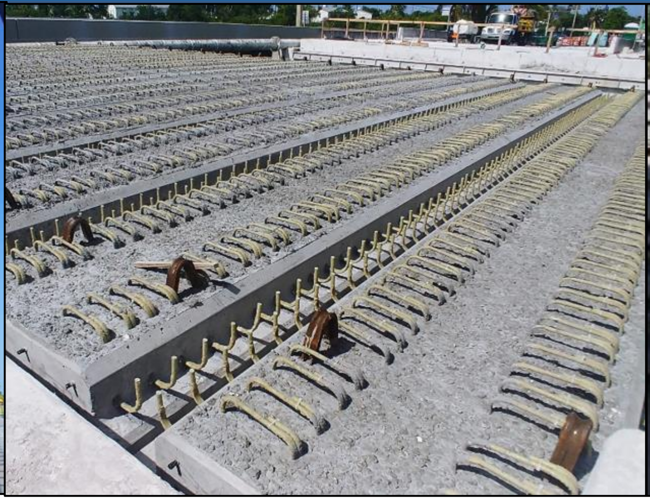
AASHTO CFRP-Prestressed Concrete Design Training Course






Florida Department of TRANSPORTATION

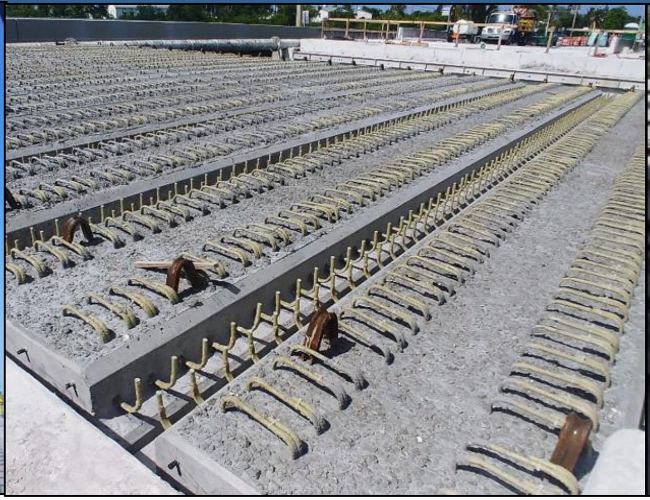
UNIVERSITY of HOUSTON

CULLEN COLLEGE of ENGINEERING

Department of Civil & Environmental Engineering

Design of Pretensioned Concrete Bridge Beams with Carbon Fiber-Reinforced Polymer (CFRP) Systems






FDOT
Florida Department of TRANSPORTATION

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

COURSE OUTLINE

1. Introduction & References
2. Prestressing CFRP
3. Flexural Design
4. Shear Design
5. Prestressed Piles
6. Design Examples

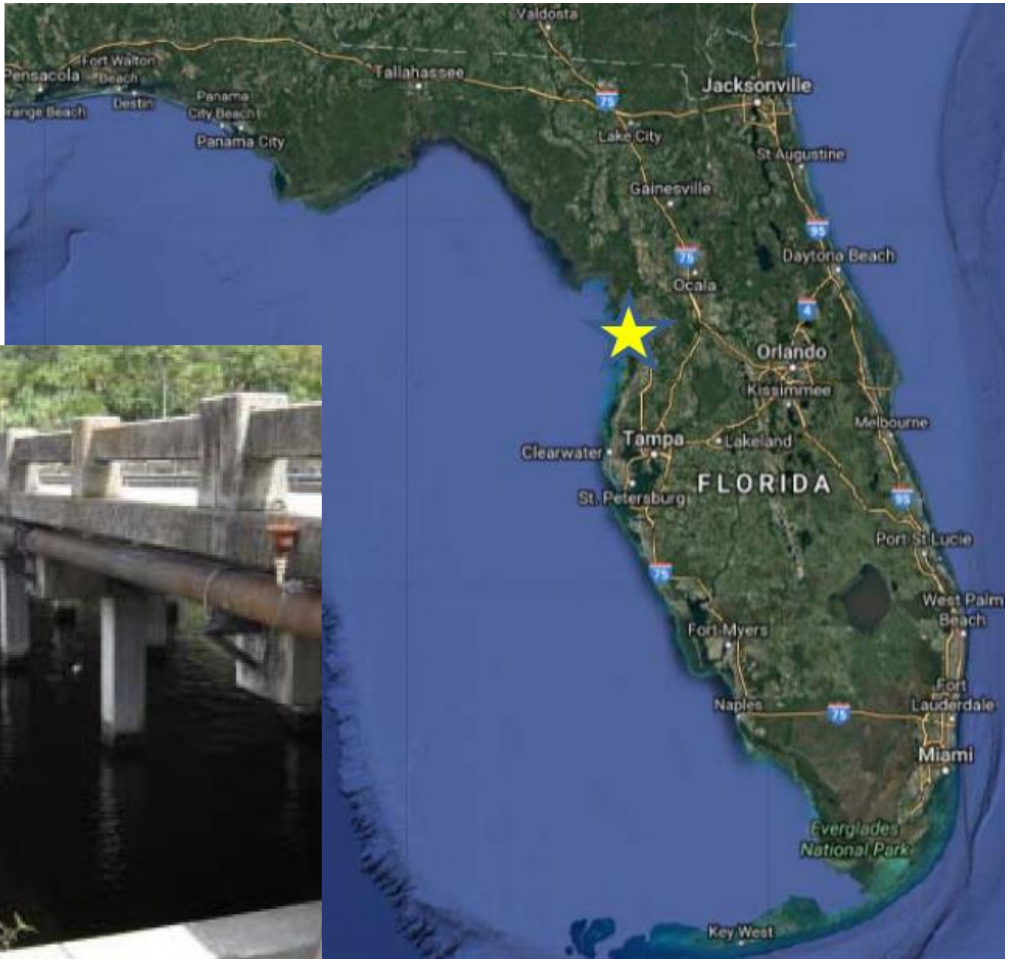
5. PRESTRESSED PILES

FDOT Florida Department of TRANSPORTATION

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

PRESTRESSED PILES

Halls River Bridge (Homosassa, FL)



PRESTRESSED PILES

Halls River Bridge (Homosassa, FL)

CFRP Prestressed Square Pile

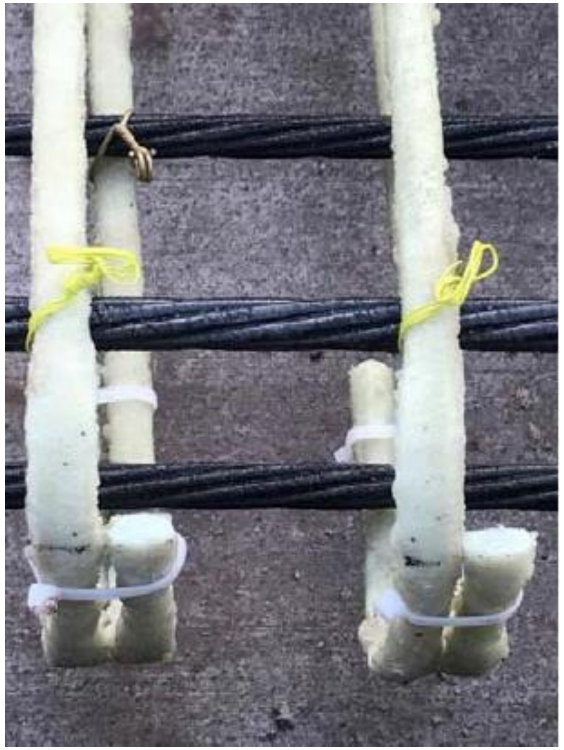
PRESTRESSED PILES

Halls River Bridge (Homosassa, FL)

CFRP Prestressed Sheet Pile

PRESTRESSED PILES

CFRP Prestressed Sheet Pile



PRESTRESSED PILES

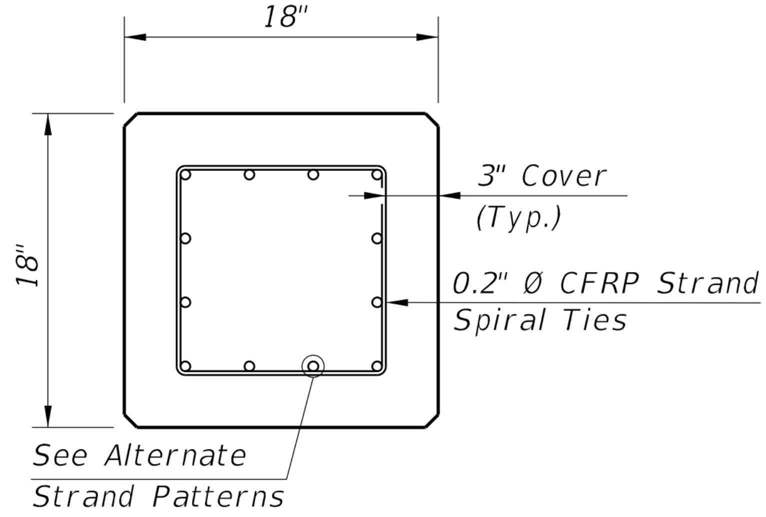
FDOT Standard Plans, FY 2020-21

455-101		Square CFRP and SS Prestressed Concrete Piles - Typical Details and Notes
455-102		Square CFRP and SS Prestressed Concrete Pile Splices
455-112	SQUARE PILE	12" Square CFRP and SS Prestressed Concrete Pile
455-114	SQUARE PILE	14" Square CFRP and SS Prestressed Concrete Pile
455-118	SQUARE PILE	18" Square CFRP and SS Prestressed Concrete Pile
455-124	SQUARE PILE	24" Square CFRP and SS Prestressed Concrete Pile
455-130	SQUARE PILE	30" Square CFRP and SS Prestressed Concrete Pile
455-154	CYLINDER PILE	54" Precast/Post-Tensioned CFRP and SS Concrete Cylinder Pile
455-160	CYLINDER PILE	60" Prestressed CFRP and SS Concrete Cylinder Pile
455-400	SHEET PILE	Precast Concrete Sheet Pile Wall (Conventional)
455-440	SHEET PILE	Precast Concrete Sheet Pile Wall (CFRP/GFRP & HSSS/GFRP)

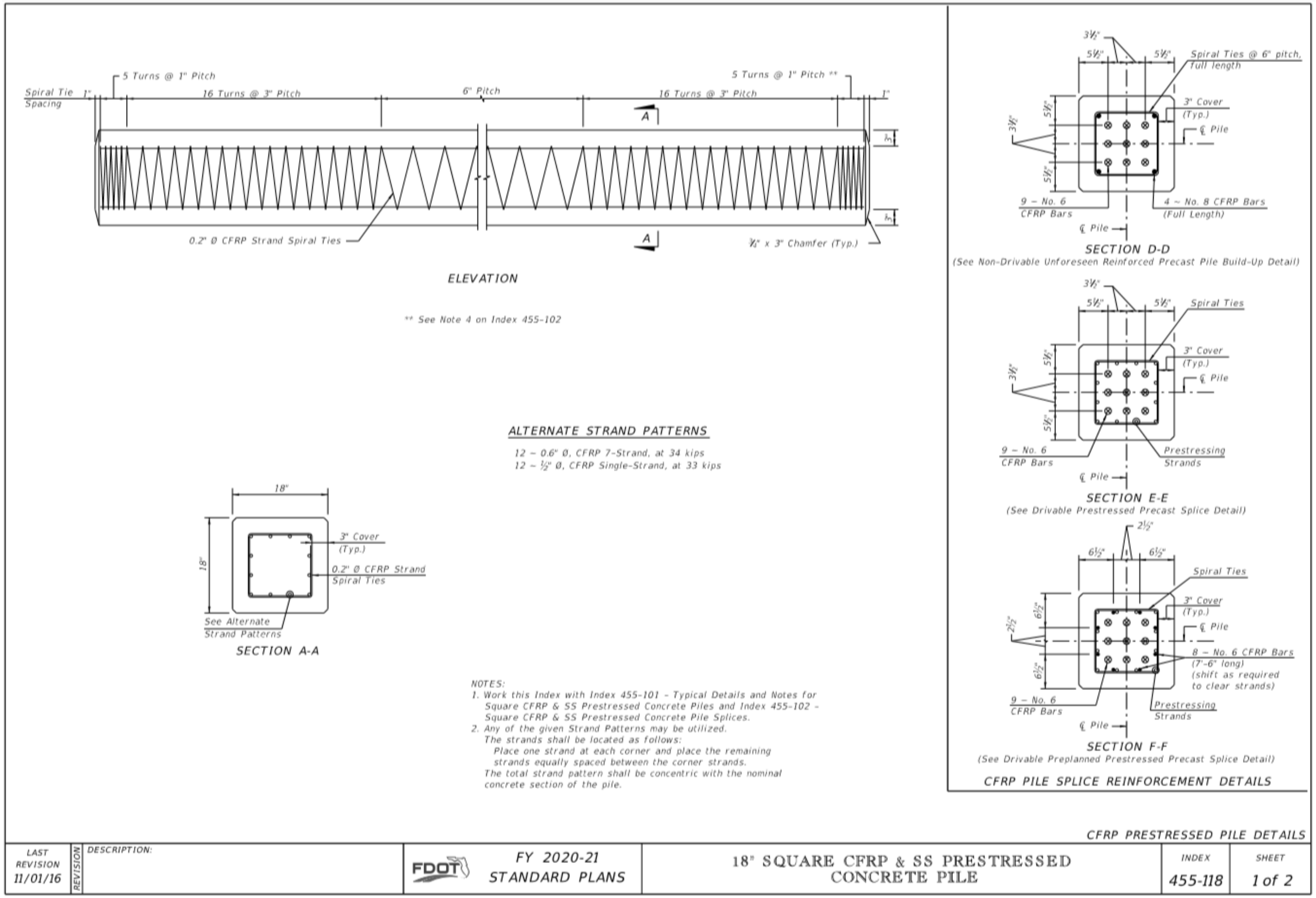
PRESTRESSED PILES

Square Pile

e.g. 18’’



SECTION A-A



[FDOT Standard Plans, Index 455-118]

PRESTRESSED PILES

FDOT ***Standard Plans Instructions (SPI)***, FY 2020-21
Index 455-101 Series Square CFRP & SS Prestressed Concrete Piles

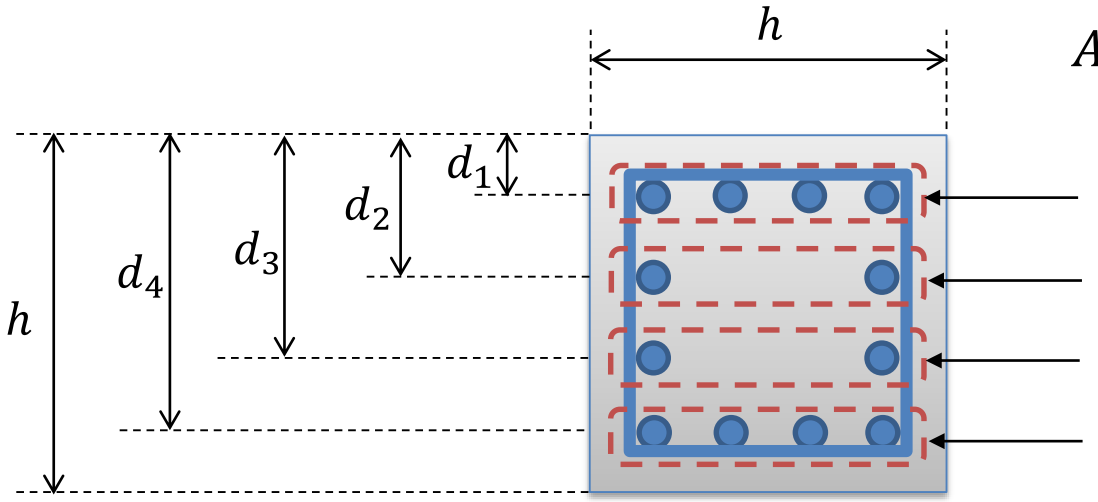
Design Assumptions and Limitations

- Standard piles are designed to have 1000 psi uniform compression after prestress losses without any applied loads *to offset tensile stresses that occur during typical driving*.
- The piles are designed to have 0.0 psi tension using a load factor of 1.5 times the pile self weight during pick-up, storage and transportation

