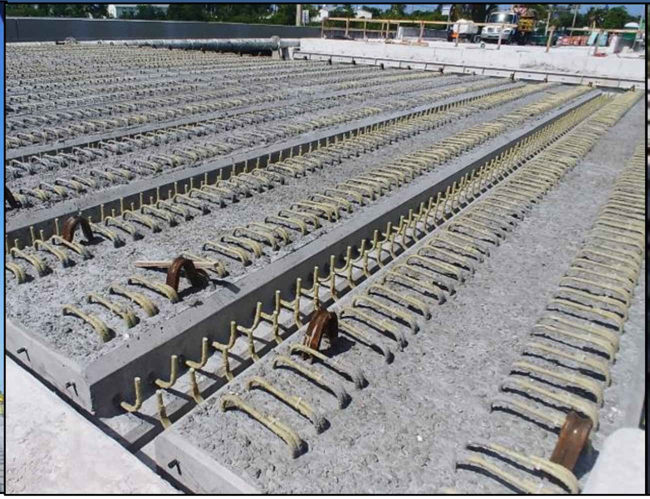
AASHTO CFRP-Prestressed Concrete Design Training Course

FDOT
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



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COURSE OUTLINE

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

4. SHEAR DESIGN

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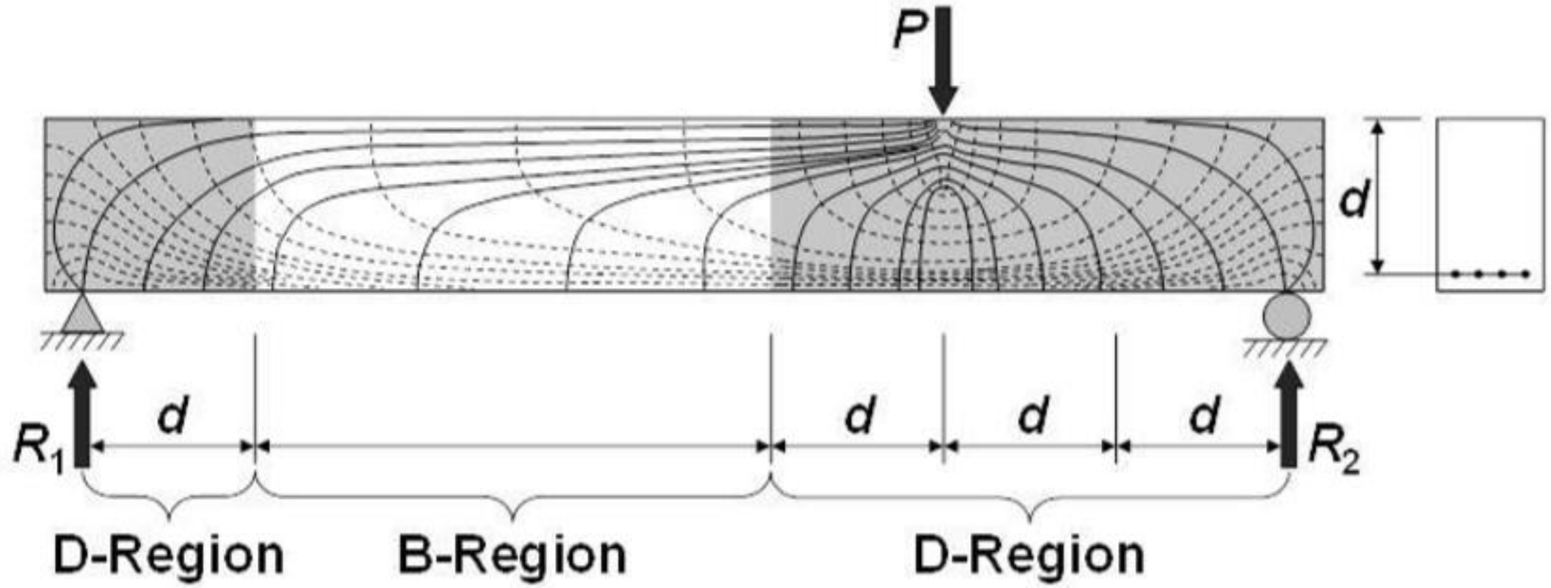
SHEAR DESIGN

- Transverse Shear
- Interface Shear Transfer
- Minimum Longitudinal Reinforcement
- Combined Shear and Torsion

SHEAR DESIGN

B- and D-region



B-region -> Sectional model, conventional beam theory applicable

D-region -> Strut-and-Tie method

SHEAR DESIGN

Transverse Shear Design

- Regions Requiring Transverse Reinforcement
- Shear Resistance
- Minimum Transverse Reinforcement
- Maximum Spacing of Transverse Reinforcement
- Deep Component

SHEAR DESIGN

Regions Requiring Transverse Reinforcement

Transverse reinforcement shall be provided where

$$V_u > 0.5\phi(V_c + V_p)$$

factored shear force

Or where consideration of torsion is required by

$$T_u > 0.25\phi T_{cr}$$

factored torsional moment

[AASHTO CFRP-1 Specifications 1.8.2.1] *[AASHTO LRFD-8 Specifications 5.7.2.3]*

SHEAR DESIGN

Shear Resistance

Resistance factor *[AASHTO LRFD-8 Specifications 5.5.4.2]*

$\phi = 0.90$ for shear and torsion in monolithic prestressed concrete sections having bonded strands or tendons

$\phi = 0.85$ for shear and torsion in monolithic prestressed concrete sections having unbonded or debonded strands or tendons

$$V_r = \phi V_n$$

Factored Shear Resistance

Nominal Shear Resistance

[AASHTO CFRP-1 Specifications 1.8.2.1] *[AASHTO LRFD-8 Specifications 5.5.4.2]*

SHEAR DESIGN

Nominal Shear Resistance

$$V_n = \min \begin{cases} V_n = V_c + V_f + V_p \\ V_n = 0.25 f_c' b_v d_v + V_p \end{cases}$$

Contribution by concrete $V_c = 0.0316\beta\sqrt{f_c'}b_v d_v$

Contribution by transverse reinforcement

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

For steel $V_s = \dfrac{A_v f_y d_v (\cot\theta + \cot\alpha)\sin\alpha}{s}$

Contribution by prestressing force in the direction of the shear force ($V_p = 0$ for straight strands, no draped)

$$V_p = p_e \cdot n_h \cdot \sin\Psi$$

Effective shear depth

Effective web width

[AASHTO LRFD-8 Specifications 5.7.3.3]

[AASHTO GFRP-2 Specifications 2.7.3.]

SHEAR DESIGN

Nominal Shear Resistance

Contribution by transverse FRP reinforcement

FDOT Standard Specification 932-3:
the strength of 90 bent bar should be greater than 60% guaranteed tensile strength of straight bar

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

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

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

f_{fv} = design tensile strength of transverse reinforcement

f_{fb} = design tensile strength of bended portion of FRP reinforcing bars

f_{fd} = design tensile strength of FRP reinforcing bars considering reductions of service environment

[AASHTO GFRP-2 Specifications 2.7.3.5]

SHEAR DESIGN

Effective web width and shear depth b_v, d_v

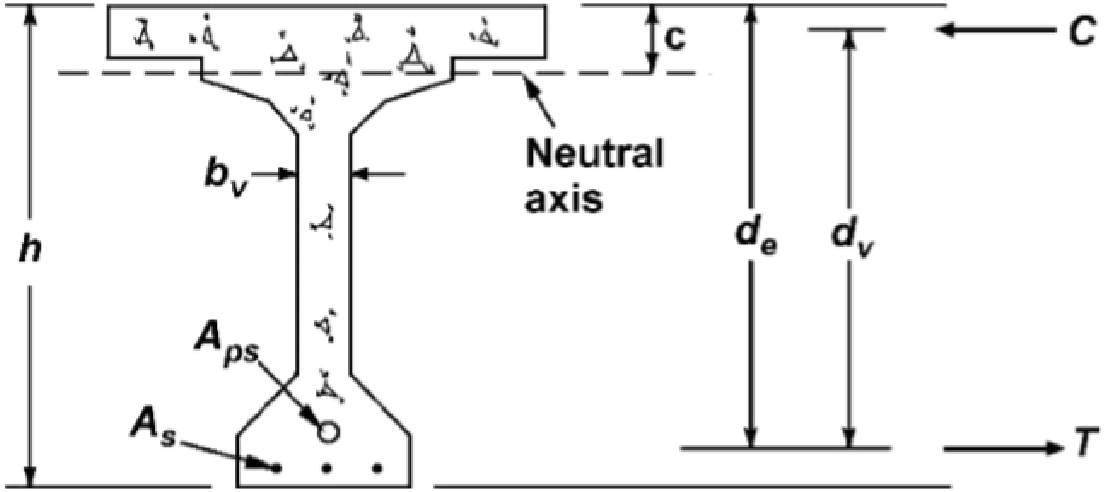


Figure C5.7.2.8-1—Illustration of the Terms b_v and d_v

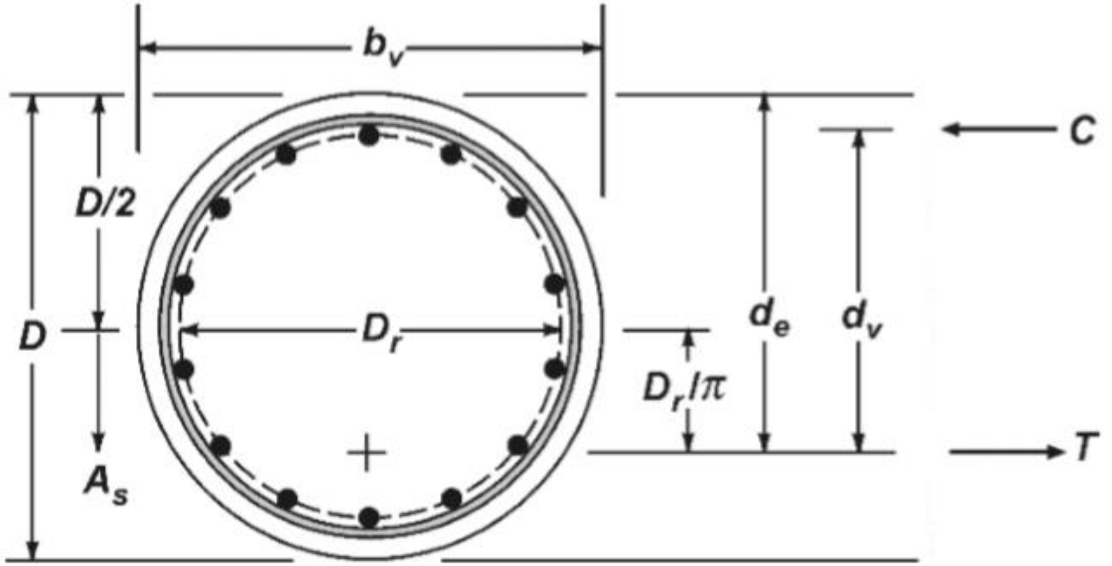


Figure C5.7.2.8-2—Illustration of Terms b_v, d_v, and d_e for Circular Sections

b_v: effective web width taken as the minimum web thickness within the depth d_v

d_v: effective shear depth taken as the distance, measured perpendicular to the neutral axis, between the resultants of the tensile and compressive forces due to flexure; it need not be taken to be less than the greater of $0.9d_e$ or $0.72h$

[AASHTO LRFD-8 Specifications 5.7.2.8] [AASHTO GFRP-2 Specifications 2.7.2.8]

SHEAR DESIGN

Procedures for Determining β and θ

Simplified Procedure

$$\beta = 5.0k \qquad \theta = 45°$$

k is the ratio of neutral axis to reinforcement depth

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

$$\rho_f = \frac{A_f}{bd} \qquad n_f = \frac{E_f}{E_c}$$

[AASHTO GFRP-2 Specifications 2.5.3 & 2.7.3.6]

SHEAR DESIGN

Procedures for Determining β and θ

General Procedure

- Sections containing at least the minimum amount of transverse reinforcement

$$A_v \geq A_{v,min}$$

- Sections containing less than the minimum amount of transverse reinforcement

$$A_v < A_{v,min}$$

[AASHTO LRFD-8 Specifications 5.7.3.4.2] [AASHTO GFRP-2 Specifications 2.7.3.6]

SHEAR DESIGN

$when\ A_v \geq A_{v,min}$

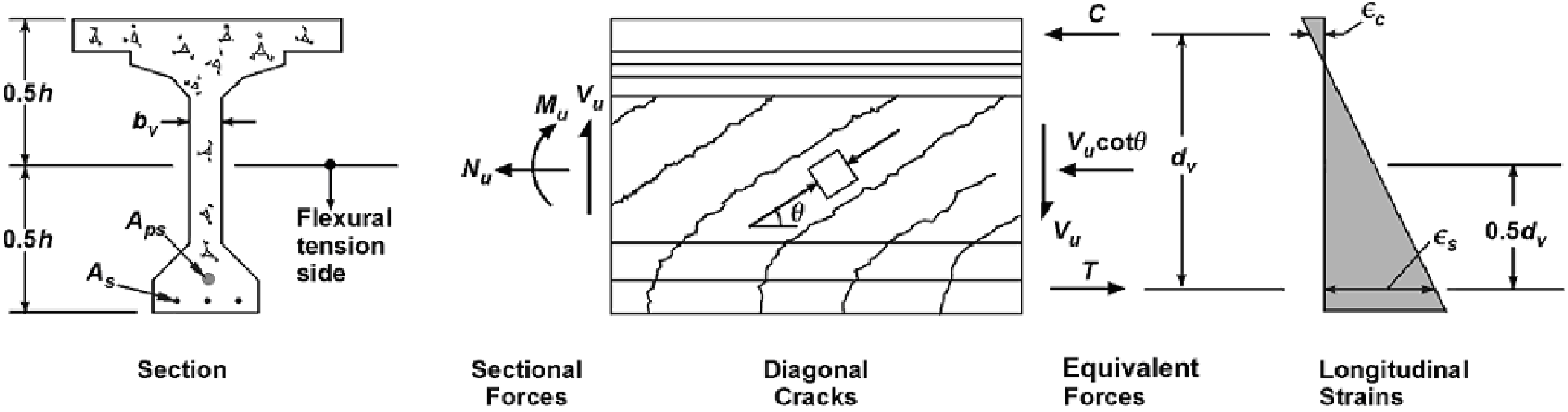


Figure 5.7.3.4.2-1—Illustration of Shear Parameters for Section Containing at Least the Minimum Amount of Transverse Reinforcement, $V_p = 0$

