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OLD KEYS BRIDGE REPAIRS
Negative Moment Strengthening of the Rockland Channel Bridge

Florida

Prepared for:

Coastal Gunite Construction Company
Hughes Brothers, Inc

(Project Code `R05FL1-1`)

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1 INTRODUCTION

This document reports on the strengthening of Rockland Channel Bridge located on the Florida Keys, USA.

Coforce is proposing a strengthening technique based on the use of Near Surface Mounted (NSM) Carbon Fiber Reinforced Polymer (CFRP) bars. A brief introduction of this technology is presented in Section 2.

Coforce calculations related to Aslan 200 CFRP bars, manufactured by Hughes Brothers, Inc., used as replacement of MMFX steel bars is presented. Such analysis is valid only when Aslan 200 CFRP bars are used.

The present analysis of Aslan 200 CFRP replacement of MMFX steel needs to be considered applicable to those regions where the original MMFX steel strengthening was supposed to be installed.

From the received drawings, it appears that the deficiency is related to the negative moment region of the overhang portion of the bridge deck. For the purpose of the design calculations that follow (intended to demonstrate the logic for the suggested alternative), the overhang is treated as a conventional reinforced concrete member supported on steel girders. Similar calculations can be performed for the case of a fully composite structure.

ACI is currently updating the document 440.2R-02 “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures” [1] to include the use of NSM technique proposed in this document. At this time, reference will be made to the paper by Parretti and Nanni titled “Strengthening of RC Members Using Near-Surface Mounted FRP Composites: Design Overview”, published in the Advances in Structural Engineering (Vol. 7, No. 6, pp. 469-483, 2004) [2]. This publication was used as the basis of the proposed ACI document revision.

2 NSM TECHNOLOGY

2.1 Introduction

The use of Near-Surface Mounted FRP bars represents a complementary technology to externally bonded FRP laminates, which have already been proven as an effective upgrade technique for reinforced concrete (RC) structures.

FRP material systems, composed of fibers embedded in a polymeric matrix, exhibit several properties suitable for their use as structural reinforcement. FRP composites are anisotropic and characterized by excellent tensile strength in the direction of the fibers. They do not exhibit yielding, but instead are elastic up to failure. FRP composites are corrosion resistant, and therefore should perform better than other construction materials in terms of weathering behavior.

The use of NSM reinforcement was developed in Europe for strengthening of RC structures in the early 1950s. Stainless steel has replaced the original black steel adopted at the onset of the development, while the cementitious grout used for embedding the reinforcement has been partially replaced by epoxy-based grouts.

Today, FRP bars have became attractive for their non-corrosive properties and the ability of tailoring the bar stiffness to the needs of the application. Epoxy-based pastes or latex-modified cement grouts can be used for their rapid setting and bond strength.

2.2 NSM FRP Bars Installation

The technique (Figure 1) involves embedment of a bar, which is achieved by grooving the concrete surface (Figure 1*a*) along the desired direction; the groove depth is minimal as to not significantly affect the concrete cover of the steel reinforcement. The groove is filled half way with epoxy paste (Figure 1*b*), and the CFRP bar is lightly pressed into the paste. The groove is then filled with more paste and the surface is leveled (Figure 1*c*).

