coforce

FOUR SEASONS HOTEL/APPTS
NEGATIVE MOMENT STRENGTHENING
Miami, FL

Prepared for:
Hughes Brothers

(Project Code R04FL1-1)

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A INTRODUCTION

This document reports on negative moment strengthening of post-tensioned slab using Near-Surface Mounted (NSM) Fiber Reinforced Polymer (FRP) bars. The slabs belong to the Four Season Hotel/Apartments located in Miami, FL.

The use of NSM FRP reinforcement is an attractive method for increasing both flexural and shear strength of deficient reinforced and prestressed concrete (RC and PC) members (De Lorenzis et al., 2000). Advantages with respect to externally bonded FRP laminates include the possibility of anchoring the reinforcement into adjacent members, and the opportunity of upgrading elements in their negative moment region with the reinforcement not exposed to potential mechanical damage typical of floor or deck systems (Nanni et al. 1999). The NSM FRP technique does not require extensive surface preparation work and requires minimal installation time compared to externally bonded FRP laminates.

The strength design approach with its strength reduction factors as used in ACI 318 (1999) is recommended for RC and PC members using NSM FRP reinforcement. Reference to this version of the Building Code rather than the 2002 edition is necessary to remain consistent with the design guide issued by ACI on the use of FRP for concrete strengthening. Additional strength reduction factors applied to the contribution of the NSM reinforcement are suggested to reflect the novelty of FRP systems compared with traditional methods. The equations presented in this report are based on principles of force equilibrium, strain compatibility, constitutive laws of the materials, and make reference to the "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures" reported by ACI Committee 440 (2002) (referred to as "ACI 440" in this document).

Figure 1 shows two pictures of NSM installation performed on a solid concrete deck slab in Rolla, MO (Casadei et al., 2003).

Figure 1 – NSM Installation on a RC Deck Bridge

B STRUCTURAL ANALYSIS

B.1 Ultimate Limit State

Coforce did not perform the members' structural analysis. In stead of the usual practice of verifying that the factored moment capacity, ϕM_n, is larger than the ultimate factored demand, M_u, a slightly different approach will be followed in this document. The post-tensioned slab needs to be strengthened in its negative moment region. The Engineer-of-Record, Joseph N. Benton of DeSimone Consulting Engineers, Coral Gables, FL, is interested in the replacement of the already designed steel bars used as negative moment strengthening with non-metallic and non-corrosive FRP material. Therefore, the design using FRP will be carried out according to the following equation:

$$(\phi M_n)_{FRP} \geq (\phi M_n)_{Steel} \qquad (1)$$

irrespectively of the required ultimate demand which is not known.

As agreed with the Engineer-of-Record during our phone conversation, the equivalent design will be performed neglecting the presence of the post-tensioned tendons. This is to simplify computations and remain conservative since tendons are not uniformly distributed in the direction where the additional reinforcement needs to be provided.

Table 1 summarizes the original and strengthened factored flexural capacity of the slab when only steel is used. The design is carried out considering the unit slab width equal to *1 ft*.

Table 1 – Steel Design

Description	$(\phi M_n)_{Steel}$ *[k-ft/ft]*
Original Slab	14.7
Steel Strengthened Slab	37.3

The strengthening of the slab is achieved using a #6 steel bar at *12 in.* on centers.

B.2 Assumptions on Slab Geometry and Steel Reinforcement

The analysis performed on Section B.1 and the results summarized in Table 1 depend on the geometry, quality of concrete and steel, and location of the in place steel reinforcement given for the as built slab. Table 2 reports the parameters assumed for the analysis as given to *Coforce* by the Engineer-of-Record.

Table 2 – Assumptions for the Design

Slab Description	*Slab Thickness h (in.)*	*Slab Width b (in.)*	*Slab Effective depth d (in.)*	*Area of Tension Reinforcement A_s (in^2/ft)*	*Concrete Compressive Strength f'_c [psi]*	*Steel Yield Strength f_y [ksi]*
Original Slab	12	12	11.25	[#6@18 in.] 0.293	7000	60
Steel Strengthened Slab	12	12	11.62	[#6@18 in. + #6@12 in.] 0.733	7000	60

Any change in the above indicated parameters will result in a change of the flexural capacities reported in Table 1.

C FRP MATERIAL PROPERTIES

C.1 CFRP BARS

CFRP material properties are summarized in Table 3. Their values represent guaranteed values as reported by the manufacturer, Hughes Brothers, Inc. The design is applicable to the material as specified in Table 3 only.

