CFRP-PC Training Course

Design Example

Square Pile 18''x18''

For Training Purposes Only, NOT To Be Used For Construction

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

P-M DIAGRAM OF 18" SQUARE PILE PRESTRESSED WITH 0.6" DIAMETER CFRP STRANDS

TABLE OF CONTENTS

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

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

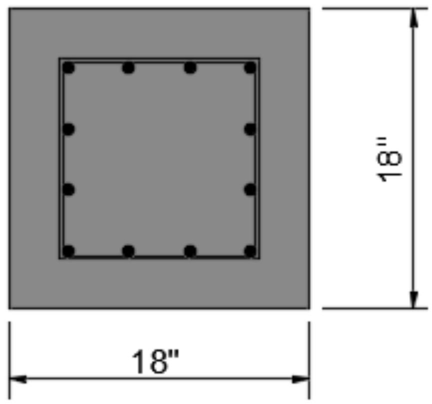
FRPG: FDOT Structures Manual, Volume 4 -Fiber Reinforced Polymer Guidelines

FDOT Standard Plans Index 455-101, 455-118

FRP Pile Standards by Zach Behring (MathCAD)

2. INPUTS

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



2.1 Geometry

18" X 18" Square pile

$hh := 18in$ — Depth of pile section

$bb := 18in$ — Width of pile section

$cham := 0.75in$ — Chamfer

$cover := 3in$ — Clear cover (Standard Plans Index 455-101)

$A_g := bb \cdot hh - 4 \cdot \frac{cham^2}{2} = 323 \cdot in^2$ — Gross pile area

$I_g := \frac{bb \cdot hh^3}{12} = 8.748 \times 10^3 \cdot in^4$ — Moment of inertia

$Perimeter := (bb + hh) \cdot 2 = 72 \cdot in$ — Perimeter of section

2.2 Concrete

$w_c := 0.145\frac{kip}{ft^3}$

Concrete unit weight
(SDG 1.4.1A)

$f'_c := 6ksi$

Specified concrete strength
(SDG Table 1.4.3-2)

$f'_{ci} := 4ksi$

Concrete strength at transfer
(Standard Plans Index 455-101)

$K_1 := 1.0$

Correction factor for aggregate
(SDG 1.4.1A)

$E_{ci} := 120000 \cdot K_1 \cdot \left(\frac{w_c}{kcf}\right)^2 \cdot \left(\frac{f'_{ci}}{ksi}\right)^{0.33} \cdot ksi = 3987 \cdot ksi$

Elastic modulus of concrete at transfer
(LRFD 5.4.2.4-1)

$E_c := 120000 \cdot K_1 \cdot \left(\frac{w_c}{kcf}\right)^2 \cdot \left(\frac{f'_c}{ksi}\right)^{0.33} \cdot ksi = 4557 \cdot ksi$

Elastic modulus of concrete
(LRFD 5.4.2.4-1)

$\alpha_1 := \min\left(\max\left(0.85 - 0.02 \cdot \frac{f'_c - 10ksi}{ksi}, 0.75\right), 0.85\right) = 0.85$

$\beta_1 := \min\left(\max\left(0.85 - 0.05 \cdot \frac{f'_c - 4ksi}{ksi}, 0.65\right), 0.85\right) = 0.75$

Concrete stress block factor
(LRFD 5.6.2.2)

2.3 Reinforcement

Stirrups

$D_{stir} := 0.2in$ — Diameter of CFRP strand spiral ties (Standard Plans Index 455-101)

Prestressing strands

[Assume 0.6in diameter CFRP Cable; Properties refer to FDOT Standard Plans Index 455-101 and 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

$n_{p.total} := 12$ — Total number of tendons

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

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

$A_{p.total} := n_{p.total} \cdot A_{pf} = 2.148 \cdot in^2$ — Total area of tendons

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

$P_u := 66.2kip$ — Ultimate tensile force for each tendon

$f'_{pu} := \frac{P_u}{A_{pf}} = 370 \cdot ksi$ — Ultimate tensile strength

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

$C_E := 1$ — Environmental reduction factor (AASHTO CFRP Table 1.4.1.2-1)

$f_{pu} := C_E \cdot f'_{pu} = 370 \cdot ksi$ — Design tensile strength of CFRP tendon

$f_{p.limit} := f_{pu} = 370 \cdot ksi$

$P_i = 32 \cdot kip$

Jacking force, need to satisfy 1) jacking stress limit 2) Standard Plans Index 455-101 requirement
(the value is defined globly later after the prestress loss estimation)