[AASHTO LRFD-8 Specifications 5.7.3.4.2]

SHEAR DESIGN

$$when\ A_v \geq A_{v,min}$$

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

$$\theta = 29 + 3500\varepsilon_f$$

Net longitudinal tensile strain

$$\varepsilon_f = \frac{\frac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - A_{pf}f_{p0}}{E_f A_{pf}}$$

Where consideration of torsion, V_u shall be replaced by V_{eff}

For solid sections:

$$V_{eff} = \sqrt{V_u{}^2 + \left(\frac{0.9p_h T_u}{2A_0}\right)^2}$$

For hollow sections:

$$V_{eff} = V_u + \frac{T_u d_s}{2A_0}$$

[AASHTO LRFD-8 Specifications 5.7.3.4.2] [AASHTO CFRP-1 Specifications 1.8.3.2]

SHEAR DESIGN

Net longitudinal tensile strain

$$\varepsilon_f = \frac{\frac{|M_u|}{d_v} + 0.5N_u + |V_u - V_p| - A_{pf} f_{p0}}{E_f A_{pf}}$$

For usual levels of prestressing, a value of $0.6\, f_{pu}$ will be appropriate for CFRP strands

area of prestressing CFRP on the flexural tension side of the member (exclude debonded strands)

effective shear depth

[AASHTO CFRP-1 Specifications 1.8.3.2] *[AASHTO LRFD-8 Specifications Appendix B5]*

SHEAR DESIGN

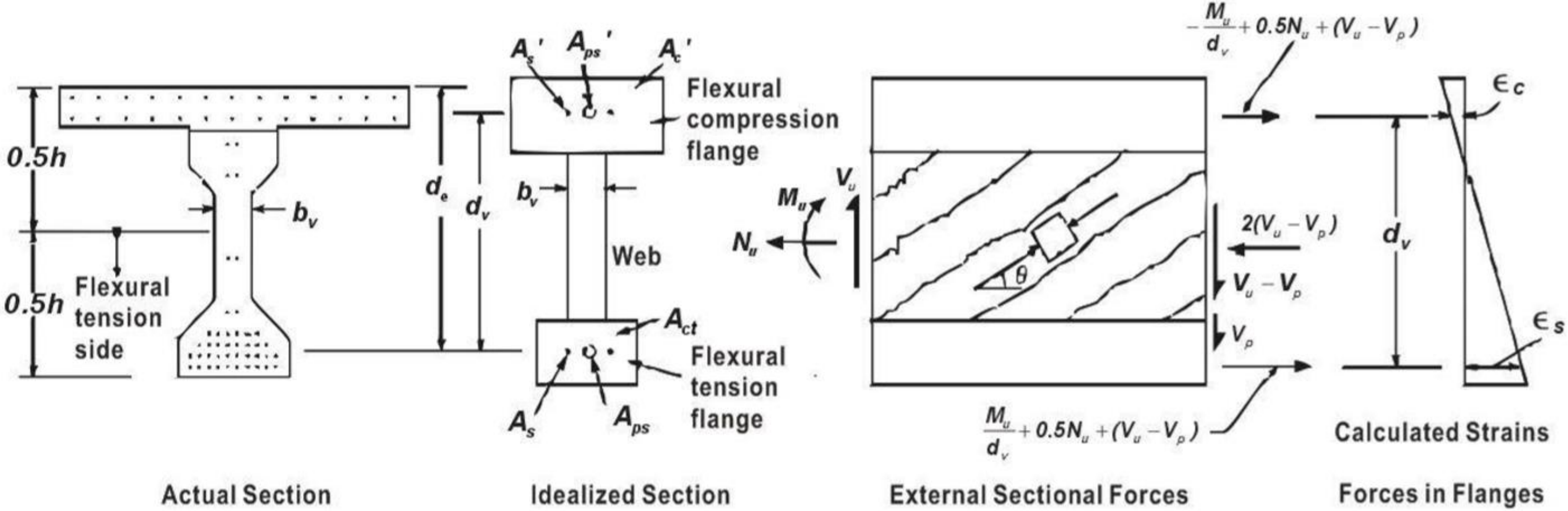


Figure C5.7.3.4.2-3—More Accurate Calculation Procedure for Determining ε_s

[AASHTO LRFD-8 Specifications 5.7.3.4]

SHEAR DESIGN

$when\ A_v < A_{v,min}$

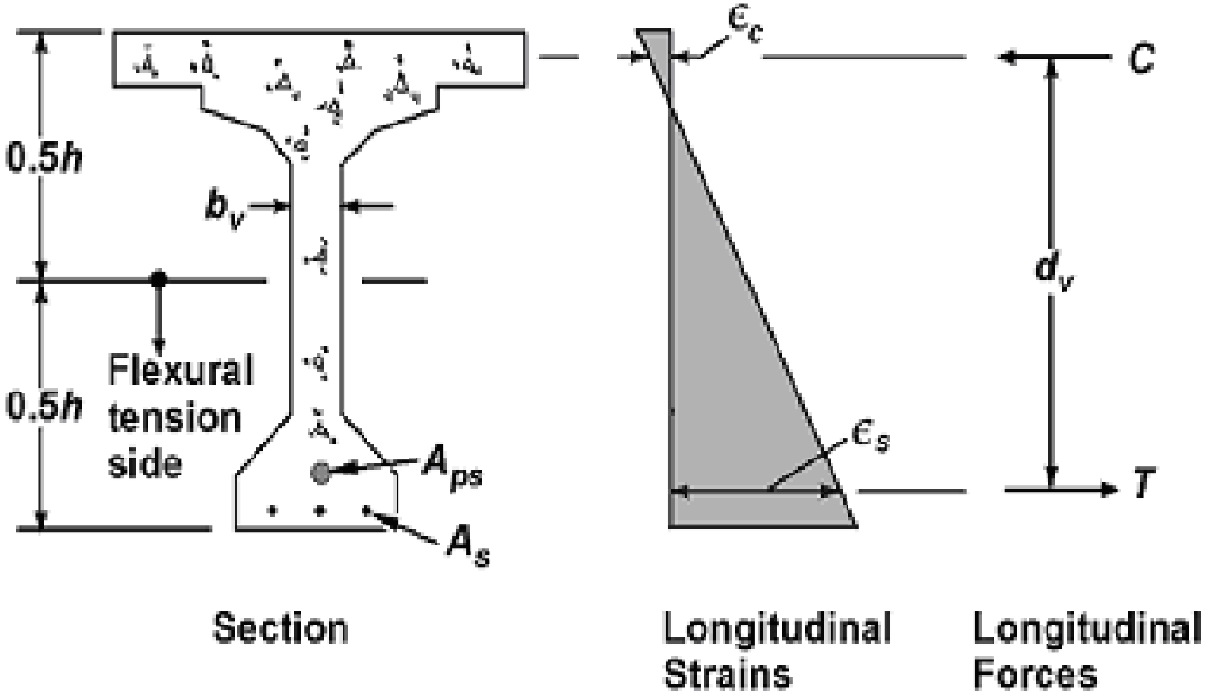


Figure 5.7.3.4.2-2—Longitudinal Strain, ε_s, for Sections Containing Less than the Minimum Amount of Transverse Reinforcement

[AASHTO LRFD-8 Specifications 5.7.3.4.2]

SHEAR DESIGN

$$when\ A_v < A_{v,min}$$

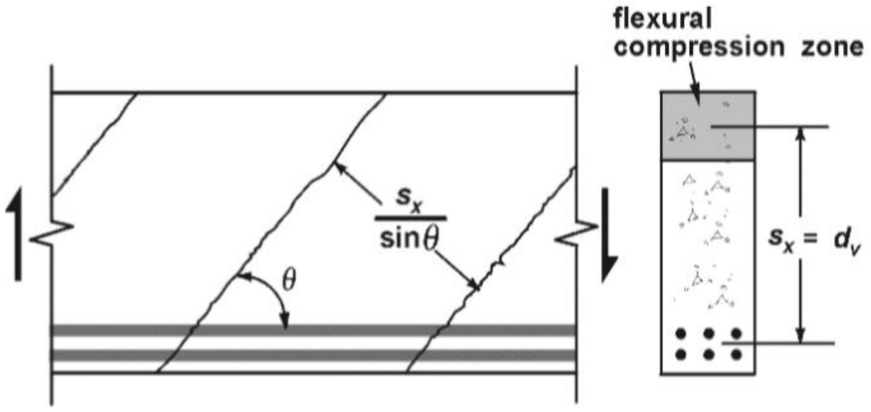
$$\beta = \frac{4.8}{1 + 750\varepsilon_f} \cdot \frac{51}{39 + s_{xe}}$$

$$\theta = 29 + 3500\varepsilon_f$$

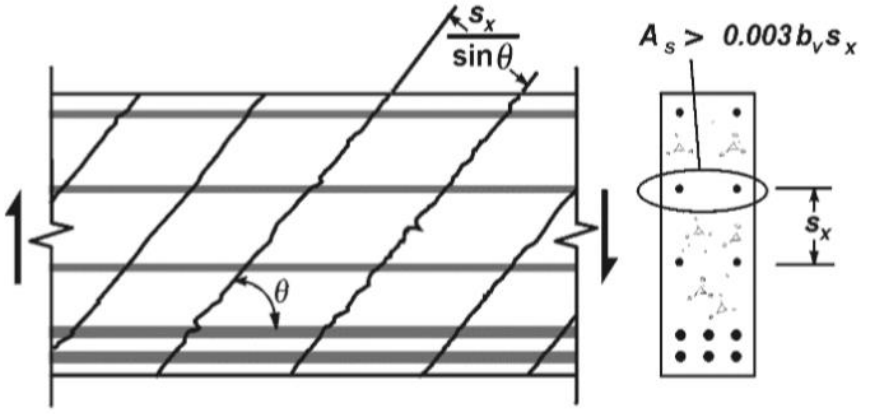
$$s_{xe} = s_x \frac{1.38}{a_g + 0.63}$$

$$12\ in. \leq s_{xe} \leq 80\ in.$$

a_g: maximum aggregate size



(a) *Member without transverse reinforcement and with concentrated longitudinal reinforcement*



(b) *Member without transverse reinforcement but with well distributed longitudinal reinforcement*

Figure 5.7.3.4.2-3—Definition of Crack Spacing Parameter, s_x

[AASHTO GFRP-2 Specifications 2.7.3.6.2]

[AASHTO LRFD-8 Specifications 5.7.3.4.2]

SHEAR DESIGN

Minimum Shear Reinforcement

ACI 440.4R-04:

$$A_{v,min} = 0.75\sqrt{f_c'}\frac{b_w s}{f_{fv}}$$

$$f_{fv} = \phi_{bend} f_{fu} \leq 0.004 \cdot E_f$$

$$0.25 \leq \phi_{bend} = \left(0.11 + 0.05\frac{r}{d_b}\right) f_{fu} \leq 1.0$$

AASHTO GFRP-2:

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

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

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

[ACI 440.4R-04 5.4] *[AASHTO GFRP-2 2.7.2.4]*

SHEAR DESIGN

Maximum Spacing of FRP Transverse Reinforcement

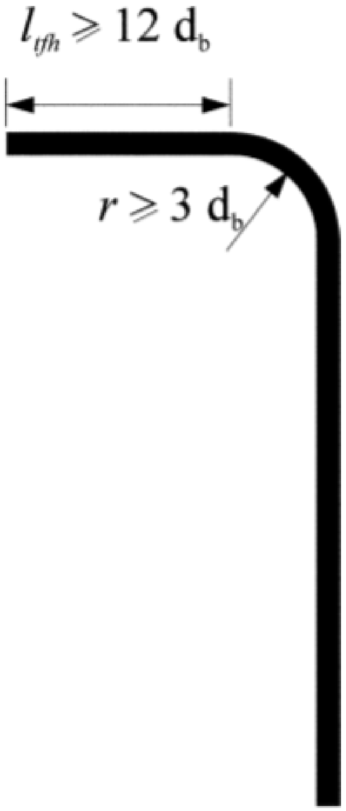
ACI 440.4R-04:

