AASHTO GFRP-Reinforced Concrete Design Training Course

FDOT

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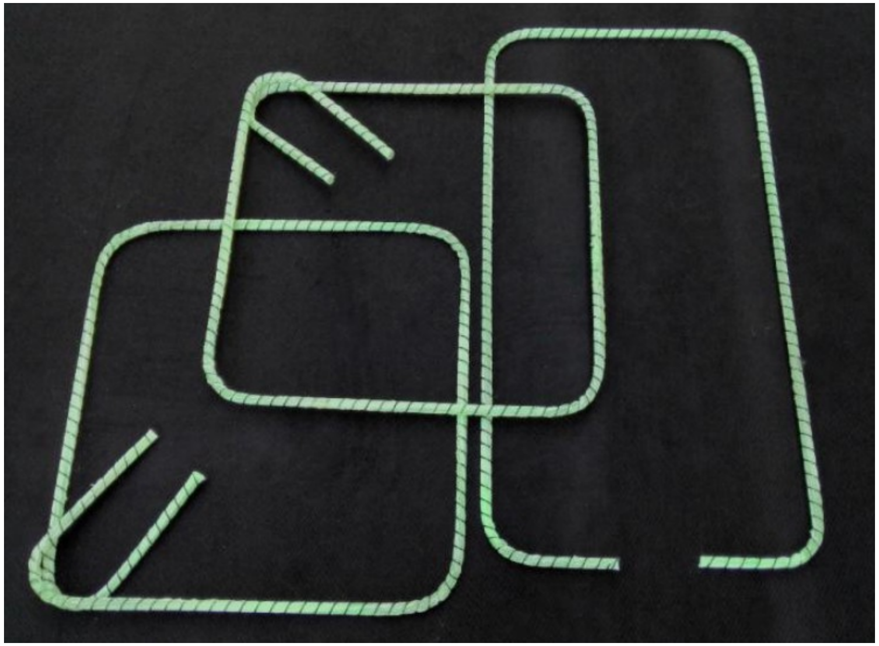
Center for Integration of Composites into Infrastructure

Course Outline

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



3. SHEAR RESPONSE OF GFRP REINFORCED CONCRETE

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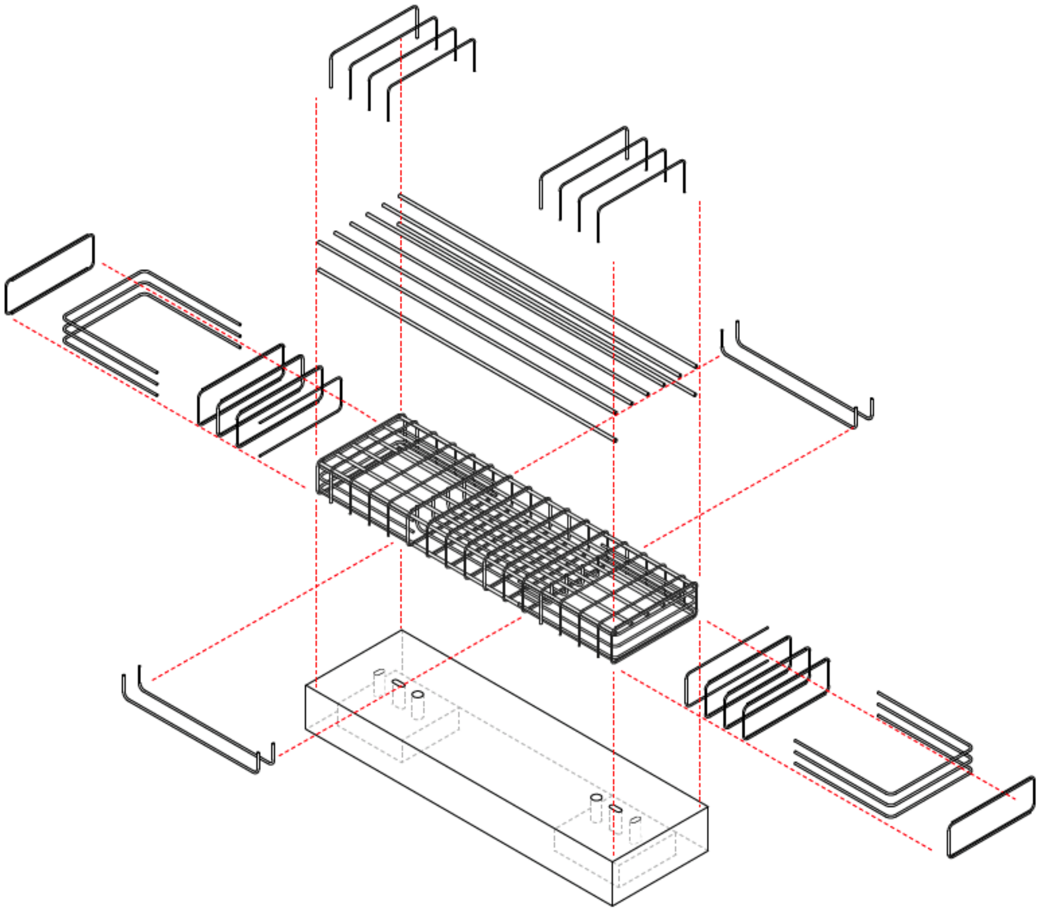
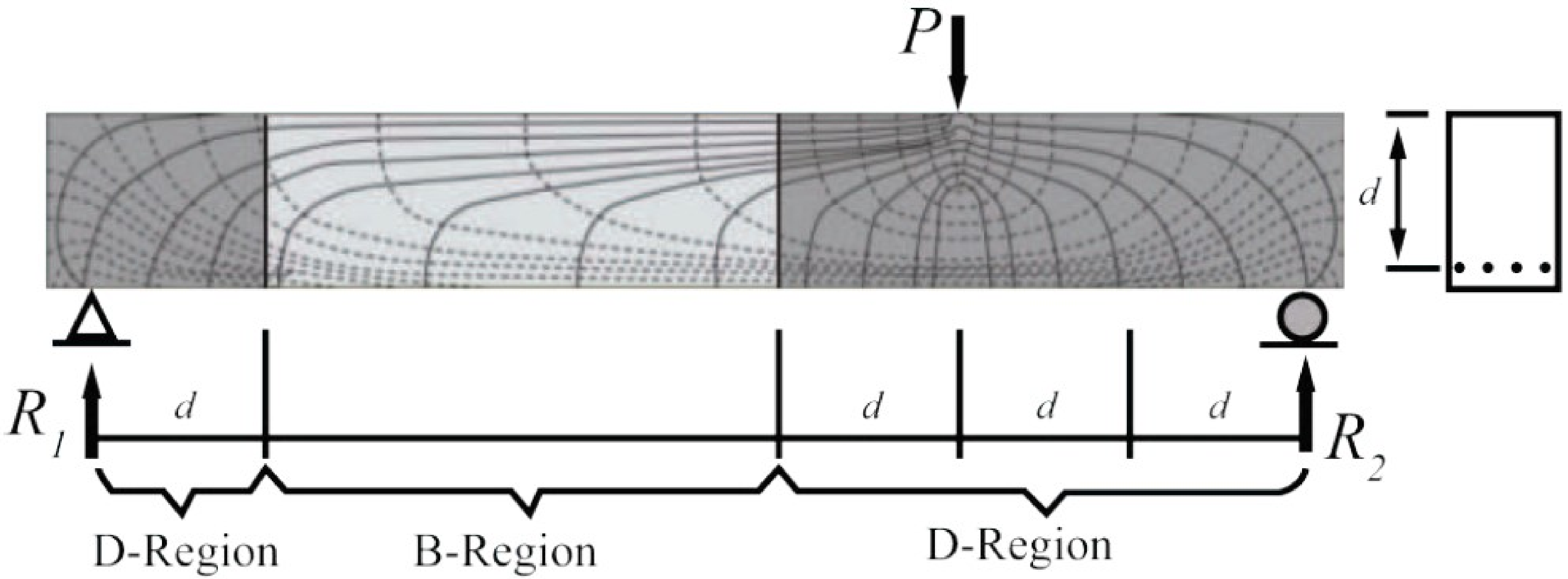


