AASHTO GFRP-Reinforced Concrete Design Training Course

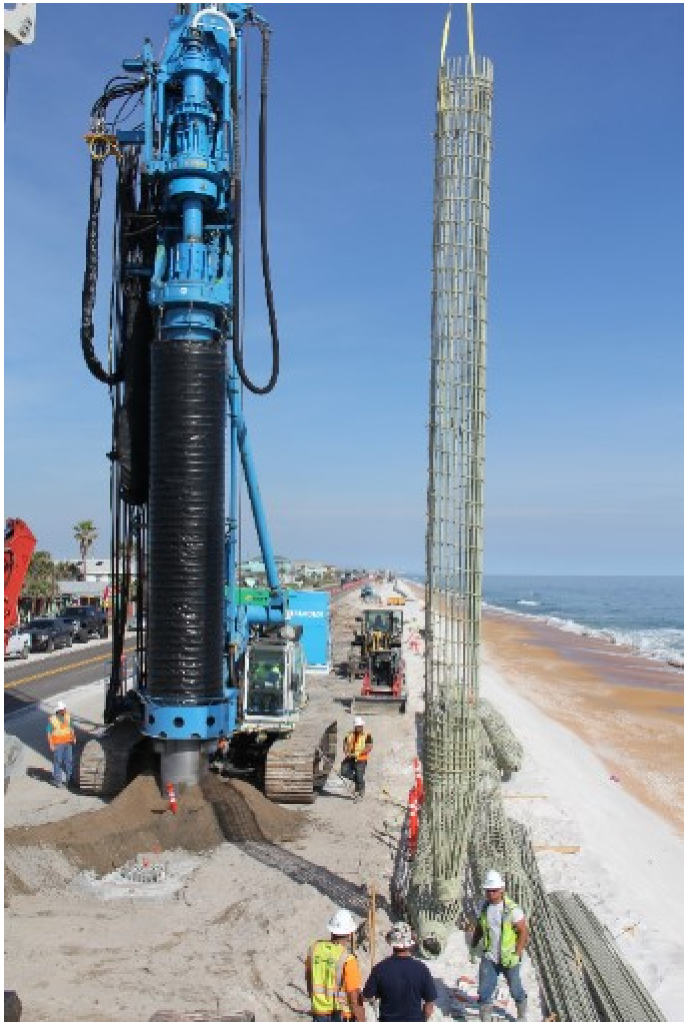
FDOT

UNIVERSITY OF MIAMI

Center for Integration of Composites into Infrastructure

Course Outline

1. Introduction & Materials
2. Flexure Response
3. Shear Response
4. **Axial Response**
5. Case Studies & Field Operations



4. AXIAL RESPONSE OF GFRP REINFORCED CONCRETE

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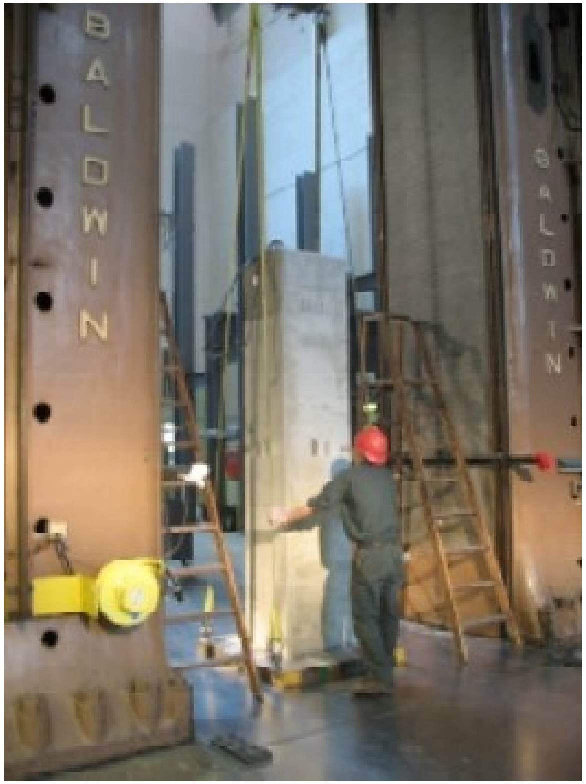
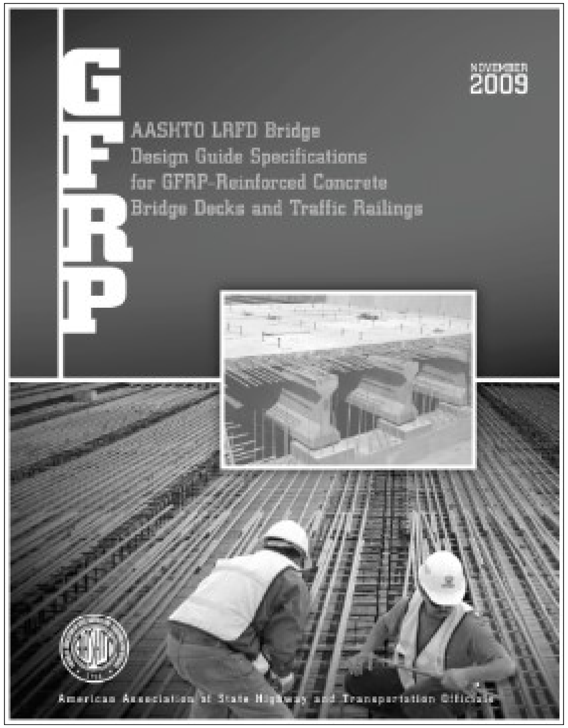
Table of Contents – Axial & More

- **Strength of GFRP-RC Columns**
- Design Considerations
- P-M Diagram Example
- Slenderness Effect
- Concluding Remarks



Design Codes


GFRP

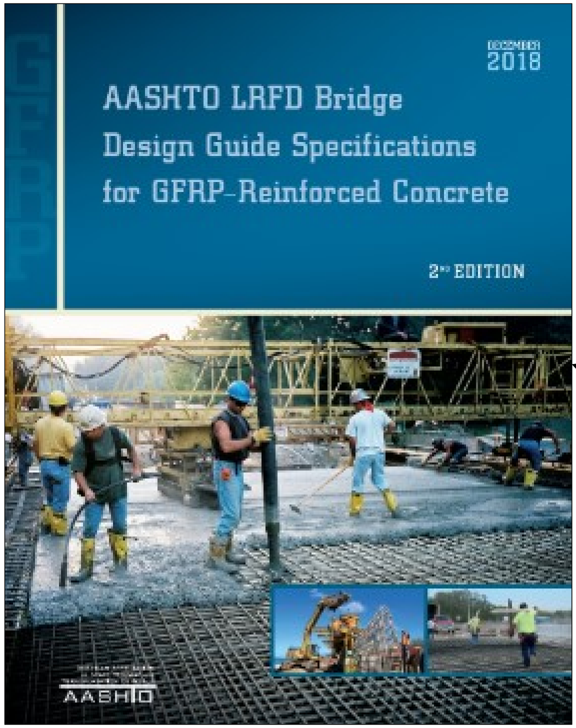
NOVEMBER
2009

AASHTO LRFD Bridge
Design Guide Specifications
for GFRP-Reinforced Concrete
Bridge Decks and Traffic Railings

American Association of State Highway and Transportation Officials

AASHTO GFRP 1st Ed.

(No provisions included)


DECEMBER
2018

AASHTO LRFD Bridge
Design Guide Specifications
for GFRP-Reinforced Concrete

2nd EDITION

AASHTO

AASHTO GFRP 2nd Ed.

(Provisions included)

Only US guide/code including compression members

Introduction – Pure Compression

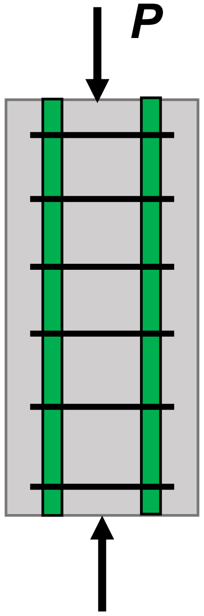
Review of Steel-RC Columns

$$P_o = P_c + P_s = 0.85 f_c' \left(A_g - A_s\right) + f_y A_s$$

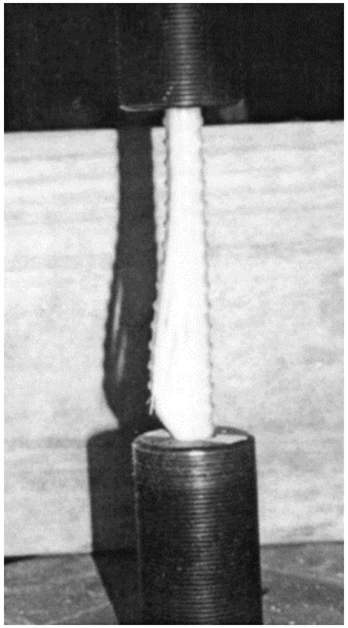
Basic Concept for GFRP-RC Columns

$$P_o = P_c + P_f = 0.85 f_c' \left(A_g - A_f\right) + \cancel{f_f A_f}$$

(**AASHTO GFRP 2.6.4.2**)



As reported in Afifi et al. (2014) and Mohamed et al., (2014), mechanical properties of GFRP in compression exceed those of concrete and therefore, equivalency could be assumed

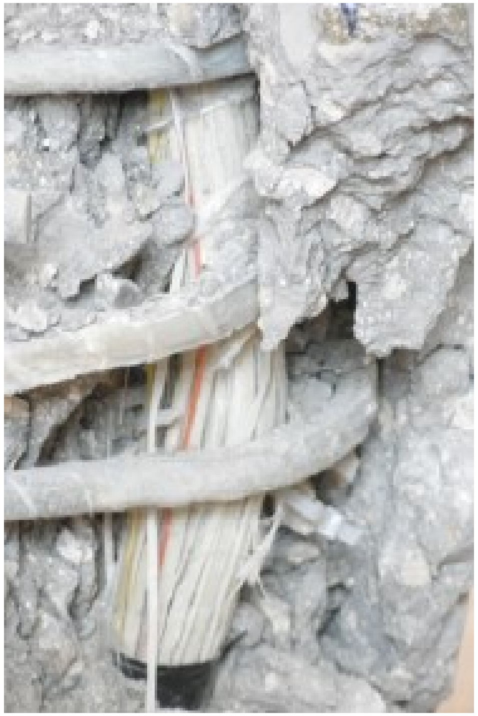


GFRP bar loaded in compression (Deitz, Harik, and Gesund, 2003)

Axial Loading Failure Modes

Column test at NIST

12-in Tie Spacing



3-in Tie Spacing

Behavior of Full-Scale Concrete Columns Internally Reinforced with Glass FRP Bars under Pure Axial Load (De Luca, et al., 2009)

Axial Loading Failure Modes

GFRP-RC Columns After Failure

Circular Concrete Columns with GFRP Longitudinal Bars, Hoops, or Spirals under Axial Loads (University of Sherbrooke; courtesy of Prof. Brahim Benmokrane)

Factored Compressive Resistance - AASHTO

Factored Pure Compressive Resistance - AASHTO

$$P_r = \phi P_n$$

(AASHTO GFRP 2.6.4.2-1)

- For members with spiral or hoop reinforcements

$$P_n = 0.85\left[0.85 f_c'\left(A_g - A_f\right)\right]$$

(AASHTO GFRP 2.6.4.2-2)

- For members with tie reinforcement

$$P_n = 0.80\left[0.85 f_c'\left(A_g - A_f\right)\right]$$

(AASHTO GFRP 2.6.4.2-3)

A_f = area of GFRP reinforcement (in^2)
A_g = gross area of section (in^2)
f'_c = specified compressive (ksi)
P_n = nominal axial resistance, without flexure (kips)
P_r = factored axial resistance, without flexure (kips)

Factored Tensile Resistance - AASHTO

Factored Pure Tensile Resistance - AASHTO

$$P_r = \phi P_n$$ **(AASHTO GFRP 2.6.6.2-1)**

in which:

$$P_n = f_{fd} A_f$$ **(AASHTO GFRP 2.6.6.2-2)**

$$f_{fd} = C_E f_{fu}$$ **(AASHTO GFRP 2.4.2.1-1)**

where:

A_f = area of GFRP reinforcement (in^2)

f_{fd} = design tensile strength of GFRP reinforcing bars considering reductions for service environment (ksi)

P_n = nominal axial resistance (kip)

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Table of Contents

Design Considerations

Minimum & Maximum Longitudinal Reinforcement

Minimum and maximum area of the longitudinal GFRP reinforcing shall be:

$$\boxed{0.01 \leq A_f / A_g \leq 0.08}$$

AASHTO GFRP 4.5.6

Provision adopted for GFRP-RC are analogous to Steel-RC design provisions in AASHTO & ACI

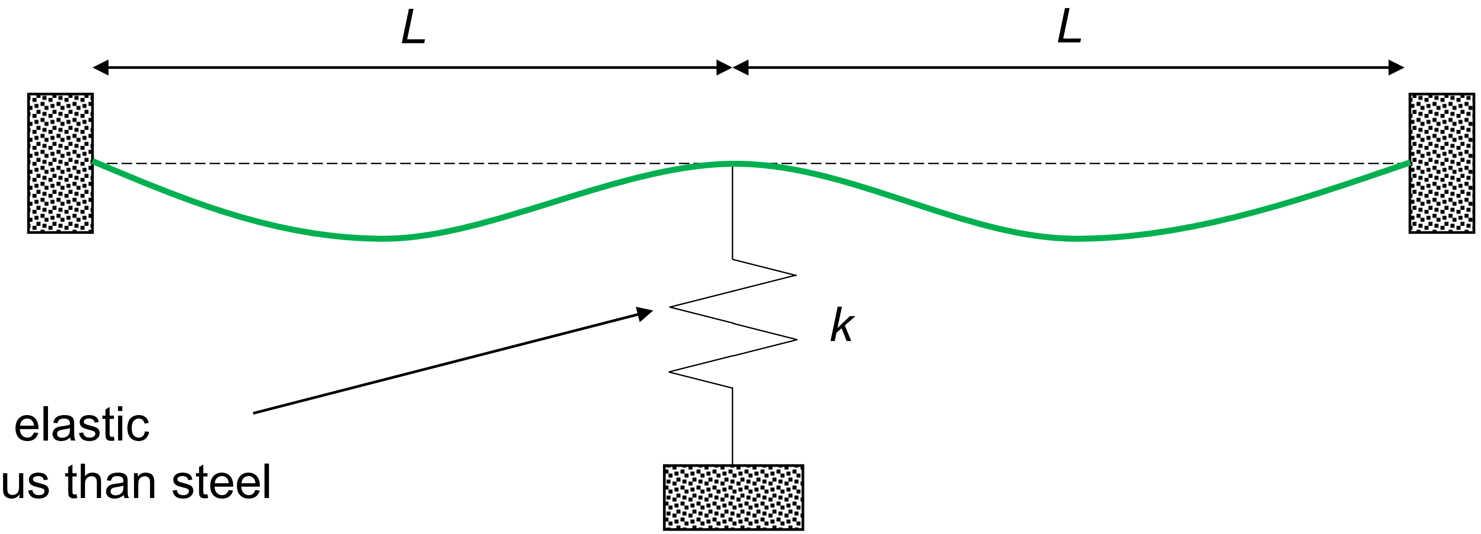
Limit on Maximum Tensile Strain in GFRP

To avoid strains that lead to unacceptable deformation and loss of stiffness of the column (Jawaheri & Nanni, 2013):