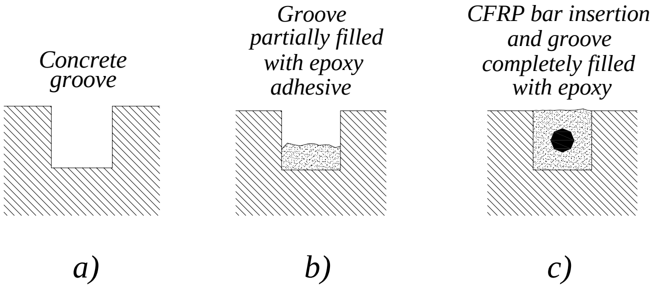


Figure 1 – NSM Technique

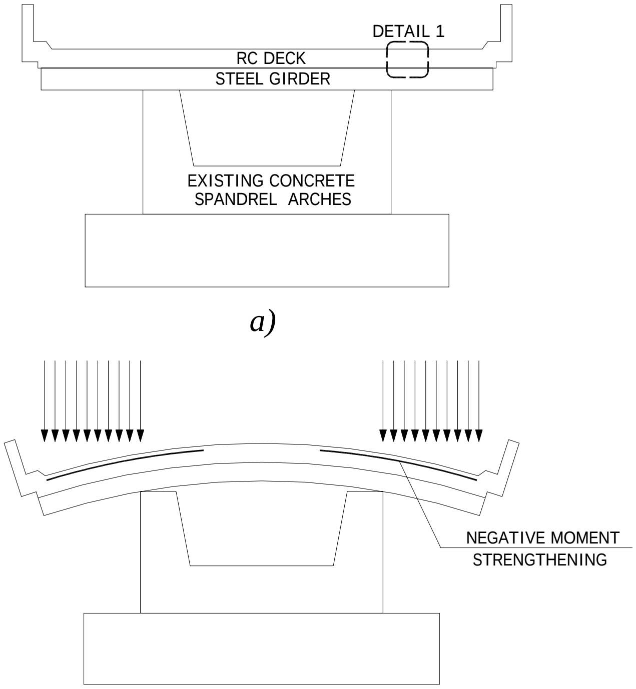
3 STRUCTURAL ANALYSIS

Coforce did not perform the bridge structural analysis. The analysis of MMFX steel replacement is performed as follows:

a. The flexural capacity adopting MMFX steel solution, $(\phi M_n)_{MMFX}$, is computed based on the information provided in the received drawings and based on the assumptions stated in this document.
b. Aslan 200 CFRP design replacement of MMFX steel is such that the flexural capacity of the proposed solution, $(\phi M_n)_{Aslan}$, is equal to or larger than $(\phi M_n)_{MMFX}$.

A typical cross-section of the bridge is shown in Figure 2*a)*. The reinforced concrete (RC) deck is considered supported on steel girders; therefore, the deck main flexural reinforcement runs in the water direction (orthogonal to the traffic direction).

Due to the support offered by the existing concrete spandrel arches, negative moment appears on the top bridge deck portion of the overhang when the loading condition is as summarized in Figure 2*b)*.



a)

b)

Figure 2 – Typical Bridge Cross-Section

The present design calls for the concrete bridge deck strengthening in its negative moment region using #6 MMFX steel bars, each inserted into a *1 ½”* wide, *3”* deep groove cut into the concrete deck and bonded with an epoxy paste. In this proposal, a replacement of MMFX bars with Aslan 200 CFRP bars is proposed. The main reasons to consider such an alternative are (Figure 3):

a. From an economical point of view, there is a large use of epoxy paste that is needed to completely fill the space between the steel bar and the groove. FRP bars call for a much smaller cut.
b. Similarly, the cost of the cutting is function of the depth of the cut.

From a technical point of view, a *3"* deep groove will result in the cutting of any existing steel reinforcement used for temperature and shrinkage (T&S).

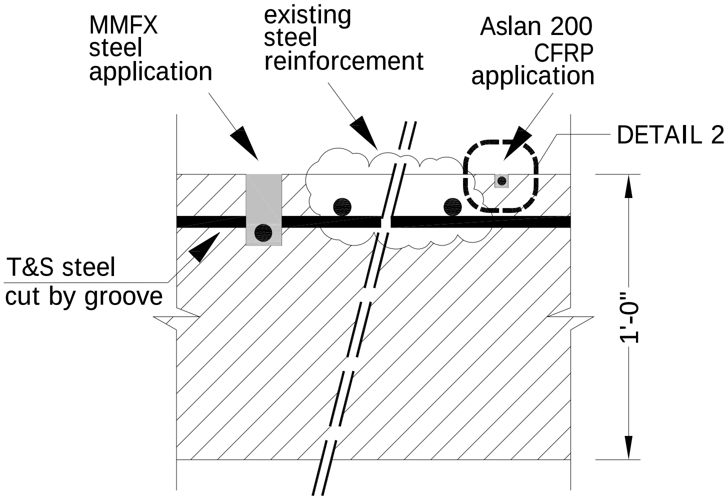


Figure 3 – Cross-Section Detail 1 (See Figure 2)

4 MATERIAL PROPERTIES

4.1 Concrete

The concrete compressive strength is assumed equal to $f'_c = 3{,}000\ psi$ as indicated in the received drawings.

4.2 MMFX Steel

MMFX Steel tensile properties are summarized in Table 1. Figure 4 shows the stress-strain diagram of MMFX steel versus traditional black steel.

Table 1 – MMFX Steel Properties

Ultimate Tensile Strength (ksi)	Modulus of Elasticity (ksi)	Design Yield Strength (ksi)
150	29,000*	80

* Not published in the MMFX brochure available.

