16.9 NEAR SURFACE MOUNTED CFRP BRIDGE DECK OVERHANG STRENGTHENING

16.9.1 GENERAL

This Bridge Design Memo provides guidance for the strengthening of bridge deck overhangs using Near Surface Mounted (NSM) Carbon Fiber Reinforced Polymer (CFRP) bars/strips.

The CFRP bar/strip used in the NSM method is a fiber-reinforced polymer (FRP) as defined in the *2023 AASHTO Guide Specifications for Design of Bonded FRP Systems for Repair and Strengthening of Concrete Bridge Elements, 2nd Edition* (AASHTO FRP) Article 1.2 and is fabricated by the pultrusion process. Note that AASHTO FRP sometimes refers to bars as rods – this memo will use both terms interchangeably. Finally, the *2023 Non-Standard Special Provision Carbon-Fiber-Reinforced Polymer Bars* (NSSP) document identifies both bars and strips as bars.

When a bridge barrier is replaced or upgraded on an existing bridge, it is often the case that the existing bridge deck overhang section does not have enough capacity to meet the *AASHTO LRFD Bridge Design Specifications with CA Amendments 10th Edition* (AASHTO-CA BDS) demands due to vehicular impact loading. A demonstrated solution to increasing the capacity of the bridge deck overhang is to add additional tension capacity in the negative moment region of the deck overhang section. High-strength prefabricated (or pultruded) CFRP bars/strips can be bonded just below the deck surface, providing enough capacity to meet the higher demands. The procedure of bonding a high-strength CFRP bar/strip in a cut groove on the surface of the bridge deck overhang is referred to as the NSM strengthening method, and the design procedure is discussed in this memo. The NSM strengthening method can also be used for general flexural or shear strengthening where appropriate.

16.9.2 NOTATION

Notations in this section are generally based on AASHTO FRP.

A = minimum cross-sectional area to be stipulated in NSSP (in.^{2})

A_f = area of FRP reinforcement (in.^{2})

a = depth of equivalent rectangular stress block (in.)

c = distance from compression face to the neutral axis (in.)

c_e = clear distance between the groove edge and beam edge for NSM FRP rods or strips (in.)

c_g = clear spacing between grooves for NSM FRP rods or strips (in.)

d_f = distance from compression face to the centroid of FRP reinforcement (in.)

d_r = diameter of NSM rod (in.)

E_c = modulus of elasticity of the concrete (ksi)

E_f = modulus of elasticity of FRP reinforcement (ksi)

f_c = stress in concrete at strain, ε_c (ksi)

f'_c = compressive strength of concrete for use in design (ksi)

f_f = stress in FRP under fatigue loading (ksi)

f_{fe} = effective stress in FRP reinforcement (ksi)

f_{fu} = ultimate tensile strength from NSSP (ksi)

f_s = stress in the steel tension reinforcement at development of nominal flexural resistance (ksi)

f_y = specified minimum yield strength of steel reinforcement (ksi)

h_g = groove depth for NSM FRP rods or strips (in.)

h_s = height of NSM FRP strip (in.)

I_{cr} = moment of inertia of cracked section (in.^{4})

I_g = moment of inertia of gross section (in.^{4})

L_{dr} = development length for NSM FRP rods (in.)

L_{ds} = development length for NSM FRP strips (in.)

M_{DL} = dead load moment from dead load present during NSM strengthening (kip-in.)

$M_{f,req}$ = difference between ultimate moment and factored resistance moment of unstrengthened member (kip-in.)

$M_{LL,C}$ = construction live load moment attributed to the beam being retrofitted (kip-in.)

M_n = nominal flexural resistance (kip-in.)

M_{nf} = nominal FRP flexural resistance (kip-in.)

M_r = factored flexural resistance (kip-in.)

M_u = factored moment demand (kip-in.)

n_s = number of NSM FRP strips

n_b = number of NSM FRP bars

R_r = factored resistance of the unstrengthened member (kip-in.)

w_g = groove width for NSM FRP rods or strips (in.)

w_s = thickness of NSM FRP strip (in.)

y_c = depth to cracked section neutral axis (in.)

α_{1f} = stress block factor when concrete compressive strain is less than 0.003 in./in. taken as the ratio of equivalent rectangular concrete compressive stress intensity to the compressive strength of concrete used in design

ε_c = compressive strain in concrete (in./in.)

