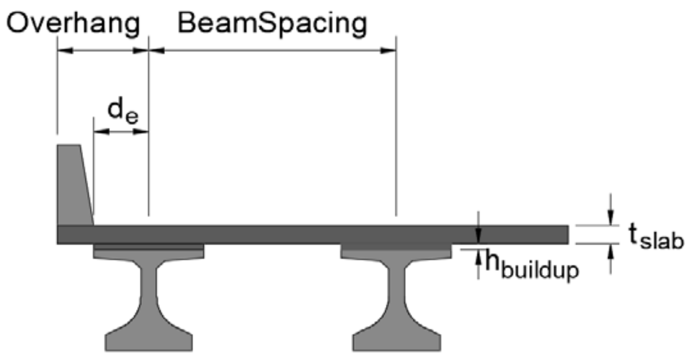
(FDOT Design example LRFDPBeamV5.2-CFRP)

$Span := \left(87 + \frac{8}{12}\right) \cdot ft = 87.667 \cdot ft$ Clear span

$BearingDistance := 9in$

$L_{beam} := Span + 2 \cdot BearingDistance = 89.167 \cdot ft$

$PadWidth := 10in$



$$Overhang := \left(3 + \frac{4}{12}\right)ft = 3.333 \cdot ft$$

$$BeamSpacing := 9ft$$

$$NumberOfBeam := 5$$

$$TotalBridgeWidth := BeamSpacing \cdot (NumberOfBeam - 1) + 2 \cdot Overhang = 42.667 \cdot ft$$

$$de := 2ft$$

2.2 FIB-36 Girder

$A_{beam} := 806.58in^2$ Cross section area

$Perimeter_{beam} := 206.57in$ Perimeter of beam section

$I_{xx.beam} := 127545in^4$ Moment of inertia

$I_{yy.beam} := 81070in^4$

$y_{beam.top} := 19.51in$ Distance from top of beam to N.A.

$y_{beam.bot} := 16.49in$ Distance from bottom of beam to N.A.

$b_{beam.top.flange} := 48in$ Top flange width

$h_{beam.top.flange} := 3.5in$ Top flange thickness

$b_{beam.bot..flange} := 38in$ Bottom flange width

$h_{beam.bot.flange} := 7in$ Bottom flange thickness

$Taper_{beam.bot.flange} := 15.5in$ Bottom flange taper

$h_{beam} := 36in$ Depth

$b_{web} := 7in$ Web width

$h_{web} := h_{beam} - h_{beam.top.flange} - 1.5in - 7in - 7.5in = 16.5 \cdot in$

Web depth

$f'_{c.beam} := 8.5ksi$ — Concrete strength

$f'_{ci.beam} := 6ksi$ — Concrete strength, at release

$$f_{r.beam} := 0.24 \cdot \left(\frac{f'_{c.beam}}{ksi} \right)^{0.5} ksi = 0.7 \cdot ksi$$

Modulus of rupture
(SDG 1.4.1B)

$\gamma_{concrete} := 0.15kcf$ — Unit weight of reinforced concrete

$\gamma_{beam} := \gamma_{concrete} = 0.15 \cdot kcf$ — Unit weight of reinforced deck concrete

$K_1 := 1.0$ — Correction factor for aggregate

(SDG 1.4.1A)

$w_c := 0.145kcf$ — Unit weight of concrete

$$E_{c.beam} := 120000 \cdot K_1 \cdot \left(\frac{w_c}{kcf} \right)^2 \cdot \left(\frac{f'_{c.beam}}{ksi} \right)^{0.33} \cdot ksi = 5112 \cdot ksi$$

Elastic modulus of beam concrete

(LRFD 5.4.2.4-1)

$$E_{ci.beam} := 120000 \cdot K_1 \cdot \left(\frac{w_c}{kcf} \right)^2 \cdot \left(\frac{f'_{ci.beam}}{ksi} \right)^{0.33} \cdot ksi = 4557 \cdot ksi$$

Elastic modulus of beam concrete, at release

(LRFD 5.4.2.4-1)

2.3 Cast in Place Deck

$t_{slab} := 8.5in$

$h_{buildup} := 1in$

$b_e := BeamSpacing = 9 \cdot ft$

Effective slab width, for interior beam (LRFD 4.6.2.6)

$A_{slab} := b_e \cdot t_{slab} = 918 \cdot in^2$

Area of slab

$A_{buildup} := b_{beam.bot..flange} \cdot h_{buildup} = 38 \cdot in^2$

Area of buildup

$f'_{c.slab} := 5.5ksi$

Concrete strength

$\gamma_{slab} := \gamma_{concrete} = 0.15 \cdot kcf$

Unit weight of reinforced deck concrete

$$E_{c.slab} := 120000 \cdot K_1 \cdot \left(\frac{w_c}{kcf}\right)^2 \cdot \left(\frac{f'_{c.slab}}{ksi}\right)^{0.33} \cdot ksi = 4428 \cdot ksi$$

Elastic modulus of deck concrete (LRFD 5.4.2.4-1)

$$n_c := \frac{E_{c.beam}}{E_{c.slab}} = 1.154$$

$$b_{e.tr} := b_e \cdot \frac{E_{c.slab}}{E_{c.beam}} = 7.796 \cdot ft$$

Effective slab width, transformed , for interior beam

(LRFD 4.6.2.6)

2.4 GFRP Reinforcing Bar

$GFRPBarSize := 5$ — Size of GFRP bar

$d_{GFRP} := \frac{GFRPBarSize}{8} in = 0.625 \cdot in$ — Nominal diameter of GFRP bar

$A_{GFRP} := \frac{1}{4} \cdot \pi \cdot d_{GFRP}^{2} = 0.307 \cdot in^{2}$ — Area of one GFRP bar

$f^{*}_{fu.GFRP} := \frac{29.1kip}{A_{GFRP}} = 94.851 \cdot ksi$ — Tensile strength of GFRP bar (FDOT Standard Specifications, Section 932, Table 3-1)

$C_{E.GFRP} := 0.7$ — Environmental reduction factor for GFRP (AASHTO-GFRP Table 2.6.1.2-1) Here assume "concrete exposed to earth and weather"

$f_{fu.GFRP} := C_{E.GFRP} \cdot f^{*}_{fu.GFRP} = 66.396 \cdot ksi$ — Design tensile strength

$E_{GFRP} := 6500ksi$ — Elastic modulus of GFRP bar (No less than 6500 ksi per FDOT Standard Specifications, Section 932)

$\phi_{bend} = f_{fu} \cdot \left(0.11 + 0.05 \frac{r}{d_b}\right)$ — Strength reduction for bent FRP stirrup (ACI 440.4R 5.4)

$\phi_{bend.GFRP} := 0.6$ — take 0.6 in this design example

$n_b := \frac{E_{GFRP}}{E_{c.beam}} = 1.271$

2.5 Prestressing CFRP Strand

[Assume 0.6in diameter CFRP Cable; Properties refer to FDOT Standard Specification Section 933 Table 1-2, 7-strand-15.2mm CFRP prestressing strand]

$StrandType_{CFRP} := 1$ — CFRP strand type: 1 for Cable; 2 for Bar

$D_p := 0.6in$ — Diameter of CFRP prestressing tendon

$A_{pf} := 0.179in^2$ — Effective cross-sectional area of each tendon

$E_p := 22480ksi$ — Elastic modulus of prestressing tendon

$P_u := 61kip$ — Ultimate tensile force for each tendon

$f'_{pu} := \frac{P_u}{A_{pf}} = 341 \cdot ksi$ — Ultimate tensile strength

Design tensile strength , f_{pu}, is defined later in "other inputs"

$C_{E.CFRP} := 1$ — Environmental reduction factor for CFRP (AASHTO CFRP Table 1.4.1.2-1)

$f_{pu} := C_{E.CFRP} \cdot f'_{pu} = 341 \cdot ksi$ — Design tensile strength of CFRP tendon

$\varepsilon_{pu} := \frac{f_{pu}}{E_p} = 0.015$ — Design tensile strain

$$f_{pi.limit} := \begin{cases} 0.70 \cdot f_{pu} & \text{if } StrandType_{CFRP} = 1 \\ 0.65 \cdot f_{pu} & \text{if } StrandType_{CFRP} = 2 \end{cases} = 238.5 \cdot ksi$$

Jacking stress limit (AASHTO CFRP Table 1.9.1.1)

$f_{pi} := f_{pi.limit} = 239 \cdot ksi$ — Jacking stress

$P_i := f_{pi} \cdot A_{pf} = 42.7 \cdot kip$ — Jacking force

$$f_{pe.limit} := \begin{cases} 0.65 \cdot f_{pu} & \text{if } StrandType_{CFRP} = 1 \\ 0.60 \cdot f_{pu} & \text{if } StrandType_{CFRP} = 2 \end{cases} = 221.5 \cdot ksi$$

Service stress limit (after all losses)

(AASHTO CFRP Table 1.9.1.1)

$$n_p := \frac{E_p}{E_{c.beam}} = 4.397$$

$$L_{transfer} := 50 \cdot D_p = 30 \cdot in$$

Transfer length
(AASHTO CFRP 1.9.3.2)

2.6 Other Inputs

Environment := "Extremely"

$RH := 75$

Ambient relative humidity

(SDG 4.6.6)

$\Delta f_{pTH} := 0$

Prestress loss due to temperature change. Not considered in this example

$t_i := 1$

Age at transfer (day)

$t_d := 120$

Age at deck placement (day)

$t_f := 10000$

Final time (day)

$\phi_{moment} := 0.75$

Reduction factor for CFRP prestressed girder - Moment
(AASHTO CFRP 1.5.3.2)

$\phi_{shear} := 0.9$

Reduction factor for CFRP prestressed girder - Shear
(AASHTO CFRP 1.8.2.1, LRFD 5.5.4.2)

3. SECTION PROPERTIES

3.1 Section Propertiy - Non-Composite Section (I-girder)

$h_g := h_{beam} = 36 \cdot in$ Depth

$b_w := b_{web} = 7 \cdot in$ Web thickness

$A_g := A_{beam} = 806.58 \cdot in^2$ Area

$I_g := I_{xx.beam} = 1.275 \times 10^5 \cdot in^4$ Moment inertia

$y_{g.top} := y_{beam.top} = 19.51 \cdot in$ Distance from top fiber (beam) to N.A

$y_{g.bot} := y_{beam.bot} = 16.49 \cdot in$ Distance from bottom fiber (beam) to N.A

$$S_{g.top} := \frac{I_g}{y_{g.top}} = 6.537 \times 10^3 \cdot in^3$$

$$S_{g.bot} := \frac{I_g}{y_{g.bot}} = 7.735 \times 10^3 \cdot in^3$$

3.2 Section Propertiy - Composite Section (I-girder+Deck)

$h_{g.comp} := t_{slab} + h_{buildup} + h_{beam} = 45.5 \cdot in$

Overall height of the section

$A_{deck.comp} := t_{slab} \cdot b_{e.tr} = 795.159 \cdot in^2$

$A_{buildup.comp} := h_{buildup} \cdot b_{beam.top.flange} \cdot \frac{E_{c.slab}}{E_{c.beam}} = 41.577 \cdot in^2$

$A_{g.comp} := A_{beam} + A_{deck.comp} + A_{buildup.comp} = 1.643 \times 10^3 \cdot in^2$

Area

$$y_{g.comp.bot} := \frac{A_{deck.comp} \cdot \left(h_{g.comp} - \frac{t_{slab}}{2}\right) \ldots + A_{buildup.comp} \cdot \left(h_{g.comp} - t_{slab} - \frac{h_{buildup}}{2}\right) \ldots + A_{beam} \cdot y_{g.bot}}{A_{g.comp}} = 28.977 \cdot in$$

Distance from bottom fiber (beam) to N.A

$y_{g.comp.top} := h_{g.comp} - y_{g.comp.bot} = 16.523 \cdot in$

Distance from top fiber (slab) to N.A

$y_{g.comp.topbeam} := h_{beam} - y_{g.comp.bot} = 7.023 \cdot in$

Distance from top fiber (beam) to N.A

$$I_{g.comp} := \frac{1}{12} \cdot \left(b_e \cdot \frac{E_{c.slab}}{E_{c.beam}}\right) \cdot t_{slab}^3 + A_{deck.comp} \cdot \left(y_{g.comp.top} - \frac{t_{slab}}{2}\right)^2 \ldots + \frac{1}{12} \cdot \left(b_{beam.top.flange} \cdot \frac{E_{c.slab}}{E_{c.beam}}\right) \cdot h_{buildup}^3 \ldots + A_{buildup.comp} \cdot \left(h_{g.comp} - t_{slab} - \frac{h_{buildup}}{2}\right)^2 \ldots + I_g + A_g \cdot \left(y_{g.comp.bot} - y_{g.bot}\right)^2 = 4.333 \times 10^5 \cdot in^4$$

Moment inertia

$$S_{g.comp.top} := \frac{I_{g.comp}}{y_{g.comp.top}} = 2.622 \times 10^{4} \cdot in^{3}$$

$$S_{g.comp.bot} := \frac{I_{g.comp}}{y_{g.comp.bot}} = 1.495 \times 10^{4} \cdot in^{3}$$

$$S_{g.comp.topbeam} := \frac{I_{g.comp}}{y_{g.comp.topbeam}} = 6.169 \times 10^{4} \cdot in^{3}$$

$$e_g := y_{g.top} + h_{buildup} + \frac{t_{slab}}{2} = 24.76 \cdot in$$

Distance between the c.g. of the basic beam and deck

4. LOAD AND LOAD DISTRIBUTION

4.1 Dead Load

$w_{beam} := A_g \cdot \gamma_{beam} = 0.840 \cdot \frac{kip}{ft}$

Self weight of beam

$w_{slab} := A_{slab} \cdot \gamma_{slab} = 0.956 \cdot \frac{kip}{ft}$

Self weight of slab

$w_{buildup} := A_{buildup} \cdot \gamma_{slab} = 0.040 \cdot \frac{kip}{ft}$

Self weight of buildup

$w_{slab.buildup} := w_{slab} + w_{buildup} = 0.996 \cdot \frac{kip}{ft}$

Sum of self weight of slab and buildup

$w_{barrier.each} := 0.430 \frac{kip}{ft}$

Traffic railing barrier DL,
"SR 687/4th Street, NB bridge"

$w_{barrier} := \frac{2 \cdot w_{barrier.each}}{NumberOfBeam} = 0.172 \cdot \frac{kip}{ft}$

For purpose of this design example, all barrier loads are equally distributed to the total number of beams

$w_{forms} := 20psf \cdot \left(BeamSpacing - b_{beam.top.flange}\right) = 0.100 \cdot \frac{kip}{ft}$

Stay-in-place forms, 20 psf
"SR 687/4th Street, NB bridge"

$w_{fws} := 0 \frac{kip}{ft}$

Future wearing surface

$w_{utility} := 0 \frac{kip}{ft}$

Utility dead load

for interior beams

DC Dead load
(LRFD 3.3.2)

$$M_{sf.beam}(x) := \frac{w_{beam} \cdot Span}{2} \cdot x - \frac{w_{beam} \cdot x^2}{2}$$

Self weight of beam
(x distance from support)

$$V_{sf.beam}(x) := \frac{w_{beam} \cdot Span}{2} - w_{beam} \cdot x$$

$$M_{sf.slab}(x) := \frac{w_{slab.buildup} \cdot Span}{2} \cdot x - \frac{w_{slab.buildup} \cdot x^2}{2}$$

Self weight of deck and buildup

$$V_{sf.slab}(x) := \frac{w_{slab.buildup} \cdot Span}{2} - w_{slab.buildup} \cdot x$$

$$M_{forms}(x) := \frac{w_{forms} \cdot Span}{2} \cdot x - \frac{w_{forms} \cdot x^2}{2}$$

Stay-in-place forms

$$V_{forms}(x) := \frac{w_{forms} \cdot Span}{2} - w_{forms} \cdot x$$

$$M_{barrier}(x) := \frac{w_{barrier} \cdot Span}{2} \cdot x - \frac{w_{barrier} \cdot x^2}{2}$$

Barriers

$$V_{barrier}(x) := \frac{w_{barrier} \cdot Span}{2} - w_{barrier} \cdot x$$

Total DC dead load

$$w_{DC} := w_{beam} + w_{slab.buildup} + w_{forms} + w_{barrier} = 2.108 \cdot \frac{kip}{ft}$$

$$M_{DC}(x) := M_{sf.beam}(x) + M_{sf.slab}(x) + M_{forms}(x) + M_{barrier}(x)$$

$$V_{DC}(x) := V_{sf.beam}(x) + V_{sf.slab}(x) + V_{forms}(x) + V_{barrier}(x)$$

DW Dead load

(LRFD 3.3.2)

Future wearing surface
(x distance from support)

$$M_{fws}(x) := \frac{w_{fws} \cdot Span}{2} \cdot x - \frac{w_{fws} \cdot x^2}{2}$$

$$V_{fws}(x) := \frac{w_{fws} \cdot Span}{2} - w_{fws} \cdot x$$

Utility

$$M_{utility}(x) := \frac{w_{utility} \cdot Span}{2} \cdot x - \frac{w_{utility} \cdot x^2}{2}$$

$$V_{utility}(x) := \frac{w_{utility} \cdot Span}{2} - w_{utility} \cdot x$$

Total DW dead load

$$w_{DW} := w_{fws} + w_{utility} = 0 \cdot \frac{kip}{ft}$$

$$M_{DW}(x) := M_{fws}(x) + M_{utility}(x)$$

$$V_{DW}(x) := V_{fws}(x) + V_{utility}(x)$$

4.2 Live Load

$IM_{fatigue} := 1.15$

Impact factor (dynamic load effects) for fatigue limit states

(LRFD Table 3.6.2.1-1)

$IM := 1.33$

Impact factor (dynamic load effects) for limit states other than fatigue and fracture

(LRFD Table 3.6.2.1-1)

$w_{lane} := 0.64 \frac{kip}{ft}$

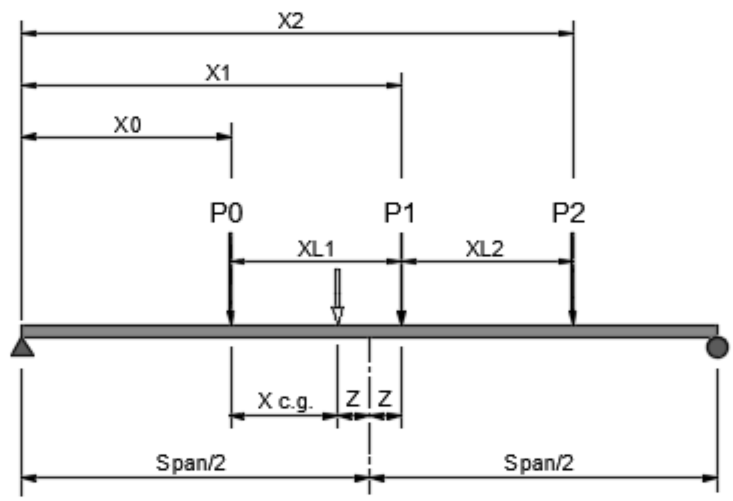
Uniformly distributed design lane load

(LRFD 3.6.1.2.4)

$$M_{lane}(x) := \frac{w_{lane} \cdot Span}{2} \cdot x - \frac{w_{lane} \cdot x^2}{2}$$