$f_{pi} := \frac{P_i}{A_{pf}} = 179 \cdot ksi$

Jacking stress

$$f_{pi.limit} := \begin{vmatrix} 0.70 \cdot f_{pu} \ \text{ if } \ StrandType_{CFRP} \le 1 \\ 0.65 \cdot f_{pu} \ \text{ if } \ 1 < StrandType_{CFRP} \le 2 \end{vmatrix} = 258.9 \cdot ksi$$

Jacking stress limit

(AASHTO CFRP Table 1.9.1.1)

$$Check_{fpi.limit} := \begin{vmatrix} \text{"OK"} \ \text{ if } \ f_{pi} \le f_{pi.limit} \\ \text{"NOT GOOD"} \ \text{ if } \ f_{pi} > f_{pi.limit} \end{vmatrix} = \text{"OK"}$$

Arrangement of prestressing tendons

$$n_p := \begin{pmatrix} 4 \\ 2 \\ 2 \\ 4 \end{pmatrix}$$

Number of tendons in rows 1, 2, 3, 4
(sum of np = np, total)

$$A_p := n_p \cdot A_{pf} = \begin{pmatrix} 0.716 \\ 0.358 \\ 0.358 \\ 0.716 \end{pmatrix} \cdot in^2$$

Area of tendons in rows 1, 2, 3, 4

$$d'_{p0} := \left(cover + \frac{D_p}{2} \right) + D_{stir} = 3.5 \cdot in$$

Distance from top of the section to the center of the 1st row tendons

$$d_{ps0} := \frac{hh - 2 \cdot d'_{p0}}{rows(n_p) - 1} = 3.667 \cdot in$$

Space of rows

$$d_p := \begin{pmatrix} d'_{p0} \\ d'_{p0} + d_{ps0} \\ d'_{p0} + 2d_{ps0} \\ d'_{p0} + 3d_{ps0} \end{pmatrix} = \begin{pmatrix} 3.500 \\ 7.167 \\ 10.833 \\ 14.500 \end{pmatrix} \cdot in$$

Distance from top of the section to each tendon

$e_{pg} := 0 \cdot in$

Eccentricity of prestressing force (non-composite section)
0 for prestressed piles

$e_{pc} := 0in$

Eccentricity of prestressing force with respect to composite section
0 for prestressed piles

(LRFD 5.9.3.4.3)

2.4 Other Inputs

$H := 75$

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 pile installation (day)

$t_f := 10000$

final time (day)

3. DETERMINE 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)

3.1 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)

Use variables defined in this example,

$$f_{cgp} := \frac{A_{p.total} \cdot f_{pi}}{A_g} = 1.189 \cdot ksi$$

Concrete stress at gravity center of the prestressing force at transfer
(c.g. is the center of the cross-section)

$$\Delta f_{pES} := \frac{E_p}{E_{ci}} f_{cgp} = 6.707 \cdot ksi$$

Prestress loss due to elastic shortening

(AASHTO CFRP 1.4.2)

$$f_{pt} := f_{pi} - \Delta f_{pES} = 172 \cdot ksi$$

Prestress stress at transfer

3.2 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 pile installation
df - time between pile installation and the final time

(LRFD 5.9.3.4.1-1)

--------Time-Dependent losses between transfer and pile installation--------

Shrinkage of pile concrete (i->d)

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

(LRFD 5.9.3.4)

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

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

(LRFD 5.4.2.3.2)

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

Humidiy factor for shrinkage

(LRFD 5.4.2.3.3)

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

Humidiy factor for creep

(LRFD 5.4.2.3.2)

$$k_f := \frac{5}{1 + \frac{f'_{ci}}{ksi}} = 1.000$$

Factor for the effect of concrete strength

(LRFD 5.4.2.3.2)

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

Time development factor

(LRFD 5.4.2.3.2)

$$k_{td}(t_i, t_d) = 0.739$$

Time development factor
Time from transfer to pile installation

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

Time development factor
Time from transfer to final time

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

Time development factor
Time from pile installation to final time

$\varepsilon_{bid} := k_s \cdot k_{hs} \cdot k_f \cdot k_{td}(t_i, t_d) \cdot 0.48 \cdot 10^{-3} = 3.370 \times 10^{-4}$

Shrinkage strain of pile concrete
(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)