ε_{cu} = failure strain of concrete in compression (in./in.)

ε_{fe} = effective strain in FRP reinforcement (in./in.)

ε_{fi} = strain at FRP-concrete interface (in./in.)

ε_{fu} = FRP ultimate strain (in./in.)

ε_{fu} = minimum rupture strain from NSSP (in./in.)

$\varepsilon_{f,u}$ = strain in FRP at ultimate demand (in./in.)

ε_i = strain in concrete substrate at time of FRP installation (in./in.)

$\varepsilon_{f,y}$ = strain in FRP at initiation of yielding in tension steel (in./in.)

η = strain limitation coefficient that is less than unity

τ_a = average bond strength (ksi)

ϕ = resistance factor specified in AASHTO-CA BDS Article 5.5.4.2

ϕ_{EM} = environmental reduction factor for FRP material

ϕ_{Ei} = environmental reduction factor for FRP-concrete bond

ϕ_f = FRP resistance factor

16.9.3 DESIGN PROCESS

The first step in the design process is to calculate the moment demands on the bridge deck overhang section according to Bridge Design Memo 16.8 – *Analysis of Deck Overhangs on Existing Bridges for Solid Parapet Rail Collision Forces* (BDM 16.8). Deck overhang moment demand should be calculated at the toe of the barrier rail and at the face of the exterior girder. In most cases, the critical demand is at the toe of the barrier; however, both sections should be checked for each of the design cases specified in BDM 16.8. For slab bridges, the distribution at the toe of the rail is assumed to be the same as a bridge deck overhang. In addition to calculating the moment demand at the barrier, moment demand should be calculated in one-foot increments from the edge of the barrier to establish how the moment demand decays. Once the flexural demand has been established, the factored flexural capacity of the section is calculated and compared with the flexural demand to ensure the design is acceptable. The design must then be checked for ductility, serviceability, and fatigue requirements. Additionally, the design details should conform to the detailing requirements.

Demand and capacity can be established by following the guidance in BDM 16.8, while the other criteria can be established with AASHTO FRP, and this memo, which generally follows AASHTO FRP, but also provides some Caltrans-specific guidance. Sample Problem 2 of AASHTO FRP can generally be followed alongside this memo, although readers should be aware that deck sections will be rectangular sections, as opposed to the example's T-section. Finally, readers should also be aware of the ACI *Design and Construction of Externally Bonded Fiber-Reinforced Polymer Systems for Strengthening Concrete Structures – Guide* (ACI PRC 440.2-23), which maybe able to supplement information from AASHTO FRP.

16.9.3.1 Assumptions

The following assumptions are made in this memo, per AASHTO FRP Article 5.2:

- Distribution of strains over the depth of the member is linear, and conditions of force equilibrium and strain compatibility are satisfied.
- Perfect bonding exists between the reinforcing steel and the concrete and between the FRP reinforcement and the concrete.
- The contribution of tensile stresses in the concrete to flexural strength is neglected.
- The stress-strain behavior of FRP reinforcement is linear-elastic to the point of failure.
- The stress-strain behavior of steel reinforcement is bilinear, with elastic behavior up to yielding and perfectly plastic behavior thereafter.
- The maximum usable compressive strain in the concrete is equal to 0.003 (in./in.).

16.9.3.2 Design Material and Bond Properties

Material properties for CFRP bars/strips vary, but they must conform to the guidelines outlined in the NSSP document and the AASHTO FRP Chapter 4 requirements. The NSSP requirements will supersede those from AASHTO FRP. NSSP requirements are summarized in Table 16.9.3.2-1.

Table 16.9.3.2-1 NSM CFRP Material Properties (NSSP 2023)[a]

Quality Characteristic	Test Method[b]	Requirement
Minimum Cross-Sectional Area, A (in^2, min)	N/A[c]	0.11[d]
Ultimate Tensile Strength, f_{fu} (ksi, min)	ASTM D3039/ D7205	315[e]
Minimum Rupture Strain, ε_{fu} (%, min)	ASTM D3039/D7205	1.5
Tensile Modulus of Elasticity, E_f (ksi, min)	ASTM D3039/D7205	18,000

[a] The variables are added to the table to correspond with AASHTO FRP variables.
[b] Use D3039 for strips, and D7205 for bars/rods.
[c] Report measured cross-sectional area as specified in ASTM D7205.
[d] A = 0.11 in^2 with dimensions of 0.177" x 0.63" for #3 strip and 3/8" diameter for #3 bar and A = 0.2 in^2 with ½" diameter for #4 bar.
[e] f_{fu} = 300 (ksi, min) for #4 bar.