Uncracked Section

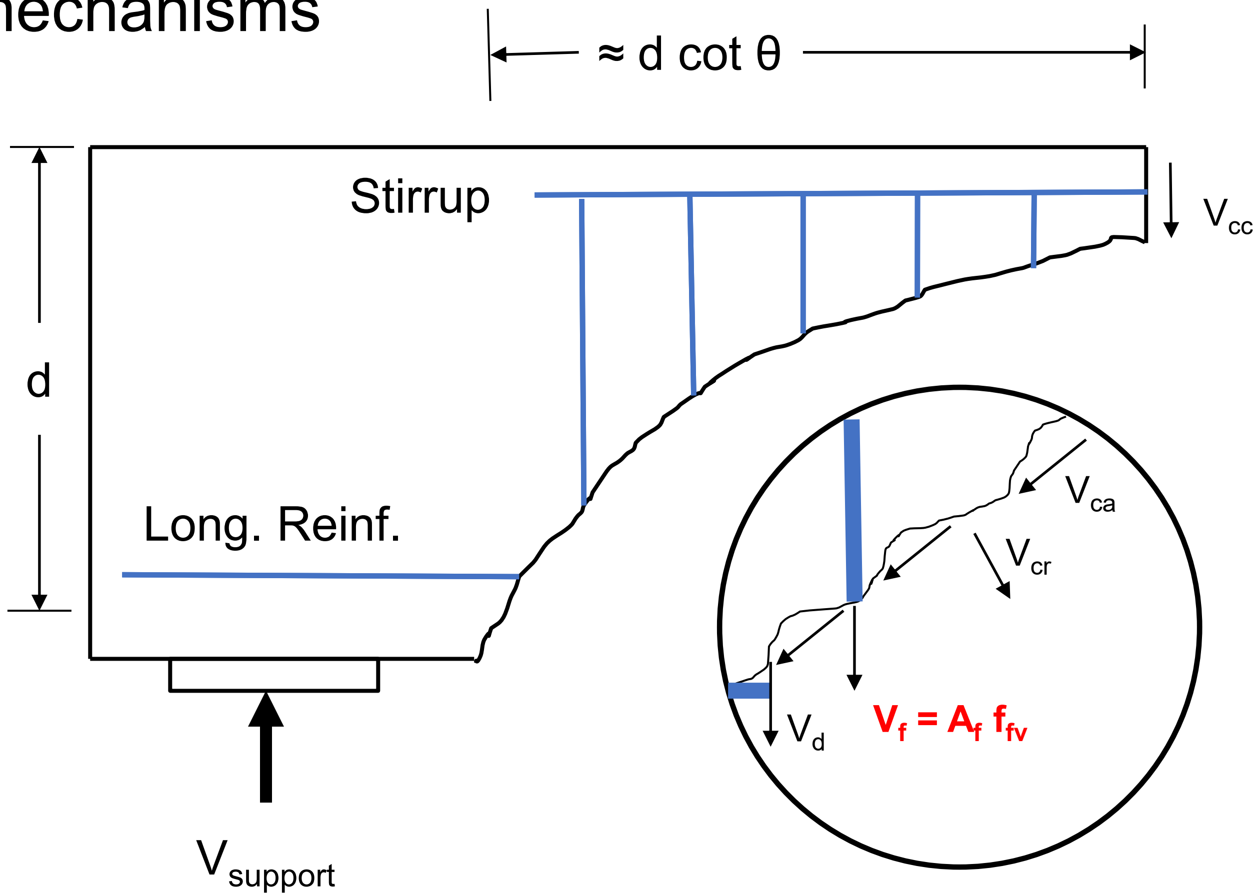
In **uncracked sections**, shear is carried by the concrete itself

Typically, shear crack starts from a flexural crack once the cracking moment exceeds the cracking strength of concrete (tensile rupture)



Cracked Section

In **cracked sections**, shear is carried by complex transfer mechanisms



V_{cc} : Compression Zone Contribution

V_d : Dowel Action

V_{ca} : Aggregate Interlock

V_{cr} : Residual Tensile Strength of Concrete

V_f : GFRP Stirrup Contribution

Components of Shear Resistance in Structural Concrete Beams

Shear Failure

Shear failure modes of members with FRP stirrups

- **Shear-tension failure mode**
  (controlled by the rupture of FRP shear reinforcement)

- **Shear-compression failure mode**
  (controlled by the crushing of the concrete web)

RC with FRP Shear Reinforcement

- Low modulus of elasticity
- High tensile strength and no yield point
- Tensile strength of the bent portion lower than the straight portion
- Low transverse shear resistance (i.e., low dowel action of flexural bars)
- Larger crack widths compared to steel (i.e., lower N.A. depth)

Substitution of FRP for steel on an equal area basis would typically result in **lower shear strength** in both shear reinforced and non-shear reinforced members

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- General Behavior
- **Shear Capacity**
- Punching Shear
- Special Considerations
- Concluding Remarks

Shear Capacity

Ultimate Limit State $V_u \leq \phi V_n$ $\phi = 0.75$

Nominal Shear Resistance $V_n = V_c + V_f$

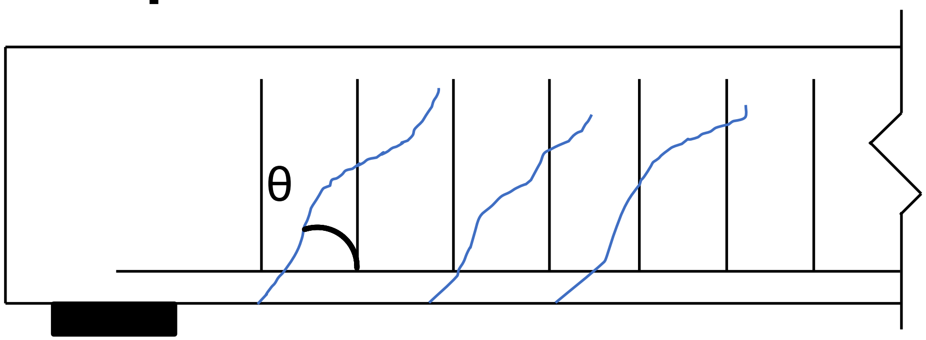
Shear Resistance of Concrete $V_c = 0.0316\beta\sqrt{f_c'}b_v d_v$

(AASHTO 2.7.3.4-1)

Shear Resistance of GFRP Stirrups

$$V_f = \frac{A_{fv} f_{fv} d_v \cot(\theta)}{s}$$

(AASHTO 2.7.3.5-1)



β and ***θ*** are function of the level of strain in the reinforcement (MCFT*), but align to ACI values if the simplified method is used.

*Modified Compression Field Theory

Factor β and θ

β: Factor indicating ability of diagonally cracked concrete to transmit tension and shear
θ: Angle of inclination of diagonal compressive stresses

- **Simplified Method** $\beta = 5k \qquad \theta = 45°$ ***(AASHTO 2.7.3.6.1)***

$$k = \sqrt{2\rho_f n_f + (\rho_f n_f)^2} - \rho_f n_f$$

k: ratio of depth of neutral axis to depth of flexural reinforcement ***(AASHTO 2.5.3-4)***

- **General Method** $\theta = 29 + 3500\varepsilon_f$ ***(AASHTO 2.7.3.6.2-3)***

-Sections with minimum transverse reinforcement ***(AASHTO 2.7.3.6.2-1)***

$$\beta = \frac{4.8}{1 + 750\varepsilon_f}$$

-Sections without minimum transverse reinforcement ***(AASHTO 2.7.3.6.2-2)***

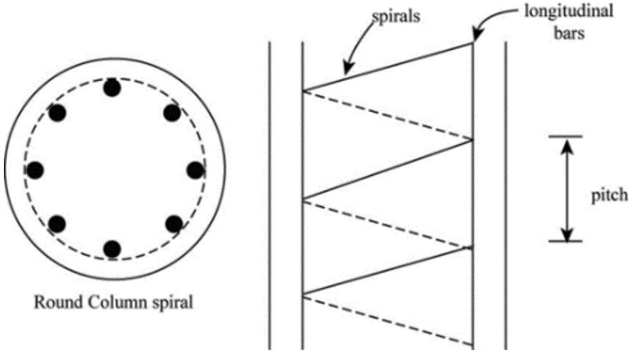
$$\beta = \left(\frac{4.8}{1 + 750\varepsilon_f}\right)\left(\frac{51}{39 + s_{xe}}\right)$$

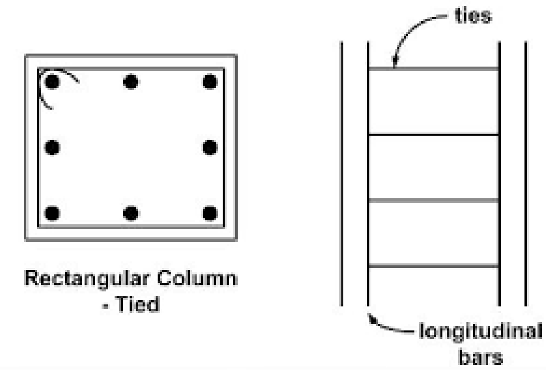
ε_f: longitudinal tensile strain of the GFRP
s_{xe}: crack spacing as influenced by aggregate size ***(AASHTO 2.7.3.6.2-7)***

Transverse Reinforcement

Types of Transverse Reinforcement

- Stirrups or ties
- Spirals or hoops





Shear resistance of FRP reinforcement when using spirals

$$V_f = \frac{A_{fv}\, f_{fv}\, d_v\, (cot\theta + cot\alpha) sin\alpha}{s}$$

(AASHTO 2.7.3.5)

S: Pitch of spiral

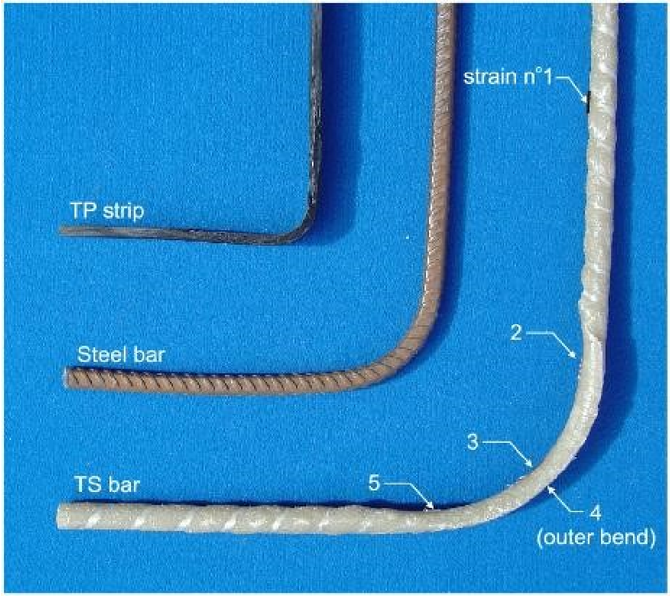
α: Angle of inclination of transverse reinforcement to longitudinal axis

θ: Angle between a strut and the longitudinal axis of a member

Design Tensile Strength

Design Tensile Strength for Shear $f_{f,sd}$

$$f_{f,sd} = min(f_{fv}, f_{fb}, f_{fd})$$ ***(AASHTO 2.7.3.5)***



Tensile Strength of GFRP for Shear Design

$$f_{fv} = 0.004E_f \leq f_{fb}$$

← Typically governs for GFRP

Tensile Strength of GFRP at Bends

$$f_{fb} = \left(0.05\,\frac{r_b}{d_b} + 0.3\right) f_{fu} \leq f_{fu}$$

r_b = internal radius of bend of reinforcing bar
d_b = diameter of reinforcing bar