Moment and shear introduced by design lane load
x distance from left support

$$V_{lane}(x) := \frac{w_{lane} \cdot Span}{2} - w_{lane} \cdot x$$



Maximum Live Load Moment

(FDOT design examples)

----------- *Live Load (except for fatigue limit state)* ------------

$$P := \begin{pmatrix} 32 \\ 32 \\ 8 \end{pmatrix} \cdot kip$$

HL-93 Truck load, axle loads and spacing (LRFD 3.6.1.2.2)

$$XL := \begin{pmatrix} 0 \\ 14 \\ 14 \end{pmatrix} \cdot ft$$

$$x_{cg} := \frac{P_0 \cdot XL_0 + P_1 \cdot (XL_0 + XL_1) + P_2 \cdot (XL_0 + XL_1 + XL_2)}{P_0 + P_1 + P_2} = 9.333 \text{ ft}$$

Center of gravity for axle loads

$$z := \frac{XL_1 - x_{cg}}{2} = 2.333 \cdot ft$$

Distance from c.g. of axle loads to centerline of span

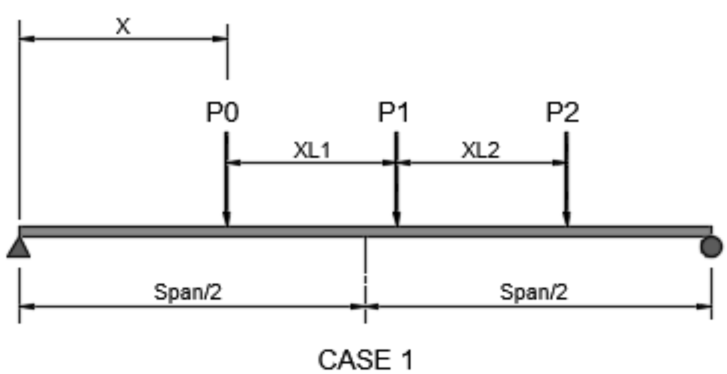
$$X_{left} := \frac{Span}{2} - z - x_{cg} = 32.167 \text{ ft}$$

$$X := \begin{pmatrix} X_{left} \\ X_{left} + XL_1 \\ X_{left} + XL_1 + XL_2 \end{pmatrix} = \begin{pmatrix} 32.167 \\ 46.167 \\ 60.167 \end{pmatrix} ft$$

Distance from left support to axle loads

Live load moments and shear - One HL-93 truck

Case 1

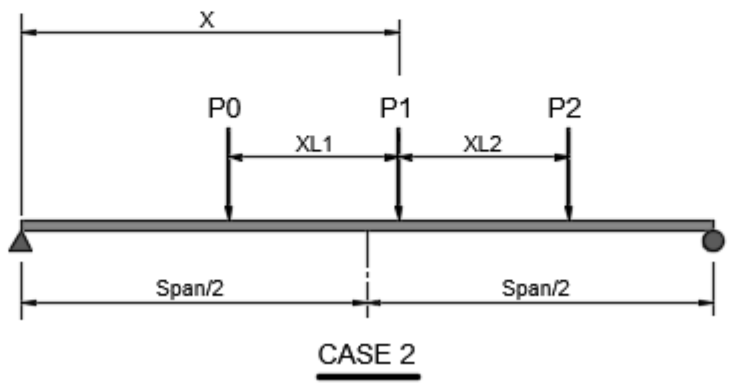


(FDOT design examples)

$$M_{truck1}(x) := P_0 \cdot \frac{(Span - x) \cdot x}{Span} + P_1 \cdot \frac{(Span - x - XL_1) \cdot x}{Span} + P_2 \cdot \frac{(Span - x - XL_1 - XL_2) \cdot x}{Span}$$

$$V_{truck1}(x) := P_0 \cdot \frac{(Span - x)}{Span} + P_1 \cdot \frac{(Span - x - XL_1)}{Span} + P_2 \cdot \frac{(Span - x - XL_1 - XL_2)}{Span}$$

Case 2



(FDOT design examples)

$$M_{truck2}(x) := P_0 \cdot \frac{(Span - x) \cdot (x - XL_1)}{Span} + P_1 \cdot \frac{(Span - x) \cdot x}{Span} + P_2 \cdot \frac{(Span - x - XL_2) \cdot x}{Span}$$

$$V_{truck2}(x) := P_0 \cdot \frac{-(x - XL_1)}{Span} + P_1 \cdot \frac{(Span - x)}{Span} + P_2 \cdot \frac{(Span - x - XL_2)}{Span}$$

$$M_{truck}(x) := \max(M_{truck1}(x), M_{truck2}(x))$$

Moment and shear introduced by Truck HL-93

$$V_{truck}(x) := \max(V_{truck1}(x), V_{truck2}(x))$$

$$M_{LL.IM}(x) := M_{truck}(x) \cdot IM + M_{lane}(x)$$

Live load (truck and lane) moment and shear, including impact (IM is for limit states other than fatigue)

$$V_{LL.IM}(x) := V_{truck}(x) \cdot IM + V_{lane}(x)$$

$M_{LL}(x) := M_{truck}(x) + M_{lane}(x)$

Live load (truck and lane) moment and shear, excluding impact

$V_{LL}(x) := V_{truck}(x) + V_{lane}(x)$

----------- Live Load for fatigue limit state ------------

$P_f := \begin{pmatrix} 32 \\ 32 \\ 8 \end{pmatrix} \cdot kip \qquad XL_f := \begin{pmatrix} 0 \\ 30 \\ 14 \end{pmatrix} \cdot ft$

HL-93 Truck load, axle loads and spacing (LRFD 3.6.1.2.2)

$$x_{cg.f} := \frac{P_{f_0} \cdot XL_{f_0} + P_{f_1} \cdot \left(XL_{f_0} + XL_{f_1}\right) + P_{f_2} \cdot \left(XL_{f_0} + XL_{f_1} + XL_{f_2}\right)}{P_{f_0} + P_{f_1} + P_{f_2}} = 18.222\ ft$$

Center of gravity for axle loads

$$z_f := \frac{XL_{f_1} - x_{cg.f}}{2} = 5.889 \cdot ft$$

Distance from c.g. of axle loads to centerline of span

$$X_{left.f} := \frac{Span}{2} - z_f - x_{cg.f} = 19.722\ ft$$

$$X_f := \begin{pmatrix} X_{left.f} \\ X_{left.f} + XL_{f_1} \\ X_{left.f} + XL_{f_1} + XL_{f_2} \end{pmatrix} = \begin{pmatrix} 19.722 \\ 49.722 \\ 63.722 \end{pmatrix} ft$$

Distance from left support to axle loads

Live load moments and shear - One HL-93 truck

Case 1

$$M_{truck1.f}(x) := P_{f_0} \cdot \frac{(Span - x) \cdot x}{Span} + P_{f_1} \cdot \frac{\left(Span - x - XL_{f_1}\right) \cdot x}{Span} + P_{f_2} \cdot \frac{\left(Span - x - XL_{f_1} - XL_{f_2}\right) \cdot x}{Span}$$

$$V_{truck1.f}(x) := P_{f_0} \cdot \frac{(Span - x)}{Span} + P_{f_1} \cdot \frac{\left(Span - x - XL_{f_1}\right)}{Span} + P_{f_2} \cdot \frac{\left(Span - x - XL_{f_1} - XL_{f_2}\right)}{Span}$$

Case 2

$$M_{truck2.f}(x) := P_{f_0} \cdot \frac{(Span - x) \cdot \left(x - XL_{f_1}\right)}{Span} + P_{f_1} \cdot \frac{(Span - x) \cdot x}{Span} + P_{f_2} \cdot \frac{\left(Span - x - XL_{f_2}\right) \cdot x}{Span}$$

$$V_{truck2.f}(x) := P_{f_0} \cdot \frac{-\left(x - XL_{f_1}\right)}{Span} + P_{f_1} \cdot \frac{(Span - x)}{Span} + P_{f_2} \cdot \frac{\left(Span - x - XL_{f_2}\right)}{Span}$$

$$M_{truck.f}(x) := \max\left(M_{truck1.f}(x), M_{truck2.f}(x)\right)$$

Moment and shear introduced by Truck HL-93, for fatigue limit state

$$V_{truck.f}(x) := \max\left(V_{truck1.f}(x), V_{truck2.f}(x)\right)$$

$$M_{LL.IM.f}(x) := M_{truck.f}(x) \cdot IM_{fatigue}$$

Fatigue Live load (truck) moment and shear

$$V_{LL.IM.f}(x) := V_{truck.f}(x) \cdot IM_{fatigue}$$

at midspan

$$M_{LL.IM.f}\left(\frac{Span}{2}\right) = 1198 \cdot kip \cdot ft$$

$$V_{LL.IM.f}\left(\frac{Span}{2}\right) = 24 \cdot kip$$

4.3 Live Load Distribution Factors

(LRFD 4.6.2.2)

Live load on the deck must be distributed to the precast prestressed beams. AASHTO provides factors for the distribution of live load into the beams. The factors can be used if the following criteria is met:
(1) Width of deck is constant
(2) Number of beams is not less than four
(3) Beams are parallel and have approximately the same stiffness
(4) The overhang minus the barrier width does not exceed 3.0 feet
(5) Curvature in plan is less than the limit specified in LRFD 4.6.1.2.4
(6) Cross-section is consistent with one of the cross-sections shown in Table 4.6.2.2.1-1

In this example, all the conditions are satisfied

$$K_g := \frac{E_{c.beam}}{E_{c.slab}} \cdot \left(I_g + A_g \cdot e_g^{\ 2}\right) = 7.181 \times 10^5 \cdot in^4$$

Longitudinal stiffness parameter
(LRFD 4.6.2.2.1)

Type k cross-section in LRFD Table 4.6.2.2.1

Moment distribution factor for interior beams

When one design lane loaded

$$g_{m.1} = 0.06 + \left(\frac{S}{14}\right)^{0.4} \cdot \left(\frac{S}{L}\right)^{0.3} \cdot \left(\frac{K_g}{12.0 \cdot L \cdot t_s^{\ 3}}\right)^{0.1}$$

(LRFD Table 4.6.2.2.2b-1)

$$g_{m.1} := 0.06 + \left(\frac{BeamSpacing}{14 \cdot ft}\right)^{0.4} \cdot \left(\frac{BeamSpacing}{Span}\right)^{0.3} \cdot \left(\frac{K_g}{12.0 \cdot \frac{in}{ft} \cdot Span \cdot t_{slab}^{\ 3}}\right)^{0.1} = 0.488$$

Distribution factor for moment in interior beams when one lane is loaded

When two or more design lane loaded

$$g_{m.2} = 0.075 + \left(\frac{S}{9.5}\right)^{0.6} \cdot \left(\frac{S}{L}\right)^{0.2} \cdot \left(\frac{K_g}{12.0 \cdot L \cdot t_s^{\ 3}}\right)^{0.1}$$

(LRFD Table 4.6.2.2.2b-1)

$$g_{m.2} := 0.075 + \left(\frac{BeamSpacing}{9.5 \cdot ft}\right)^{0.6} \cdot \left(\frac{BeamSpacing}{Span}\right)^{0.2} \cdot \left(\frac{K_g}{12.0 \cdot \frac{in}{ft} \cdot Span \cdot t_{slab}^{\ 3}}\right)^{0.1} = 0.696$$

Distribution factor for moment in interior beams when two or more lanes are loaded

$$g_m := \max\left(g_{m.1}, g_{m.2}\right) = 0.696$$

Distribution factor for moment in interior beams

Verify if the distribution factor satisfies LRFD criteria for "Range of Applicability"

$$g_{m.check} := \left| \begin{array}{l} S \leftarrow 3.5ft \le BeamSpacing \le 16ft \\ t_s \leftarrow 4.5in \le t_{slab} \le 12in \\ L \leftarrow 20ft \le Span \le 240ft \\ N_b \leftarrow NumberOfBeam \ge 4 \\ K_g \leftarrow 10000in^4 \le K_g \le 7000000in^4 \\ \text{"OK"} \quad \text{if } \left(S \cdot t_s \cdot L \cdot N_b \cdot K_g\right) = 1 \\ \text{"NG"} \quad \text{otherwise} \end{array} \right. = \text{"OK"}$$

$$g_{m.check} = \text{"OK"}$$

<u>Shear distribution factor</u> for interior beams

When one design lane loaded

$$g_{v.1} = 0.36 + \frac{S}{25.0}$$

(LRFD Table 4.6.2.2.3a-1)

$$g_{v.1} := 0.36 + \frac{BeamSpacing}{25.0 \cdot ft} = 0.72$$

Distribution factor for shear in interior beams when one lane is loaded

When two or more design lane loaded

$$g_{m.2} = 0.2 + \frac{S}{12} - \left(\frac{S}{35}\right)^{2.0}$$

(LRFD Table 4.6.2.2.3a-1)

$$g_{v.2} := 0.2 + \frac{BeamSpacing}{12 \cdot ft} - \left(\frac{BeamSpacing}{35 \cdot ft}\right)^{2.0} = 0.884$$

Distribution factor for shear in interior beams when two or more lanes are loaded

$$g_v := \max(g_{v.1}, g_{v.2}) = 0.884$$

Distribution factor for shear in interior beams

Verify if the distribution factor satisfies LRFD criteria for "Range of Applicability"

$$g_{v.check} := \left| \begin{array}{l} S \leftarrow 3.5ft \le BeamSpacing \le 16ft = \text{"OK"} \\ t_s \leftarrow 4.5in \le t_{slab} \le 12in \\ L \leftarrow 20ft \le Span \le 240ft \\ N_b \leftarrow NumberOfBeam \ge 4 \\ \text{"OK"} \quad \text{if } (S \cdot t_s \cdot L \cdot N_b) = 1 \\ \text{"NG"} \quad \text{otherwise} \end{array} \right.$$

$$g_{v.check} = \text{"OK"}$$

Summary of live load distribution factors, interior beams

$g_m = 0.696$ — Distribution factor for moment in interior beams

$g_v = 0.884$ — Distribution factor for shear in interior beams

$$M_{LL.IM}(x) := g_m \cdot M_{LL.IM}(x)$$

$$V_{LL.IM}(x) := g_v \cdot V_{LL.IM}(x)$$

Re-define
Live load (truck and lane) moment and shear, including impact (IM is for limit states other than fatigue)
Consider LL distribution factor

$$M_{LL}(x) := g_m \cdot M_{LL}(x)$$

$$V_{LL}(x) := g_v \cdot V_{LL}(x)$$

Re-define
Live load (truck and lane) moment and shear, excluding impact
Consider LL distribution factor

$$M_{LL.IM.f}(x) := \frac{g_m}{1.2} \cdot M_{LL.IM.f}(x)$$

$$V_{LL.IM.f}(x) := \frac{g_v}{1.2} \cdot V_{LL.IM.f}(x)$$

Re-define
Live load (truck) moment and shear, including impact (IM is for fatigue)
Consider LL distribution factor

Noted that the distribution factor calculated in LRFD 4.6.2.2 for a single lane loaded already includes the 1.2 "multiple presence factor" for a single lane, therefore, this value may be used for the service and strength limit states. However, multiple presence factors should not be used for the fatigue limit state. Therefore, the multiple presence factor of 1.2 for the single lane is required to be removed from the value calculated above to determine the factor used for the fatigue limit state

4.4 Summary of Moments and Shear Forces

$\text{Strength1} = 1.25DC + 1.5DW + 1.75LL$ Strength I limit state

$\text{Service1} = 1.0DC + 1.0DW + 1.0LL$ Service I limit state

$\text{Service3} = 1.0DC + 1.0DW + 0.8LL$ Service III limit state

$\text{Fatigue1} = 1.75LL_{fatigue}$ Fatigue I limit state

$M_{Str1}(x) := 1.25 \cdot M_{DC}(x) + 1.5 \cdot M_{DW}(x) + 1.75 \cdot M_{LL.IM}(x)$ Strength I limit state

$M_{Srv1}(x) := 1.0 \cdot M_{DC}(x) + 1.0 \cdot M_{DW}(x) + 1.0 \cdot M_{LL.IM}(x)$ Service I limit state

$M_{Srv3}(x) := 1.0 \cdot M_{DC}(x) + 1.0 \cdot M_{DW}(x) + 0.8 \cdot M_{LL.IM}(x)$ Service III limit state

$M_{fatigue}(x) := 1.75 \cdot M_{LL.IM.f}(x)$ Fatigue I limit state

$V_{Str1}(x) := 1.25 \cdot V_{DC}(x) + 1.5 \cdot V_{DW}(x) + 1.75 \cdot V_{LL.IM}(x)$ Strength I limit state

$V_{Srv1}(x) := 1.0 \cdot V_{DC}(x) + 1.0 \cdot V_{DW}(x) + 1.0 \cdot V_{LL.IM}(x)$ Service I limit state

$V_{Srv3}(x) := 1.0 \cdot V_{DC}(x) + 1.0 \cdot V_{DW}(x) + 0.8 \cdot V_{LL.IM}(x)$ Service III limit state

$V_{fatigue}(x) := 1.75 \cdot V_{LL.IM.f}(x)$ Fatigue I limit state

at mispan

$M_{DC.mid} := M_{DC}\left(\frac{Span}{2}\right) = 2025 \cdot kip \cdot ft$ Due to DC

$M_{DW.mid} := M_{DW}\left(\frac{Span}{2}\right) = 0 \cdot kip \cdot ft$ Due to DW

$M_{LL.IM.mid} := M_{LL.IM}\left(\frac{Span}{2}\right) = 1628 \cdot kip \cdot ft$ Due to LL

$M_{LL.IM.fatigue.mid} := M_{LL.IM.f}\left(\frac{Span}{2}\right) = 695 \cdot kip \cdot ft$ Due to LL

$M_{Str1.mid} := 1.25 \cdot M_{DC.mid} + 1.5 \cdot M_{DW.mid} + 1.75 \cdot M_{LL.IM.mid} = 5381 \cdot kip \cdot ft$