Per AASHTO FRP Article 4.2.4.1, environmental reduction factors are required for the FRP material and the FRP-concrete bond. There are two Environmental Exposure Categories – A and B. Category A applies to overpass bridges, bridges over dry surfaces, and bridges exposed to periodic rain or seasonal de-icing agent spray. Category B applies to bridges that are continuously or frequently in contact with water or located in high moisture environments, such as bridges in coastal regions, over waterways, or near bodies of water.

The FRP material environmental reduction factor, ϕ_{EM}, is determined per AASHTO FRP Article 4.2.4.2, and the FRP-concrete bond environmental reduction factor, ϕ_{Ei}, is determined per AASHTO FRP Article 4.3.2.2. Bridges reinforced with NSM CFRP laminates that are bonded to the concrete with epoxy resin will have a ϕ_{EM} of 0.95 and a ϕ_{Ei} of 0.90 for Environmental Exposure Category A, and a ϕ_{EM} of 0.90 and a ϕ_{Ei} of 0.80 for Environmental Exposure Category B.

AASHTO FRP also stipulates further material requirements in Article 4.2.5 and 4.2.6. These include, but are not limited to: glass transition temperatures for the bond and FRP, moisture equilibrium content, impact tolerance, and strength retention when exposed to differing climates. Further guidelines for niche situations are provided in Articles 4.2.4, 4.2.5, and 4.3 of the AASHTO FRP Commentary.

The minimum bond strength for NSM applications must be 1.0 ksi, per AASHTO FRP Article 4.3.1. Additionally, per AASHTO FRP Article 3.1.2, if the specified compressive strength of the concrete, f'_c, exceeds 10 ksi, it should be capped at 10 ksi for the analysis.

16.9.3.3 Initial Calculations

Standard reinforced concrete analysis is used to calculate the nominal flexural capacity of the unstrengthened section, and then the factored resistance for moment capacity, R_r, is calculated using BDM 16.8 and AASHTO-CA BDS Article 5.6.3.2.

Once the factored capacity has been calculated, the existing strain ε_i on the surface where the CFRP will be applied needs to be determined. This is done by performing a cracked section analysis of the existing overhang while only considering loads that would exist during CFRP installation. For construction that only has dead load, Eq. 16.9.3.3-1 is used, and for construction that has live load, Eq. 16.9.3.3-2 is used (note that Eq. 16.9.3.3-2 has a typo in AASHTO FRP Sample Problem 2 – it uses I_g instead of I_{cr}).

$$\varepsilon_i = \frac{M_{DL}\left(d_f - y_c\right)}{E_c I_{cr}} \tag{16.9.3.3-1}$$

$$\varepsilon_i = \frac{\left(M_{DL} + M_{LL,C}\right)\left(d_f - y_c\right)}{E_c I_{cr}} \tag{16.9.3.3-2}$$

An estimate of the required area of FRP reinforcement can be calculated using Eq. 16.9.3.3-3. The required CFRP bar/strip spacing can be calculated from A_f and should be in accordance with Section 16.9.3.7 of this BDM.

$$A_f \geq \frac{M_{f,req}}{f_{fe}\left(d_f - \frac{a}{2}\right)} \tag{16.9.3.3.-3}$$

To calculate the effective stress, ffe, in Eq. 16.9.3.3-3, an effective strain, ε_{fe}, must be calculated. For this preliminary calculation, it can be assumed that the FRP-concrete interface strain, ε_{fi}, will control the failure mode and can therefore be taken as the effective strain. To calculate the FRP-concrete interface strain, use AASHTO FRP Eq. 5.2.1-5 for rods and AASHTO FRP Eq. 5.2.1-6 for strips. Then apply the FRP concrete-bond reduction factor to determine the effective strain, as shown in the second row of AASHTO FRP Eq. 5.4.1-6. The required additional moment can be calculated by subtracting the flexural demand from the factored resistance for moment capacity found earlier. The depth of the equivalent rectangular stress block, a, can be taken as the same value used for the unstrengthened section, and the depth to the centroid of the CFRP from the extreme compressive fiber, d_f, can be taken as the distance from the extreme compressive fiber to the centroid of the groove.