*[FDOT **Standard Plans**, Instructions, Index 455-101]*

Square Pile

- Clear cover cc
- Concrete compressive strength f_c'
- CFRP ultimate strength f_{fu}
- CFRP effective prestressing stress f_{fe} (after losses)



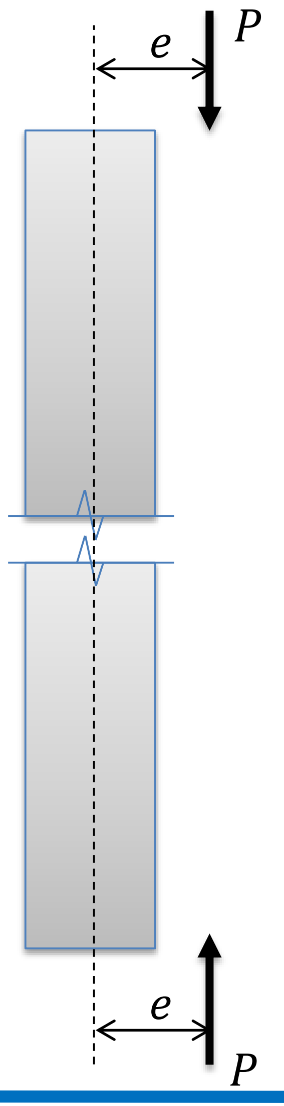
$$A_{f,total} = \sum A_{fi}$$

$$A_{f1} = 4 \cdot A_f$$

$$A_{f2} = 2 \cdot A_f$$

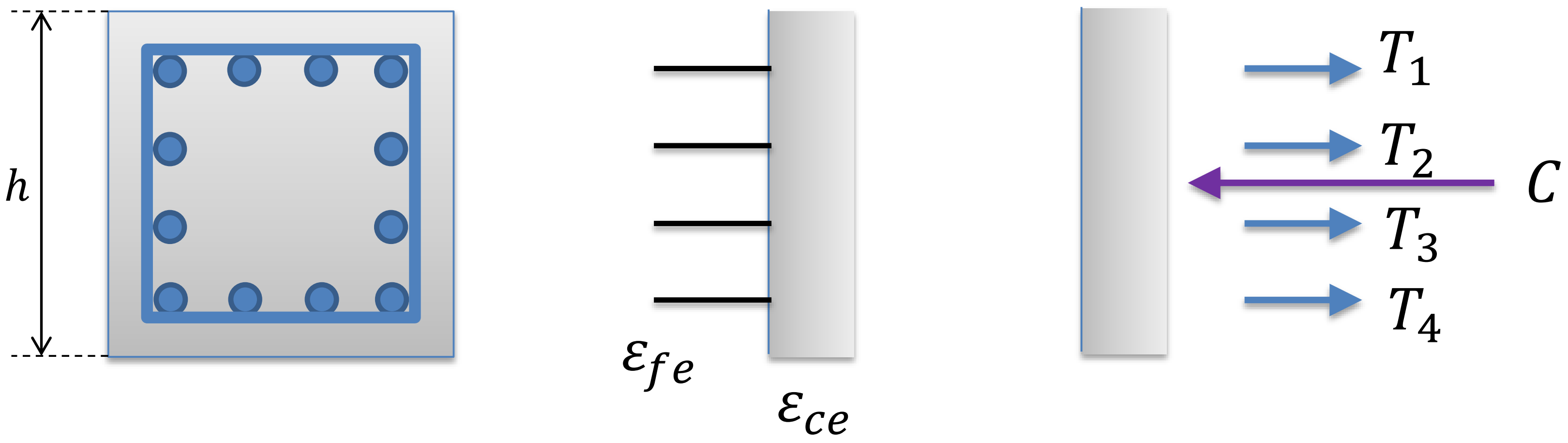
$$A_{f3} = A_{f2}$$

$$A_{f4} = A_{f1}$$



PRESTRESSED PILES

Square Pile: Under Prestressing Force Only



$$\varepsilon_{fe} = \frac{f_{fe}}{E_f}$$

$$\varepsilon_{ce} = \frac{f_{ce}}{E_c}$$

$$\sum T_i = C$$

$$A_{f,total} \cdot f_{fe} = A_c \cdot f_{ce}$$

$$f_{ce} = \frac{A_{f,total} \cdot f_{fe}}{A_c} = \frac{A_{f,total} \cdot f_{fe}}{h^2}$$

PRESTRESSED PILES

Square Pile: Under Prestressing Force Only

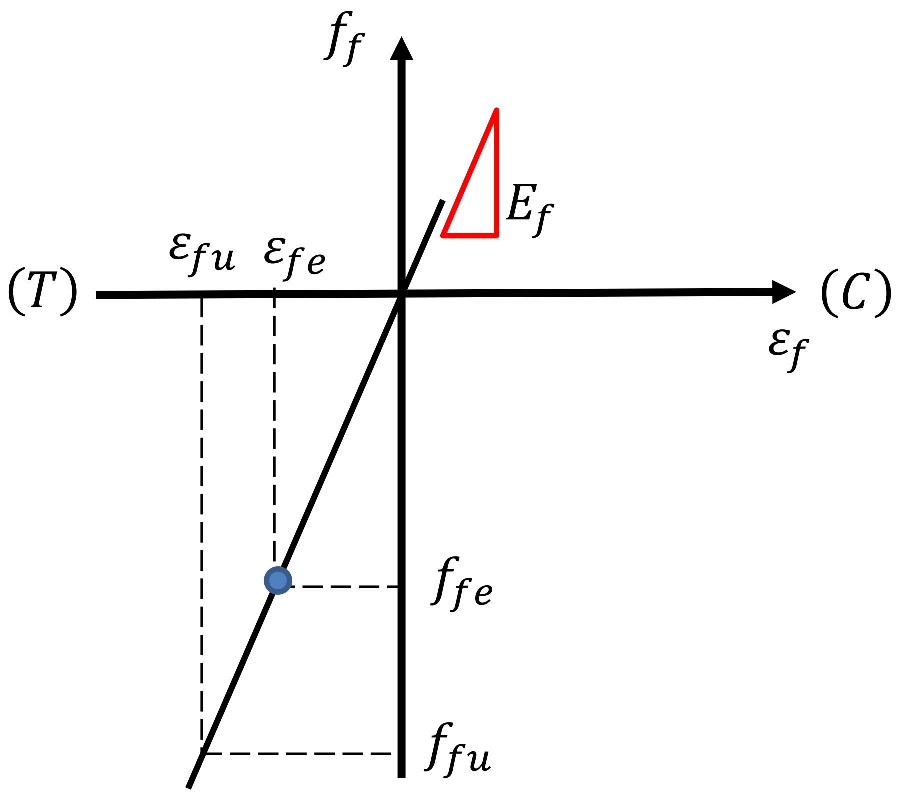
$$f_{ce} = \frac{A_{f,total} \cdot f_{fe}}{h^2}$$

Adjust jacking force until satisfy

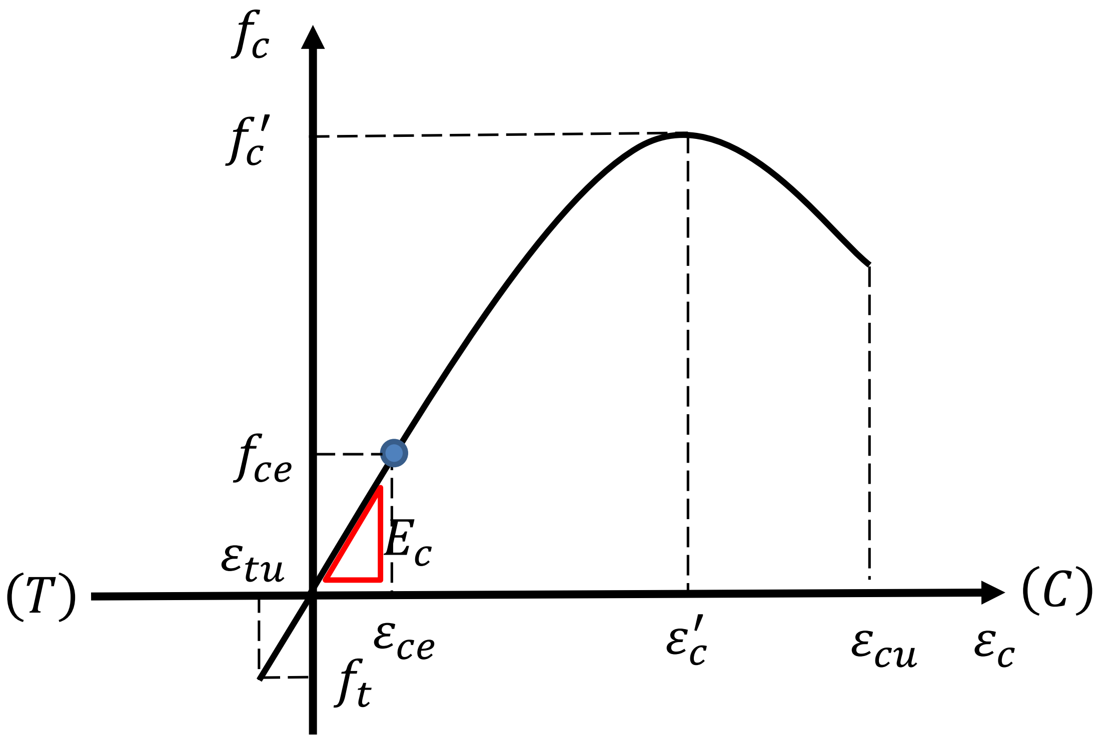
$f_{ce} = 1000\,psi$ uniform compression at time of installation

[FDOT Standard Plans Instructions, FY 2020-21
Index 455-101 Series Square CFRP & SS Prestressed Concrete Piles]

PRESTRESSED PILES



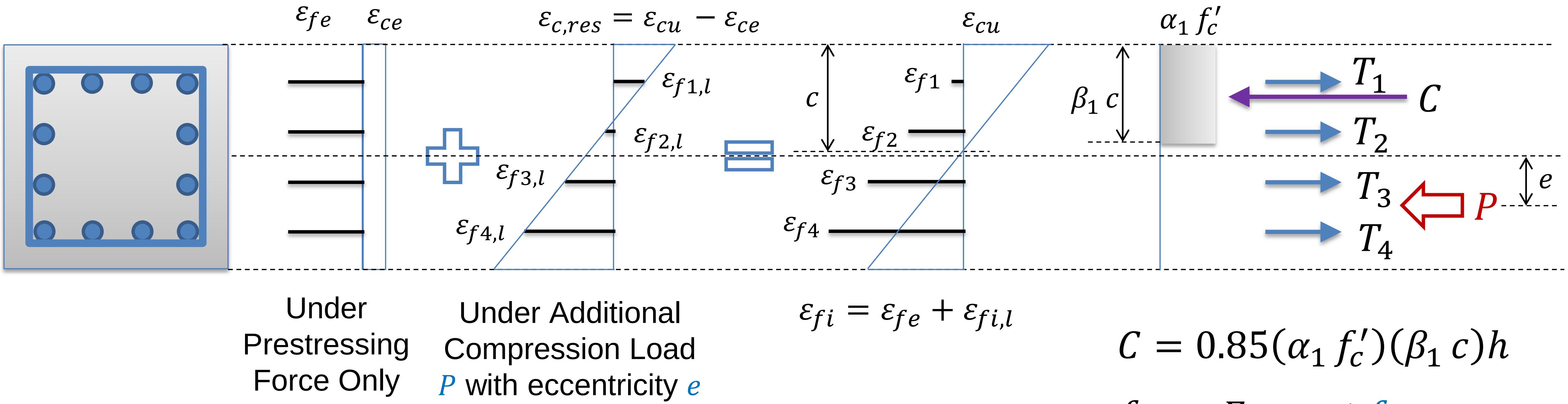
CFRP



Concrete

Square Pile: P-M diagram

Assume a compression depth c



$$\varepsilon_{fi} = \varepsilon_{fe} + \varepsilon_{fi,l}$$

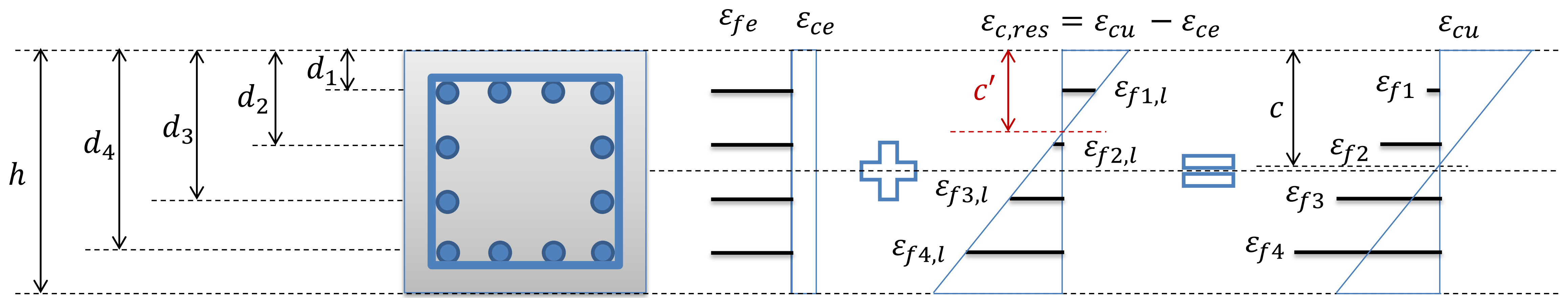
$$C = 0.85(\alpha_1 f_c')(\beta_1 c)h$$

$$f_{fi} = E_f \varepsilon_{fi} \leq f_{fu}$$

$$T_i = A_{fi} f_{fi}$$

Square Pile: P-M diagram

Assume a compression depth c



Under Prestressing Force Only

Under Additional Compression Load P with eccentricity e

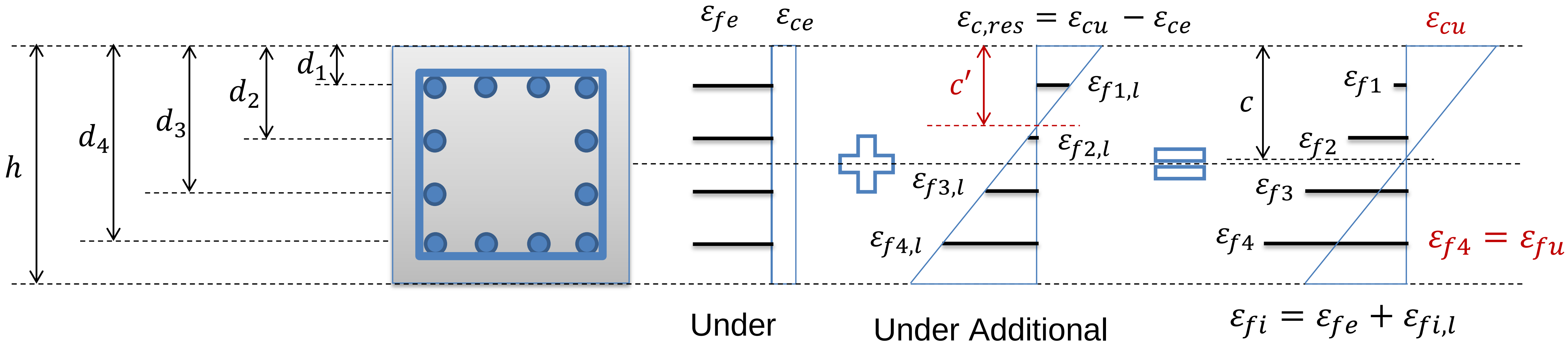
$$\varepsilon_{fi} = \varepsilon_{fe} + \varepsilon_{fi,l}$$

$$\frac{\varepsilon_{c,res}}{c'} = \frac{\varepsilon_{cu}}{c} \rightarrow c' = \frac{\varepsilon_{cu} - \varepsilon_{ce}}{\varepsilon_{cu}} c$$

$$\frac{\varepsilon_{c,res}}{c'} = \frac{\varepsilon_{fi,l}}{c' - d_i} \rightarrow \varepsilon_{fi,l} = \varepsilon_{c,res} \frac{c' - d_i}{c'} = (\varepsilon_{cu} - \varepsilon_{ce}) \frac{\left(\frac{\varepsilon_{cu} - \varepsilon_{ce}}{\varepsilon_{cu}} c\right) - d_i}{\left(\frac{\varepsilon_{cu} - \varepsilon_{ce}}{\varepsilon_{cu}} c\right)}$$