Tensile Strength of GFRP

$$f_{fd} = C_E f_{fu}^{*}$$

← **FDOT 932-3** requires this to ≥ 60% of straight bars for qualification

Transverse Reinforcement

- For any member required when: $V_u > \dfrac{\phi V_c}{2}$
- Except for the slabs and footings: $V_u > \phi V_c$

Minimum GFRP Transverse Reinforcement

$$A_{fv,min} \geq 0.05\frac{b_v s}{f_{fv}}$$ ***(AASHTO 2.7.2.4-1)***

Maximum GFRP Transverse Reinforcement

$$V_f \leq 0.25\sqrt{f_c'}\,b_v d_v$$ ***(AASHTO 2.7.2.5)***

Maximum Spacing of Transverse Reinforcement

$$S \leq Min\,\{0.5d\,,24\;in.\}$$ ***(AASHTO 2.7.2.6)***

FRP Stirrups

- GFRP stirrups should be provided with 90-degree hooks
- Required tail length for GFRP stirrups: $L_{thf} \geq 12d_b$ ***(AASHTO C2.10.2.3.2)***
- Maximum tensile strain in FRP shear reinforcement: ***0.004*** ***(AASHTO 2.7.3.5-2)***
- A minimum $\frac{r_b}{d_b} = 3$ is recommended

r_b= bend radius
d_b=bar diameter

TABLE 4 Minimum Inside Bend Diameter of Bent Bars[A]

Bar Designation, mm [U.S. Standard]	Minimum Bend Diameter mm [in.]
M6 [2]	38 [1.50]
M10 [3]	58 [2.25]
M13 [4]	76 [3.00]
M16 [5]	96 [3.75]
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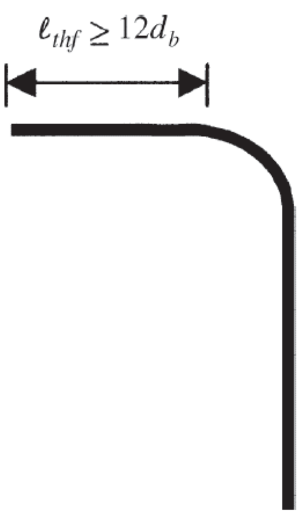
(ASTM D7957)



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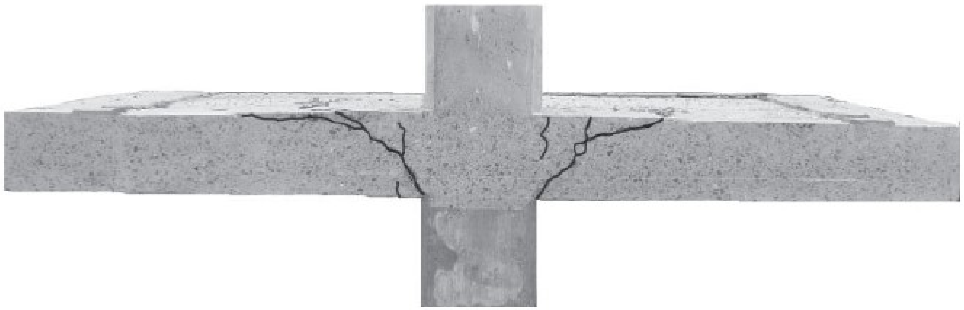

Punching Shear

Shear Resistance of the Concrete

Two-way shear $V_c = 0.316k\sqrt{f_c'}\,b_0\,d_v$ ***(AASHTO 2.10.5.1.3)***

k: ratio of depth of neutral axis to depth of flexural reinforcement

b_0: computed $\frac{d}{2}$ away from the column face

For Members with Transverse Reinforcement

$$V_f = \frac{A_{fv}\,f_{fv}\,d_v}{s}$$

(AASHTO 2.10.5.1.3)

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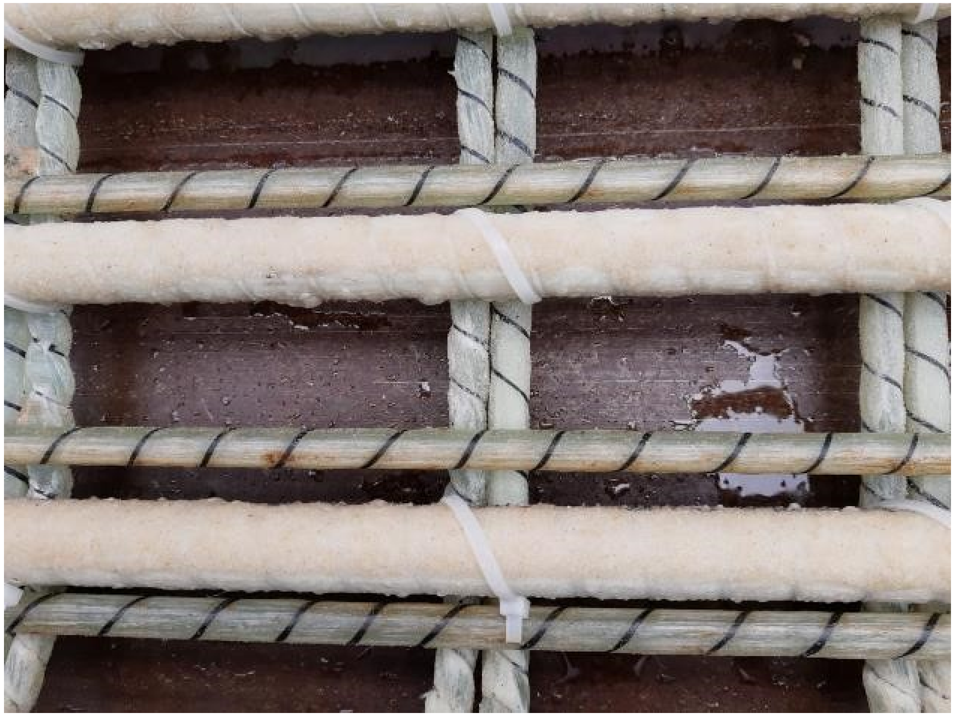
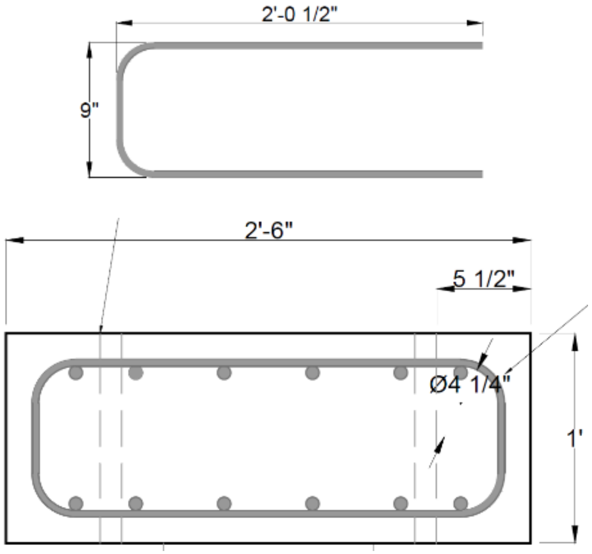
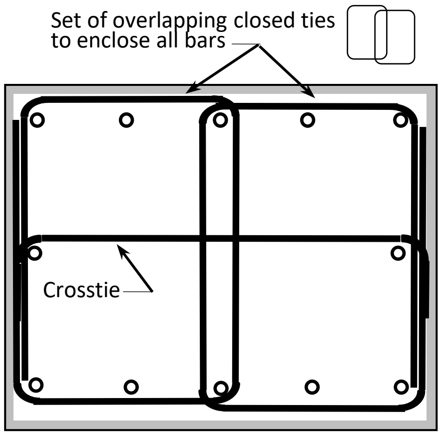


Special Considerations

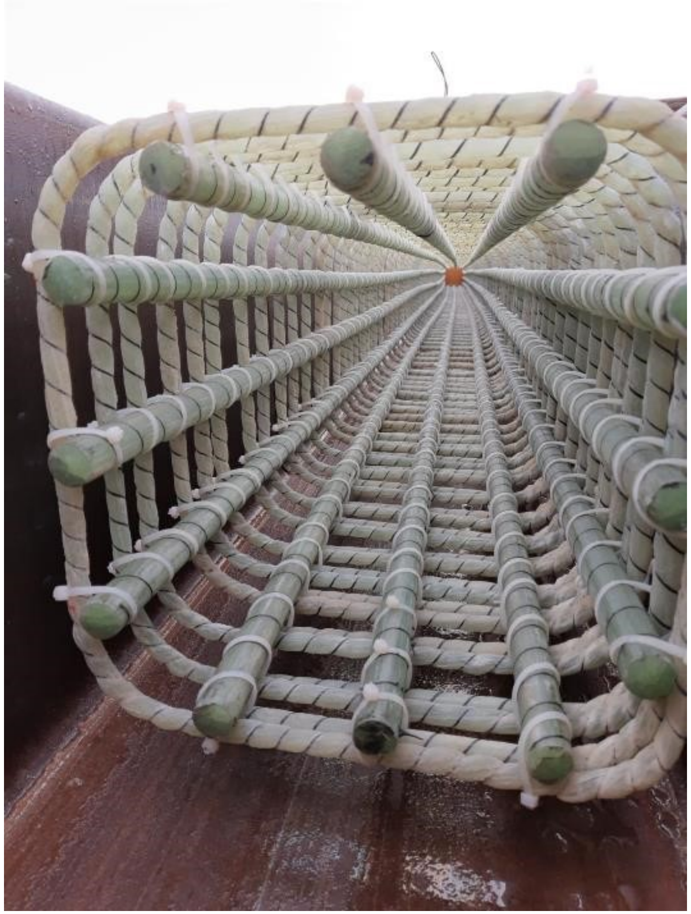
- **90-degree bends** instead of 135-degree
- Typically **two overlapping "C or U" stirrups** are used instead of a closed loop stirrup