$\Psi_b(t_d, t_i) = 1.348$

Creep coefficient
Time from transfer to installation

$\Psi_b(t_f, t_i) = 1.816$

Creep coefficient
Time from transfer to final time

$\Psi_b(t_f, t_d) = 1.032$

Creep coefficient
Time from installation to final time

$$K_{id} := \frac{1}{1 + \frac{E_p}{E_{ci}} \cdot \frac{A_{p.total}}{A_g} \cdot \left(1 + \frac{A_g \cdot e_{pg}^{2}}{I_g}\right) \cdot \left(1 + 0.7 \cdot \Psi_b(t_d, t_i)\right)} = 0.932$$

Transformed section coefficient
(LRFD 5.9.3.4.2)

$\Delta f_{pSR} := \varepsilon_{bid} \cdot E_p \cdot K_{id} = 7.062 \cdot ksi$

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

Creep of pile concrete (i->d)

$\Delta f_{pCR} := \frac{E_p}{E_{ci}} f_{cgp} \cdot \Psi_b(t_d, t_i) \cdot K_{id} = 8.427 \cdot ksi$

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

Relaxation of prestressing CFRP (i->d)

$f_{pu} = 370 \cdot ksi$ Design tensile strength

$f_{pt} = 172 \cdot ksi$ Prestress stress at transfer

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

Prestress loss due to relaxation

(AASHTO CFRP 1.9.2.5.2)

$\Delta f_{pR1} := \Delta f_{pR}(t_i, t_d) = 2.863 \cdot ksi$ Prestress loss due to relaxation

Time from transfer to installation

Total time-depedent prestress loss between transfer and pile installation

$$\Delta f_{pLT.id} := \Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1} = 18.351 \cdot ksi$$

<u>--------Time-Dependent losses between pile installation to final time--------</u>

Shrinkage of pile concrete (d->f)

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

$$\varepsilon_{bdf} := k_s \cdot k_{hs} \cdot k_f \cdot k_{td}(t_d, t_f) \cdot 0.48 \cdot 10^{-3} = 4.541 \times 10^{-4}$$

Shrinkage strain of pile concrete

(LRFD 5.4.2.3.3)

$e_{pc} = 0$

Eccentricity of prestressing force with respect to composite section
0 for prestressed piles

(LRFD 5.9.3.4.3)

$I_c := I_g = 8.748 \times 10^3 \cdot in^4$

Moment inertia for transformed composite section

$A_c := A_g = 323 \cdot in^2$

Area for transformed composite section

$$K_{df} := \frac{1}{1 + \frac{E_p}{E_{ci}} \cdot \frac{A_{p.total}}{A_c} \cdot \left(1 + \frac{A_c \cdot e_{pc}^2}{I_c}\right) \cdot \left(1 + 0.7 \cdot \Psi_b\left(t_f, t_d\right)\right)} = 0.939$$

Transformed section coefficient

(LRFD 5.9.3.4.3)

$\Delta f_{pSD} := \varepsilon_{bdf} \cdot E_p \cdot K_{df} = 9.588 \cdot ksi$

Prestress loss due to
Shrinkage of pile concrete

(LRFD 5.9.3.4.3)

Creep of pile concrete (d->f)

$$\Delta f_{cd} := \frac{-\Delta f_{pLT.id} \cdot A_{p.total}}{A_g} = -0.122 \cdot ksi$$

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

(for piles, it is simplified)

$$\Delta f_{pCD} := \frac{E_p}{E_{ci}} f_{cgp} \cdot \left(\Psi_b\left(t_f, t_i\right) - \Psi_b\left(t_d, t_i\right)\right) \cdot K_{df} + \frac{E_p}{E_c} \Delta f_{cd} \cdot \Psi_b\left(t_f, t_d\right) \cdot K_{df} = 2.365 \cdot ksi$$

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

Relaxation of prestressing CFRP (d->f)

$f_{pu} = 370 \cdot ksi$

Design tensile strength

$f_{pt} = 172 \cdot ksi$ — Prestress stress at transfer

$\Delta f_{pR2} := \Delta f_{pR}(t_d, t_f) = 4.452 \cdot ksi$ — Prestress loss due to relaxation

Time from transfer to installation

Shrinkage of deck concrete (d->f)

$\Delta f_{pSS} := 0ksi$ — Not applicable to piles

(LRFD 5.9.3.4.3)