$\varepsilon_{fd} = \min(\varepsilon_{fu}, 0.010)$ and $f_{fd} = \min(f_{fu}, 0.010E_f)$

Design Considerations

Limits on maximum spacing of Transverse Reinforcement: confinement, buckling of longitudinal reinforcement



Lower elastic modulus than steel

Theoretical:

$$\boxed{s_{max} \approx 14d_b}$$

AASHTO GFRP 4.7.5.4 – Tied Members

$$\boxed{s_{max} = min\begin{cases} least\ dimension\ of\ column \\ d/4 \\ 12\ inches \end{cases}}$$

Table of Contents

- Strength of GFRP-RC Columns
- Design Considerations
- **P-M Diagram Example**
- Slenderness Effect
- Concluding Remarks

Context

GFRP Cage Assembly, Casting and Installation of RC Piles

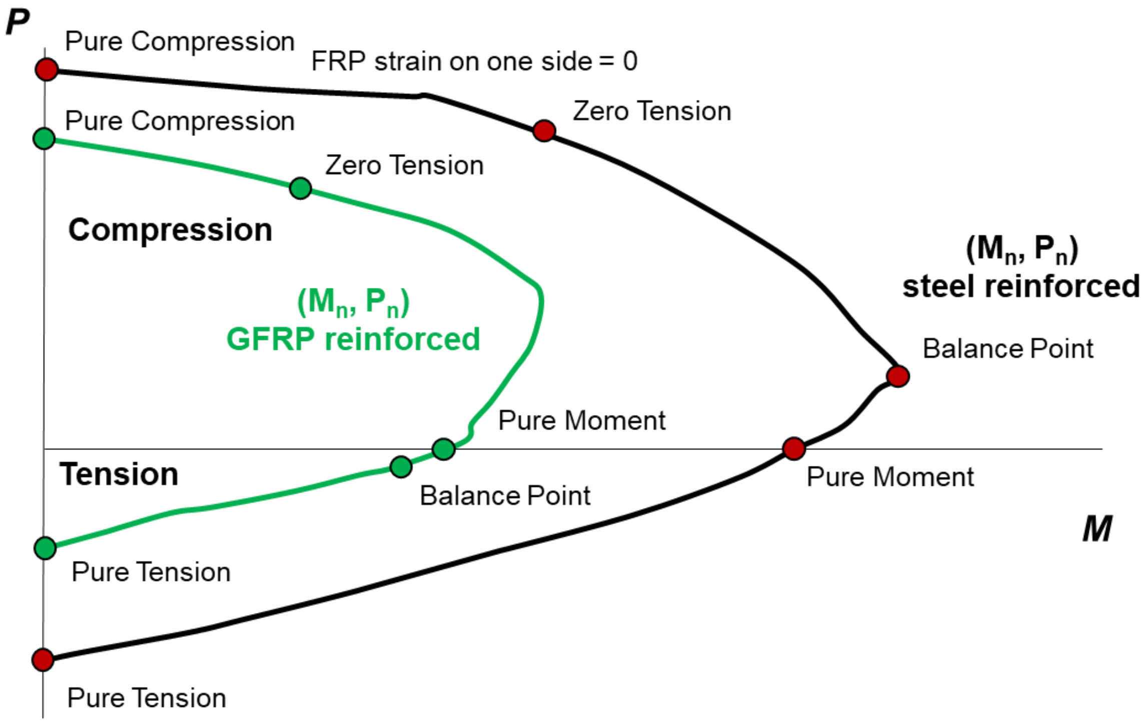
Combined P-M Failure Modes

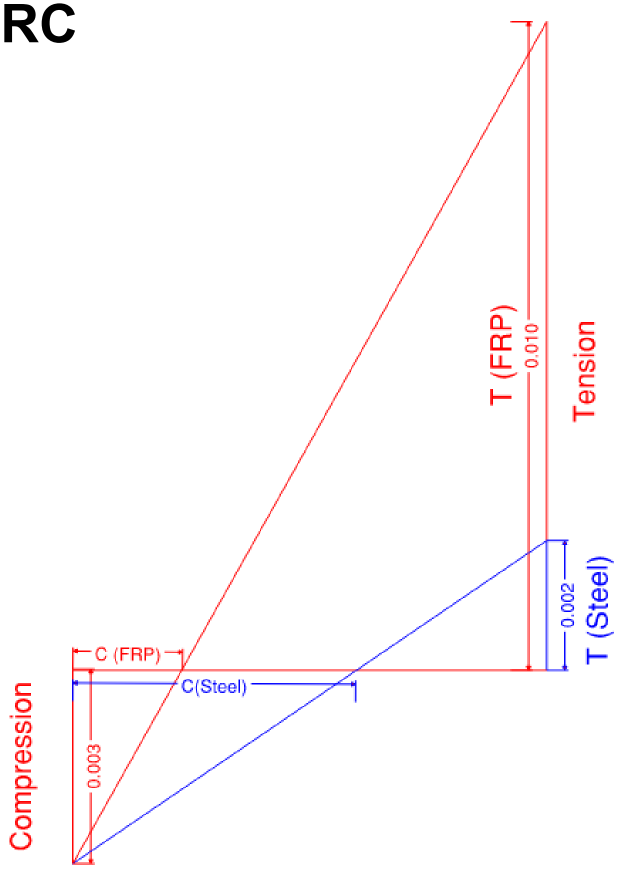
Rectangular Concrete Column Failure with GFRP Bars and Ties (Guérin et al., 2018)

Compression Side Side View Tension Side

Developing P-M Interaction Diagram

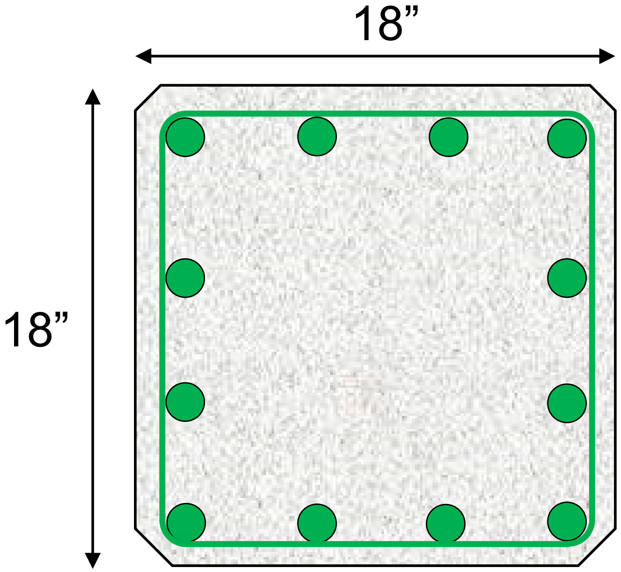
Schematic P-M diagram for two identical columns having the same amounts of GFRP and steel reinforcement. Include the following five points. Note location of **balance point for GFRP-RC**





Developing P-M Interaction Diagram

Create a P-M interaction diagram for the following tied column section:



Equivalent FDOT standard index non-prestressed

18”x18”, 12 GFRP bars

f'_c = 5,000 psi

E_f = 6,500 ksi E_c= 4,291 ksi

f_{fd} = 59.2 ksi ε_{fd} = 0.00911

12 - #8 GFRP bars evenly spaced

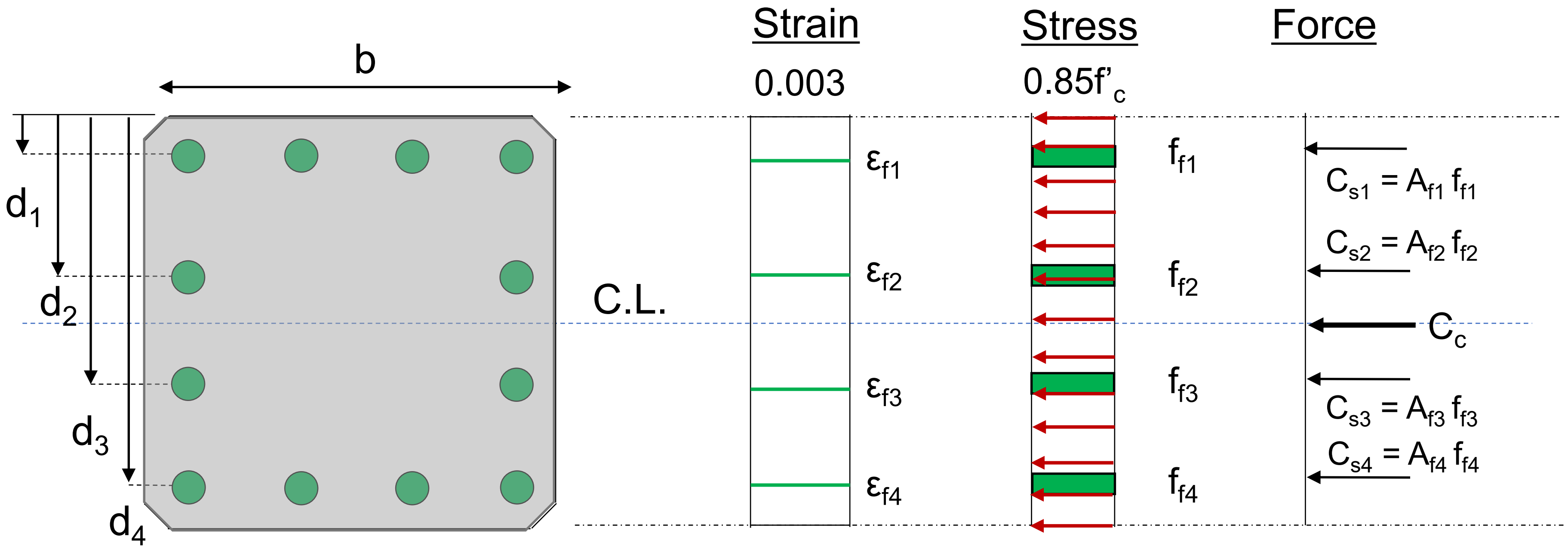
Include the following points:

- Pure compression
- Zero tension
- Pure flexure
- Balance point
- Pure tension

Developing P-M Interaction Diagram

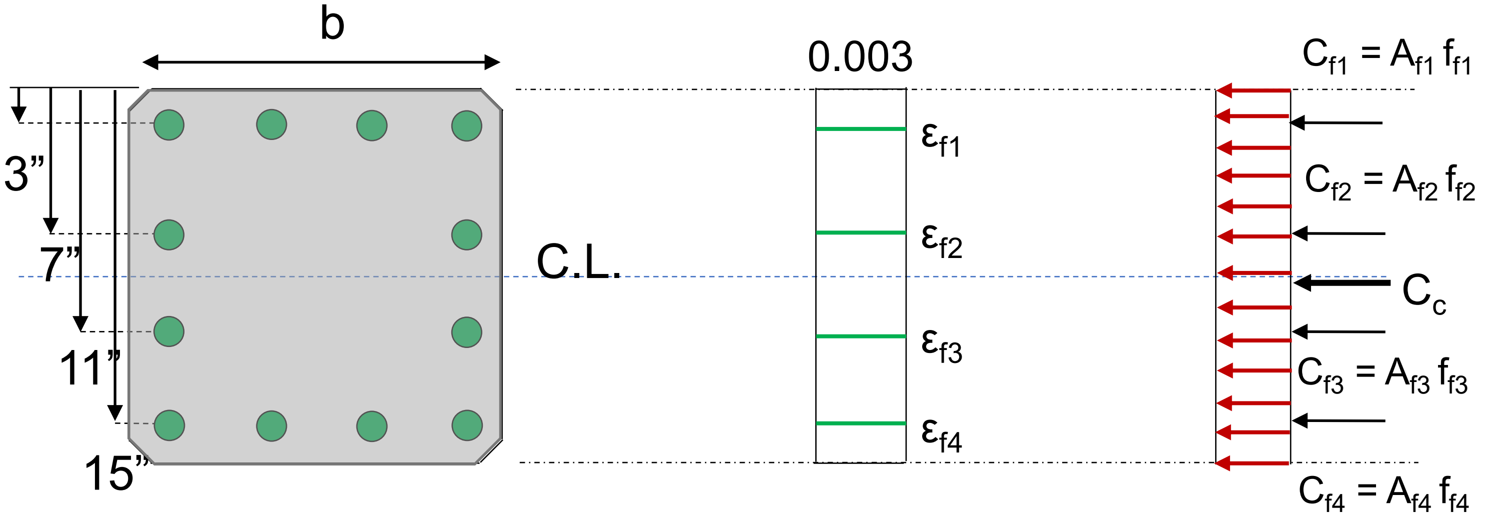
Pure Compression

Strain in GFRP reinforcement cannot exceed the strain maximum strain in concrete (0.003). Contribution of GFRP in compression is difficult assess, show zero and non-zero contribution



Developing P-M Interaction Diagram

Pure Compression



Moment at this point: $\boxed{M = 0\ k - in}$

Should we add this term?

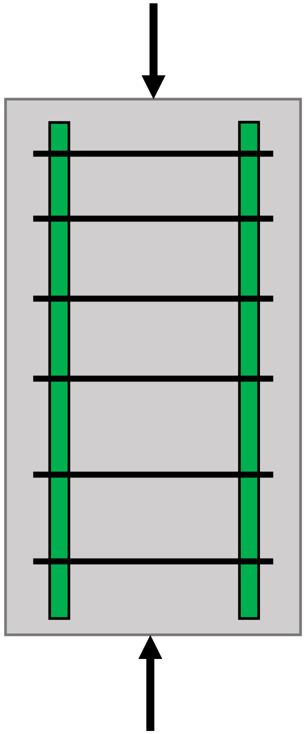
Capacity in pure compression: $P = \mathbf{0.85 f'_c (A_g - A_f)} + A_{f,tot}(\varepsilon_{cu} E_c)$

$\boldsymbol{C_c} = (0.85)(5ksi)(324in^2 - 9.48in^2) = \mathbf{1337\ k}$ (**AASHTO GFRP 2.6.4.2**)

Developing P-M Interaction Diagram

Discussion on contribution of GFRP in Compression

- Current AASHTO provisions do not account for GFRP compression contribution
- Force up to 0.003 compressive strain times a stiffness conservatively equal to that of concrete is appropriate
- For pure compression: $A_{f,tot}(\varepsilon_{cu}E_c)$



Developing P-M Interaction Diagram

Adding the compressive component of GFRP reinforcement ($\varepsilon_f = 0.003$)

$$C_{f1} = 4(0.79in^2)(\mathbf{4291}\boldsymbol{ksi})(0.003)\frac{(18" - 0")}{18"} = 40.7k$$

$$C_{f2} = 2(0.79in^2)(\mathbf{4291}\boldsymbol{ksi})(0.003)\frac{(18" - 0")}{18"} = 20.3k$$

$$C_{f3} = 2(0.79in^2)(\mathbf{4291}\boldsymbol{ksi})(0.003)\frac{(18" - 0")}{18"} = 20.3k$$

$$C_{f4} = 4(0.79in^2)(\mathbf{4291}\boldsymbol{ksi})(0.003)\frac{(18" - 0")}{18"} = 40.7k$$