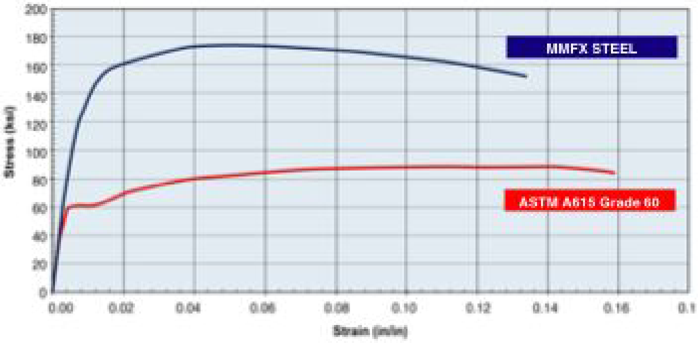


Figure 4 – Stress-Strain Relationship for MMFX and Grade 60 Steel

Few comments on the tensile properties of both materials reported in Figure 4 are offered here:

a. From the stress-strain diagram (taken from a MMFX brochure), it is unclear why the design yield strength should be *80 ksi*. A possible reason for such a low value is due to the fatigue performance of MMFX steel: at *25* years f_y has an endurance limit of *80 ksi*.
b. The value of the modulus of elasticity is not published in the MMFX brochure available. Because the two curves displayed in Figure 4 related to MMFX steel and grade 60 steel show the same stiffness, *Coforce* will assume $E_{MMFX} = E_{grade\ 60\ steel} = 29{,}000\ ksi$.

4.3 CFRP

CFRP material properties are summarized in Table 2. Their values represent guaranteed values as reported by the manufacturer, Hughes Brothers, Inc Seward, NE (USA). The design is applicable to the material as specified in Table 2 only.

Similarly to grade 40 and grade 60 steel, different CFRP bar properties can be obtained depending upon the specific tensile properties of the carbon fiber employed as shown in Aslan 200 CFRP Bar Types 1 and 2 of Table 2.

The design presented in this document considers both Types 1 and 2 CFRP material. The contractor can choose the more appropriate solution to the site operation.

Table 2 – GFRP Properties

Aslan 200 CFRP Bar Type	Bar Size	*Bar Area* A_f [in^2]	*Guaranteed Tensile Strength* f^*_{fu} [ksi]	*Young's Modulus* E_f [ksi]	*Guaranteed Tensile Strain* ε^*_{fu} [-]
1	#3	0.10	250	20,000	0.0125
2	#3	0.10	339	21,000	0.0161

Coforce will not be held responsible for conclusions, interpretations, or recommendations of others adapting the present design to different FRP systems.

5 PROPOSED CFRP DESIGN USING NSM BARS

5.1 Design Tensile Properties

Material properties of CFRP reinforcement reported by manufacturers, such as the ultimate tensile strength, typically do not consider long-term exposure to environmental conditions, and should be considered as initial properties. FRP properties to be used in all design equations are given as follows (ACI 440):

$$\begin{aligned} f_{fu} &= C_E f^*_{fu} \\ \varepsilon_{fu} &= C_E \varepsilon^*_{fu} \end{aligned} \tag{1}$$

where f_{fu} and ε_{fu} are the FRP design tensile strength and ultimate strain considering the environmental reduction factor $(C_E=0.85)$ as given in Table 8.1 [1], and f^*_{fu} and ε^*_{fu} represent the FRP guaranteed tensile strength and ultimate strain as reported by the manufacturer (see Table 2). The FRP design modulus of elasticity is the value E_f as reported by the manufacturer.

5.2 Flexural Design

5.2.1 General Assumptions

The flexural design of RC members strengthened with FRP uses the same assumptions of conventional RC theory, namely:

1) A plane section before loading remains plane after loading;
2) The tensile strength of the concrete is neglected;
3) The maximum concrete compressive strain is 0.003.

In addition, the assumption of linear-elastic stress-strain relationship needs to be introduced to take into account for the particular nature of FRP reinforcement.

Because the use of FRP as strengthening technique could reduce the ductility of the strengthened member, the strength reduction factor, ϕ, needs to be determined ad-hoc as stated in the next Section.

5.2.2 Strength Reduction Factor

The approach taken by ACI 440 follows the same philosophy of ACI 318-99 [3] (Appendix B) where a section with low ductility should be compensated with a higher reserve of strength. The ACI 440 proposed equation is as follows:

$$\phi = \begin{cases} 0.90 \quad if \quad \varepsilon_s \geq 0.005 \\ 0.70 + \dfrac{0.20\left(\varepsilon_s - \varepsilon_{sy}\right)}{0.005 - \varepsilon_{sy}} \quad if \quad \varepsilon_{sy} < \varepsilon_s < 0.005 \\ 0.70 \quad if \quad \varepsilon_s \leq 0.005 \end{cases} \tag{2}$$

where ε_s is the calculated strain in the existing steel reinforcement, and ε_{sy} represents the strain in the steel at yielding.