If $V_{frp} \leq 4.0\sqrt{f_c'}b_v d_v$ $s_{max} = 0.75h \leq 24\ in.$

If $V_{frp} > 4.0\sqrt{f_c'}b_v d_v$ $s_{max} = 0.375h \leq 12\ in.$

AASHTO GFRP-2:

$$s_{max} = 0.5d \leq 24\ in.$$

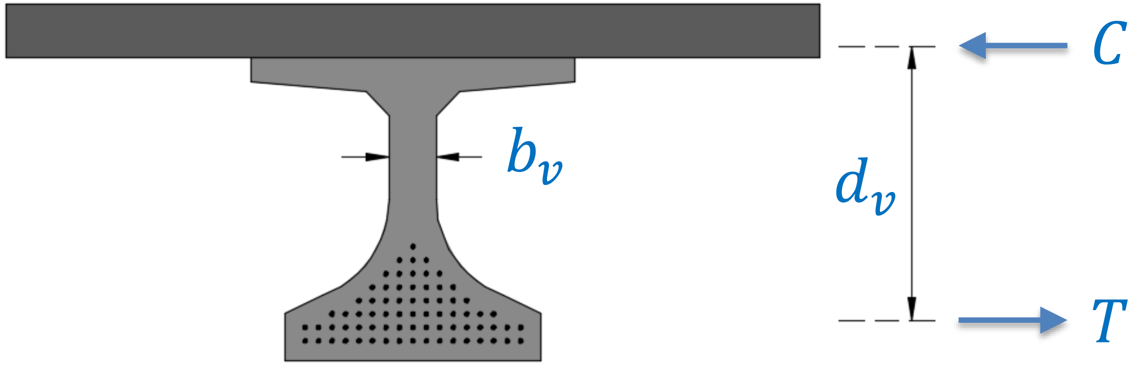


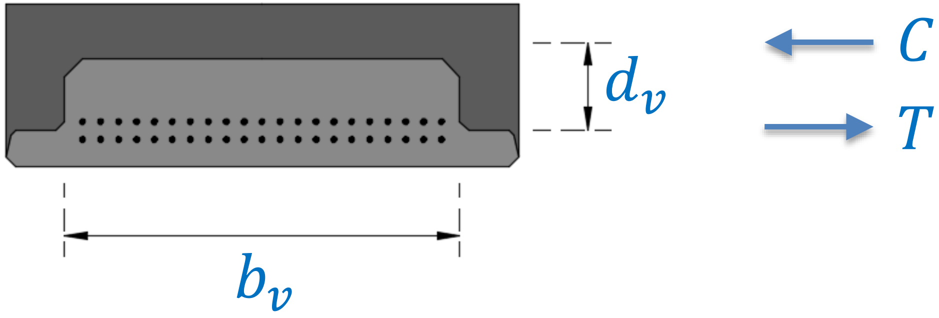
Minimum radius and tail length of a stirrup bend

[ACI 440.4R-04 5.3] [AASHTO GFRP-2 2.7.2.6]

SHEAR DESIGN

e.g. FIB/FSB





- Find critical section and corresponding V_u
- Compute β and θ
- Concrete contribution

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

- CFRP prestressing strand contribution (if straight strands, no draped)

$$V_p = 0$$

SHEAR DESIGN

e.g. FIB/FSB (cont'd)

- Need to compute the amount of FRP transverse reinforcement for shear?

No, if $V_u \leq 0.5\phi(V_c + V_p)$ $\longrightarrow$ Provide $\frac{A_v}{s} \geq \left(\frac{A_v}{s}\right)_{min}$, check spacing s_{max}

Yes, if $V_u > 0.5\phi(V_c + V_p)$ $\longrightarrow$ Compute $\left(\frac{A_v}{s}\right)_{req}$

$$\left.\begin{array}{r} \phi V_n \geq V_u \\ V_n = V_c + V_f + V_p \leq 0.25 f_c' b_v d_v + V_p \end{array}\right\} V_{f,req}$$

$$\left.\begin{array}{c} V_{f,req} \\ V_f = \dfrac{f_{fv} A_v d_v}{s} \\ \left(\dfrac{A_v}{s}\right)_{min} \end{array}\right\} \left(\frac{A_v}{s}\right)_{req} \longrightarrow$$

Provide $\frac{A_v}{s} \geq \left(\frac{A_v}{s}\right)_{min}$

Check spacing s_{min}, s_{max}

SHEAR DESIGN

a) Components in which the distance from the point of **zero shear** to the face of the support is less than $2d_p$

b) Components in which a load causing more than ½ of the shear at a support is closer than $2d_p$ from the face of the support

Deep Component

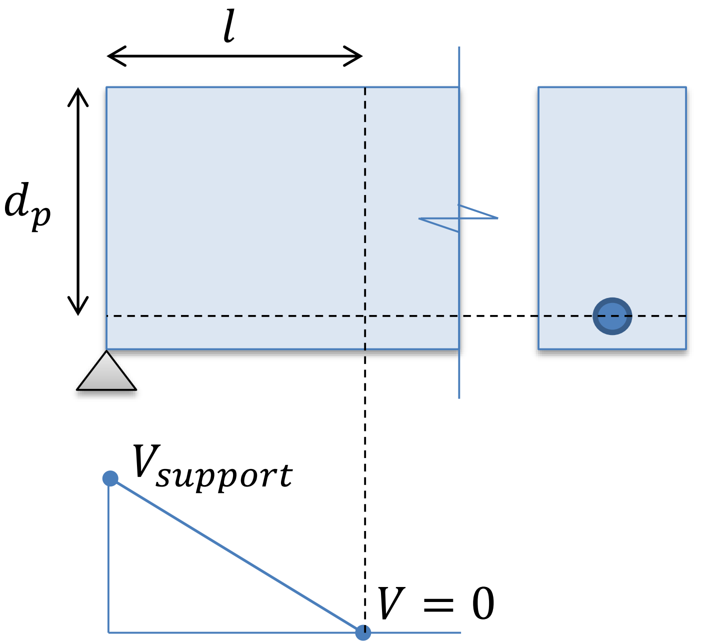
use

[AASHTO CFRP-1 Specifications 1.6.3]

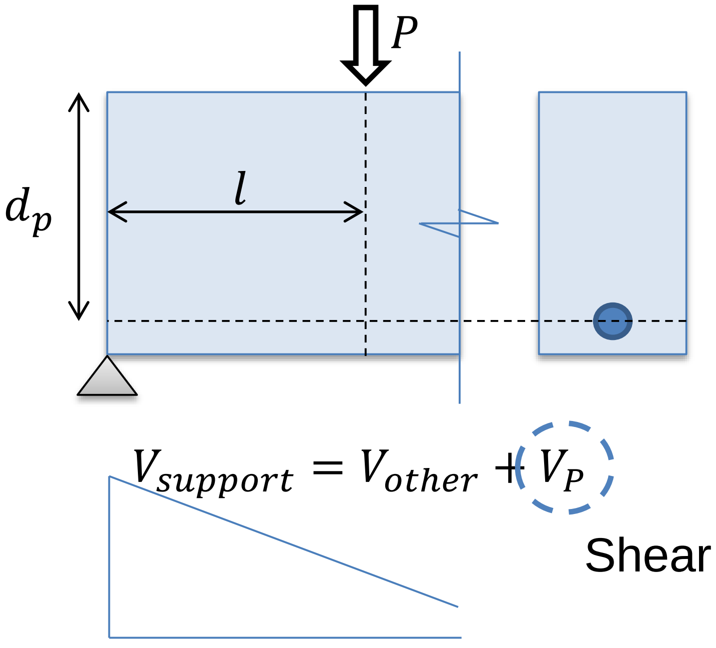
[AASHTO LRFD-8 Specifications 5.8.2]

e.g.

$a)\ if\ l < 2d_p$



$b)\ if\ V_P > 0.5V_{support}\ and\ l < 2d_p$



Shear at the support caused by P

SHEAR DESIGN

Interface Shear Transfer

- Interface shear resistance
- Cohesion and friction factors
- Interface shear force for girder/slab bridges
- Interface shear in box girder bridges
- Minimum area of interface shear reinforcement

SHEAR DESIGN

Interface shear transfer shall be considered across a given plane at:

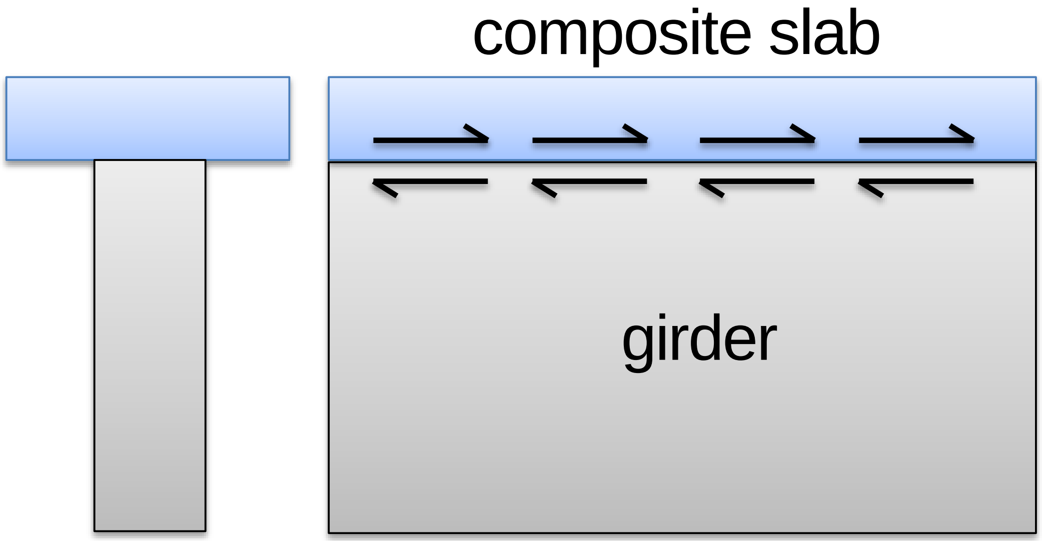
- ✓ An existing or potential crack
- ✓ An interface between dissimilar materials
- ✓ An interface between two concretes cast at different time
- ✓ The interface between different elements of the cross-section

[AASHTO LRFD-8 Specifications 5.7.4]

SHEAR DESIGN

Shear displacement along an interface plane may be resisted by

- ✓ Cohesion
- ✓ Aggregate interlock
- ✓ Shear friction



$$v_h = \frac{VQ}{Ib} \longrightarrow v_h \cong \frac{V}{bd} \xrightarrow{\text{unit length}} v_h \cong \frac{V}{d}$$

[AASHTO LRFD-8 Specifications 5.7.4]

SHEAR DESIGN

Interface Shear Resistance

Resistance factor

$$V_{ri} = \phi V_{ni} \geq V_{ui}$$

Factored Interface Shear Resistance

Factored interface shear force due to total load based on the applicable strength and extreme event load combinations

Nominal Interface Shear Resistance

[AASHTO LRFD-8 Specifications 5.7.4.3]

SHEAR DESIGN

Nominal Interface Shear Resistance

Nominal Interface Shear Resistance

$$V_{ni} = cA_{cv} + \mu\left(A_{cf} f_{fv} + P_c\right)$$

[Replaced f_y with f_{fv}]

V_{ni} used in the design shall satisfy:

$$V_{ni} \leq K_1 f_c' A_{cv}$$

$$V_{ni} \leq K_2 A_{cv}$$

[AASHTO LRFD-8 Specifications 5.7.4.3]

SHEAR DESIGN

Nominal Interface Shear Resistance

cohesion factor

friction factor

Use the minimum transfer shear strength $f_{fv,min} = 22\text{ ksi}$ for GFRP & CFRP bars (per *FDOT Materials Spec. 932-3*), due to the potential for premature failure modes, until more testing completed

$$V_{ni} = cA_{cv} + \mu\left(A_{cf} f_{fv} + P_c\right)$$

[Replaced f_y with f_{fv}]

permanent net compressive force normal to the shear plane, $P_c = 0$ if tension

area of reinforcement crossing the shear plane

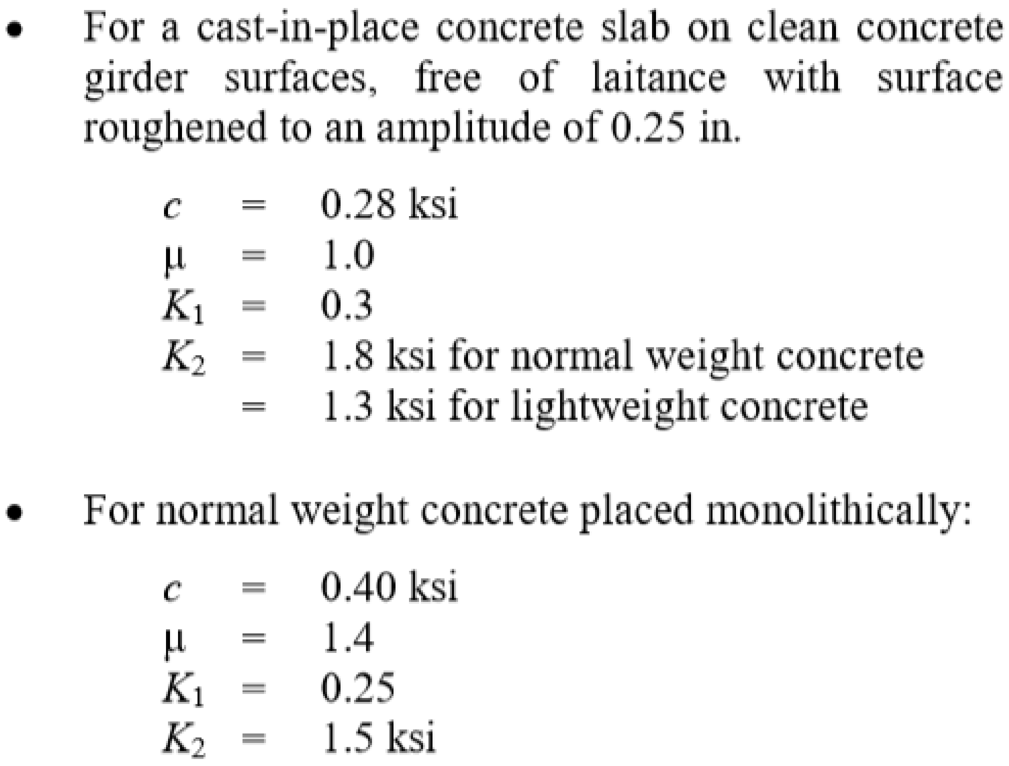
area of concrete engaged in shear transfer $A_{cv} = b_{vi} L_{vi}$

[AASHTO LRFD-8 Specifications 5.7.4.3]

SHEAR DESIGN

Cohesion and Friction Factors c, μ, K_1, K_2

e.g.