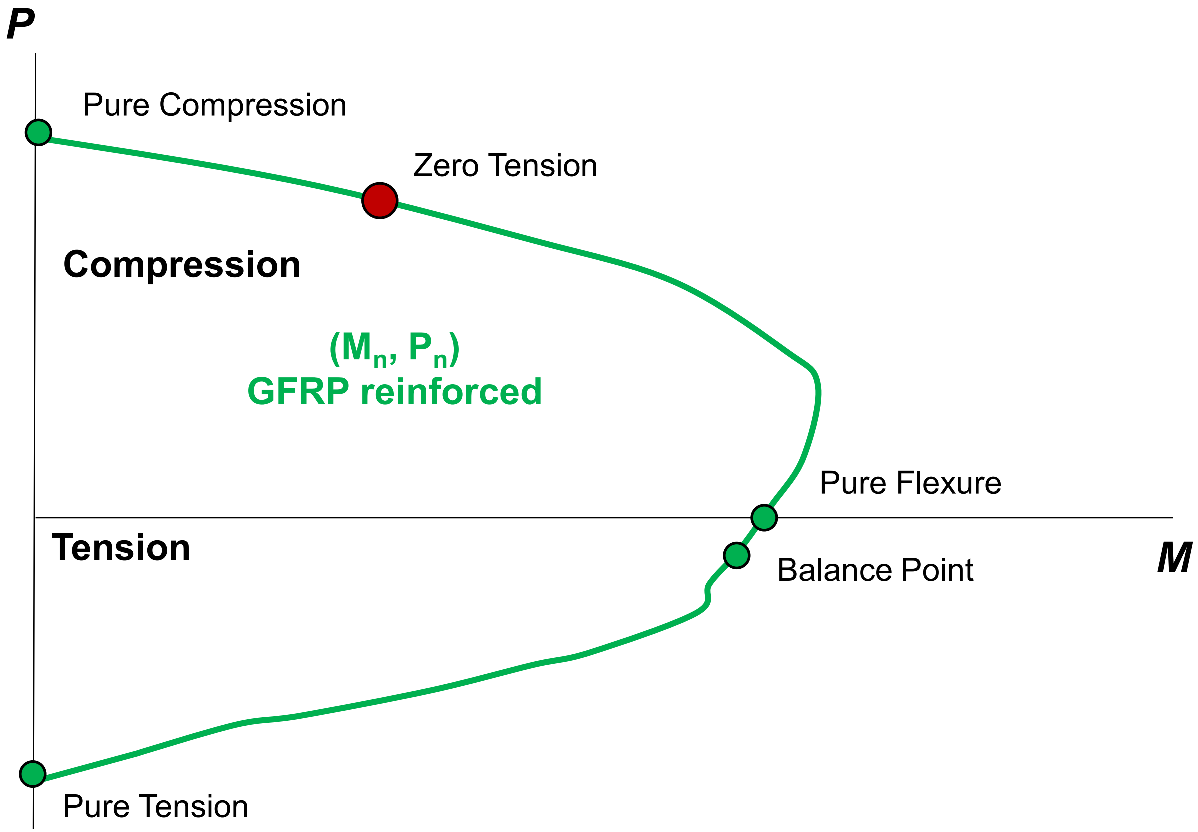
Adding all forces:

$$\boxed{P = 1337k + 40.7k + 20.3k + 20.3k + 40.7k = \mathbf{1459}\ \boldsymbol{k}}$$

9% increase over current AASHTO equation

Developing P-M Interaction Diagram

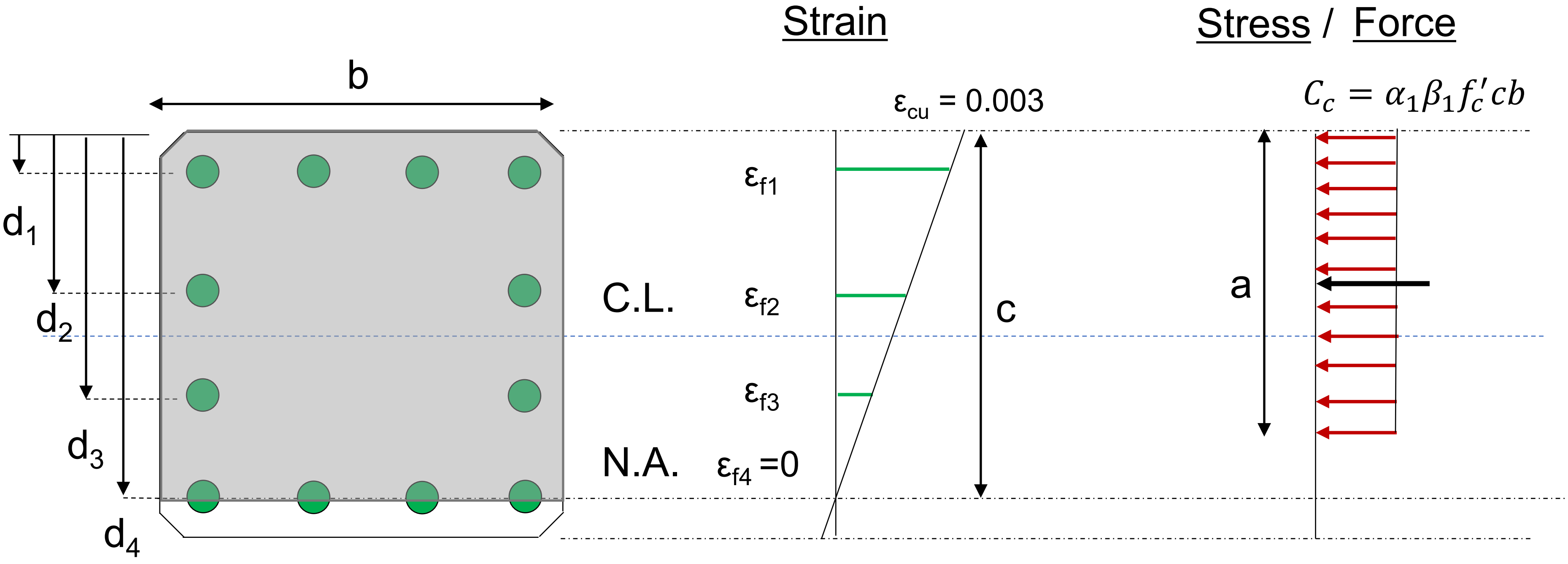
Next point: Zero tension on the extreme GFRP bar layer



Developing P-M Interaction Diagram

Zero Tension

Point where there is zero tension in the bottom reinforcement layer



Developing P-M Interaction Diagram

Zero Tension

$c = d$ neutral axis

Strain at bottom GFRP reinforcement layer is zero
GFRP bars in compression are treated as concrete

$\boxed{T_{f4} = 0\ kip}$ *Zero tension*

Calculate the force in concrete

$$C_c = (b \cdot a)\alpha_1 f_c' = (b \cdot \beta_1 c)\alpha_1 f_c' = (18in \cdot 0.80 \cdot 15in)(0.85)(5ksi) = 918kip$$

Calculate the axial force

$$P = \sum F = C_c \qquad \boxed{= 918k}$$

Developing P-M Interaction Diagram

Zero Tension (Continued)

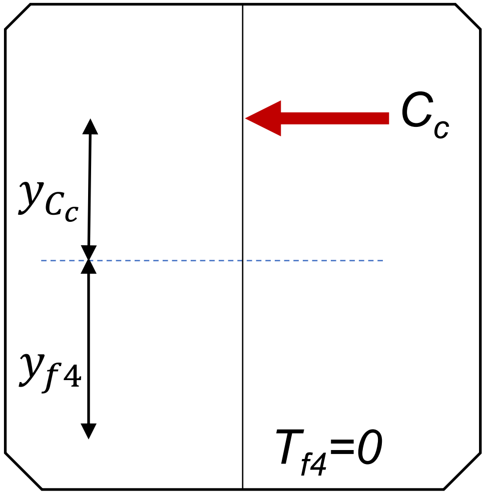
Calculate distance of forces from center line and then solve using for moment

Concrete level:

$$y_{C_c} = y_{N.A.} - \frac{\beta_1 c}{2}$$

$$= 9in - \frac{(0.8)(15in)}{2} = 3in$$

4th Level: $y_{f4} = d_4 - y_{N.A.} = 15in - 9in = 6in$

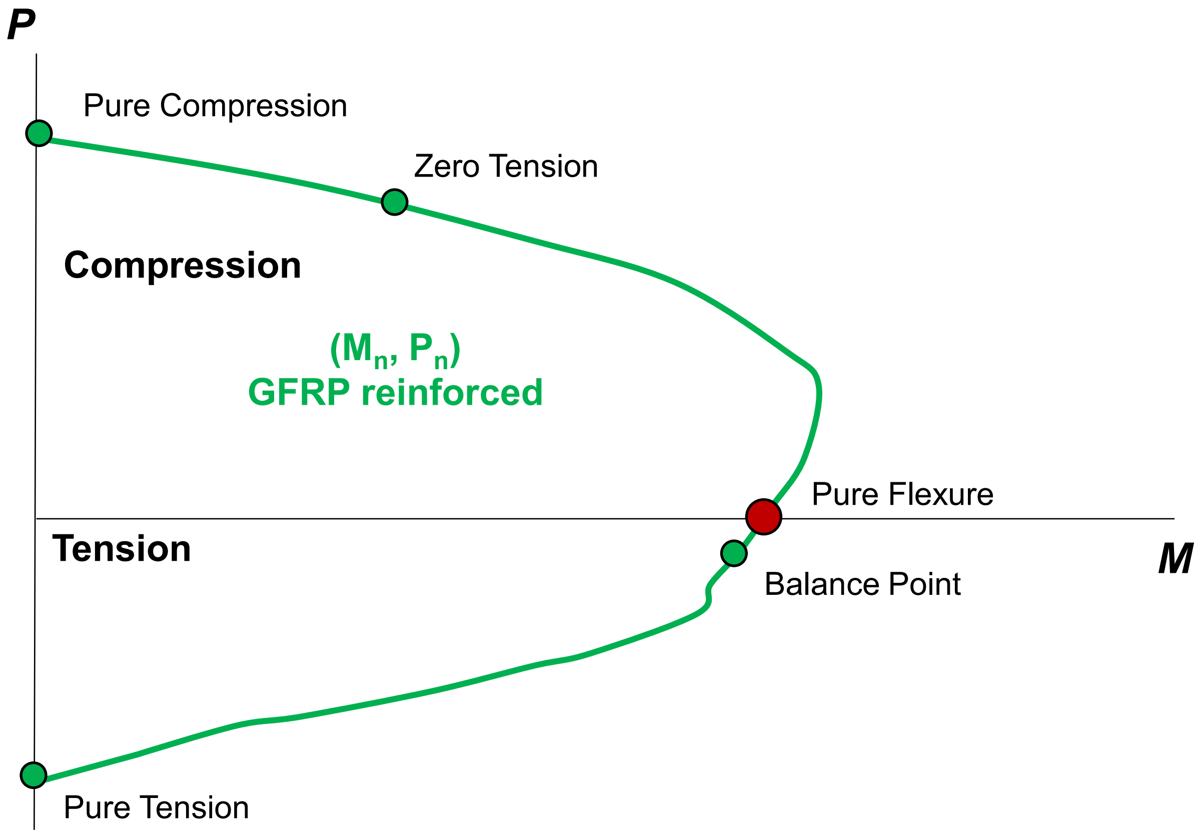


Taking moments

$$\boxed{M = y_{Cc}F_{Cc} + y_{f4}T_{f4} = 918k(3in) + 0k(6in) = 229\ k - ft}$$

Developing P-M Interaction Diagram

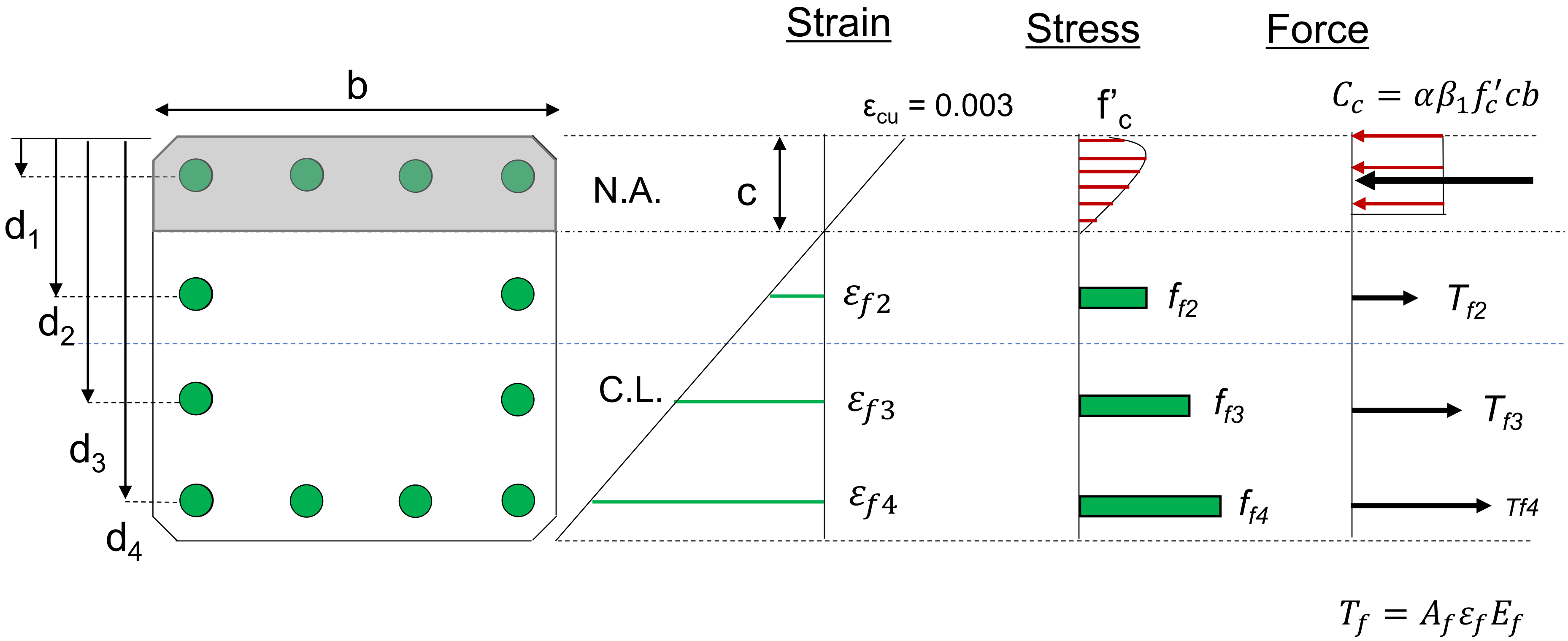
Next point: Pure flexure (P= zero)



Developing P-M Interaction Diagram

Pure Flexure

Pure flexure occurs when axial load is zero and the failure mode is governed by concrete crushing (potentially also by GFRP failure depending on cross-section)



Developing P-M Interaction Diagram

Pure Flexure

$$P = \sum F = C_c + T_{f2} + T_{f3} + T_{f4} = 0k$$

Calculate forces in terms of c, and then solve by imposing horizontal equilibrium

$$T_{f2} = 2 \cdot (0.79in^2)(6500ksi)(0.003)\left(\frac{c - 7in}{c}\right)$$

$$T_{f3} = 2 \cdot (0.79in^2)(6500ksi)(0.003)\left(\frac{c - 11in}{c}\right)$$

$$T_{f4} = 4 \cdot (0.79in^2)(6500ksi)(0.003)\left(\frac{c - 15in}{c}\right)$$

Developing P-M Interaction Diagram

$$C_c = 0.85(0.8)(5ksi)(18in)c = 61.2c$$

Solving for c:

$$T_{f2} = 30.8\left(\frac{c-7}{c}\right)$$

$$T_{f3} = 30.8\left(\frac{c-11}{c}\right)$$

$$T_{f4} = 61.6\left(\frac{c-15}{c}\right)$$

Substituting into equilibrium equation:

$$30.8\left(\frac{c-7}{c}\right) + 30.8\left(\frac{c-11}{c}\right) + 61.6\left(\frac{c-15}{c}\right) + 61.2c = 0$$

$$\boxed{\mathrm{c} = 4.01in.}$$

Developing P-M Interaction Diagram

Pure Flexure (Continued)