5.2.3 Member Capacity

Coforce assumes that the bridge deck cross-section is *1'-0"* thick. Because no information is provided on the existing internal steel reinforcement, *Coforce* will assume that top steel reinforcement area is equal to *50%* of ρ_{max} ($A_s=0.67$ in^2/ft). The effective depth, *d*, of the internal steel reinforcement is assumed equal to *10 in.*, while its yield strength is assumed to be *40 ksi* (Grade 40 steel).

The actual spacing of MMFX steel shown in the received drawings is equal to *1.28 ft. (=10.25 ft/8 bars)*. The corresponding area of MMFX steel is calculated as follows: *(1/1.28) x Area 1#6=0.34* in^2/ft.

Table 3 summarizes the data used in the calculations and the corresponding flexural capacities when both MMFX steel and Aslan 200 CFRP bars are used

Table 3 – Assumed Data for the Design

Bar Type	**b** (in.)	**d** (in.)	**Bar Size**	**Bar Spacing**	**Area** (in^2/ft)	κ_m (-)	ϕM_n (k-ft)
MMFX	12	10.5	#6	15" (*)	0.34	0.7	32.5
Aslan 200 Type 1	12	11.7	#3	8"	0.15	0.7	33.7
Aslan 200 Type 2	12	11.7	#3	12"	0.10	0.7	32.5

(*) 15" represents an equivalent MMFX bar spacing because the as designed spacing is not uniformly distributed (slots at 6" then 2'-7").

The κ_m factor takes into account debonding as a possible failure mode and it has been assumed equal to 0.7 has suggested in [2]. In fact, as shown in the literature [4], the κ_m factor accounts for the failure occurring at the interface between concrete and epoxy paste or in the concrete itself and is independent of the bar material type.

5.3 *Development Length*

Bond properties between CFRP reinforcement and concrete are similar to that of steel reinforcement. From the equilibrium condition of a bar embedded in the concrete, the following equation can be derived for the development length:

$$l_d = \frac{d_b}{4(0.5\tau_{\max})} f_{fe} \tag{3}$$

where the maximum bond stress, τ_{max}, has been assumed equal to *1000 psi*. The resulting development length is shown in Table 4.

Table 4 – Development Length

Aslan 200 Bar Type	f_{fe} (psi)	l_d (in.)	Aslan 200 Total Bar Length
1	175,000	*3'-0"*	*5'-0"+3'-0"=8'-0"*
2	201,600	*3'-6"*	*5'-0"+3'-6"=8'-6"*

The total bar length is the sum of the overhang length *(5'-0")* and the development length l_d.

5.4 Reinforcement Detail and Bill of Reinforcement

For surface preparation work and NSM installation process see Section 2.2.

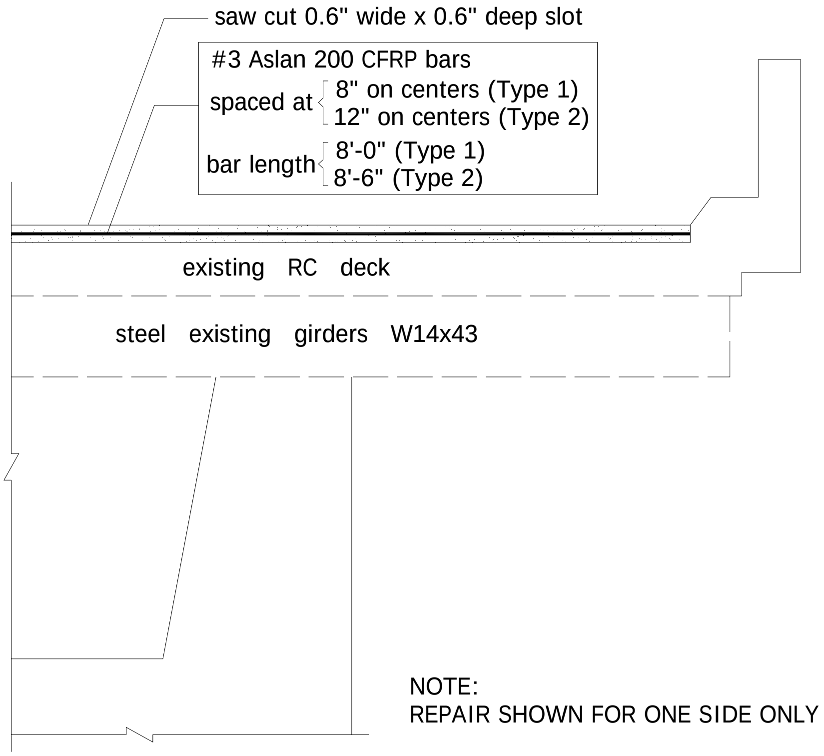
The minimum dimension of the grooves is taken at least *1.5* times the diameter of CFRP bar (Figure 6).

