- The nominal diameter of the bars,
- 1.33 times the maximum size of the coarse aggregate, and
- 1.0 in.

*2.9.3.1.3—Multilayers*

Except in decks where parallel reinforcing is placed in two or more layers, with a clear distance between the layers not exceeding 6.0 in., each bar in the upper layers shall be placed such that its longitudinal axis lies on the same vertical plane of the bar directly below in the bottom layer, and the clear distance between layers shall not be less than 1.0 in. or the nominal diameter of the bars.

*2.9.3.1.4—Splices*

The clear distance limitations between bars that are specified in Articles 2.9.3.1.1 and 2.9.3.1.2 shall also apply to the clear distance between a contact lap splice and adjacent splices or bars.

*2.9.3.1.5—Bundled Bars*

Bundled bars are not recommended except in the case of lap splicing.

*C2.9.3.1.5*

Based on large-scale tests, Matta et al. (2008) demonstrated that the flexural response of concrete beams reinforced with GFRP bars subject to service and ultimate loads can be accurately predicted. However, at this time, there is limited experience in design, construction, and performance of bundled GFRP bars in reinforced concrete members.

**2.9.3.2—Maximum Spacing of Reinforcing Bars**

Unless otherwise specified by the Owner, the spacing of the reinforcement in walls and slabs shall not be greater than the lesser of the following:

- 1.5 times the thickness of the member, and
- 18.0 in.

The maximum spacing of spirals, ties, and temperature shrinkage reinforcement shall be as specified in Article 2.9.6.

**2.9.4—Transverse Reinforcement for Compression Members**

Transverse reinforcement shall consist of ties, spirals, or equivalent hoops.

**2.9.4.1—Columns and Piers**

Transverse reinforcement for columns and piers shall be as specified in Article 4.5.7.

**2.9.4.2—Precast Concrete Piles**

Transverse reinforcement for precast piles shall be as specified in Article 4.6.12.4.

#### 2.9.4.3—Cast-in-Place Concrete Piles

Transverse reinforcement for cast-in-place piles shall be as specified in Article 4.6.13.4.

#### 2.9.4.4—Drilled Shafts

Transverse reinforcement for drilled shafts shall be as specified in Article 4.6.14.5.

### 2.9.5—Transverse Reinforcement for Flexural Members

Reinforcement in compression zones in flexural members, except deck slabs, shall be enclosed by stirrups that shall be equivalent to No. 3 bars for No. 10 or smaller bars.

The spacing of transverse reinforcement along the longitudinal axis of a member shall comply with the provisions of Article 2.7.2.6.

### 2.9.6—Shrinkage and Temperature Reinforcement

Reinforcement for shrinkage and temperature stresses shall be provided near surfaces of concrete exposed to daily temperature changes and in structural mass concrete. Temperature and shrinkage reinforcement shall be sufficient to ensure that the total reinforcement on exposed surfaces is not less than that specified herein.

The area of shrinkage and temperature reinforcement, divided between each face and in each direction, shall not be less than the area associated with the ratio of GFRP shrinkage and temperature reinforcement area to gross concrete area given by Eq. 2.9.6-1:

$$\rho_{f,st} = \max\left(\frac{3{,}132}{E_f f_{fd}};\ 0.0014\right) \leq 0.0036 \qquad (2.9.6\text{-}1)$$

where:

$E_f$ = tensile modulus of elasticity of GFRP reinforcement (ksi)

$f_{fd}$ = design tensile strength of GFRP reinforcing bars considering reductions for service environment (Eq.2.4.2.1-1) (ksi)

The spacing of GFRP reinforcing bars used as shrinkage and temperature reinforcement shall not exceed three times the slab thickness or 12 in., whichever is less.

For components greater than 6 in. in thickness, the minimum specified GFRP shrinkage and temperature reinforcement may be evenly distributed on both faces.