Square Pile: P-M diagram *Balanced Condition*

Assume a compression depth c



$$\frac{\varepsilon_{c,res}}{c'} = \frac{\varepsilon_{cu}}{c} \rightarrow c' = \frac{\varepsilon_{c,res}}{\varepsilon_{cu}} c$$

$$\frac{\varepsilon_{c,res}}{c'} = \frac{\varepsilon_{fi,l}}{c' - d_i} \rightarrow \varepsilon_{fi,l} = \varepsilon_{c,res} \frac{c' - d_i}{c'} = \varepsilon_{c,res} \frac{\left(\frac{\varepsilon_{c,res}}{\varepsilon_{cu}} c\right) - d_i}{\left(\frac{\varepsilon_{c,res}}{\varepsilon_{cu}} c\right)}$$

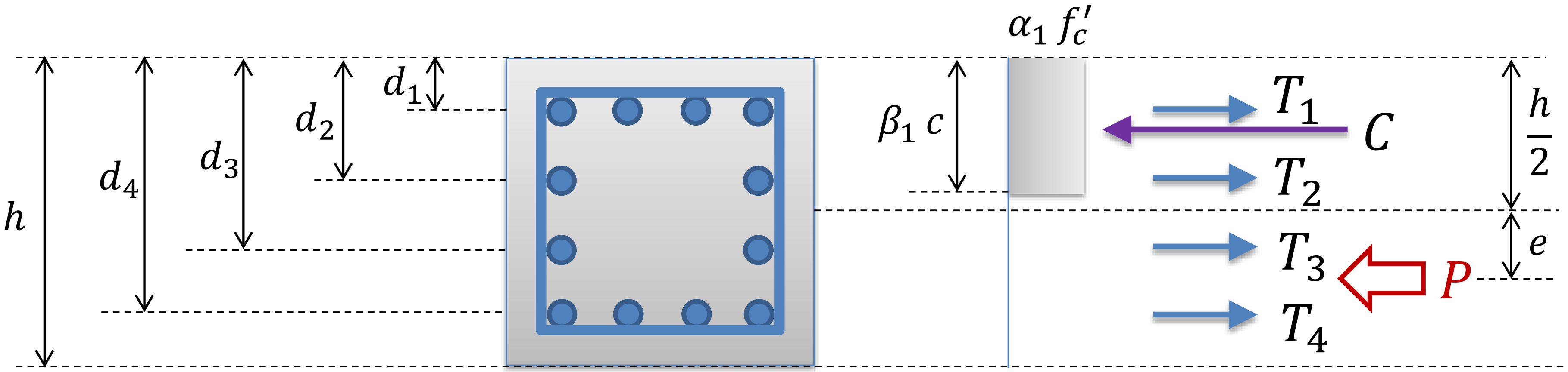
PRESTRESSED PILES

Square Pile: P-M diagram

$$C = (\alpha_1 f_c')(\beta_1 c)h$$

$$T_i = A_{fi} f_{fi} \qquad f_{fi} = E_f \varepsilon_{fi} \le f_{fu}$$

Assume a compression depth c



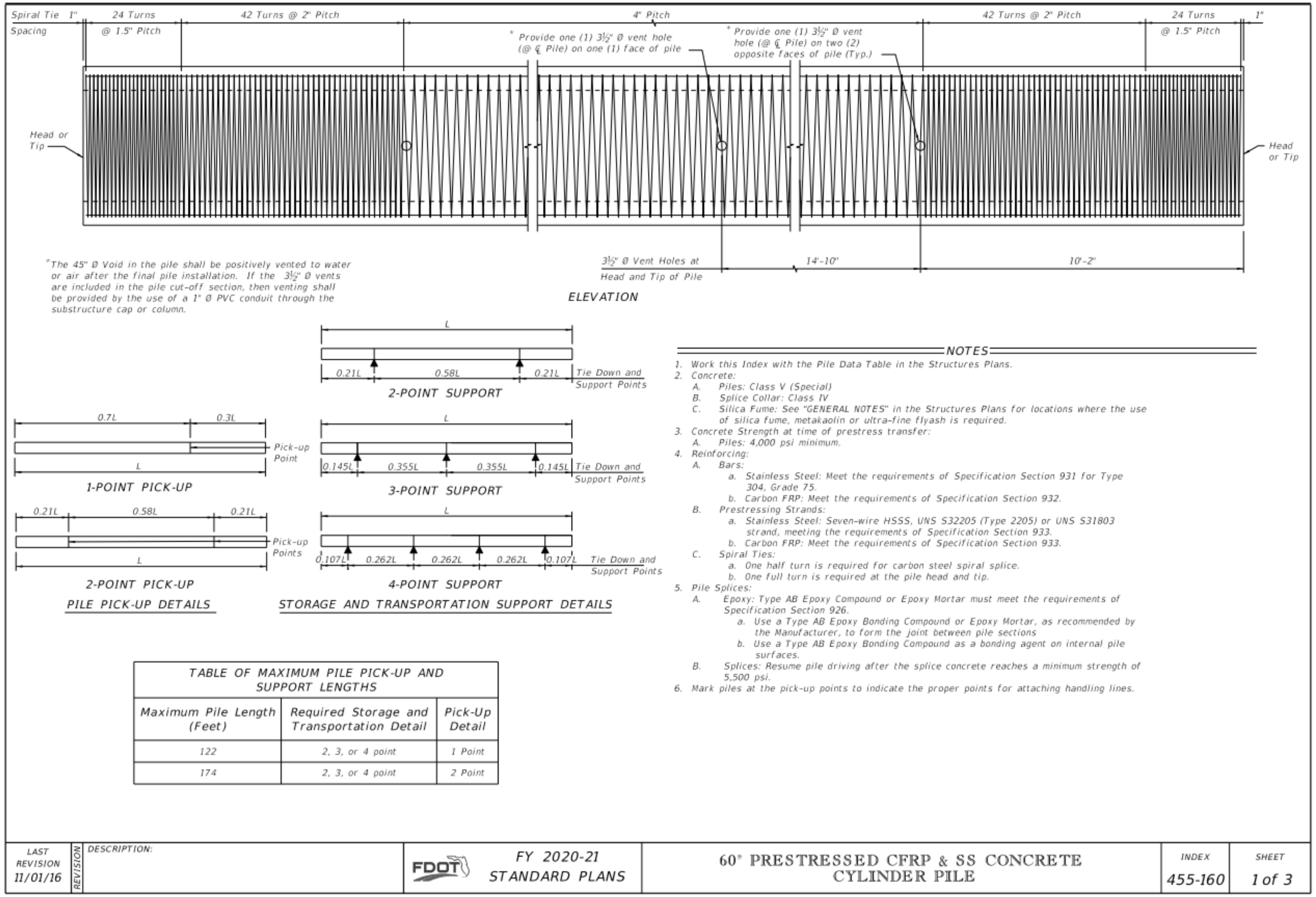
$$Pe = M = C\left(\frac{h}{2} - \frac{\beta_1 c}{2}\right) - T_1\left(\frac{h}{2} - d_1\right) - T_2\left(\frac{h}{2} - d_2\right) + T_3\left(d_3 - \frac{h}{2}\right) + T_4\left(d_4 - \frac{h}{2}\right)$$

$$\sum T_i = C + P \longrightarrow P, M \xrightarrow{\emptyset = 0.75} \emptyset P, \emptyset M$$

PRESTRESSED PILES

Cylinder Pile

The first 66” cylinder pile cast for the Harry Nice Bridge replacement. These pile have CFCC strand and spiral and exceed 200’ in length. Pile produced from Cape Charles plant (June 2020)

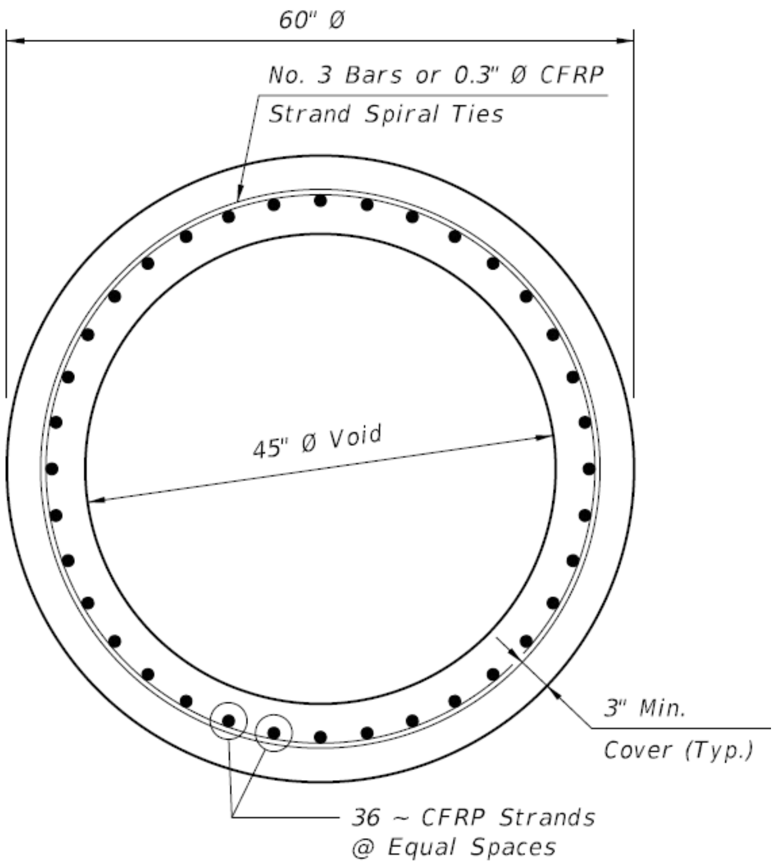


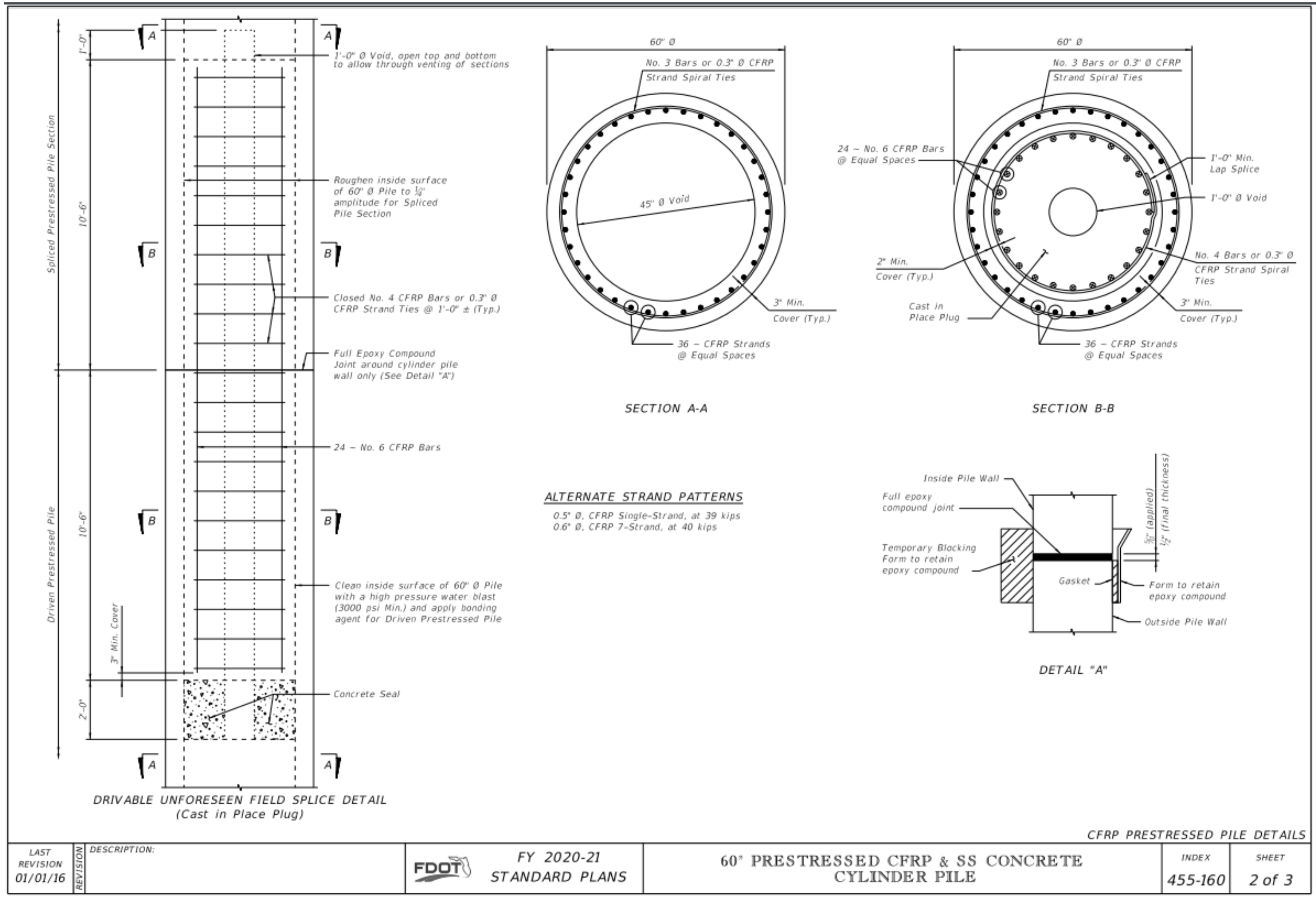
[FDOT **Standard Plans**, Index 455-160]

PRESTRESSED PILES

Cylinder Pile

e.g. 60’’