$$\varepsilon_{fi} = \text{larger of} \begin{cases} 0.006\,\text{in./in.} \leq 0.8\varepsilon_{fu} \\ 0.40\varepsilon_{fu} \leq 0.008\,\text{in./in.} \end{cases} (\text{rods}) \qquad \text{(AASHTO FRP 5.2.1-5)}$$

$$\varepsilon_{fi} = \text{larger of} \begin{cases} 0.007\,\text{in./in.} \le 0.8\varepsilon_{fu} \\ 0.45\varepsilon_{fu} \le 0.008\,\text{in./in.} \end{cases} (\text{strips}) \qquad \text{(AASHTO FRP 5.2.1-6)}$$

Since $\varepsilon_{fe} = \phi_{Ei}\varepsilon_{fi}$ (AASHTO FRP 5.4.1-6)

Then the effective stress can be calculated per AASHTO FRP Eq. 5.4.1-5.

$$f_{fe} = E_f \varepsilon_{fe} \qquad \text{(AASHTO FRP 5.4.1-5)}$$

Once the estimated area has been calculated, the required number of strips/bars can also be estimated using Eq. 16.9.3.3-4 for strips, and Eq. 16.9.3.3-5 for bars. The amount selected should conform to the detailing guidelines provided in AASHTO FRP Article and Commentary 5.5.5.

$$n_s \ge \frac{A_f}{h_s w_s} (\text{strips}) \qquad \text{(16.9.3.3-4)}$$

$$n_b \ge \frac{4A_f}{\pi d_r^2} (\text{bars}) \qquad \text{(16.9.3.3-5)}$$

Next, the effective strain, ε_{fe}, is determined by considering the three different failure modes in AASHTO FRP Eq. 5.4.1-6 – FRP rupture, FRP-concrete interface failure, and concrete crushing.

$$\varepsilon_{fe} = \text{lesser of} \begin{cases} \phi_{EM} 0.6\varepsilon_{fu} \\ \phi_{Ei}\varepsilon_{fu} \\ \phi_{Ei}\left[\dfrac{\varepsilon_{cu}(d_f - c}{c} - \varepsilon_i\right] \end{cases} \qquad \text{(AASHTO FRP 5.4.1-6)}$$

With the effective strain selected, the effective stress is then determined using AASHTO FRP Eq. 5.4.1-5.

If the compressive strain is less than 0.003 in./in., a different stress block is utilized to describe the distribution of stress in the compressive zone. The depth of the stress block is equal to the depth to the neutral axis, and the stress in the concrete is calculated per AASHTO FRP Eq. 5.2.2-1 and then, depending on the compressive strength of the concrete, AASHTO FRP Eq. 5.2.2-2 or AASHTO FRP Eq. 5.2.2-3. Further information on this stress block can be found in AASHTO FRP Commentary 5.2.2.

$$f_c = \alpha_{1f} f_c' \qquad \text{(AASHTO FRP 5.2.2-1)}$$

$$\alpha_{1f} = 0.75 \text{ for } 2.5\,\text{ksi} \le f_c^{'} \le 5\,\text{ksi} \quad \text{(AASHTO FRP 5.2.2-2)}$$

$$\alpha_{1f} = 0.75 - 0.05\left(f_c^{'} - 5\right) \text{ for } 5\,\text{ksi} < f_c^{'} \le 10\,\text{ksi} \quad \text{(AASHTO FRP 5.2.2-3)}$$

Utilizing standard reinforced concrete analysis, an iterative process is then followed to determine the depth to the neutral axis of the section.

16.9.3.4 Nominal Flexural Capacity

The flexural capacity is calculated using AASHTO FRP Eq. 5.4.2-1. The resistance factor, ϕ, is calculated per AASHTO-CA BDS Article 5.5.4.2. The flexural FRP resistance factor, ϕ_f, is taken as 1.0, per AASHTO FRP Article 5.4.2.

$$M_r = \phi M_n + \phi_f M_{nf} \quad \text{(AASHTO FRP 5.4.2-1)}$$

The nominal flexural resistance, M_n, and nominal FRP flexural resistance, M_{nf}, are calculated per AASHTO FRP Article 5.4.2.2. M_{nf} can be calculated using the last term of AASHTO FRP Eq. 5.4.2.1-1 without ϕ_f.