Strength I limit state

$M_{Srv1.mid} := 1.0 \cdot M_{DC.mid} + 1.0 \cdot M_{DW.mid} + 1.0 \cdot M_{LL.IM.mid} = 3654 \cdot kip \cdot ft$

Service I limit state

$M_{Srv3.mid} := 1.0 \cdot M_{DC.mid} + 1.0 \cdot M_{DW.mid} + 0.8 \cdot M_{LL.IM.mid} = 3328 \cdot kip \cdot ft$

Service III limit state

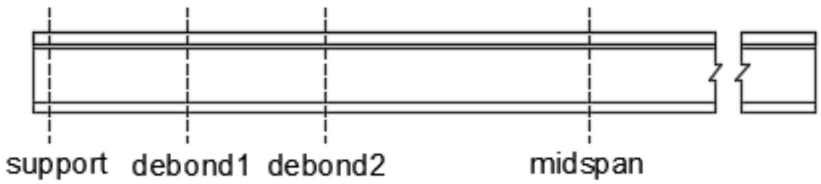
$M_{fatigue.mid} := 1.75 \cdot M_{LL.IM.fatigue.mid} = 1216 \cdot kip \cdot ft$

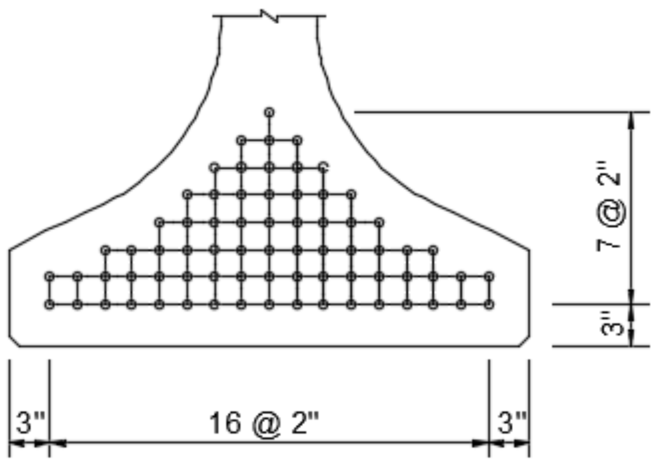
Fatigue I limit state

5. STRAND PATTERN

for FIB-36 Beam

The pattern of strands need to be adjusted according to limit states





support := 0ft — Distance from left support

debond1 := 10ft — Debond place1, "0" if no need debonding

debond2 := 20ft — Debond place2, "0" if no need debonding

$$\text{midspan} := \frac{\text{Span}}{2} = 43.833\ \text{ft}$$

Max number of strands in each row, from bottom up

$$n_{max} := \begin{pmatrix} 17 \\ 17 \\ 13 \\ 9 \\ 7 \\ 5 \\ 3 \\ 1 \end{pmatrix} \qquad n := \begin{pmatrix} 17 \\ 17 \\ 5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Number of strands in each row, from bottom up

<u>Adjust the numbers to satisfy Service III and Strength I limit states (Sections 9 and 11 in this example)</u>

<u>Note: Service I can be satisfied by debonding (Section 8 in this example)</u>

$$n_{total} := \sum_{i=0}^{rows(n)-1} n_i = 39$$

Total number of strands

$$A_p := n \cdot A_{pf} = \begin{pmatrix} 3.043 \\ 3.043 \\ 0.895 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot in^2$$

Total area of strands in each row

$$A_{p.total} := \sum_{i=0}^{rows(n)-1} A_{p_i} = 6.981 \cdot in^2$$

Total area of strands

$$d_p := \begin{pmatrix} h_g - 3in \\ h_g - 5in \\ h_g - 7in \\ h_g - 9in \\ h_g - 11in \\ h_g - 13in \\ h_g - 15in \\ h_g - 17in \end{pmatrix} = \begin{pmatrix} 33 \\ 31 \\ 29 \\ 27 \\ 25 \\ 23 \\ 21 \\ 19 \end{pmatrix} \cdot in$$

Distance from top beam section to the center of each strand row

$$d_{p.strands.c.g} := \frac{\sum_{i=0}^{rows(n)-1} \left(A_{p_i} \cdot d_{p_i}\right)}{A_{p.total}} = 31.615 \cdot in$$

Distance from top beam section to the gravity center of strand group

$$d_{p.strands.c.g.bot} := h_g - d_{p.strands.c.g} = 4.385 \cdot in$$

Distance from bottom beam section to the gravity center of strand group

6. TRANSFORMED SECTION PROPERTIES

6.1 Transformed Section Properties - Non-Composite Section (Girder+Strands)

$n_p = 4.397$ Elastic modulus ratio, Ep/Ec

$A_{g.tr} := A_g + (n_p - 1)A_{p.total} = 830.295 \cdot in^2$ Area

$$y_{g.tr.top} := \frac{A_g \cdot y_{g.top} + \sum_{i=0}^{rows(n)-1} \left[A_{p_i} \cdot (n_p - 1) \cdot d_{p_i}\right]}{A_{g.tr}} = 19.856 \cdot in$$

Distance from top fiber (beam) to N.A

$y_{g.tr.bot} := h_g - y_{g.tr.top} = 16.144 \cdot in$ Distance from bottom fiber (beam) to N.A

$$I_{g.tr} := I_g + A_g \cdot (y_{g.tr.top} - y_{g.top})^2 + \sum_{i=0}^{rows(n)-1} \left[(n_p - 1) \cdot A_{p_i} \cdot \left(d_{p_i} - y_{g.tr.top}\right)^2\right] = 1.31 \times 10^5 \cdot in^4$$

Moment inertia

$$S_{g.tr.top} := \frac{I_{g.tr}}{y_{g.tr.top}} = 6.596 \times 10^3 \cdot in^3$$

$$S_{g.tr.bot} := \frac{I_{g.tr}}{y_{g.tr.bot}} = 8.112 \times 10^3 \cdot in^3$$

$e_{g.tr.cg.strands} := y_{g.tr.bot} - d_{p.strands.c.g.bot} = 11.76 \cdot in$

eccentricity of strand group

6.2 Transformed Section Properties - Composite Section (Girder+Deck+Strands+Bars)

Assume #5 GFRP bar at 12" spacing, longitudinal direction, in both top and bottom of the deck slab

$n_b = 1.271$

Elastic modulus ratio, Egfrp/Ec

$$A_{deck.rebar} := \frac{b_e}{12in} \cdot A_{GFRP} \cdot 2 = 5.522 \cdot in^2$$

$$y_{rebar} := h_g + h_{buildup} + \frac{t_{slab}}{2} = 3.437\ ft$$

Distance from c.g. of rebar group (in deck slab) to bottom of girder section

$$A_{g.comp.tr} := A_{g.comp} + (n_p - 1)A_{p.total} + (n_b - 1) \cdot A_{deck.rebar} = 1.669 \times 10^3 \cdot in^2$$

Area

$$y_{g.comp.tr.top} := \frac{A_{g.comp} \cdot y_{g.comp.top} + \sum_{i=0}^{rows(n)-1} \left[A_{p_i} \cdot (n_p - 1) \cdot d_{p_i} \right] \ldots + (n_b - 1) \cdot A_{deck.rebar} \cdot \frac{t_{slab}}{2}}{A_{g.comp.tr}} = 16.726 \cdot in$$

Distance from top fiber (deck) to N.A

$$y_{g.comp.tr.bot} := h_{g.comp} - y_{g.comp.tr.top} = 28.774 \cdot in$$

Distance from bottom fiber (beam) to N.A

$$y_{g.comp.tr.topbeam} := y_{g.comp.tr.top} - t_{slab} - h_{buildup} = 7.226 \cdot in$$

Distance from top fiber of the beam to N.A

$$I_{g.comp.tr} := I_{g.comp} + A_{g.comp} \cdot (y_{g.comp.tr.top} - y_{g.comp.top})^2 \ldots + \sum_{i=0}^{rows(n)-1} \left[(n_p - 1) \cdot A_{p_i} \cdot (d_{p_i} - y_{g.comp.tr.top})^2 \right] \ldots + (n_b - 1) \cdot A_{deck.rebar} \cdot \left(\frac{t_{slab}}{2} - y_{g.comp.tr.top} \right)^2 = 4.389 \times 10^5 \cdot in^4$$

Moment inertia

$$S_{g.comp.tr.top} := \frac{I_{g.comp.tr}}{y_{g.comp.tr.top}} = 2.624 \times 10^{4} \cdot in^{3}$$

$$S_{g.comp.tr.bot} := \frac{I_{g.comp.tr}}{y_{g.comp.tr.bot}} = 1.525 \times 10^{4} \cdot in^{3}$$

$$S_{g.comp.tr.topbeam} := \frac{I_{g.comp.tr}}{y_{g.comp.tr.topbeam}} = 6.073 \times 10^{4} \cdot in^{3}$$

$$e_{g.comp.tr.cg.strands} := y_{g.comp.tr.bot} - d_{p.strands.c.g.bot} = 24.389 \cdot in$$

Eccentricity of strand group

7. PRESTRESS LOSSES

$\Delta f_p = \Delta f_{pES} + \Delta f_{pLT} + \Delta f_{pTH}$

Total prestress loss
(AASHTO CFRP 1.9.2.1)

Δf_{pES}: prestress loss due to elastic shortening

Δf_{pLT}: long-term time-dependent prestress losses, due to shrinkage, creep, and relaxation

Δf_{pTH}: prestress losses due to temperature change (Not considered in this example)

7.1 Prestress Loss due to Elastic Shortening

$$\Delta f_{pES} = \frac{E_f}{E_{ct}} f_{cgp}$$

Prestress loss due to elastic shortening

(AASHTO CFRP 1.4.2)

$f_{pi} = 239 \cdot ksi$

Jacking stress

$F_{pi} := A_{p.total} \cdot f_{pi} = 1.665 \times 10^3 \cdot kip$

Total jacking force

$e_{g.tr.cg.strands} = 11.76 \cdot in$

Eccentricity of strand group to N.A. of the transformed non-composite section

$M_{sf.beam.midspan} := M_{sf.beam}\left(\frac{Span}{2}\right) = 807.152 \cdot kip \cdot ft$

Moment at midspan due to self weight of beam

$$f_{cgp} := \frac{F_{pi}}{A_{g.tr}} + \frac{F_{pi} \cdot e_{g.tr.cg.strands}^2}{I_{g.tr}} - \frac{M_{sf.beam.midspan} \cdot e_{g.tr.cg.strands}}{I_{g.tr}} = 2.894 \cdot ksi$$

Concrete stress at gravity center of the prestressing force at transfer

$$\Delta f_{pES} := \frac{E_p}{E_{ci.beam}} f_{cgp} = 14.277 \cdot ksi$$

Prestress loss due to elastic shortening

(AASHTO CFRP 1.4.2)

$f_{pt} := f_{pi} - \Delta f_{pES} = 224.27 \cdot ksi$

Prestress stress at transfer

7.2 Long-Term Time-Dependent Prestress Losses (Refined Estimation)

$$\Delta f_{pLT} = \left(\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1}\right)_{id} + \left(\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} - \Delta f_{pSS}\right)_{df}$$

Total long-term time-dependent losses
id - time between transfer and deck placement
df - time between deck placement and the final time

(LRFD 5.9.3.4.1-1)

--------Time-Dependent losses between transfer and deck placement--------

Shrinkage of girder concrete (i->d)

$$\Delta f_{pSR} = \varepsilon_{bid} \cdot E_p \cdot K_{id}$$

(LRFD 5.9.3.4)

$$k_s := \max\left(1.45 - 0.13 \frac{A_g}{Perimeter_{beam} \cdot in}, 1.0\right) = 1.000$$

Factor for the effect of the volume-to-surface ratio of the component

(LRFD 5.4.2.3.2)

$$k_{hs} := 2.00 - 0.014RH = 0.950$$

Humidiy factor for shrinkage

(LRFD 5.4.2.3.3)

$$k_{hc} := 1.56 - 0.008RH = 0.960$$

Humidiy factor for creep

(LRFD 5.4.2.3.2)

$$k_f := \frac{5}{1 + \frac{f'_{ci.beam}}{ksi}} = 0.714$$

Factor for the effect of concrete strength

(LRFD 5.4.2.3.2)

$$k_{td}(t_0, t_1) := \frac{t_1 - t_0}{12\left(\frac{100 - 4 \cdot \frac{f'_{ci.beam}}{ksi}}{\frac{f'_{ci.beam}}{ksi} + 20}\right) + (t_1 - t_0)}$$

Time development factor

(LRFD 5.4.2.3.2)

$$k_{td}(t_i, t_d) = 0.772$$

Time development factor
Time from transfer to deck placement

$$k_{td}(t_i, t_f) = 0.997$$

Time development factor
Time from transfer to final time

$k_{td}(t_d, t_f) = 0.996$

Time development factor
Time from deck placement to final time

$\varepsilon_{bid} := k_s \cdot k_{hs} \cdot k_f \cdot k_{td}(t_i, t_d) \cdot 0.48 \cdot 10^{-3} = 2.516 \times 10^{-4}$

Shrinkage strain of girder

(LRFD 5.4.2.3.3)

$\Psi_b(t_1, t_0) := 1.9 \cdot k_s \cdot k_{hc} \cdot k_f \cdot k_{td}(t_0, t_1) \cdot t_0^{-0.118}$

Creep coefficient

(LRFD 5.4.2.3.2)

$\Psi_b(t_d, t_i) = 1.006$

Time development factor
Time from transfer to deck placement

$\Psi_b(t_f, t_i) = 1.298$

Time development factor
Time from transfer to final time

$\Psi_b(t_f, t_d) = 0.738$

Time development factor
Time from deck placement to final time

$$K_{id} := \frac{1}{1 + \frac{E_p}{E_{ci.beam}} \cdot \frac{A_{p.total}}{A_{g.tr}} \cdot \left(1 + \frac{A_{g.tr} \cdot e_{g.tr.cg.strands}^{\;2}}{I_{g.tr}}\right) \cdot \left(1 + 0.7 \cdot \Psi_b(t_f, t_i)\right)} = 0.871$$

Transformed section coefficient

(LRFD 5.9.3.4.2)

$\Delta f_{pSR} := \varepsilon_{bid} \cdot E_p \cdot K_{id} = 4.924 \cdot ksi$

Prestress loss due to
Shrinkage of girder concrete
(LRFD 5.9.3.4)

Creep of girder concrete (i->d)

$\Delta f_{pCR} := \frac{E_p}{E_{ci.beam}} f_{cgp} \cdot \Psi_b(t_d, t_i) \cdot K_{id} = 12.508 \cdot ksi$

Prestress loss due to
Creep of girder concrete
(LRFD 5.9.3.4)

Relaxation of prestressing CFRP (i->d)

$f_{pu} = 341 \cdot ksi$ Design tensile strength

$f_{pt} = 224 \cdot ksi$ Prestressing stress at transfer

$$\Delta f_{pR}(t_0, t_1) := \begin{cases} \left[\left(0.019 \frac{f_{pt}}{f_{pu}} - 0.0066\right) \cdot \log\left[24 \cdot (t_1 - t_0)\right] \cdot f_{pu}\right] & \text{if } StrandType_{CFRP} = 1 \\ \left[\left(0.013 \frac{f_{pt}}{f_{pu}} - 0.006\right) \cdot \log\left[24 \cdot (t_1 - t_0)\right] \cdot f_{pu}\right] & \text{if } StrandType_{CFRP} = 2 \end{cases}$$

Prestress loss due to relaxation

(AASHTO CFRP 1.9.2.5.2)

$\Delta f_{pR1} := \Delta f_{pR}(t_i, t_d) = 6.953 \cdot ksi$ Prestress loss due to relaxation

Time from transfer to deck placement

Total time-depedent prestress loss betweem transfer and deck placement

$\Delta f_{pLT.id} := \Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1} = 24.385 \cdot ksi$

--------Time-Dependent losses between deck placement to final time--------

Shrinkage of girder concrete (d->f)

$\Delta f_{pSD} = \varepsilon_{bdf} \cdot E_p \cdot K_{df}$ (LRFD 5.9.3.4.3)

$\varepsilon_{bdf} := k_s \cdot k_{hs} \cdot k_f \cdot k_{td}(t_d, t_f) \cdot 0.48 \cdot 10^{-3} = 3.246 \times 10^{-4}$

Shrinkage strain of girder

(LRFD 5.4.2.3.3)

$e_{g.comp.tr.cg.strands} = 24.389 \cdot in$ Eccentricity of prestressing force with respect to composite section

(LRFD 5.9.3.4.3)

$I_{g.comp.tr} = 4.389 \times 10^5 \cdot in^4$ Moment inertia for transformed composite section

$A_{g.comp.tr} = 1.669 \times 10^3 \cdot in^2$

Area for transformed composite section

$$K_{df} := \frac{1}{1 + \frac{E_p}{E_{ci.beam}} \cdot \frac{A_{p.total}}{A_{g.comp.tr}} \cdot \left(1 + \frac{A_{g.comp.tr} \cdot e_{g.comp.tr.cg.strands}^2}{I_{g.comp.tr}}\right) \cdot \left(1 + 0.7 \cdot \Psi_b(t_f, t_i)\right)} = 0.886$$

Transformed section coefficient

(LRFD 5.9.3.4.3)

$\Delta f_{pSD} := \varepsilon_{bdf} \cdot E_p \cdot K_{df} = 6.465 \cdot ksi$

Prestress loss due to
Shrinkage of girder concrete

(LRFD 5.9.3.4.3)

Creep of girder concrete (d->f)

$P_{pLT.id} := \Delta f_{pLT.id} \cdot A_{p.total} = 170.229 \cdot kip$

Prestress force loss between transfer to deck placement

$$M_{DL.nc} := M_{sf.slab}\left(\frac{Span}{2}\right) + M_{forms}\left(\frac{Span}{2}\right) = 1.053 \times 10^3 \cdot kip \cdot ft$$

Permanent dead load moment at midspan (exclude self weight of beam) acting on non-composite section

$$M_{DL.comp} := M_{barrier}\left(\frac{Span}{2}\right) + M_{fws}\left(\frac{Span}{2}\right) + M_{utility}\left(\frac{Span}{2}\right) = 165.237 \cdot kip \cdot ft$$

Permanent dead load moment at midspan acting on composite section

$$\Delta f_{cd} := (-1)\left[\frac{P_{pLT.id}}{A_{g.tr}} + \frac{P_{pLT.id} \cdot (e_{g.tr.cg.strands})^2}{I_{g.tr}} \ldots \atop + \frac{M_{DL.nc} \cdot e_{g.tr.cg.strands}}{I_{g.tr}} + \frac{M_{DL.comp} \cdot e_{g.comp.tr.cg.strands}}{I_{g.comp.tr}}\right] = -1.629 \cdot ksi$$