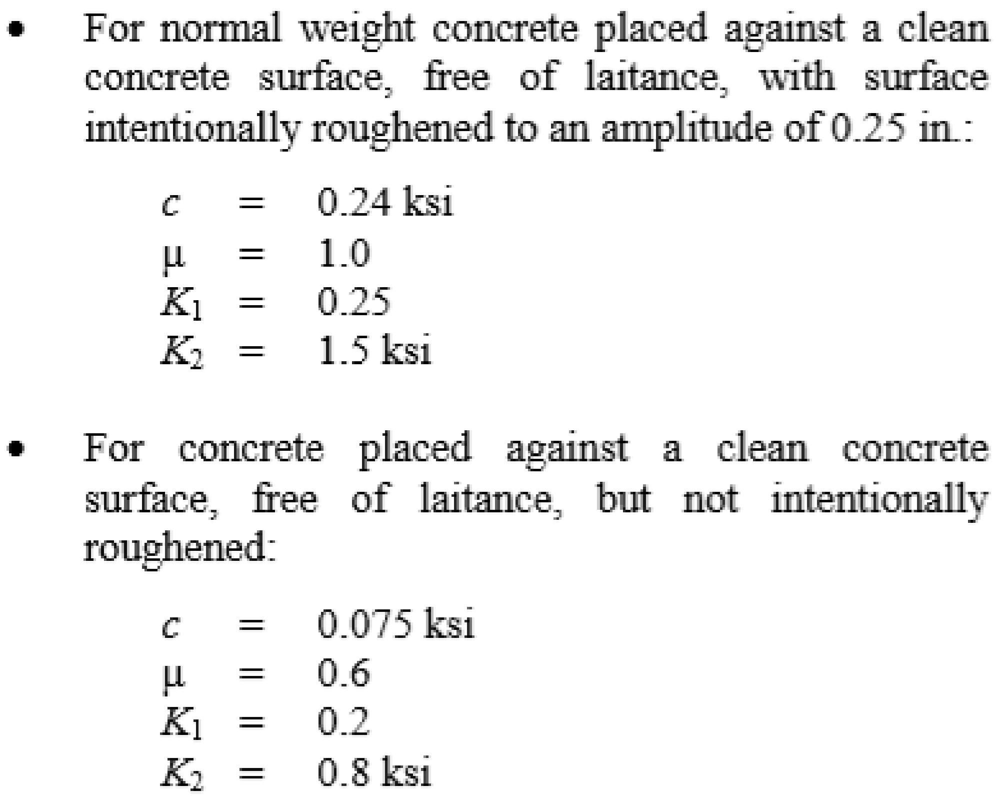


- For a cast-in-place concrete slab on clean concrete girder surfaces, free of laitance with surface roughened to an amplitude of 0.25 in.

  c = 0.28 ksi
  μ = 1.0
  K_1 = 0.3
  K_2 = 1.8 ksi for normal weight concrete
  = 1.3 ksi for lightweight concrete

- For normal weight concrete placed monolithically:

  c = 0.40 ksi
  μ = 1.4
  K_1 = 0.25
  K_2 = 1.5 ksi



- For normal weight concrete placed against a clean concrete surface, free of laitance, with surface intentionally roughened to an amplitude of 0.25 in.:

  c = 0.24 ksi
  μ = 1.0
  K_1 = 0.25
  K_2 = 1.5 ksi

- For concrete placed against a clean concrete surface, free of laitance, but not intentionally roughened:

  c = 0.075 ksi
  μ = 0.6
  K_1 = 0.2
  K_2 = 0.8 ksi

[AASHTO LRFD-8 Specifications 5.7.4.4]

SHEAR DESIGN

Interface Shear Force for Girder/Slab Bridges

Factored interface shear stress

$$v_{ui} = \frac{V_{u1}}{b_{vi} d_v}$$

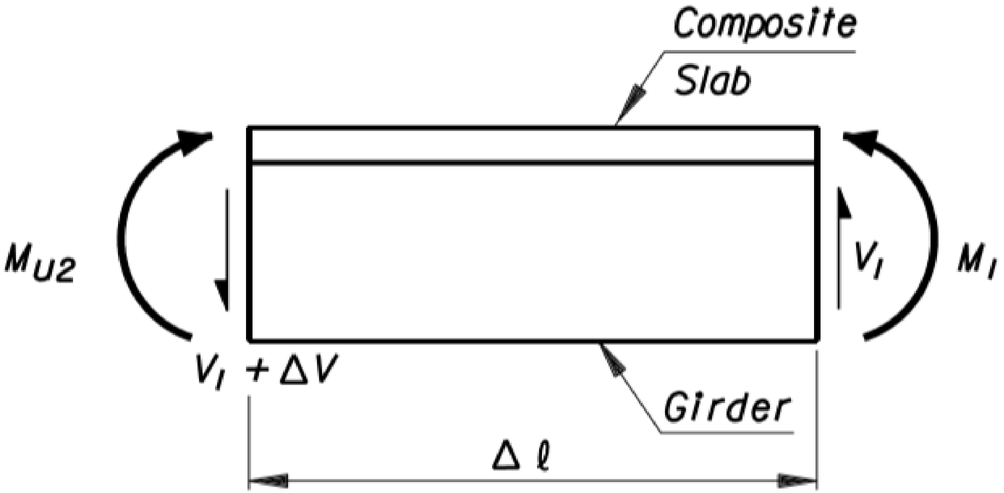
Factored interface shear force (kips/ft)

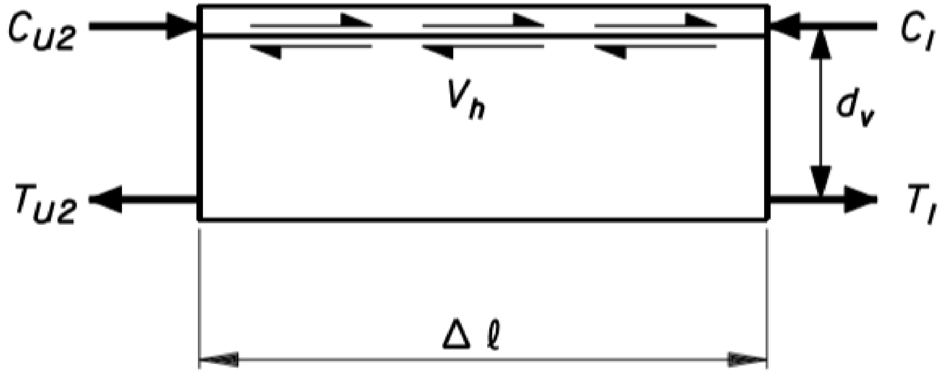
$$V_{ui} = v_{ui} A_{cv} = v_{ui} \cdot 12 b_{vi}$$

If the net force P_c is tensile, additional reinforcement shall be provided as

$$A_{vpc} = \phi \frac{P_c}{f_{fv}}$$

[Replaced f_y with f_{fv}]





[AASHTO LRFD-8 Specifications 5.7.4.5]

SHEAR DESIGN

Interface Shear in Box Girder Bridges

Adequate shear transfer reinforcement shall be provided at the web/flange in box girders to transfer flange longitudinal forces at the strength limit state

[AASHTO LRFD-8 Specifications 5.7.4.6]

SHEAR DESIGN

Minimum Area of Interface Shear Reinforcement

$$A_{vf.min} = \frac{0.05 A_{cv}}{f_{fv}}$$

[Replaced f_y with f_{fv}]

A_{cv} = Area of concrete considered to be engaged in interface shear transfer (in^2)

A_{vf} = Area of interface shear reinforcement crossing the shear plane within the area A_{cv} (in^2)

f'_{fv} = Design transverse strength for shear for FRP bar. Use the minimum transfer shear strength $f_{fv,min} = 22 \text{ ksi}$ for GFRP & CFRP bars (per *FDOT Materials Spec. 932-3*), due to the potential for premature failure modes, until more testing completed.

[AASHTO LRFD-8 Specifications 5.7.4.2]

SHEAR DESIGN

Minimum Area of Interface Shear Reinforcement

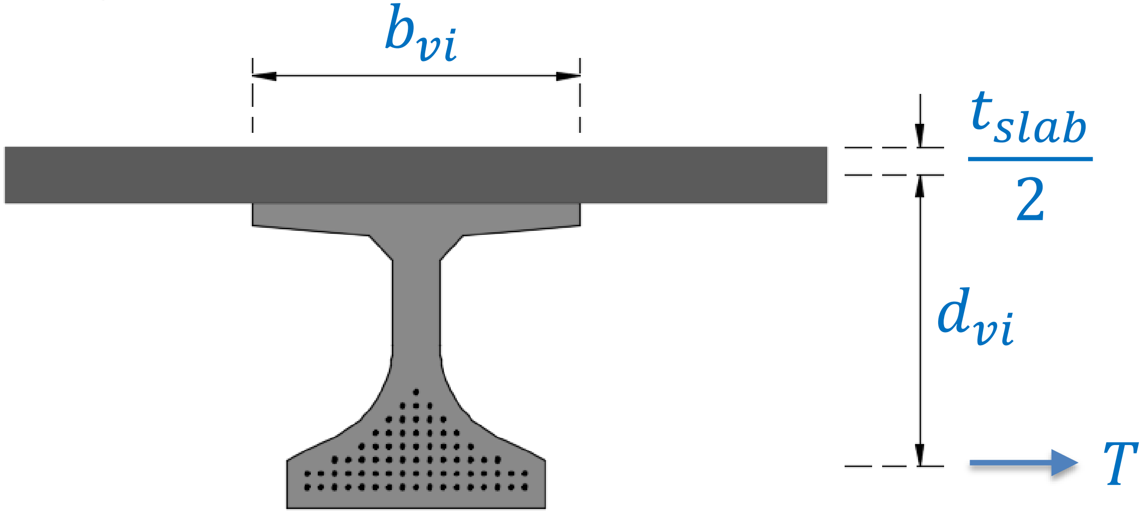
For Cast-In-Place concrete slab on clean concrete girder surfaces free of laitance, additional requirements apply

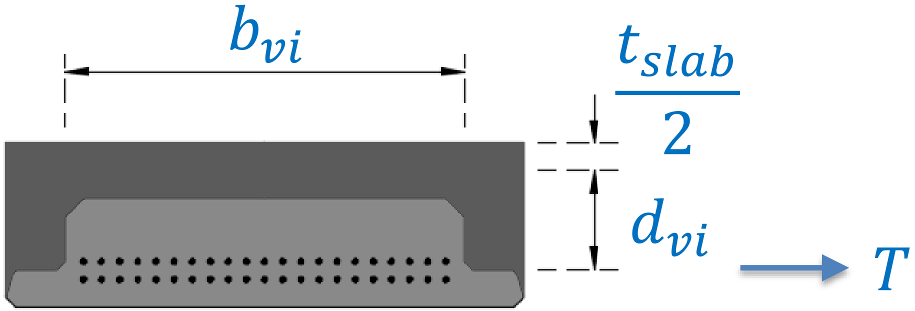
- The minimum interface shear reinforcement, need not exceed the lesser of $A_{vf.min}$ and the amount needed to resist $1.33 \cdot V_{ui}/\phi$
- The minimum interface shear reinforcement requirements shall be waived for girder/slab interfaces with surface roughened to an amplitude of 0.25 inch where the factored interface shear stress is less than 0.21 ksi, and all vertical transverse shear reinforcement is extended across the interface and adequately anchored in the slab

[AASHTO LRFD-8 Specifications 5.7.4.2]

SHEAR DESIGN

e.g. FIB/FSB





- Find critical section and corresponding interface shear force V_{ui}
- Factored interface shear force per unit length v_{hi} (kip/ft)

$$v_{hi} = \frac{V_{ui}}{d_{vi}}$$

- Required nominal interface shear force per unit length $v_{ni,req}$ (kip/ft)

$$v_{ni,req} = \frac{v_{hi}}{\phi}$$

SHEAR DESIGN

e.g. FIB/FSB (cont'd)

- Required nominal interface shear reinforcement per unit length (in^2/ft)

$$\left.\begin{array}{r} v_{ni,req} = \dfrac{v_{hi}}{\phi} \\[2ex] v_{ni} = cA_{cv} + \mu\left(A_{cf} f_{fv} + P_c\right) \\[2ex] v_{ni} \leq K_1 f_c' A_{cv} \\[2ex] v_{ni} \leq K_2 A_{cv} \\[2ex] A_{cf,min} \end{array}\right\} \quad A_{cf,req} \quad \longrightarrow \quad \text{Provide} \quad A_{cf} \geq A_{cf,req}$$