Calculate the Moment: Sum moments around center line

Concrete lever arms:

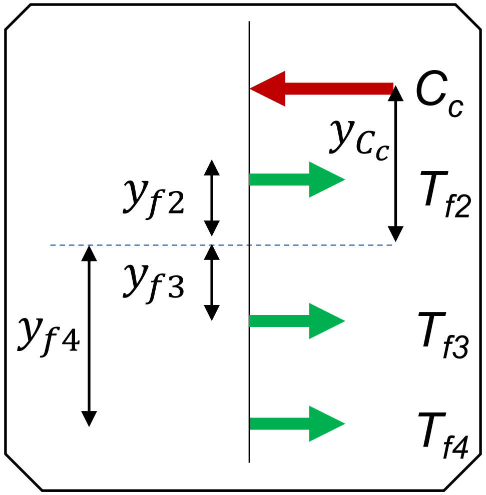
Summing Moments Around Cente

$$y_{C_c} = y_{N.A.} - \frac{\beta_1 c}{2} = 9in - \frac{(0.8)(4.01in)}{2} = 7.4in$$

$$y_{f2} = y_{N.A.} - d_2 = 9in - 7in = 2in$$

$$y_{f3} = d_3 - y_{N.A.} = 11in - 9in = 2in$$

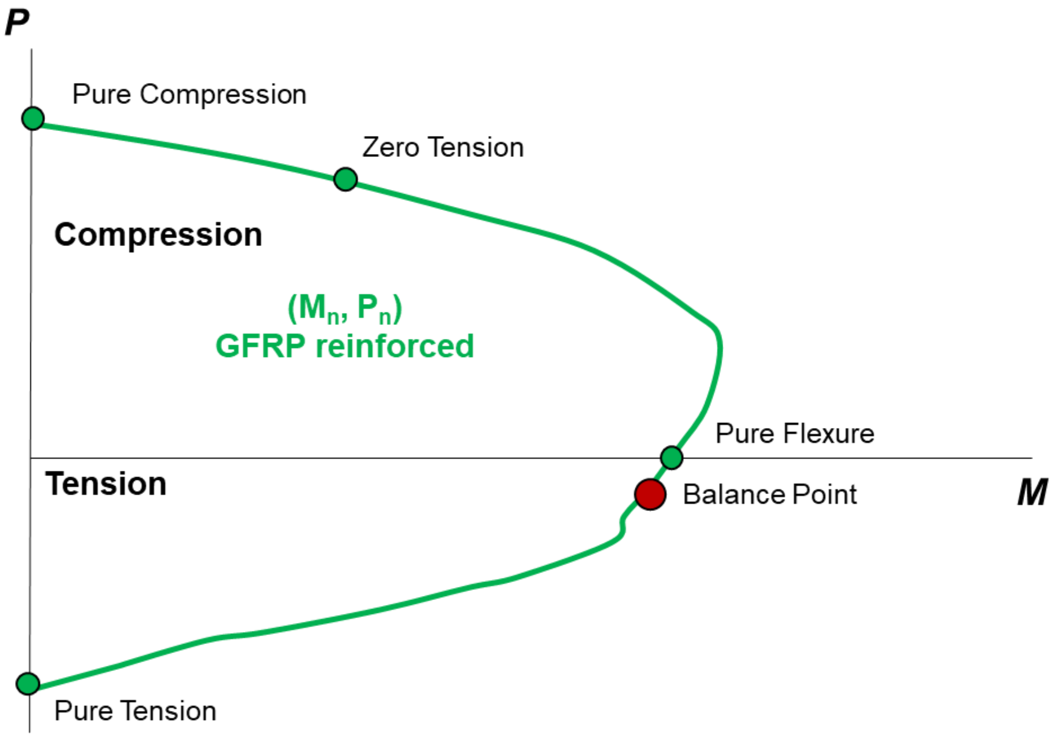
$$y_{f4} = d_4 - y_{N.A.} = 15in - 9in = 6in$$

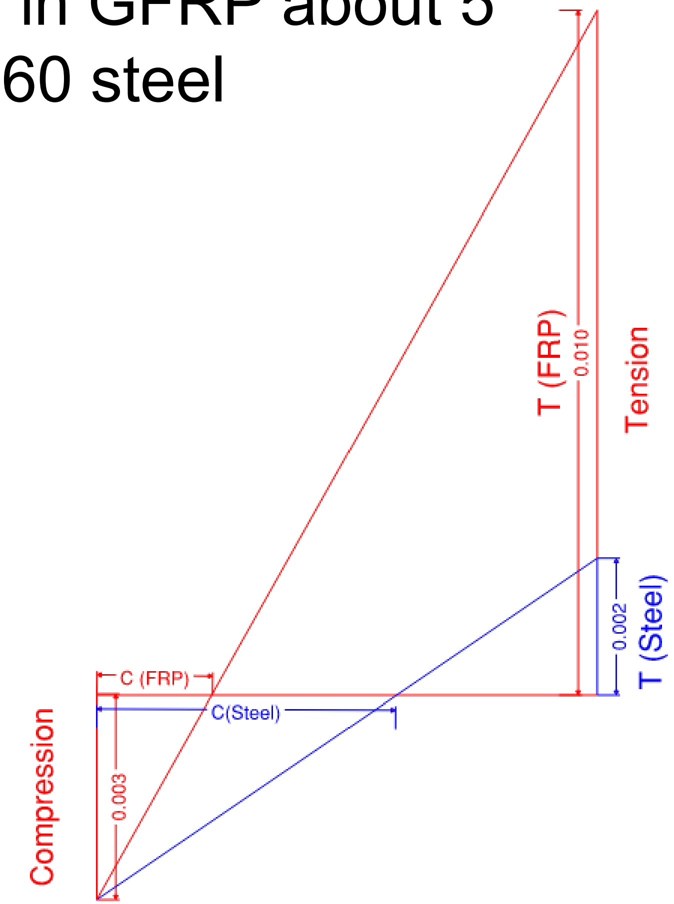


$$\boxed{M = y_{Cc}C_c + y_{f2}T_{f2} + y_{f3}T_{f3} + y_{f4}T_{f4} = 231\ k - ft}$$

Developing P-M Interaction Diagram

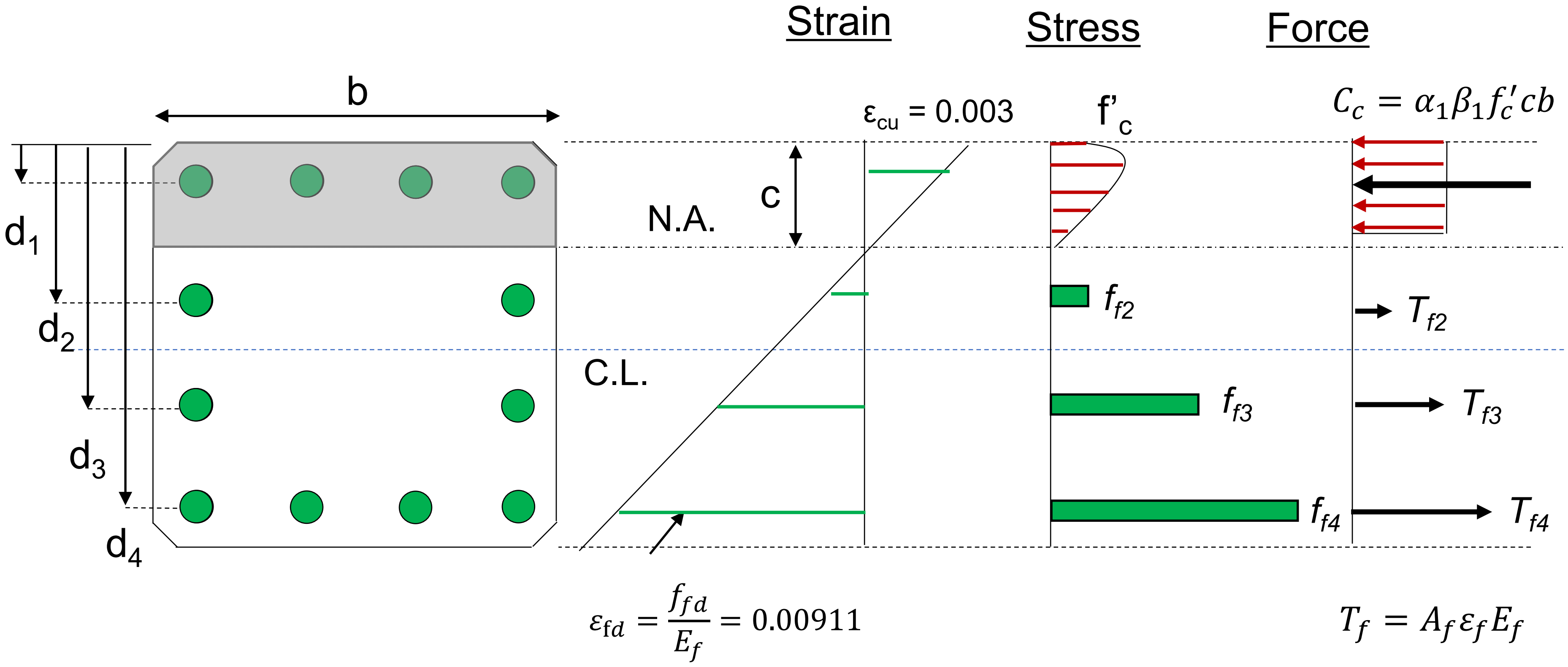
Next point: Balance failure, simultaneous GFRP rupture and concrete crushing. Design failure strain in GFRP about 5 times larger than yield strain for Grade 60 steel





Developing P-M Interaction Diagram

Balance Point: strain, stress and force distribution (equivalent stress block)



$C_c = \alpha_1 \beta_1 f_c' cb$

$\varepsilon_{fd} = \frac{f_{fd}}{E_f} = 0.00911$

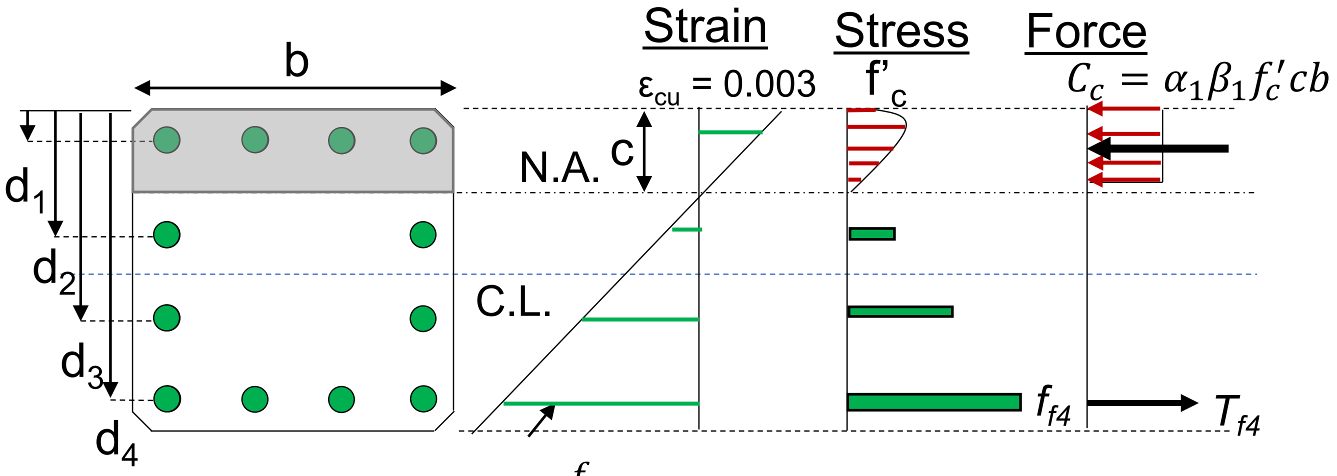
$T_f = A_f \varepsilon_f E_f$

Developing P-M Interaction Diagram

Balance Point

d_1=3"; d_2=7";

d_3=11"; d_4=15"



$$\varepsilon_{fd} = \frac{f_{fd}}{E_f} = 0.00911$$

$$T_f = A_f\varepsilon_f E_f$$

Find the neutral axis:

$$c = d\left(\frac{\varepsilon_{cu}}{\varepsilon_{fd} + \varepsilon_{cu}}\right)$$

$$c = (15in)\left(\frac{0.003}{0.00911 + 0.003}\right) = 3.72in$$

Developing P-M Interaction Diagram

Calculate GFRP strain and stresses:

Second layer GFRP strain

$$\varepsilon_{f2} = \varepsilon_{cu}\left(\frac{c - d_2}{c}\right) = 0.003\left(\frac{3.72in - 7in}{3.72in}\right) = -0.00265$$

$$f_{f2} = E_f\varepsilon_{f2} = (6500ksi)(-0.00265) = -17.2\ ksi$$

Third layer GFRP strain

$$\varepsilon_{f3} = \varepsilon_{cu}\left(\frac{c - d_3}{c}\right) = 0.003\left(\frac{3.72in - 11in}{3.72in}\right) = -0.00588$$

$$f_{f3} = E_f\varepsilon_{f3} = (6500ksi)(-0.00588) = -38.2\ ksi$$

Fourth layer GFRP strain

$$\varepsilon_{f4} = \varepsilon_{cu}\left(\frac{c - d_4}{c}\right) = 0.003\left(\frac{3.72in - 15in}{3.72in}\right) = -0.00911$$

$$f_{f4} = E_f\varepsilon_{f4} = (6500ksi)(-0.00911) = -59.2\ ksi = \mathbf{f_{fd}}$$

Developing P-M Interaction Diagram

Balance Point (Continued)