Change in concrete stress at centroid of prestressing strands due to long-term losses between transfer and deck placement, combined with deck weight and superimposed loads

$$\Delta f_{pCD} := \frac{E_p}{E_{ci.beam}} f_{cgp} \cdot \left(\Psi_b(t_f, t_i) - \Psi_b(t_d, t_i)\right) \cdot K_{df} + \frac{E_p}{E_{c.beam}} \Delta f_{cd} \cdot \Psi_b(t_f, t_d) \cdot K_{df} = -0.99 \cdot ksi$$

Prestress loss due to
Creep of girder concrete
(LRFD 5.9.3.4.3)

Relaxation of prestressing CFRP (d->f)

$f_{pu} = 341 \cdot ksi$

Design tensile strength

$f_{pt} = 224 \cdot ksi$

Prestress stress at transfer

$\Delta f_{pR2} := \Delta f_{pR}(t_d, t_f) = 10.814 \cdot ksi$

Prestress loss due to relaxation

Time from transfer to deck placement

Shrinkage of deck concrete (d->f)

$$k_{s.deck} := \max\left(1.45 - 0.13 \frac{A_{slab}}{2 \cdot b_e \cdot in}, 1.0\right) = 1.000$$

Factor for the effect of the
volume-to-surface ratio of the component

(LRFD 5.4.2.3.2)

$k_{hs} = 0.950$

Humidiy factor for shrinkage
(LRFD 5.4.2.3.3)

$k_{hc} = 0.960$

Humidiy factor for creep

(LRFD 5.4.2.3.2)

$$k_{f.deck} := \frac{5}{1 + \frac{f'_{c.slab}}{ksi}} = 0.769$$

Factor for the effect of concrete strength

(LRFD 5.4.2.3.2)

$$k_{td.deck}(t_0, t_1) := \frac{t_1 - t_0}{12\left(\frac{100 - 4 \cdot \frac{f'_{c.slab}}{ksi}}{\frac{f'_{c.slab}}{ksi} + 20}\right) + (t_1 - t_0)}$$

Time development factor

(LRFD 5.4.2.3.2)

$k_{td.deck}(t_d, t_f) = 0.996$

Time development factor
Time from deck placement to final time

$\varepsilon_{ddf} := k_{s.deck} \cdot k_{hs} \cdot k_{f.deck} \cdot k_{td.deck}(t_d, t_f) \cdot 0.48 \cdot 10^{-3} = 3.495 \times 10^{-4}$

Shrinkage strain of deck

(LRFD 5.4.2.3.3)

$\Psi_{b.deck}(t_1, t_0) := 1.9 \cdot k_{s.deck} \cdot k_{hc} \cdot k_{f.deck} \cdot k_{td.deck}(t_0, t_1) \cdot t_0^{-0.118}$

Creep coefficient

(LRFD 5.4.2.3.2)

$\Psi_{b.deck}(t_f, t_d) = 0.795$

Time development factor
Time from deck placement to final time

$e_{deck.comp} := y_{g.comp.tr.top} - \frac{t_{slab}}{2} = 12.476 \cdot in$

Eccentricity of deck with respect to N.A. of transformed composite section

$$\Delta f_{cdf} := \frac{\varepsilon_{ddf} \cdot A_{slab} \cdot E_{c.slab}}{1 + 0.7 \cdot \Psi_{b.deck}(t_f, t_d)} \cdot \left(\frac{1}{A_{g.comp.tr}} - \frac{e_{g.tr.cg.strands} \cdot e_{deck.comp}}{I_{g.comp.tr}} \right) = 0.242 \cdot ksi$$

Change in concrete stress at centroid of prestressing strands due to shrinkage of deck concrete

$$\Delta f_{pSS} := \frac{E_p}{E_{c.beam}} \cdot \Delta f_{cdf} \cdot K_{df} \cdot \left(1 + 0.7 \cdot \Psi_b(t_f, t_d)\right) = 1.43 \cdot ksi$$

Prestress loss due to shrinkage of deck concrete
(LRFD 5.9.3.4.3)

Total time-depedent prestress loss between deck placement and final time

$\Delta f_{pLT.df} := \Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} - \Delta f_{pSS} = 14.86 \cdot ksi$

Total time-depedent prestress loss between deck placement and final time

$\Delta f_{pLT} := \Delta f_{pLT.id} + \Delta f_{pLT.df} = 39.245 \cdot ksi$

7.3 Summary -Prestress Loss

$\Delta f_p := \Delta f_{pES} + \Delta f_{pLT} + \Delta f_{pTH} = 53.522 \cdot ksi$

Total prestress loss

(AASHTO CFRP 1.9.2.1)

$Loss\% := \frac{\Delta f_p}{f_{pi}} = 22.4 \cdot \%$

Total prestress loss percentage

$\Delta f_{pES} = 14.277 \cdot ksi$

Prestress loss due to elastic shortening

$\Delta f_{pTH} = 0$

Prestress loss due to temperature change (not considered)

$\Delta f_{pLT} = 39.245 \cdot ksi$

Total long-term time-dependent prestess loss

$\Delta f_{pLT.id} = 24.385 \cdot ksi$

Long-term time-dependent prestess loss between transfer and deck placement

$\Delta f_{pLT.df} = 14.86 \cdot ksi$

Long-term time-dependent prestess loss between deck placement and final time

$f_{pi} = 239 \cdot ksi$

Jacking stress

$f_{pt} = 224 \cdot ksi$

Prestressing stress at transfer

$f_{pe} := f_{pi} - \Delta f_p = 185 \cdot ksi$

Effect prestressing stress after all losses

$$Check_{pe.limit} := \begin{vmatrix} \text{"OK"} & \text{if } f_{pe} \le f_{pe.limit} \\ \text{"NG"} & \text{if } f_{pe} > f_{pe.limit} \end{vmatrix}$$

$Check_{pe.limit} = \text{"OK"}$

Service stress limit (after all losses)

(AASHTO CFRP Table 1.9.1.1)

8. STRESS LIMITS FOR CONCRETE -TEMPORARY STRESSES BEFORE LOSSES (LRFD 5.9.2.3.1)

for temporary stresses before losses (at release) (Compression +, Tension -)

$$f_{compressive.allow.before.loss} := 0.65 \cdot f'_{ci.beam} = 3.900 \cdot ksi$$

Compressive stress limit for concrete (LRFD 5.9.2.3.1a)

Note: assume minimum tension reinforcement satisfy SDG 4.3.1-1 and LRFD 5.9.2.3.1

$$f_{tensile.allow.15\%.before.loss} := -0.24 \cdot \left(\frac{f'_{ci.beam}}{ksi}\right)^{0.5} ksi = -0.588 \cdot ksi$$

Tensile stress limit for concrete in outer 15% regions (FDOT SDG 4.3.1)

$$f_{tensile.allow.70\%.bond.before.loss} := -0.24 \cdot \left(\frac{f'_{ci.beam}}{ksi}\right)^{0.5} ksi = -0.588 \cdot ksi$$

Tensile stress limit for concrete in middle 70% regions, for bonded reinforcements (FDOT SDG 4.3.1, LRFD 5.9.2.3.1b)

$$f_{tensile.allow.70\%.unbond.before.loss} := -\min\left[0.0948 \cdot \left(\frac{f'_{ci.beam}}{ksi}\right)^{0.5} ksi, 0.2ksi\right] = -0.2 \cdot ksi$$

Tensile stress limit for concrete in middle 70% regions, for bonded reinforcements (FDOT SDG 4.3.1, LRFD 5.9.2.3.1b)

At release, loads include self-weight of beam and the prestressing force

$$P_{pi} := A_{p.total} \cdot f_{pi} = 1.665 \times 10^{3} \cdot kip$$

Total prestress force at release

8.1 At Mid-Span Section

$midspan = 43.833\,ft$

$$f_{c.topbeam.midspan} := \frac{P_{pi}}{A_{g.tr}} + \frac{M_{sf.beam}(midspan) - P_{pi} \cdot e_{g.tr.cg.strands}}{S_{g.tr.top}} = 0.505 \cdot ksi$$

Concrete stress at top fiber of the beam at mid-span

$$f_{c.botbeam.midspan} := \frac{P_{pi}}{A_{g.tr}} - \frac{M_{sf.beam}(midspan) - P_{pi} \cdot e_{g.tr.cg.strands}}{S_{g.tr.bot}} = 3.226 \cdot ksi$$

Concrete stress at bottom fiber of the beam at mid-span

$f_{compressive.allow.before.loss} = 3.900 \cdot ksi$

$f_{tensile.allow.70\%.bond.before.loss} = -0.588 \cdot ksi$

in the pretensioned beams, at the midspan, "bonded reinforcements"

$$Check_{top.midspan} := \begin{cases} \text{if } f_{c.topbeam.midspan} \geq 0ksi & \begin{cases} \text{"OK"} & \text{if } f_{c.topbeam.midspan} \leq f_{compressive.allow.before.loss} \\ \text{"NG"} & \text{otherwise} \end{cases} \\ \text{if } f_{c.topbeam.midspan} < 0ksi & \begin{cases} \text{"OK"} & \text{if } -f_{c.topbeam.midspan} \leq -f_{tensile.allow.70\%.bond.before.loss} \\ \text{"NG"} & \text{otherwise} \end{cases} \end{cases}$$

$Check_{top.midspan} = \text{"OK"}$

Check concrete stress limits at the midspan, at release

$$Check_{bot.midspan} := \begin{cases} \text{if } f_{c.botbeam.midspan} \geq 0ksi & \begin{cases} \text{"OK"} & \text{if } f_{c.botbeam.midspan} \leq f_{compressive.allow.before.loss} \\ \text{"NG"} & \text{otherwise} \end{cases} \\ \text{if } f_{c.botbeam.midspan} < 0ksi & \begin{cases} \text{"OK"} & \text{if } -f_{c.botbeam.midspan} \leq -f_{tensile.allow.70\%.bond.before.loss} \\ \text{"NG"} & \text{otherwise} \end{cases} \end{cases}$$

$Check_{bot.midspan} = \text{"OK"}$

Check concrete stress limits at the midspan, at release

8.2 At Support (transfer length) Section

After transfer length, the prestressing forces are transfered to concrete, so the section that needs to check is located at transfer length distance from the support

$$support_{check} := support + L_{transfer} = 2.5\,ft$$

$$f_{c.topbeam.at.release2} := \frac{P_{pi}}{A_{g.tr}} + \frac{M_{sf.beam}\left(support_{check}\right) - P_{pi}\cdot e_{g.tr.cg.strands}}{S_{g.tr.top}} = -0.801\cdot ksi$$

Concrete stress at top fiber of the beam at support

$$f_{c.botbeam.at.release2} := \frac{P_{pi}}{A_{g.tr}} - \frac{M_{sf.beam}\left(support_{check}\right) - P_{pi}\cdot e_{g.tr.cg.strands}}{S_{g.tr.bot}} = 4.287\cdot ksi$$

Concrete stress at bottom fiber of the beam at support

$$f_{compressive.allow.before.loss} = 3.9\cdot ksi$$

$$f_{tensile.allow.15\%.before.loss} = -0.588\cdot ksi$$

$$Check_{sp.top} := \begin{cases} \text{"OK"} & \text{if } f_{c.topbeam.at.release2} \geq 0ksi \wedge \dfrac{f_{c.topbeam.at.release2}}{f_{compressive.allow.before.loss}} \leq 1 \\ \text{"OK"} & \text{if } f_{c.topbeam.at.release2} < 0ksi \wedge \dfrac{-f_{c.topbeam.at.release2}}{-f_{compressive.allow.before.loss}} \leq 1 \\ \text{"NG"} & \text{otherwise} \end{cases}$$

$$Check_{sp.top} = \text{"OK"}$$

in the pretensioned beams, at the support, "bonded reinforcements" check concrete stress limits at top fiber of beam

$$Check_{sp.bot} := \begin{cases} \text{"OK"} & \text{if } f_{c.botbeam.at.release2} \geq 0ksi \wedge \dfrac{f_{c.botbeam.at.release2}}{f_{compressive.allow.before.loss}} \leq 1 \\ \text{"OK"} & \text{if } f_{c.botbeam.at.release2} < 0ksi \wedge \dfrac{-f_{c.botbeam.at.release2}}{-f_{compressive.allow.before.loss}} \leq 1 \\ \text{"NG"} & \text{otherwise} \end{cases}$$

$$Check_{sp.bot} = \text{"NG"}$$

in the pretensioned beams, at the support, "bonded reinforcements" check concrete stress limits at bot fiber of beam

$$Check_{db} := \begin{cases} \text{"No Need to Debond Strands"} & \text{if } Check_{sp.top} = \text{"OK"} \wedge Check_{sp.bot} = \text{"OK"} \\ \text{"Need to Debond Strand"} & \text{otherwise} \end{cases}$$

$Check_{db}$ = "Need to Debond Strand"

Need to debond strands?

Debond some strands at support to satisfy concrete stress limites (*__if necessary__*)

Adjust

$$n = \begin{pmatrix} 17 \\ 17 \\ 5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad n_{max.debond} := n \cdot 40\% = \begin{pmatrix} 6.8 \\ 6.8 \\ 2 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \qquad n_{dbs} := \begin{pmatrix} 6 \\ 4 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Note: the number of partially debonded strands should NOT exceed 30% of the total number of strands (SDG 4.3.1); in any horizontal row, the number of debonded strands should NOT exceed 40% of the total strands in that row (LRFD 5.9.4.3.3.)

$$n_{after.dbs} := n - n_{dbs} = \begin{pmatrix} 11 \\ 13 \\ 5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Number of bonded strands in each row after debonding at support dbs bottom up, 0...8

$$n_{after.dbs.total} := \sum_{i=0}^{rows(n)-1} n_{after.dbs_i} = 29$$

Remaining total number of debonded strands after debonding support

$$Check_{30\%} := \begin{cases} \text{"OK"} & \text{if } \dfrac{n_{total} - n_{after.dbs.total}}{n_{total}} \le 30\% \\ \text{"NG"} & \text{otherwise} \end{cases}$$

Check if total debonded strands exceed 30% of total strands (SDG 4.3.1)

$Check_{30\%} = \text{"OK"}$

$$Check_{40\%} := \begin{cases} \text{"NG"} & \text{if for } i \in 0 .. rows(n) - 1 \\ & \quad \left| \begin{array}{l} n_{dbs_i} > 40\% \cdot n_i \\ \text{break} \end{array} \right. \\ \text{"OK"} & \text{otherwise} \end{cases}$$

Check if debonded strands in each row exceed 40% of total strands in that row (LRFD 5.9.4.3.3)

$Check_{40\%} = \text{"OK"}$

$P_{pi.dbs} := n_{after.dbs.total} \cdot A_{pf} \cdot f_{pi} = 1.238 \times 10^3 \cdot kip$

Total prestress force at release, after debonding support

$$A_{p.dbs} := n_{after.dbs} \cdot A_{pf} = \begin{pmatrix} 1.969 \\ 2.327 \\ 0.895 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot in^2$$

Total area of strands in each row, after debonding support

$$A_{p.total.dbs} := \sum_{i=0}^{rows(n)-1} A_{p.dbs_i} = 5.191 \cdot in^2$$

Total area of strands, after debonding support

$$d_{p.strands.c.g.dbs} := \frac{\displaystyle\sum_{i=0}^{rows(n)-1} \left(A_{p.dbs_i} \cdot d_{p_i}\right)}{A_{p.total.dbs}} = 31.414 \cdot in$$

Distance from top beam section to the gravity center of strand group, after debonding support

$d_{p.strands.c.g.bot.dbs} := h_g - d_{p.strands.c.g.dbs} = 4.586 \cdot in$

Distance from bottom beam section to the gravity center of strand group,after debonding support

Need to recalculate transformed section properties - Non-Composite (Girder+Strands), at support section, after debonding support

$A_{g.tr.dbs} := A_g + \left(n_p - 1\right) A_{p.total.dbs} = 824.215 \cdot in^2$

Area

$$y_{g.tr.top.dbs} := \frac{A_g \cdot y_{g.top} + \displaystyle\sum_{i=0}^{rows(n)-1} \left[A_{p.dbs_i} \cdot \left(n_p - 1\right) \cdot d_{p_i}\right]}{A_{g.tr.dbs}} = 19.765 \cdot in$$

Distance from top fiber (beam) to N.A after debonding support

$y_{g.tr.bot.dbs} := h_g - y_{g.tr.top.dbs} = 16.235 \cdot in$

Distance from bottom fiber (beam) to N.A after debonding support

$$I_{g.tr.dbs} := I_g + A_g \cdot \left(y_{g.tr.top.dbs} - y_{g.top}\right)^2 \ldots + \sum_{i=0}^{rows(n)-1} \left[\left(n_p - 1\right) \cdot A_{p.dbs_i} \cdot \left(d_{p_i} - y_{g.tr.top.dbs}\right)^2 \right] = 1.3 \times 10^5 \cdot in^4$$

Moment inertia, after debonding support

$$S_{g.tr.top.dbs} := \frac{I_{g.tr.dbs}}{y_{g.tr.top.dbs}} = 6.579 \times 10^3 \cdot in^3$$

$$S_{g.tr.bot.dbs} := \frac{I_{g.tr.dbs}}{y_{g.tr.bot.dbs}} = 8.009 \times 10^3 \cdot in^3$$

$$e_{g.tr.cg.strands.dbs} := y_{g.tr.bot.dbs} - d_{p.strands.c.g.bot.dbs} = 11.649 \cdot in$$

eccentricity of strand group
after debonding support

Check concrete stress limits at support section, after debonding support

$$f_{c.topbeam.support} := \frac{P_{pi.dbs}}{A_{g.tr.dbs}} + \frac{M_{sf.beam}\left(support_{check}\right) - P_{pi.dbs} \cdot e_{g.tr.cg.strands.dbs}}{S_{g.tr.top.dbs}}$$

$$f_{c.topbeam.support} = -0.527 \cdot ksi$$

Concrete stress at top fiber of the beam at support

$$f_{c.botbeam.support} := \frac{P_{pi.dbs}}{A_{g.tr.dbs}} - \frac{M_{sf.beam}\left(support_{check}\right) - P_{pi.dbs} \cdot e_{g.tr.cg.strands.dbs}}{S_{g.tr.bot.dbs}}$$

$$f_{c.botbeam.support} = 3.17 \cdot ksi$$

Concrete stress at bottom fiber of the beam at support

$$f_{compressive.allow.before.loss} = 3.9 \cdot ksi$$

$$f_{tensile.allow.15\%.before.loss} = -0.588 \cdot ksi$$

in the pretensioned beams, at the support, "bonded reinforcements"

$$Check_{top.dbs} := \begin{cases} \text{if } f_{c.topbeam.support} \geq 0ksi \\ \quad \begin{cases} \text{"OK"} & \text{if } f_{c.topbeam.support} \leq f_{compressive.allow.before.loss} \\ \text{"NG"} & \text{otherwise} \end{cases} \\ \text{if } f_{c.topbeam.support} < 0ksi \\ \quad \begin{cases} \text{"OK"} & \text{if } -f_{c.topbeam.support} \leq -f_{tensile.allow.15\%.before.loss} \\ \text{"NG"} & \text{otherwise} \end{cases} \end{cases}$$