SHEAR DESIGN

Longitudinal Reinforcement

At each section, the tensile capacity of the longitudinal reinforcement on the flexural tension side of the member shall be proportioned to satisfy

$$\sum_{x=1}^{n} A_{px} f_{px} \geq \frac{|M_u|}{d_v \phi_f} + 0.5\frac{N_u}{\phi_c} + \left[\left|\frac{V_u}{\phi_v} - V_p\right| - 0.5V_f\right]\cot\theta$$

[Replaced V_s with V_f]

ϕ_f, ϕ_c, ϕ_v are resistance factor of flexure, compression/tension, and shear, respectively

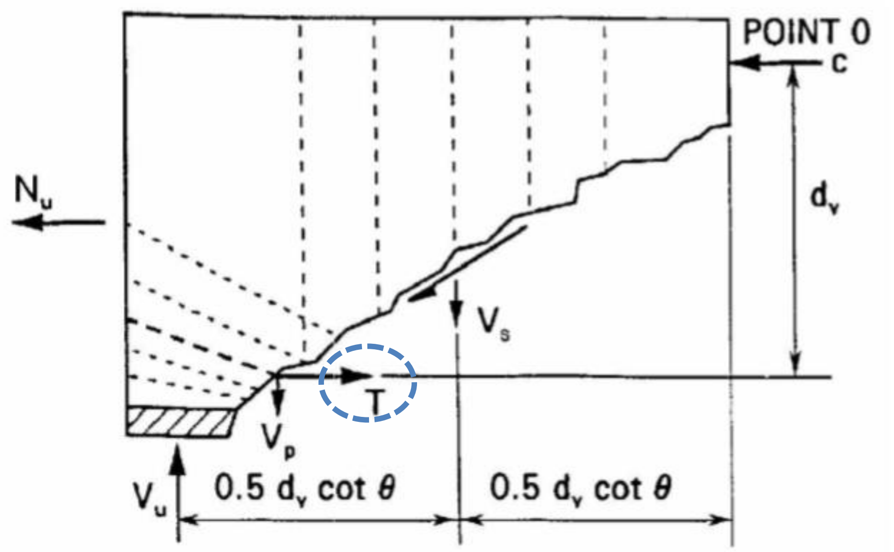


Figure C5.7.3.5-1—Forces Assumed in Resistance Model Caused by Moment and Shear

[AASHTO CFRP-1 Specifications 1.8.3.3]

SHEAR DESIGN

Combined Shear and Torsion

- Transverse Reinforcement
- Torsion Resistance
- Longitudinal Reinforcement

SHEAR DESIGN

Transverse Reinforcement

Total Transverse Reinforcement = Transverse Shear Reinforcement + Torsion Reinforcement

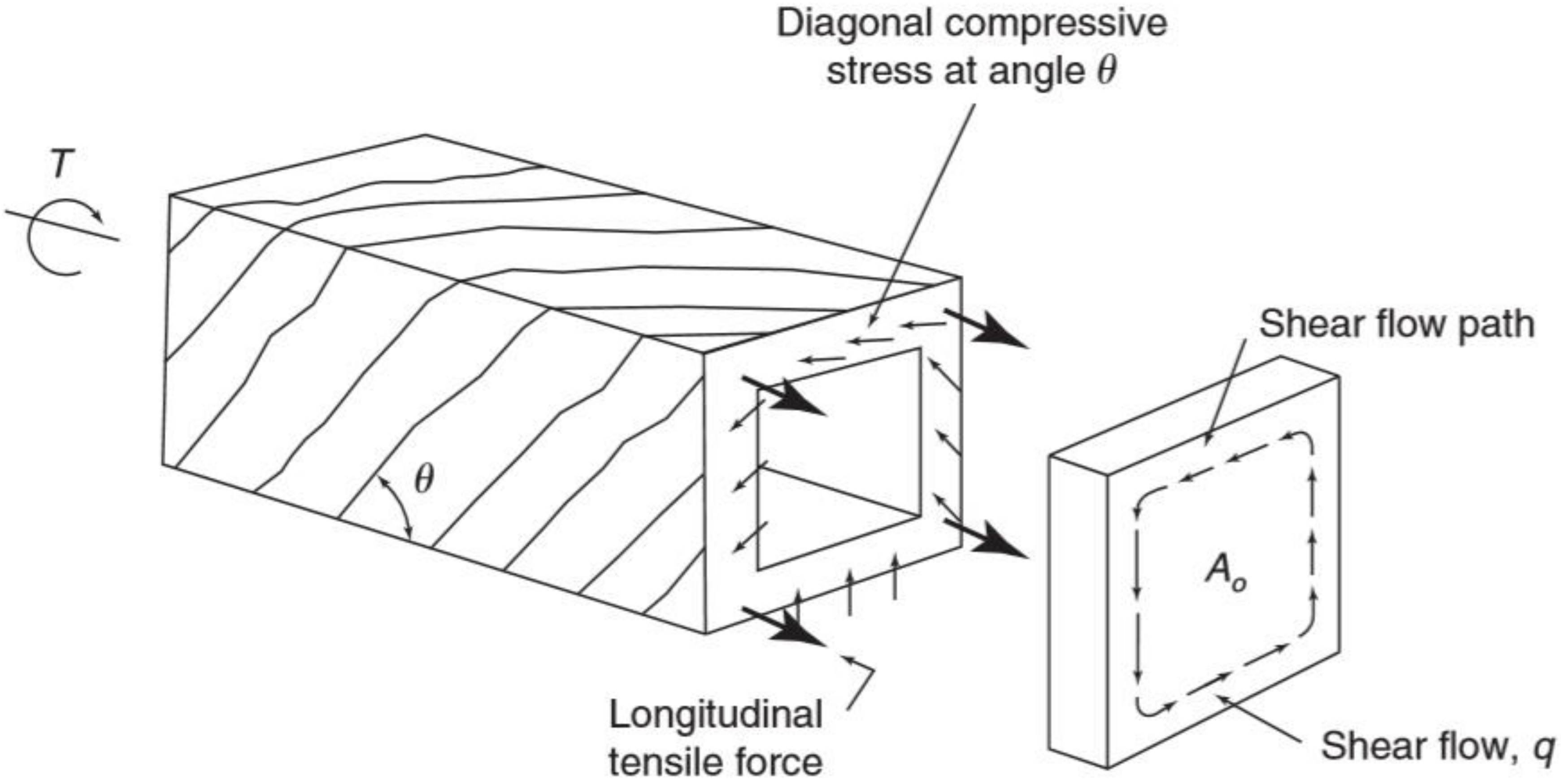
[AASHTO LRFD-8 Specs 5.7.3.3]

[AASHTO LRFD-8 Specs 5.7.2.1]

[AASHTO LRFD-8 Specs 5.7.3.6.2]

[AASHTO LRFD-8 Specifications 5.7.3.6]

SHEAR DESIGN



Thin-walled tube analogy.

[Reinforced Concrete: Mechanics & Design (6 ed.), Wight and MacGregor, 2011]

SHEAR DESIGN

Nominal Torsional Resistance

Area enclosed by the shear flow path, including an area of holes therein

$$T_n = \frac{2A_0 A_t f_{pu} \cot\theta}{s}$$

Angle of inclination of diagonal compressive stresses

[Replaced f_y with f_{pu}]

<u>For solid member:</u> area of one leg of enclosed transverse torsion reinforcement in solid members,

<u>For hollow member:</u> total area of transverse torsion reinforcement in the exterior web and flange

[AASHTO LRFD-8 Specifications 5.7.3.6.2]

SHEAR DESIGN

Longitudinal Reinforcement

In solid sections:

$$A_{pf}f_{pf} + A_sf_y \geq \frac{|M_u|}{\phi d_v} + \frac{0.5N_u}{\phi} + \cot\theta\sqrt{\left(\left|\frac{V_u}{\phi} - V_p\right| - 0.5V_f\right)^2 + \left(\frac{0.45p_hT_u}{2A_0\phi}\right)^2}$$

In box sections, longitudinal reinforcement for torsion (in addition to flexural reinforcement)

$$A_l \geq \frac{T_up_h}{2A_0f_{pu}}$$

[Replaced f_y with f_{pu}]

[Replaced V_s with V_f]

[AASHTO LRFD-8 Specifications 5.7.3.6.2]

Questions?

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Department of Civil & Environmental Engineering

4. SHEAR DESIGN

4.1 Review Questions: Fundamentals

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Department of Civil & Environmental Engineering

REVIEW QUESTIONS

4.1.1) For GFRP transverse reinforcements, does the maximum amount of transverse reinforcement requirement similar to steel transverse reinforcements still apply:_____

a. True

b. False

REVIEW QUESTIONS

Minimum GFRP Transverse Reinforcement

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

Maximum GFRP Transverse Reinforcement

$$V_f \leq 0.25 f_c' b_v d_v$$

[AASHTO GFRP-2 2.7.2.4]

REVIEW QUESTIONS

4.1.1) For GFRP transverse reinforcements, does the maximum amount of transverse reinforcement requirement similar to steel transverse reinforcements still apply:_____

a. <u>True</u>

b. False

REVIEW QUESTIONS

4.1.2) The shear strength of PC members with GFRP transverse reinforcements_____

a. Is comparable to the shear strength of PC members with steel transverse reinforcements

b. Is lower than the shear strength of PC members with steel transverse reinforcements

c. Is higher than to the shear strength of PC members with steel transverse reinforcements

a. Cannot be compared to the shear strength of PC members with steel transverse reinforcements

REVIEW QUESTIONS

Nominal Shear Resistance

Contribution by concrete $V_c = 0.0316\beta\sqrt{f_c'}b_v d_v$

Contribution by GFRP transverse reinforcement

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

$$V_n = \min \begin{cases} V_n = V_c + V_f + V_p \\ V_n = 0.25 f_c' b_v d_v + V_p \end{cases}$$

Contribution by prestressing force in the direction of the shear force ($V_p = 0$ for straight strands, no draped)

$$V_p = p_e \cdot n_h \cdot \sin\Psi$$

Effective shear depth

Effective web width

[AASHTO LRFD-8 Specifications 5.7.3.3]

[AASHTO GFRP-2 Specifications 2.7.3.]

REVIEW QUESTIONS

4.1.2) The shear strength of PC members with GFRP transverse reinforcements_____

a. Is comparable to the shear strength of PC members with steel transverse reinforcements

b. <u>Is lower than the shear strength of PC members with steel transverse reinforcements</u>

c. Is higher than to the shear strength of PC members with steel transverse reinforcements

a. Cannot be compared to the shear strength of PC members with steel transverse reinforcements

REVIEW QUESTIONS

4.1.3) The required tail length of FRP stirrups is at least equal to or more than _____ times the bar diameter

a. 4

b. 8

c. 12

a. 16

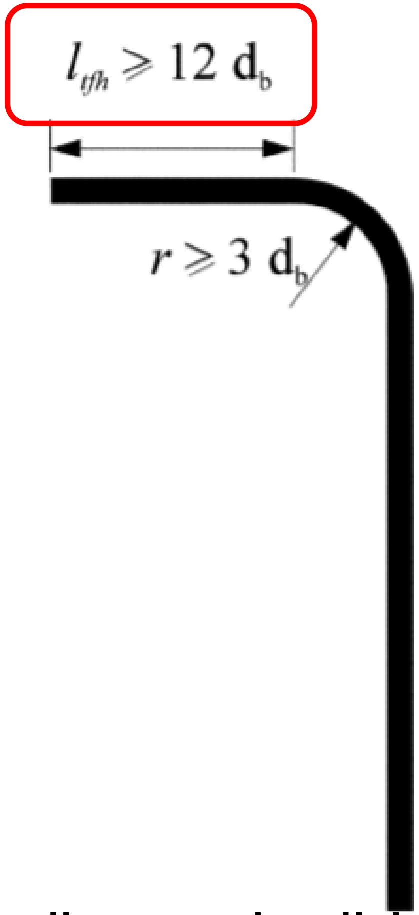
REVIEW QUESTIONS

Maximum Spacing of FRP Transverse Reinforcement

ACI 440.4R-04:

If $V_{frp} \leq 4.0\sqrt{f_c'}b_v d_v$ $\quad s_{max} = 0.75h \leq 24\ in.$

If $V_{frp} > 4.0\sqrt{f_c'}b_v d_v$ $\quad s_{max} = 0.375h \leq 12\ in.$



Minimum radius and tail length of a stirrup bend

AASHTO GFRP-2:

$$s_{max} = 0.5d \leq 24\ in.$$

[ACI 440.4R-04 5.3] [AASHTO GFRP-2 2.7.2.6]

REVIEW QUESTIONS

4.1.3) The required tail length of GFRP stirrups is at least equal to or more than _____ times the bar diameter

a. 4

b. 8

c. <u>12</u>

a. 16

REVIEW QUESTIONS

4.1.4) The maximum spacing of transverse GFRP reinforcement is generally _____ per AASHTO GFRP-2.

a. 12 in.

b. 24 in.

c. 0.5d*

d. Min (0.5d*, 24 in.)