$$M_{nf} = A_f f_{fe}\left(d_f - \frac{c}{2}\right) \quad \text{(AASHTO FRP 5.4.2.1-1)}$$

The nominal flexural strength is then compared with the demand calculated at the start, as shown in Eq. 16.9.3.4-1.

$$M_r > M_u \quad \text{(16.9.3.4-1)}$$

16.9.3.5 Ductility Limit

Per AASHTO FRP Article 5.4.3, to satisfy the ductility requirement, the FRP strain at the ultimate demand must be greater than or equal to 2.5 times the FRP strain when the tensile steel starts yielding. This is calculated by Eq. 16.9.3.5-1.

$$\frac{\varepsilon_{f,u}}{\varepsilon_{f,y}} \ge 2.5 \quad \text{(16.9.3.5-1)}$$

16.9.3.6 Serviceability/Fatigue Limits

Per AASHTO FRP Article 5.3.1, the compressive stress in the concrete and the tensile stress in the reinforcing steel must satisfy the Serviceability limits, which are defined by AASHTO FRP Eq. 5.3.1-1 and AASHTO FRP Eq. 5.3.1-2. Serviceability limits are assessed with the Service 1 load combination, as specified in AASHTO-CA BDS Article 3.4.1.

$$f_c \le 0.6f_c^{'} \qquad \text{(AASHTO FRP 5.3.1-1)}$$

$$f_s \le 0.8f_y \qquad \text{(AASHTO FRP 5.3.1-2)}$$

Per AASHTO FRP Article 5.3.2, the stress in the FRP under the fatigue load combination must satisfy AASHTO FRP Eq. 5.3.2-1. The strain limitation coefficient, η, is to be based on experimental data and stipulated by the Engineer of Record. If there is no experimental data, then the value for CFRP is to be taken as 0.55. The fatigue load combination is specified in AASHTO-CA BDS Article 3.4.1.

$$f_f \le \text{lesser of} \begin{cases} \eta E_f \varepsilon_{fu} \\ E_f \varepsilon_{fe} \end{cases} \qquad \text{(AASHTO FRP 5.3.2-1)}$$

16.9.3.7 Detailing and NSM FRP Development Length

Per AASHTO FRP Article 5.5.5 (unless otherwise noted), FRP rods/strips used in NSM strengthening should be limited to the following:

- FRP rod diameter, d_r, should not be larger than 0.5 in.
- FRP strip thickness, w_s, and height, h_s, should not be larger than 0.2 in. and 0.75 in., respectively, per Caltrans recommendation.
- Epoxy resin should be used for the bonding of FRP rods/strips. Per AASHTO FRP Commentary 5.5.5, the use of cementitious adhesive is not recommended without durability tests.

When using FRP rods in NSM strengthening, AASHTO FRP Article 5.5.5 stipulates that the minimum groove width, w_g, and minimum groove depth, h_g, should be 1.5 times the diameter of the rod, d_r. Caltrans also includes a maximum groove depth limit, which is shown in Figure 16.9.3.7-1 below.