$Check_{top.dbs} = \text{"OK"}$

Check concrete stress limits at the support, top fiber, at release

$$Check_{bot.dbs} := \begin{cases} \text{if } f_{c.botbeam.support} \geq 0ksi \\ \quad \begin{cases} \text{"OK"} & \text{if } f_{c.botbeam.support} \leq f_{compressive.allow.before.loss} \\ \text{"NG"} & \text{otherwise} \end{cases} \\ \text{if } f_{c.botbeam.support} < 0ksi \\ \quad \begin{cases} \text{"OK"} & \text{if } -f_{c.botbeam.support} \leq -f_{tensile.allow.15\%.before.loss} \\ \text{"NG"} & \text{otherwise} \end{cases} \end{cases}$$

$Check_{bot.dbs} = \text{"OK"}$

Check concrete stress limits at the support, bottom fiber, at release

8.3 At Debond1 Section

$debond1 = 10\,ft$ — debond distance, defined at strand pattern

$\frac{debond1}{Span} = 11.4\cdot\%$ — Check if the debond distance is within 15% span range to beam ends

Adjust

$$n = \begin{pmatrix}17\\17\\5\\0\\0\\0\\0\\0\end{pmatrix} \quad n_{dbs} = \begin{pmatrix}6\\4\\0\\0\\0\\0\\0\\0\end{pmatrix} \quad n_{db1} := \begin{pmatrix}2\\0\\0\\0\\0\\0\\0\\0\end{pmatrix} \quad n_{after.db1} := n - n_{db1} = \begin{pmatrix}15\\17\\5\\0\\0\\0\\0\\0\end{pmatrix}$$

Number of bonded strands in each row after debond 1 (db1) bottom up, 0...8

Note: the number of partially debonded strands should NOT exceed 30% of the total number of strands (SDG 4.3.1); in any horizontal row, the number of debonded strands should NOT exceed 40% of the total strands in that row (LRFD 5.9.4.3.3.)

$$n_{after.db1.total} := \sum_{i=0}^{rows(n)-1} n_{after.db1_i} = 37$$

Number of bonded strands after debond 1

$$P_{pi.db1} := n_{after.db1.total}\cdot A_{pf}\cdot f_{pi} = 1.58\times 10^3\cdot kip$$

Total prestress force at release, after debond1

$$A_{p.db1} := n_{after.db1}\cdot A_{pf} = \begin{pmatrix}2.685\\3.043\\0.895\\0.000\\0.000\\0.000\\0.000\\0.000\end{pmatrix}\cdot in^2$$

Total area of strands in each row, after debond1

$$A_{p.total.db1} := \sum_{i=0}^{rows(n)-1} A_{p.db1_i} = 6.623\cdot in^2$$

Total area of strands, after debond1

$$d_{p.strands.c.g.db1} := \frac{\sum_{i=0}^{rows(n)-1} \left(A_{p.db1_i}\cdot d_{p_i}\right)}{A_{p.total.db1}} = 31.541\cdot in$$

Distance from top beam section to the gravity center of strand group, after debond1

$d_{p.strands.c.g.bot.db1} := h_g - d_{p.strands.c.g.db1} = 4.459 \cdot in$

Distance from bottom beam section to the gravity center of strand group,after debond1

Need to recalculate transformed section properties - Non-Composite (Girder+Strands), in debond 1 region

$A_{g.tr.db1} := A_g + (n_p - 1)A_{p.total.db1} = 829.079 \cdot in^2$ Area

$$y_{g.tr.top.db1} := \frac{A_g \cdot y_{g.top} + \sum_{i=0}^{rows(n)-1} \left[A_{p.db1_i} \cdot (n_p - 1) \cdot d_{p_i}\right]}{A_{g.tr.db1}} = 1.653\ ft$$

Distance from top fiber (beam) to N.A after debond1

$y_{g.tr.bot.db1} := h_g - y_{g.tr.top.db1} = 1.347\ ft$

Distance from bottom fiber (beam) to N.A after debond1

$$I_{g.tr.db1} := I_g + A_g \cdot (y_{g.tr.top.db1} - y_{g.top})^2 \ldots + \sum_{i=0}^{rows(n)-1} \left[(n_p - 1) \cdot A_{p.db1_i} \cdot \left(d_{p_i} - y_{g.tr.top.db1}\right)^2\right] = 1.308 \times 10^5 \cdot in^4$$

Moment inertia after debond1

$$S_{g.tr.top.db1} := \frac{I_{g.tr.db1}}{y_{g.tr.top.db1}} = 6.592 \times 10^3 \cdot in^3$$

$$S_{g.tr.bot.db1} := \frac{I_{g.tr.db1}}{y_{g.tr.bot.db1}} = 8.09 \times 10^3 \cdot in^3$$

$e_{g.tr.cg.strands.db1} := y_{g.tr.bot.db1} - d_{p.strands.c.g.bot.db1} = 11.704 \cdot in$

eccentricity of strand group after debond1

Check concrete stress limits at debond1 section, after debond1

$$f_{c.topbeam.debond1} := \frac{P_{pi.db1}}{A_{g.tr.db1}} + \frac{M_{sf.beam}(debond1) - P_{pi.db1} \cdot e_{g.tr.cg.strands.db1}}{S_{g.tr.top.db1}} = -0.306 \cdot ksi$$

Concrete stress at top fiber of the beam at debond1 section

$$f_{c.botbeam.debond1} := \frac{P_{pi.db1}}{A_{g.tr.db1}} - \frac{M_{sf.beam}(debond1) - P_{pi.db1} \cdot e_{g.tr.cg.strands.db1}}{S_{g.tr.bot.db1}} = 3.707 \cdot ksi$$

Concrete stress at bottom fiber of the beam at debond1 section

$$f_{compressive.allow.before.loss} = 3.9 \cdot ksi$$

$$f_{tensile.allow.debond1} := \begin{cases} f_{tensile.allow.15\%.before.loss} & \text{if } \frac{debond1}{Span} \le 15\% \\ f_{tensile.allow.70\%.bond.before.loss} & \text{if } \frac{debond1}{Span} > 15\% \end{cases} = -0.588 \cdot ksi$$

in the pretensioned beams, at the debond1 section, "bonded reinforcements"

$$Check_{top.db1} := \begin{array}{|l} \text{if } f_{c.topbeam.debond1} \ge 0ksi \\ \quad \begin{array}{|ll} \text{"OK"} & \text{if } f_{c.topbeam.debond1} \le f_{compressive.allow.before.loss} \\ \text{"NG"} & \text{otherwise} \end{array} \\ \text{if } f_{c.topbeam.debond1} < 0ksi \\ \quad \begin{array}{|ll} \text{"OK"} & \text{if } -f_{c.topbeam.debond1} \le -f_{tensile.allow.debond1} \\ \text{"NG"} & \text{otherwise} \end{array} \end{array}$$

$$Check_{top.db1} = \text{"OK"}$$

Check concrete stress limits at the debond1 section, top fiber, at release

$$Check_{bot.db1} := \begin{array}{l} \text{if } f_{c.botbeam.debond1} \geq 0ksi \\ \quad \begin{array}{|l} \text{"OK" if } f_{c.botbeam.debond1} \leq f_{compressive.allow.before.loss} \\ \text{"NG" otherwise} \end{array} \\ \text{if } f_{c.botbeam.debond1} < 0ksi \\ \quad \begin{array}{|l} \text{"OK" if } -f_{c.botbeam.debond1} \leq -f_{tensile.allow.debond1} \\ \text{"NG" otherwise} \end{array} \end{array}$$

$Check_{bot.db1} = \text{"OK"}$

Check concrete stress limits at the debond1 section, bottom fiber, at release

8.4 At Debond2 Section

$debond2 = 20\,ft$

debond distance, defined at strand pattern

$\frac{debond2}{Span} = 22.8 \cdot \%$

Adjust

$n = \begin{pmatrix} 17 \\ 17 \\ 5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$ $n_{dbs} = \begin{pmatrix} 6 \\ 4 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$ $n_{db1} = \begin{pmatrix} 2 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$ $n_{db2} := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$

make all 0,
means no debonding after debond2

Note: the number of partially debonded strands should NOT exceed 30% of the total number of strands (SDG 4.3.1); in any horizontal row, the number of debonded strands should NOT exceed 40% of the total strands in that row (LRFD 5.9.4.3.3.)

$n_{after.db2} := n - n_{db2} = \begin{pmatrix} 17 \\ 17 \\ 5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$

Number of bonded strands in each row after debond 2 (db2)
bottom up, 0...8

$n_{after.db2.total} := \sum_{i=0}^{rows(n)-1} n_{after.db2_i} = 39$

Number of bonded strands after debond 2

$P_{pi.db2} := n_{after.db2.total} \cdot A_{pf} \cdot f_{pi} = 1.665 \times 10^3 \cdot kip$

Total prestress force at release, after debond2

$A_{p.db2} := n_{after.db2} \cdot A_{pf} = \begin{pmatrix} 3.043 \\ 3.043 \\ 0.895 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \\ 0.000 \end{pmatrix} \cdot in^2$

Total area of strands in each row, after debond2

$$A_{p.total.db2} := \sum_{i=0}^{rows(n)-1} A_{p.db2_i} = 6.981 \cdot in^2$$

Total area of strands, after debond2

$$d_{p.strands.c.g.db2} := \frac{\sum_{i=0}^{rows(n)-1} \left(A_{p.db2_i} \cdot d_{p_i}\right)}{A_{p.total.db2}} = 31.615 \cdot in$$

Distance from top beam section to the gravity center of strand group, after debond2

$$d_{p.strands.c.g.bot.db2} := h_g - d_{p.strands.c.g.db2} = 4.385 \cdot in$$

Distance from bottom beam section to the gravity center of strand group,after debond2

Need to recalculate transformed section properties - Non-Composite (Girder+Strands), in debond 2 region

$$A_{g.tr.db2} := A_g + \left(n_p - 1\right) A_{p.total.db2} = 830.295 \cdot in^2$$

Area

$$y_{g.tr.top.db2} := \frac{A_g \cdot y_{g.top} + \sum_{i=0}^{rows(n)-1} \left[A_{p.db2_i} \cdot \left(n_p - 1\right) \cdot d_{p_i}\right]}{A_{g.tr.db2}} = 19.856 \cdot in$$

Distance from top fiber (beam) to N.A after debond2

$$y_{g.tr.bot.db2} := h_g - y_{g.tr.top.db2} = 16.144 \cdot in$$

Distance from bottom fiber (beam) to N.A after debond2

$$I_{g.tr.db2} := I_g + A_g \cdot \left(y_{g.tr.top.db2} - y_{g.top}\right)^2 \ldots + \sum_{i=0}^{rows(n)-1} \left[\left(n_p - 1\right) \cdot A_{p.db2_i} \cdot \left(d_{p_i} - y_{g.tr.top.db2}\right)^2\right] = 1.31 \times 10^5 \cdot in^4$$

Moment inertia after debond2

$$S_{g.tr.top.db2} := \frac{I_{g.tr.db2}}{y_{g.tr.top.db2}} = 6.596 \times 10^3 \cdot in^3$$

$$S_{g.tr.bot.db2} := \frac{I_{g.tr.db2}}{y_{g.tr.bot.db2}} = 8.112 \times 10^3 \cdot in^3$$

$$e_{g.tr.cg.strands.db2} := y_{g.tr.bot.db2} - d_{p.strands.c.g.bot.db2} = 11.76 \cdot in$$

eccentricity of strand group after debond2

Check concrete stress limits at debond2 section, after debond2

$$f_{c.topbeam.debond2} := \frac{P_{pi.db2}}{A_{g.tr.db2}} + \frac{M_{sf.beam}(debond2) - P_{pi.db2} \cdot e_{g.tr.cg.strands.db2}}{S_{g.tr.top.db2}} = 0.071 \cdot ksi$$

Concrete stress at top fiber of the beam at debond2 section

$$f_{c.botbeam.debond2} := \frac{P_{pi.db2}}{A_{g.tr.db2}} - \frac{M_{sf.beam}(debond2) - P_{pi.db1} \cdot e_{g.tr.cg.strands.db2}}{S_{g.tr.bot.db2}} = 3.455 \cdot ksi$$

Concrete stress at bottom fiber of the beam at debond2 section

$$f_{compressive.allow.before.loss} = 3.9 \cdot ksi$$

$$f_{tensile.allow.debond2} := \begin{cases} f_{tensile.allow.15\%.before.loss} & \text{if } \frac{debond2}{Span} \le 15\% \\ f_{tensile.allow.70\%.bond.before.loss} & \text{if } \frac{debond2}{Span} > 15\% \end{cases} = -0.588 \cdot ksi$$

in the pretensioned beams, at the debond2 section, "bonded reinforcements"

$$Check_{top.db2} := \begin{array}{|l} \text{if } f_{c.topbeam.debond2} \geq 0ksi \\ \quad \begin{array}{|ll} \text{"OK"} & \text{if } f_{c.topbeam.debond2} \leq f_{compressive.allow.before.loss} \\ \text{"NG"} & \text{otherwise} \end{array} \\ \text{if } f_{c.topbeam.debond2} < 0ksi \\ \quad \begin{array}{|ll} \text{"OK"} & \text{if } -f_{c.topbeam.debond2} \leq -f_{tensile.allow.debond2} \\ \text{"NG"} & \text{otherwise} \end{array} \end{array}$$

$Check_{top.db2} = \text{"OK"}$

Check concrete stress limits at the debond2 section, top fiber, at release

$$Check_{bot.db2} := \begin{array}{|l} \text{if } f_{c.botbeam.debond2} \geq 0ksi \\ \quad \begin{array}{|ll} \text{"OK"} & \text{if } f_{c.botbeam.debond2} \leq f_{compressive.allow.before.loss} \\ \text{"NG"} & \text{otherwise} \end{array} \\ \text{if } f_{c.botbeam.debond2} < 0ksi \\ \quad \begin{array}{|ll} \text{"OK"} & \text{if } -f_{c.botbeam.debond2} \leq -f_{tensile.allow.debond2} \\ \text{"NG"} & \text{otherwise} \end{array} \end{array}$$

$Check_{bot.db2} = \text{"OK"}$

Check concrete stress limits at the debond2 section, bottom fiber, at release

8.5 Summary

at midspan

$\text{midspan} = 43.833\ \text{ft}$

$\text{Check}_{\text{top.midspan}} = \text{"OK"}$

$\text{Check}_{\text{bot.midspan}} = \text{"OK"}$

at support

$L_{\text{transfer}} = 2.5\ \text{ft}$

$\text{Check}_{\text{sp.top}} = \text{"OK"}$

$\text{Check}_{\text{sp.bot}} = \text{"NG"}$

$\text{Check}_{\text{db}} = \text{"Need to Debond Strand"}$

Need to debond strands?

$\text{Check}_{\text{top.dbs}} = \text{"OK"}$

$\text{Check}_{\text{bot.dbs}} = \text{"OK"}$

at debond1

$\text{debond1} = 10\ \text{ft}$

$\text{Check}_{\text{top.db1}} = \text{"OK"}$

$\text{Check}_{\text{bot.db1}} = \text{"OK"}$

at debond2

$\text{debond2} = 20\ \text{ft}$

$\text{Check}_{\text{top.db2}} = \text{"OK"}$

$\text{Check}_{\text{bot.db2}} = \text{"OK"}$

Strand pattern

without debond	debond number at support	debond number at debond1	debond number at debond2
$n = \begin{pmatrix} 17 \\ 17 \\ 5 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$	$n_{dbs} = \begin{pmatrix} 6 \\ 4 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$	$n_{db1} = \begin{pmatrix} 2 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$	$n_{db2} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$

9. STRESS LIMITS FOR CONCRETE STRESSES AT SERVICE LIMIT STATE (AFTER ALL LOSSES) (LRFD 5.9.2.3.2)

(Compression +, Tension -)

for stresses after all losses

$P_{pe} := A_{p.total} \cdot f_{pe} = 1.292 \times 10^{3} \cdot kip$

Total prestress force, at service, after all losses

$f_{compressive.allow.after.loss1.deck} := 0.45 \cdot f'_{c.slab} = 2.475 \cdot ksi$

Compressive stress limit for deck concrete due to (Service I) the sum of effective prestress and permanent loads (LRFD 5.9.2.3.2a)

$f_{compressive.allow.after.loss1.beam} := 0.45 \cdot f'_{c.beam} = 3.825 \cdot ksi$

Compressive stress limit for beam concrete due to (Service I) the sum of effective prestress and permanent loads (LRFD 5.9.2.3.2a)

$f_{compressive.allow.after.loss2.deck} := 0.60 \cdot f'_{c.slab} = 3.3 \cdot ksi$

Compressive stress limit for deck concrete due to (Service I) the sum of effective prestress, permanent loads, and transient loads (LRFD 5.9.2.3.2a)

$f_{compressive.allow.after.loss2.beam} := 0.60 \cdot f'_{c.beam} = 5.1 \cdot ksi$

Compressive stress limit for beam concrete due to (Service I) the sum of effective prestress, permanent loads, and transient loads (LRFD 5.9.2.3.2a)

$$f_{tensile.allow.after.loss.beam} := \begin{cases} \left[-\min\left[0.24 \cdot \left(\frac{f'_{ci.beam}}{ksi}\right)^{0.5} ksi, 0.6ksi\right]\right] & \text{if Environment = "Extremely"} \\ \left[-\min\left[0.0948 \cdot \left(\frac{f'_{ci.beam}}{ksi}\right)^{0.5} ksi, 0.3ksi\right]\right] & \text{otherwise} \end{cases}$$

$f_{tensile.allow.after.loss.beam} = -0.588 \cdot ksi$

Tensile stress limit for concrete, after all losses (LRFD 5.9.2.3.2b) (Service III)

9.1 Service I Limit State:under Effective Prestress and Permanent Loads

Critical section: mid span

for deck, check compression limit

Note : slab under load of utility, wearing surface, and barriers (due to construction stages)