Total time-depedent prestress loss between pile installation and final time

$$\Delta f_{pLT.df} := \Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} - \Delta f_{pSS} = 16.405 \cdot ksi$$

Total time-depedent prestress loss between transfer and final time

$$\Delta f_{pLT} := \Delta f_{pLT.id} + \Delta f_{pLT.df} = 34.757 \cdot ksi$$

3.3 Summary -Prestress Loss

$\Delta f_p := \Delta f_{pES} + \Delta f_{pLT} + \Delta f_{pTH} = 41.463 \cdot ksi$

Total prestress loss

(AASHTO CFRP 1.9.2.1)

$Loss\% := \frac{\Delta f_p}{f_{pi}} = 23.2 \cdot \%$

Total prestress loss percentage

$\Delta f_{pES} = 6.707 \cdot ksi$

Prestress loss due to elastic shortening

$\Delta f_{pTH} = 0$

Prestress loss due to temperature change (not considered)

$\Delta f_{pLT} = 34.757 \cdot ksi$

Total long-term time-dependent prestess loss

$\Delta f_{pLT.id} = 18.351 \cdot ksi$

Long-term time-dependent prestess loss between transfer and pile installation

$\Delta f_{pLT.df} = 16.405 \cdot ksi$

Long-term time-dependent prestess loss between pile installation and final time

4. DETERMINE JACKING STRESS/FORCE

$\Delta f_{p.installation} := \Delta f_{pES} + \Delta f_{pLT.id} + \Delta f_{pTH} = 25.058 \cdot ksi$

Total prestress loss at time of pile installation

$$f_{c.installation} := \frac{A_{p.total} \cdot \left(f_{pi} - \Delta f_{p.installation}\right)}{A_g} = 1.02 \cdot ksi$$

Concrete stress (compression) at time of pile installation

$P_i \equiv 32kip$

Jacking force (Need to adjust this value to let $\sigma_{c.installation}$ slightly greater than 1 ksi)

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

(FDOT 455-101 series)

$$P\% := \frac{P_i}{P_u} = 48.3 \cdot \%$$

Jacking percentage

5.SECTION CAPACITY CALCULATION

5.1 Summary of Strain/Stress

$f_{pu} = 370 \cdot ksi$	Design tensile strength
$f_{pi} = 179 \cdot ksi$	Jacking stress
$f_{pei} := f_{pi} - \Delta f_{p.installation} = 154 \cdot ksi$	Effective prestress at time of pile installation
$f_{c.installation} = 1.023 \cdot ksi$	Concrete stress (compression) at time of pile installation
$f_{pe} := f_{pi} - \Delta f_{p} = 137 \cdot ksi$	Final effective prestress in tendons
$f_{ce} := \frac{A_{p.total} \cdot f_{pe}}{A_g} = 0.913 \cdot ksi$	Concrete stress (compression) at final time
$\varepsilon_{pe} := \frac{f_{pe}}{E_p} = 6.108 \times 10^{-3}$	Strain in prestressing tendons at final time due to prestress force
$\varepsilon_{ce} := \frac{f_{ce}}{E_c} = 2.004 \times 10^{-4}$	Strain in concrete at final time due to prestress force
$\varepsilon_{cu} := 0.003$	Concrete crushing strain
$\varepsilon_{pu} := \frac{f_{pu}}{E_p} = 0.016$	CFRP rupture strain
$\varepsilon_{p.limit} := \frac{f_{p.limit}}{E_p} = 0.016$	
$\varepsilon_{c.rest} := \varepsilon_{cu} - \varepsilon_{ce} = 2.800 \times 10^{-3}$	Remaining strain in concrete until crushing
$\varepsilon_{p.rest} := \varepsilon_{pu} - \varepsilon_{pe} = 0.010$	Remaining strain in CFRP until ruputure

5.2 P-M Diagram

$\alpha_1 = 0.85$

Concrete stress block factors (LRFD 5.6.2.2)

$\beta_1 = 0.75$

$\phi := 0.75$

Resistance factor (AASHTO CFRP 1.5.3.2)

$$k_c := \min\left(\max\left(0.85 - 0.02 \cdot \frac{f'_c - 10ksi}{ksi}, 0.75\right), 0.85\right) = 0.85$$

$$P_{max} := 0.85 \cdot \left[k_c \cdot f'_c \cdot \left(A_g - A_{p.total}\right) - A_{p.total} \cdot \left(f_{pe} - E_p \cdot \varepsilon_{cu}\right)\right] = 1263 \cdot kip$$