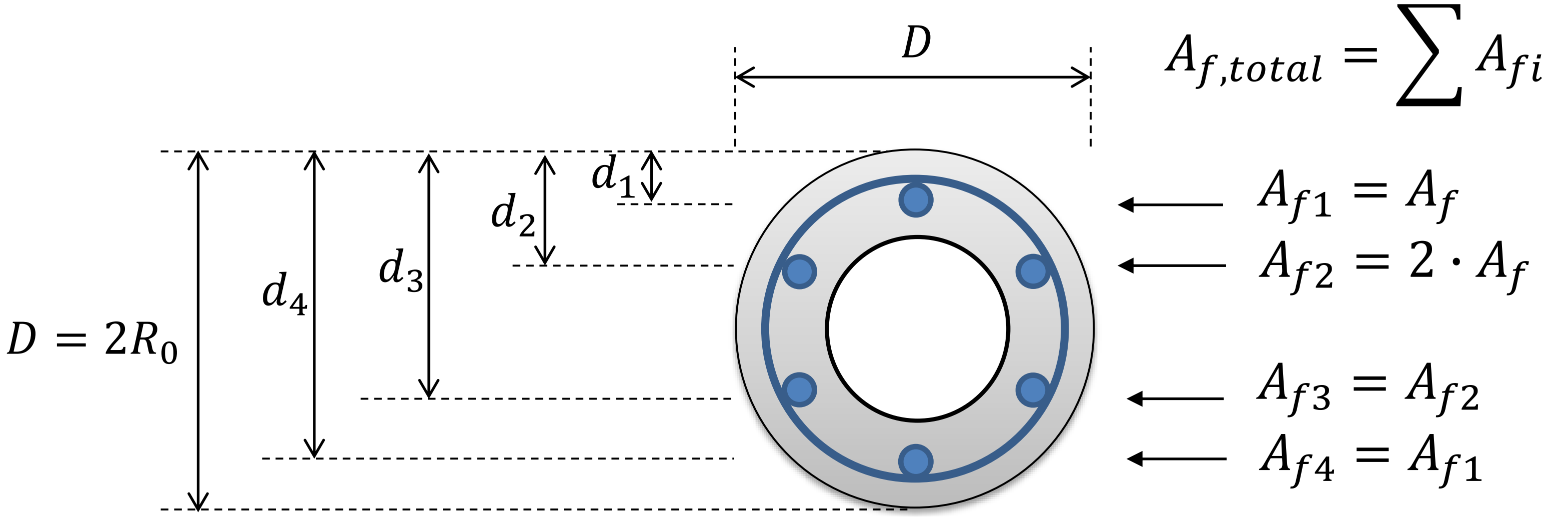


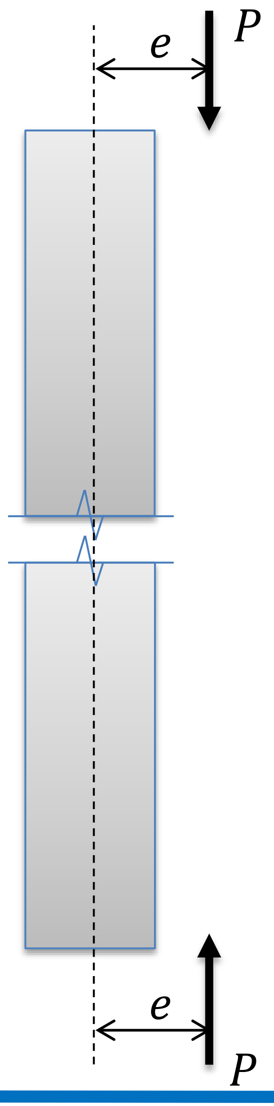


PRESTRESSED PILES

Cylinder Pile

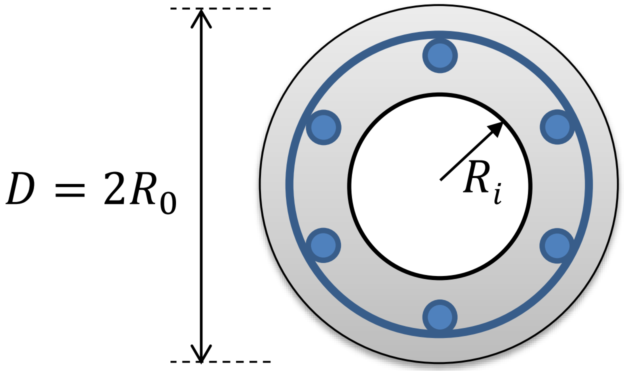
- Concrete compressive strength f_c'
- CFRP ultimate strength f_{fu}
- CFRP effective prestressing stress f_{fe} (after losses)

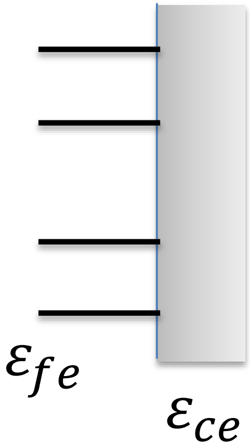


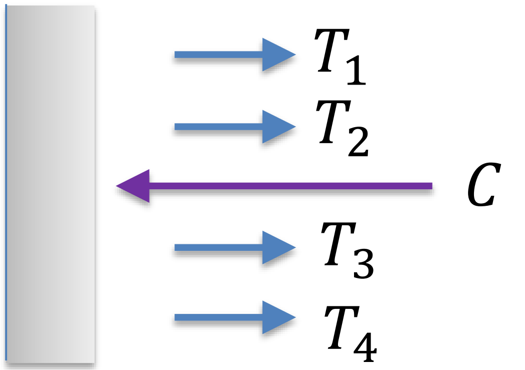


PRESTRESSED PILES

Cylinder Pile: Under Prestressing Force Only







$$\varepsilon_{fe} = \frac{f_{fe}}{E_f}$$

$$\varepsilon_{ce} = \frac{f_{ce}}{E_c}$$

$$\sum T_i = C$$

$$A_{f,total} \cdot f_{fe} = A_c \cdot f_{ce}$$

$$f_{ce} = \frac{A_{f,total} \cdot f_{fe}}{A_c} = \frac{A_{f,total} \cdot f_{fe}}{\pi({R_o}^2 - {R_i}^2)}$$

PRESTRESSED PILES

Cylinder Pile: Under Prestressing Force Only

$$f_{ce} = \frac{A_{f,total} \cdot f_{fe}}{\pi({R_o}^2 - {R_i}^2)}$$

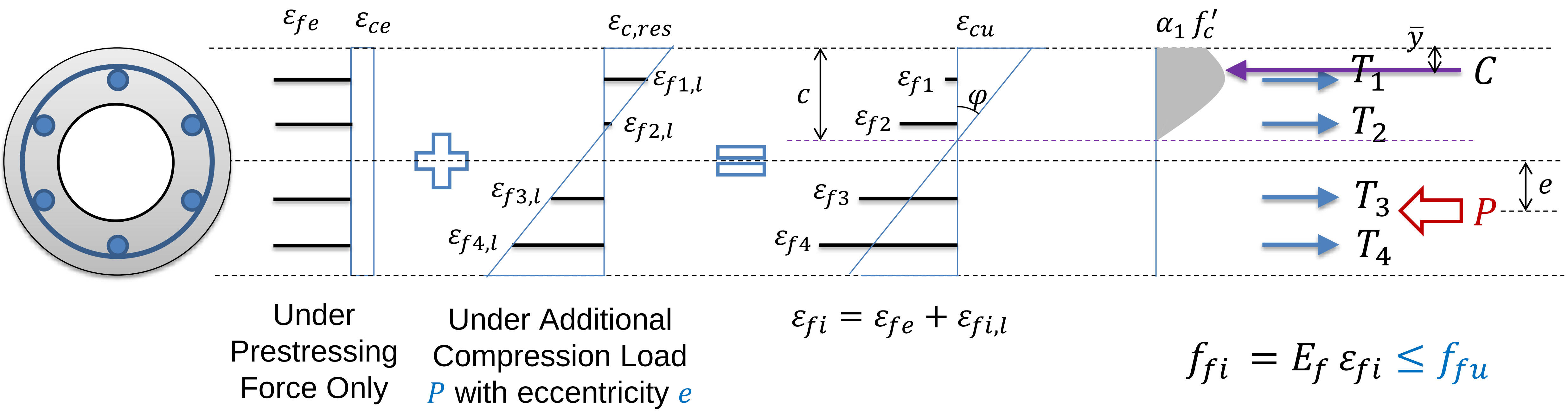
Adjust jacking force until satisfy

$f_{ce} = 1000\, psi$ uniform compression at time of installation

[FDOT Standard Plans Instructions, FY 2020-21
Index 455-101 Series Square CFRP & SS Prestressed Concrete Piles]

Cylinder Pile: P-M diagram

Assume a compression depth c

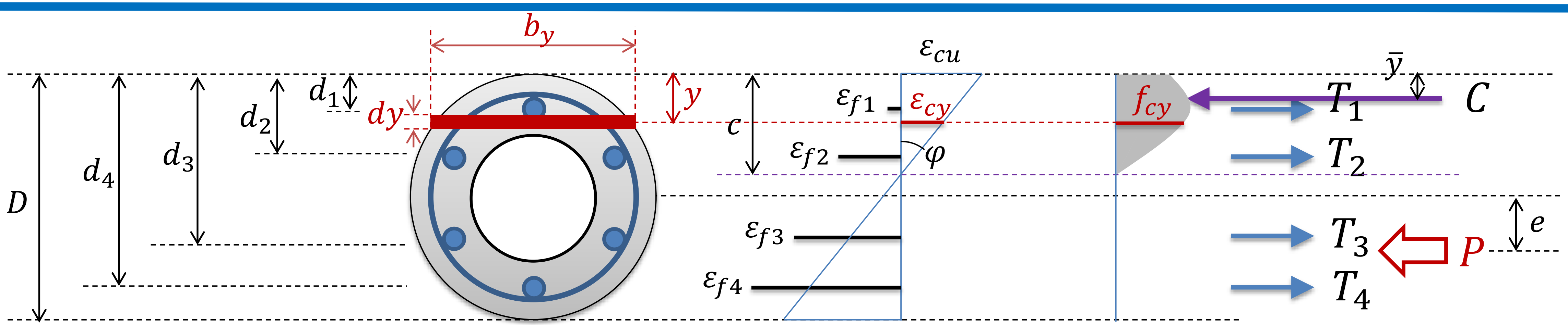


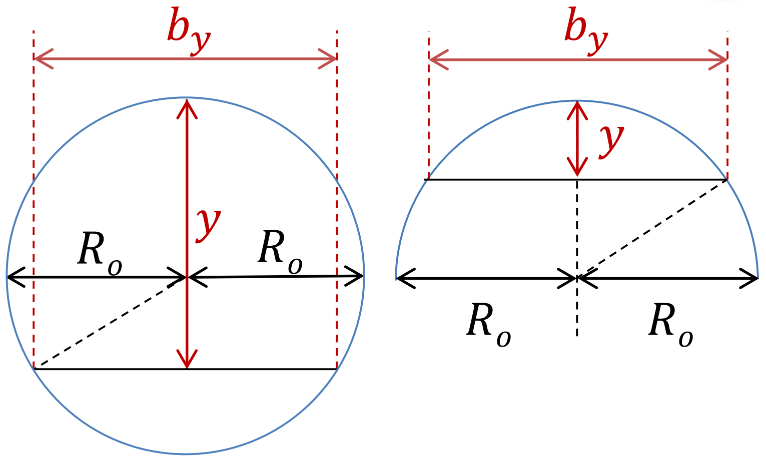
$$\varepsilon_{fi} = \varepsilon_{fe} + \varepsilon_{fi,l}$$

$$f_{fi} = E_f \, \varepsilon_{fi} \le f_{fu}$$

$$T_i = A_{fi} \, f_{fi}$$

PRESTRESSED PILES





$$\varepsilon_{fi} = \varepsilon_{fe} + \varepsilon_{fi,l}$$

$$\varphi = \frac{\varepsilon_{cu}}{c} \qquad \varepsilon_{cy} = \varphi(c - y)$$

$$f_{cy} = f_c(\varepsilon_{cy})$$

$$C = \int_0^c b_y \cdot f_{cy}\, dy$$

$$\bar{y} = \frac{\int_0^c (b_y \cdot f_{cy} \cdot y)\, dy}{C}$$

When $R_o - Ri < y < R_o + R_i$, $\quad y_i = y - (R_o - Ri)$

$$b_y = 2\sqrt{{R_o}^2 - (R_o - y)^2} - 2\sqrt{{R_i}^2 - (R_i - yi)^2}$$

Otherwise $b_y = 2\sqrt{{R_o}^2 - (R_o - y)^2}$

Concrete stress-strain relationship

e.g. parabolic

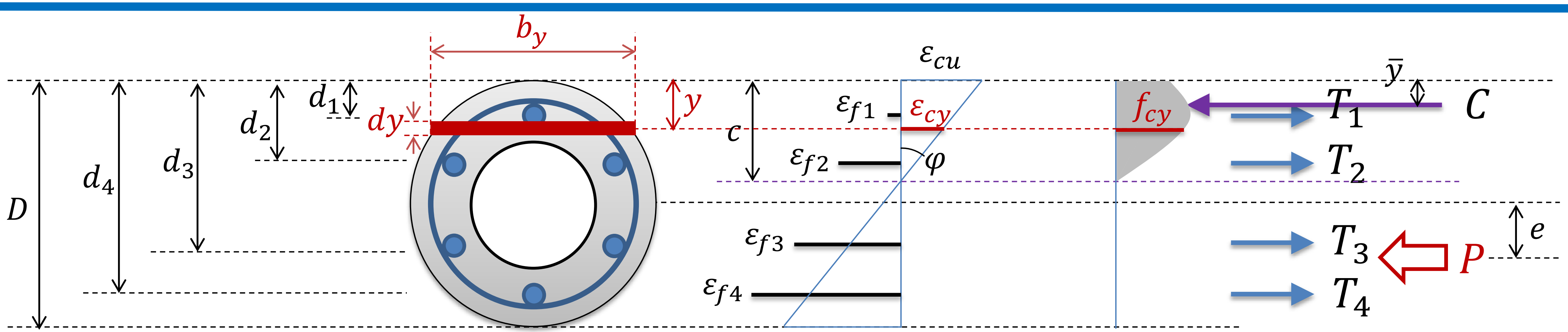
$$f_c = f_c'\left[2\frac{\varepsilon_c}{\varepsilon_c'} - \left(\frac{\varepsilon_c}{\varepsilon_c'}\right)^2\right]$$

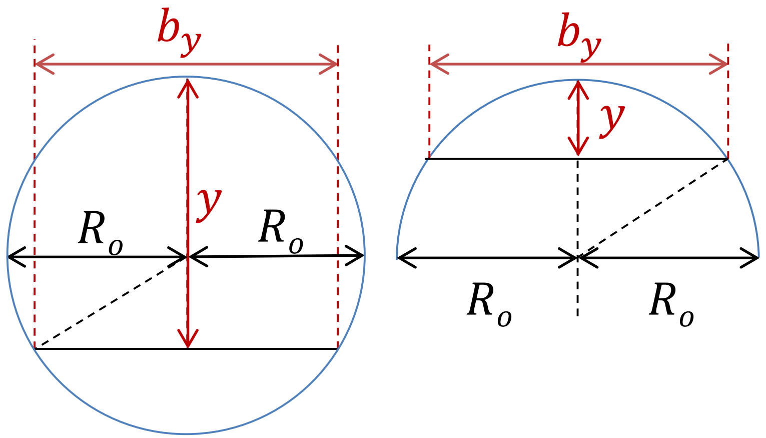
e.g. Thorenfeldt model

$$f_c = f_c'\frac{n(\varepsilon_c/\varepsilon_c')}{n - 1 + (\varepsilon_c/\varepsilon_c')^{nk}}$$

FDOT UH

PRESTRESSED PILES





$$\varepsilon_{fi} = \varepsilon_{fe} + \varepsilon_{fi,l}$$

$$\varphi = \frac{\varepsilon_{cu}}{c} \qquad \varepsilon_{cy} = \varphi(c-y)$$

$$f_{cy} = f_c\left(\varepsilon_{cy}\right)$$

$$C = \int_0^c b_y \cdot f_{cy}\, dy$$

$$\bar{y} = \frac{\int_0^c \left(b_y \cdot f_{cy} \cdot y\right) dy}{C}$$

When $R_o - Ri < y < R_o + R_i$, $\quad y_i = y - (R_o - Ri)$

$$b_y = 2\sqrt{R_o{}^2 - (R_o - y)^2} - 2\sqrt{R_i{}^2 - (R_i - yi)^2}$$

Otherwise $\quad b_y = 2\sqrt{R_o{}^2 - (R_o - y)^2}$

Concrete stress-strain relationship

e.g. parabolic

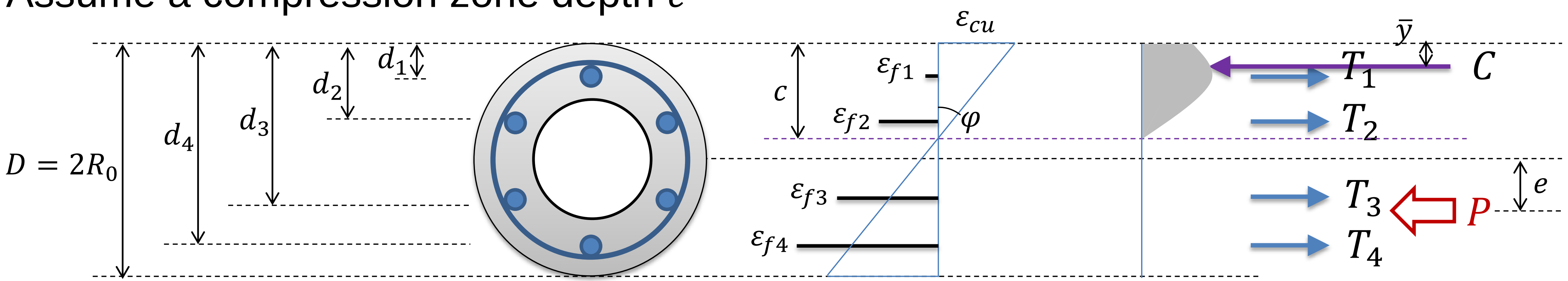
$$f_c = f_c'\left[2\frac{\varepsilon_c}{\varepsilon_c'} - \left(\frac{\varepsilon_c}{\varepsilon_c'}\right)^2\right]$$

e.g. Thorenfeldt model

$$f_c = f_c'\frac{n(\varepsilon_c/\varepsilon_c')}{n-1+(\varepsilon_c/\varepsilon_c')^{nk}}$$