*Flexural reinforcement depth

REVIEW QUESTIONS

Maximum Spacing of FRP Transverse Reinforcement

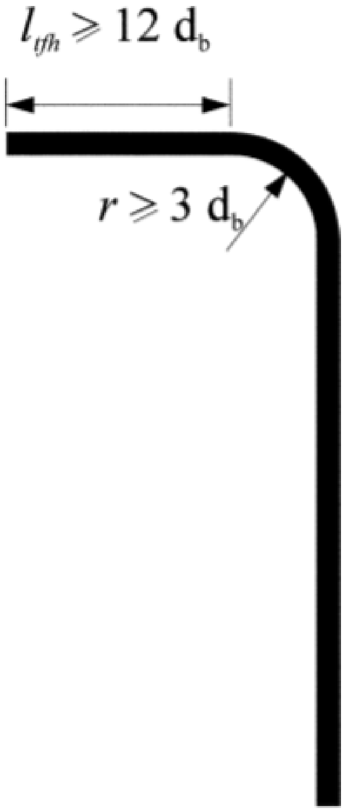
ACI 440.4R-04:

If $V_{frp} \leq 4.0\sqrt{f_c'}b_v d_v$ $\qquad s_{max} = 0.75h \leq 24\ in.$

If $V_{frp} > 4.0\sqrt{f_c'}b_v d_v$ $\qquad s_{max} = 0.375h \leq 12\ in.$

AASHTO GFRP-2:

$$s_{max} = 0.5d \leq 24\ in.$$



Minimum radius and tail length of a stirrup bend

[ACI 440.4R-04 5.3] [AASHTO GFRP-2 2.7.2.6]

REVIEW QUESTIONS

4.1.4) The maximum spacing of transverse GFRP reinforcement is generally _____ per AASHTO GFRP-2.

a. 12 in.

b. 24 in.

c. 0.5d*

d. <u>Min (0.5d*, 24 in.)</u>

*Flexural reinforcement depth

REVIEW QUESTIONS

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

a. True

b. False

REVIEW QUESTIONS

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

REVIEW QUESTIONS

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

a. True

b. <u>False</u>

4. SHEAR DESIGN

4.2 Design Example: FIB 36

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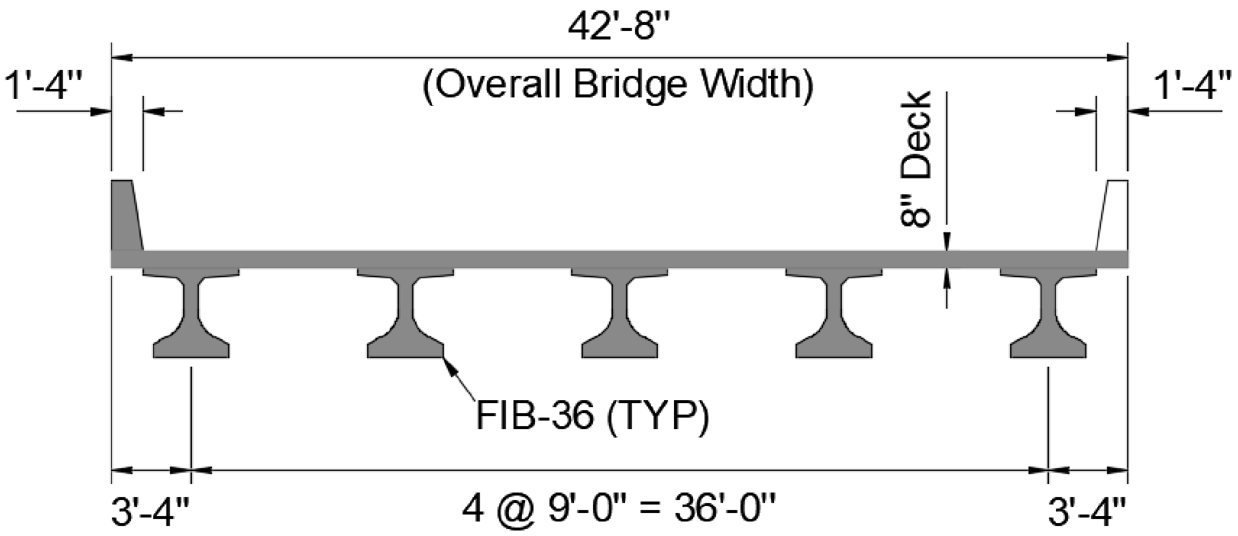
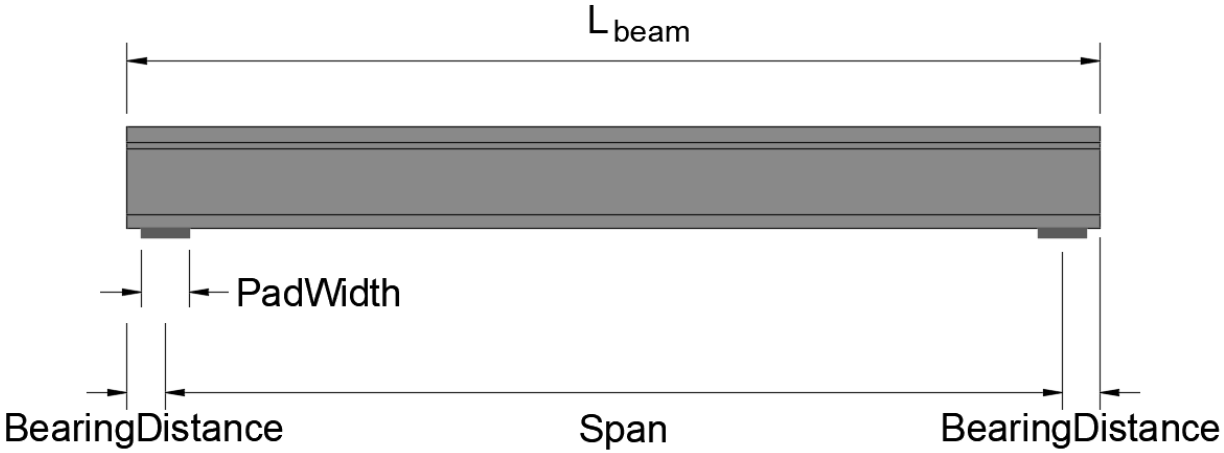
DESIGN EXAMPLE: FIB

- Transverse Shear
- Interface Shear Transfer
- Minimum Longitudinal Reinforcement

DESIGN EXAMPLE: FIB

Geometry ***This example is simplified from "SR 687/4th Street, NB bridge" project***





$\text{Beam Span} = 87.667\ \text{ft}$

$\text{BeamSpacing} = 9\ \text{ft}$

$\text{BridgeWidth} = 42.667\ \text{ft}$

$\text{Slab thickness } t_{slab} = 8.5\ \text{in}$

$\text{Beam depth } h_{beam} = 36\ \text{in}$

DESIGN EXAMPLE: FIB

Concrete

Beam $f'_{c.beam} = 8.5\text{ ksi}$

Beam $f'_{ci.beam} = 6\text{ ksi}$

Beam $E_{c.beam} = 5112\text{ ksi}$

Beam $E_{ci.beam} = 4557\text{ ksi}$

Slab $f'_{c.slab} = 5.5\text{ ksi}$

Slab $E_{c.slab} = 4428\text{ ksi}$

Unit weight $\gamma_c = \boxed{150\text{ pcf}}$

Note: 145 pcf is permitted

CFRP strand

Diameter $D_p = 0.6\text{ in}$

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

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

Design tensile strength $f_{pu} = 341\text{ ksi}$

Design tensile strain $\varepsilon_{pu} = 0.015\text{ ksi}$

Jacking stress $f_{pj} = 239\text{ ksi}$

GFRP rebar

Bar size $= \#\ 5$

Diameter $d_{GFRP} = 0.625\text{ in}$

Elastic modulus $E_{GFRP} = 6500\text{ ksi}$

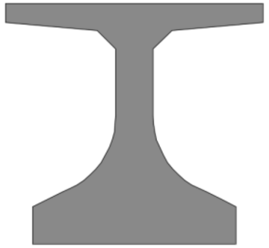
Design tensile strength

$f_{fu.GFRP} = 66.4\text{ ksi}$

Bend $\varphi_{bend} = 0.6$

DESIGN EXAMPLE: FIB

Section Properties
Non-Composite Section



$h_g = 36 \text{ in}$

$A_g = 807 \text{ in}^2$

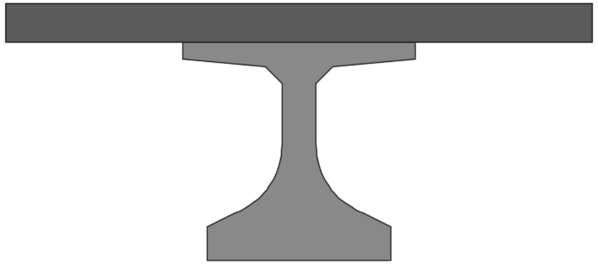
$I_g = 1.275 \times 10^5 \text{ in}^4$

$y_{g.t} = 19.51 \text{ in}$ $y_{g.b} = 16.49 \text{ in}$

$S_{g,t} = 6537 \text{ in}^3$ $S_{g,b} = 7735 \text{ in}^3$

$d_v = 38.80 \text{ in}$ $b_v = 7 \text{ in}$

Section Properties
Composite Section



$h_{g.c} = 45.5 \text{ in}$

$A_{g.c} = 1643 \text{ in}^2$

$I_{g.c} = 4.333 \times 10^5 \text{ in}^4$

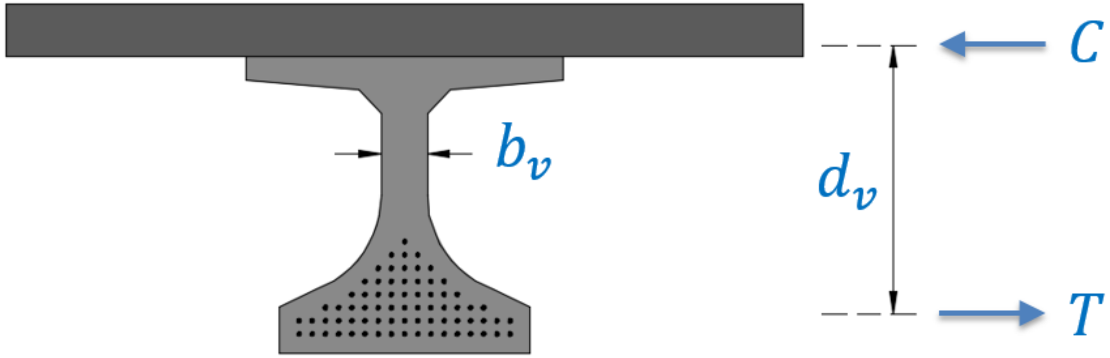
$y_{g.c.t} = 16.52 \text{ in}$ $y_{g.c.b} = 28.98 \text{ in}$

$S_{g,c.t} = 2.622 \times 10^4 \text{ in}^3$

$S_{g,c.b} = 1.495 \times 10^4 \text{in}^3$

DESIGN EXAMPLE: FIB

Critical Section for Shear



Critical Section is d_v from support

Strength I

$$V_u = 272 \text{ kip}$$

$$M_u = 886 \text{ kip}$$

$$N_u = 0$$

$$d_v = \max(d_v\,, 0.72 d_e, 0.72 h_{g.c}) = 38.80 \text{ in}$$

$$b_v = 7 \text{ in}$$

DESIGN EXAMPLE: FIB

Nominal Shear Strength

$$V_n = \min \begin{cases} V_n = V_c + V_f + V_p \\ V_n = 0.25 f_c' b_v d_v + V_p \end{cases}$$

Concrete Contribution

$$V_c = 0.316 \beta \lambda \sqrt{f_c'} b_v d_v = 147 \text{ kip}$$

Prestressing CFRP Contribution

$V_p = 0$ *(Straight strands)*

DESIGN EXAMPLE: FIB

Need to compute the amount of FRP transverse reinforcement for shear?

No, if $V_u \le 0.5\phi\left(V_c + V_p\right) \longrightarrow$ Provide $\frac{A_v}{s} \ge \left(\frac{A_v}{s}\right)_{min}$, check spacing s_{max}

Yes, if $V_u > 0.5\phi\left(V_c + V_p\right) \longrightarrow$ Compute $\left(\frac{A_v}{s}\right)_{req}$

$$\left.\begin{array}{r}\left.\begin{array}{r}\phi V_n \ge V_u \\ V_n = V_c + V_f + V_p \le 0.25 f_c' b_v d_v + V_p\end{array}\right\} V_{f,req} \\ V_f = \frac{f_{fv} A_v d_v}{s} \\ \left(\frac{A_v}{s}\right)_{min}\end{array}\right\} \left(\frac{A_v}{s}\right)_{req} \longrightarrow$$

Provide $\frac{A_v}{s} \ge \left(\frac{A_v}{s}\right)_{min}$

Check spacing s_{min}, s_{max}

DESIGN EXAMPLE: FIB

$$V_u = 272 \text{ kip} > 0.5\phi\left(V_c + V_p\right) = 66 \text{ kip}$$

⇩

Need to compute the amount of FRP transverse reinforcement for shear

$$V_{f,req} = 155 \text{ kip}$$

⇩

Assume double-leg #5 GFRP stirrups $A_v = 0.614 \text{ in}^2$

⇩

$$s_{f,req} \leq 3.38 \text{ in}$$

DESIGN EXAMPLE: FIB

Provide double-leg #5 GFRP stirrups @ 3’’

$$A_v \geq A_{v,min} = 0.05\frac{b_v s}{f_{fv}} \qquad \textbf{OK}$$

$$s \leq s_{max} = \min(0.5d_v, 24\text{ in}) \qquad \textbf{OK}$$

DESIGN EXAMPLE: FIB

Concrete Contribution $V_c = 0.316\beta\lambda\sqrt{f_c'}b_v d_v = 147\text{ kip}$