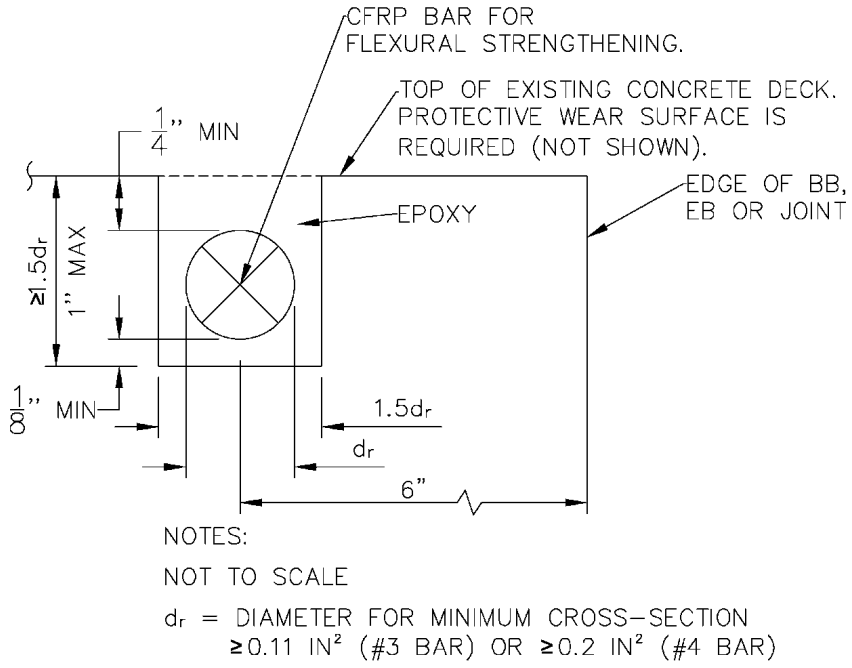


Figure 16.9.3.7-1 Detail for NSM CFRP Bar

When using FRP strips in NSM strengthening, AASHTO FRP Article 5.5.5 stipulates that the minimum groove width should be 3 times the strip's width, w_s, and the minimum groove depth should be 1.5 times the strip height, h_s. Caltrans guidance, which supersedes AASHTO FRP guidance, stipulates that the minimum groove width should be between two and three times the strip width. This, alongside the maximum depth limit, is shown in Figure 16.9.3.7-2 below.

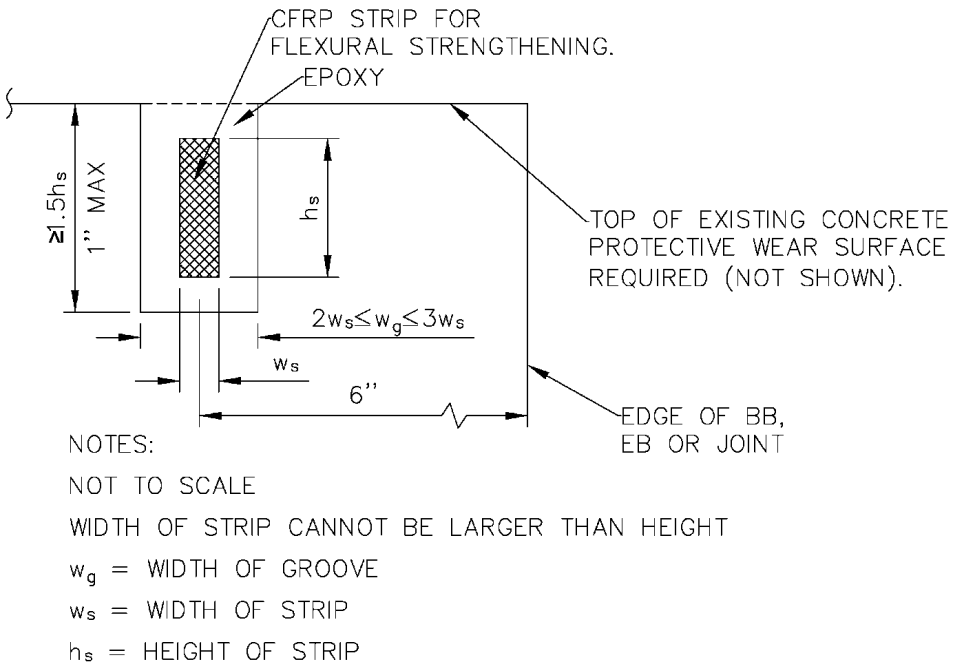


Figure 16.9.3.7-2 Detail for NSM CFRP Strip

Per AASHTO FRP Article 5.5.5, the minimum clear spacing between grooves, c_g, should be 2 times the groove depth for both FRP rods and strips used in NSM strengthening. Additionally, a minimum clear distance between a groove edge and a beam edge, c_e, should be 4 times the groove depth. For both FRP rods and strips, the groove width must always be either less than or equal to the groove depth. Caltrans guidance, which supersedes AASHTO FRP guidance, stipulates that the minimum spacing between grooves should be 4 inches and that the distance to any edge must be 6 inches, as shown in Figure 16.9.3.7-1 and Figure 16.9.3.7-2.