Calculate the Forces:

$$C_c = (b \cdot a)\alpha_1\beta_1 f_c'$$

$$C_c = (18in \cdot 0.85 \cdot 3.72in)(0.8)(5ksi) = 277.5k$$

$$P = \sum F = C_c + T_{f2} + T_{f3} + T_{f4}$$

Sum forces by multiplying GFRP stress by areas

$$P = 277.5k - (17.2ksi)(1.58in^2) - (38.2ksi)(1.58in^2) - (59.2ksi)(3.16in^2)$$

$\boxed{\text{P} = -47.1k}$

Balance point occurs when axial load is tension

Developing P-M Interaction Diagram

Calculate the Moment: Sum moments around section centerline

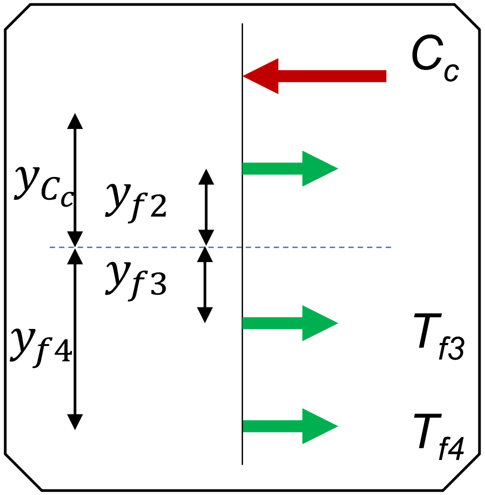
Concrete and GFRP bars lever arms:

$$y_{C_c} = y_{N.A.} - \frac{\beta_1 c}{2} = 9in - \frac{(0.8)(3.72in)}{2} = 7.5in$$

$$y_{f2} = y_{N.A.} - d_2 = 9in - 7in = 2in$$

$$y_{f3} = d_3 - y_{N.A.} = 11in - 9in = 2in$$

$$y_{f4} = d_4 - y_{N.A.} = 15in - 9in = 6in$$

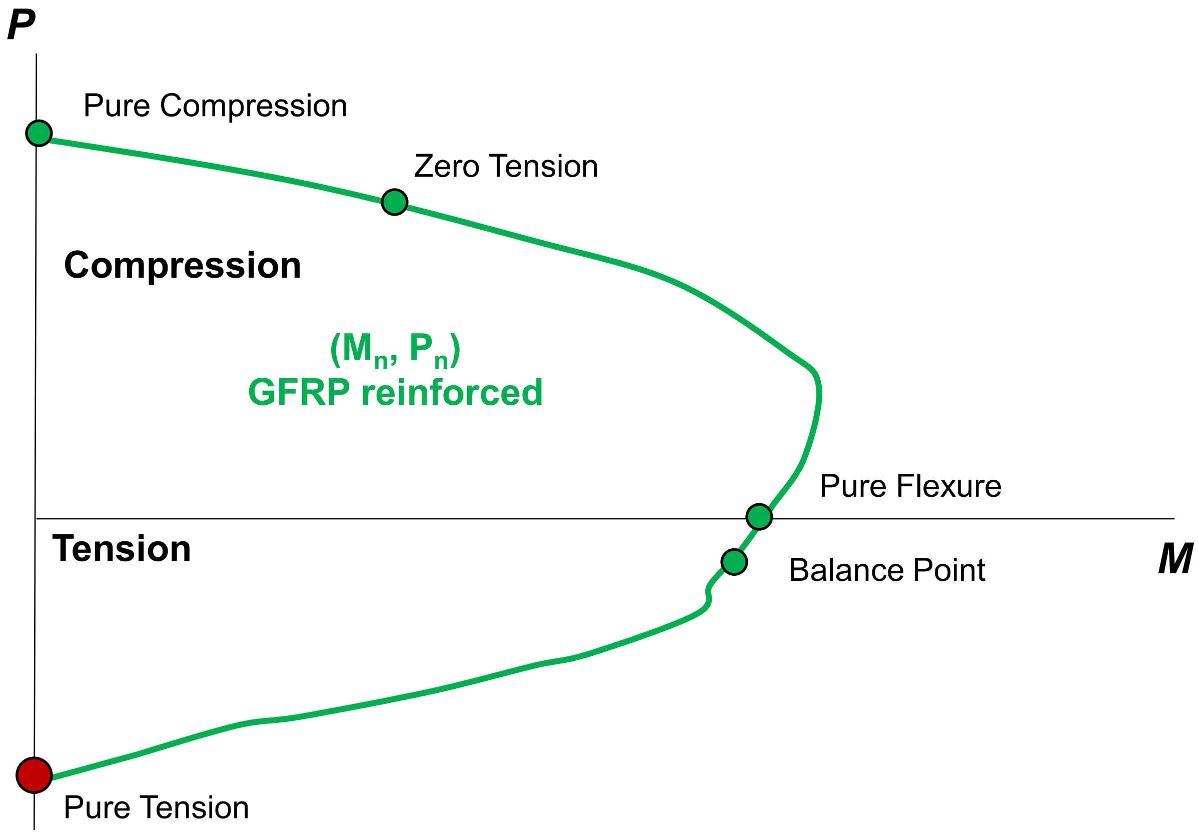


Summing Moments Around Center Line

$$\boxed{M = C_c y_{C_c} - y_{f2} T_{f2} + y_{f2} T_{f3} + y_{f4} T_{f4} = 241\ k - ft}$$

Developing P-M Interaction Diagram

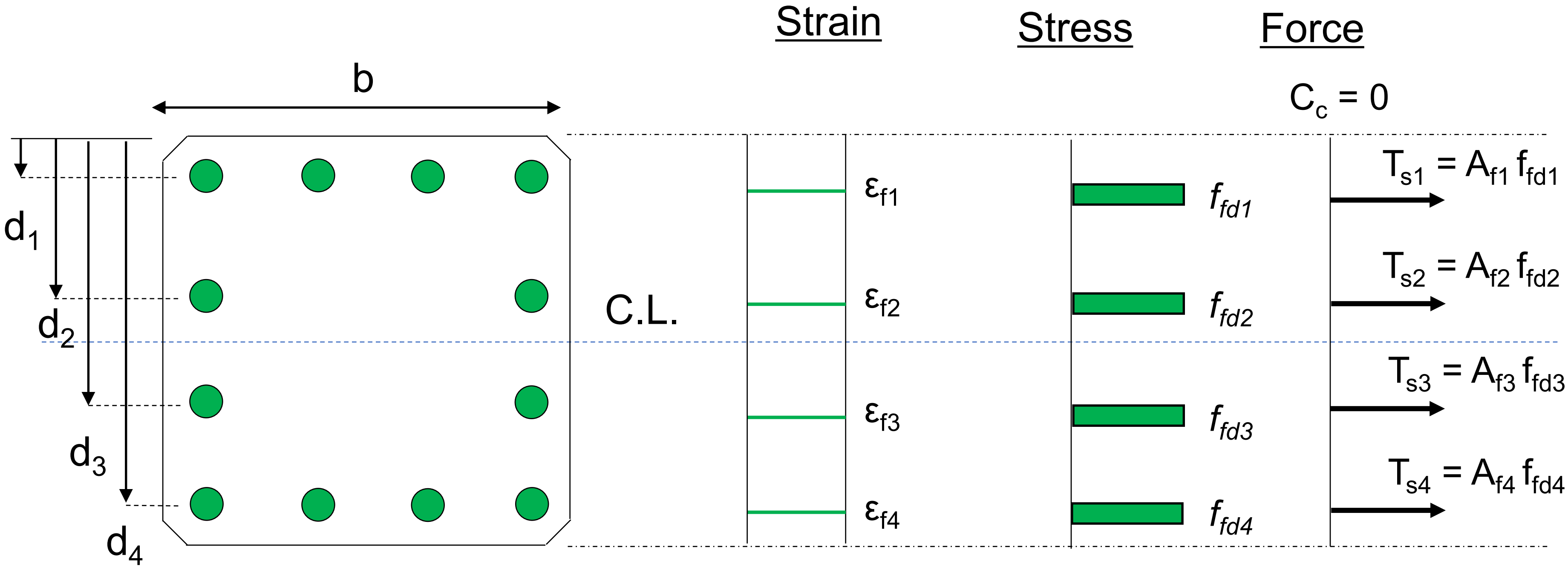
Next point: Pure axial tension. There is no concrete contribution



Developing P-M Interaction Diagram

Zero Moment (Tension)

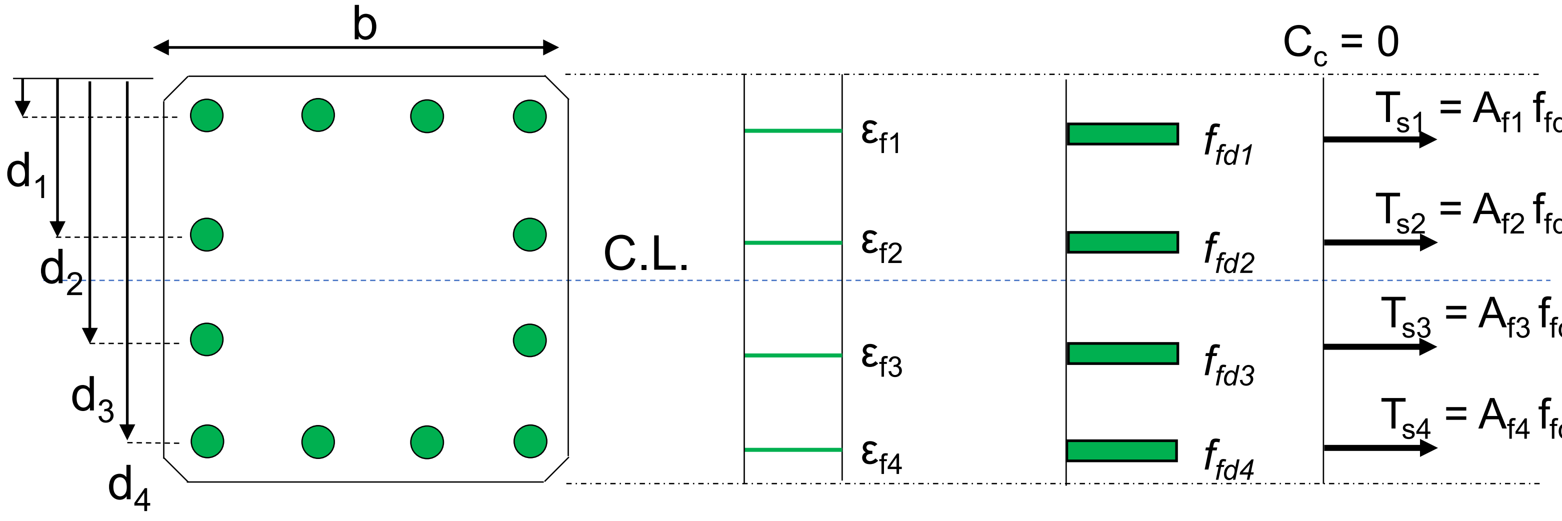
The first point is tension only, so the concrete is assumed to not contribute



$$\varepsilon_f = \varepsilon_{fd}$$

Developing P-M Interaction Diagram

Zero Moment (Tension)



$$\varepsilon_f = \varepsilon_{fd}$$

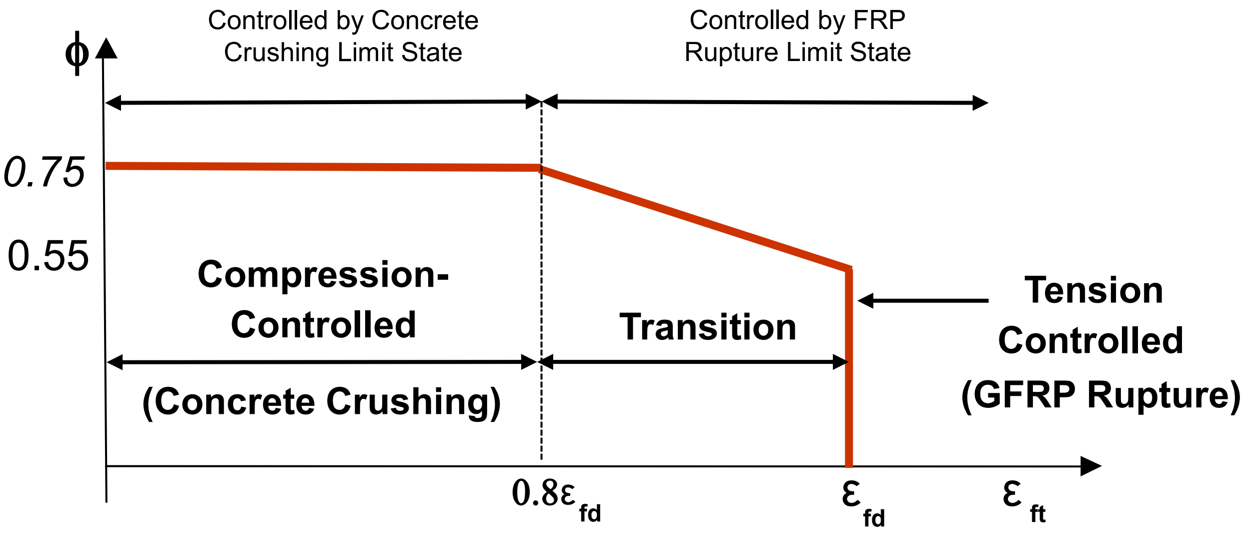
Calculate force components assuming all GFRP bars rupture

$$P = \sum F = F_{f1} + F_{f2} + F_{f3} + F_{f4}$$

$$\boxed{P = 12(0.79 in^2)(59.2 ksi) = 561.1 kip}$$

$$\boxed{\text{M} = 0 kip - ft}$$

AASHTO Resistance Factor for GFRP



The safety factor Φ needs to be calculated for each moment-axial load combination (as each P-M point has a different stress in tension reinforcement)

Developing P-M Interaction Diagram

Limiting the factored compressive load:

0.85 = spiral or hoop reinforcement
0.80 = tie reinforcement

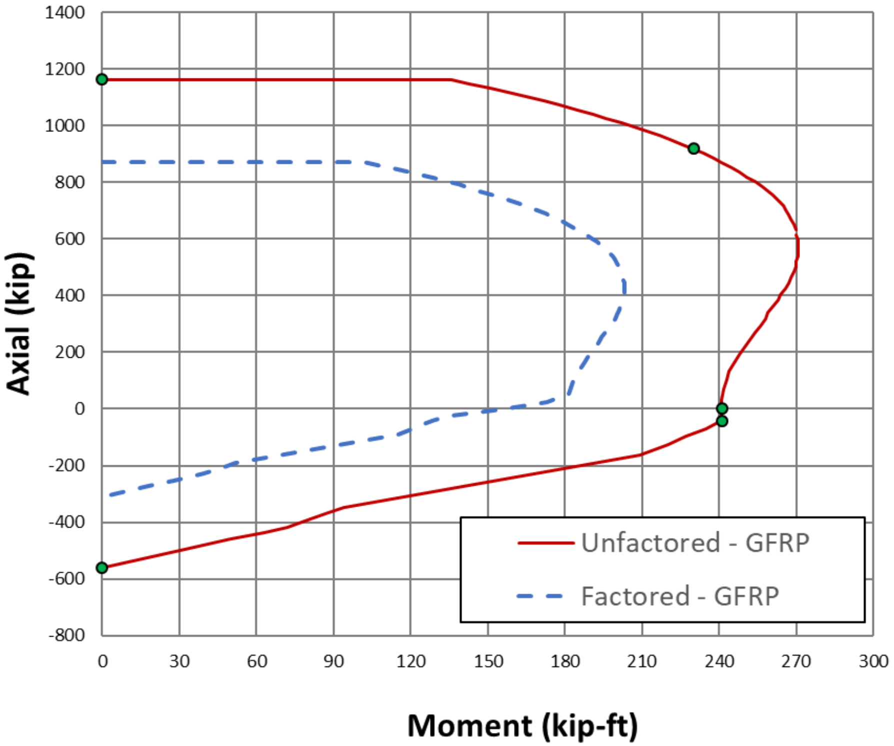
$$P_{n,.max} = 0.80[0.85(5ksi)(324in^2 - 9.48in^2)]$$

$$P_{n,.max} = 1070.6kip$$

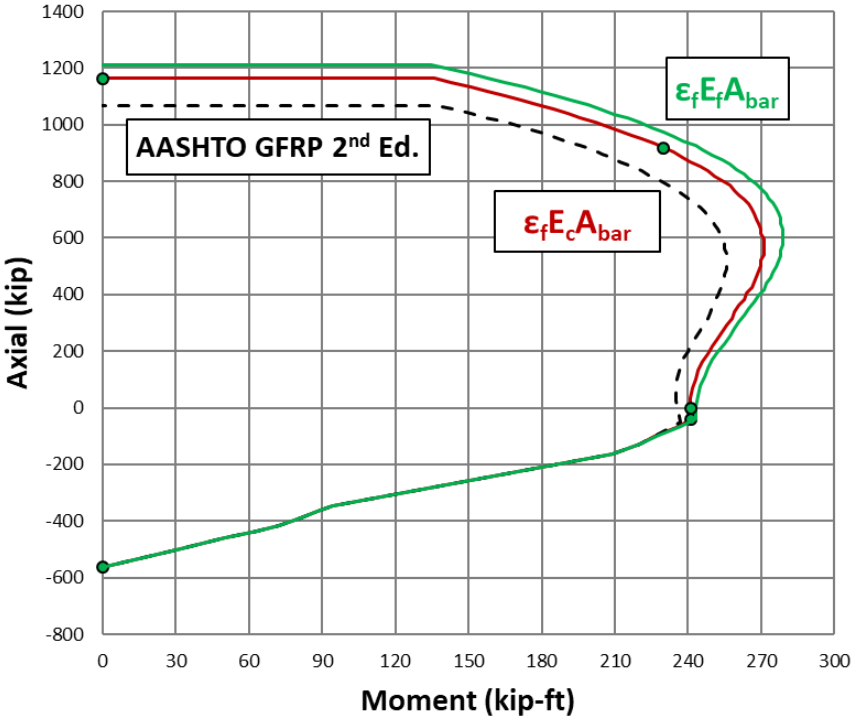
Point	M_n	P_n	ϕ	ϕM_n	ϕP_n
Pure Compression	0 k-ft	1070 k	0.75	0 k-ft	802 k
Zero Tension	229 k-ft	918 k	0.75	172 k-ft	689 k
Pure Moment	231 k-ft	0 k	0.64	148 k-ft	0 k
Balance Point	241 k-ft	-47 k	0.55	133 k-ft	-26 k
Pure Tension	0 k-ft	-561 k	0.55	0 k-ft	-309 k