Table 3 – GFRP Properties

Bar Code	*Bar Cross Section*	*Bar Type*	*Bar Area (in^2)*	*Ultimate Tensile Strength f^*_{fu} [ksi]*	*Strain at Rupture ε^*_{fu} [in./in.]*	*Young's Modulus E_f [ksi]*
Aslan 200	Circular	#2	0.046	300	0.017	18,000
		#3	0.101	300	0.017	18,000
Aslan 500	Rectangular	Tape	0.112	300	0.017	18,000

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

D PROPOSED CFRP DESIGN

D.1 Design Tensile Properties

Material properties of the FRP 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):

$$\begin{aligned} f_{fu} &= C_E f^*_{fu} \\ \varepsilon_{fu} &= C_E \varepsilon^*_{fu} \end{aligned} \tag{2}$$

where f_{fu} and ε_{fu} are the FRP design tensile strength and ultimate strain considering the environmental reduction factor (C_E) as given in Table 8.1 (ACI 440), and f^*_{fu} and ε^*_{fu} represent the FRP guaranteed tensile strength and ultimate strain as reported by the manufacturer (see Table 3). The FRP design modulus of elasticity is the average value as reported by the manufacturer.

Assuming interior exposure condition, the environmental reduction factor, C_E, can be taken equal to *0.95*.

D.2 Flexural Design

D.2.1 Ultimate Limit State

The flexural design of a FRP strengthened RC member is similar to the design of a steel reinforced concrete member. The main difference is that both concrete crushing and FRP rupture are allowed mechanisms of failure. To account for the different behavior displayed by tension-controlled failures, a modified strength reduction factor needs to be introduced as briefly summarized in the next section.

D.2.1.1 Strength Reduction Factor

Because a reinforced concrete member strengthened using NSM FRP bars could be less ductile than the original member, the strength reduction factor, ϕ, needs to be revisited according to the findings of the following equation (ACI 440):

$$\phi = \begin{cases} 0.90 & for \quad \varepsilon_s \geq 0.005 \\ 0.70 + \dfrac{0.20(\varepsilon_s - \varepsilon_{sy})}{0.005 - \varepsilon_{sy}} & for \quad \varepsilon_{sy} < \varepsilon_s < 0.005 \\ 0.70 & for \quad \varepsilon_s \leq \varepsilon_{sy} \end{cases} \tag{3}$$

where all symbols are reported in APPENDIX I.

Eq. (3) sets the reduction factor equal to *0.90* for ductile sections and equal to *0.70* for brittle sections where the steel does not reach the yielding point. Furthermore, it provides a linear transition for ϕ when steel strain at failure is between *0.005* and *0.00207*.

D.2.1.2 Member Flexural Capacity

The flexural capacity of a RC section strengthened using NSM FRP bars can be written as follows (ACI 440):

$$M_n = A_s f_s \left(d - \frac{\beta_1 c}{2} \right) + \psi_f A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2} \right) \tag{4}$$

where all symbols are reported in APPENDIX I and Figure 2. The additional reduction factor, ψ_f, to be applied to the FRP contribution has been taken equal to *0.85* as suggested by ACI 440.

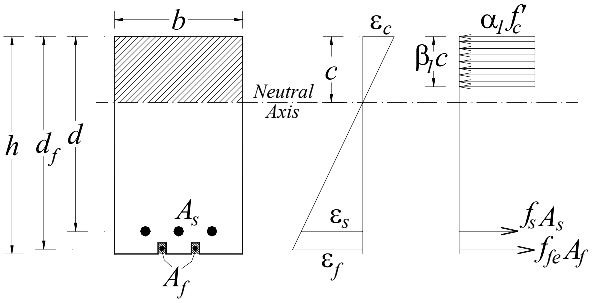

Figure 2 – Ultimate Internal Strain and Stress Distribution for Rectangular Sections

Table 4 summarizes ultimate flexural capacities of the FRP strengthened slab as a function of the reinforcement adopted.

Table 4 – Aslan CFRP Flexural Design

Bar Code	*Bar Type*	*Bar Spacing (in.)*	*Effective Depth, d [mm]*	*FRP Flexural Capacity, $(\phi M_n)_{FRP}$ [k-ft/ft]*	*Steel Flexural Capacity, $(M_u)_{Steel}$ [k-ft/ft]*
Aslan 200	#2	9	11.7	24.2	33.7 (See Table 1)
		6	11.7	29.0	
	#3	12	11.7	29.0	
		9	11.7	33.7	
Aslan 500	Tape	12	11.7	30.9	
		9	11.7	36.3	

In order for Eq. (1) to be satisfied the two following proposal of strengthening could be adopted:

- Use Aslan 200, #3 CFRP bar at *9 in.* on centers; or
- Use Aslan 500, CFRP Tape at *9 in.* on centers.