Nominal axial resistance (LRFD 5.6.4.4)

$a_{max} := hh = 18 \cdot in$

$$c_{max} := \frac{a_{max}}{\beta_1} = 24 \cdot in$$

Max compression depth

$c_{increment} := 0.01in$

Compression depth c increment

$$n_{c.max} := \frac{c_{max}}{c_{increment}} = 2400$$

$$cc_0 := \left| \begin{array}{l} \text{for } i \in 0 .. n_{c.max} - 1 \\ \quad cc_{0_i} \leftarrow c_{increment} \cdot \left(n_{c.max} - i\right) \\ cc_0 \end{array} \right.$$

Give a compression depth from top of the section to N.A.

$$\varepsilon_{f0} := \left| \begin{array}{l} \text{for } j \in 0..\text{rows}(cc_0) - 1 \\ \quad \left| \begin{array}{l} \text{for } i \in 0..\text{rows}(d_p) - 1 \\ \quad \varepsilon_{f0_{j,i}} \leftarrow \varepsilon_{pe} + \varepsilon_{c.rest} \cdot \dfrac{d_{p_i} - \dfrac{\varepsilon_{c.rest}}{\varepsilon_{cu}} \cdot cc_{0_j}}{\dfrac{\varepsilon_{c.rest}}{\varepsilon_{cu}} \cdot cc_{0_j}} \\ \quad (\text{break}) \ \text{ if } \varepsilon_{f0_{j,i}} \ge \varepsilon_{p.limit} \end{array} \right. \\ \varepsilon_{f0} \end{array} \right.$$

CFRP strain calculation
"break" the loop when CFRP strain is greater than rupture strain

"Good" compression depth

$$cc := \left| \begin{array}{l} \text{for } i \in 0..\left(\text{rows}(\varepsilon_{f0}) - 2\right) \\ \quad \left| \begin{array}{l} j \leftarrow n_{c.max} - \left(\text{rows}(\varepsilon_{f0}) - 2\right) + i \\ cc_i \leftarrow j \cdot c_{increment} \end{array} \right. \\ cc \end{array} \right.$$

= (table below) $\cdot$ in

	0
0	3.31
1	3.32
2	3.33
3	3.34
4	3.35
5	3.36
6	3.37
7	3.38
8	3.39
9	3.4
10	3.41
11	3.42
12	3.43
13	3.44
14	3.45
15	...

Note: “Good” compression depth refers to those compression depths that should be included in the P-M diagram calculation. In these cases, the compression depth of the section is large enough so that CFRP stresses are smaller than the stress limits according to AASHTO-CFRP Table 1.9.1. If a small compression depth is selected, the tensile strain at CFRP will be larger than the rupture strain. These cases are excluded in the P-M diagram since CFRP already ruptured and the section already failed before reaching to this point.

$$aa := \beta_1 \cdot cc$$

$$\varepsilon_f := \left| \begin{array}{l} \text{for } j \in 0..\text{rows}(cc) - 1 \\ \quad \text{for } i \in 0..\text{rows}(d_p) - 1 \\ \quad \quad \varepsilon_{f_{j,i}} \leftarrow \varepsilon_{pe} + \varepsilon_{c.rest} \cdot \dfrac{d_{p_i} - \dfrac{\varepsilon_{c.rest}}{\varepsilon_{cu}} \cdot cc_j}{\dfrac{\varepsilon_{c.rest}}{\varepsilon_{cu}} \cdot cc_j} \\ \varepsilon_f \end{array} \right.$$

$$f_f := \begin{array}{|l} \text{for } j \in 0..\text{rows}(cc)-1 \\ \quad \text{for } i \in 0..\text{rows}(d_p)-1 \\ \quad\quad f_{f_{j,i}} \leftarrow E_p \cdot \varepsilon_{f_{j,i}} \\ f_f \end{array}$$

CFRP stress calculation
only for parts when stress < fp.limit

$$T_f := \begin{array}{|l} \text{for } j \in 0..\text{rows}(cc)-1 \\ \quad \text{for } i \in 0..\text{rows}(d_p)-1 \\ \quad\quad T_{f_{j,i}} \leftarrow E_p \cdot \varepsilon_{f_{j,i}} \cdot n_{p_i} \cdot A_{pf} \\ T_f \end{array}$$