Cylinder Pile: P-M diagram

Assume a compression zone depth c



$$\varepsilon_{fi} = \varepsilon_{fe} + \varepsilon_{fi,l}$$

$$Pe = M = C(R_o - \bar{y}) - T_1(R_o - d_1) - T_2(R_o - d_2) + T_3(d_3 - Ro) + T_4(d_4 - R_o)$$

$$\sum T_i = C + P \longrightarrow P, M \xrightarrow{\emptyset = 0.75} \emptyset P, \emptyset M$$

PRESTRESSED PILES

Factored Axial Resistance

For compressive components symmetrical about both principal axes

$$P_r = \phi P_n$$

FRP does NOT have compressive strength

Spiral reinforcement $P_n = 0.85\left[k_c f_c'\left(A_g - A_{ft} - A_{pf}\right) - A_{pf}\left(f_{pe} - E_p \varepsilon_{cu}\right)\right]$

Tie reinforcement $P_n = 0.80\left[k_c f_c'\left(A_g - A_{ft} - A_{pf}\right) - A_{pf}\left(f_{pe} - E_p \varepsilon_{cu}\right)\right]$

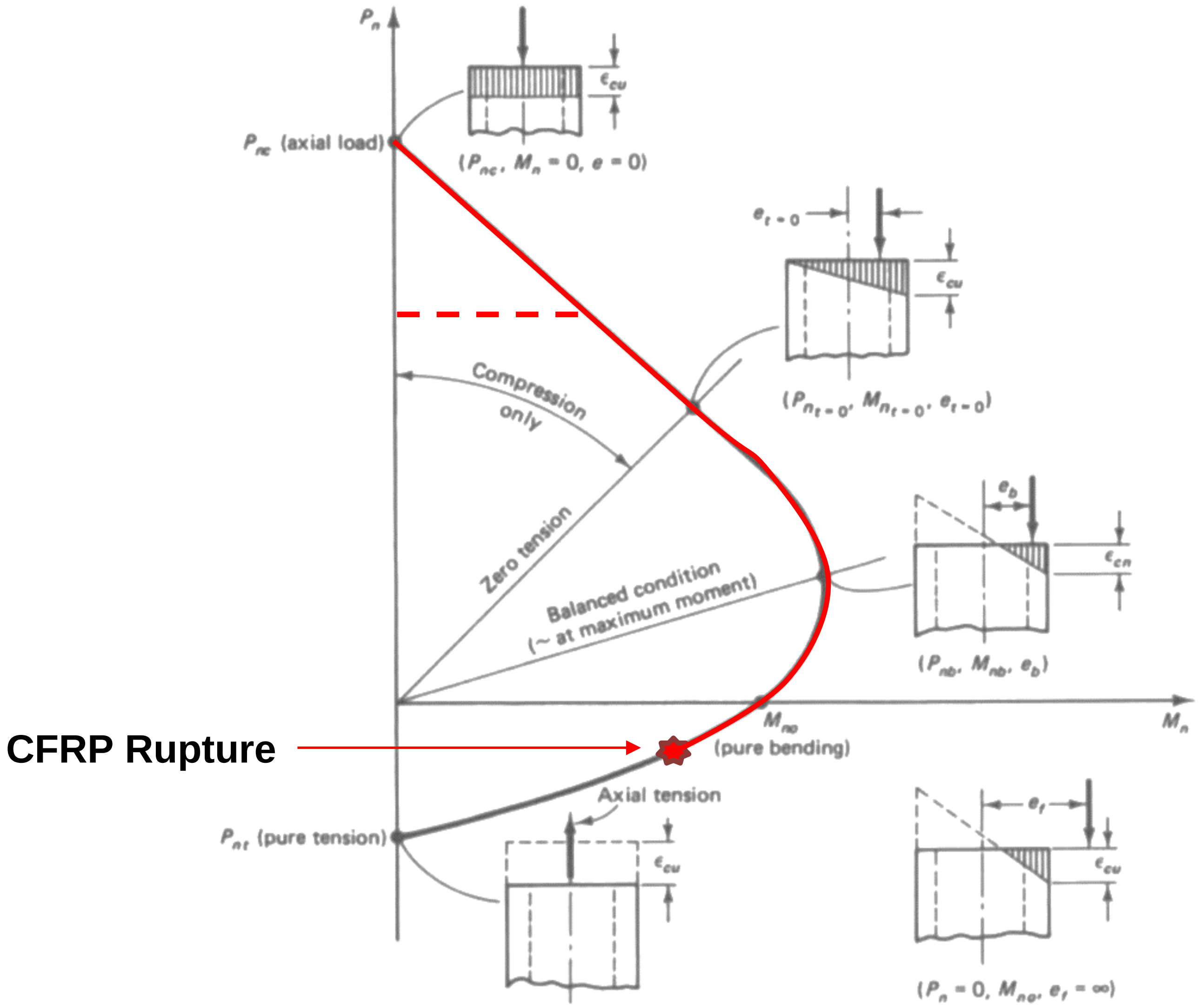
[Replaced steel (s) with CFRP (f), f_y with f_{pu}]

$$k_c = \begin{cases} 0.85 & \text{when } f_c' \leq 10 \text{ ksi} \\ 0.85 - 0.02(f_c' - 10) \geq 0.75 & \text{when } f_c' > 10 \text{ ksi} \end{cases}$$

PRESTRESSED PILES

P-M Interaction Diagram

- Pure compression
- Pure tension
- Pure bending
- Balanced condition
- Zero tension



Questions?

Florida Department of TRANSPORTATION

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

5. PRESTRESSED PILES

5.1 Review Questions: Fundamentals

Florida Department of TRANSPORTATION

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

REVIEW QUESTIONS

5.1.1) When constructing a P-M diagram for a CFRP prestressed piles, the balance points refers to:_____?

a. The point at which the CFRP yields and concrete crushes

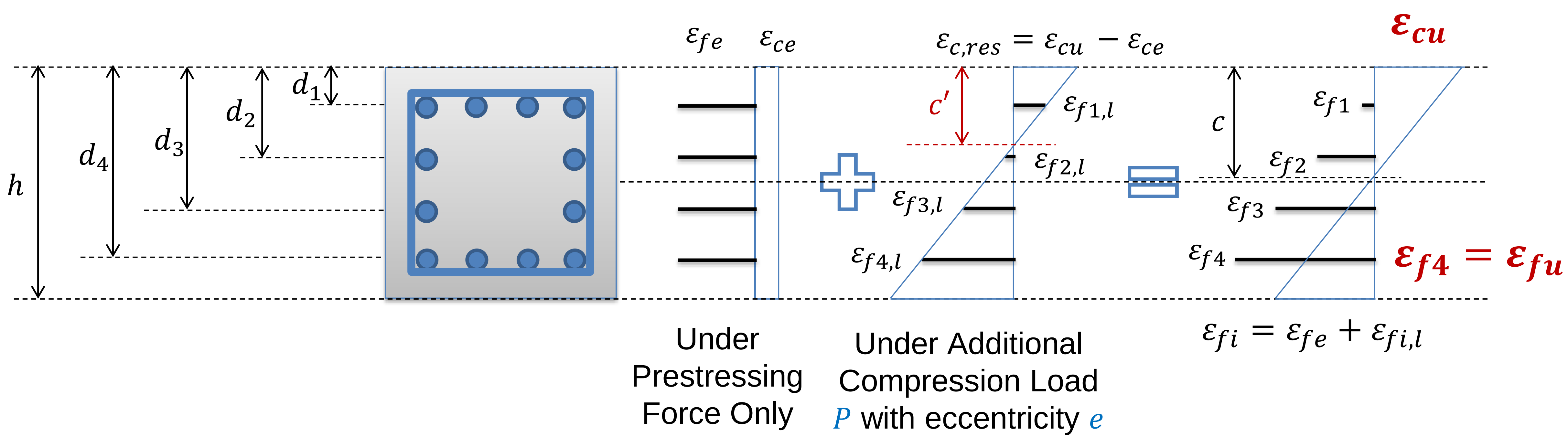
b. The point at which the CFRP ruptures and concrete crushes

c. The point at which the CFRP yields before concrete crushes

d. The point at which the concrete crushes, but the CFRP has not ruptured

REVIEW QUESTIONS

P-M diagram: Balanced Condition



REVIEW QUESTIONS

5.1.1) When constructing a P-M diagram for a CFRP prestressed piles, the balance points refers to:_____?

a. The point at which the CFRP yields and concrete crushes

b. <u>The point at which the CFRP ruptures and concrete crushes</u>

c. The point at which the CFRP yields before concrete crushes

d. The point at which the concrete crushes, but the CFRP has not ruptured

REVIEW QUESTIONS

5.1.2) For FDOT 455-101 Series Square CFRP Prestressed Concrete Piles, which of the below statement(s) is/are TRUE?

a. Prestressed piles are designed to have 1000 psi uniform compression after prestress losses without any applied loads to offset tensile stresses that occur during typical driving

b. Prestressed piles are designed to have 0.0 psi tension using a load factor of 1.5 times the pile self weight during pick-up, storage and transportation

c. Both (a) and (b)

d. None of above

REVIEW QUESTIONS

FDOT ***Standard Plans Instructions (SPI)***, FY 2020-21
Index 455-101 Series Square CFRP & SS Prestressed Concrete Piles

Design Assumptions and Limitations

- Standard piles are designed to have 1000 psi uniform compression after prestress losses without any applied loads *to offset tensile stresses that occur during typical driving*.

- The piles are designed to have 0.0 psi tension using a load factor of 1.5 times the pile self weight during pick-up, storage and transportation

REVIEW QUESTIONS

5.1.2) For FDOT 455-101 Series Square CFRP Prestressed Concrete Piles, which of the below statement(s) is/are TRUE?

a. Prestressed piles are designed to have 1000 psi uniform compression after prestress losses without any applied loads to offset tensile stresses that occur during typical driving

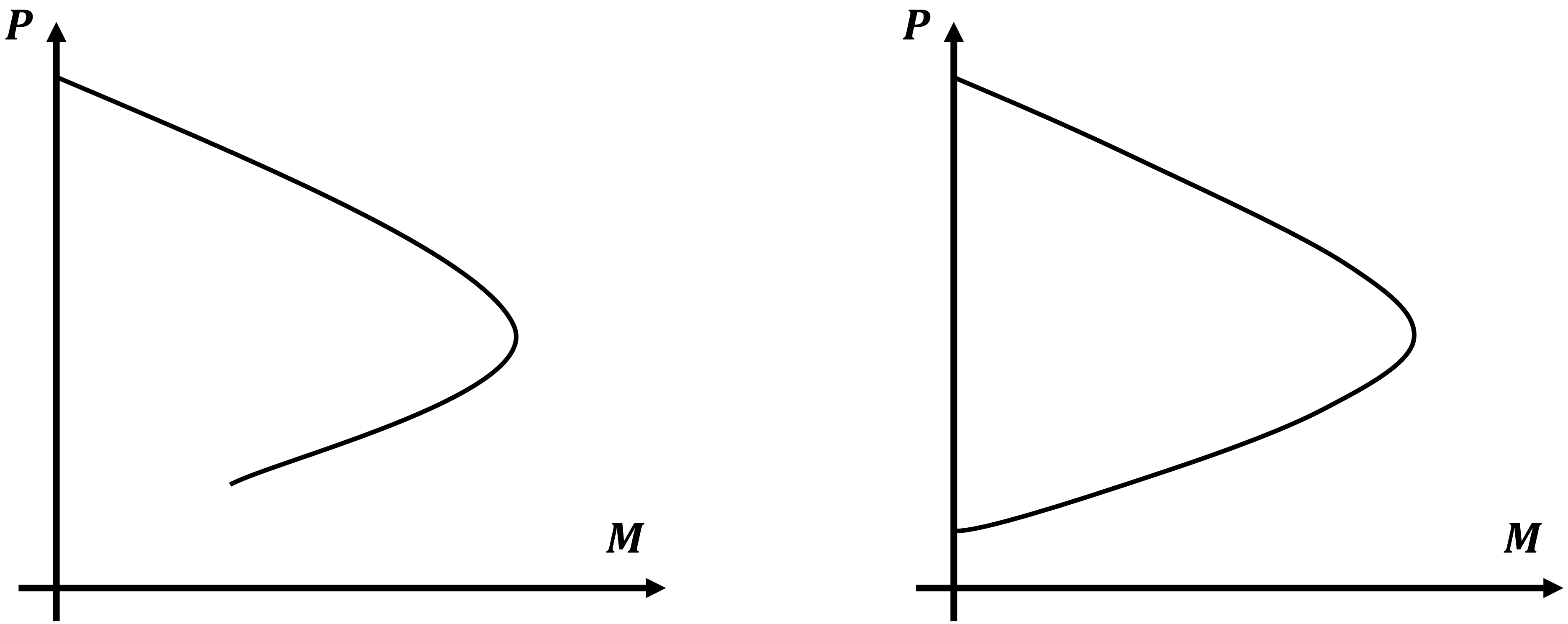
b. Prestressed piles are designed to have 0.0 psi tension using a load factor of 1.5 times the pile self weight during pick-up, storage and transportation

c. **<u>Both (a) and (b)</u>**

d. None of above

REVIEW QUESTIONS

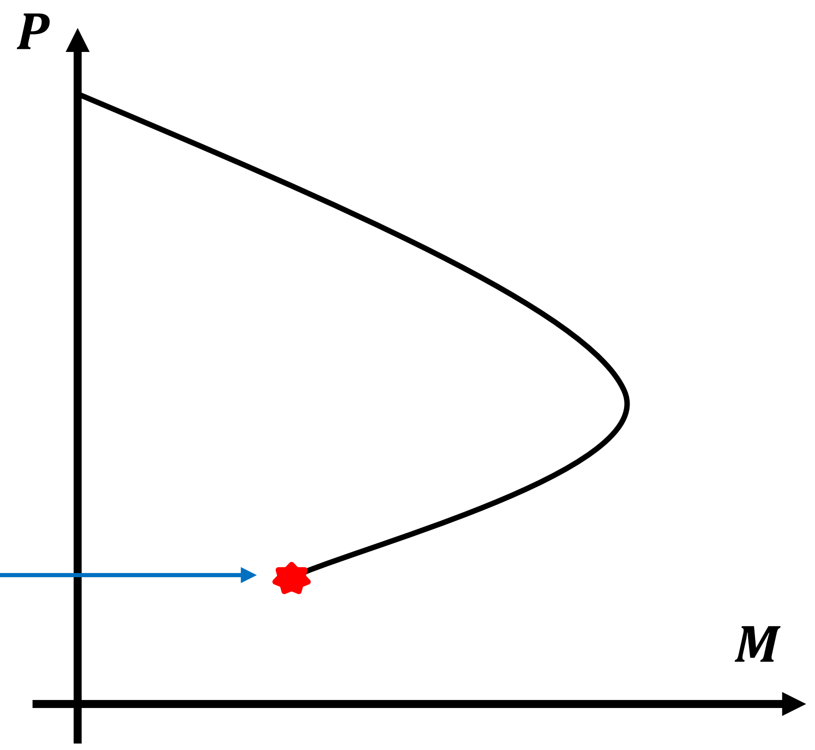
5.1.3) Which of below P-M diagram is for a CFRP prestressed concrete pile?