Developing P-M Interaction Diagram

P-M Diagram for factored and unfactored values



Unfactored P-M diagram for different assumptions on GFRP compression contribution



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- Strength of GFRP-RC Columns
- Design Considerations
- P-M Diagram Example
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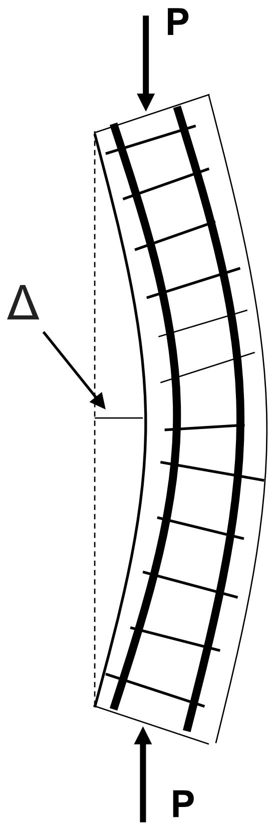
- Concluding Remarks

Slenderness Effect

Slender Columns



As column bends, there is an out-of-plane deflection (Δ). Δ will cause second-order moment

$$M_{2nd\ order} = P\Delta$$

This second-order moment is in addition to any other moment applied to the column and decreases the strength of the overall column

By definition, a column is considered slender when this second order moment decreases the capacity by more than 5%

Criterion $$\frac{P_{long}}{P_{short}} \leq 0.95$$

Determination of EI

Flexural stiffness, ***EI,*** ad effective length, ***kL***, are the parameters determining the slenderness effect

GFRP-RC columns are affected more by slenderness due to smaller ***EI***

Jawaheri & Nanni, 2017 offer both simplified and detailed expressions for ***EI*** analogous to ACI 318-14:

Simplified

$$EI = \frac{0.2E_cI_g}{1+\beta_{dns}} + 0.03E_cI_g$$

Detailed

$$EI = \frac{0.2E_cI_g}{1+\beta_{dns}} + 0.75E_fI_f$$

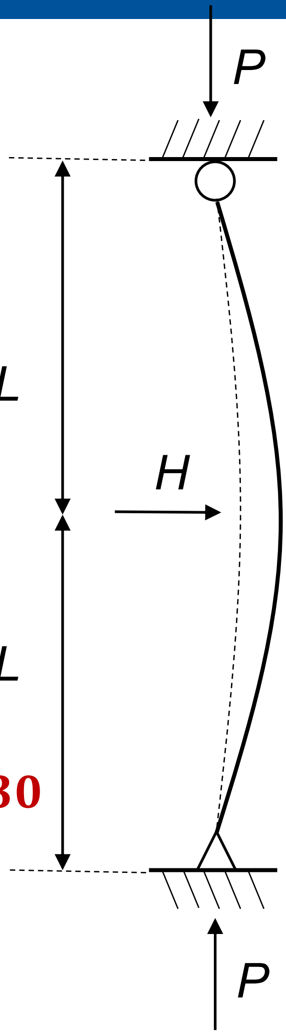
where

$$\beta_{dns} = \frac{P_{u,sustained}}{P_u}$$

Design Considerations

Slenderness Ratio

Mirmiran et al., 2001 showed that, for GFRP-RC columns not braced against side-way, the limit should be reduced to 17



(a) Sway permitted

$$\frac{kL}{r} \leq 22 \quad \text{(ACI 318-14)} \quad \longrightarrow \quad \frac{kL}{r} \leq \mathbf{17}$$

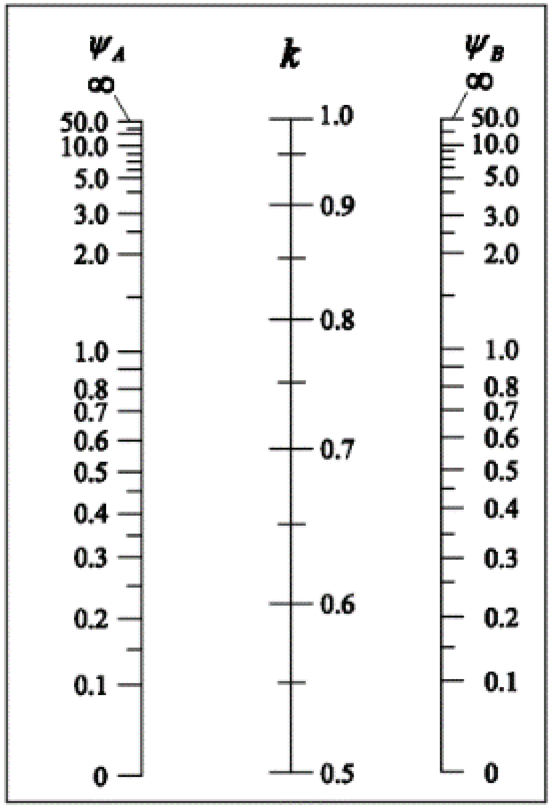
(b) Braced

$$\frac{kL}{r} \leq 34 + 12\left(\frac{M_1}{M_2}\right) \leq 40 \text{ (ACI 318-14)} \quad \longrightarrow \quad \frac{kL}{r} \leq \mathbf{29} + 12\left(\frac{M_1}{M_2}\right) \leq \mathbf{30}$$

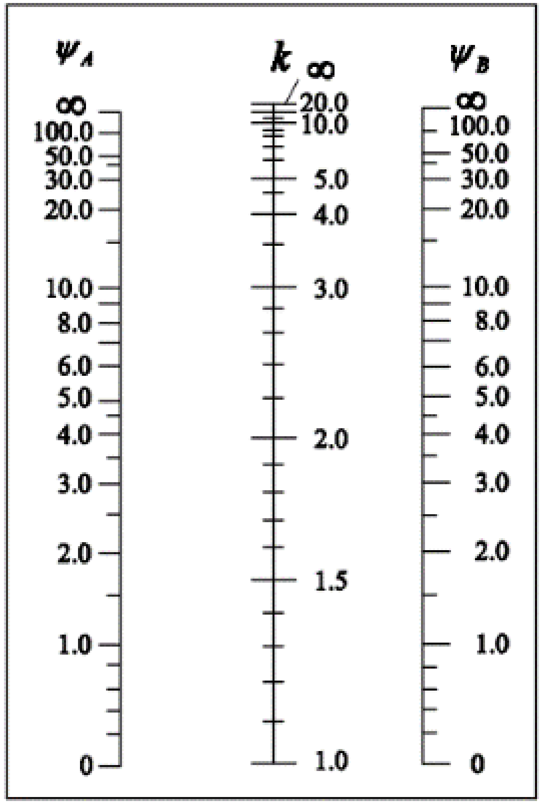
M_1/M_2 is negative if column is bent in single curvature, and positive for double curvature

Alignment Charts

The coefficient ***k*** can be determined through the use of alignment charts based on relative stiffness of framing members

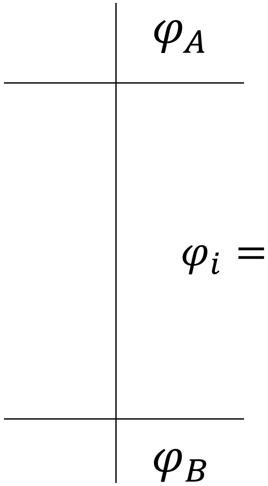


(a) Nonsway Frames



(b) Sway Frames

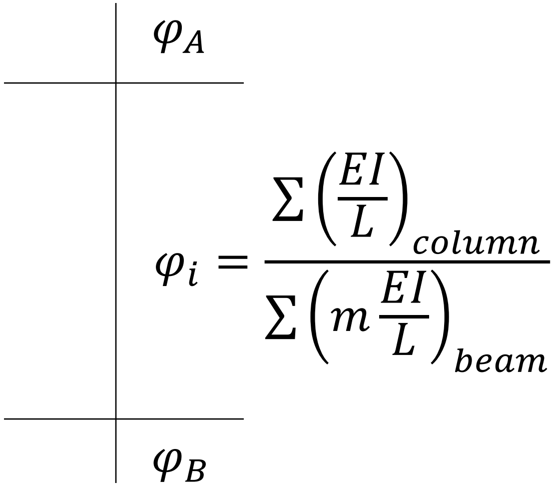
ψ_A and ψ_B are found based upon members framing into joint



$$\varphi_i = \frac{\sum\left(\frac{EI}{L}\right)_{column}}{\sum\left(\frac{EI}{L}\right)_{beam}}$$

Determination of EI

For GFRP reinforced concrete members, stiffness of restraining members needs approximation. Values are provided below in the table



$$\varphi_i = \frac{\sum\left(\frac{EI}{L}\right)_{column}}{\sum\left(m\frac{EI}{L}\right)_{beam}}$$

Member and condition		Moment of Inertia	Cross-sectional area
Columns		$0.40I_g$	$1.0A_g$
Walls	Uncracked	$0.40I_g$	
	Cracked	$0.15I_g$	
Beams		$0.15I_g$	
Flat plates and flat slabs		$0.15I_g$	

Approved by ACI 440 committee adapting Bischoff (2017) for expected range of reinforcing ratios and elastic modulus. Jawaheri, H. & Nanni, A., (2017) provide further information.

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- **Concluding Remarks**

Concluding Remarks

- Elastic modulus of GFRP in compression matches that of concrete (conservative assumption)
- Transverse reinforcement spacing affected by smaller elastic modulus of GFRP
- Minimum longitudinal GFRP reinforcement ratio for columns same as for steel
- P-M diagram can be constructed using similar procedure as for steel-RC columns
- GFRP-RC not appropriate for seismic application

Questions?

Thank U

AXIAL RESPONSE OF GFRP REINFORCED CONCRETE

4.1 Review Questions: *Fundamentals*

Applied Question

4.1.1) The compressive capacity of GFRP reinforcement ______________________________.

a. Is used to improve ductility

b. Is used to satisfy maximum strain requirements of AASHTO

c. Is not considered for low loads

d. Can be used in design up until a concrete strain of 0.003

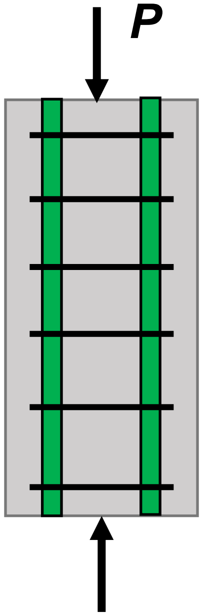
Introduction

Review of Steel RC Columns

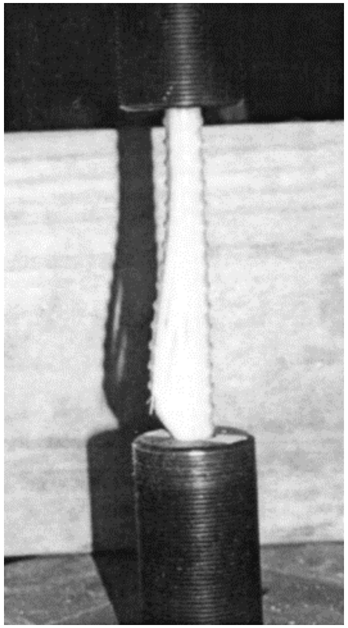
$$P_o = P_c + P_s = 0.85 f_c'(A_g - A_s) + f_y A_s$$

Basic Concept for GFRP RC Columns

$$P_o = P_c + P_s = 0.85 f_c'(A_g - A_s) + \cancel{f_y A_s}$$



As reported in reference, the mechanical properties of GFRP exceed those of concrete and therefore, equivalency can be assumed.



GFRP bar loaded in compression (Deitz, Harik, and Gesund, 2003)

Applied Question

4.1.1) The compressive capacity of GFRP reinforcement __________________________.

a. Is used to improve ductility

b. Is used to satisfy maximum strain requirements of AASHTO

c. Is not considered for low loads

d. Can be used in design up until a concrete strain of 0.003

Applied Question

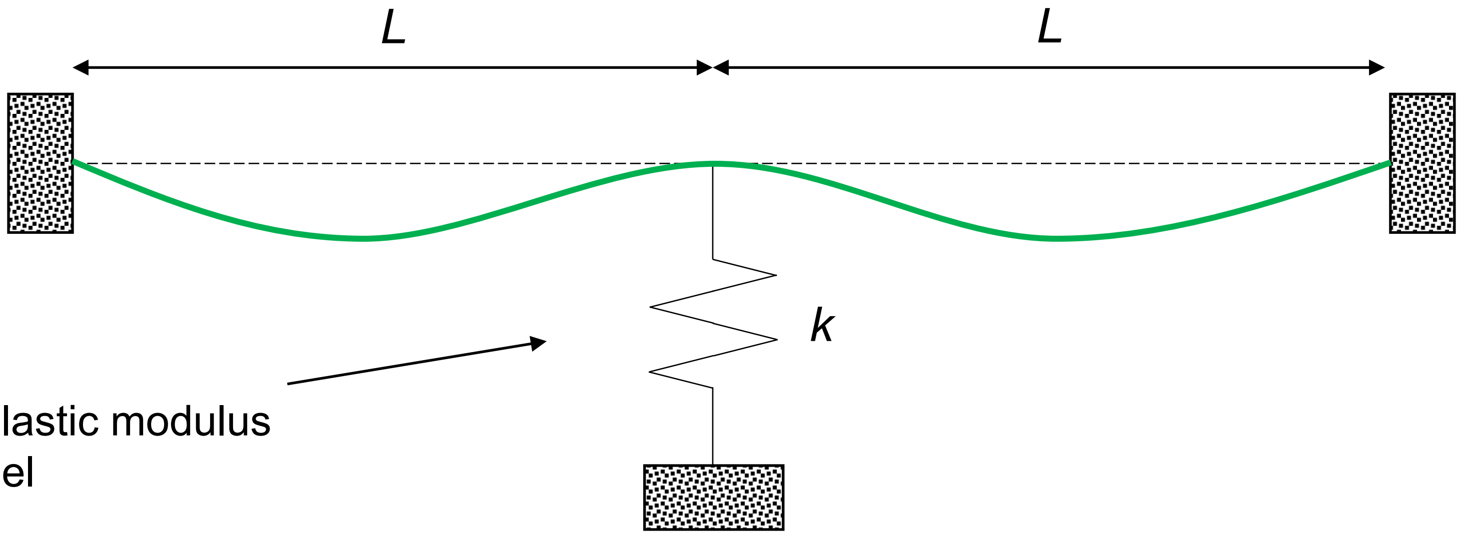
4.1.2) Compared to steel reinforced columns, the transverse spacing requirements for GFRP reinforced columns are the same.