Prestressing CFRP Contribution $V_p = 0$

GFRP Stirrup Contribution $V_f = \dfrac{A_v f_{fv} d_v}{s} = 175\text{ kip}$

Nominal Shear Strength

$$V_n = \min \begin{cases} V_n = V_c + V_f + V_p \\ V_n = 0.25 f_c' b_v d_v + V_p \end{cases} = 322\text{ kip}$$

$$\boldsymbol{\phi V_n > V_u = 272\text{ kip} \quad \text{OK}}$$

DESIGN EXAMPLE: FIB

Interface Shear

$$\phi V_{ni} \geq V_{ui}$$

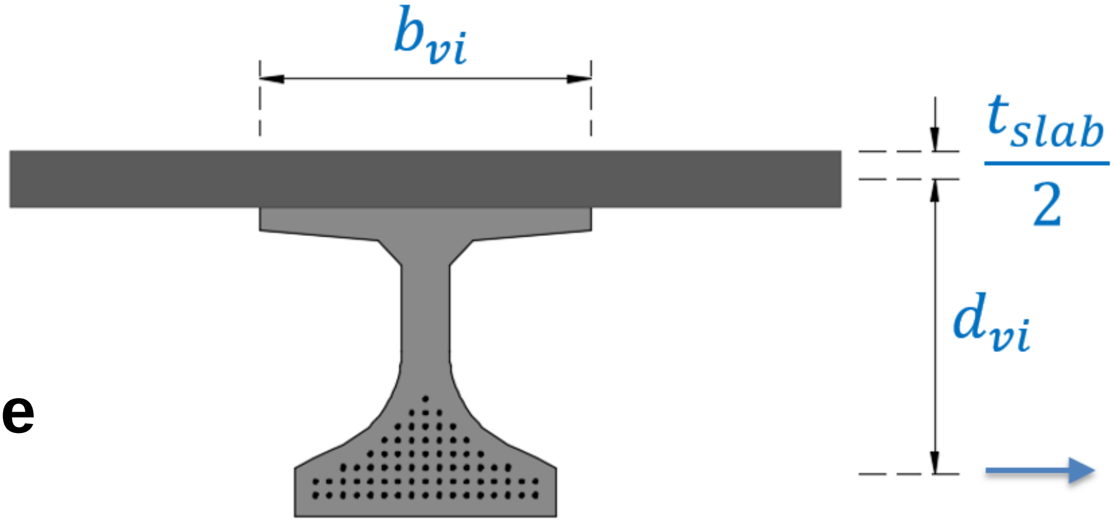
$$\left.\begin{array}{r} v_{ni,req} = \dfrac{v_{hi}}{\phi} \\[2ex] v_{ni} = cA_{cv} + \mu\left(A_{cf} f_{fv} + P_c\right) \\[2ex] v_{ni} \leq K_1 f_c' A_{cv} \\[2ex] v_{ni} \leq K_2 A_{cv} \\[2ex] A_{cf,min} \end{array}\right\} \quad A_{cf,req} \longrightarrow$$

Provide $A_{cf} \geq A_{cf,req}$

DESIGN EXAMPLE: FIB

Factored interface shear

$$v_{hi} = \frac{V_{ui}}{d_{vi}} = 89.0\ \text{kip/ft}$$



Required nominal interface shear resistance

$$v_{ni,req} = \frac{v_{hi}}{\phi} = 98.9\ \text{kip/ft}$$

Provided nominal interface shear resistance

$\mu = 1$ $c = 0.28\ \text{ksi}$

$$v_{ni} = cA_{cv} + \mu\left(A_{cf} f_{fv} + P_c\right) = 215\ \text{kip/in} > v_{ni,req}$$ **OK**

DESIGN EXAMPLE: FIB

Provided nominal interface shear resistance

$\mu = 1$ $\quad c = 0.28\ \text{ksi}$ $\quad K_1 = 0.3$ $\quad K_2 = 1.8\ \text{ksi}$

$v_{ni} = cA_{cv} + \mu(A_{cf} f_{fv} + P_c) = 215\ \text{kip/ft} > v_{ni,req}$ **OK**

$v_{ni} \leq K_1 f_c' A_{cv} = 1469\ \text{kip/ft}$ **OK**

$v_{ni} \leq K_2 A_{cv} = 1037\ \text{kip/ft}$ **OK**

For cast-in-place concrete slab on clean concrete girder surfaces free of laitance, the minimum interface shear reinforcement, need not exceed the lesser of $A_{vf.min}$ and the amount needed to resist $1.33 \cdot V_{ui}/\phi$

$v_{ni} > 1.33 \cdot v_{ui}/\phi$ NO Need to Satisfy $A_{cf} > A_{vf.min} = \dfrac{0.05A_{cv}}{f_{fv}} = 1.1\ \text{in}^2/\text{ft}$

DESIGN EXAMPLE: FIB

Longitudinal Reinforcement

At each section, the tensile capacity of the longitudinal reinforcement on the flexural tension side of the member shall be proportioned to satisfy

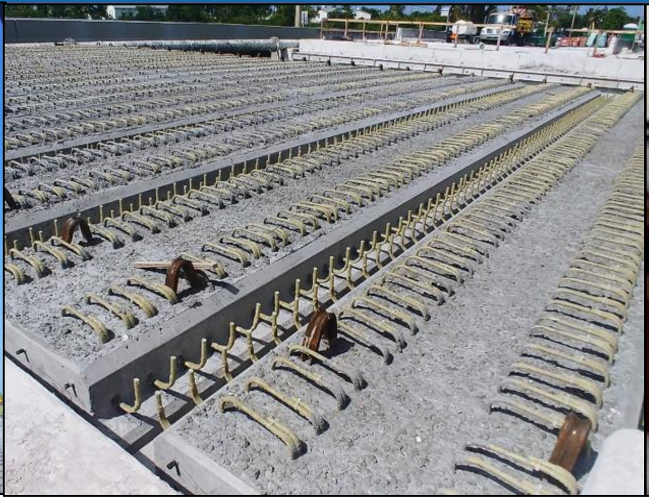
$$\sum_{x=1}^{n} A_{px} f_{px} \geq \frac{|M_u|}{d_v \phi_f} + 0.5 \frac{N_u}{\phi_c} + \left[\left| \frac{V_u}{\phi_v} - V_p \right| - 0.5 V_f \right] \cot \theta$$

For example, at support location

$563 \text{ kip} \geq 442 \text{ kip}$ **OK** **No Additional Longitudinal Reinforcement is Required**

4. SHEAR DESIGN

4.3 Design Example: FSB 12x57



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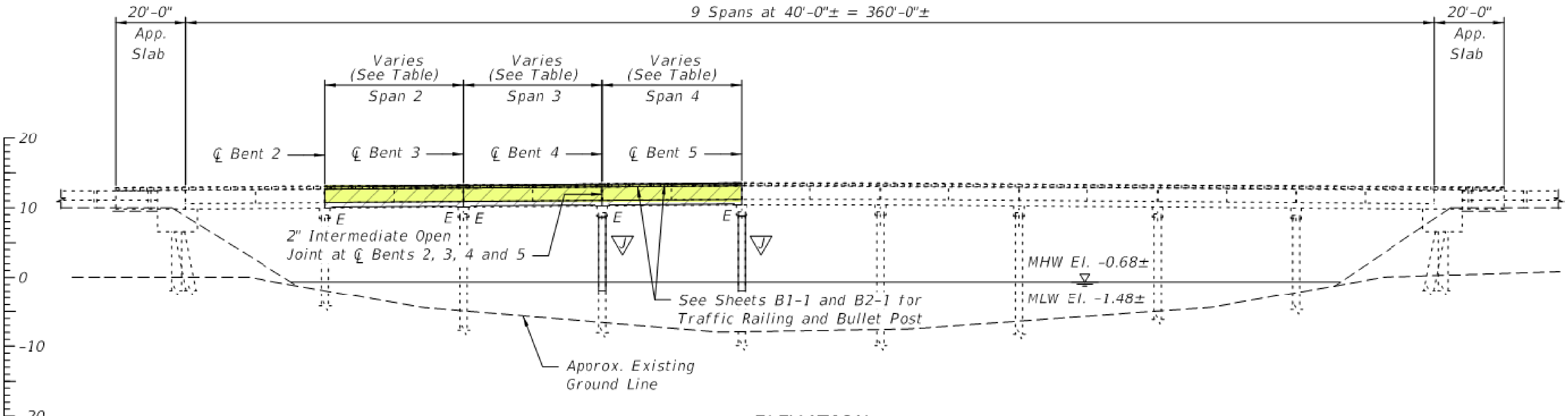
DESIGN EXAMPLE: FSB

US 1 Over Cow Key Channel, Key West, Florida

DESIGN EXAMPLE: FSB

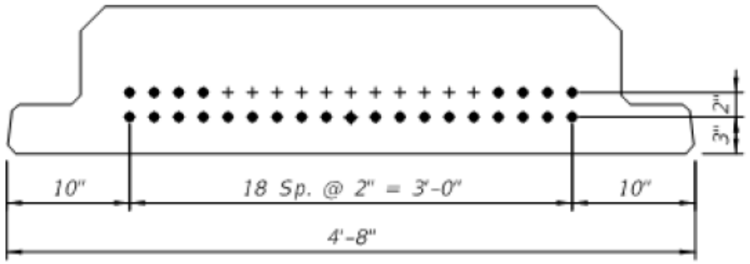
Geometry, from US 1 Over Cow Key Channel, Key West, Florida



ELEVATION

DESIGN EXAMPLE: FSB

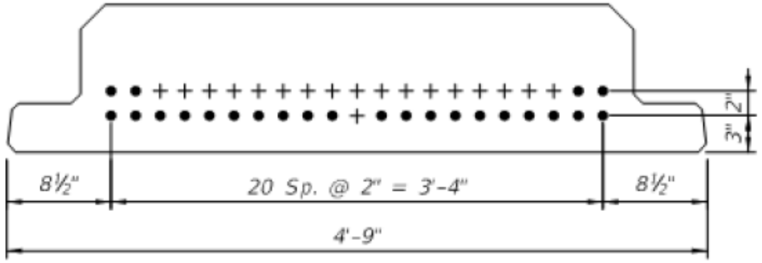
US 1 Over Cow Key Channel, Key West, Florida



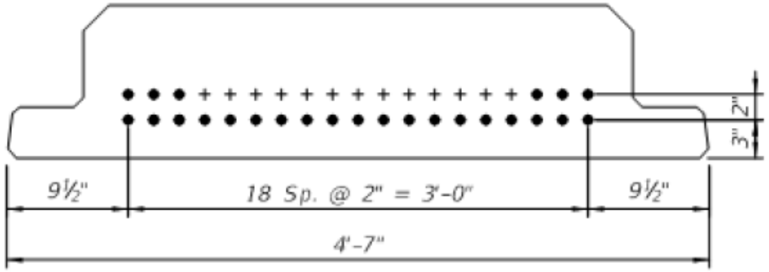
TYPE ① 27 STRANDS

FIBER-REINFORCED POLYMER REINFORCING:

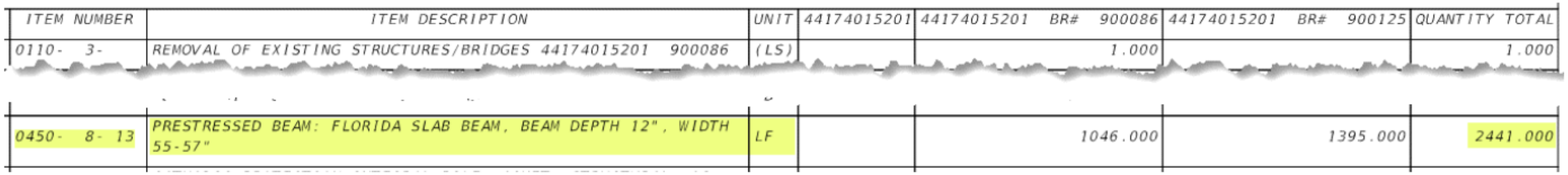
1. *FSB precast panels shall be reinforced using Glass-Fiber Reinforced Polymer (GFRP) and shall be prestressed using Carbon-Fiber Reinforced Polymer (CFRP).*
2. *All FRP reinforcing shall be per Specification Section 932 and 933.*
3. *FRP reinforcing detail dimensions are out-to-out of bars.*
4. *For standard bar bending detail for FRP, see FDOT Developmental Design Index D21310.*