### C2.9.6

No test data are available for the minimum GFRP reinforcement ratio for shrinkage and temperature. For the case of slabs reinforced with steel bars having a yield stress in excess of 60 ksi at a yield strain of 0.0035, the ratio of reinforcement to gross concrete area should be equal to or greater than $0.0018 \times 60/f_y$, where $f_y$ is in ksi, and not less than 0.0014 (ACI, 2014). These provisions are modified accounting for the tensile modulus of elasticity and strength of shrinkage and temperature GFRP reinforcement:

$$\rho_{f,st} = 0.0018 \times \frac{60}{f_{fd}} \frac{29{,}000}{E_f} \geq 0.0014 \qquad (C2.9.6\text{-}1)$$

The constant values in Eq. C2.9.6-1 are lumped to obtain Eq. 2.9.6-1.

## 2.9.7—Development and Splices of Reinforcement

### 2.9.7.1—General

### C2.9.7.1

FRP bars made with a thermoset resin cannot be bent once they are manufactured. FRP bars can be fabricated with bends, but in this case a strength reduction of approximately 40 percent compared to the tensile strength of the straight bar may occur in the bent region. The reduction is caused by fiber buckling and stress concentration.

### 2.9.7.2—Basic Requirements

The calculated force effects in the GFRP reinforcement at each section shall be developed on each side of that section by embedment length. Hooks and end anchors may be used in developing GFRP reinforcing bars in tension. The performance of end anchors shall be demonstrated by the GFRP reinforcing bar manufacturer by performing tests equivalent to ASTM D3916 and approved by the Owner.

### 2.9.7.3—Flexural Reinforcement

*2.9.7.3.1—General*

Critical sections for development of GFRP reinforcement in flexural members shall be taken at points of maximum stress and at points within the span where adjacent reinforcement terminates.

Except at supports of simple spans and at the free ends of cantilevers, GFRP reinforcement shall be extended beyond the point at which it is no longer required to resist flexure for a distance no less than the larger of the following:

- The effective depth of the member,
- 15 times the GFRP reinforcing bar diameter, and
- one-twentieth of the clear span.

Continuing GFRP reinforcement shall extend not less than the development length, $\ell_d$, specified in Article 2.9.7.4.1, beyond the point where bent or terminated tensile reinforcement is no longer required to resist flexure.

No more than 50 percent of the GFRP reinforcement shall be terminated at any section, and adjacent bars should not be terminated in the same section.

*2.9.7.3.2—Positive Moment Reinforcement*

At least one-third of the positive moment reinforcement in simple span members and one-fourth of the positive moment reinforcement in continuous members shall extend along the same face of the member beyond the centerline of the support. In beams, such extension shall not be less than the tension development length, $\ell_d$, specified in Article 2.9.7.4.1, unless the GFRP reinforcement terminates beyond the centerline of simple supports by a standard hook or a mechanical anchorage in compliance with the provisions of Article 2.9.7.5.

*2.9.7.3.3—Negative Moment Reinforcement*

At least one-third of the total tensile reinforcement provided for negative moment at a support shall have an embedment length beyond the point of inflection not less than the greatest of the following:

- The effective depth of the member,
- 12.0 times the nominal bar diameter, and
- one-sixteenth of the clear span.

*2.9.7.3.4—Moment Resisting Joints*

Flexural reinforcement in continuous, restrained, or cantilever members or in any member of a rigid frame shall be detailed to provide continuity of reinforcement at intersections with other members to develop the nominal moment re-sistance of the joint.

**2.9.7.4—Development of Reinforcement**

*2.9.7.4.1—Deformed Bars in Tension*

The tension development length, $\ell_d$, shall satisfy Eq. 2.9.7.4.1-1, unless otherwise specified by the Owner or established by independent testing approved by the Owner:

$$\ell_d \geq \max\left(\frac{31.6\,\alpha\dfrac{f_{fr}}{\sqrt{f'_c}}-340}{13.6+\dfrac{C}{d_b}}d_b;\ 20d_b\right) \quad (2.9.7.4.1\text{-}1)$$

where:

$\alpha$ = bar location modification factor

$f'_c$ = specified compressive strength of concrete (ksi)

$f_{fr}$ = required GFRP reinforcing bar stress as determined in Article 2.7.3.7 (ksi)

$C$ = lesser of the cover to the center of the bar or one-half of the center-to-center spacing of the bars being developed (in.)

