LRFD Design Example

P-M Diagram of GFRP Reinforced Pile

About this Example

Description

This section provides an example calculation of computing a GFRP reinforced P-M diagram in accordance with AASHTO GFRP 2nd Edition. The hypothetical example considers the FDOT Index 455 series with GFRP reinforcement as bars. Note: Consideration of pile driving stress limits are not covered in this example.

Page Contents

CALCULATIONS

P-M Diagram of GFRP Reinforced Pile

Design Specifications & References

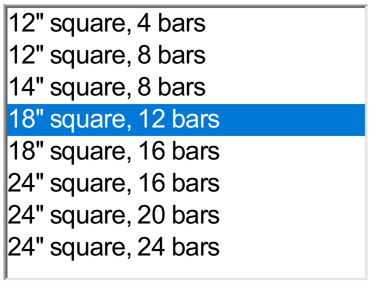
- [LRFD GFRP] AASHTO LRFD Bridge Design Guide Specification for GFRP-Reinforced Concrete, 2nd Edition 2018
- [SDM] FDOT Structure Design Manual, January 2020
- [FDOT] FDOT Standard Specifications, January 2020

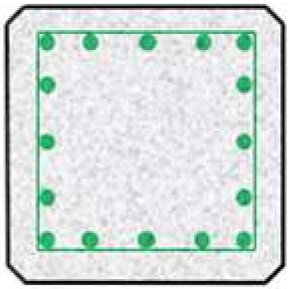
A. General Criteria

A1. GFRP Pile Properties

Geometric Properties

Pile Type

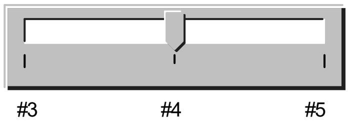

12" square, 4 bars
12" square, 8 bars
14" square, 8 bars
18" square, 12 bars
18" square, 16 bars
24" square, 16 bars
24" square, 20 bars
24" square, 24 bars



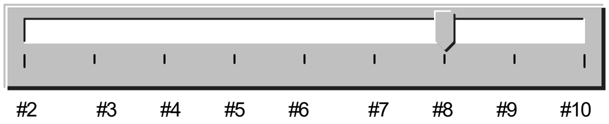
Generic Pile Cross Section

Reinforcing Properties

$Stirrup_{Size}$ Size of GFRP stirrups



$BarSize_A$ Size of Prestressed GFRP Reinforcement



Concrete Cover

$Cover_{pile}$ pile concrete cover *(2" for GFRP)* 2 in

A.2 Material Properties

Concrete Properties

$f'_{c.pile}$ concrete compressive strength of pile 5.0 ksi

γ_{conc} unit weight of reinforced concrete 145 pcf

Reinforcing Properties

Select default based upon generation type or input custom values

[✓ 1st Generation]
2nd Generation
Custom

E_f	tensile modulus of elasticity of GFRP reinforcing	6500	ksi
C_E	environmental reduction factor for GFRP reinforcing	0.7	
C_b	bond reduction factor for GFRP reinforcing	0.83	
C_c	creep rupture reduction factor of GFRP reinforcing	0.3	

▸ Intialize Data

▸ Reinforcing Bar Properties

▸ Intialize Reinforcing Data

▸ GFRP Pile Properties

B. GFRP Pile M-N Diagram

$\text{ORIGIN} := 1$

B.1 Geometric Calculations

12" Pile, 4 bars

12" Pile, 8 bars

14" Pile, 8 bars

18" Pile, 12 bars

18" Pile. 16 bars

24" Pile, 16 bars

24" Pile, 20 bars

24" Pile, 24 bars

$$\text{num}_s := \begin{pmatrix} 4 \\ 8 \\ 8 \\ 12 \\ 16 \\ 16 \\ 20 \\ 20 \end{pmatrix}$$

number of bars in each pile size

$D_{bar} := d\left(\text{BarSize}_A\right) = 1 \cdot \text{in}$ — diameter of bar

$n_{bar} := \text{num}_{s_{P_{type}}} = 12$ — total number of bars

$A_{bar} := A\left(\text{BarSize}_A\right) = 0.79 \cdot \text{in}^2$ — area of reinforcing bar