(a) (b)

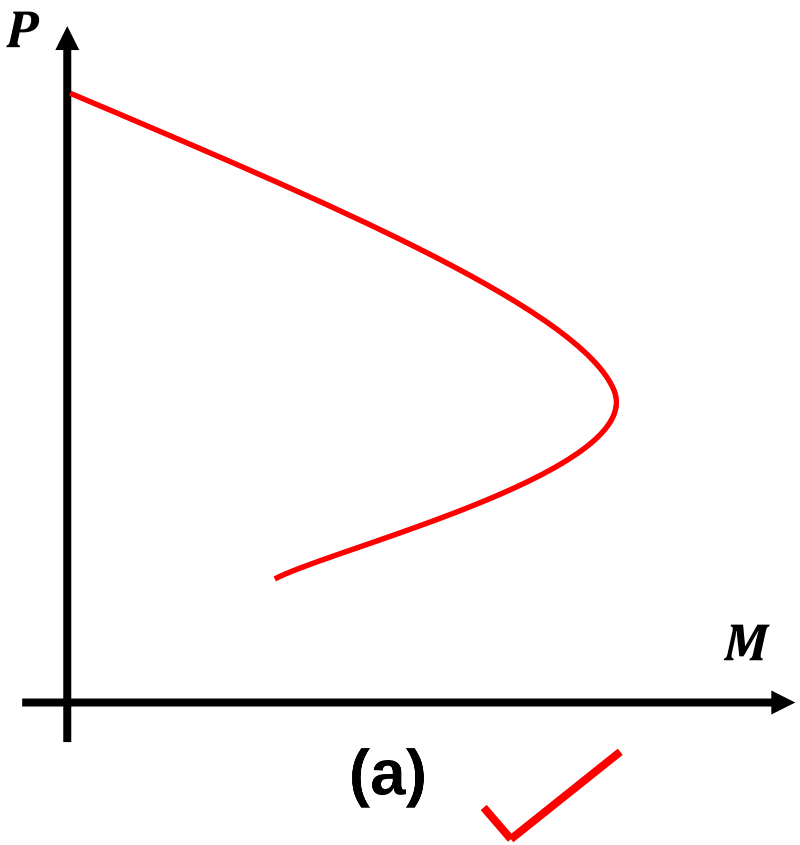
REVIEW QUESTIONS

CFRP Rupture

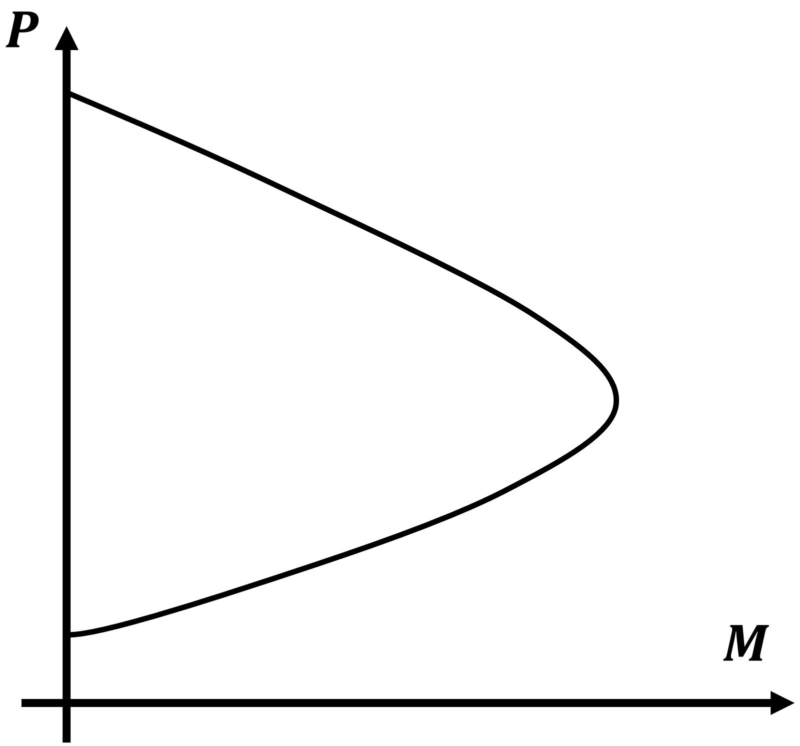


REVIEW QUESTIONS

5.1.3) Which of below P-M diagram is for a CFRP prestressed concrete pile?



(a)



(b)

REVIEW QUESTIONS

5.1.4) _____spiral ties should be used in CFRP prestressed piles?

a. CFRP

b. Steel

REVIEW QUESTIONS

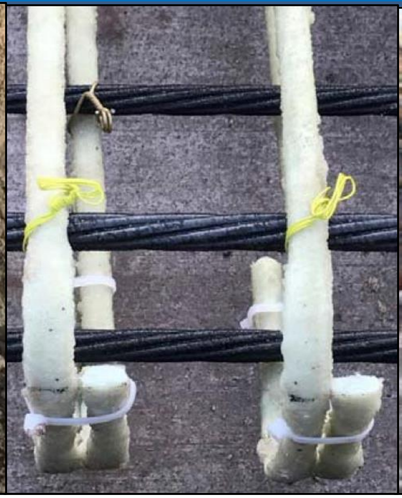
5.1.4) _____spiral ties should be used in CFRP prestressed piles?

a. **CFRP**

b. Steel

5. PRESTRESSED PILES

5.2 Design Example: Square Pile -18"x18"

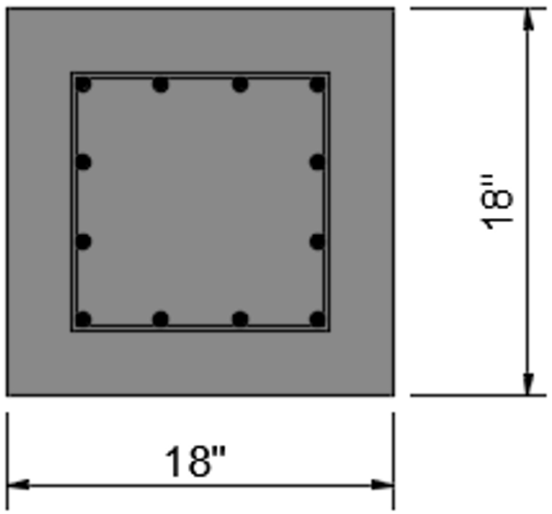


FDOT Florida Department of TRANSPORTATION

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

DESIGN EXAMPLE: SQUARE PILE

Geometry



b = h = 18 in

cover = 3 in

$A_g = 323\ \text{in}^2$

$I_g = 8748\ \text{in}^4$

Concrete

$f'_c = 6\ \text{ksi}$

$f'_{ci} = 4\ \text{ksi}$

$E_c = 4557\ \text{ksi}$

$E_{ci} = 3987\ \text{ksi}$

$\alpha_1 = 0.85$

$\beta_1 = 0.75$

CFRP strand

$D_p = 0.6\ \text{in}$

$A_{pf} = 0.179\ \text{in}^2$

$E_f = 22{,}480\ \text{ksi}$

$f_{pu} = 370\ \text{ksi}$

CFRP wire

$D_{wire} = 0.2\ \text{in}$

DESIGN EXAMPLE: SQUARE PILE

FDOT ***Standard Plans Instructions (SPI)***, FY 2020-21
Index 455-101 Series Square CFRP & SS Prestressed Concrete Piles

- Standard piles are designed to have 1000 psi uniform compression after prestress losses without any applied loads *to offset tensile stresses that occur during typical driving*.

⇧

Jacking force P_j is adjusted (trial and error) to satisfy this requirement

$$\boldsymbol{P_j = 32\ \mathrm{kip}}$$

$$f_{ce} = \frac{A_{f,total} \cdot f_{fe}}{h^2} = 1.02\ \mathrm{ksi}\quad \mathbf{OK} \qquad f_{pj} = 179\ \mathrm{ksi} < f_{pj.limit} = 0.70 f_{pu} = 259\ \mathrm{ksi}\quad \mathbf{OK}$$

DESIGN EXAMPLE: SQUARE PILE

Total Prestress Losses

Elastic shortening $\Delta f_{pES} = 6.707 \text{ ksi}$

Long-Term Losses $\Delta f_{pLT} = \left(\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1}\right)_{id} + \left(\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} - \Delta f_{pSS}\right)_{df} = 34.757 \text{ ksi}$

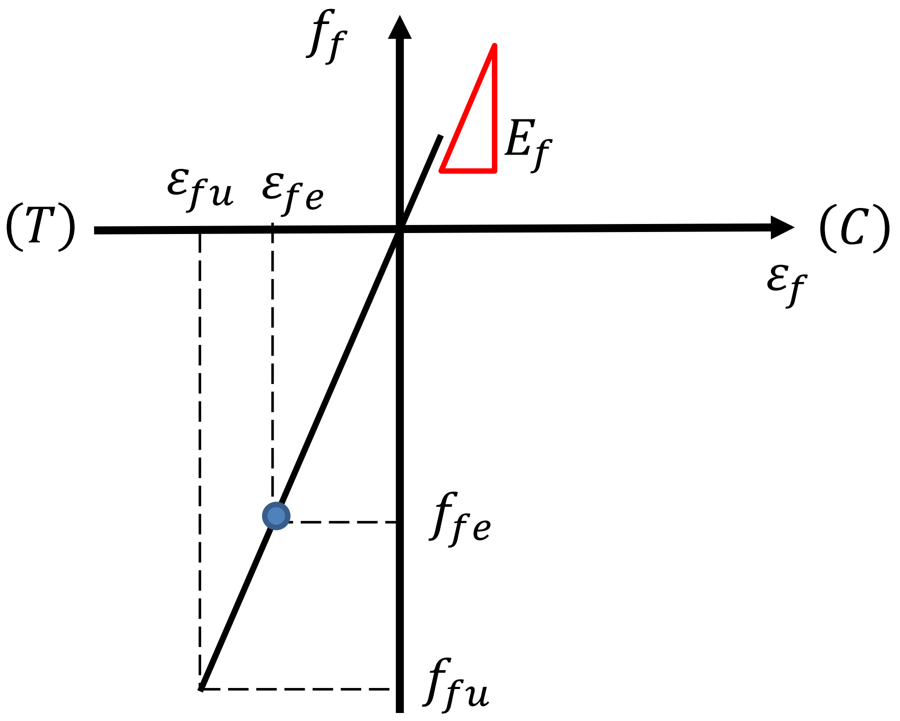
Loss due to temperature change (Assume 0 in this example) $\Delta f_{pTH} = 0$

Total prestress loss $\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pLT} + \Delta f_{pTH} = 41.463 \text{ ksi} \quad (23.2\%)$

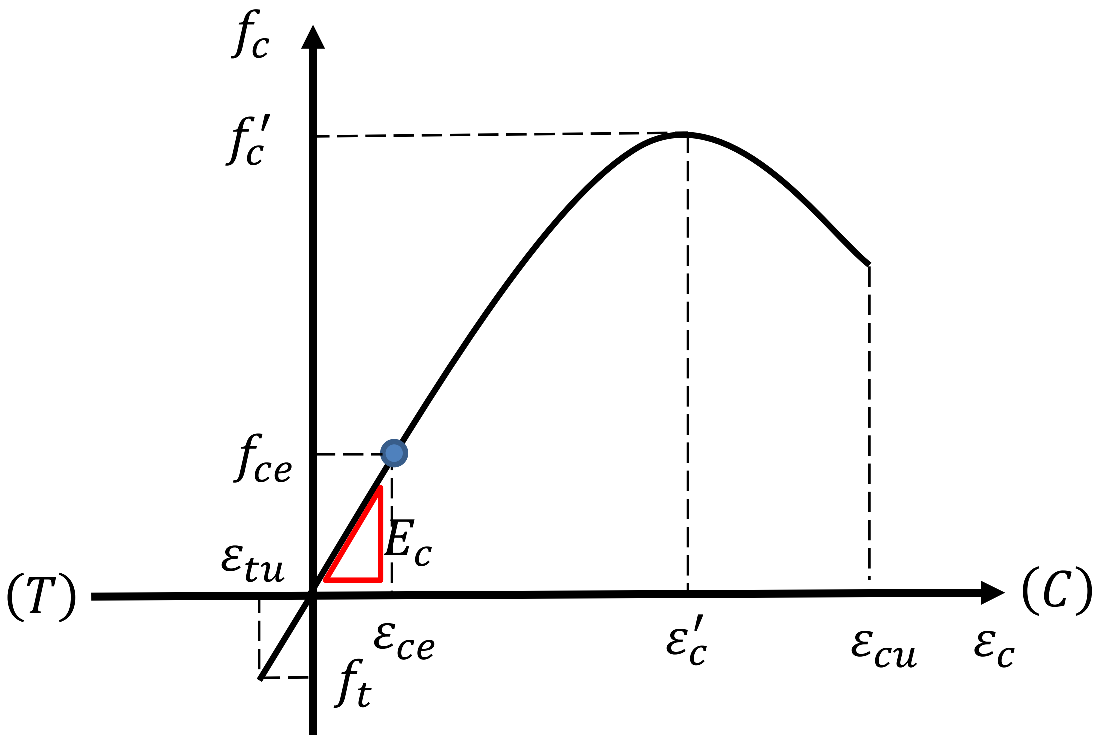
Effective prestress after all losses

$f_{pe} = 137 \text{ ksi} < f_{pe.limit} = 0.65 f_{pu} = 241 \text{ ksi} \quad \textbf{OK}$

DESIGN EXAMPLE: SQUARE PILE



CFRP



Concrete

DESIGN EXAMPLE: SQUARE PILE

Summary of Stresses

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

Jacking stress $f_{pi} = 179 \text{ ksi}$

Effective prestress at time of pile installation $f_{pei} = 154 \text{ ksi}$

Concrete stress (compression) at time of installation $f_{c,install} = 1.02 \text{ ksi}$

Final effective prestress in prestressing CFRP cables $f_{pe} = 137 \text{ ksi}$

Concrete stress (compression) at final time $f_{ce} = 0.913 \text{ ksi}$

DESIGN EXAMPLE: SQUARE PILE

Summary of Strains

Concrete crushing strain $\varepsilon_{cu} = 0.003$

CFRP strand rupture strain $\varepsilon_{pu} = 0.016$

Strain in prestressing strand at final time due to prestress force $\varepsilon_{pe} = 0.00611$

Strain in concrete at final time due to prestress force $\varepsilon_{ce} = 0.0002$

Remainder of strain in prestressing CFRP until rupture $\varepsilon_{p,rest} = 0.010$

Remainder of strain in concrete until crushing $\varepsilon_{c,rest} = 0.0028$

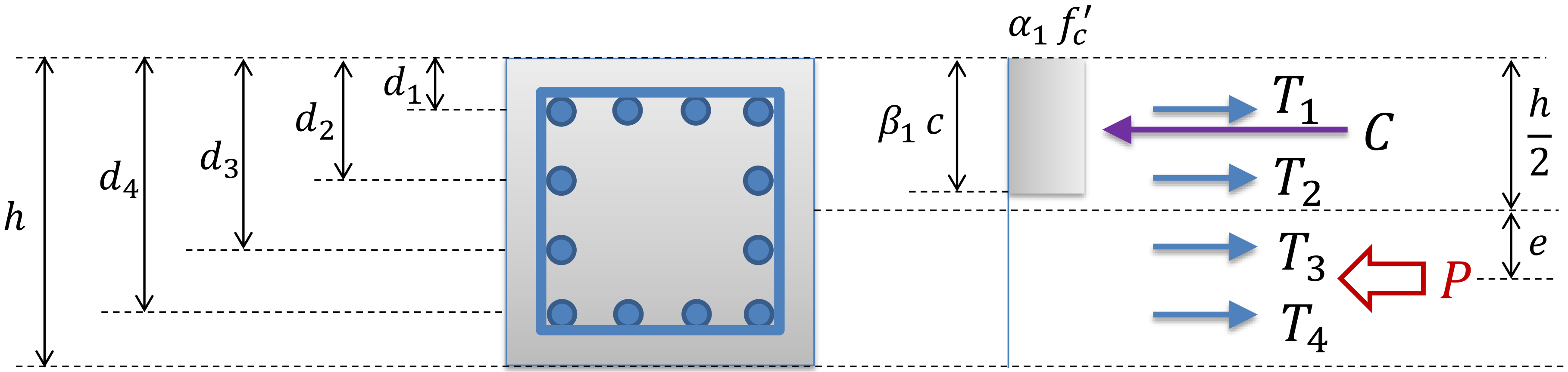
DESIGN EXAMPLE: SQUARE PILE

Square Pile: P-M diagram

$$C = (\alpha_1 f_c')(\beta_1 c)h$$

Assume a compression zone depth c

$$T_i = A_{fi} f_{fi} \qquad f_{fi} = E_f \varepsilon_{fi} \leq f_{fu}$$



$$Pe = M = C\left(\frac{h}{2} - \frac{\beta_1 c}{2}\right) - T_1\left(\frac{h}{2} - d_1\right) - T_2\left(\frac{h}{2} - d_2\right) + T_3\left(d_3 - \frac{h}{2}\right) + T_4\left(d_4 - \frac{h}{2}\right)$$

$\sum T_i = C + P$ → P, M —($\emptyset = 0.75$)→ $\emptyset P, \emptyset M$

DESIGN EXAMPLE: SQUARE PILE

Square Pile:
P-M diagram

Concrete Compression Depth

c

	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	...