D.3 Shear Design

No information were provided on shear. *Coforce* assumes that shear is not an issue in this strengthening proposal.

D.4 Development Length

The development length, ℓ_d, of a straight bar is highly dependant upon bar dimensions, groove size (See Section D.5), internal steel reinforcement ratio and steel lay out, and concrete and adhesive properties.

An equivalent method to compute development length for NSM bars is under consideration by ACI Committee 440. It refers to the equilibrium condition of an embedded FRP bar subjected to a pull out force. The pull out force in the bar is resisted by an assumed triangular shear stress distribution along the embedded length of the bar itself. Assuming an average shear stress equal to $0.5\,\tau_{max}$, the development length for circular and rectangular bars can be expressed as follows:

$$\begin{aligned} l_d &= \frac{d_b}{4(0.5\tau_{\max})} f_{fe} \qquad \textit{Circular bar} \\ l_d &= \frac{a \cdot b}{2(a+b)(0.5\tau_{\max})} f_{fe} \qquad \textit{Rectangular bar} \end{aligned} \tag{5}$$

where all symbols are reported in APPENDIX I. The effective stress, f_{fe}, acting on the bar is calculated as follows:

$$f_{fe} = \varepsilon_{fe} E_f \tag{6}$$

where ε_{fe} represents the FRP strain at section failure not necessarily coincident with the ultimate tensile strain of the bar.

ACI Committee 440 is considering for τ_{max} a conservative value of *1.0 ksi*.

Table 5 summarizes the development length calculated using Eq. (5) as a function of the strengthening method adopted.

Table 5 – Development Lengths

Bar Code	*Bar Type*	*Development Length* l_d *[in.]*
Aslan 200	#2	25
	#3	38
Aslan 500	Tape	30

D.5 Groove Size

When a circular bar is used, the minimum dimension of the groove should be at least 1.5 times the FRP bar diameter; in case of rectangular bars, however, this limitation may loose of significance due to constructability. In such a case a minimum groove size of $3.0a \times 1.5b$ could be used, where *a* and *b* are the smallest and largest bar dimension.

Figure 3 shows a cross-section of the negative moment region of the strengthened slab with the suggested minimum groove dimensions. In some instances, the minimum groove dimension could be the result of installation requirement, rather than engineering.

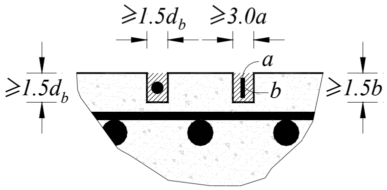

Figure 3 – Minimum Groove Dimensions for Circular and Rectangular Bars

E REFERENCES

ACI 318-99, “Building Code Requirements for Structural Concrete and Commentary”, Reported by Committee 318, American Concrete Institute, Farmington Hills.

ACI 440.2R-02, “Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures”, Reported by Committee 440, American Concrete Institute, Farmington Hills

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Nanni, A., Alkhrdaji, T., Barker, M., Chen, G., Mayo, R., and Yang, X., (1999). “Overview of Testing to Failure Program of a Highway Bridge Strengthened with FRP Composites”, *Proceedings of Fourth International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-4),* SP-188, C. W. Dolan, S. Rizkalla, and A. Nanni, Eds., American Concrete Institute, Farmington Hills, Mich., pp. 69-75.

APPENDIX I

a = Smallest FRP rectangular bar dimension
A_s = Area of mild tension steel reinforcement
A_f = Area of FRP reinforcement
b = Slab width, and largest FRP rectangular bar dimension
c = Distance from extreme compression fiber to neutral axis
C_E = Coefficient of environmental exposure
d = Effective depth
d_b = FRP bar diameter
d_f = Effective depth of FRP reinforcement
E_f = FRP modulus of elasticity
f'_c = Concrete compressive strength
f_{fe} = Effective stress in FRP reinforcement
f_{fu} = FRP design tensile strength
f^*_{fu} = FRP guaranteed tensile strength
f_s = Stress of mild tension steel at failure
f_y = Yield strength of mild tension steel
h = Slab thickness
l_d = FRP development length
M_n = Member nominal flexural capacity
M_u = Ultimate flexural demand (factored)
β_1 = factor defined in Section 10.2.7.3 of ACI 318-99
ϕM_n = Member factored flexural capacity
ε_c = Concrete compressive strain at failure
ε_f = FRP strain at failure
ε_s = Steel strain at failure
ε_{sy} = Steel strain at yielding
ε_{fu} = FRP design tensile strain
ε^*_{fu} = FRP guaranteed tensile strain
ϕ = Strength reduction factor
τ_{max} = Maximum shear stress for an embedded FRP bar
ψ_f = Additional reduction factor for RC member strengthened with FRP