$A_{bar.total} := n_{bar} \cdot A\left(\text{BarSize}_A\right) = 9.5 \cdot \text{in}^2$ — total area of bars

B.2 Clear Distance Check

$\text{Clr}_{req} := 1.33 \cdot 1\text{in} = 1.33 \cdot \text{in}$

minimum clear spacing assuming 1" aggregate size (AASHTO GFRP is an addendum to AASHTO BDS, use LRFD 5.9.4.1)

$$n_{s.bar} := \frac{\text{num}_{s_{P_{type}}}}{4} = 3$$

number of bar spaces on one face of pile

$$\text{Clr} := \frac{\text{Pile}_{size} - 2 \cdot \text{Cover} - 2 \cdot D_{stir} - D_{bar}}{n_{s.bar}} = 4 \cdot \text{in}$$

clear spacing between bars

$\boxed{\text{Check}_{clr} := \text{if}\left(\text{Clr} \geq \text{Clr}_{req}, \text{"OK"}, \text{"NG"}\right) = \text{"OK"}}$

B.3 Bar Force Calculation

$$\alpha_1 := \mathrm{if}\left[f'_{c.pile} \le 10\mathrm{ksi}, 0.85, \max\left[0.75, 0.85 - 0.02\cdot\left(\frac{f'_{c.pile}}{\mathrm{ksi}} - 10\right)\right]\right] = 0.85$$

stress block factor (LRFD 5.6.2.2)

$$\beta_1 := \mathrm{if}\left[f'_{c.pile} \le 4\mathrm{ksi}, 0.85, \max\left[0.85 - 0.05\cdot\left(\frac{f'_{c.pile}}{\mathrm{ksi}} - 4\right), 0.65\right]\right] = 0.8$$

stress block factor (LRFD 5.6.2.2)

$$\varepsilon_c := 0.003$$

failure strain of concrete (LRFD 5.6.2.1)

$$d_s := ht - Cover - \frac{D_{bar}}{2} - D_{stir} = 15\cdot in$$

distance from extreme compression fiber to centroid of GFRP bar in tension zones

$$d'_s := ht - d_s = 3\cdot in$$

distance from extreme compression fiber to centroid of GFRP bar in compression zones

```
n_cs :=  | for  $j \in 1 .. ns \leftarrow n_{bar}\cdot$ | $\left(\frac{1}{4} + \frac{1}{n_{bar}}\right)$  if  $P_{type} \le 7$
         |                                            | $\frac{2}{n_{bar}}$  if  $P_{type} \ge 8$
         |     | $n_s \leftarrow$ | ns  if  $P_{type} \le 7$
         |     |                  | $\frac{n_{bar}}{2}$  if  $P_{type} \ge 8$
         |     | $n_j \leftarrow 2$
         |     | $n_1 \leftarrow n_s$
         |     | $n_{ns} \leftarrow n_s$
         | n
```

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

number of bars in each row of the cross section

```
$d_{ps} :=$ for $j \in 1..lr \leftarrow rows(n_{cs})$
    $d_j \leftarrow Cover + D_{stir} + \frac{1}{2}D_{bar}$
    $d_j \leftarrow d_{j-1} + \frac{ht - 2\cdot Cover - 2\cdot D_{stir} - D_{bar}}{rows(n_{cs}) - 1}$  if $j \neq 1$
  $d$
```

$$= \begin{pmatrix} 3 \\ 7 \\ 11 \\ 15 \end{pmatrix} \cdot in$$

distance from extreme compression fiber to the centroid reinforcement measured

$$range := 1 .. 4\cdot\frac{ht}{in\cdot\beta_1}$$

range variable to accommodate an increasing increment of 0.25" for the value 'c'

```
$c :=$ $c_1 \leftarrow \frac{ht}{\beta_1}$
  for $j \in 1..\left(4\cdot\frac{ht}{in\cdot\beta_1} - 1\right)$
    $c_{j+1} \leftarrow c_j - 0.25in$
  $c$
```