Special Considerations

- Field bending or straightening of GFRP bars **not possible**
- All stirrups are **pre-bent**



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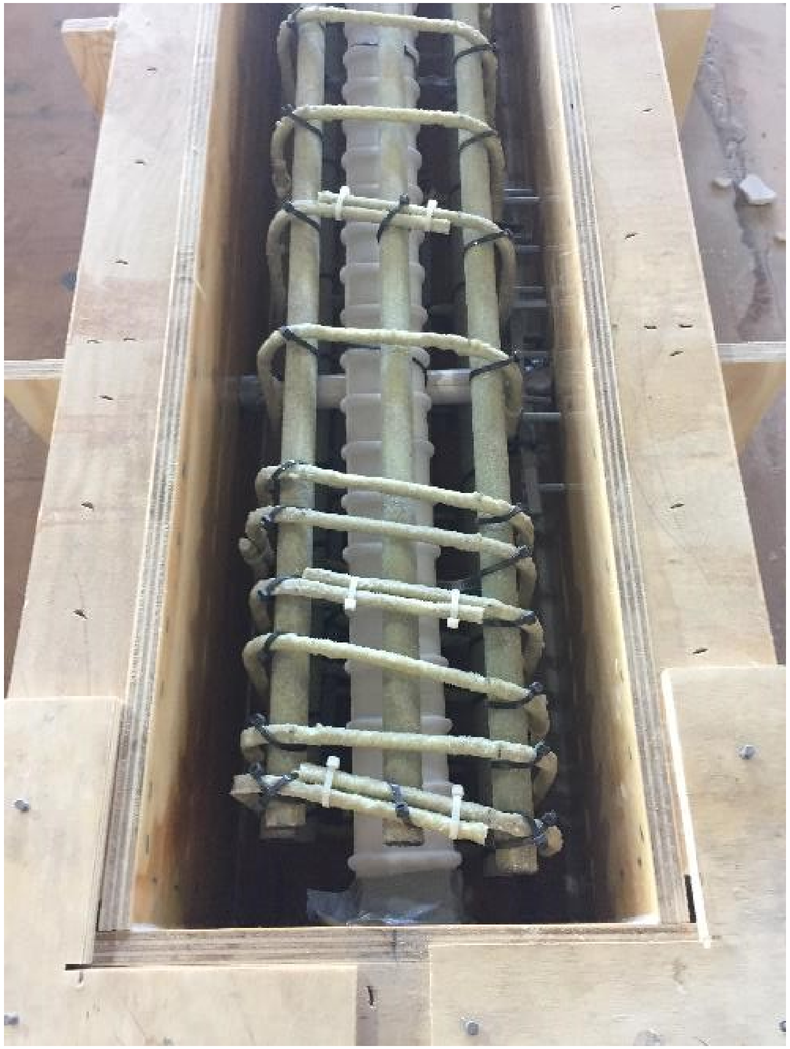

Concluding Remarks

- Shear equations and structural theory remain mostly the same as for conventional steel-RC
- The contribution of both concrete and stirrups to **shear capacity is reduced** in FRP-RC
- Closer stirrup spacing because of lower strength and stiffness
- Strength of FRP stirrups is reduced at bends
- A limit on FRP stirrup strain is imposed because of crack width concerns
- Complex bent shapes are currently not available, but technology is advancing

Questions?

Thank U

SHEAR RESPONSE OF GFRP REINFORCED CONCRETE

3.1 Review Questions: Fundamentals

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Review Questions

3.1.1) For GFRP stirrups, does the maximum amount of transverse reinforcement requirement similar to steel-RC still apply: ___________________________.

a. True

b. False

Transverse Reinforcement

- Required when: $V_u > \frac{\phi V_c}{2}$
- For the slabs and footings: $V_u > \phi V_c$

Minimum GFRP Transverse Reinforcement

$$A_{fv,min} \geq 0.05 \frac{b_v s}{f_{fv}}$$

Maximum GFRP Transverse Reinforcement

$$V_f \leq 0.25\sqrt{f_c'} b_v d_v$$

(AASHTO 2.7.2.5)

Maximum Spacing of Transverse Reinforcement

$$S \leq Min\,\{0.5d\,, 24in.\}$$

(AASHTO 2.7.2.6)

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Review Questions

3.1.1) For GFRP stirrups, does the maximum amount of transverse reinforcement requirement similar to steel-RC still apply: ___________________________.

a. True

b. False

Review Questions

3.1.2) The shear strength of GFRP-RC members: ________________________.

a. Is comparable to the shear strength of steel-RC members

b. Is lower than the shear strength of steel-RC members

c. Is higher than to the shear strength of steel-RC members

d. Cannot be compared to the shear strength of steel-RC members

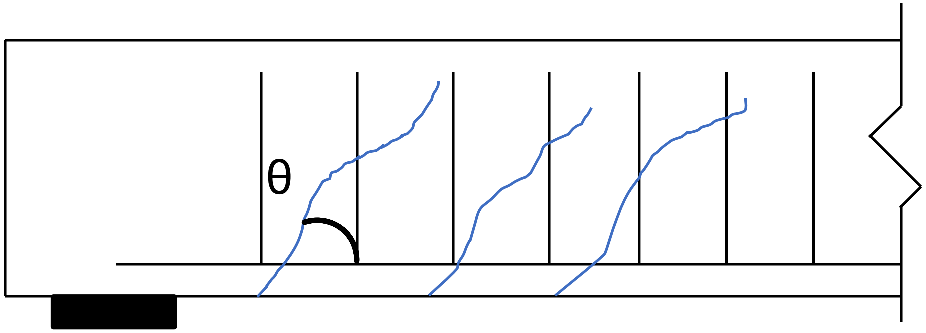
Shear Capacity

Ultimate Limit State $V_u \leq \phi\, V_n$ $\phi = 0.75$

Nominal Shear Resistance $V_n = V_c + V_f$

Shear Resistance of Concrete $V_c = 0.0316\beta\sqrt{f_c'}\,b_v d_v$ ***(AASHTO 2.7.3.4)***

Shear Resistance of GFRP Stirrups $V_f = \dfrac{A_{fv}\, f_{fv}\, d_v \cot(\theta)}{s}$ ***(AASHTO 2.7.3.5)***



β and θ are a function of the level of strain in the reinforcement (MCFT) but aligns to ACI values if the simplified method is used

Review Questions

3.1.2) The shear strength of GFRP-RC members:
_______________________.

a. Is comparable to the shear strength of steel-RC members

b. Is lower than the shear strength of steel-RC members

c. Is higher than to the shear strength of steel-RC members

d. Cannot be compared to the shear strength of steel-RC members

Review Questions

3.1.3) The required tail length of GFRP stirrups is at least equal to or more than: ______________________________.

a. 4 times the bar diameter

b. 8 times the bar diameter

c. 12 times the bar diameter

d. 16 times the bar diameter

FRP Stirrups

- GFRP stirrups should be provided with 90-degree hooks
- Required tail length for GFRP stirrups: $L_{thf} \geq 12d_b$ ***(AASHTO C2.10.2.3.2)***
- Maximum tensile strain in FRP shear reinforcement: 0.004 ***(AASHTO 2.7.3.5-2)***
- A minimum $\frac{r_b}{d_b} = 3$ is recommended

r_b= bend radius
d_b=bar diameter

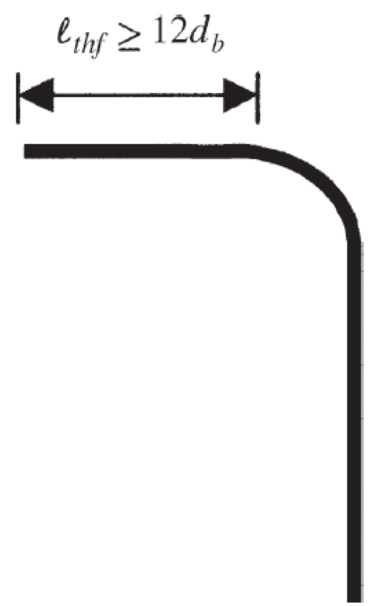


TABLE 4 Minimum Inside Bend Diameter of Bent Bars[A]

Bar Designation, mm [U.S. Standard]	Minimum Bend Diameter mm [in.]
M6 [2]	38 [1.50]
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M22 [7]	134 [5.25]
M25 [8]	152 [6.00]

(ASTM D7957)

Review Questions

3.1.3) The required tail length of GFRP stirrups is at least equal to or more than: ______________________________.