$f_{compressive.allow.after.loss1.deck} = 2.475 \cdot ksi$

Compressive stress limit for deck concrete due to (Service I) the sum of effective prestress and permanent loads (LRFD 5.9.2.3.2a)

$$M_{permanent2} := M_{utility}(midspan) + M_{fws}(midspan) + M_{barrier}(midspan) = 165.237 \cdot kip \cdot ft$$

$$f_{c.deck.top1} := \frac{M_{permanent2}}{S_{g.comp.tr.top}} = 0.076 \cdot ksi$$

Concrete stress at the top fiber of deck

$$Check_{topdeck1} := \begin{cases} \text{"OK"} & \text{if } f_{c.deck.top1} \le f_{compressive.allow.after.loss1.deck} \\ \text{"NG"} & \text{otherwise} \end{cases}$$

$Check_{topdeck1} = \text{"OK"}$

Concrete stress at the top fiber of deck

for beam, check compression limit

$f_{compressive.allow.after.loss1.beam} = 3.825 \cdot ksi$

Compressive stress limit for beam concrete due to (Service I) the sum of effective prestress and permanent loads (LRFD 5.9.2.3.2a)

$$M_{permanent1} := M_{sf.beam}(midspan) + M_{sf.slab}(midspan) + M_{forms}(midspan) = 1.86 \times 10^3 \cdot kip \cdot ft$$

$$f_{c.beam.top1} := \left(\frac{P_{pe}}{A_{g.tr}} - \frac{P_{pe} \cdot e_{g.tr.cg.strands}}{S_{g.tr.top}}\right) + \frac{M_{permanent1}}{S_{g.tr.top}} + \frac{M_{permanent2}}{S_{g.comp.tr.topbeam}}$$

M.permanent1 (self weight of beam, slab, and forms) was applied to non-composite section; M.permanent2 (utility, wearding surface, and barriers) was applied to composite section

$f_{c.beam.top1} = 2.669 \cdot ksi$

Concrete stress at the top fiber of beam

$$Check_{topbeam1} := \begin{cases} \text{"OK"} & \text{if } f_{c.beam.top1} \le f_{compressive.allow.after.loss1.beam} \\ \text{"NG"} & \text{otherwise} \end{cases}$$

$Check_{topbeam1} = \text{"OK"}$

Concrete stress at the top fiber of beam

9.2 Service I Limit State:under Effective Prestress, Permanent Loads, and Transient Loads

Note: loading during shipping and handling is not included in this example

Critical section: mid span

for deck, check compression limit

$f_{compressive.allow.after.loss2.deck} = 3.3 \cdot ksi$

Compressive stress limit for deck concrete due to (Service I)
the sum of effective prestress, permanent loads, and transient loads (LRFD 5.9.2.3.2a)

$M_{LL.IM.mid} = 1.628 \times 10^3 \cdot kip \cdot ft$

Moment due to Live Loads (truck and lane)

$$f_{c.deck.top2} := f_{c.deck.top1} + \frac{M_{LL.IM.mid}}{S_{g.comp.tr.top}} = 0.82 \cdot ksi$$

Concrete stress at the top fiber of deck

$$Check_{topdeck2} := \begin{cases} \text{"OK"} & \text{if } f_{c.deck.top2} \le f_{compressive.allow.after.loss2.deck} \\ \text{"NG"} & \text{otherwise} \end{cases}$$

$Check_{topdeck2} = \text{"OK"}$

Concrete stress at the top fiber of deck

for beam, check compression limit

$f_{compressive.allow.after.loss2.beam} = 5.1 \cdot ksi$

Compressive stress limit for beam concrete due to (Service I) the sum of effective prestress, permanent loads, and transient loads (LRFD 5.9.2.3.2a)

$$f_{c.beam.top2} := f_{c.beam.top1} + \frac{M_{LL.IM.mid}}{S_{g.comp.tr.topbeam}} = 2.991 \cdot ksi$$

Concrete stress at the top fiber of beam

$$Check_{topbeam2} := \begin{cases} \text{"OK"} & \text{if } f_{c.beam.top2} \le f_{compressive.allow.after.loss2.beam} \\ \text{"NG"} & \text{otherwise} \end{cases}$$

$Check_{topbeam2} = \text{"OK"}$

Concrete stress at the top fiber of beam

9.3 Service III Limit State

Note: loading during shipping and handling is not included in this example

Critical section: mid span

for beam, check tensile limit at the bottom fiber

$f_{tensile.allow.after.loss.beam} = -0.588 \cdot ksi$

Tensile stress limit for concrete, after all losses (LRFD 5.9.2.3.2b) (Service III)

$$f_{c.beam.bot} := \frac{P_{pe}}{A_{g.tr}} + \frac{P_{pe} \cdot e_{g.tr.cg.strands}}{S_{g.tr.bot}} \ldots + \frac{-M_{permanent1}}{S_{g.tr.bot}} + \frac{-M_{permanent2}}{S_{g.comp.tr.bot}} + (0.8)\frac{-M_{LL.IM.mid}}{S_{g.comp.tr.bot}} = -0.478 \cdot ksi$$

Concrete stress at the bottom fiber of beam

$Check_{botbeam} := \begin{cases} \text{"OK"} & \text{if } -f_{c.beam.bot} \le -f_{tensile.allow.after.loss.beam} \\ \text{"NG"} & \text{otherwise} \end{cases}$

$Check_{botbeam} = \text{"OK"}$

Concrete stress at the bottom fiber of beam

9.4 Summary

$Check_{topdeck1} = \text{"OK"}$ $\quad \dfrac{f_{c.deck.top1}}{f_{compressive.allow.after.loss1.deck}} = 0.031$ Service I

$Check_{topbeam1} = \text{"OK"}$ $\quad \dfrac{f_{c.beam.top1}}{f_{compressive.allow.after.loss1.beam}} = 0.698$ Service I

$Check_{topdeck1} = \text{"OK"}$ $\quad \dfrac{f_{c.deck.top2}}{f_{compressive.allow.after.loss2.deck}} = 0.249$ Service I

$Check_{topbeam1} = \text{"OK"}$ $\quad \dfrac{f_{c.beam.top2}}{f_{compressive.allow.after.loss2.beam}} = 0.586$ Service I

$Check_{botbeam} = \text{"OK"}$ $\quad \dfrac{-f_{c.beam.bot}}{-f_{tensile.allow.after.loss.beam}} = 0.813$ Service III

10. FATIGUE LIMIT STATE

Acoording to AASHTO CFRP 1.5.2,

In regions of compressive stress due to unfactored loads and prestress in reinforced concrete componentss, fatigue shall be checked only if this stress compressive strength is less than the maximum tensile live load stress resulting from the Fatigue I load combination.

Fatigue of the reinforcement need not be checked for prestressed components designed to have extreme fiber tensile stress due to the Service III Limit State within the stress limit specified in LRFD Table 5.9.2.3.2b-1

at midspan

$$f_{c.topbeam} := \frac{P_{pe}}{A_{g.tr}} - \frac{P_{pe} \cdot e_{g.tr.cg.strands}}{S_{g.tr.top}} + \frac{M_{permanent1}}{S_{g.tr.top}} + \frac{M_{permanent2}}{S_{g.comp.tr.topbeam}} = 2.669 \cdot ksi$$

compressive stress at top fiber of the beam due to unfactored loads and prestress

$$f_{t.bot.fatigue} := \frac{M_{fatigue}(midspan)}{S_{g.comp.tr.bot}} = 0.956 \cdot ksi$$

$$Check_{fatigue} := \begin{cases} \text{"Need to Check Fatigue"} & \text{if } \dfrac{f_{c.topbeam}}{f_{t.bot.fatigue}} < 1 \\ \text{"No Need to Check Fatigue"} & \text{otherwise} \end{cases}$$

$$Check_{fatigue} = \text{"No Need to Check Fatigue"}$$

Fatigue of the reinforcement need not be checked since the prestressed beam is designed to have extreme fiber tensile stress due to the Service III Limit State within the stress limit specified in LRFD Table 5.9.2.3.2b-1 (shown in section 9.3 of this example)

11. STRENGTH LIMIT STATE -MOMENT CAPACITY

Note: for strength calculations, deck reinforcement is conservatively ignored

$P_{pe} = 1.292 \times 10^{3} \cdot kip$

Total prestress force, at service, after all losses

$M_u := M_{Str1.mid} = 5.381 \times 10^{3} \cdot kip \cdot ft$

Strength I limit state moment at midspan

$\phi_{moment} = 0.75$

Reduction factor for CFRP prestressed girder - Moment

$$\alpha_{1.beam} := \min\left(\max\left(0.85 - 0.02 \cdot \frac{f'_{c.beam} - 10ksi}{ksi}, 0.75\right), 0.85\right) = 0.85$$

$$\beta_{1.beam} := \min\left(\max\left(0.85 - 0.05 \cdot \frac{f'_{c.beam} - 4ksi}{ksi}, 0.65\right), 0.85\right) = 0.65$$

$\beta_1 := \beta_{1.beam} = 0.65$

$$\alpha_{1.slab} := \min\left(\max\left(0.85 - 0.02 \cdot \frac{f'_{c.slab} - 10ksi}{ksi}, 0.75\right), 0.85\right) = 0.85$$

$$\beta_{1.slab} := \min\left(\max\left(0.85 - 0.05 \cdot \frac{f'_{c.slab} - 4ksi}{ksi}, 0.65\right), 0.85\right) = 0.775$$

Concrete stress block factor

(LRFD 5.6.2.2)

$\varepsilon_{pu} = 0.015$

Rupture strain of CFRP strand

$\varepsilon_{pe} := \frac{f_{pe}}{E_p} = 8.231 \times 10^{-3}$

Effective prestress strain of CFRP

$\varepsilon_{cu} := 0.003$

Concrete crushing strain

$$A_p = \begin{pmatrix} 3.043 \\ 3.043 \\ 0.895 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot in^2$$

Area of strands in each row
bottom up, 0...8

$$d_{pf} := \left| \begin{array}{l} \text{for } i \in 0 .. \text{rows}(n) - 1 \\ \quad d_{pf_i} \leftarrow d_{p_i} + t_{slab} + h_{buildup} \\ d_{pf} \end{array} \right. = \begin{pmatrix} 42.5 \\ 40.5 \\ 38.5 \\ 36.5 \\ 34.5 \\ 32.5 \\ 30.5 \\ 28.5 \end{pmatrix} \cdot in$$

Distance from top slab section (composite section) to the center of each strand row
bottom up, 0...8

11.1 Compression-Controlled Section

$cc_C = 9.032 \cdot in$

Concrete compression depth
This number is defined later to satisfy C=T

$aa_C := \beta_1 \cdot cc_C = 5.871 \cdot in$

$\varepsilon_{cc.C} := \varepsilon_{cu} = 0.003$

$$\varepsilon_{f.C} := \left| \begin{array}{l} \text{for } i \in 0 .. \text{rows}(n) - 1 \\ \quad \varepsilon_{f.C_i} \leftarrow \varepsilon_{pe} + \varepsilon_{cc.C} \cdot \left(\dfrac{d_{pf_i} - cc_C}{cc_C} \right) \\ \varepsilon_{f.C} \end{array} \right. = \begin{pmatrix} 0.019 \\ 0.019 \\ 0.018 \\ 0.017 \\ 0.017 \\ 0.016 \\ 0.015 \\ 0.015 \end{pmatrix}$$

CFRP strain in each row
bottom up, 0...8

$$f_{f.C} := \left| \begin{array}{l} \text{for } i \in 0 .. \text{rows}(n) - 1 \\ \quad f_{f.C_i} \leftarrow \varepsilon_{f.C_i} \cdot E_p \\ f_{f.C} \end{array} \right. = \begin{pmatrix} 435 \\ 420 \\ 405 \\ 390 \\ 375 \\ 360 \\ 345 \\ 330 \end{pmatrix} \cdot \text{ksi}$$

CFRP stress in each row bottom up, 0...8

$$\text{Check}_{fp.C} := \left| \begin{array}{ll} \text{"CFRP Rupture Before Concrete Crushing, Assumption Not Satisfied"} & \text{if } f_{f.C_0} > f_{pu} \\ \text{"Compression Controlled Section, Assumption Satisfied"} & \text{otherwise} \end{array} \right.$$

$$\text{Check}_{fp.C} = \text{"CFRP Rupture Before Concrete Crushing, Assumption Not Satisfied"}$$

$$T_{f.C} := \left| \begin{array}{l} \text{for } i \in 0 .. \text{rows}(n) - 1 \\ \quad T_{f.C_i} \leftarrow f_{f.C_i} \cdot A_{p_i} \\ T_{f.C} \end{array} \right. = \begin{pmatrix} 1323 \\ 1278 \\ 363 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot \text{kip}$$

CFRP tension force in each row bottom up, 0...8

$$T_{CFRP.C} := \sum_{i=0}^{\text{rows}(n)-1} T_{f.C_i} = 2.964 \times 10^3 \cdot \text{kip}$$

Total tension force in all CFRP strands

Define differnt depth of compression zone

$$tt1 := t_{slab} = 8.5 \cdot \text{in}$$

$$tt2 := tt1 + h_{buildup} = 9.5 \cdot \text{in}$$

$$tt3 := tt2 + h_{beam.top.flange} = 13 \cdot \text{in}$$

$$h_{tf} := h_{beam.top.flange}$$

Beam, top flange thickness

$$b_{tf} := b_{beam.top.flange}$$

Beam, top flange width

$$C_{concrete.C} := \begin{cases} \alpha_{1.slab}\cdot f'_{c.slab}\cdot aa_C\cdot b_e & \text{if } aa_C \le tt1 \\ \left(\alpha_{1.slab}\cdot f'_{c.slab}\cdot t_{slab}\cdot b_e\right) \dots \\ +\left[\alpha_{1.slab}\cdot f'_{c.slab}\cdot\left(aa_C - tt1\right)\cdot b_{tf}\right] & \text{if } tt1 < aa_C \le tt2 \\ \left(\alpha_{1.slab}\cdot f'_{c.slab}\cdot t_{slab}\cdot b_e\right) \dots \\ +\left(\alpha_{1.slab}\cdot f'_{c.slab}\cdot h_{buildup}\cdot b_{tf}\right) \dots \\ +\left[\alpha_{1.beam}\cdot f'_{c.beam}\cdot\left(aa_C - tt2\right)\cdot b_{tf}\right] & \text{if } tt2 < aa_C \le tt3 \\ \left(\alpha_{1.slab}\cdot f'_{c.slab}\cdot t_{slab}\cdot b_e\right) \dots \\ +\left(\alpha_{1.slab}\cdot f'_{c.slab}\cdot h_{buildup}\cdot b_{tf}\right) \dots \\ +\left(\alpha_{1.beam}\cdot f'_{c.beam}\cdot h_{tf}\cdot b_{tf}\right) \dots \\ +\left[\alpha_{1.beam}\cdot f'_{c.beam}\cdot\left(aa_C - tt3\right)\cdot b_{web}\right] & \text{if } aa_C > tt3 \end{cases}$$

Compression force from concrete

Note: here FIB 36 section dimensions are simplified

$$C_{concrete.C} = 2.964 \times 10^3\cdot kip$$

$$M_{n.C} := \begin{cases} \sum_{i=0}^{rows(n)-1} \left(T_{f.C_i} \cdot d_{pf_i}\right) \dots \\ + (-1) \cdot \left[\left(\alpha_{1.slab} \cdot f'_{c.slab} \cdot aa_C \cdot b_e\right) \cdot \left(\frac{aa_C}{2}\right)\right] & \text{if } aa_C \le tt1 \\ \sum_{i=0}^{rows(n)-1} \left(T_{f.C_i} \cdot d_{pf_i}\right) \dots \\ + (-1) \cdot \left(\alpha_{1.slab} \cdot f'_{c.slab} \cdot t_{slab} \cdot b_e\right) \cdot \left(\frac{tt1}{2}\right) \dots \\ + (-1) \cdot \left[\alpha_{1.slab} \cdot f'_{c.slab} \cdot \left(aa_C - tt1\right) \cdot b_{tf}\right] \cdot \left(tt1 + \frac{aa_C - tt1}{2}\right) & \text{if } tt1 < aa_C \le tt2 \\ \sum_{i=0}^{rows(n)-1} \left(T_{f.C_i} \cdot d_{pf_i}\right) \dots \\ + (-1) \cdot \left(\alpha_{1.slab} \cdot f'_{c.slab} \cdot t_{slab} \cdot b_e\right) \cdot \left(\frac{tt1}{2}\right) \dots \\ + (-1) \cdot \left(\alpha_{1.slab} \cdot f'_{c.slab} \cdot h_{buildup} \cdot b_{tf}\right) \cdot \left(tt1 + \frac{h_{buildup}}{2}\right) \dots \\ + (-1) \cdot \left[\alpha_{1.beam} \cdot f'_{c.beam} \cdot \left(aa_C - tt2\right) \cdot b_{tf}\right] \cdot \left(tt2 + \frac{aa_C - tt2}{2}\right) & \text{if } tt2 < aa_C \le tt3 \\ \sum_{i=0}^{rows(n)-1} \left(T_{f.C_i} \cdot d_{pf_i}\right) \dots \\ + (-1) \cdot \left(\alpha_{1.slab} \cdot f'_{c.slab} \cdot t_{slab} \cdot b_e\right) \cdot \left(\frac{tt1}{2}\right) \dots \\ + (-1) \cdot \left(\alpha_{1.slab} \cdot f'_{c.slab} \cdot h_{buildup} \cdot b_{tf}\right) \cdot \left(tt1 + \frac{h_{buildup}}{2}\right) \dots \\ + (-1) \cdot \left(\alpha_{1.beam} \cdot f'_{c.beam} \cdot h_{tf} \cdot b_{tf}\right) \cdot \left(tt2 + \frac{h_{tf}}{2}\right) \dots \\ + (-1) \cdot \left[\alpha_{1.beam} \cdot f'_{c.beam} \cdot \left(aa_C - tt3\right) \cdot b_{web}\right] \cdot \left(tt3 + \frac{aa_C - tt2}{2}\right) & \text{if } aa_C > tt3 \end{cases}$$

$M_{n.C} = 9.439 \times 10^3 \cdot kip \cdot ft$ — Moment capacity (with respect to top fiber of the composite section)

$Check_{CT.C} := C_{concrete.C} - T_{CFRP.C} = 0 \cdot kip$ — Tension = Compression

$Check_{fp.C}$ = "CFRP Rupture Before Concrete Crushing, Assumption Not Satisfied"

$cc_C \equiv 9.032 in$ — Adjust cc until C-T~0

$SectionControl := \begin{cases} \text{"Tension Controlled Section"} & \text{if } f_{f.C_0} > f_{pu} \\ \text{"Compression Controlled Section"} & \text{otherwise} \end{cases}$