a. True

a. False

Design Considerations

Limits on Maximum Spacing of Transverse Reinforcement: confinement, buckling of longitudinal reinforcement



Lower elastic modulus than steel

Theoretical:

$$\boxed{s_{max} \approx 14 d_b}$$

AASHTO 4.7.5.4 – Tied Members

$$s_{max} = min \begin{cases} least\ dimension\ of\ column \\ d/4 \\ 12\ inches \end{cases}$$

Applied Question

4.1.2) Compared to steel reinforced columns, the transverse spacing requirements for GFRP reinforced columns are the same.

a. True

b. False

Applied Question

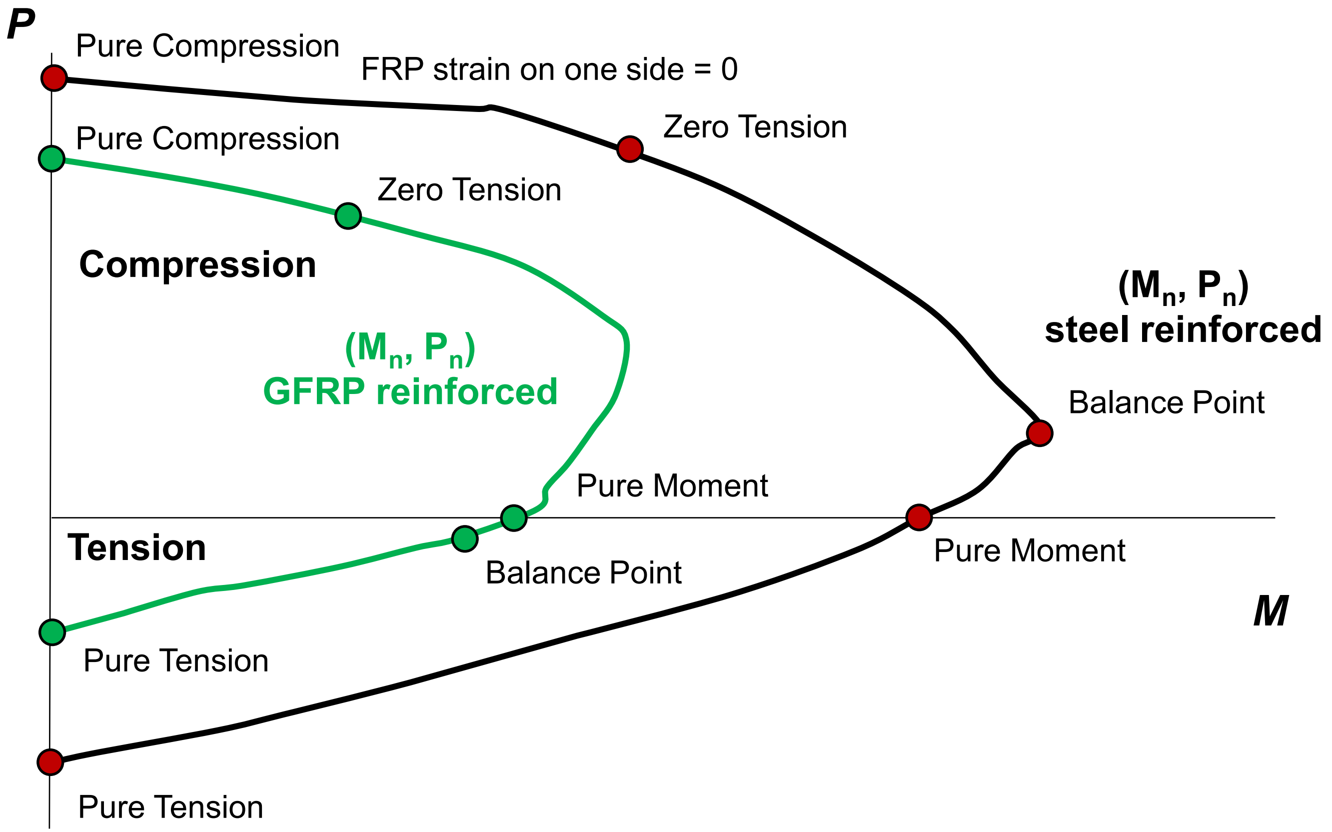
4.1.3) Compared to steel reinforced columns, the ultimate tensile capacity is reduced.

a. True

b. False

Developing P-M Interaction Diagram

Schematic P-M diagram for two identical columns having the same amounts of GFRP and steel reinforcement



Applied Question

4.1.3) Compared to steel reinforced columns, the ultimate tensile capacity is reduced.

- **a. True**
- b. False

Applied Question

4.1.4) When constructing a moment-interaction diagram for a GFRP reinforced column, the balance points refers to: ________________.

a. The point at which the GFRP reinforcement yields and concrete crushes

b. The point at which the GFRP reinforcement ruptures and concrete crushes

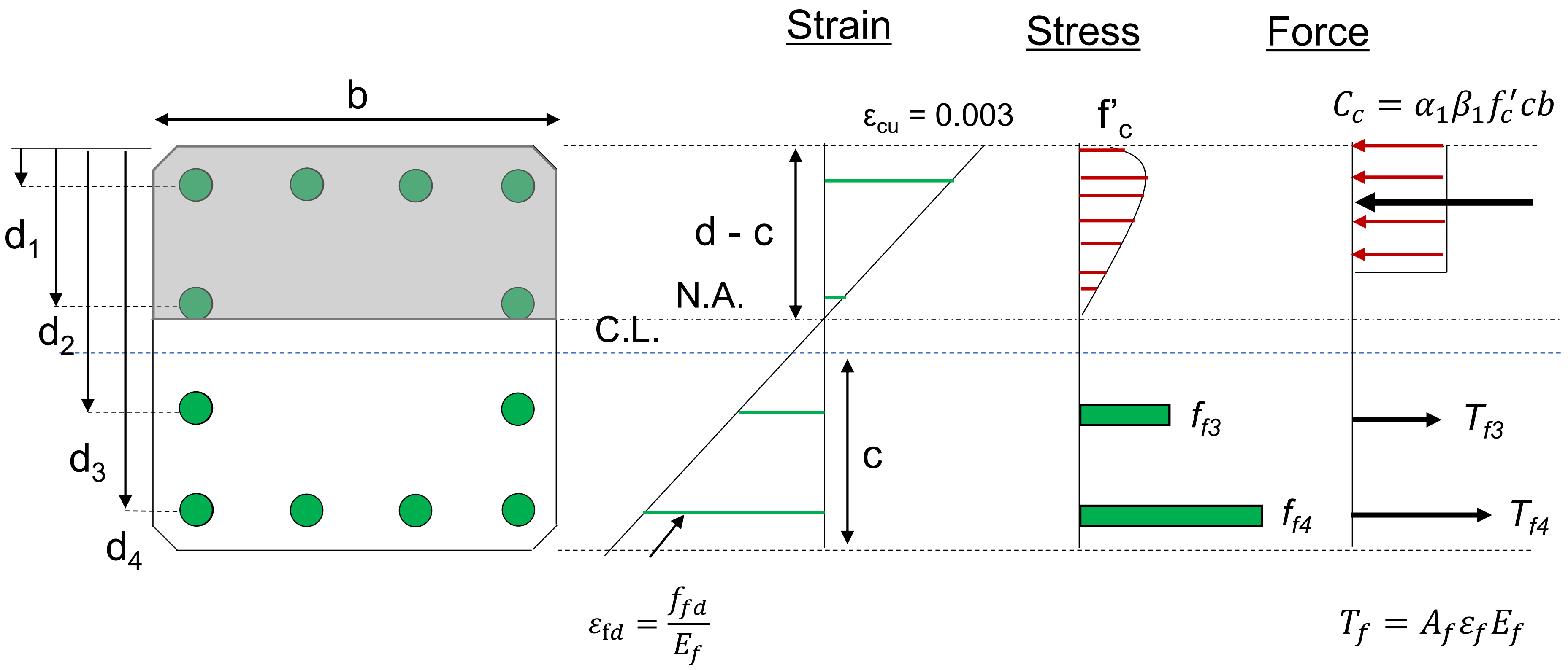
c. The point at which the GFRP reinforcement yields before concrete crushes

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

Developing P-M Interaction Diagram

Balance Point

Balance point is when concrete crushes and tension reinforcement ruptures simultaneously. (Since there is no yielding of GFRP)



Applied Question

4.1.4) When constructing a moment-interaction diagram for a GFRP reinforced column, the balance points refers to: ________________.

a. The point at which the GFRP reinforcement yields and concrete crushes

b. The point at which the GFRP reinforcement ruptures and concrete crushes

c. The point at which the GFRP reinforcement yields before concrete crushes

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

Applied Question

4.1.5) When designing a slender GFRP reinforced column, special considerations should be made to determining slenderness ratio and EI?

a. True

b. False

Determination of EI

Effect of Creep

Jawaheri & Nanni, 2017 offer both simplified and detailed expressions analogous to ACI 318-14:

Simplified

$$EI = \frac{0.2E_cI_g}{1+\beta_{dns}} + 0.03E_cI_g$$

Detailed

$$EI = \frac{0.2E_cI_g}{1+\beta_{dns}} + 0.75E_fI_f$$

where

$$\beta_{dns} = \frac{P_{u,sustained}}{P_u}$$

Applied Question

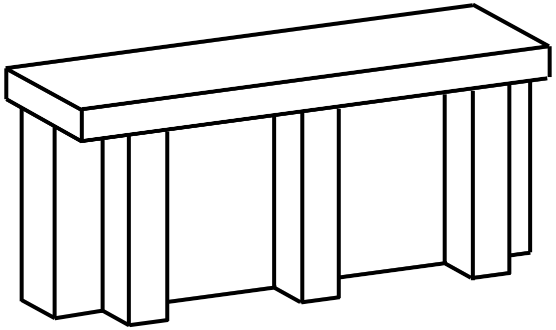
4.1.5) When designing a slender GFRP reinforced column, special considerations should be made to determining slenderness ratio and EI?

a. True

b. False

AXIAL RESPONSE OF GFRP REINFORCED CONCRETE

4.2 Design Example: Solider Pile in Wing Wall



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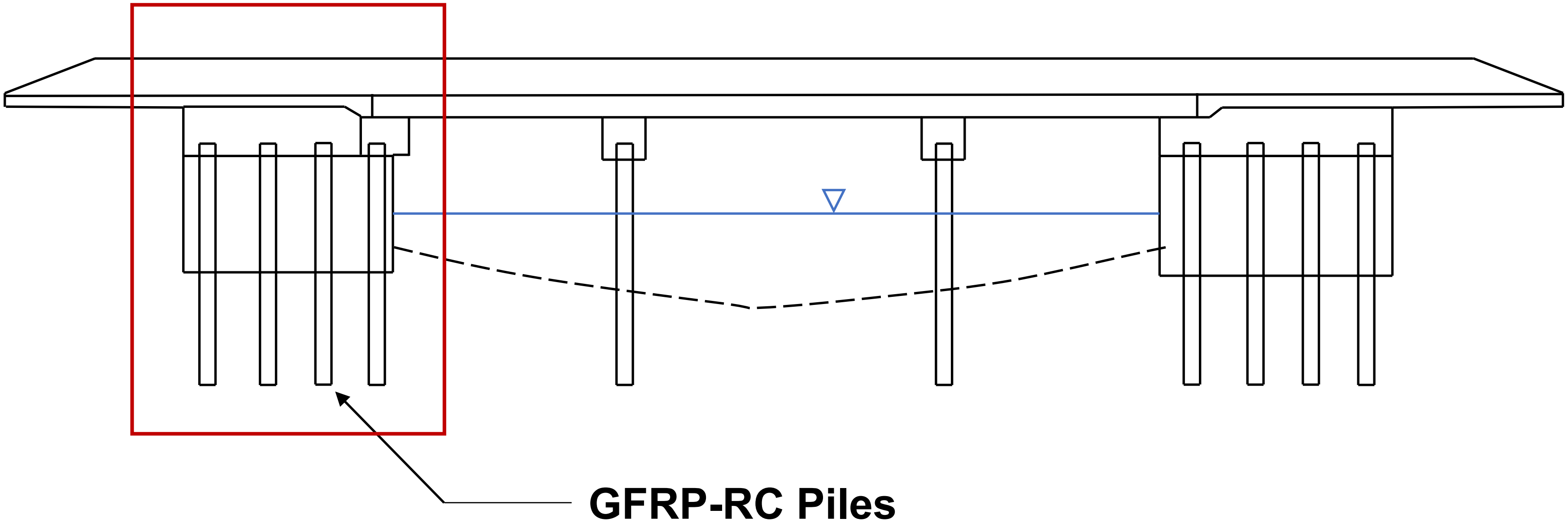
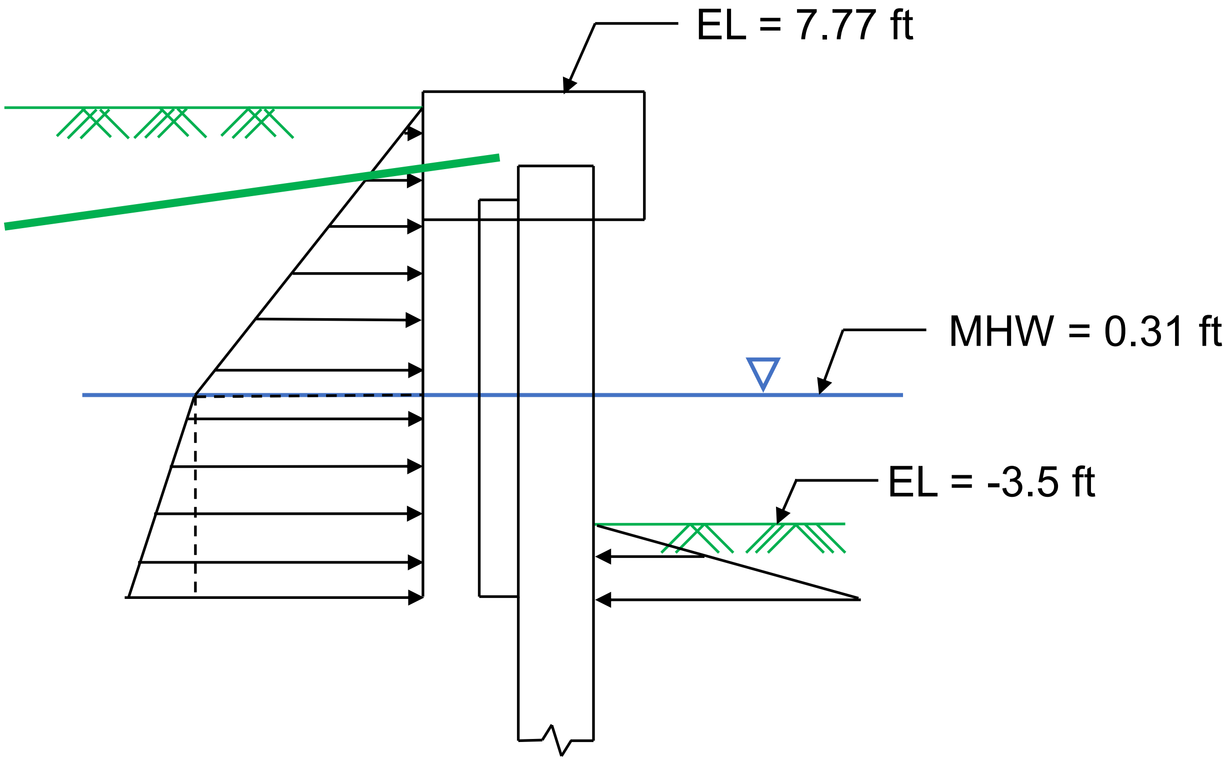
Pile Example