$d_b$ = GFRP reinforcing bar diameter (in.)

The term $C/d_b$ shall not be taken larger than 3.5.

The bar location modification factor shall be set equal to 1.0 except for bars with more than 12 in. of concrete cast below the reinforcement, for which a value of 1.5 shall be adopted.

*C2.9.7.4.1*

Wambeke and Shield (2006) followed the methodology for the determination of development length of FRP reinforcing bars originally adopted for steel bars. Accordingly, a consolidated database of 269 beam bond tests was created and this database was limited to beam-end tests, notch-beam tests, and splice tests. The majority of the reinforcing bars represented in the database were GFRP bars. The bar surface finish (spiral wrap versus helical lug) and the presence of confining reinforcement did not appear to affect the results. GFRP bars have a very low relative rib area and, therefore, the presence of confinement may not increase the average bond stress.

During concrete placement, air, water, and fine particles migrate upward through the concrete. This phenomenon can cause a significant drop in bond strength under the reinforcing bars horizontally placed. From the database assembled by Wambeke and Shield (2006), there were 15 tests where horizontal reinforcement had more than 12 in. of concrete below it at the time of embedment. Accordingly, a bar location modification factor was proposed and set to 1.5.

*2.9.7.4.2—Deformed Bars in Compression*

GFRP reinforcement shall not be used to provide additional strength in concrete compression members as indicated in Article 1.3.

*2.9.7.4.3—Standard Hooks in Tension*

GFRP reinforcing bars are typically manufactured without end bends as indicated in Article 1.3. When hooks are provided, the development length, $\ell_{dh}$, shall not be less than the value given by Eq. 2.9.7.4.3-1:

$$\ell_{dh} = \begin{cases} 63.2\dfrac{d_b}{\sqrt{f'_c}} & \text{for } f_{fd} \le 75 \text{ ksi} \\ \dfrac{f_{fd}}{1.2}\dfrac{d_b}{\sqrt{f'_c}} & \text{for } 75 \text{ ksi} < f_{fd} < 150 \text{ ksi} \\ 126.4\dfrac{d_b}{\sqrt{f'_c}} & \text{for } f_{fd} \ge 150 \text{ ksi} \end{cases} \quad (2.9.7.4.3\text{-}1)$$

where:

$d_b$ = GFRP reinforcing bar diameter (in.)

$f'_c$ = specified compressive strength of concrete (ksi)

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

The development length $\ell_{dh}$ shall not be less than the greater of $12d_b$ and 9 in.

These values are based on experimental evidence reported by Ehsani et al. (1995) where the tensile strength and slip-page of hooked GFRP bars stabilized for tail lengths near $12d_b$.

The minimum required tail length shall be as specified in Article 2.7.2.7.2.

**2.9.7.5—Development by Mechanical Anchorages**

Any mechanical device capable of developing the strength of GFRP reinforcement without damage to concrete or the bar itself may be used as an anchorage. Performance of mechanical anchorages shall be verified by laboratory tests.

Development of reinforcement may consist of a combination of mechanical anchorage and the additional embedment length of reinforcement between the point of maximum bar stress and the mechanical anchorage.

If mechanical anchorages are to be used, complete details shall be shown in the contract documents or preapproved by the Owner.

#### 2.9.7.6—Splices of GFRP Reinforcing Bar

Permissible locations, types, and dimensions of splices, including staggers, for GFRP reinforcing bars shall be shown in the contract documents.

The length of lap for tension GFRP reinforcing bars shall not be less than 12 in. or $1.3\ell_d$, whichever is greater.

The length of lap for compression GFRP reinforcing bars shall not be less than 12 in. or $1.3\,\ell_d$, where $\ell_d$ is computed using Eq. 2.9.7.4.1-1 where $f_{fr} = 0.25\,f_{fu}$.