Tensile force of each layer of CFRP
only for parts when stress < fp.limit

$\varepsilon_f =$

	0	1	2	3
0	$6.481 \cdot 10^{-3}$	$9.804 \cdot 10^{-3}$	0.013	0.016
1	$6.471 \cdot 10^{-3}$	$9.784 \cdot 10^{-3}$	0.013	0.016
2	$6.462 \cdot 10^{-3}$	$9.765 \cdot 10^{-3}$	0.013	0.016
3	$6.452 \cdot 10^{-3}$	$9.746 \cdot 10^{-3}$	0.013	0.016
4	$6.443 \cdot 10^{-3}$	$9.726 \cdot 10^{-3}$	0.013	0.016
5	$6.433 \cdot 10^{-3}$	$9.707 \cdot 10^{-3}$	0.013	0.016
6	$6.424 \cdot 10^{-3}$	$9.688 \cdot 10^{-3}$	0.013	0.016
7	$6.415 \cdot 10^{-3}$	$9.669 \cdot 10^{-3}$	0.013	0.016
8	$6.406 \cdot 10^{-3}$	$9.651 \cdot 10^{-3}$	0.013	0.016
9	$6.397 \cdot 10^{-3}$	$9.632 \cdot 10^{-3}$	0.013	0.016
10	$6.388 \cdot 10^{-3}$	$9.613 \cdot 10^{-3}$	0.013	0.016
11	$6.379 \cdot 10^{-3}$	$9.595 \cdot 10^{-3}$	0.013	0.016
12	$6.37 \cdot 10^{-3}$	$9.577 \cdot 10^{-3}$	0.013	0.016
13	$6.361 \cdot 10^{-3}$	$9.558 \cdot 10^{-3}$	0.013	0.016
14	$6.352 \cdot 10^{-3}$	$9.54 \cdot 10^{-3}$	0.013	0.016
15	$6.343 \cdot 10^{-3}$	$9.522 \cdot 10^{-3}$	0.013	...

$f_f =$ (ksi)

	0	1	2	3
0	146	220	295	370
1	145	220	294	369
2	145	220	294	368
3	145	219	293	367
4	145	219	292	366
5	145	218	292	365
6	144	218	291	365
7	144	217	291	364
8	144	217	290	363
9	144	217	289	362
10	144	216	289	361
11	143	216	288	360
12	143	215	287	359
13	143	215	287	359
14	143	214	286	358
15	143	214	286	...

$\cdot ksi$

$T_f =$ (kip)

	0	1	2	3
0	104.3	78.9	105.6	264.8
1	104.2	78.7	105.4	264.1
2	104.0	78.6	105.2	263.5
3	103.9	78.4	104.9	262.9
4	103.7	78.3	104.7	262.3
5	103.6	78.1	104.5	261.6
6	103.4	78.0	104.2	261.0
7	103.3	77.8	104.0	260.4
8	103.1	77.7	103.8	259.8
9	103.0	77.5	103.6	259.2
10	102.8	77.4	103.3	258.6
11	102.7	77.2	103.1	258.0
12	102.5	77.1	102.9	257.4
13	102.4	76.9	102.7	256.8
14	102.2	76.8	102.4	256.2
15	102.1	76.6	102.2	...

$\cdot kip$

$$C_{concrete} := \begin{array}{|l} \text{for } i \in 0..rows(f_f) - 1 \\ \quad C_{concrete_i} \leftarrow \alpha_1 \cdot f'_c \cdot \beta_1 \cdot cc_i \cdot bb \\ C_{concrete} \end{array}$$

Compression force from concrete

$$T_{CFRP} := \begin{array}{|l} \text{for } i \in 0..rows(f_f) - 1 \\ \quad T_{CFRP_i} \leftarrow \sum_{j=0}^{rows(d_p)-1} T_{f_{i,j}} \\ T_{CFRP} \end{array}$$

Total tensile force from CFRP

$$P := C_{concrete} - T_{CFRP}$$

$$M := \begin{array}{|l} \text{for } i \in 0..rows(f_f) - 1 \\ \quad M_i \leftarrow C_{concrete_i} \cdot \left(\frac{hh}{2} - \frac{\beta_1 \cdot cc_i}{2} \right) + \sum_{j=0}^{rows(d_p)-1} \left[T_{f_{i,j}} \cdot \left(d_{p_j} - \frac{hh}{2} \right) \right] \\ M \end{array}$$