a. 4 times the bar diameter

b. 8 times the bar diameter

c. 12 times the bar diameter

d. 16 times the bar diameter

Review Questions

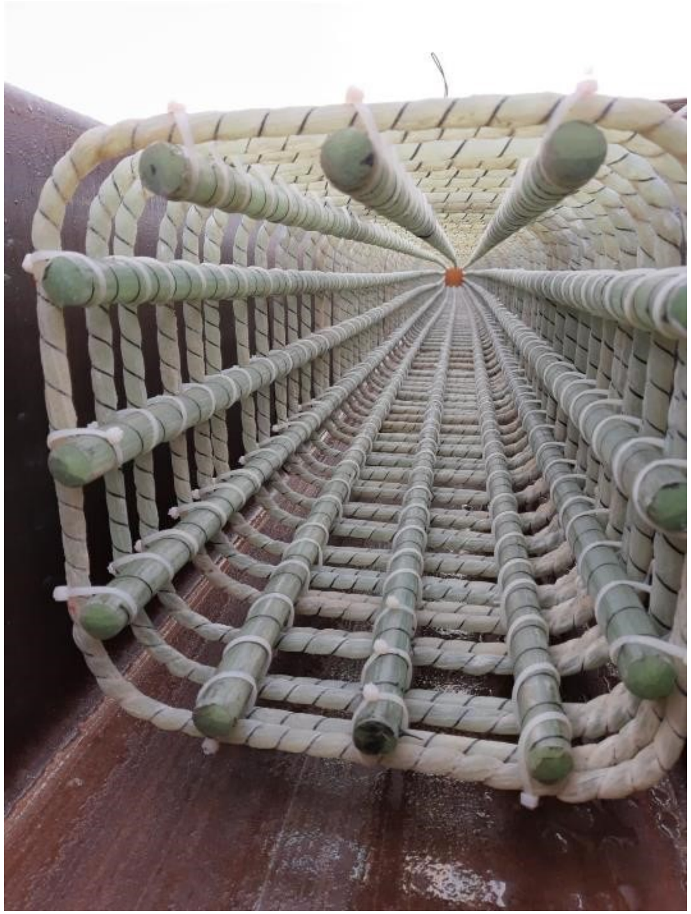
3.1.4) GFRP stirrups can be bent on site with EOR approval?

a. True

b. False

Special Considerations

- Field bending or straightening of GFRP bars **not possible**
- All stirrups are **pre-bent**



Review Questions

3.1.4) GFRP stirrups can be bent on site with EOR approval?

a. True

b. False

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Review Questions

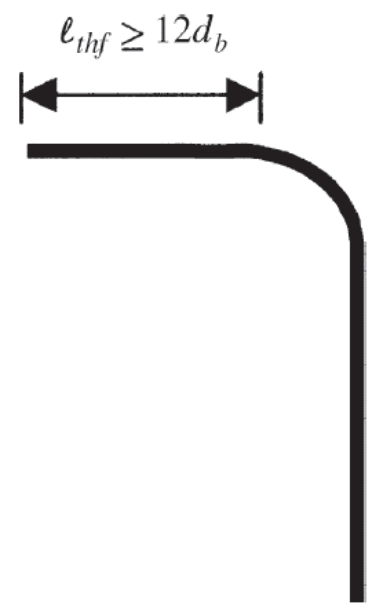
3.1.5) The minimum bent radius allowed for a GFRP stirrup is generally ___________. (Select all that apply)

a. Larger than required for steel, with a minimum of $r_b/d_b = 3$
b. Can be equivalent to steel, if verified by manufacturer
c. Smaller than required for steel reinforcement due to lower elastic modulus
d. Dependent on field bending and cannot be prescribed

FRP Stirrups

- GFRP stirrups should be provided with 90-degree hooks
- Required tail length for GFRP stirrups: $L_{thf} \geq 12d_b$ ***(AASHTO C2.10.2.3.2)***
- Maximum tensile strain in FRP shear reinforcement: ***0.004*** ***(ACI 440.1R8.3)***
- A minimum $\frac{r_b}{d_b} = 3$ is recommended

r_b= bend radius
d_b=bar diameter



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(ASTM D7957)

Review Questions

3.1.5) The minimum bent radius allowed for a GFRP stirrup is generally ___________. (Select all that apply)

a. **Larger than required for steel, with a min. of $r_b/d_b = 3$**
b. **Can be equivalent to steel, if verified by manufacturer**
c. Smaller than required for steel reinforcement due to lower elastic modulus
d. Dependent on field bending and cannot be prescribed

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Review Questions

3.1.6) When designing GFRP shear reinforcement, the following shapes are possible to manufacturer: __________. (Select all that apply)

a. Two C's

b. Two U's

c. Closed stirrup, providing the tails overlap

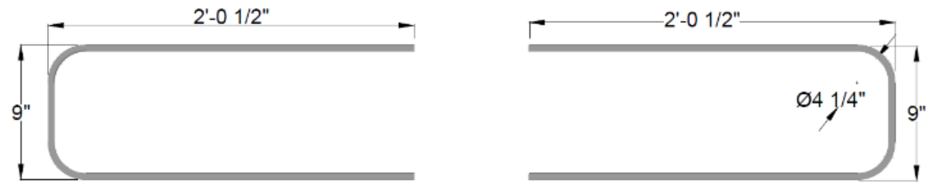
d. L shapes for end hooks

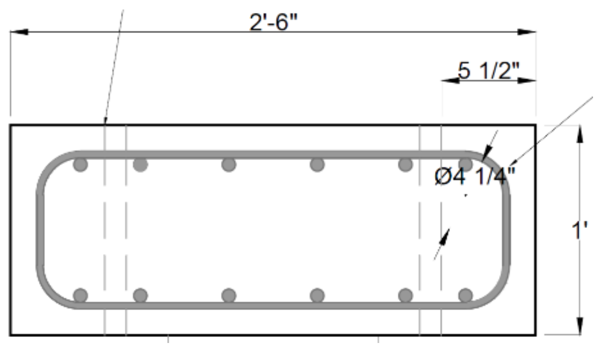
e. Special bends for complex shapes

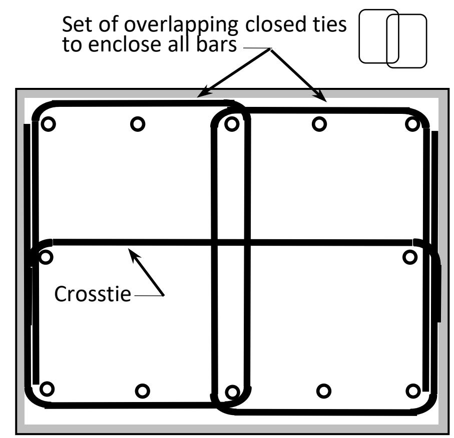
Special Considerations

- **90-degree bends** instead of 135-degree

- Typically **two overlapping "C or U" stirrups** are used instead of a closed loop stirrup.







Applied Questions

3.1.6. When designing GFRP shear reinforcement, the following shapes are possible to manufacturer: __________. (Select all that apply)

- **a. Two C's**
- **b. Two U's**
- **c. Closed stirrup, providing the tails overlap**
- **d. L shapes for end hooks**
- **e. Special bends for complex shapes**

Review Questions

3.1.7) The maximum spacing of transverse GFRP reinforcement is generally ___________.

a. 12 in.

b. 24 in.

c. 0.5d

d. Minimum value of 0.5d* or 24in.

* Flexural reinforcement depth

Transverse Reinforcement

- Required when: $V_u > \frac{\phi V_c}{2}$
- For the slabs and footings: $V_u > \phi V_c$

Minimum GFRP Transverse Reinforcement

$$A_{fv,min} \geq 0.05 \frac{b_v s}{f_{fv}}$$

Maximum GFRP Transverse Reinforcement

$$V_f \leq 0.25\sqrt{f_c'} b_v d_v$$

(AASHTO 2.7.2.5)

Maximum Spacing of Transverse Reinforcement

$$S \leq Min\,\{0.5d\,, 24in.\}$$

(AASHTO 2.7.2.6)

Review Questions

3.1.7) The maximum spacing of GFRP transverse reinforcement is generally ___________.

a. 12 in.

b. 24 in.

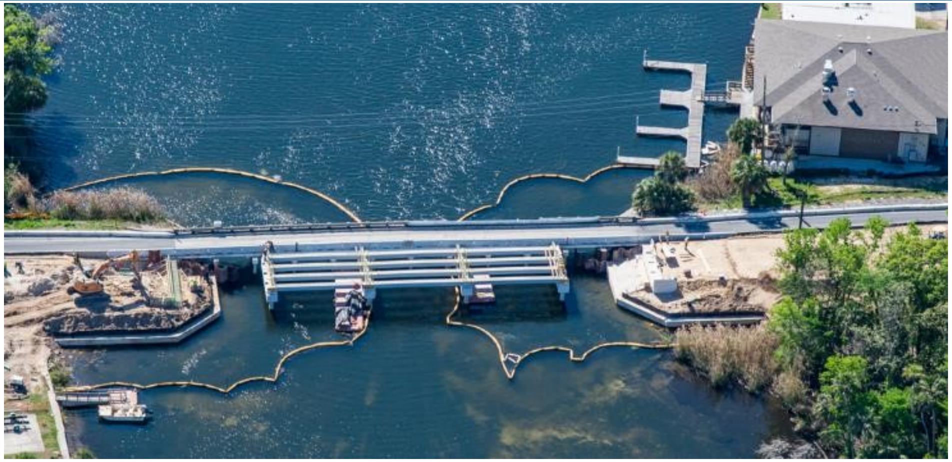
c. 0.5 d

d. Minimum value of 0.5d* or 24in.