Bars spliced by noncontact lap splices in flexural members shall not be spaced center-to-center farther apart transversely than the lesser of one-fifth the required lap splice length and 6 in.

Splicing GFRP reinforcing bars by mechanical connections is not permitted unless the full tensile capacity of the GFRP reinforcing bar is achieved as substantiated by tensile test data per ASTM D7205/D7205M.

## 2.10—PROVISIONS FOR STRUCTURE COMPONENTS AND TYPES

### 2.10.1—Deck Slabs

Requirements for deck slabs in addition to those specified in Section 2 shall comply with Section 3.

Reinforcing bars larger than No. 10 shall not be used in concrete bridge decks.

### 2.10.2—Slab Superstructures

#### 2.10.2.1—Cast-in-Place Solid Slab Superstructures

Cast-in-place slabs longitudinally reinforced with GFRP bars may be used as slab-type bridges.

The distribution of live load may be determined by a refined analysis or as specified in Article 4.6.2.3 of the *AASHTO LRFD Bridge Design Specifications*.

Edge beams shall be provided as specified in Article 3.7.1.4.

Transverse distribution reinforcement shall be placed in the bottoms of all slabs, except bridge slabs where the depth of fill over the slab exceeds 2.0 ft. For longitudinal reinforced concrete construction, the amount of the bottom transverse reinforcement may be determined by two-dimensional analysis, or the amount of distribution reinforcement may be taken as the percentage of the main reinforcement required for positive moment taken as:

$$\frac{100}{\sqrt{L}} \leq 50\% \qquad (2.10.2.1\text{-}1)$$

where:

$L$ = span length (ft)

#### C2.10.2.1

In this simple bridge superstructure, the deck slab also serves as the principal load-carrying component. The concrete slab, which may be solid, voided, or ribbed, is supported directly on the substructures.

#### 2.10.2.2—Precast Deck Bridges

Requirements for precast deck bridges in addition to those specified in Section 2 and Section 3 shall be as specified in Article 5.12.2.3 of the *AASHTO LRFD Bridge Design Specifications*.

### 2.10.3—Beams and Girders

Requirements for beams and girders in addition to those specified in Section 2 shall be as specified in Article 5.12.3 of the *AASHTO LRFD Bridge Design Specifications*.

### 2.10.4—Diaphragms

Diaphragms subjected primarily to shear and torsion and whose depth is large relative to their span shall be analyzed and designed using the strut-and-tie method or legacy methods as specified in Article 2.8.

Unless otherwise specified, diaphragms shall be provided at abutments, piers, and hinge joints to resist applied forces and transmit them to points of support.

Intermediate diaphragms may be used between beams in curved systems or where necessary to provide torsional resistance and to support the deck at points of discontinuity or at right-angle points of discontinuity or at angle points in girders.

For spread box beams having an inside radius less than 800 ft, intermediate diaphragms shall be used.

### C2.10.4

In certain types of construction, end diaphragms may be replaced by an edge beam or a strengthened strip of slab made to act as a vertical frame with the beam ends. Such types are low I-beams and double-T beams. These frames should be designed for wheel loads.

The diaphragms should be essentially solid, except for access openings and utility holes, where required.

For curved bridges, the need for and the required spacing of diaphragms depends on the radius of curvature and the proportions of the webs and flanges.

### 2.10.5—Footings

Requirements for concrete footings reinforced with GFRP bars in addition to those specified in Section 2 shall be as specified in Article 4.9.

#### 2.10.5.1—Shear in Slabs and Footings

*2.10.5.1.1—Critical Sections for Shear*

The critical sections for shear shall be determined in accordance with the provisions of Article 5.12.8.6.1 of the *AASHTO LRFD Bridge Design Specifications*.

*2.10.5.1.2—One-Way Action*

For one-way action, the shear resistance of the footing or slab shall satisfy the requirements specified in Article 2.7.3.