distance from top of section to neutral axis

Based upon future provisions in the ACI and AASHTO documents, it is recommended that the compressive strain in GFRP reinforcement be limited to 0.3% and the tensile strain to a maximum of 1%.

```
$T_s :=$ for $j \in range$
  for $z \in 1..rows(n_{cs})$
    $T_z \leftarrow n_{cs_z}\cdot A_{bar}\cdot E_f\left[\min\left[1\%, \max\left[-0.3\%, -\frac{(c_j - d_{ps_z})}{c_j}\cdot\varepsilon_c\right]\right]\right]$  if $c_j \geq d_{ps_z}$
    $T_z \leftarrow \min\left[n_{cs_z}\cdot A_{bar}\cdot E_f\cdot\varepsilon_{fd}, n_{cs_z}\cdot A_{bar}\cdot E_f\cdot\left[\min\left[1\%, \max\left[-0.3\%, \frac{(d_{ps_z} - c_j)}{c_j}\cdot\varepsilon_c\right]\right]\right]\right]$  if $c_j < d_{ps_z}$
    $T_{s_{j,z}} \leftarrow T_z$
  $T_s$
```

bar force in each row with varying compression zone 'c'

Note: The above formula does not consider the compressive strains (negative in this program) to be equal to at least the elastic modulus of concrete or zero per AASHTO GFRP 2nd Edition.

B.4 Compression Force Calculation

$$a_{range} := \text{if}\left(\beta_1 \cdot c_{range} \le Cover\,,\, 0in\,,\, \text{if}\left(\beta_1 \cdot c_{range} \ge ht\,,\, ht\,,\, \beta_1 \cdot c_{range}\right)\right)$$

depth of compression zone, zeroed if within zone of no confinement. Can be left as just $\beta_1 c$

$$C_{pile} := (b \cdot a) \cdot \alpha_1 \cdot f'_{c.pile}$$

compression capacity of pile section with varying compression zone 'c'

$$y_{range} := \frac{a_{range}}{2}$$

distance from bottom of the compression zone to the centroid of the net pile section

B.5 Interaction Diagram

$$\varepsilon_t := \varepsilon_c \cdot \frac{\left(d_{ps_{rows(n_{cs})}} - c\right)}{c}$$

tensile strain in the extreme tensile bar

$$\phi GFRP_{range} := \begin{vmatrix} 0.75 & \text{if} \quad \varepsilon_{t_{range}} \le 0.80 \cdot \varepsilon_{fd} \\ \left(1.55 - \dfrac{\varepsilon_{t_{range}}}{\varepsilon_{fd}}\right) & \text{if} \quad 0.80 \cdot \varepsilon_{fd} < \varepsilon_{t_{range}} < \varepsilon_{fd} \\ 0.55 & \text{otherwise} \end{vmatrix}$$

resistance factor for flexural strength GFRP (LRFD GFRP 2.6.3)

$$k_c := \alpha_1 = 0.85$$

ratio of maximum concrete compressive stress to the design compressive strength of concrete (LRFD 5.6.4.4)

$$P_{max} := 0.8 \cdot \left(k_c f'_{c.pile} A_{pile}\right) = 1097.8 \cdot kip$$