Consider the following example:



Pile Example



Cross Section

Soil Properties

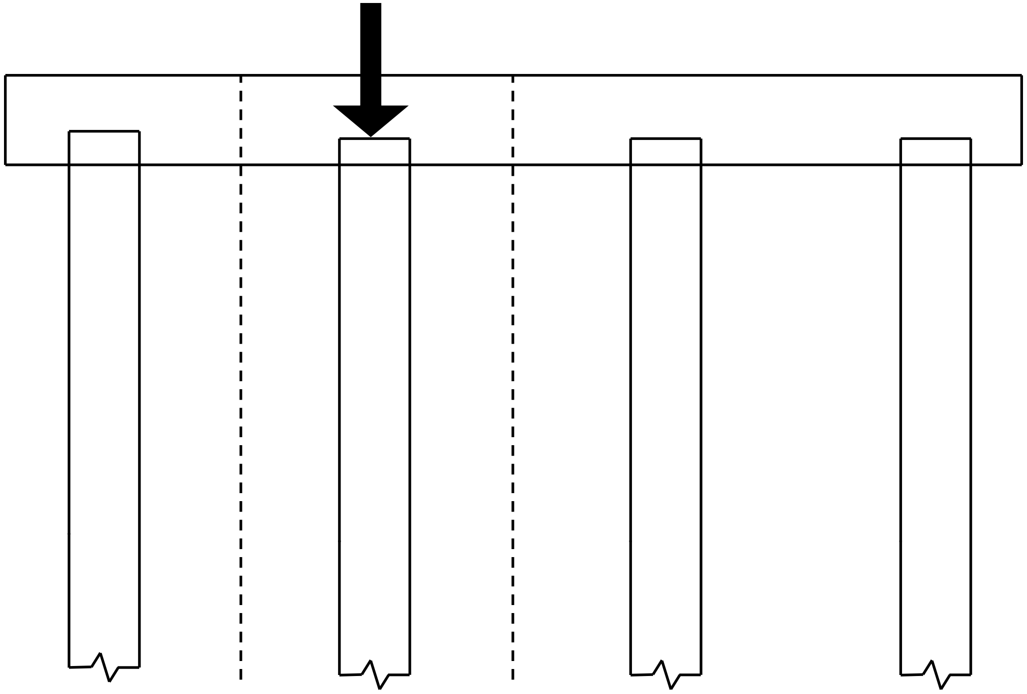
$\gamma = 110\ pcf$

$\phi = 30\ degrees$

$c = 0\ ksf$

Pile Example

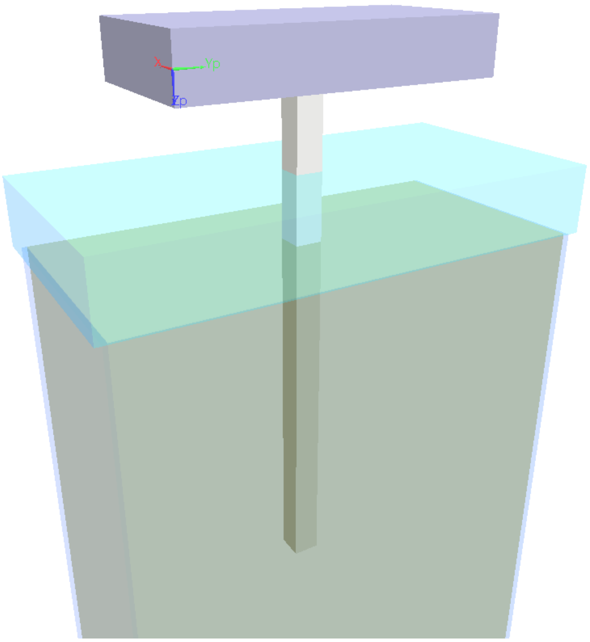
$$P_{cap} = Pile\ Spacing \times Cap_{Height} \times Cap_{Width} \times \gamma_c$$

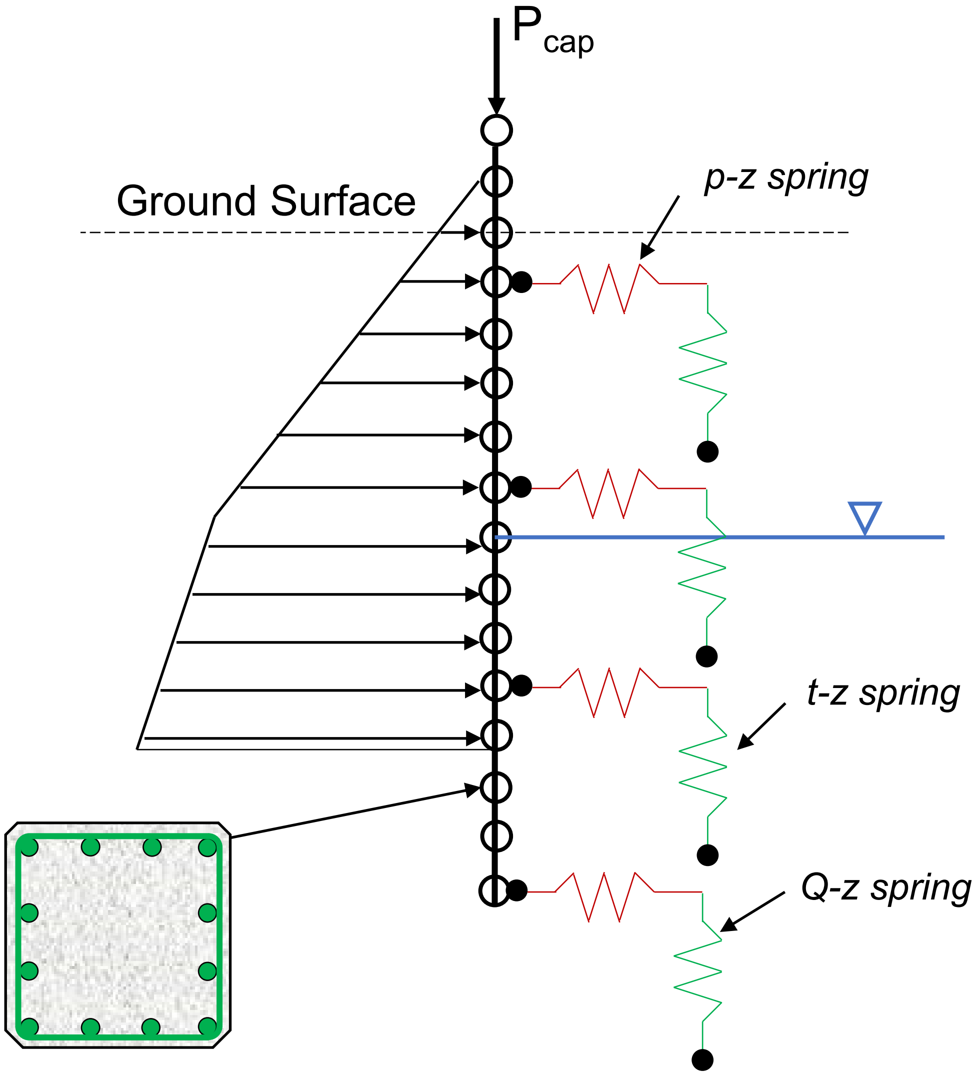


$$Distributed\ Force = Resultant\ Earth\ Pressure \times Pile\ Spacing$$

Pile Example

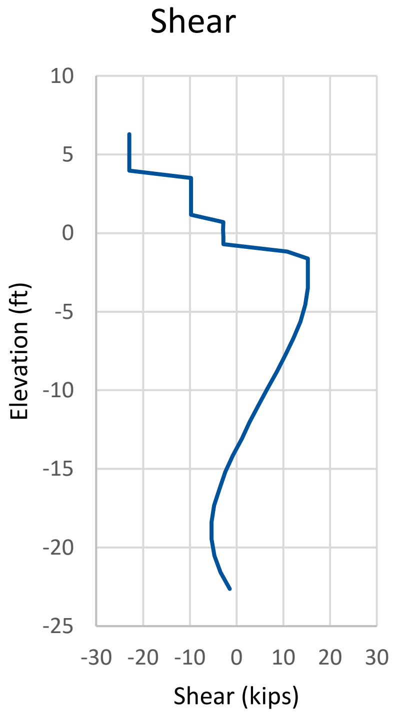
Laterally Loaded Pile Model

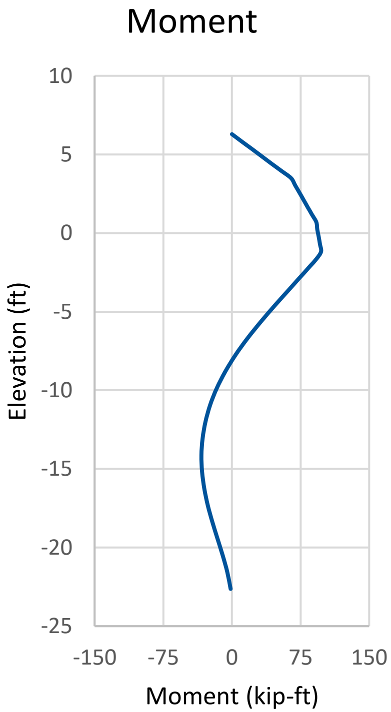


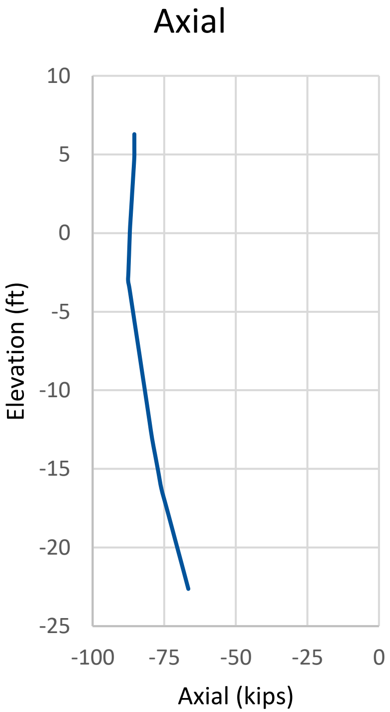


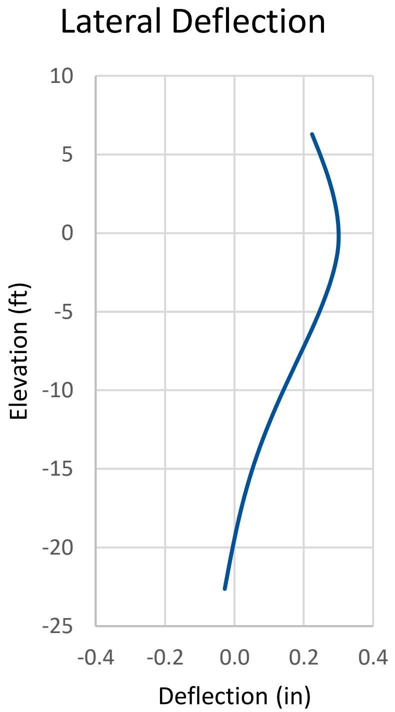
Pile Example

Laterally Loaded Pile Results





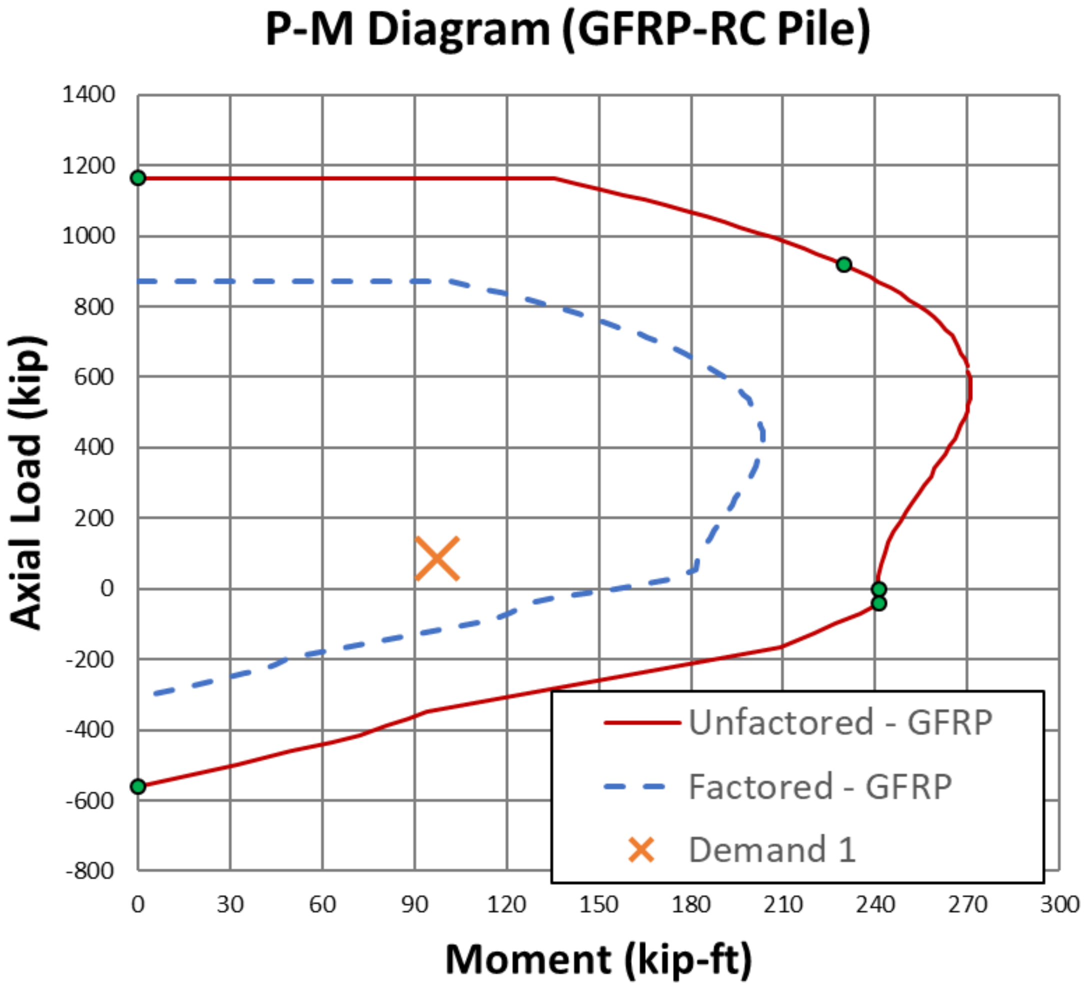




Max:	15.3 kip	97.4 kip-ft	87.7 kip	0.301 in
Min:	-22.9 kip	-33.4 kip-ft	-63.0 kip	-0.037 in

Pile Example

Plotting Demand Point in P-M Diagram



Questions?