Figure 5 shows a typical bridge cross-section strengthened with Aslan 200 CFRP bars.

Table 5 summarizes the schedule of Aslan 200 CFRP reinforcement needed for strengthening at the appropriate locations.

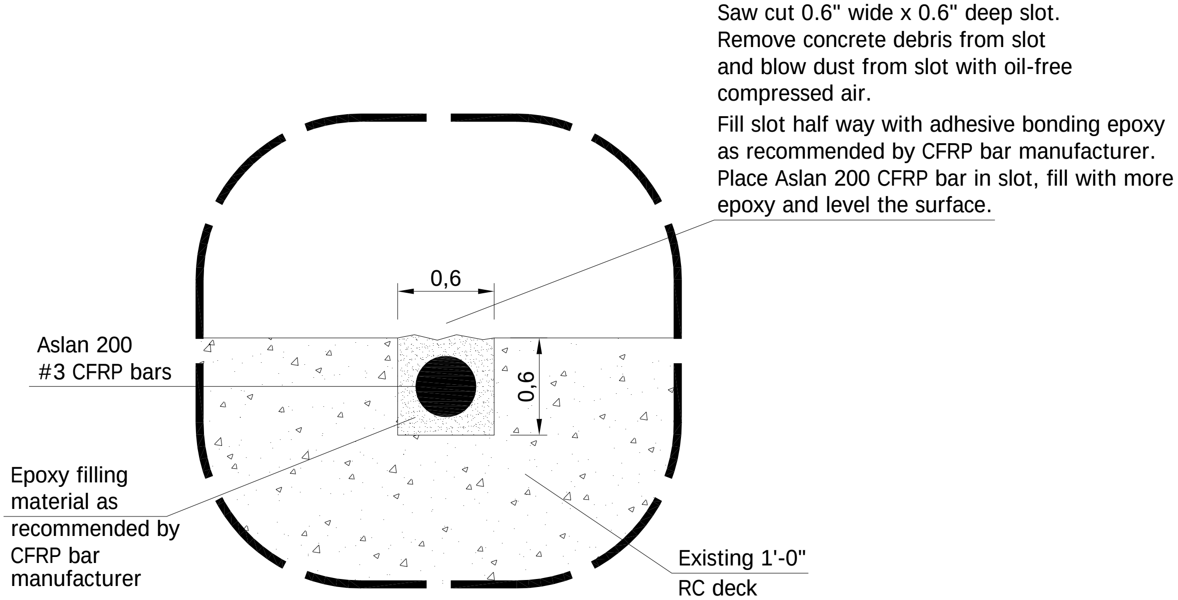
Table 5 – Schedule of Aslan 200 CFRP Reinforcement

CFRP Bar Type	CFRP Bar Size	CFRP Bar Length	Spacing of CFRP Bars
1	#3	*8'-0"*	*8"*
2	#3	*8'-6"*	*12"*



NOTE:
REPAIR SHOWN FOR ONE SIDE ONLY

Figure 5 – Bridge Strengthening Cross-Section (Not to Scale)



Saw cut 0.6" wide x 0.6" deep slot. Remove concrete debris from slot and blow dust from slot with oil-free compressed air.

Fill slot half way with adhesive bonding epoxy as recommended by CFRP bar manufacturer. Place Aslan 200 CFRP bar in slot, fill with more epoxy and level the surface.

Figure 6 – Detail 2 (see Figure 3) (Measure in in., Not to scale)

6 REFERENCES

[1] ACI 440.2R-02, 2002: “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures,” Published by the *American Concrete Institute*, Farmington Hills, MI.

[2] Parretti, R., and Nanni, A., 2005: “Strengthening of RC Members Using Near-Surface Mounted FRP Composites: Design Overview”, *Advances in Structural Engineering*, Vol. 7, No. 9, pp. 469-483.

[3] ACI 318-95, 1999: “Building Code Requirements for Structural Concrete and Commentary (318R-99),” Published by the American Concrete Institute, Farmington Hills, MI.

[4] Hassan, T., and Rizkalla, S., 2003: “Investigation of Bond in Concrete Structures Strengthened with Near Surface Mounted Carbon Fiber Reinforced Polymer Strips” Journal for Composite for Construction, Vol. 7, No. 3, pp. 499-509.