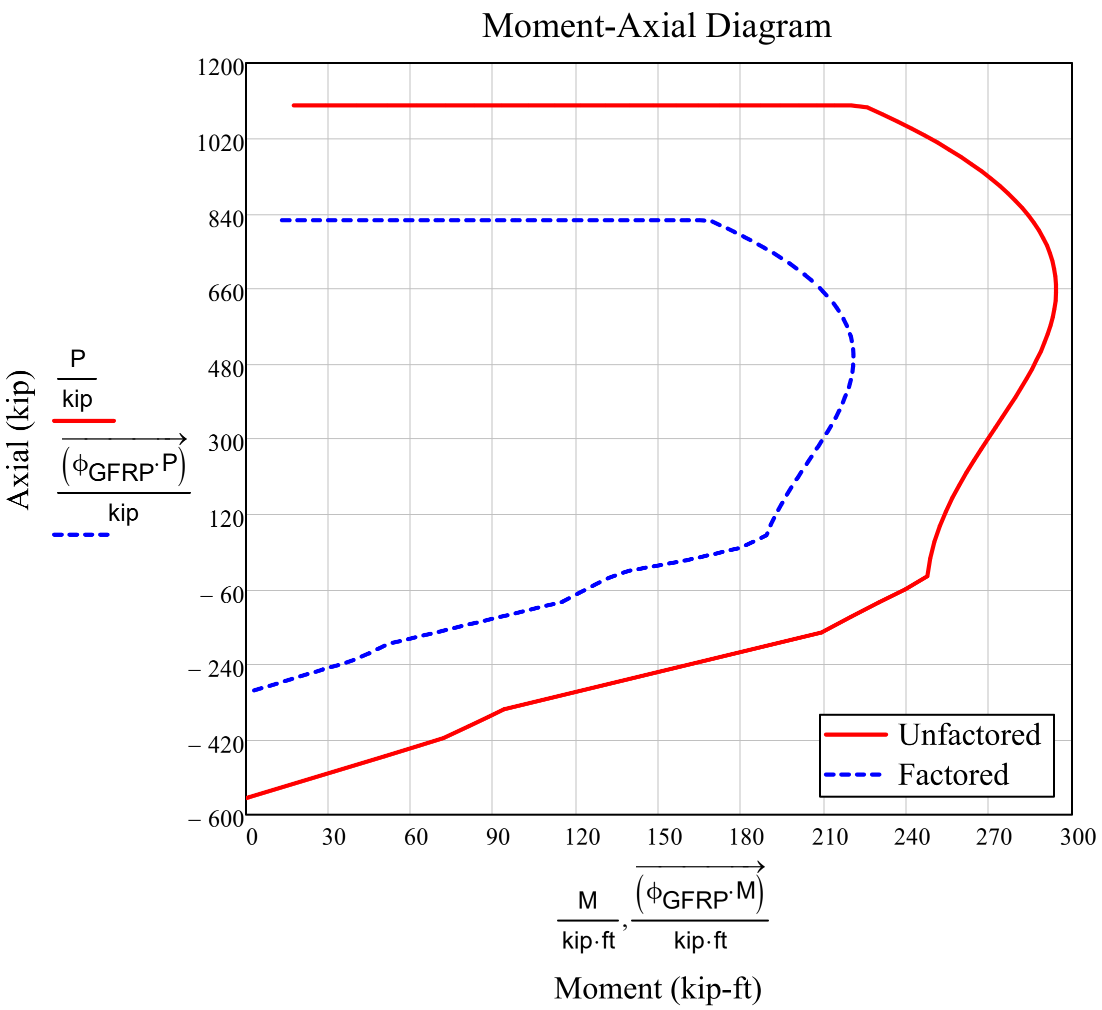
nominal axial resistance, with or without flexure (LRFD 5.6.4.4-2)
*modified for GFRP-RC
0.85 = spiral or hoop reinforcement
0.80 = tie reinforcement

$$P := \begin{vmatrix} \text{for} \quad j \in range \\ \quad P_j \leftarrow \min\left(P_{max}\,,\, C_{pile_j} - \sum_{z=1}^{rows(n_{cs})} T_{s_{j,z}}\right) \\ P \end{vmatrix}$$

axial compression force on pile section

$$M := \begin{vmatrix} \text{for} \quad j \in range \\ \quad M_j \leftarrow C_{pile_j}\left(\frac{ht}{2} - y_j\right) + \sum_{z=1}^{rows(n_{cs})} \left[T_{s_{j,z}} \cdot \left(d_{ps_z} - \frac{ht}{2}\right)\right] \\ M \end{vmatrix}$$

moment on pile section


Moment-Axial Diagram
1200
1020
840
660
480
300
120
– 60
– 240
– 420
– 600
Axial (kip)
P / kip
(ϕGFRP·P) / kip
0
30
60
90
120
150
180
210
240
270
300
M / kip·ft , (ϕGFRP·M) / kip·ft
Moment (kip-ft)
Unfactored
Factored