$\cdot in$

Prestressing CFRP stress

f_{f1} f_{f2} f_{f3} f_{f4}

$f_f =$

	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	...

$\cdot ksi$

DESIGN EXAMPLE: SQUARE PILE

Square Pile: P-M diagram

aa = (·in)

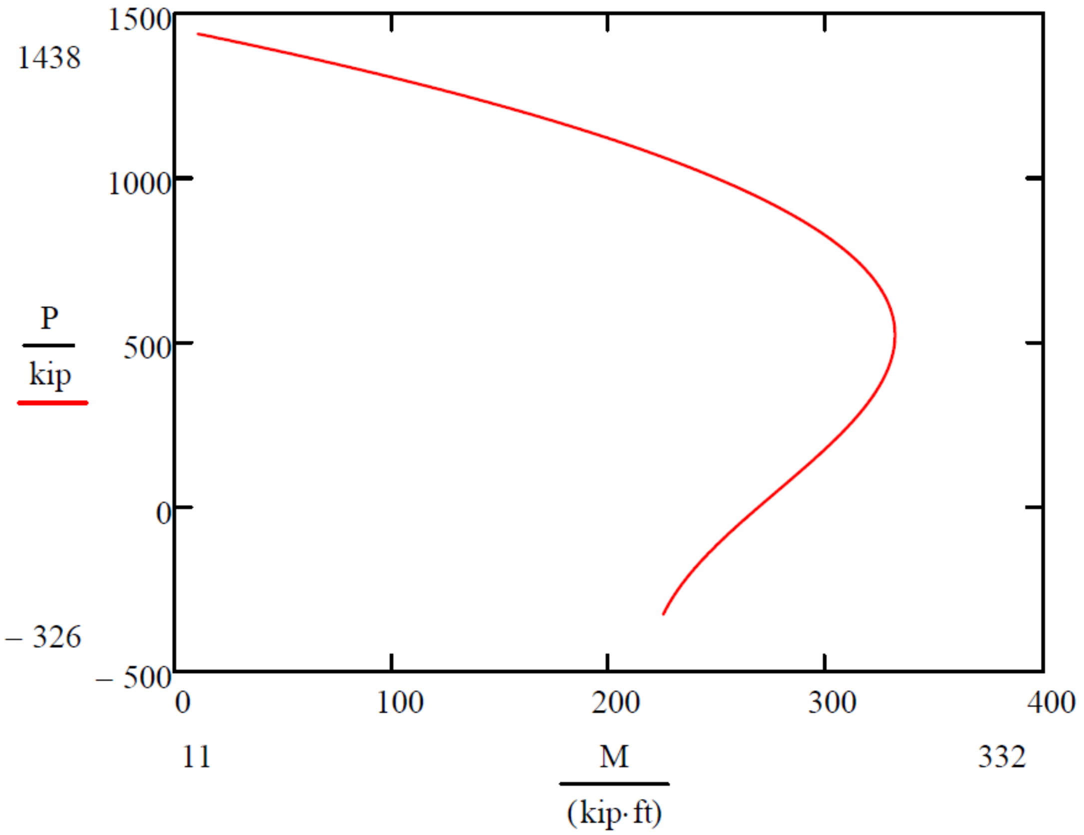
	0
0	2.482
1	2.49
2	2.498
3	2.505
4	2.513
5	2.52
6	2.527
7	2.535
8	2.542
9	2.55
10	2.558
11	2.565
12	2.572
13	2.58
14	2.588
15	...

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	...

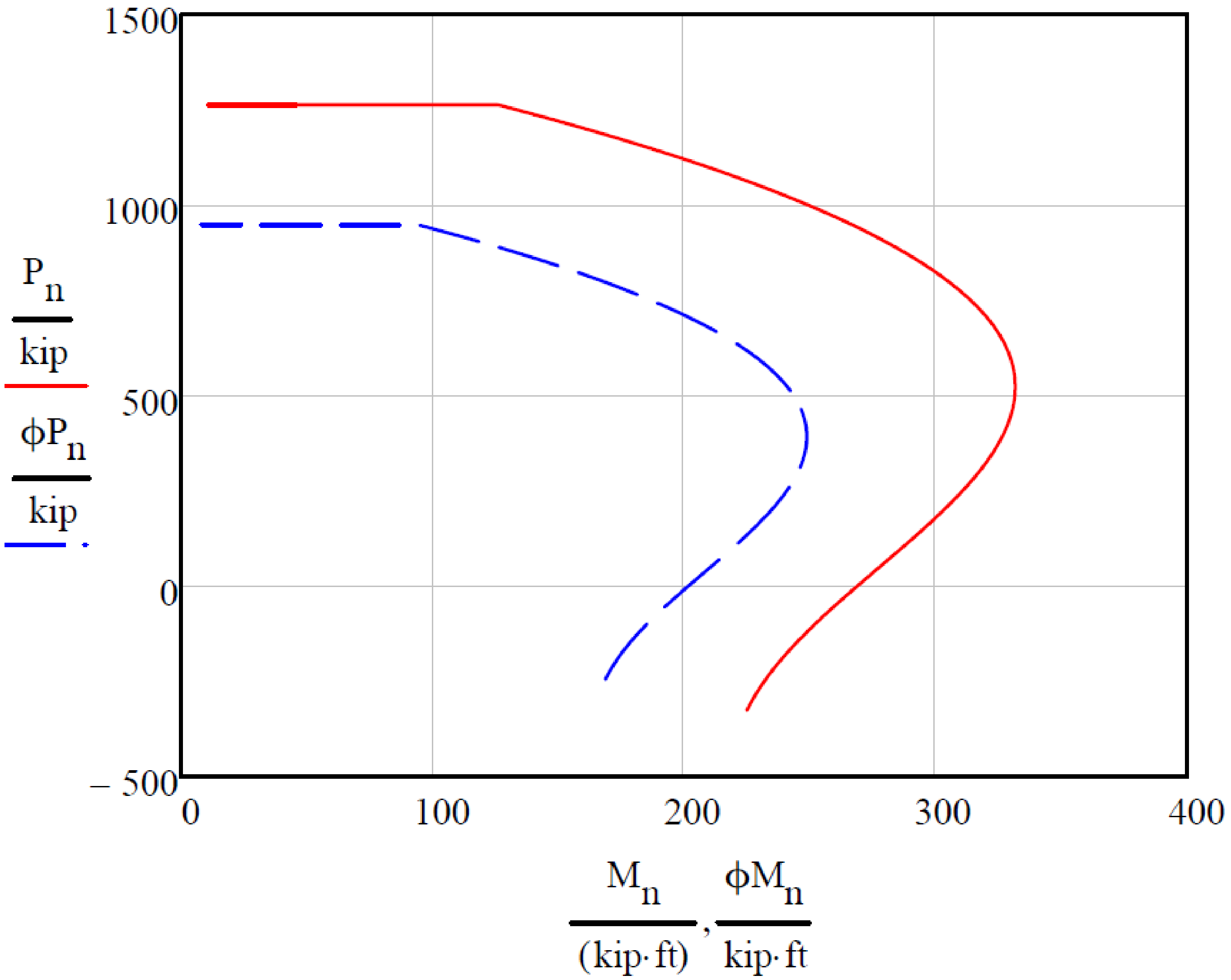


DESIGN EXAMPLE: SQUARE PILE

Square Pile:

P_n - M_n diagram

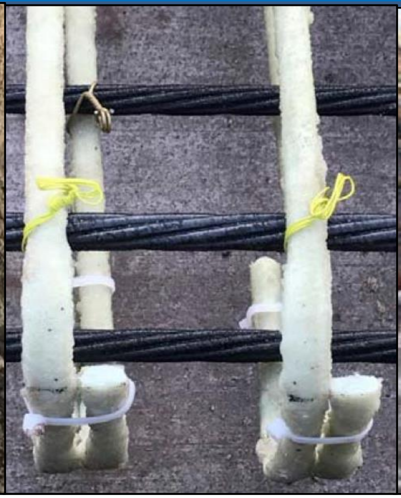
ΦP_n - ΦM_n diagram



5. PRESTRESSED PILES

5.3 Design Example: Sheet Pile - 12"x30"



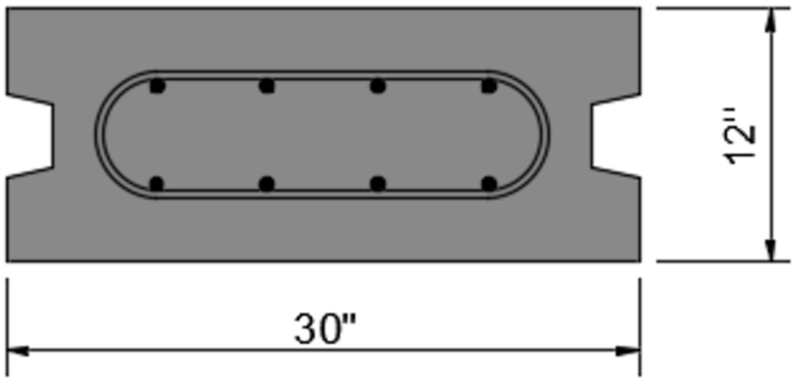


Florida Department of TRANSPORTATION

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

DESIGN EXAMPLE: SHEET PILE

Geometry



$b = 30$ in

$h = 12$ in

cover $= 3$ in

$A_g = 359$ in^2

$I_g = 4320$ in^4

Concrete

$f'_c = 6$ ksi

$f'_{ci} = 4$ ksi

$E_c = 4557$ ksi

$E_{ci} = 3987$ ksi

$\alpha_1 = 0.85$

$\beta_1 = 0.75$

CFRP strand

$D_p = 0.6$ in

$A_{pf} = 0.179$ in^2

$E_p = 22{,}480$ ksi

$f_{pu} = 370$ ksi

GFRP stirrup

$D_{GFRP} = 0.5$ in

DESIGN EXAMPLE: SHEET PILE

Assume jacking force $\boldsymbol{P_j = 0.70P_u = 46.34\ \mathrm{kip}}$

$$f_{pj} = 259\ \mathrm{ksi}$$

This requirement does NOT apply to Sheet Piles

FDOT ***Standard Plans Instructions (SPI)***, FY 2020-21
Index 455-101 Series Square CFRP & SS Prestressed Concrete Piles

- Standard piles are designed to have 1000 psi uniform compression after prestress losses without any applied loads *to offset tensile stresses that occur during typical driving*.

DESIGN EXAMPLE: SHEET PILE

Total Prestress Losses

Elastic shortening $\Delta f_{pES} = 5.825 \text{ ksi}$

Long-Term Losses $\Delta f_{pLT} = \left(\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1}\right)_{id} + \left(\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} - \Delta f_{pSS}\right)_{df} = 47.689 \text{ ksi}$

Loss due to temperature change (Assume 0 in this example) $\Delta f_{pTH} = 0$

Total prestress loss $\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pLT} + \Delta f_{pTH} = 53.514 \text{ ksi} \quad (20.7\%)$

Effective prestress after all losses

$f_{pe} = 205 \text{ ksi} < f_{pe.limit} = 0.65 f_{pu} = 241 \text{ ksi}$ **OK**

DESIGN EXAMPLE: SHEET PILE

Summary of Stresses

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

Jacking stress $f_{pi} = 259\ \text{ksi}$

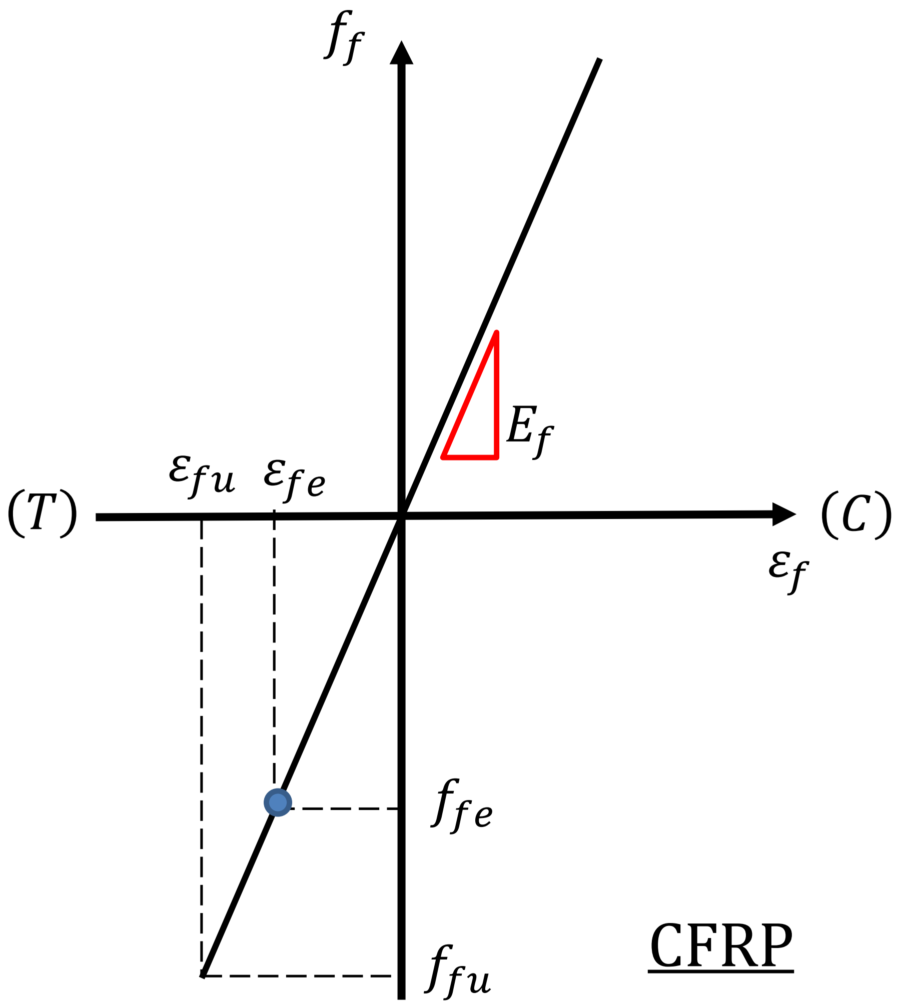
Effective prestress at time of pile installation $f_{pei} = 230\ \text{ksi}$