*Flexural reinforcement depth

SHEAR RESPONSE OF GFRP REINFORCED CONCRETE

3.2 Design Example: Bent Cap (Halls River Bridge)



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Shear Design Flowchart

Shear Design

$$V_u \leq V_r = \phi V_n = 0.75(V_c + V_f)$$

Find nominal shear resistance of the concrete (V_c)

$$V_c = 0.0316\beta\sqrt{f_c'}\,b_v d_v$$

Find shear strength of transverse reinforcement ($f_{f,sd}$)

$$f_{f,sd} = min(f_{fv}, f_{fb}, f_{fd})$$

Shear Design Flowchart

Find design tensile strength of GFRP (f_{fd})

$$f_{fd} = C_E \cdot f_{fu}$$

Find design tensile strength of bent (f_{fb})

$$f_{fb} = min\left(0.05\,\frac{r_b}{d_b} + 0.3, 1\right) f_{fd}$$

Find tensile strength of GFRP for shear design (f_{fv})

$$f_{fv} = \min(\,0.004E_f, f_{fb})$$

Shear Design Flowchart

Select $A_{fv} \geq A_{fv.min}$

$$A_{fv,min} \geq 0.05 \frac{b_v s}{f_{fv}}$$

Find shear resistance of GFRP (V_f)

$$V_f = \frac{A_{fv} f_{fv} d_v \cot(\theta)}{s}$$

Find nominal shear strength

$$V_n = V_c + V_f$$

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Shear Design Flowchart

Check shear design

↓

$$V_u \le V_r = \phi V_n = 0.75(V_c + V_f)$$

↓

Check spacing of GFRP stirrups

↓

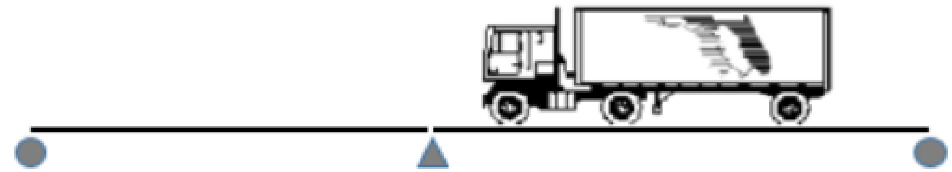
$$S = Min\{0.5d\,, 24in.\}$$

↓

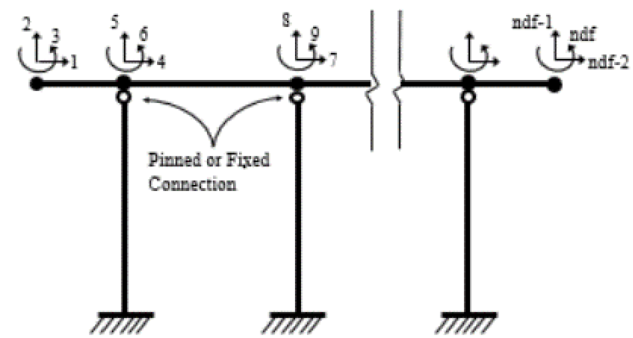
Finish

Bent Cap- Halls River Bridge

Part 1: Load Generator

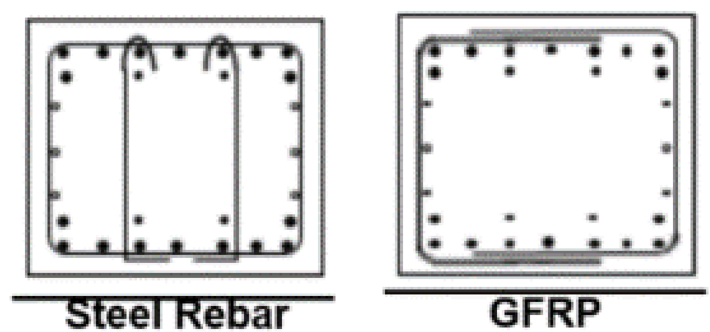


Part 2: Frame Analysis



Bent Cap Analysis Model

Part 3: Design & AASHTO Checks



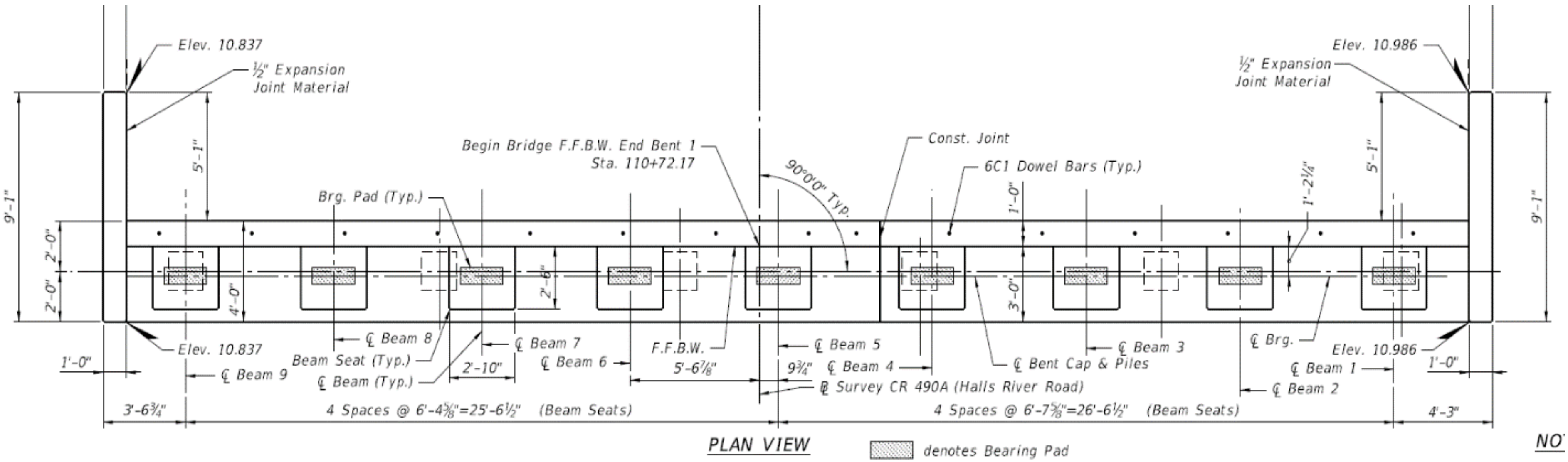
Bent Cap- Halls River Bridge

Part 1: Load Generator

Input Data

Number of columns	6
Column spacing	10.38 ft.
Column width	18 in.

Number of beams	9
Beam spacing	6.63 ft.
Beam width	24 in.
Beam height	21 in.
Beam self weight	181 plf.

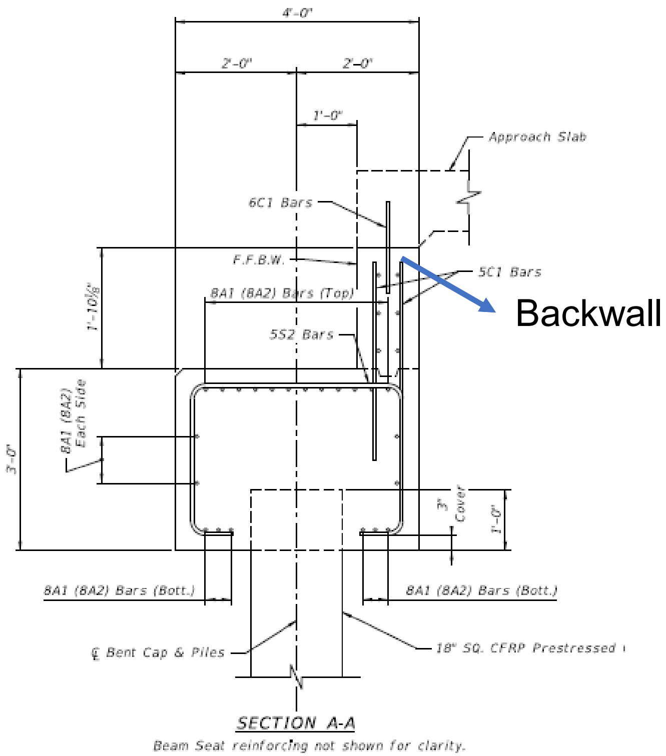


Bent Cap- Halls River Bridge

Part 1: Load Generator

Input Data

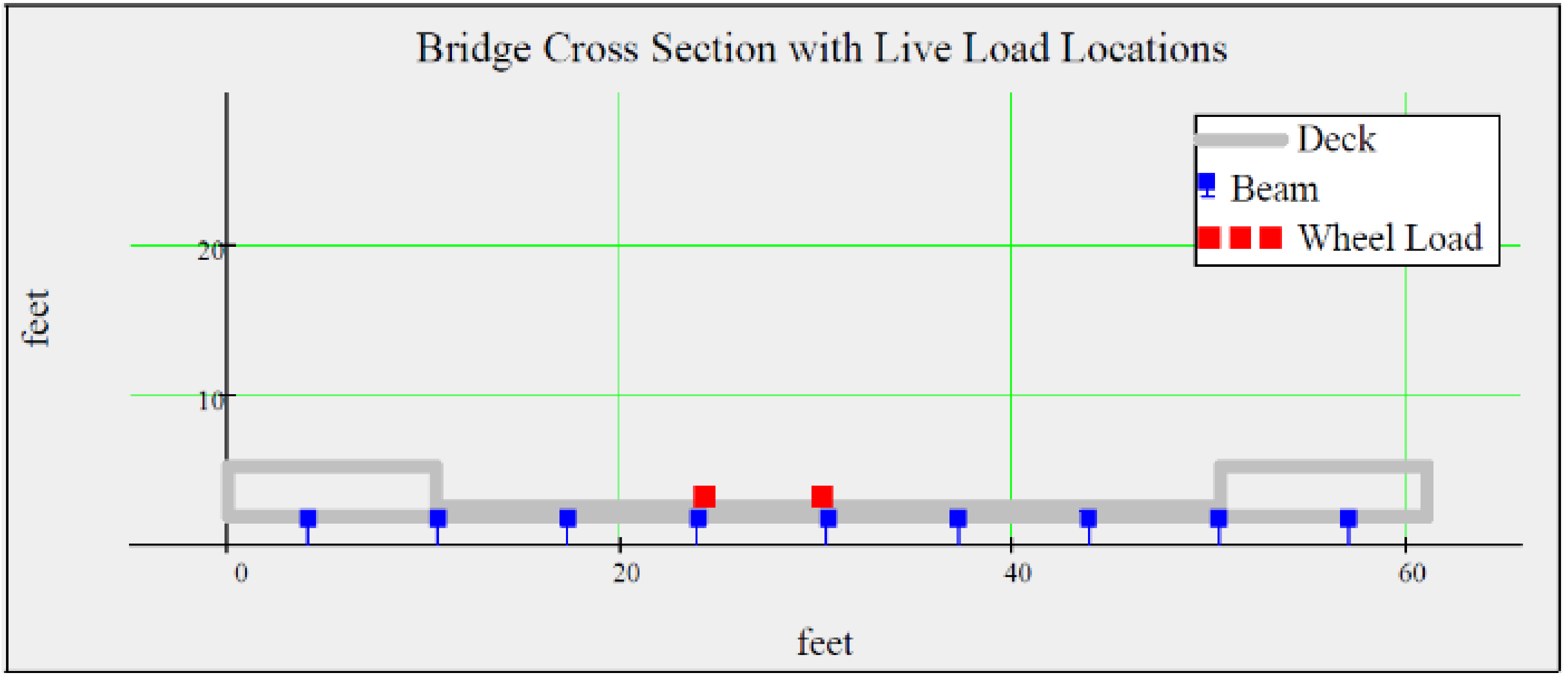
Cap height	36 in.
Cap width	48 in.
Cap length	59.9 ft.