Per AASHTO FRP Article 5.5.5, the development length of FRP bars can be calculated using AASHTO FRP Eq. 5.5.5-1, and the development length of FRP strips can be calculated using AASHTO FRP Eq. 5.5.5-2. The average bond strength, τ_a, is taken as 1.0 ksi unless available test data shows a higher bond strength.

$$L_{dr} \geq \text{Larger of} \begin{cases} \dfrac{d_r}{4} f_{fe} \,(\text{bars}) \\ 12\,\text{in.} \end{cases} \qquad \text{(AASHTO FRP 5.5.5-1)}$$

$$L_{ds} \geq \text{Larger of} \begin{cases} \dfrac{w_s h_s}{2(w_s + h_s)\tau_a} f_{fe} \,(\text{strips}) \\ 12\,\text{in.} \end{cases} \qquad \text{(AASHTO FRP 5.5.5-2)}$$

Additional guidelines from AASHTO FRP Commentary 5.5.5 recommend the installation of fewer strips that are thicker and taller because it leads to an increase in spacing between strips, which will reduce stress interaction and increase confinement.

Caltrans does not recommend splicing NSM bars; however, in localized cases where it cannot be avoided, the bars should be spliced vertically in the groove, and the groove depth adjusted to accommodate the splice. AASHTO FRP Commentary 5.5.5 also notes that NSM FRP bars that need to be spliced in the same groove should have a splice length of $110d_r$. This only applies to NSM FRP bars with diameters less than 0.4 in. that are bonded in concrete with a f'_c less than 6.5 ksi.

16.9.3.8 Detailing at Bridge Skew Joints

NSM grooves are typically orthogonal to the Edge-of-Deck (EOD); however, at skewed joints, the first groove adjacent to the joint should be parallel to the joint, and subsequent grooves should tend to be orthogonal to the EOD at 5 feet from the joint, as shown in Figure 16.9.3.8-1. Note that, for an acute joint skew, these grooves will converge, and they may violate the minimum separation distance. In this case, after the first NSM bar, every other bar can be reduced in length by at least 1 foot out to 5 feet from the joint so that the NSM bars avoid converging together with a distance less than 4 inches. For an obtuse joint, the first groove will be parallel to the joint and will tend to diverge up to 5 feet from the joint.

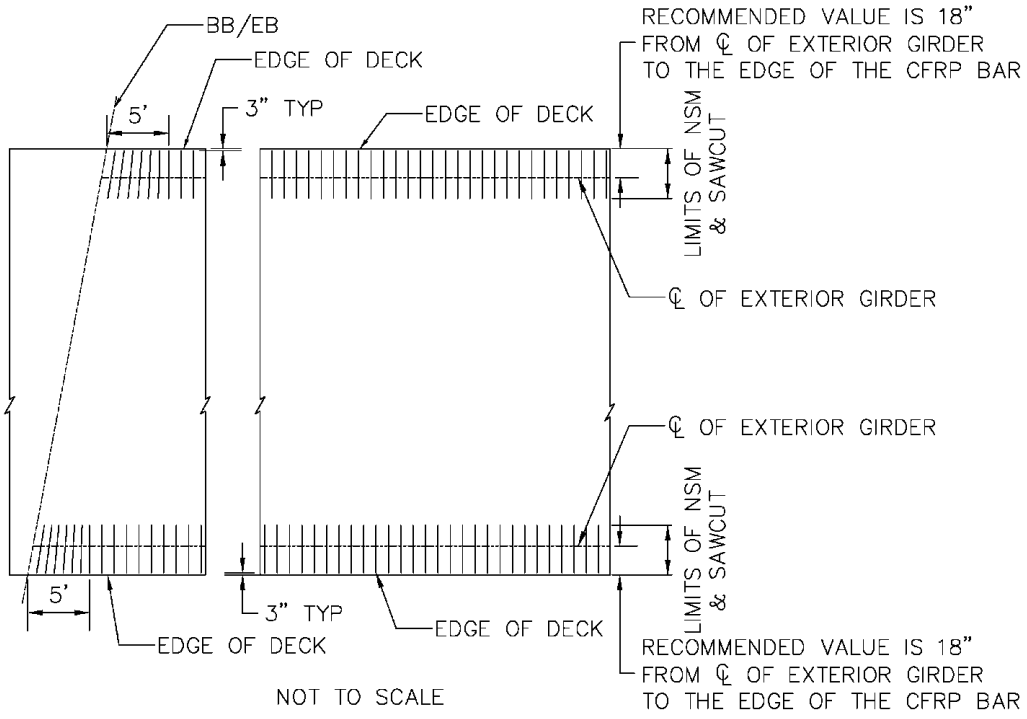


Figure 16.9.3.8-1 Detail for Bridge Skew Joints

16.9.4 REFERENCES

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