$SectionControl = \text{"Tension Controlled Section"}$

11.2 Tension-Controlled Section

$cc_T = 7.12 \cdot in$

Concrete compression depth
This number is defined later to satisfy C=T

$aa_T := \beta_1 \cdot cc_T = 4.628 \cdot in$

$\varepsilon_{pf.T} := \varepsilon_{pu} = 0.0152$

CFRP strain in bottom row is rupture strain

$\varepsilon_{cc.T} := (\varepsilon_{pu} - \varepsilon_{pe}) \cdot \left(\frac{cc_T}{d_{pf_0} - cc_T} \right) = 1.394 \times 10^{-3}$

Concrete strain at the top fiber of the section (deck)

$Check_{cc.T} := \begin{cases} \text{"OK"} & \text{if } \varepsilon_{cc.T} \le \varepsilon_{cu} \\ \text{"NG, Concrete Strain Exceeds εcu. Compression-Controlled Section"} & \text{otherwise} \end{cases}$

$Check_{cc.T} = \text{"OK"}$

$$\varepsilon_{f.T} := \begin{array}{|l} \text{for } i \in 0 .. rows(n) - 1 \\ \quad \varepsilon_{f.T_i} \leftarrow \varepsilon_{pe} + \varepsilon_{cc.T} \cdot \left(\frac{d_{pf_i} - cc_T}{cc_T} \right) \\ \varepsilon_{f.T} \end{array} = \begin{pmatrix} 0.0152 \\ 0.0148 \\ 0.0144 \\ 0.0140 \\ 0.0136 \\ 0.0132 \\ 0.0128 \\ 0.0124 \end{pmatrix}$$

CFRP strain in each row bottom up, 0...8

$$f_{f.T} := \left| \begin{array}{l} \text{for } i \in 0..\text{rows}(n)-1 \\ \quad f_{f.T_i} \leftarrow \varepsilon_{f.T_i} \cdot E_p \\ f_{f.T} \end{array} \right. = \begin{pmatrix} 341 \\ 332 \\ 323 \\ 314 \\ 306 \\ 297 \\ 288 \\ 279 \end{pmatrix} \cdot \text{ksi}$$

CFRP stress in each row bottom up, 0...8

$$\text{Check}_{fp.T} := \left| \begin{array}{ll} \text{"CFRP Rupture, Assumption Not Satisfied"} & \text{if } f_{f.T_0} > f_{pu} \\ \text{"OK"} & \text{otherwise} \end{array} \right.$$

$$\text{Check}_{fp.T} = \text{"OK"}$$

CFRP not rupture

$$T_{f.T} := \left| \begin{array}{l} \text{for } i \in 0..\text{rows}(n)-1 \\ \quad T_{f.T_i} \leftarrow f_{f.T_i} \cdot A_{p_i} \\ T_{f.T} \end{array} \right. = \begin{pmatrix} 1037 \\ 1010 \\ 289 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \cdot \text{kip}$$

CFRP tension force in each row bottom up, 0...8

$$T_{CFRP.T} := \sum_{i=0}^{\text{rows}(n)-1} T_{f.T_i} = 2.336 \times 10^3 \cdot \text{kip}$$

Total tension force in all CFRP strands

$$C_{concrete.T} := \begin{cases} \alpha_{1.slab} \cdot f'_{c.slab} \cdot aa_T \cdot b_e & \text{if } aa_T \le tt1 \\ \left(\alpha_{1.slab} \cdot f'_{c.slab} \cdot t_{slab} \cdot b_e\right) \cdots \\ \quad + \left[\alpha_{1.slab} \cdot f'_{c.slab} \cdot \left(aa_T - t_{slab}\right) \cdot b_{beam.bot..flange}\right] & \text{if } tt1 < aa_T \le tt2 \\ \left(\alpha_{1.slab} \cdot f'_{c.slab} \cdot t_{slab} \cdot b_e\right) \cdots \\ \quad + \left(\alpha_{1.slab} \cdot f'_{c.slab} \cdot h_{buildup} \cdot b_{beam.bot..flange}\right) \cdots \\ \quad + \left[\alpha_{1.beam} \cdot f'_{c.beam} \cdot \left(aa_T - tt2\right) \cdot b_{beam.bot..flange}\right] & \text{if } tt2 < aa_T \le tt3 \\ \left(\alpha_{1.slab} \cdot f'_{c.slab} \cdot t_{slab} \cdot b_e\right) \cdots \\ \quad + \left(\alpha_{1.slab} \cdot f'_{c.slab} \cdot h_{buildup} \cdot b_{beam.bot..flange}\right) \cdots \\ \quad + \left(\alpha_{1.beam} \cdot f'_{c.beam} \cdot h_{beam.top.flange} \cdot b_{beam.bot..flange}\right) \cdots \\ \quad + \left[\alpha_{1.beam} \cdot f'_{c.beam} \cdot \left(aa_T - tt3\right) \cdot b_{web}\right] & \text{if } aa_T > tt3 \end{cases}$$

Compression force from concrete

Note: here FIB 36 section dimensions are simplified

$C_{concrete.T} = 2.337 \times 10^3 \cdot kip$

$$M_{n.T} := \begin{cases} \sum_{i=0}^{rows(n)-1} \left(T_{f.T_i} \cdot d_{pf_i}\right) + (-1)\cdot\left[\left(\alpha_{1.slab}\cdot f'_{c.slab}\cdot aa_T \cdot b_e\right)\cdot\left(\frac{aa_T}{2}\right)\right] & \text{if } aa_T \le tt1 \\ \sum_{i=0}^{rows(n)-1} \left(T_{f.T_i} \cdot d_{pf_i}\right) + (-1)\cdot\left(\alpha_{1.slab}\cdot f'_{c.slab}\cdot t_{slab} \cdot b_e\right)\cdot\left(\frac{tt1}{2}\right) + (-1)\cdot\left[\alpha_{1.slab}\cdot f'_{c.slab}\cdot\left(aa_T - tt1\right)\cdot b_{tf}\right]\cdot\left(tt1 + \frac{aa_T - tt1}{2}\right) & \text{if } tt1 < aa_T \le tt2 \\ \sum_{i=0}^{rows(n)-1} \left(T_{f.T_i} \cdot d_{pf_i}\right) + (-1)\cdot\left(\alpha_{1.slab}\cdot f'_{c.slab}\cdot t_{slab} \cdot b_e\right)\cdot\left(\frac{tt1}{2}\right) + (-1)\cdot\left(\alpha_{1.slab}\cdot f'_{c.slab}\cdot h_{buildup}\cdot b_{tf}\right)\cdot\left(tt1 + \frac{h_{buildup}}{2}\right) + (-1)\cdot\left[\alpha_{1.beam}\cdot f'_{c.beam}\cdot\left(aa_T - tt2\right)\cdot b_{tf}\right]\cdot\left(tt2 + \frac{aa_T - tt2}{2}\right) & \text{if } tt2 < aa_T \le tt3 \\ \sum_{i=0}^{rows(n)-1} \left(T_{f.T_i} \cdot d_{pf_i}\right) + (-1)\cdot\left(\alpha_{1.slab}\cdot f'_{c.slab}\cdot t_{slab} \cdot b_e\right)\cdot\left(\frac{tt1}{2}\right) + (-1)\cdot\left(\alpha_{1.slab}\cdot f'_{c.slab}\cdot h_{buildup}\cdot b_{tf}\right)\cdot\left(tt1 + \frac{h_{buildup}}{2}\right) + (-1)\cdot\left(\alpha_{1.beam}\cdot f'_{c.beam}\cdot h_{tf}\cdot b_{tf}\right)\cdot\left(tt2 + \frac{h_{tf}}{2}\right) + (-1)\cdot\left[\alpha_{1.beam}\cdot f'_{c.beam}\cdot\left(aa_T - tt3\right)\cdot b_{web}\right]\cdot\left(tt3 + \frac{aa_T - tt2}{2}\right) & \text{if } aa_T > tt3 \end{cases}$$

$M_{n.T} = 7.56 \times 10^3 \cdot kip \cdot ft$ — Moment capacity (with respect to top fiber of the composite section)

$Check_{CT.T} := C_{concrete.T} - T_{CFRP.T} = 0 \cdot kip$ — Equilibrium check

$Check_{fp.T} = $ "OK" — CFRP strain limits check

$Check_{cc.T} = $ "OK" — Concrete strain limits check

$cc_T \equiv 7.12in$ — Adjust cc until C-T~0

11.3 Summary

SectionControl = "Tension Controlled Section"

$cc := \begin{cases} cc_T \text{ if SectionControl = "Tension Controlled Section"} \\ cc_C \text{ if SectionControl = "Compression Controlled Section"} \end{cases} = 7.12 \cdot in$

Compression Depth

$M_n := \begin{cases} M_{n.T} \text{ if SectionControl = "Tension Controlled Section"} \\ M_{n.C} \text{ if SectionControl = "Compression Controlled Section"} \end{cases} = 7.56 \times 10^3 \cdot kip \cdot ft$

Moment capacity

$M_r := \phi_{moment} \cdot M_n = 5670 \cdot kip \cdot ft$

$M_u = 5381 \cdot kip \cdot ft$

$Check_M := \begin{cases} \text{"OK" if } M_r \geq M_u \\ \text{"NG" if } M_r < M_u \end{cases}$

$Check_M = \text{"OK"}$

Strength I, moment capacity

12. MINIMUM REINFORCEMENT -PRESTRESSING CFRP

For tension-controlled beams,
the minimum reinforcement requirements ensure the factored moment capacity provided is at least equal to the lesser of the cracking moment Mcr and 1.33 times the factored moment required by the applicable strength load combinations (Mu).

(AASHTO CFRP 1.7.3.3.1)

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

Cracking moment

(AASHTO CFRP 1.7.3.3.1-1)

$$f_{r.beam} = 0.7 \cdot ksi$$

Modulus of rupture of beam concrete
(SDG 1.4.1B)

$$\gamma_1 := 1.6$$

flexural cracking vaiability factor

$$\gamma_2 := 1.1$$

Prestress variability factor
1.1 for bonded prestressing CFRP
1.0 for unbonded prestressing CFRP

(AASHTO CFRP 1.7.3.3.1)

$$\gamma_3 := 1.0$$

$$f_{cpe} := \frac{P_{pe}}{A_{g.tr}} + \frac{P_{pe} \cdot e_{g.tr.cg.strands}}{S_{g.tr.bot}} = 3.428 \cdot ksi$$

Compressive stress in concrete due to effective prestress forces only (after all losses) at extreme fiber of section where tensile stress is caused by externally applied loads

$$M_{dnc} := M_{sf.beam}(midspan) + M_{sf.slab}(midspan) \ldots = 1.86 \times 10^3 \cdot kip \cdot ft$$
$$+ M_{forms}(midspan)$$

Total unfactored dead load moment acting on the noncomposite section

$$M_{cr} := \gamma_3 \cdot \left[\left(\gamma_1 \cdot f_{r.beam} + \gamma_2 \cdot f_{cpe} \right) \cdot S_{g.comp.tr.bot} - M_{dnc} \cdot \left(\frac{S_{g.comp.tr.bot}}{S_{g.tr.bot}} - 1 \right) \right] = 4.579 \times 10^3 \cdot kip \cdot ft$$

Cracking moment

(AASHTO CFRP 1.7.3.3.1-1)

$M_{req} := \min(M_{cr}, 1.33M_u) = 4.579 \times 10^3 \cdot kip \cdot ft$

Required minimum amount of CFRP shall develop the moment capacity Mreq

SectionCT := | "C" if SectionControl = "Compression Controlled Section"
| "T" if SectionControl = "Tension Controlled Section"

$Check_{minCFRP}$:= | "Compression Controlled Section, Not Applicable" if SectionCT = "C"
| "OK" if SectionCT = "T" $\wedge M_n \geq M_{req}$
| "NG" if SectionCT = "T" $\wedge M_n < M_{req}$

$Check_{minCFRP}$ = "OK"

minimum amount of prestressing CFRP

13. TRANSVERSE SHEAR DESIGN

$V_u \le V_r = \phi_{shear} \cdot V_n$ (AASHTO CFRP 1.8.2.1)

$\phi_{shear} = 0.9$ Reduction factor for CFRP prestressed girder - Shear (AASHTO CFRP 1.8.2.1, LRFD 5.5.4.2)

$V_n = \min(V_{n1}, V_{n2})$

$V_{n1} = V_c + V_f + V_p$ Vc, Vf, Vp are shear resistance contribution by concrete, FRP stirrup, and CFRP prestressing strands

$V_{n2} = 0.25 f'_c \cdot b_v \cdot d_v + V_p$

$V_u > 0.5 \cdot \phi_{shear} \cdot (V_c + V_p)$ Transverse reinforcement should be provided in this case (LRFD 5.7.3.2-1)

13.1 Critical Section for Shear

critical section for shear shall be taken as dv from the internal face of support

$d_{e.shear} := h_{g.comp} - d_{p.strands.c.g.bot} = 41.115 \cdot in$ Effective depth from the extreme compression fiber to the centroid of the tensile force in the tensile reinforcements

$$d_v := \max\left(d_{e.shear} - \frac{\beta_1 \cdot cc}{2}, 0.9 \cdot d_{e.shear}, 0.72 \cdot h_{g.comp}\right) = 38.801 \cdot in$$

Effective shear depth (LRFD 5.7.2.8)

$$shearcheck := d_v + \frac{PadWidth}{2} = 3.65\,ft$$

Critical shear section, from left support

$b_v := b_{web} = 7 \cdot in$ Width of web (LRFD 5.7.2.7)

13.2 Contribution by Prestressing CFRP

$V_p := 0$

Straight strands, no draped, Vp=0

13.3 Contribution by Concrete, Vc

$V_c = 0.0316 \cdot \beta \cdot \sqrt{f'_{c.beam}} \cdot b_v \cdot d_v$

(LRFD 5.7.3.3-3)

Determine paremeters β and θ

Note: assume the section containing ***at least*** *the minimum amount of transverse reinforcement*

$$\varepsilon_{f.shear} = \frac{\frac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - A_{pf} \cdot f_{p0}}{E_f \cdot A_{pf}}$$

Net longitudinal tensile strain
(AASHTO CFRP 1.8.3.2)

$N_{u.shear} := 0$

Factored axial force at shear critical section

$V_{u.shear} := V_{Str1}(\text{shearcheck}) = 271.846 \cdot kip$

Factored shear at shear critical section

$M_{Str1}(\text{shearcheck}) = 885.949 \cdot kip \cdot ft$

$M_{u.shear} := \max\left(M_{Str1}(\text{shearcheck}), |V_{u.shear} - V_p| \cdot d_v\right) = 885.949 \cdot kip \cdot ft$

Factored moment at shear critical section
(AASHTO CFRP 1.8.3.2)

$f_{p0.shear} := 0.6 \cdot f_{pu} = 204.469 \cdot ksi$

(AASHTO CFRP 1.8.3.2)

$$A_{pf.shear} := \begin{cases} A_{p.total.dbs} & \text{if } shearcheck < debond1 \\ A_{p.total.db1} & \text{if } debond1 \le shearcheck < debond2 \\ A_{p.total.db2} & \text{if } shearcheck \ge debond2 \end{cases}$$

$$A_{pf.shear} = 5.191 \cdot in^2$$

Area of prestressing CFRP on the flextual tension side of the member, exclude debonded strands

$$\varepsilon_{f.shear1} := \min\left(\varepsilon_{pu}, \frac{\frac{|M_{u.shear}|}{d_v} + 0.5N_{u.shear} + |V_{u.shear} - V_p| - A_{pf.shear} \cdot f_{p0.shear}}{E_p \cdot A_{pf.shear}}\right)$$

$$\varepsilon_{f.shear1} = -4.418 \times 10^{-3}$$

$$A_{ct.shear} := A_g - b_{tf} \cdot (h_{tf} + 1.5in) - b_{web} \cdot (h_g - 0.5 \cdot h_{web} - h_{tf}) - A_{p.total} = 389.849 \cdot in^2$$

Area of concrete on the flexural tenson side of the member (LRFD B5.2) Approximate

$$\varepsilon_{f.shear2} := \min\left(\varepsilon_{pu}, \frac{\frac{|M_{u.shear}|}{d_v} + 0.5N_{u.shear} + |V_{u.shear} - V_p| - A_{pf.shear} \cdot f_{p0.shear}}{A_{ct.shear} \cdot E_{c.beam} + E_p \cdot A_{pf.shear}}\right)$$

$$\varepsilon_{f.shear2} = -2.444 \times 10^{-4}$$

$$\varepsilon_{f.shear} := \begin{cases} \varepsilon_{f.shear1} & \text{if } \varepsilon_{f.shear1} \ge 0 \\ \max(-0.0004, \varepsilon_{f.shear2}) & \text{if } \varepsilon_{f.shear1} < 0 \end{cases} = -2.444 \times 10^{-4}$$

$$\beta := \frac{4.8 \cdot deg}{1 + 750 \cdot \varepsilon_{f.shear}} = 5.9 \cdot deg$$ (LRFD 5.7.3.4.2-1)

$$\theta := (29 + 3500 \cdot \varepsilon_{f.shear}) \cdot deg = 28.1 \cdot deg$$ (LRFD 5.7.3.4.2-3)

$$V_c := 0.0316 \cdot \frac{\beta}{deg} \cdot \sqrt{\frac{f'_{c.beam}}{ksi}} \cdot \frac{b_v}{in} \cdot \frac{d_v}{in} \cdot kip = 147.064 \cdot kip$$ (LRFD 5.7.3.3-3)

13.4 Required Shear Reinforcement

$$CheckVf := \begin{cases} \text{"Need Shear Reinforcement"} & \text{if } V_{u.shear} \geq 0.5 \cdot \phi_{shear} \cdot (V_c + V_p) \\ \text{"Shear Reinforcement Not Needed"} & \text{if } V_{u.shear} < 0.5 \cdot \phi_{shear} \cdot (V_c + V_p) \end{cases}$$

$CheckVf = \text{"Need Shear Reinforcement"}$

$d_{v.shear} := d_{GFRP} = 0.625 \cdot in$ — Diameter of GFRP stirrup

$A_{v.shear} := A_{GFRP} = 0.307 \cdot in^2$ — Area of each GFRP bar

$E_{v.shear} := E_{GFRP} = 6.5 \times 10^3 \cdot ksi$ — Elastic modulus of GFRP stirrup

$f_{v.shear} := f_{fu.GFRP} = 66.396 \cdot ksi$ — Tensile strength of GFRP stirrup

$\phi_{bend.GFRP} = 0.6$ — take 0.6 in this design example

$$V_n := \min\left(\frac{V_{u.shear}}{\phi_{shear}}, 0.25 \cdot f'_{c.beam} \cdot b_v \cdot d_v + V_p\right) = 302.052 \cdot kip$$