Dead load of wearing surfaces and utilities	165 lb./ft.
Additional dead load of structural and nonstructural attachments	20 lb./ft.

Part 1: Load Generator

Bridge cross section with live load locations generated by MathCad program



Beam Live Loads

$$P_{LL.beam}^{T} = (0.0 \quad 0.0 \quad 0.0 \quad 59.5 \quad 59.9 \quad 0.0 \quad 0.0 \quad 0.0 \quad 0.0) \cdot kip$$

Part 1: Load Generator

Summary of factored loads on cap generated by Mathcad

Mathcad worksheet computes all loads on the bent cap from the beam reactions. Live loads are generated for each beam using the lever rule and tributary area methods

Factored total load parallel to cap (x)

$$P_{cap.x} = \begin{pmatrix} 0 \\ 11.37 \\ 8.02 \\ 7.01 \\ 0 \\ 0 \\ 0 \\ 11.37 \\ 8.02 \\ 0 \end{pmatrix} \cdot kip$$

Factored total load perpendicular to cap (z)

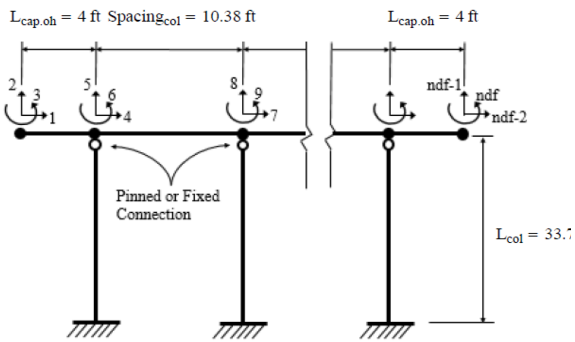
$$P_{cap.z} = \begin{pmatrix} 80.32 \\ 8.07 \\ 66.43 \\ 49.65 \\ 36.72 \\ 0 \\ 80.32 \\ 8.07 \\ 66.43 \\ 0 \end{pmatrix} \cdot kip$$

Load cases per LRFD

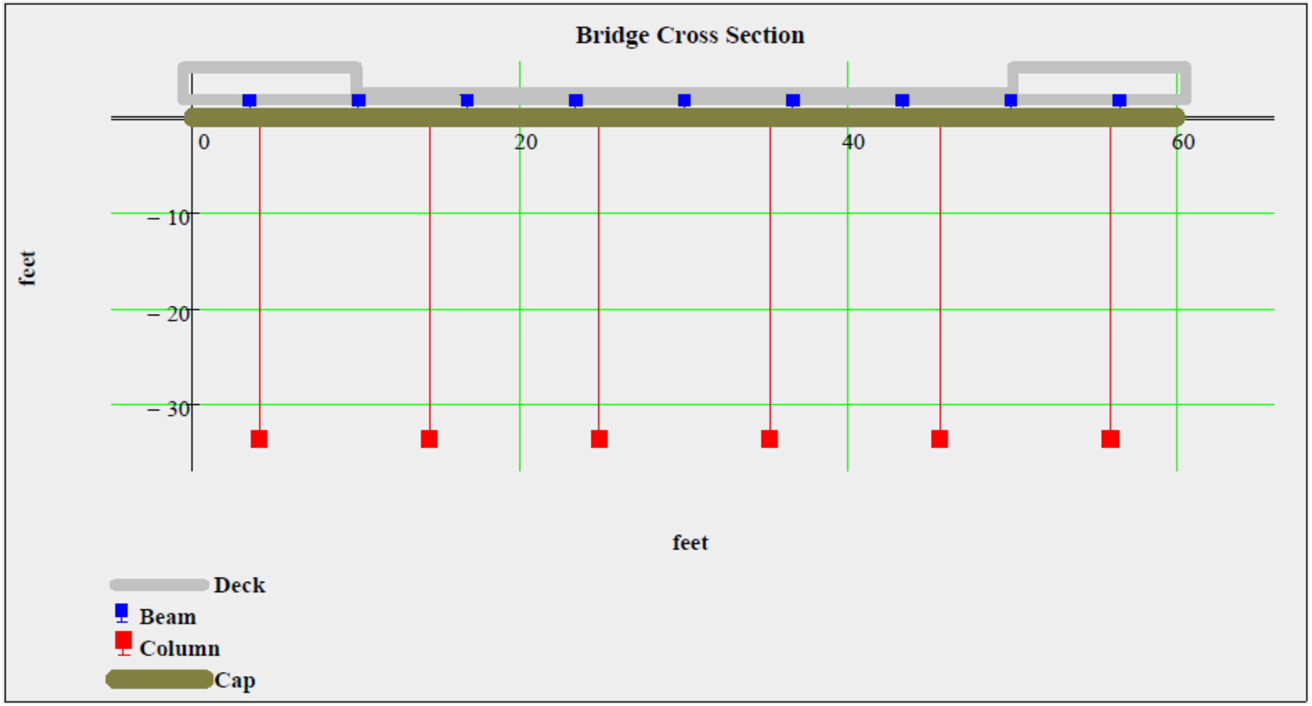
$$\begin{pmatrix} \text{"Strength I max vertical"} \\ \text{"Strength III max vertical"} \\ \text{"Strength V max vertical"} \\ \text{"Service I"} \\ \text{"Service III"} \\ \text{"Sustained load: DL+0.2LL"} \\ \text{"Strength I min vertical"} \\ \text{"Strength III min vertical"} \\ \text{"Strength V min vertical"} \\ \text{"DL+Fatigue I"} \end{pmatrix}$$