Concrete stress (compression) at time of installation $f_{c,install} = 0.918\ \text{ksi}$

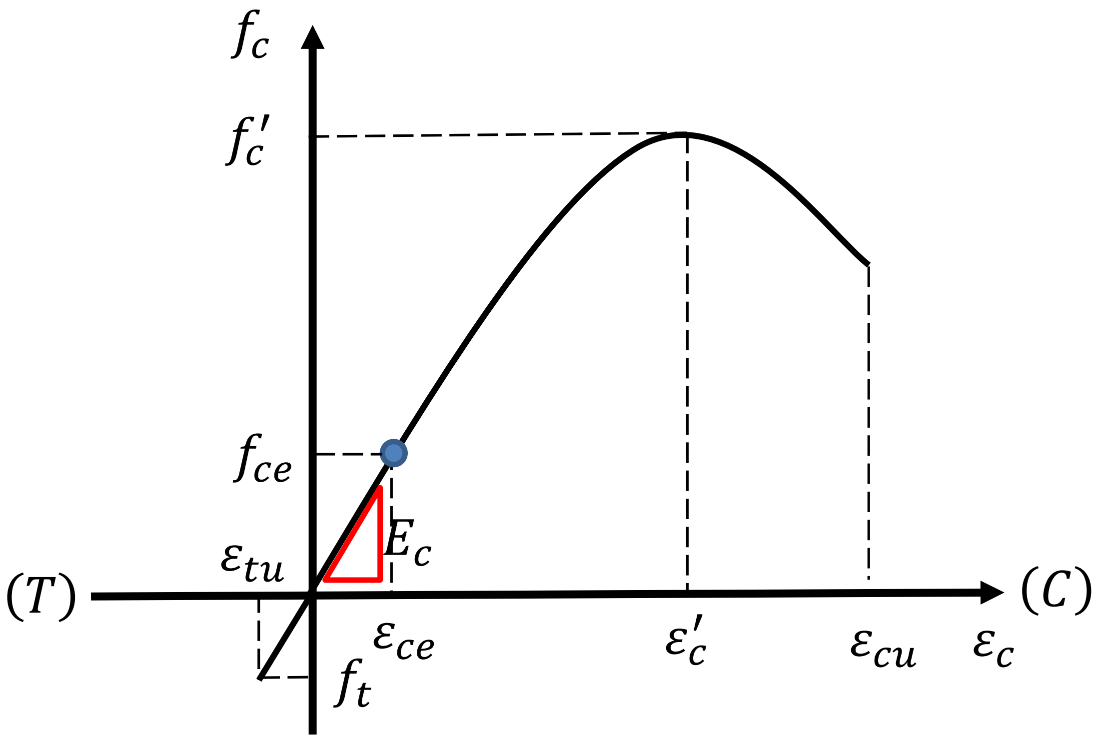
Final effective prestress in prestressing CFRP cables $f_{pe} = 205\ \text{ksi}$

Concrete stress (compression) at final time $f_{ce} = 0.819\ \text{ksi}$

DESIGN EXAMPLE: SHEET PILE



CFRP



Concrete

DESIGN EXAMPLE: SHEET PILE

Summary of Strains

Concrete crushing strain $\varepsilon_{cu} = 0.003$

CFRP strand rupture strain $\varepsilon_{pu} = 0.016$

Strain in prestressing strand at final time due to prestress force $\varepsilon_{pe} = 0.00914$

Strain in concrete at final time due to prestress force $\varepsilon_{ce} = 0.000180$

Remainder of strain in prestressing CFRP until rupture $\varepsilon_{p,rest} = 0.00732$

Remainder of strain in concrete until crushing $\varepsilon_{c,rest} = 0.00282$

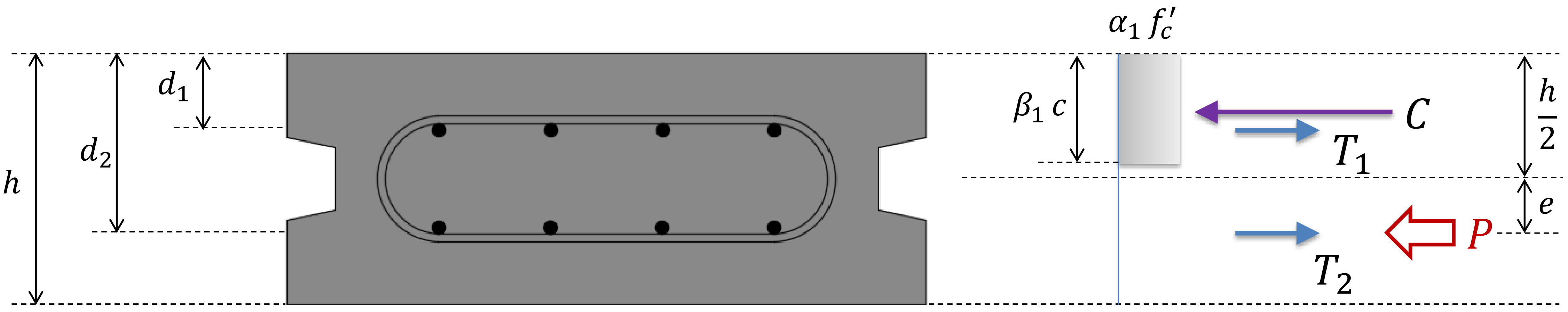
DESIGN EXAMPLE: SHEET PILE

Sheet Pile: P-M diagram

$$C = (\alpha_1 f_c')(\beta_1 c)h$$

Assume a compression zone depth c

$$T_i = A_{fi} f_{fi} \qquad f_{fi} = E_f \varepsilon_{fi} \le f_{fu}$$



$$Pe = M = C\left(\frac{h}{2} - \frac{\beta_1 c}{2}\right) - T_1\left(\frac{h}{2} - d_1\right) + T_2\left(\frac{h}{2} - d_2\right)$$

$$\sum T_i = C + P \longrightarrow P, M \xrightarrow{\emptyset = 0.75} \emptyset P, \emptyset M$$

DESIGN EXAMPLE: SHEET PILE

Sheet Pile:
P-M diagram

Compression zone depth c

Top row CFRP stress f_{f1}

Bottom row CFRP stress f_{f2}

$cc =$ (in)

	0
0	2.43
1	2.44
2	2.45
3	2.46
4	2.47
5	2.48
6	2.49
7	2.5
8	2.51
9	2.52
10	2.53
11	2.54
12	2.55
13	2.56
14	2.57
15	...

$f_f =$ (ksi)

	0	1
0	247	370
1	247	369
2	247	368
3	246	367
4	246	366
5	245	365
6	245	364
7	244	363
8	244	362
9	244	361
10	243	361
11	243	360
12	242	359
13	242	358
14	242	357
15	241	...

DESIGN EXAMPLE: SHEET PILE

Sheet Pile: P-M diagram

aa = (in)

	0
0	1.822
1	1.83
2	1.837
3	1.845
4	1.852
5	1.86
6	1.867
7	1.875
8	1.882
9	1.89
10	1.897
11	1.905
12	1.912
13	1.92
14	1.927
15	...

·in

P =

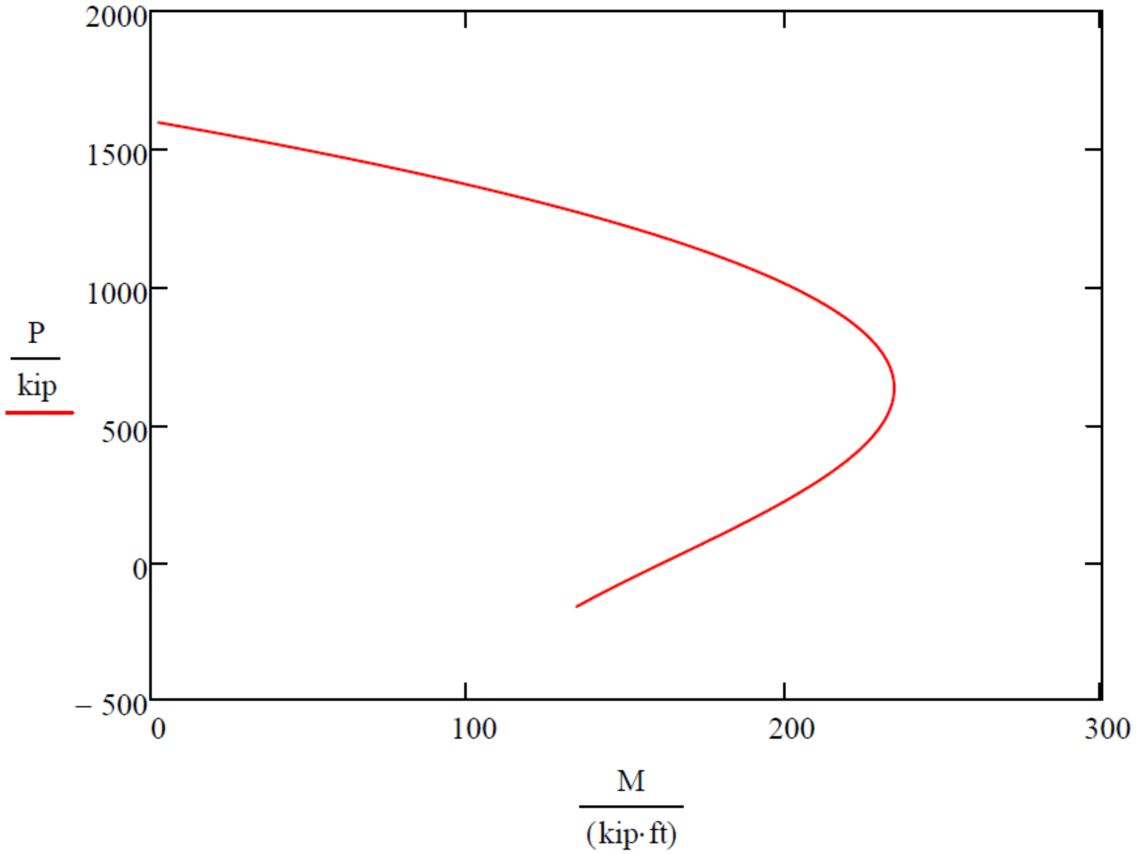
	0
0	-163
1	-161
2	-159
3	-157
4	-154
5	-152
6	-150
7	-148
8	-146
9	-144
10	-142
11	-140
12	-138
13	-136
14	-134
15	...

·kip

M =

	0
0	134
1	135
2	135
3	135
4	136
5	136
6	136
7	137
8	137
9	137
10	138
11	138
12	138
13	139
14	139
15	...

·kip·ft

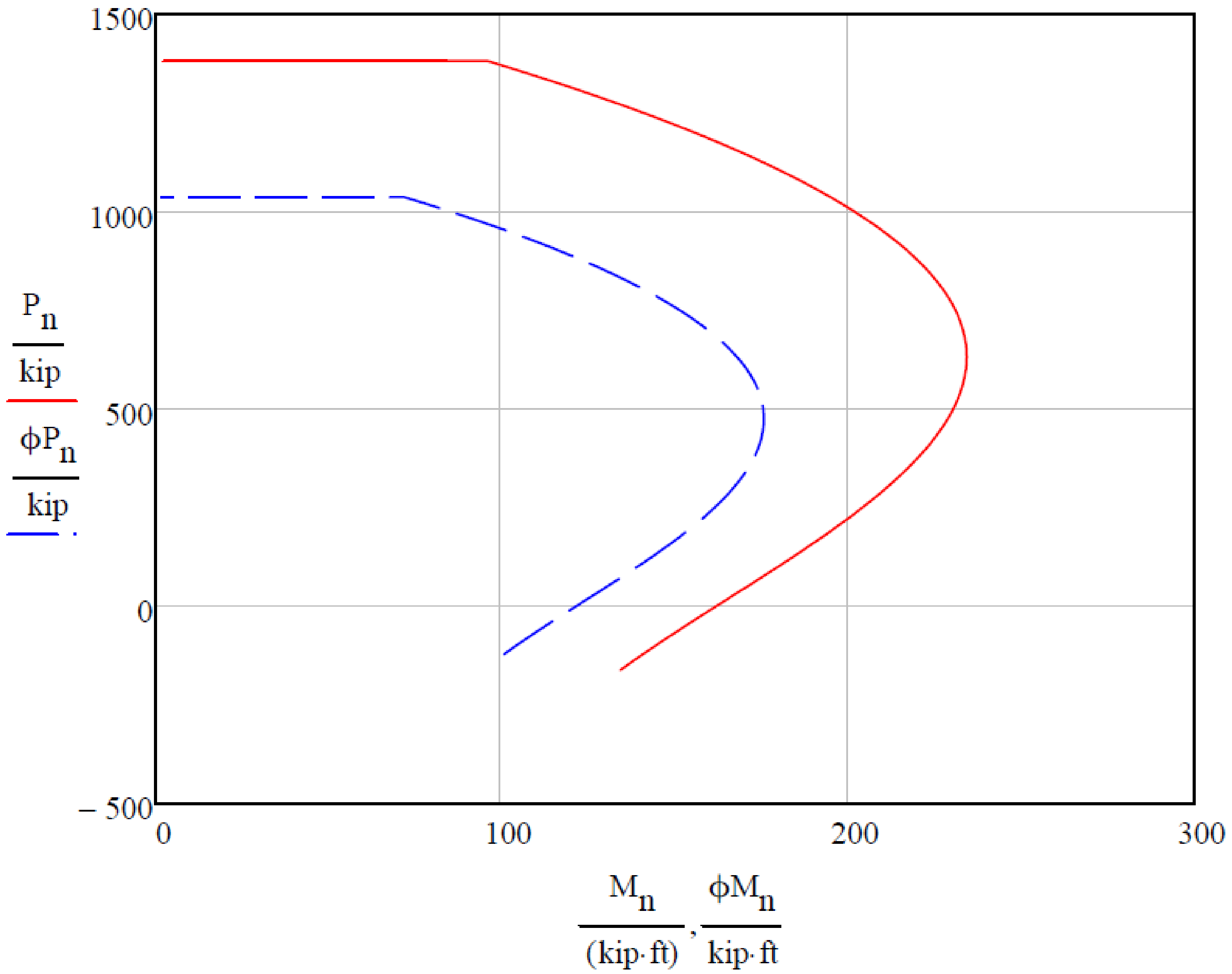


DESIGN EXAMPLE: SHEET PILE

Sheet Pile:

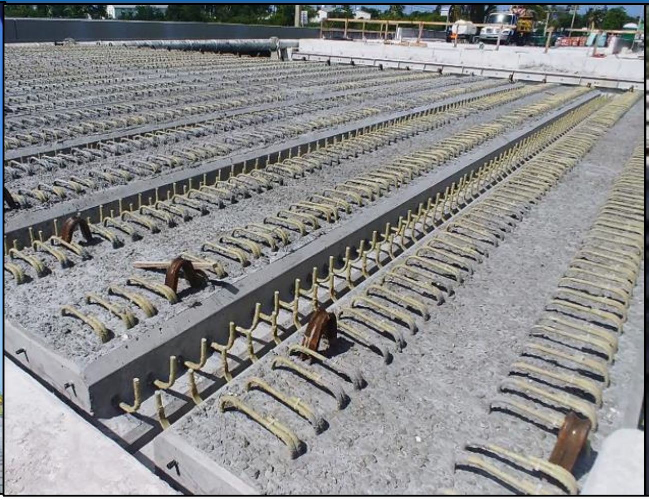
P_n - M_n diagram

ΦP_n - ΦM_n diagram



AASHTO CFRP-Prestressed Concrete Design Training Course






Florida Department of TRANSPORTATION

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