$aa =$ (in)

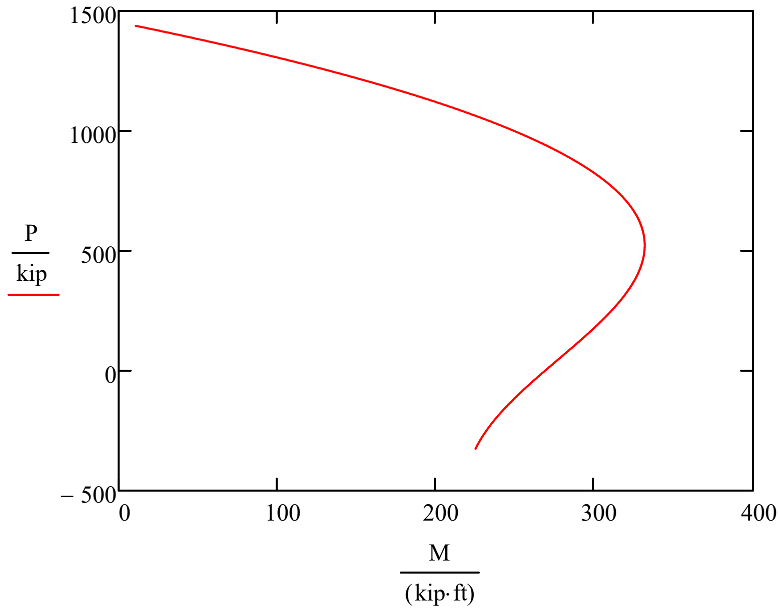
	0
0	2.482
1	2.49
2	2.498
3	2.505
4	2.513
5	2.52
6	2.527
7	2.535
8	2.542
9	2.55
10	2.558
11	2.565
12	2.572
13	2.58
14	2.588
15	...

$P =$ (kip)

	0
0	-326
1	-324
2	-322
3	-320
4	-318
5	-316
6	-315
7	-313
8	-311
9	-309
10	-307
11	-306
12	-304
13	-302
14	-300
15	...

$M =$ (kip·ft)

	0
0	225
1	225
2	225
3	225
4	226
5	226
6	226
7	226
8	226
9	226
10	226
11	227
12	227
13	227
14	227
15	...

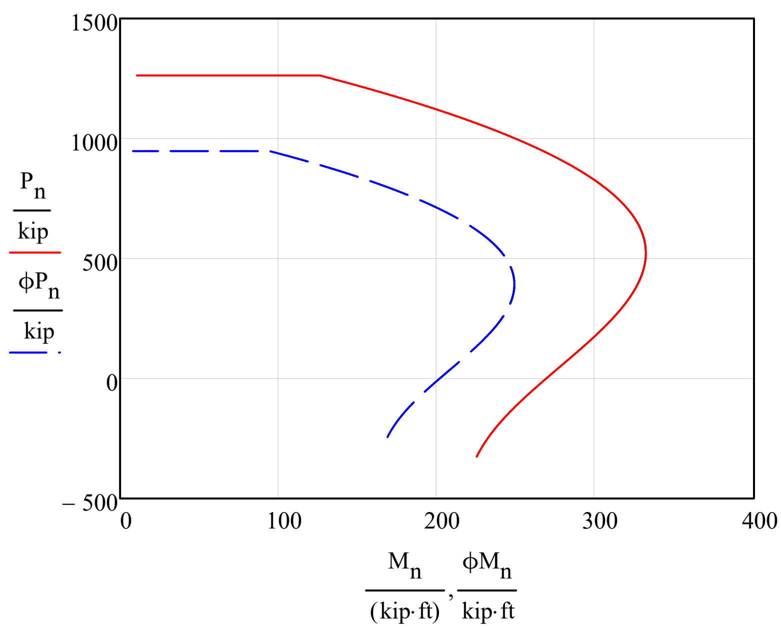


$$P_n := \left| \begin{array}{l} \text{for } i \in 0 .. \text{rows}(P) - 1 \\ \quad P_{n_i} \leftarrow \min\left(P_i, P_{max}\right) \\ P_n \end{array} \right.$$

$M_n := M$

$\phi P_n := \phi \cdot P_n$

$\phi M_n := \phi \cdot M_n$



$P_{tension} := A_{p.total} \cdot \left(f_{p.limit} - f_{pe}\right) = 499 \cdot kip$