Part 2: Frame Analysis

Connection of columns to bent cap (Fixed or Pinned)	Fixed
Beam load	Distributed

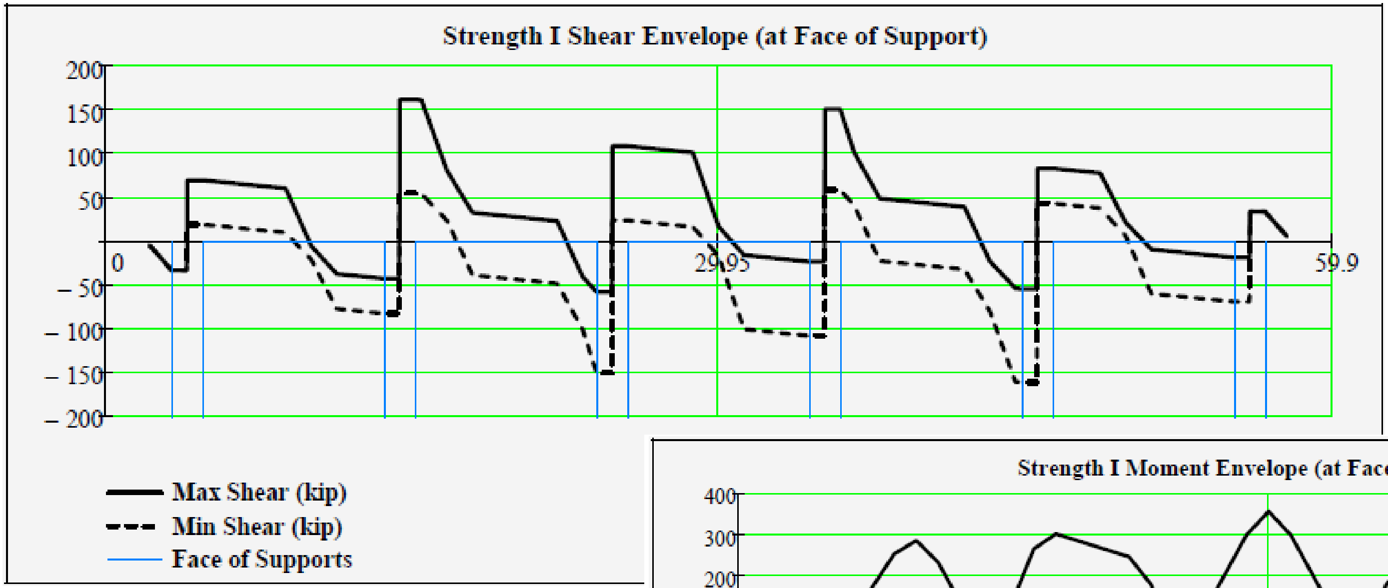


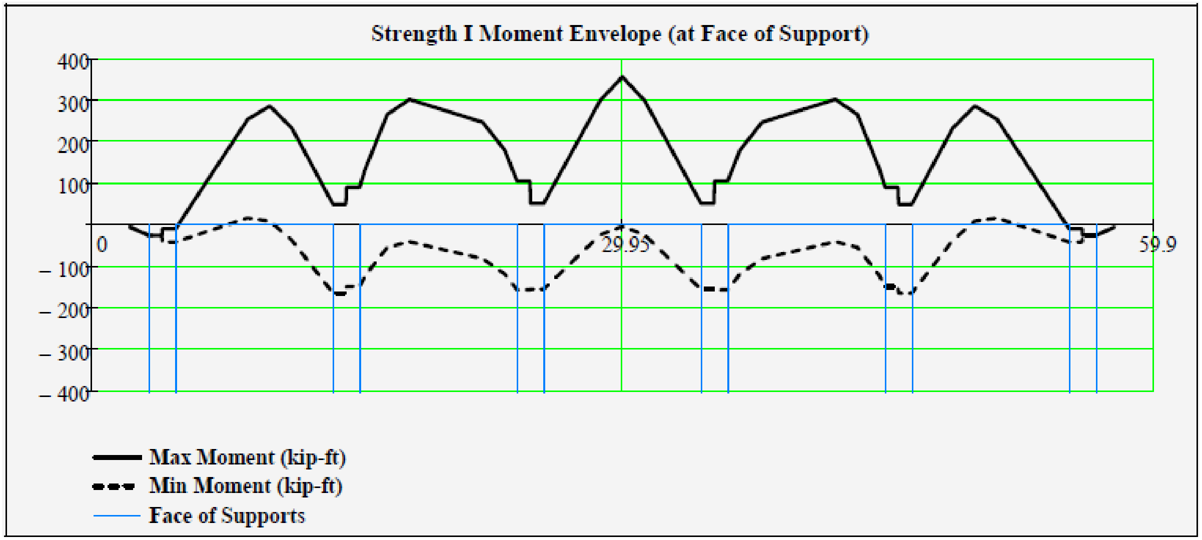
Bent Cap Analysis Model



Part 2: Frame Analysis

Shear and Moment Diagrams for Limit State Strength I (max vertical load)





Part 3: GFRP Design & AASHTO Checks

Environmental reduction factor (C_E)	0.7
Tensile modulus of elasticity (E_f)	6,500 ksi

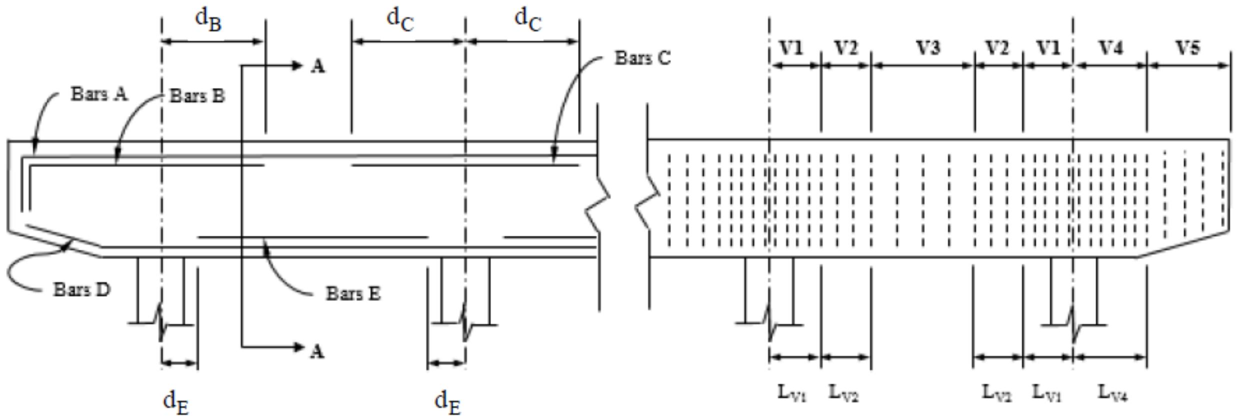
Shear Reinforcement

Zone V1

Size of stirrup bar	4
No. of bar legs	4
Spacing	4 in.
Length of Zone V1 (L_{v1})	36 in.

Zone V2

Size of stirrup bar	4
No. of bar legs	4
Spacing	8 in.
Length of Zone V2 (L_{v2})	36 in.

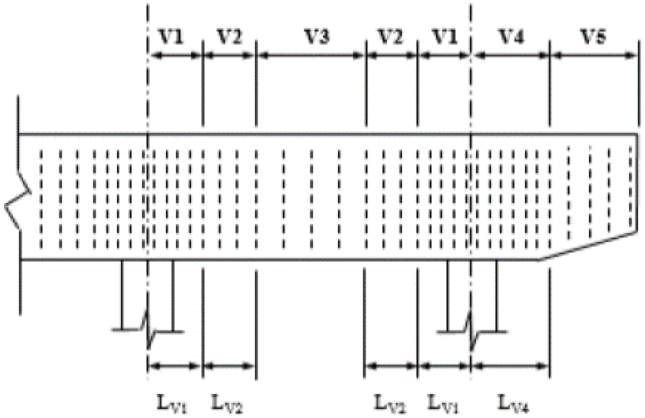


Zone V3

Size of stirrup bar	4
No. of bar legs	4
Spacing	12 in.

Zone V4 (Cap overhang)

Size of stirrup bar	4
No. of bar legs	4
Spacing	12 in.
Length of Zone V4 (L_{v4})	36 in.



Zone V5 (Cap overhang)

Size of stirrup bar	4
No. of bar legs	4
Spacing	12 in.

Shear Design Example

Nominal Shear Resistance of the Concrete

$$V_c = 0.0316\beta\sqrt{f_c'}b_v d_v = 64.75 \text{ kip}$$

Simplified method for concrete sections not subjected to axial tension

$\beta = 5k$ ***(AASHTO 2.7.3.6.1)***

Shear Resistance of GFRP Reinforcement

$$V_f = \frac{A_{fv}\, f_{fv}\, d_v \cot(\theta)}{s} = 137\ kip$$

The Maximum Demand to Capacity Ratio

$V_u = 162\ kip$

$V_r = 0.75\ (64.75 + 137) = 151 kip$

$$\boldsymbol{max\ \frac{V_u}{V_r} = 1.07}$$

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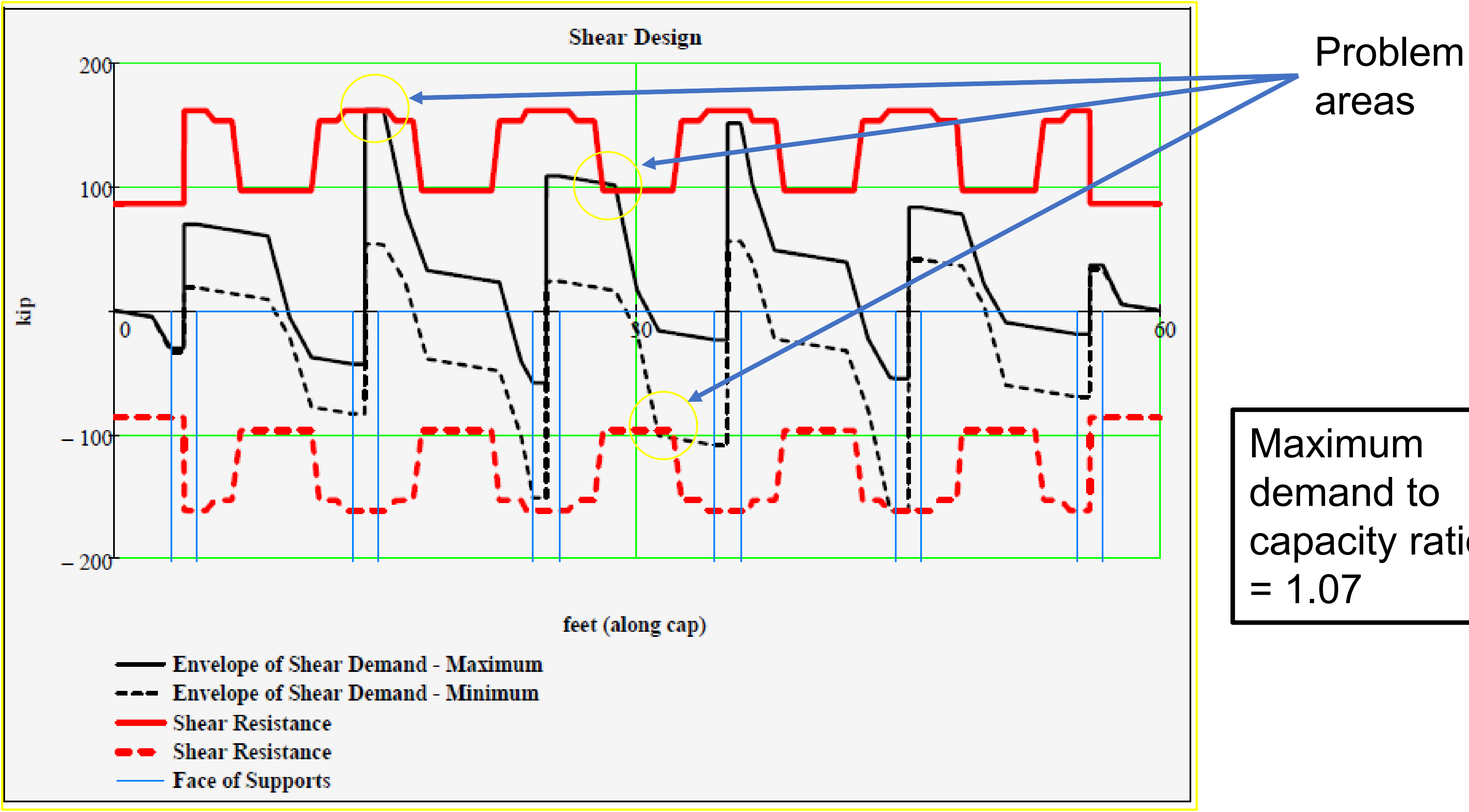
Shear Design Example



Maximum demand to capacity ratio = 1.07

AASHTO GFRP-Reinforced Concrete Design Training Course

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