$V_{FRP.req} := \max(0, V_n - V_c - V_p) = 154.987 \cdot kip$ — Required shear provided by FRP stirrup

$$V_{FRP.req} = \frac{f_{fv} \cdot A_{v.shear.total} \cdot d_v}{s_{shear}}$$ (AASHTO GFRP 2.10.3.2.2)

$f_{fv} := \min(0.004 \cdot E_{v.shear}, \phi_{bend.GFRP} \cdot f_{v.shear}, 22ksi) = 22 \cdot ksi$

Max bended FRP tensile stress (AASHTO GFRP 2.10.3.2.2), modifed with FDOT Material Spec 932-3, which limits the shear strength to 22 ksi

$leg_{stirrup} := 2$ — Number of legs of stirrup

$A_{v.shear.total} := leg_{stirrup} \cdot A_{v.shear} = 0.614 \cdot in^2$

$$s_{shear.req} := \begin{cases} 1000in & \text{if } V_{FRP.req} = 0 \\ \dfrac{f_{fv} \cdot A_{v.shear.total} \cdot d_v}{V_{FRP.req}} & \text{otherwise} \end{cases} = 3.38 \cdot in$$

Required FRP stirrup spacing from calculation
(if not needed, output 1000 inch spacing)

$$s_{shear.max} := \begin{cases} \min(0.75 \cdot h_g, 24in) & \text{if } V_{FRP.req} \le 4.0 \cdot \sqrt{\dfrac{f'_{c.beam}}{ksi}} \cdot b_v \cdot d_v \cdot ksi \\ \min(0.375 \cdot h_g, 12in) & \text{if } V_{FRP.req} > 4.0 \cdot \sqrt{\dfrac{f'_{c.beam}}{ksi}} \cdot b_v \cdot d_v \cdot ksi \end{cases} = 24 \cdot in$$

Maximum FRP stirrup spacing
(ACI 440.4R 5.3)

$$A_{v.min} = 0.05 \cdot \frac{s \cdot b_w}{f_{fv}}$$

Minimum GFRP transverse reinforcement
(AASHTO GFRP 2.10.2.2.1)

$$s_{shear.minAf} := \frac{A_{v.shear.total} \cdot \dfrac{f_{fv}}{ksi}}{0.05 \cdot b_{web}} = 38.569 \cdot in$$

Max spacing corresponding to minimum GFRP transverse reinforcement

$$s_{shear} := \min(s_{shear.req}, s_{shear.max}, s_{shear.minAf}) = 3.38 \cdot in$$

$$s_{shear.provide} := \mathrm{floor}\left(\frac{s_{shear}}{in}\right) \cdot in = 3 \cdot in$$

Provided transverse reinforcement spacing

$$V_{FRP} := \frac{f_{fv} \cdot A_{v.shear.total} \cdot d_v}{s_{shear.provide}} = 175 \cdot kip$$

Provided shear resistance from FRP transverse reinforcement

13.5 Summary

$V_{u.shear} = 272 \cdot kip$

$V_c = 147 \cdot kip$

$V_p = 0$

$V_{FRP} = 175 \cdot kip$

$d_{v.shear} = 0.625 \cdot in$ Diameter of GFRP stirrup

$leg_{stirrup} = 2$ Number of legs of GFRP stirrup

$s_{shear.provide} = 3 \cdot in$ Spacing of GFRP stirrup

$V_{n.provide} := V_c + V_{FRP} + V_p = 322 \cdot kip$

$$CheckShearCapacity := \begin{cases} \text{"OK"} & \text{if } V_{n.provide} \ge \min\left(\frac{V_{u.shear}}{\phi_{shear}}, 0.25 \cdot f'_{c.beam} \cdot b_v \cdot d_v + V_p\right) \\ \text{"NG"} & \text{otherwise} \end{cases}$$

$CheckShearCapacity = \text{"OK"}$ Transverse shear capacity

14. INTERFACE SHEAR DESIGN

$V_{u1} := V_{Str1}(\text{shearcheck}) = 271.846 \cdot kip$ — Factored interface shear force

$V_{ri} = \phi_{shear} \cdot V_{ni} \geq V_{ui}$ — (LRFD 5.7.4.3)

$\phi_{shear} = 0.9$

Assumed numbers:

$c_{vi} := 0.28ksi$ — Cohesion factor

$\mu_{vi} := 1$ — Friction factor

$K_{1.vi} := 0.3$ — Fraction of concrete strength available to resist interface shear

$K_{2.vi} := 1.8ksi$ — Limiting interface shear reistance

Factored interface shear force, per ft

$$d_{vi} := \begin{cases} h_{g.comp} - d_{p.strands.c.g.bot.dbs} - \frac{t_{slab}}{2} & \text{if shearcheck} < \text{debond1} \\ h_{g.comp} - d_{p.strands.c.g.bot.db1} - \frac{t_{slab}}{2} & \text{if debond1} \leq \text{shearcheck} < \text{debond2} \\ h_{g.comp} - d_{p.strands.c.g.bot.db2} - \frac{t_{slab}}{2} & \text{if shearcheck} \geq \text{debond2} \end{cases}$$

$d_{vi} = 36.664 \cdot in$ — Distance between the centriod of the tension strands and the mid-thickness of the slab

$V_{hi} := \frac{V_{u1}}{d_{vi}} = 88.975 \cdot \frac{kip}{ft}$ — Factored interface shear force, per ft

Required nominal interface shear resistance, per ft

$V_{ni} := \frac{V_{hi}}{\phi_{shear}} = 98.861 \cdot \frac{kip}{ft}$ — (LRFD 5.7.4.3)

Required interface shear reinforcement, per ft

$V_{ni} = c \cdot A_{cv} + \mu \cdot \left(A_{vf} \cdot f_y + P_c\right)$

Nonimal interface shear resistance (LRFD 5.7.4.3)

$b_{vi} := b_{tf} = 48 \cdot in$

Interface width considered to be engaged in shear transfer

$A_{cv} := b_{vi} = 576 \cdot \frac{in^2}{ft}$

Area of concrete considered to be engaged in shear transfer, per 1-ft length

$P_{c.vi} := 0$

Permanent net compression force normal to the shear plane

$$A_{vf.req} := \frac{\frac{V_{ni} - c_{vi} \cdot A_{cv}}{\mu_{vi}} - P_{c.vi}}{f_{fv}} = -2.837 \cdot \frac{in^2}{ft}$$

Required interface shear reinforcement

Minimum interface shear reinforcement, per ft

$$A_{vf.min1} := 0.05 \cdot \frac{A_{cv}}{\frac{f_{fv}}{ksi}} = 1.309 \cdot \frac{in^2}{ft}$$

$$A_{vf.min2} := \frac{\frac{1.33V_{ni} - c_{vi} \cdot A_{cv}}{\mu_{vi}} - P_{c.vi}}{f_{fv}} = -1.354 \cdot \frac{in^2}{ft}$$

$$A_{vf.min} := \min\left(A_{vf.min1}, A_{vf.min2}\right) = -1.354 \frac{1}{ft} \cdot in^2$$

Minimum interface shear reinforcemen (LRFD 5.7.4.2)

Design interface shear reinforcement, per ft

$$A_{vf.design.need} := \max\left(A_{vf.req}, A_{vf.min}, 0\right) = 0 \cdot \frac{in^2}{ft}$$

Design interface reinforcement need to provide

$$A_{vf.provide} := \frac{A_{v.shear.total}}{s_{shear.provide}} = 2.454 \cdot \frac{in^2}{ft}$$

Interface shear reinforcement already provided by GFRP stirrup

$$Check_{iv0} := \begin{cases} \text{"OK"} & \text{if } A_{vf.provide} \geq A_{vf.design.need} \\ \text{"NG"} & \text{otherwise} \end{cases}$$

$$Check_{iv0} = \text{"OK"}$$

Interface shear reinforcement, Provided > Required

Maximum interface shear resistance, per ft

$$V_{ni.provide} := c_{vi} \cdot A_{cv} + \mu_{vi} \cdot \left(A_{vf.provide} \cdot f_{fv} + P_{c.vi}\right) = 215 \cdot \frac{kip}{ft}$$

Provided nominal interface shear resistance (LRFD 5.7.4.3)

$$V_{ni.max} := \min\left(K_{1.vi} \cdot f'_{c.beam} \cdot A_{cv}, K_{2.vi} \cdot A_{cv}\right) = 1037 \cdot \frac{kip}{ft}$$

$$K_{1.vi} \cdot f'_{c.beam} \cdot A_{cv} = 1.469 \times 10^3 \cdot \frac{kip}{ft}$$

Design interface shear resistance limitation (LRFD 5.7.4.3)

$$K_{2.vi} \cdot A_{cv} = 1.037 \times 10^3 \cdot \frac{kip}{ft}$$

$$Check_{iv.max} := \begin{cases} \text{"OK"} & \text{if } V_{ni.provide} \leq \min\left(K_{1.vi} \cdot f'_{c.beam} \cdot A_{cv}, K_{2.vi} \cdot A_{cv}\right) \\ \text{"NG"} & \text{otherwise} \end{cases}$$

$$Check_{iv.max} = \text{"OK"}$$

Maximum interface shear resistance

Summary

$V_{ni.provide} = 215.276 \cdot \frac{kip}{ft}$ Nominal interface shear resistance

$V_{hi} = 88.975 \cdot \frac{kip}{ft}$ Factored interface shear force, per ft

$$Check_{vi.capacity} := \begin{cases} \text{"OK"} & \text{if } \phi_{shear} \cdot V_{ni.provide} \geq V_{hi} \\ \text{"NG"} & \text{otherwise} \end{cases}$$

$Check_{vi.capacity} = \text{"OK"}$ Check capacity

$Check_{iv.max} = \text{"OK"}$ Check max nominal resistance

15. MINIMUM LONGITUDINAL REINFORCEMENT

At each section, the tensile capacity of the longitudinal reinforcement on the flexural tension side of the member shall be proportioned to satisfy

$$\sum_{x=1}^{n} \left(A_{px} \cdot f_{px}\right) \geq \frac{|M_u|}{d_v \cdot \phi_f} + 0.5 \cdot \frac{N_u}{\phi_c} + \left(\left|\frac{V_u}{\phi_v} - V_p\right| - 0.5 \cdot V_f\right) \cdot \frac{1}{\tan(\theta)}$$

(AASHTO CFRP 1.8.3.3)

$N_u := 0$ Axial load

$\phi_{moment} = 0.75$ Resistance factor for bending

$\phi_{shear} = 0.9$ Resistance factor for shear

$\theta = 28.145 \cdot deg$ Angle of inclination of diagonal compressive stresses

$d_v = 38.801 \cdot in$ Effective shear depth

$V_p = 0$ Shear capacity contribution by prestressing CFRP

$f_{pe} = 185 \cdot ksi$ Effective prestressing stress

At the support location

$support = 0$

$$V_{f.support} := \min\left(V_{FRP}, \frac{V_{Str1}(support)}{\phi_{shear}}\right) = 174.594 \cdot kip$$ (AASHTO CFRP 1.8.3.3)

$$right := \frac{|M_{Str1}(support)|}{d_v \cdot \phi_{moment}} + \left(\left|\frac{V_{Str1}(support)}{\phi_{shear}} - V_p\right| - 0.5 \cdot V_{f.support}\right) \cdot \frac{1}{\tan(\theta)} = 442 \cdot kip$$

the crack plane crosses the c.g of the strand group at a distance

$$x_{crackplane} := BearingDistance + d_{p.strands.c.g.bot.dbs} \cdot \frac{1}{\tan(\theta)} = 17.573 \cdot in$$

$$L_{transfer} = 30 \cdot in$$

Transfer length of prestressing CFRP (AASHTO CFRP 1.9.3.2)

$$f_{px} := f_{pe} \cdot \frac{x_{crackplane}}{L_{transfer}}$$

Approximate prestressing stress at the crack plane

$$left := \sum_{i=0}^{rows(n)-1} \left(A_{p.dbs_i} \cdot f_{px} \right) = 563 \cdot kip$$

$$Check_{long.rebar} := \begin{cases} \text{"OK, No Additional Longitudinal Reinforcement is Required"} & \text{if } left \geq right \\ \text{"NG, Additional Longitudinal Reinforcement is Required"} & \text{otherwise} \end{cases}$$

$Check_{long.rebar}$ = "OK, No Additional Longitudinal Reinforcement is Required"

16. DEFLECTION AND CAMBER

Immediate deflection, due to prestressing force and DL downward -> positive

Deflection due to prestressing force at transfer

$$\Delta = \frac{M \cdot L^2}{8 \cdot E \cdot I}$$

$$\Delta_{p1} := \frac{-\left(A_{p.total.dbs} \cdot f_{pt}\right) \cdot e_{g.tr.cg.strands} \cdot (Span)^2}{8 \cdot E_{ci.beam} \cdot I_g} = -3.258 \cdot in$$

$$\Delta_{p2} := \frac{-\left[\left(A_{p.total.db1} - A_{p.total.dbs}\right) \cdot f_{pt}\right] \cdot e_{g.tr.cg.strands} \cdot (Span - 2 \cdot debond1)^2}{8 \cdot E_{ci.beam} \cdot I_g} = -0.535 \cdot in$$

$$\Delta_{p3} := \frac{-\left[\left(A_{p.total.db2} - A_{p.total.db1}\right) \cdot f_{pt}\right] \cdot e_{g.tr.cg.strands} \cdot (Span - 2 \cdot debond2)^2}{8 \cdot E_{ci.beam} \cdot I_g} = -0.066 \cdot in$$

$$\Delta_p := \Delta_{p1} + \Delta_{p2} + \Delta_{p3} = -3.86 \cdot in$$

Deflection due to self weight of beam

$$\Delta = \frac{5 \cdot w \cdot L^4}{384 \cdot E \cdot I}$$

$$\Delta_{sf.beam} := \frac{5 \cdot w_{beam} \cdot Span^4}{384 \cdot E_{ci.beam} \cdot I_g} = 1.921 \cdot in$$

Deflection due to self weight of slab, buildup, and permanent forms

$$\Delta_{permanent1} := \frac{5 \cdot \left(w_{slab} + w_{buildup} + w_{forms}\right) \cdot Span^4}{384 \cdot E_{c.beam} \cdot I_g} = 2.233 \cdot in$$

Deflection due to barrier, future wearing surface, and utility

$$\Delta_{permanent2} := \frac{5 \cdot \left(w_{barrier} + w_{fws} + w_{utility}\right) \cdot Span^4}{384 \cdot E_{c.beam} \cdot I_{g.comp}} = 0.103 \cdot in$$

17. SUMMARY OF ALL CHECKS

All "Check"

7. PRESTRESS LOSSES

7.3 Summary

$Check_{pe.limit}$ = "OK" — Service stress limit (after all losses)

8. STRESS LIMITS FOR CONCRETE -TEMPORARY STRESSES BEFORE LOSSES

8.1 At Mid-Span Section

$Check_{top.midspan}$ = "OK" — Check concrete stress limits at the midspan, at release

$Check_{bot.midspan}$ = "OK" — Check concrete stress limits at the midspan, at release

8.2 At Support Section

$Check_{sp.top}$ = "OK" — Check concrete stress limits at the support, top fiber, at release

$Check_{sp.bot}$ = "NG" — Check concrete stress limits at the support, bottom fiber, at release

$Check_{db}$ = "Need to Debond Strand" — Need to debond strands?

$Check_{30\%}$ = "OK" — Total debonded strands shall not exceed 30% of total strands (SDG 4.3.1)

$Check_{40\%}$ = "OK" — Debonded strands in each row shall not exceed 40% of total strands in that row (LRFD 5.9.4.3.3)

$Check_{top.dbs}$ = "OK" — Check concrete stress limits at the support after debond, top fiber, at release

$Check_{bot.dbs}$ = "OK" — Check concrete stress limits at the support after debond, bottom fiber, at release

8.3 At Debond1 Section

$Check_{top.db1}$ = "OK" — Check concrete stress limits at the debond1 section, top fiber, at release

$Check_{bot.db1} = \text{"OK"}$

Check concrete stress limits at the debond1 section, bottom fiber, at release

8.4 At Debond2 Section

$Check_{top.db2} = \text{"OK"}$

Check concrete stress limits at the debond2 section, top fiber, at release

$Check_{bot.db2} = \text{"OK"}$

Check concrete stress limits at the debond2 section, bottom fiber, at release

8.5 Summary

9. STRESS LIMITS FOR CONCRETE -STRESSES AT SERVICE LIMIT STATE

9.1 Service I Limit State:under Effective Prestress and Permanent Loads

$Check_{topdeck1} = \text{"OK"}$

Concrete stress at the top fiber of deck

$Check_{topbeam1} = \text{"OK"}$

Concrete stress at the top fiber of beam

9.2 Service I Limit State:under Effective Prestress, Permanent loads, and Transient loads

$Check_{topdeck2} = \text{"OK"}$

Concrete stress at the top fiber of deck

$Check_{topbeam2} = \text{"OK"}$

Concrete stress at the top fiber of beam

9.3 Service III Limit State

$Check_{botbeam} = \text{"OK"}$

Concrete stress at the bottom fiber of beam

9.4 Summary

10. FATIGUE LIMIT STATE

$Check_{fatigue} = \text{"No Need to Check Fatigue"}$

11. STRENGTH LIMIT STATE -MOMENT CAPACITY

11.1 Compression-Controlled Section

$Check_{fp.C}$ = "CFRP Rupture Before Concrete Crushing, Assumption Not Satisfied"

$Check_{CT.C} = 0 \cdot kip$ — Equilibrium

11.2 Tension-Controlled Section

$Check_{fp.T}$ = "OK" — CFRP not rupture

$Check_{cc.T}$ = "OK" — Concrete strain limits

$Check_{CT.T} = 0 \cdot kip$ — Equilibrium

11.3 Summary

SectionControl = "Tension Controlled Section"

$Check_M$ = "OK" — Strength I, moment capacity

12. MINIMUM REINFORCEMENT -PRESTRESSING CFRP

$Check_{minCFRP}$ = "OK" — Minimum amount of prestressing CFRP

13. TRANSVERSE SHEAR DESIGN

13.5 Summary

CheckShearCapacity = "OK" — Transverse shear capacity

14. INTERFACE SHEAR DESIGN

$Check_{iv0}$ = "OK" — Interface shear reinforcement, Provided > Required

$Check_{iv.max}$ = "OK" — Maximum interface shear resistance

$Check_{vi.capacity}$ = "OK" — Check interface shear capacity

15. MINIMUM LONGITUDINAL REINFORCEMENT

$Check_{long.rebar}$ = "OK, No Additional Longitudinal Reinforcement is Required"