TYPE ② 24 STRANDS



TYPE ① 25 STRANDS

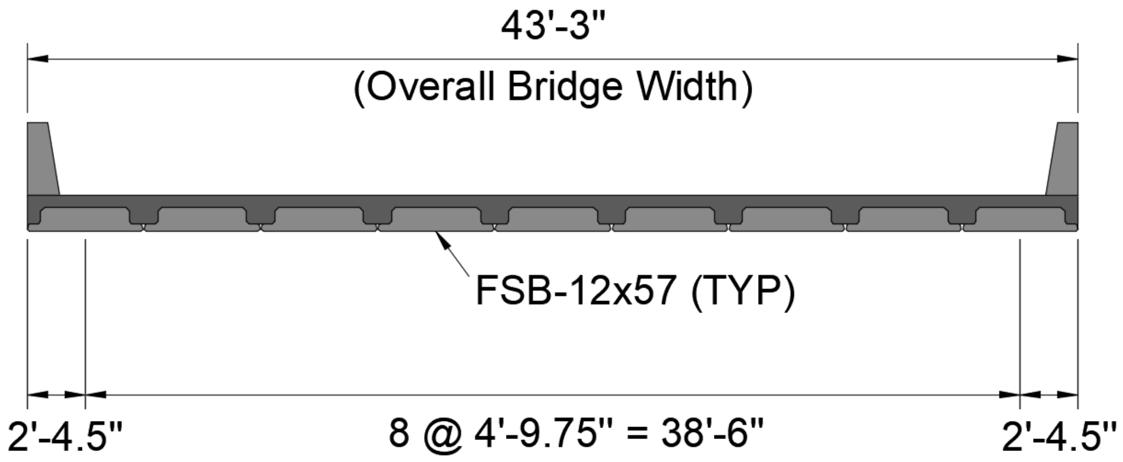


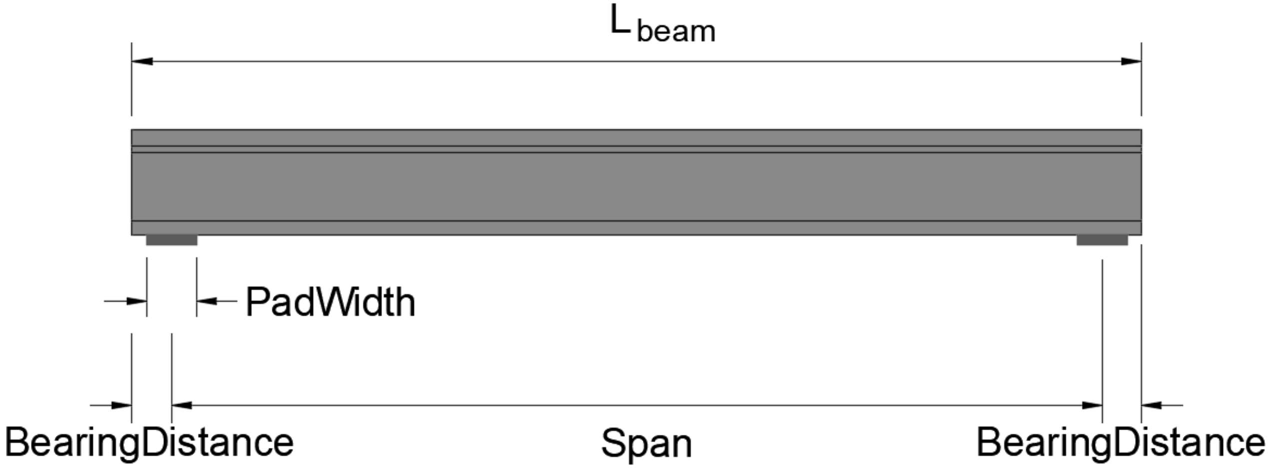
ITEM NUMBER	ITEM DESCRIPTION	UNIT	44174015201	44174015201 BR# 900086	44174015201 BR# 900125	QUANTITY TOTAL
0110- 3-	REMOVAL OF EXISTING STRUCTURES/BRIDGES 44174015201 900086	(LS)		1.000		1.000
0450- 8- 13	PRESTRESSED BEAM: FLORIDA SLAB BEAM, BEAM DEPTH 12", WIDTH 55-57"	LF		1046.000	1395.000	2441.000

DESIGN EXAMPLE: FSB

Geometry

This Example is simplified from “US 1 Over Cow Key Channel” bridge





$\text{Beam Span} = 38.917\ \text{ft}$

$\text{BeamSpacing} = 4.813\ \text{ft}$

$\text{BridgeWidth} = 43.25\ \text{ft}$

$\text{Slab thickness } t_{slab} = 6\ \text{in}$

$\text{Beam depth } h_{beam} = 12\ \text{in}$

DESIGN EXAMPLE: FSB

Concrete

Beam $f'_{c.beam} = 8.5 \text{ ksi}$

Beam $f'_{ci.beam} = 6 \text{ ksi}$

Beam $E_{c.beam} = 5112 \text{ ksi}$

Beam $E_{ci.beam} = 4557 \text{ ksi}$

Slab $f'_{c.slab} = 5.5 \text{ ksi}$

Slab $E_{c.slab} = 4428 \text{ ksi}$

Unit weight $\gamma_c = \boxed{150 \text{ pcf}}$

Note: 145 pcf is permitted

CFRP strand

Diameter $D_p = 0.6 \text{ in}$

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

Elastic modulus $E_p = 22{,}480 \text{ ksi}$

Design tensile strength $f_{pu} = 341 \text{ ksi}$

Design tensile strain $\varepsilon_{pu} = 0.015 \text{ ksi}$

Jacking stress $f_{pj} = 239 \text{ ksi}$

GFRP rebar

Bar size $= \# 4$

Diameter $d_{GFRP} = 0.5 \text{ in}$

Elastic modulus $E_{GFRP} = 6500 \text{ ksi}$

Design tensile strength

$f_{fu.GFRP} = 77.0 \text{ ksi}$

Bend $\varphi_{bend} = 0.6$

DESIGN EXAMPLE: FSB

Section Properties
Non-Composite Section

$h_g = 12\text{ in}$

$A_g = 582\text{ in}^2$

$I_g = 7084\text{ in}^4$

$y_{g.t} = 6.35\text{ in}$ $y_{g.b} = 5.65\text{ in}$

$S_{g,t} = 1116\text{ in}^3$

$S_{g,b} = 1254\text{ in}^3$

Section Properties
Composite Section

$h_{g.c} = 18\text{ in}$

$A_{g.c} = 974\text{ in}^2$

$I_{g.c} = 2.598 \times 10^4\text{ in}^4$

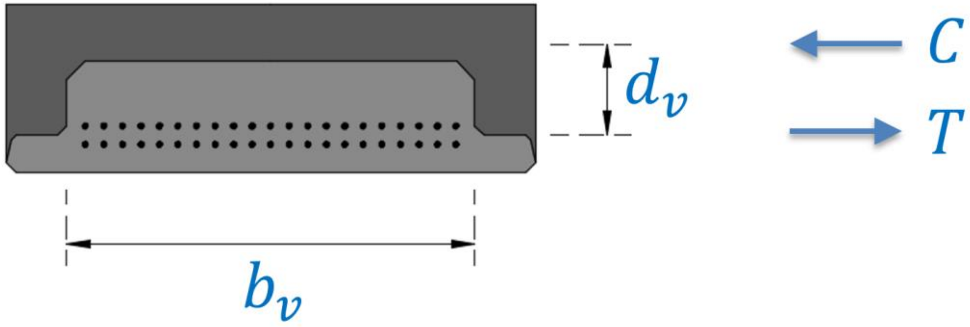
$y_{g.c.t} = 9.22\text{ in}$ $y_{g.c.b} = 8.78\text{ in}$

$S_{g,c.t} = 2819\text{ in}^3$

$S_{g,c.b} = 2959\text{ in}^3$

DESIGN EXAMPLE: FSB

Critical Section for Shear



Critical Section is d_v from support

Strength I

$$V_u = 103 \text{ kip}$$

$$M_u = 121 \text{ kip}$$

$$N_u = 0$$

$$d_v = \max(d_v\,, 0.72d_e, 0.72h_{g.c}) = 13.50 \text{ in}$$

$$b_v = 45 \text{ in}$$

DESIGN EXAMPLE: FSB

Nominal Shear Strength

$$V_n = \min \begin{cases} V_n = V_c + V_f + V_p \\ V_n = 0.25 f_c' b_v d_v + V_p \end{cases}$$

Concrete Contribution

$$V_c = 0.316 \beta \lambda \sqrt{f_c'} b_v d_v = 350 \text{ kip}$$

Prestressing CFRP Contribution

$V_p = 0$ *(Straight strands)*

DESIGN EXAMPLE: FSB

Need to compute the amount of FRP transverse reinforcement for shear?

No, if $V_u \leq 0.5\phi(V_c + V_p)$ $\longrightarrow$ Provide $\frac{A_v}{s} \geq \left(\frac{A_v}{s}\right)_{min}$, check spacing s_{max}

Yes, if $V_u > 0.5\phi(V_c + V_p)$ $\longrightarrow$ Compute $\left(\frac{A_v}{s}\right)_{req}$

$$\left.\begin{aligned} V_n &\geq \phi V_u \\ V_n = V_c + V_f + V_p &\leq 0.25 f_c' b_v d_v + V_p \end{aligned}\right\} V_{f,req}$$

$$\left.\begin{aligned} &V_{f,req} \\ &V_f = \frac{f_{fv} A_v d_v}{s} \\ &\left(\frac{A_v}{s}\right)_{min} \end{aligned}\right\} \left(\frac{A_v}{s}\right)_{req} \longrightarrow$$

Provide $\frac{A_v}{s} \geq \left(\frac{A_v}{s}\right)_{min}$

Check spacing s_{min}, s_{max}

DESIGN EXAMPLE: FSB

$$V_u = 103\ \text{kip} < 0.5\phi\left(V_c + V_p\right) = 157\ \text{kip}$$

⇩

NO need to compute the amount of FRP transverse reinforcement for shear

Provide minimum transverse shear reinforcement

⇩

Provide 4-leg #5 GFRP stirrups @ 9''

$$A_v \geq A_{v,min} = 0.05\frac{b_v s}{f_{fv}} \qquad \textbf{OK}$$

$$s \leq s_{max} \qquad \textbf{OK}$$

DESIGN EXAMPLE: FSB

Concrete Contribution $V_c = 0.316\beta\lambda\sqrt{f_c'}b_v d_v = 350\text{ kip}$

Prestressing CFRP Contribution $V_p = 0$

GFRP Stirrup Contribution $V_f = \dfrac{A_v f_{fv} d_v}{s} = 33\text{ kip}$

Nominal Shear Strength

$$V_n = \min \begin{cases} V_n = V_c + V_f + V_p \\ V_n = 0.25 f_c' b_v d_v + V_p \end{cases} = 383\text{ kip}$$

$$\boldsymbol{\phi V_n > V_u = 103\text{ kip}} \qquad \textbf{OK}$$

DESIGN EXAMPLE: FSB

Interface Shear

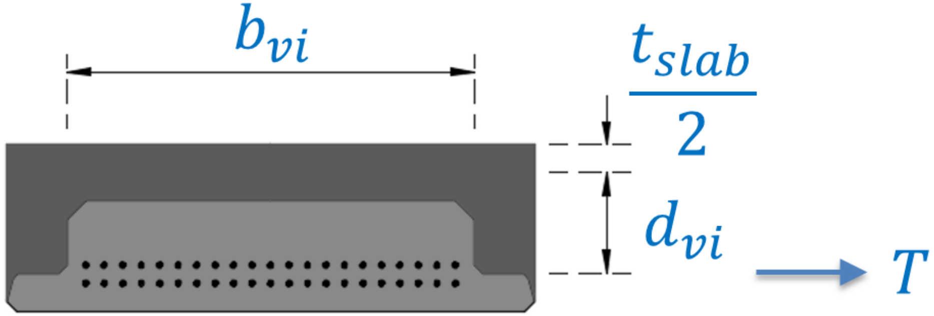
$$\phi V_{ni} \geq V_{ui}$$

$$\left.\begin{array}{r} v_{ni,req} = \dfrac{v_{hi}}{\phi} \\[2ex] v_{ni} = cA_{cv} + \mu\left(A_{cf} f_{fv} + P_c\right) \\[2ex] v_{ni} \leq K_1 f_c' A_{cv} \\[2ex] v_{ni} \leq K_2 A_{cv} \\[2ex] A_{cf,min} \end{array}\right\} A_{cf,req} \longrightarrow \text{Provide} \quad A_{cf} \geq A_{cf,req}$$

DESIGN EXAMPLE: FSB

Factored interface shear

$$v_{hi} = \frac{V_{ui}}{d_{vi}} = 103\ \text{kip/ft}$$



Required nominal interface shear resistance

$$v_{ni,req} = \frac{v_{hi}}{\phi} = 114\ \text{kip/ft}$$

Provided nominal interface shear resistance

$\mu = 1$ $c = 0.28\ \text{ksi}$

$$v_{ni} = cA_{cv} + \mu\left(A_{cf} f_{fv} + P_c\right) = 226\ \text{kip/ft} > v_{ni,req}$$ **OK**

DESIGN EXAMPLE: FSB

Provided nominal interface shear resistance

$\mu = 1$ $c = 0.28\text{ ksi}$ $K_1 = 0.3$ $K_2 = 1.8\text{ ksi}$

$v_{ni} = cA_{cv} + \mu\left(A_{cf}f_{fv} + P_c\right) = 226\text{ kip/ft} > v_{ni,req}$ **OK**

$v_{ni} \leq K_1 f_c' A_{cv} = 1790\text{kip/ft}$ **OK**

$v_{ni} \leq K_2 A_{cv} = 1264\text{ kip/ft}$ **OK**

For cast-in-place concrete slab on clean concrete girder surfaces free of laitance, the minimum interface shear reinforcement, need not exceed the lesser of $A_{vf.min}$ and the amount needed to resist $1.33 \cdot V_{ui}/\phi$

$v_{ni} > 1.33 \cdot V_{ui}/\phi$ NO need to satisfy $A_{cf} > A_{vf.min} = \dfrac{0.05A_{cv}}{f_{fv}} = 1.35\text{ in}^2\text{/ft}$

DESIGN EXAMPLE: FSB

Longitudinal Reinforcement

At each section, the tensile capacity of the longitudinal reinforcement on the flexural tension side of the member shall be proportioned to satisfy

$$\sum_{x=1}^{n} A_{px} f_{px} \geq \frac{|M_u|}{d_v \phi_f} + 0.5 \frac{N_u}{\phi_c} + \left[\left| \frac{V_u}{\phi_v} - V_p \right| - 0.5 V_f \right] \cot \theta$$

For example, at support location

$254\ \text{kip} \geq 197\ \text{kip}$ **OK** **No Additional Longitudinal Reinforcement is Required**

AASHTO CFRP-Prestressed Concrete Design Training Course

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