*2.10.5.1.3—Two-Way Action*

For two-way action for sections without transverse reinforcement, the nominal shear resistance of the concrete, $V_c$ in kips, shall be taken as:

*C2.10.5.1.3*

If shear perimeters for individual loads overlap or project beyond the edge of the member, the critical perimeter, $b_o$, should be taken as that portion of the smallest envelope of individual shear perimeter that will

$$V_c = 0.316\, k \sqrt{f'_c} b_o d_v \quad (2.10.5.1.3\text{-}1)$$

where:

$k$ = ratio of depth of neutral axis to depth of flexural reinforcement

$f'_c$ = specified compressive strength of concrete (ksi)

$b_o$ = perimeter of critical section computed at a distance of $d/2$ away from the concentrated load (in.). The shape of the critical section shall be the same as the shape of the concentrated load

$d_v$ = effective shear depth as determined in Article 2.7.2.8 (in.)

Where $V_u > \phi V_n$, shear reinforcement shall be added in compliance with Article 2.7.3.3, with the angle $\theta$ taken as 45 degrees.

For two-way action for sections with transverse reinforcement, the nominal shear resistance, $V_n$ in kips, shall be taken as:

$$V_n = V_c + V_f \quad (2.10.5.1.3\text{-}2)$$

in which the nominal shear resistance of the concrete, $V_c$ in kips, shall be calculated using Eq. 2.10.5.1.3-1, and the nominal shear resistance provided by transverse GFRP reinforcement, $V_f$ in kips, shall be taken as:

$$V_f = \frac{A_{fv} f_{fv} d_v}{s} \quad (2.10.5.1.3\text{-}3)$$

where:

$A_{fv}$ = area of transverse reinforcement within distance $s$ (in.$^2$)

$d_v$ = effective shear depth as determined in Article 2.7.2.8 (in.)

$f_{fv}$ = design tensile strength of transverse reinforcement as determined in Article 2.7.3.5 (ksi)

$s$ = spacing of transverse reinforcement measured in a direction parallel to the longitudinal reinforcement (in.)

## 2.10.6—Concrete Piles

Requirements for concrete piles reinforced with GFRP bars in addition to those specified in Section 2 shall be as specified in Article 4.6.

actually resist the critical shear for the group under consideration. One such situation is illustrated in Figure C2.10.5.1.3-1.

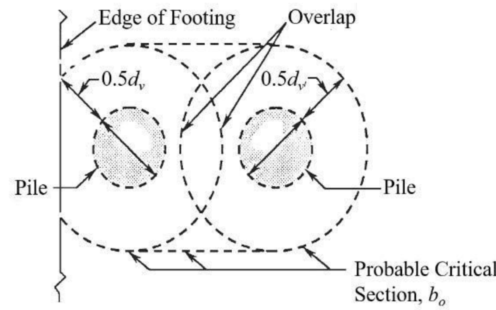


**Figure C2.10.5.1.3-1—Modified Critical Section for Shear with Overlapping Critical Perimeters**

## 2.11—ANCHORS

Requirements for anchors shall be as specified in Article 5.13 of the *AASHTO LRFD Bridge Design Specifications*.

Anchors intended to comply with the provisions of this Article shall be designed, detailed and installed using the provisions of ACI 318-14 Chapter 17 which is incorporated by reference, unless those provisions are specifically amended herein.

## 2.12—DURABILITY

Protective measures and design concepts for durability shall satisfy the provisions of Articles 2.5.2.1 and 5.14.1 of the *AASHTO LRFD Bridge Design Specifications*.

Design for concrete durability should consider detrimental regional and site-specific chemical and mechanical agents that can reduce durability, and shall comply with Article 5.14.2.1 and Articles 5.14.2.3 through 5.14.2.7 of the *AASHTO LRFD Bridge Design Specifications*.

The durability properties of GFRP reinforcement shall comply with the material specifications in ASTM D7957/D7957M. More stringent provisions may be specified by the Owner.

Design for durability of structural concrete reinforced with GFRP bars shall comply with Article 2.4.2.1.

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